SEDIMENTOLOGY, TECTONIC FRAMEWORK AND ECONOMIC POTENTIAL OF THE SINAKUMBE GROUP (?ORDOVICIAN TO DEVONIAN) AND KAROO SUPERGROUP (PERMO-CARBONIFEROUS TO LOWER JURASSIC) IN THE MID-ZAMBEZI VALLEY BASIN, SOUTHERN ZAMBIA

by

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TITLE: Sedimentology, tectonic framework and economic potential of the Sinakumbe Group (?Ordovician to Devonian) and Karoo Supergroup (Permo-Carboniferous to Lower Jurassic) in the mid-Zambezi Valley Basin, southern Zambia

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DEDICATION

(a)

(b)

This thesis is dedicated to the memories of (a) Dr. Brian R. Rust (supervisor) and (b) Mr. Benson Nyambe Imasiku (father).

Brian supervised and funded the field aspect of this project in Zambia where he contracted the malaria that led to his death in June 1990. Brian had a keen intellect, a fine sense of humour, and a burning desire to help those in need. In this regard I remember Brian urging the Canadian Commonwealth Committee (my sponsors) to change their regulations so that scholars from the developing world could do projects in their own countries, a suggestion the committee later adopted. He was however prepared to fund the entire project in the event of a negative response from the committee.

My father died in December, 1991 and is remembered for endless sacrifices and encouragement throughout my education life. I will miss both men, may their souls rest in peace.

EXTENDED ABSTRACT

Sediments of the ? Ordovician to Devonian Sinakumbe Group (~ 210 m thick) and overlying Late Carboniferous to Early Jurassic Karoo Supergroup (~ 4.5 km thick) were deposited in the mid-Zambezi Rift Valley Basin, southern Zambia. The Sinakumbe Group directly overlies the Precambrian Basement Complex, and Lower and Upper subgroups are recognised. The Karoo Supergroup unconformably overlies the Precambrian Basement or rests locally on the Sinakumbe Group. Lower and Upper groups are recognised in the Karoo, with their contact approximately at the Permian-Triassic boundary. From base to top, the Lower Karoo Group is subdivided into the Siankondobo Sandstone, Gwembe Coal, and Madumabisa Mudstone formations and the Upper Karoo Group into the Escarpment Grit, Interbedded Sandstone and Mudstone, Red Sandstone and Batoka Basalt formations. Limited palaeontological data from the mid-Zambezi Valley Basin suggest that the Siankondobo Sandstone is Late Carboniferous to Early Permian in age, the Gwembe Coal Formation is Early Permian, the Madumabisa Mudstone is late Permian, and the Interbedded Sandstone and Mudstone Formation is Early to Middle (?) Triassic.

The Sinakumbe-Karoo basin-fill succession represents deposition in a distensive fault-controlled basin of half-graben type. The succession incorporates two major fining-upward cycles that resulted from major tectonic events, one at the beginning of Sinakumbe Group sedimentation and the other at the beginning of Upper Karoo Group sedimentation. Minor tectonic pulses occurred during deposition of the two major cycles. The initial fault-controlled half-graben, with a basin slope and alluvial fan system (Lower Sinakumbe Group) draining southeastward, was apparently succeeded without intervening transitional facies by a braided river system (Upper Sinakumbe Group) draining southwestward, parallel to the basin margin. Glaciation followed by deglaciation resulted in glacio-fluvial / glacio-lacustrine Siankondobo Sandstone Formation deposits, and isostatic rebound eventually produced a broad floodplain where the coal-bearing Gwembe Coal Formation was deposited. Fault-controlled maximum subsidence is represented by the lacustrine Madumabisa Mudstone Formation. Block-faulting and downwarping, probably due to the Gondwanide Orogeny, culminated with the introduction of large quantities of sediment

through braided fluvial systems, represented by the Escarpment Grit and Interbedded Sandstone and Mudstone formations, that overwhelmed and terminated Madumabisa lake sedimentation.

The Sinakumbe Group is recognised for the first time in outcrops. The Lower Sinakumbe Group (~ 60 m thick) is a coarsening-upward allocyclic sequence that represents progradation of an alluvial fan-lobe (conglomerate facies assemblage) down slope across mud flat and sand flat environments (mudrock facies assemblage) in response to tectonic uplift followed by waning subsidence. Within this sequence, small-scale fining- and coarsening-upward cycles represent autocyclic facies changes inherent to the alluvial-fan system. The disconformably overlying Upper Sinakumbe Group (over 150 m thick) consists predominantly of massive to stratified, medium-grained to pebbly quartz arenite lithofacies with subordinate mudclast breccia lithofacies. This quartz arenite facies assemblage is interpreted as braided-stream deposits in which the mudclast breccia lithofacies represents channel bank collapse.

The Permo-Carboniferous Siankondobo Sandstone Formation (90 m thick) contains three facies assemblages. A diamictite facies assemblage is interpreted as subaqueous debris flow deposits from glacier melt-water. A succeeding siltstone facies assemblage is attributed to density underflows of sediment-laden meltwater flowing into a glacial lake, and sediment settling from suspension. A sandstone facies assemblage was emplaced by a variety of grain-support mechanisms, probably as subaqueous gravity flows in channels, and the downstream accretion surfaces in the upper part of the assemblage indicate fluvial deposition in a deltaic setting.

The Lower Permian Gwembe Coal Formation (280 m thick) represents deposition of sandstones, siltstones and mudstones in fluvial channels and on flood plains, and of coals in shallow swampy areas. Fourteen lithofacies in the formation are grouped into four facies assemblages. The Maamba Sandstone facies assemblage is probably a high-sinuosity meandering stream deposit. Accumulation of organic deposits (coal facies assemblage) in the swamps was interrupted by deposition of channel, crevasse channel and splay, levee (Interseam Sandstone) and overbank fine deposits. One sandstone body (Sandstone A facies assemblage) represents a change in fluvial style from proximal braided system to high-sinuosity meandering stream. The mudrock facies assemblage is mainly overbank fine deposits with abundant concretionary siderite beds that were diagenetically precipitated.

The Upper Permian Madumabisa Mudstone Formation (700 m thick) comprises two facies assemblages. Sediments of a massive mudrock facies assemblage were probably deposited from suspension from sediment-laden river water entering a lake. Concretionary calcilutite beds probably mark the positions of palaeosediment-water interfaces where calcite was precipitated. A laminated mudrock facies assemblage is attributed to proximal to distal lacustrine deposition from sheetfloods and inflowing rivers. Repeated thickening-upward cycles are evidence of upward shallowing, interrupted by events of more abrupt deepening. Sandstone interbeds are interpreted as fluvial deposits laid down during low lake stands. A fossil biota of ostracods, bivalves, gastropods, fish scales, the alga *Botryococcus* sp. and fossil burrows are consistent with a lacustrine origin of the formation.

The Triassic Escarpment Grit Formation (up to 500 m thick), consists of coarse to very coarse grained stratified sandstone (grit), with locally abundant conglomeratic sandstone lags, that grades into finer-grained sandstone and intercalated mudstone. This sandstone/mudrock facies assemblage occurs in poorly arranged fining-upward cycles interpreted as braided river deposits. The Middle (?) Triassic Interbedded Sandstone and Mudstone Formation (up to 2000 m thick), consists of a mudrock/sandstone facies assemblage arranged in fining-upwards cycles of sandstone (pebbly to very fine-grained, with basal lags and conglomerates), siltstone and mudstone. The sequence represents sandy braided river deposits transitional to a high-sinuosity meandering stream system.

The Karoo Supergroup has promising economic potential for energy and mineral resources (e.g. 5-12 m thick Main Seam of Gwembe Coal Formation). Coal is currently mined and indications are that, owing to block faulting, some coal-bearing sub-basins are buried and not yet discovered. The thermal alteration index of 2 (~ 5%Ro reflectance index) of the coals in the Gwembe Coal Formation and of the dark grey thinly laminated mudstone of the Madumabisa Mudstone Formation, and the presence of the alga *Botryococcus* sp. in the latter, coupled with considerable burial depth, indicate strong potential for liquid hydrocarbons. The braided fluvial deposits of the Escarpment Grit and Interbedded Sandstone and Mudstone formations are known to contain uranium mineralisation that is worth further investigation.

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In a broad study such as this, there are numerous persons and organisations to be acknowledged. Just as Douglas Stewart did in his 1991 doctoral thesis acknowledgements, I will also break the tradition of first thanking individuals and organisations that financed and supervised the study, and start with my family. I would like to thank my spouse Elizabeth Nyambe, for her endless patience, understanding, taking care of our three children (Anayawa, Sikopo, and Sanyambe) and typing the thesis. My daughter, Anayawa helped type parts of the thesis with a skilful invention of new English words that would take time to correct. My second daughter Sikopo Pauline, contributed with endless questions off topic. Perhaps the most significant contribution came from my third daughter, Sanyambe, born in the final academic year of this study, who, because of the sleepless nights she presented me, assisted in keeping me awake and thus, continuing work on my thesis. My mother and late father are remembered for their continued encouragement and sacrifices throughout my education life. The entire extended family is thanked for encouragement and assistance to my family during my absence from Zambia. Special thanks are due to aunt Sitamulaho Lifanu, my brothers Muliunda Mufalo and Mushimbei Nyambe and families.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

1.0 INTRODUCTION

1.1 GENERAL STATEMENT

"Karoo" is a term broadly applied mainly to continental rift sediments that are preserved in many parts of what was eastern Gondwana from Late Palaeozoic to Early Jurassic. The sediments were deposited in a series of rifts or half graben basins initiated during the break-up of Gondwana. Coeval sediments are present in southern South America, India, Pakistan, southern Tibet, New Zealand, Australia, New Guinea and Antarctica (Utting and Wielens, 1992). In Africa, Karoo sediments are confined to southern Africa (Fig. 1.0), occurring in Angola, Botswana, Ethiopia, Gabon, Kenya, Madagascar, Malawi, Mozambique, Namibia, Somalia, South Africa, Tanzania, Zaire, Zambia and Zimbabwe (Worku and Austin, 1992). The type locality for Karoo sediments of Gondwana is the Karoo Basin in South Africa (Fig. 1.0).

In Zambia, strata of the Sinakumbe Group and Karoo Supergroup, Ordovician to Early Jurassic age, are largely confined to rift valley basins (Fig. 1.1) which are down faulted troughs except for the largest basin (Barotse Basin) which is considered a cratonic sag. The other basins are the Kafue, mid-Zambezi Valley, Lukusashi, Luangwa Valley and Rufunsa (Fig. 1.1). Some coal deposits are currently mined in the mid-Zambezi Valley where the Karoo Supergroup forms over 95% of the surface exposures. The coal-bearing Karoo sequence in the mid-Zambezi Valley was a centre of exploration activities between 1965 and 1968 that resulted in a number of publications. Since 1968, practically no investigations have been conducted in the general aspects of geological conditions and only two studies in the economic aspect by British Mining Consultants Ltd. (1984) and the Nuclear Power Reactor Corporation (1987). The present study looks at the sedimentological characteristics of nearly the entire sedimentary succession in a portion of the mid-Zambezi Valley Basin centred on the four coalfield areas in order to interpret the depositional environments of the succession.

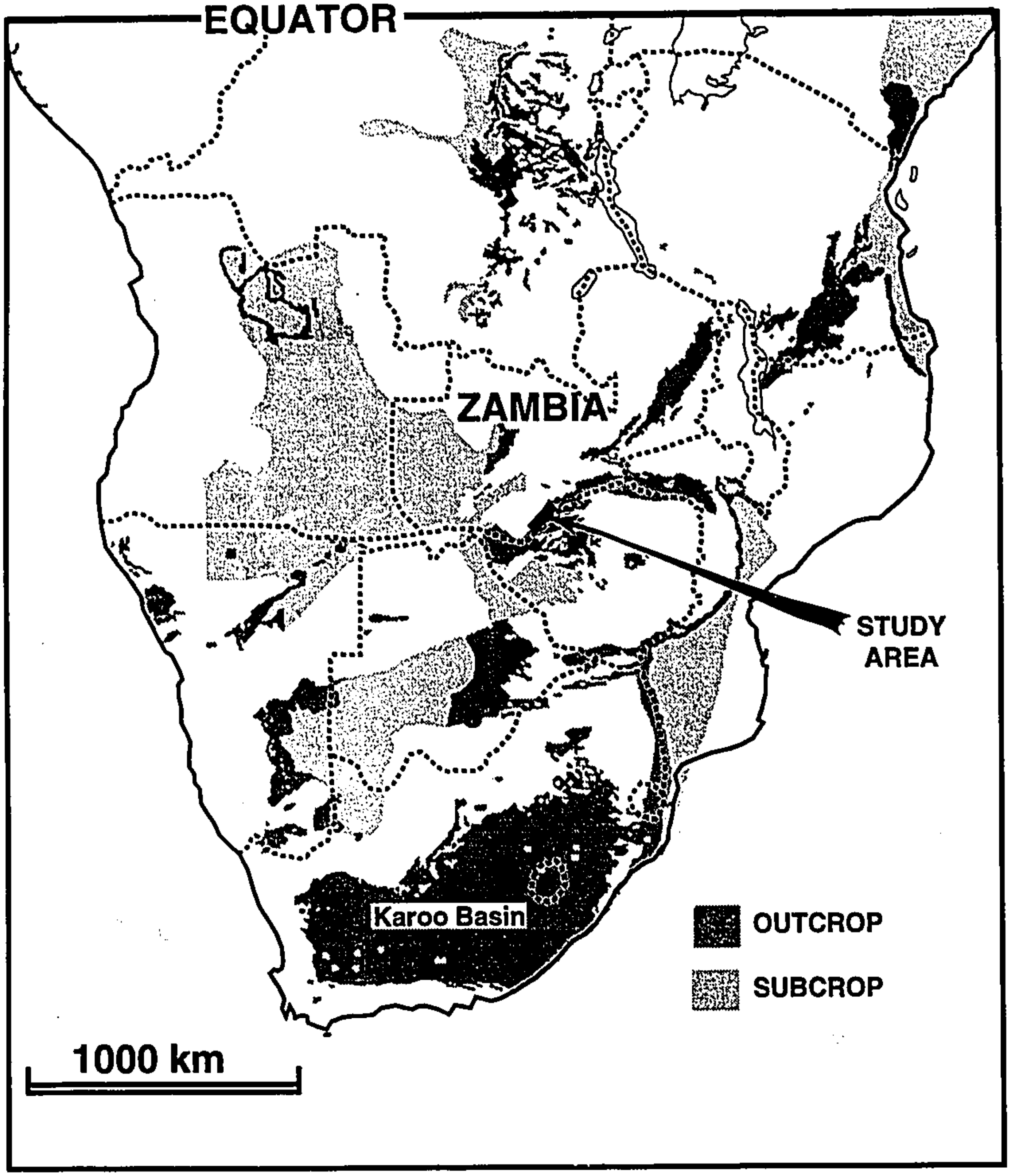


Fig. 1.0 Location of basins with Karoo sediments (stippled) in southern Africa (after Verniers et al., 1989), and study area in the mid-Zambezi Valley Basin, Zambia.

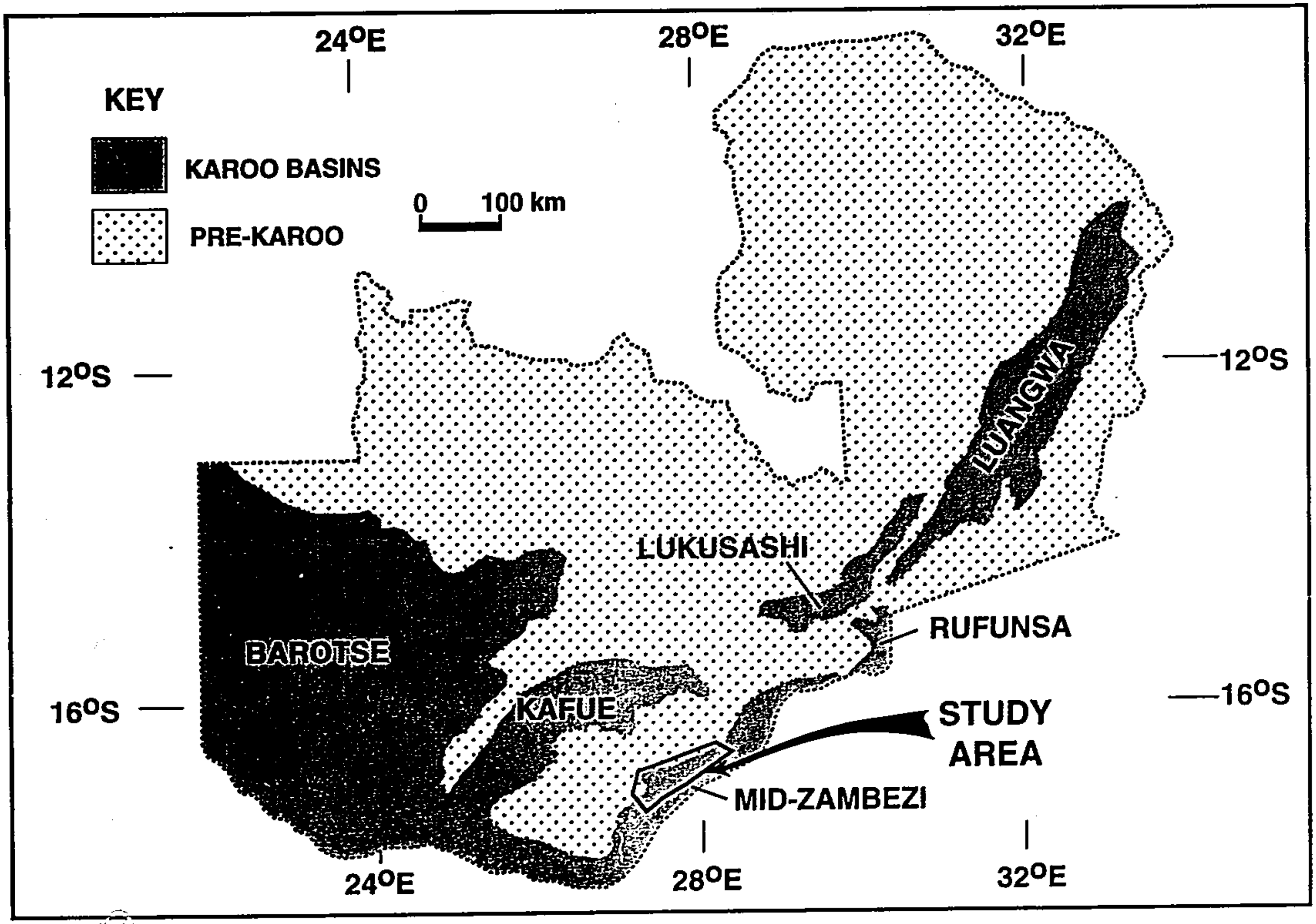


Fig. 1. 1 Karoo basins in Zambia

The geomorphology, climate, soils, vegetation, population and agriculture sections that follow have been modified from the unpublished Geological Survey of Zambia Bulletin 6 (Money et al., 1974).

1.2 STUDY AREA

The mid-Zambezi Valley is a rift-like topographical feature, occupying an area approximately 550 km long and 330 km wide (on the largest bulge) in southern Zambia and northern Zimbabwe (Fig. 1.2). The central part of the valley is occupied by Lake Kariba. The study area occupies approximately 1140 km^2 (Fig. 1.3) within the mid-Zambezi Valley in the Sinazongwe District, Southern Province, Zambia, approximately between latitudes 17° 06' and 17°36' S and longitudes 26° 59' and 27° 28' E. This study area was selected to include four coalfields in order to utilise the large amount of subsurface data available at the operating Maamba Mine. The Siankondobo coalfield comprises the Kazinze, Izuma and Maamba areas, and lies between the Nkandabwe field to the northeast, and Sinakumbe-Maze and Mulungwa fields to the southwest (Fig. 1.3). The Mulungwa field is currently being investigated as a joint project between the Maamba Collieries Ltd. and the Geological Survey of Zambia.

1.2.1 LOCATION AND ACCESS

The study area lies on the northwestern margin of the northeast-trending mid-Zambezi Valley. Access is provided by a tarmac road that extends southeast from the Great North Road that links Livingstone, Lusaka and the Copperbelt. Alternative routes to Siankondobo are a gravel road from Choma to Masuku, and then a rough track down the escarpment to the valley floor, or a track that follows the serial ropeway from Masuku to Maamba. These routes are often impassable during the rainy season, and four-wheel drive vehicles are recommended at all times. The coalfields of Mulungwa, Maze and Sinakumbe in the southern part of the study area can be reached by an unsurfaced track from Maamba (Fig. 1.3).

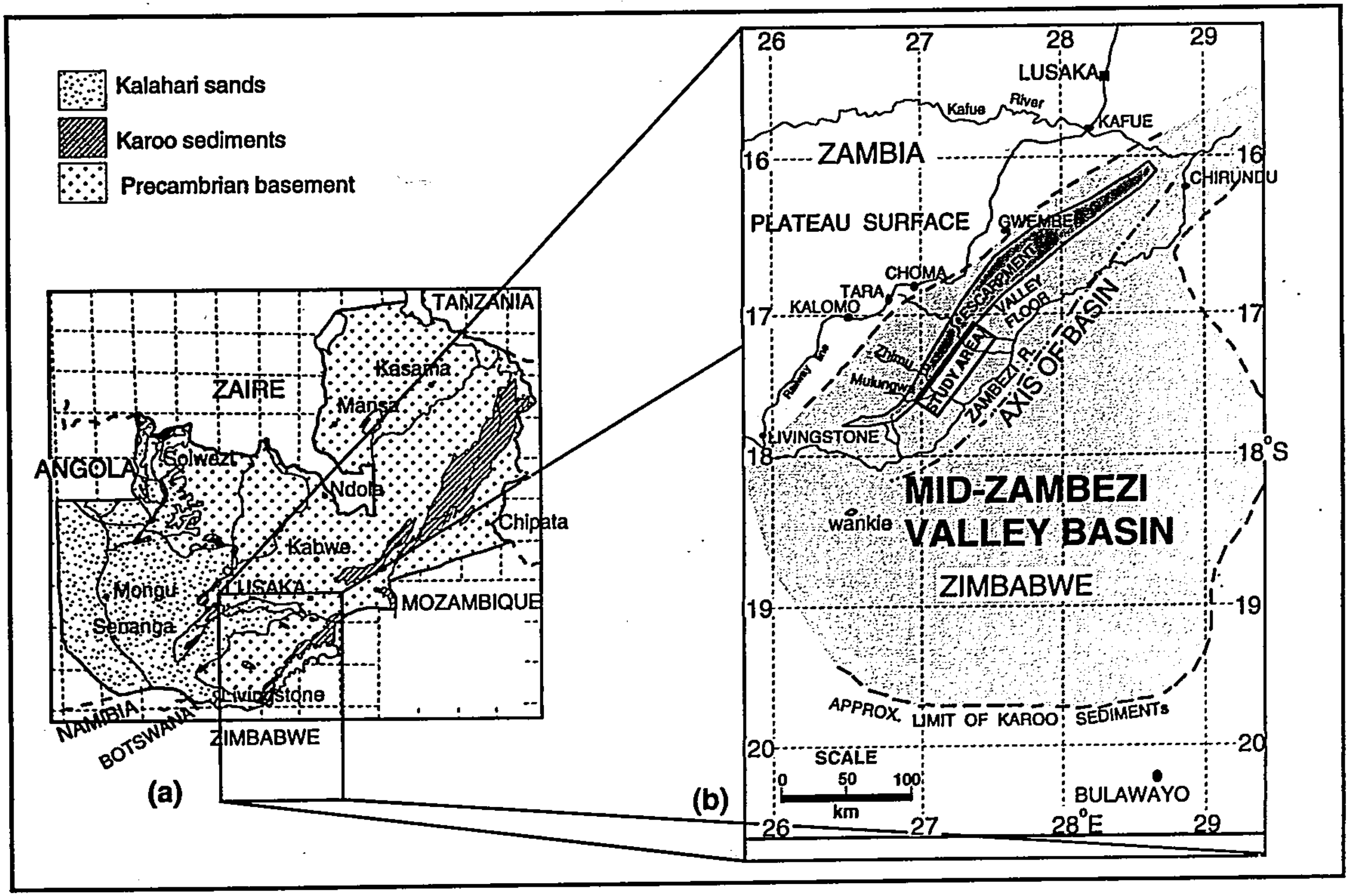


Fig. 1.2 (a) Location of mid-Zambezi Valley Basin in Zambia (patterned area in rectangle) and Zimbabwe.
(b) Approximate limit of the basin (stippled area) and location of the Study Area.
Zambia/Zimbabwe border approximately follows the Zambezi River.

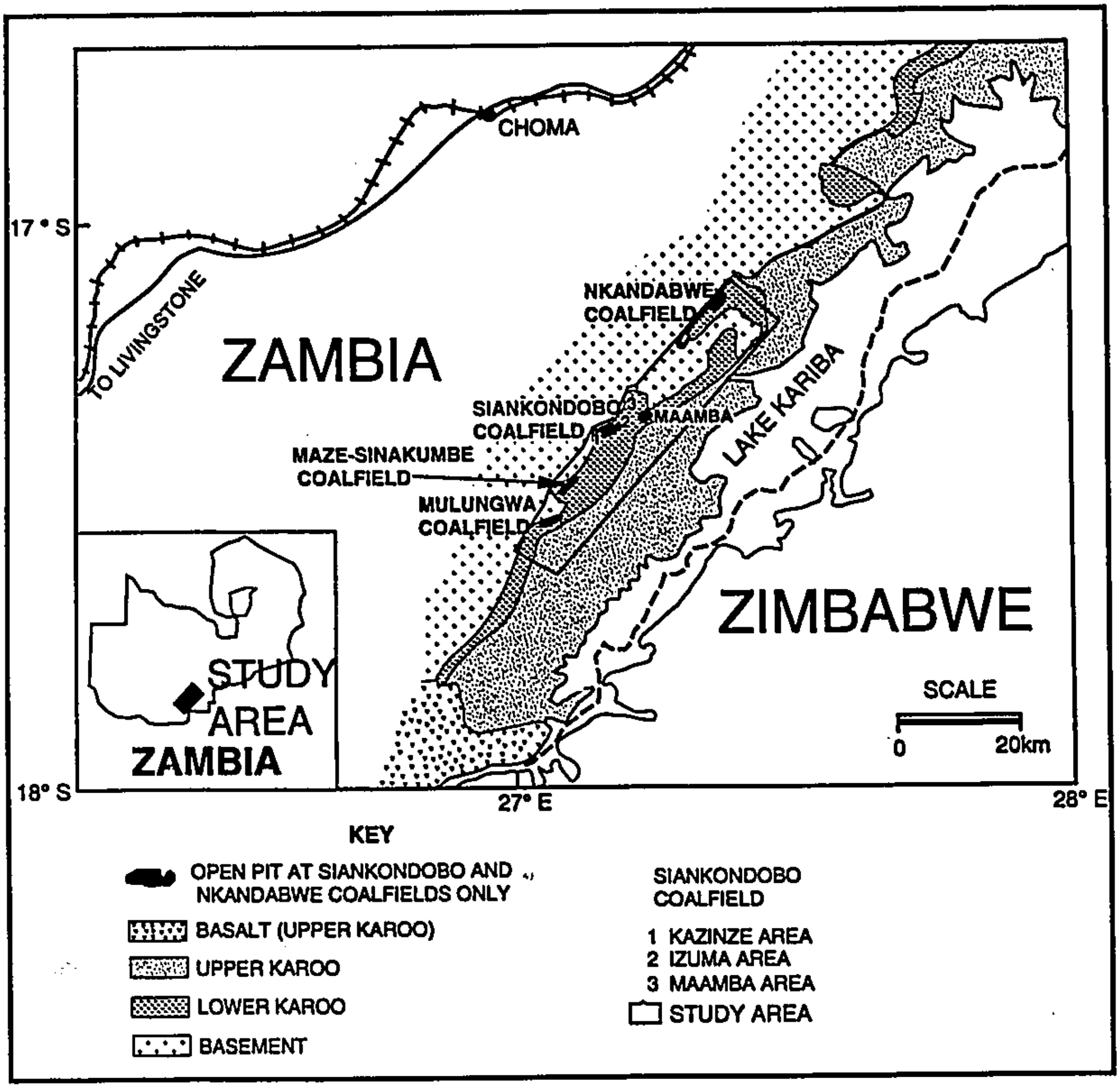


Fig. 1. 3 Location of the study area, coalfield localities and the general geology of the mid-Zambezi Valley Basin, Sinazongwe District, southern Zambia.

1.2.2 GEOMORPHOLOGY

The Southern Province may be divided into three geomorphological units: the plateau, the escarpment and the valley. The plateau, north and northwest of the study area, is at an elevation of about 1,200 m (valley ~300 to 600 m below plateau), and is part of an extensive erosional surface known as the Gondwana and African surfaces (King, 1948, 1967; Dixey, 1945). This plateau is younger than post-Karoo tectonism, but older than Tertiary downwarping and faulting.

The escarpment is a deeply dissected hilly zone, from 5 to 25 km wide (average width of 15 km) that forms the northwestern part of the study area. The escarpment which is elongate parallel to the plateau, is largely the downwarped and eroded edge of the plateau from which much of the Karoo sediments has been removed. The valley is bordered by tilted blocks that resulted from a series of step faults that overprint earlier faults. The remainder of the area is occupied by the valley floor. The abrupt change from base of escarpment to valley floor is accompanied by changes in lithology, soil and vegetation.

The floor of the northeast-trending valley ranges in altitude from 600 m at the foot of the escarpment to approximately 500 m along the shoreline of Lake Kariba. The floor, interrupted by many low northeast-trending sandstone ridges up to 150 m high, can be subdivided into three belts:

(i) an irregular belt at the foot of the escarpment, underlain by Lower Karoo mudstones and finer-grained clastics, forming a generally flat to undulating surface where coarser clastics are present.

(ii) a wider belt, 100 to 150 m in relief, of scarp and dip slopes formed of coarse-grained Upper Karoo sandstones.

(iii) a narrow belt of low-lying sandstones along Lake Kariba (outside the study area).

Minor waterfalls and recent downcutting are evident, and coarse detritus forms alluvial fans along the scarp, suggesting minor recent movements.

The study area is drained by former tributaries of the Zambezi, which now flow directly into Lake Kariba. Except for the Muzuma River, all of the rivers are ephemeral and become dry by early June. Major ones include the Zhimu, Maze, Kazinze and

Nkandabwe. These rivers and their numerous tributaries form a complex drainage system in the escarpment zone of the area. Zhimu and Muzuma rivers have their source on the plateau; the others begin in the escarpment zone.

Because some rivers and streams cross the Karoo sequence at almost right angles to strike, the control of drainage appears to have been initiated by faulting and uplift that gave rise to the escarpment and valley; most of the rivers and streams closely correspond with faults. Both Zhimu and Muzuma rivers cross the Escarpment Grit of the Upper Karoo Group at weaker points after adjusting to the structure and lithology. The Zhimu River for example, meanders through the mudstones before cutting the Upper Karoo. The basement blocks, faults and fault-line scarps control the drainage of the area. On the Upper Karoo sandstone beds, particularly in Mulungwa area, superimposed streams show adjustment to structure, in that they run parallel to strike and have adopted an incipient trellis pattern.

It is possible that the valley was infilled during post-Karoo times and subsequently denuded to give the present topographic expression after the general uplift of Central and Southern Africa in mid-Tertiary times.

1.2.3 CLIMATE

Zambia is centrally located on the high plateau of central and southern Africa. The climate is dependent largely on latitude, elevation and position on the continent. The plateau has a temperate climate, whereas the mid-Zambezi valley (including the study area) is hot and humid during the rainy season (late October to early April). Temperatures for most of the year are 5° to 7° C higher in the mid-Zambezi Valley than on the plateau. The mean minimum and maximum are 17° and 32° C, with absolute minimum and maximum of 2° and 42° C. Rainfall up to 100 cm is common along the foot of the escarpment; in the valley it varies from 80 to 90 cm. Most of the Zambian rainfall is controlled by convection, with local increases due to significant relief, as is the case along the escarpment belt of the valley.

1.2.4 SOILS

The mid-Zambezi Valley soils are derived from the underlying rock type, and are dependent on the topography. For example, the low-lying valley belt, underlain by fine clastics of Karoo formations, is characterised by fine-grained, greyish clay-rich soils that are thick and fertile due to a high lime content in the mudstones. In the escarpment zone, the soil cover is more variable, depending on the underlying rocks. For instance, coarse-grained, light-coloured and sandy soils predominate over quartzites, granites and gneisses. Because of topography, the soils are generally thin in comparison to those in the valley. Water saturation in the valley tends to make the soils alkaline, particularly in the rainy season.

Ferricrete is present owing to the leaching of iron from rocks and precipitation in the soil profile. This process is accentuated by seasonal rainfall and high evaporation rates in the dry season.

1.2.5 VEGETATION

Zambia is covered by savannah-type woodlands. In the mid-Zambezi Valley, the vegetation types are closely related to the soils, such that in areas of poor rock exposure, the soil generally can be a reliable indicator of underlying lithology.

The predominant vegetation of the Miombo woodlands (constituent species are listed in unpublished Bulletin 6 of the Geological Survey of Zambia) extends from the plateau across the escarpment belt to isolated areas on the valley floor. The Mopane woodlands of the low-lying areas and flats generally are underlain by Karoo mudstones. Thickets on alluvial soils along stream courses are a hindrance to mapping, because some of the best exposures are within the streams.

1.2.6 POPULATION AND AGRICULTURE

The area is fairly densely populated (15-20 per km^2), mainly by Tonga people (Kay, 1967). The valley Tonga live in villages ranging in size from less than a dozen to more than a hundred families depending on the availability of water, fertile soils and distribution of tse-tse flies. Flooding of Lake Kariba has had a tremendous impact on the social and cultural environment of the people, because they had to leave their fertile flood plains to resettle in the escarpment belt and the non-flooded valley floor. The start of coal mining has resulted in a marked influx of people, especially to Maamba.

Goats, cattle and poultry are kept in most villages. Goats are a menace to campers. The staple food is corn (maize) which is grown with bulrush millet, together with groundnuts, pumpkins, cassava and drought-resistant sorghum.

Crops are grown for family consumption (subsistence farming), so agricultural methods are simple, and include the use of hand hoes and cattle-drawn ploughs.

1.3 SIGNIFICANCE OF THE STUDY

The Karoo Supergroup in Zambia is a continental succession of promising economic potential for energy resources. The Gwembe Coal Formation of the Karoo Supergroup is an important coal producer. The coal was first exploited in the now-abandoned Nkandabwe open-pit, and is presently being mined in the Kazinze and Izuma open-pits of the Maamba Mine, named after the nearby Maamba village, now a township. Of the four seams in the Kazinze open pit (A, B, C, and D), A and B are widely developed, and B contains the best grade coal (Maamba Collieries Company Report, 1972). Although oil and gas have not yet been discovered, the potential for their recovery appears to be good (Utting and Wielens, 1992). The discovery of coal seams in the mid-60s attracted exploration drilling, thus providing some subsurface data. In addition, drilling for uranium mineralisation in the Upper Karoo strata resulted in additional subsurface data. The abundance of outcrops in the mid-Zambezi valley in contrast to other basins in Zambia, the potential for hydrocarbons in rift valley basins (the mid-Zambezi Valley in particular), the large expected data base (outcrop and subsurface), and a fairly well-known stratigraphy, were the principal reasons for selecting the mid-Zambezi Valley Basin for this study.

The sedimentology, stratigraphy and resource potential of the Sinakumbe Group-Karoo Supergroup strata have not received adequate attention in Zambia. In comparison to studies done in industrialised nations, even the coal-bearing formation has not received adequate attention; the use of lateral profiling in the Kazinze Open pit, for example, provides a better understanding of facies changes. Many of the studies in the late 1960s relied heavily on sparsely distributed borehole data, and only one sedimentological study of the coal- bearing succession has been carried out utilising a combination of subsurface and outcrop data. More importantly, sedimentary concepts have undergone large changes during the last 20 years, such as the development and application of the facies model concept (Miall, 1977; Walker and James, 1992). The Sinakumbe and Karoo strata reflect a variety of environments that have not been studied and documented adequately and require some of these new techniques. For example, the Sinakumbe Group was defined in one borehole (GS96), and was not previously described in surface outcrops in the Sikalamba-Muzuma corridor, Nkandabwe map area and northeast of Siankondobo map area. Its stratigraphy and sedimentology, therefore, are poorly known. Among the Lower Karoo formations (Siankondobo Sandstone, Gwembe Coal, Madumabisa Mudstone), the Gwembe Coal Formation received the most attention due to the economic importance of coal mining, whereas the other two received minor attention. The Upper Karoo formations (Escarpment Grit, Interbedded Mudstone and Sandstone, Red Sandstone, and Batoka Basalt) equally have been neglected and so the stratigraphy remains poorly understood. Recent studies in the Upper Karoo, associated with uranium exploration in the area, provide little information on sedimentology. Sedimentological profiles (graphic logs from outcrops) and photomosaics (documenting lateral variation of facies), necessary for the delineation of lithofacies and facies assemblages in this study, are applied for the first time to these rocks. In order to achieve the maximum new understanding of the geology, stratigraphy and sedimentology of the area, more time was devoted to parts of the stratigraphic sequence that were for the most part overlooked by previous workers, such as the formations of the Sinakumbe Group, the Siankondobo Sandstone and Madumabisa Mudstone formations of Lower Karoo Group, and the formations of the Upper Karoo Group.

This study was undertaken to provide a detailed, comprehensive documentation and interpretation of the sedimentology of the Sinakumbe Group and Karoo Supergroup in the mid-Zambezi Valley Basin. It focusses on (i) definition, detailed description and interpretation of lithofacies, (ii) analysis of vertical and lateral facies changes, and (iii) analysis of depositional systems architecture, linking the vertical and lateral changes with autocyclic (tectonic) and allocyclic controls on deposition. Economic potential is assessed in relation to the depositional systems and syndepositional structural movements in the basin. To provide a predictive framework based on models of the various depositional systems, a combination of data from outcrop (e.g. profiles, palaeocurrent data), drillholes, palynological study, and laboratory studies (thin section, SEM, XRD, and geochemistry) have been integrated in this study.

1.4 OBJECTIVES, SCOPE AND SCIENTIFIC CONTRIBUTIONS OF THIS STUDY

This study overall addresses objectives in four interrelated areas:

(i) **stratigraphy:** to establish a stratigraphic framework within the Sinakumbe Group, and to revise the stratigraphy of the Lower and Upper Karoo groups,

(ii) **sedimentology:** to document the lithofacies and facies assemblages present, their spatial distribution and geometry, and to integrate them in a depositional system model,

(iii) **structure:** to determine the structural characteristics of the basin and relate the depositional history and basin evolution to syn- and post- tectonic movements, and

(iv) **economic potential:** to assess the economic potential of the area in relation to the three subjects listed above as well as in relation to the palynological data.

This study has made a number of new contributions that advance the understanding of the sedimentary succession (Sinakumbe Group and Karoo Supergroup) in the mid-Zambezi Valley Basin:

1. **Changes to the geological map of the area:** For example, the present study has shown that extensive outcrops in Nkandabwe map area, and the northeastern part of Siankondobo map area, shown as Siankondobo Sandstone Formation (Lower Karoo Group) on previous maps, in reality belong to the Sinakumbe Group.
2. **Description of the Sinakumbe Group:** Seven lithofacies and three facies assemblages defined in the group represent the first detailed outcrop description of the group.

3. **Redefinition of Sinakumbe Group stratigraphy:** Recognition that the Sinakumbe Group can be readily divided into two formations (not four formations as in Borehole GS96) will facilitate regional mapping and correlations in the area. Definition of formal stratigraphic names has not been undertaken in the thesis and informal names are used. It is the author's intention to formalize the names in a Geological Survey of Zambia bulletin to be published.
4. **A new interpretation of the Sinakumbe Group:** The Sinakumbe Group is re-interpreted based on this first detailed documentation of surface exposures.
5. **Documentation of physical, chemical and biological sedimentary processes:** The 38 lithofacies described in this thesis are the basis for interpreting a broad range of sedimentary processes that operated in the mid-Zambezi Valley Basin through time and space, providing a basis for comparison with modern and other ancient examples.
6. **Documentation of facies assemblages, facies changes:** The 14 facies assemblages recognized provide the basis for the interpretation of depositional environments and application of facies models.
7. **Documentation of relationships between depositional systems and structural style of the basin:** The organisation of the enclosed sediments (facies changes, etc.) provide the basis for linking basin evolution to syntectonic events.
8. **Documentation of economic potential:** This thesis documents sedimentologic characteristics useful for the prediction of resource potential by comparison with modern and ancient examples.
9. **Documentation of palynological data:** Palynological data from the Madumabisa Mudstone and Interbedded Sandstone and Mudstone formations are documented for the first time, and provide the first reliable age information for these units.

1.5 FORMAT OF THESIS

This thesis is organised into eight chapters. Following this introductory chapter (Chapter 1), Chapter 2 outlines previous work and regional structure, geology and stratigraphy of the study area. Methods of study are summarised in Chapter 3. Chapter 4 defines, documents, describes and interprets lithofacies and facies assemblages, vertical and lateral distribution of the facies assemblages, and palaeocurrent and palynological data. Chapter 5 integrates the preceding data in an interpretation of the depositional systems of the Sinakumbe, Lower and Upper Karoo groups. Tectonic controls on sediment dispersal, and palaeogeography are discussed in Chapter 6. Chapter 7 comments on the economic potential of the Sinakumbe Group and Karoo Supergroup in the mid-Zambezi Valley. Concluding remarks are outlined in Chapter 8. The descriptions and results presented in this study are those of the author; observations and ideas already available in literature have been referenced. All data for this study are filed separately and can be obtained from the author at the University of Zambia or from Dr. O. Dixon of the University of Ottawa.

Finally, several aspects of presentation of the thesis have been adopted specifically to be of benefit to readers and potential users. Substantial use is made of field photographs, to be helpful both to examiners who may have no first-hand familiarity with the area or succession, and to potential subsequent users of the thesis in Zambia. Major use of the thesis by Maamba Mine and Geological Survey of Zambia geologists, and various companies engaged in exploration in the mid-Zambezi Valley Basin, is foreseen. The extensive reference list provides an important bibliographic source for these potential users, whose access to full library resources and search sources is limited. For a similar reason, initial text-book style reviews have been incorporated in Chapters 5 and 6 to provide convenient summaries of current thinking on those topics.

CHAPTER II

REGIONAL GEOLOGICAL SETTING AND STRATIGRAPHY

2.1 PREVIOUS WORK

Geological work began in the area before establishment of the Geological Survey of Zambia, formerly Northern Rhodesia.

The present understanding of the geology and palaeontology of the Karoo Supergroup in southern Africa is the result of accumulated observations of a number of workers, beginning with those of Andrew Geddes Bain (1856, as quoted in Money et al., 1974). Molyneux (1909) established the presence of the Karoo System in the mid-Zambezi Valley. Based on Lightfoot's work (1914, 1929), the Karoo in the Wankie Coalfield (Zimbabwe) is regarded as the type succession in central Africa (Drysdall, 1962).

In the mid-Zambezi Valley, coal fragments were reported in alluvium near the confluence of the Chilola and Zambezi rivers by David Livingstone in 1865 (Gair, 1959 and Tavener-Smith, 1960). Coal prospecting has taken place sporadically in the valley (Zambian side) since the turn of the century (Molyneux, 1907; Edwards, 1913; Maufe, 1918; and Mennell, 1920, 1929). The first systematic survey of the coal resources of the area was undertaken by Mark C. Malamphy and Company for the Northern Rhodesian coal syndicate (Malamphy, 1950). Bancroft (1951, as quoted in Money et al., 1974) concluded erroneously that there are no workable coal deposits in Northern Rhodesia and their search was a waste of time.

The first comprehensive systematic geologic surveys in the mid-Zambezi Valley were carried out from 1951 to 1955 by the Geological Survey of Zambia. The results are contained in various progress reports of the geological survey (Gair,1954, 1959; Reeve 1956a, 1956b, 1963; and Tavener-Smith, 1957, 1960). It was during these surveys that the now-abandoned Nkandabwe coal deposit was found.

Drilling and exploration at Nkandabwe prior to 1965 indicated recoverable reserves of 17 million tons of coal with an ash content of 24%, averaging 5600 cal/kg to a depth of 300 m. During this period various reports related to the exploration of coal were compiled by the geological survey. Reports that discuss aspects of the stratigraphy and sedimentary environments include Gair (1954, 1956, 1959), Reeve (1952, 1958) and Tavener-Smith (1955; 1956a, b; 1957; 1960; 1962). Aspects of tectonics and structural development of the area were described by Hays (1958) and Lambert (1957, as quoted in Money et al., 1974); Bond (1954) documented the palaeontological specimens collected.

Further work carried out by the Anglo American Corporation in 1965 (Cornwall, 1965) in the Nkandabwe area led to the opening of the Nkandabwe Mine. More coal investigations by the geological survey were initiated in 1965, and a 5 m coal seam in what is now known as the Siankondobo Coalfield (Izuma river) was revealed. These investigations continued some 50 km along strike to Mulungwa, and were completed in late 1969. After 1965, knowledge of the Nkandabwe-Siankondobo-Mulungwa area grew primarily in the economic aspect of coal exploration and development. It is not surprising, therefore, that these investigations culminated in a number of economic reports that include Pagella and Drysdall (1966); Drysdall et al. (1967a, 1967b, 1967c); Denman and Money (1968); Radosevic (1968); Drysdall et al. (1969); Sofremines (1968) and Alpren (1968). General papers on other aspects such as stratigraphy and sedimentary environments of the coal sequence include Drysdall and Weller (1966); Brown (1968); Denman et al. (1968); Money et al. (1968); Radosevic et al. (1968); Denman and Money (1970); and Money and Drysdall (1975). Descriptions of the basement complex are contained in Legg (1972), Matheson (1972) and Stillman (1967).

2.2 REGIONAL STRUCTURAL SETTING

2.2.1 GENERAL REMARKS

Information in this section is extracted mainly from the unpublished Bulletin 6 of the Geological Survey of Zambia (Money et al., 1974), which in turn was derived mainly from descriptions in previous reports of the Geological Survey of Zambia.

The pre-Karoo rocks (Basement Complex) comprising gneiss, granite, granulite and schist show two major phases of folding (F_1 and F_2) related to orogenies. The basement shows a dominant structural trend of east-northeast to northeast, parallel to the Irumide orogenic belt (Fig. 2.0), though an older trend related to the Tumbide orogeny may also be represented (De Swardt and Drysdall, 1964; Cahen and Snelling, 1966). According to the tectonic map of southern Africa (Haughton, 1969), the present mid-Zambezi trough follows one of the old post-Waterberg-Umkondo zones of crustal weakness between the Kalomo-Hook batholith (Zambian Craton) to the north and the Zimbabwe-Kalahari shield to the south. This precursor southwest-trending trough (geosyncline) was a site of extensive tectonism in which subsidence, sedimentation, metamorphism and folding took place about east-west axes during the Katangan-Lufilian orogeny (Cahen and Snelling, 1966, p.154), as evident from imprints of the orogeny on the basement structure, although the Katangan metasediments are poorly represented in the coalfields except locally in the north (De Swardt and Drysdall, 1964). Subsequent tectonism, downwarping along earlier planes of weakness and sedimentation in this northeast- trending precursor basin resulted in deposition of the Sinakumbe and Sijarira groups in Zambia and Zimbabwe, respectively. Later, rejuvenation led to Karoo sedimentation and the present day mid-Zambezi Valley Basin flanked by the main positive areas of the Choma-Kalomo batholith to the north and the Zimbabwian-Botswana block to the south.

The mid-Zambezi belt is approximately parallel to the northeasterly-trending shear zones of old orogenic belts in the basement (Fig. 2.0), indicating that the mid-Zambezi Valley is related to the basement structure (Cox, 1970; De Swardt, 1962). Sinakumbe and Karoo sedimentation was therefore largely controlled by the basement structures and by tectonism which followed zones of weakness within the Precambrian Basement. This is further supported by the general parallelism of the strike of the basement rocks in the escarpment zone and the Karoo sediments in the valley, and the fact that faults in the basement parallel to those of the Karoo do not cut the latter, but pass beneath them (Tavener-Smith, 1962). As further supporting evidence, the sedimentary succession in the mid-Zambezi Valley shows significant variation from 5 km thickness on the Zambian side to 1.3 km on the Zimbabwe side, indicating maximum subsidence along a linear zone of weakness adjacent to the Choma-Kalomo batholith relative to moderate movements along the Zimbabwian-Botswana Craton.

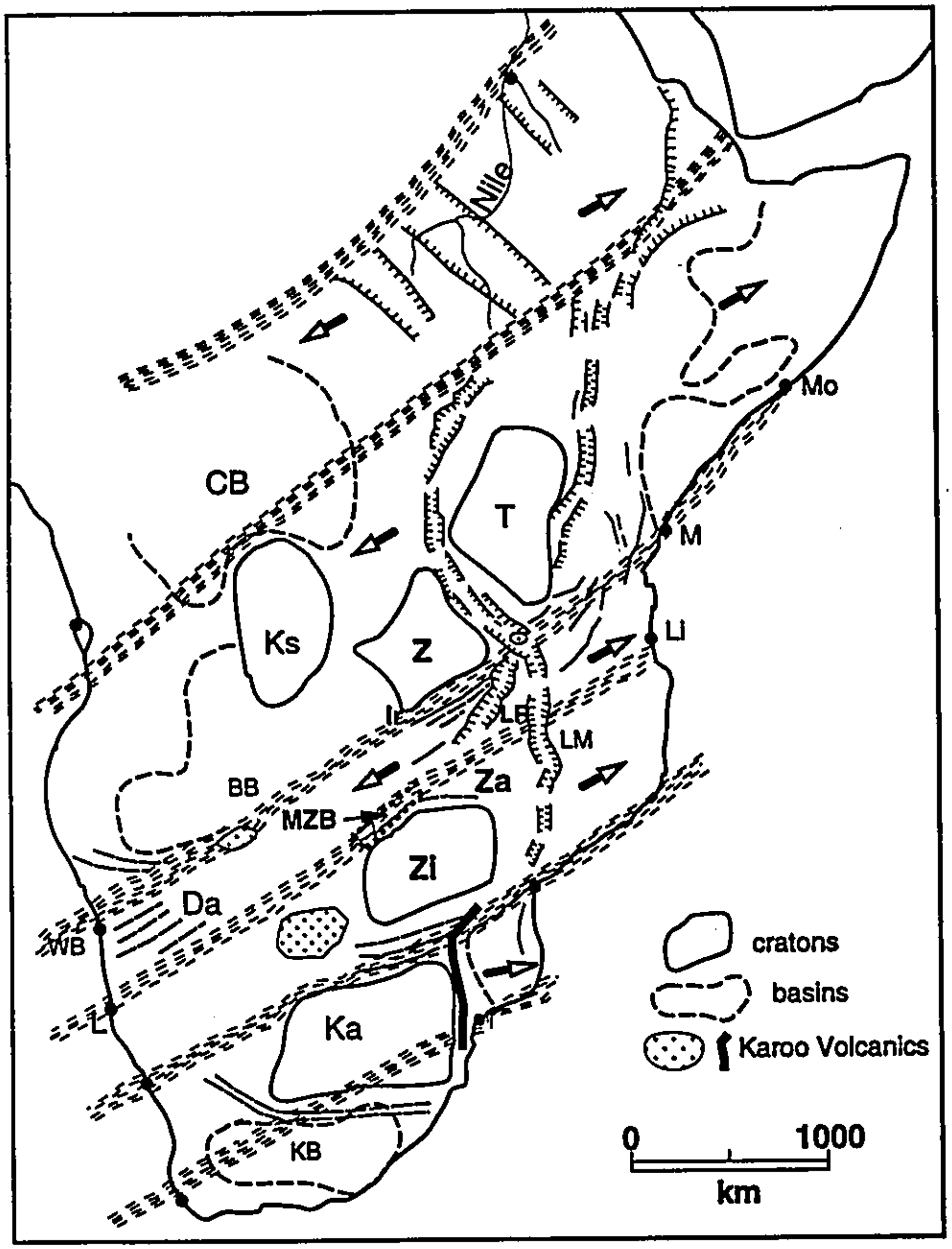


Fig. 2.0 The position of the mid-Zambezi Valley Basin (**MZB**) relative to ENE transform lineaments (fine dashes) extended to the South Atlantic transform faults, and to the N-S East African rift system (hatchured lines). Arrows indicate general kinematic and dynamic directions of relative movement. KB = Karoo Basin, Ka = Kaapvaal craton, **Zi** = Zimbabwian craton, **Za** = Precambrian Zambezi mobile belt, LM = Lake Malawi, **LR** = Luangwa Rift, WB-M-Mo = Walvis Bay-Mombasa-Mogadishu Lineament, Z = Zambian craton, Da = Precambrian Damara mobile belt, **Ir** =Precambrian Irumide belt, T= Tanzanian craton, BB = Barotse Basin, Ks = Kasai craton, L-Li = Luderitz-Lindi Lineament, CB = Congo Basin (modified from Katz,1986).

2.2.2 FAULTING IN THE MID-ZAMBEZI VALLEY BASIN

The mid-Zambezi Valley Basin is a broad linear depression, in which repeated tensional movements along older planes of weakness within the basement resulted in a series of northeast- and east-trending major normal faults (Fig. 2.1) parallel or sub-parallel to the northwestern (Zambian) valley margin. Minor faults occur within the Karoo succession (see Fig. 2.3a, section 2.2.3.1). The major faults are not confined to the Karoo-Basement boundary, but also occur within the outcrop of basement and Karoo.

The major faults are inclined towards Kariba Lake, while minor ones hade in the opposite direction resulting in antithetic faulting and tilted blocks with steep scarp slopes facing northwestward, further emphasizing the trough-like character of the valley. Generally, the antithetic faults are related to the major faults, but where the latter are absent, they are a function of downwarping which had its greatest expression in the escarpment zone. In general, the inclination is between 30° and 60° and displacements vary considerably from place to place. The downthrow on the major faults is up to at least 1 km where the Jurassic Batoka Basalt Formation (see section 2.3.5.4) rests against the basement, and up to about 10 m on minor faults. For example, Money et al. (1974) suggested a throw of more than 760 m in the Namazambwe area, where Upper Karoo rocks are faulted against basement.

Many of these faults represent renewed movements along pre-existing (pre-Karoo) faults, and a number of the faults are older than the Batoka Basalt Formation. Where the faults are well defined, they usually expose wide bands of fault breccia containing abundant recrystallized and quartz-veined fragments of the faulted lithology. For example, where arenaceous rocks are faulted against basement rocks, they are strongly silicified, hematitised and indurated with abundant secondary silica, whereas faulting in mudstone (e.g. Madumabisa Mudstone) usually results in silicified argillite with calcite veining.

The present coarse detritus in alluvial fans, some incised streams and minor waterfalls along the scarp indicate that recent movements have taken place along the earlier fault lines of the downwarped edge.

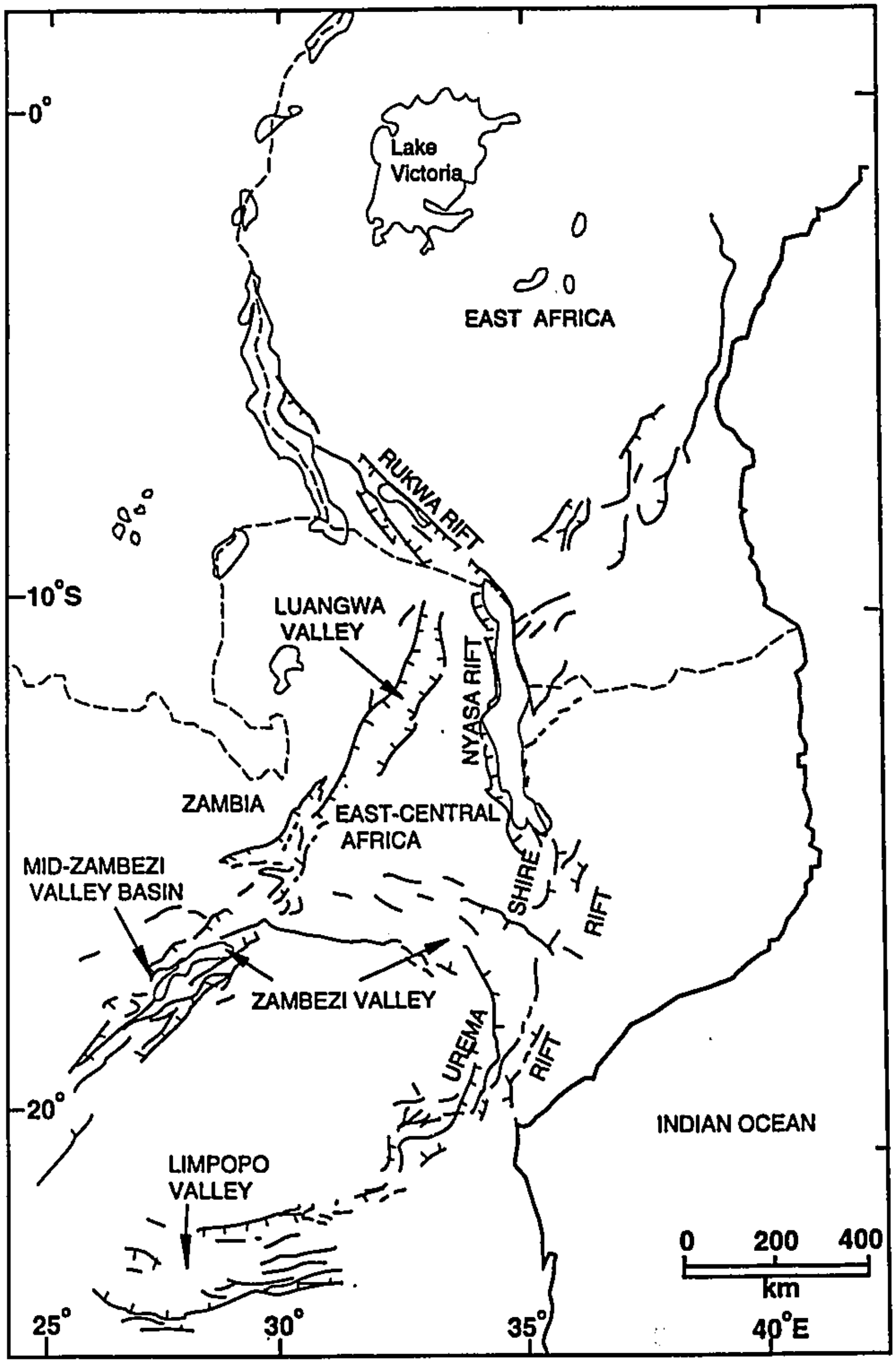


Fig. 2.1 Rift faults in East and East-Central Africa which were active in the Mesozoic. The position of the mid-Zambezi Valley Basin is indicated (from Sowerbutts, 1972).

2.2.3 STRUCTURE IN THE STUDY AREA

Figure 2.2 represents the structural features of the study area as currently recognised. The maps are based on compilations of earlier work, mainly by the Geological Survey of Zambia, with important modifications according to the field work carried out in this study. For convenience of description, the study area has been divided into four map areas, each named after an existing or a prospective coalfield in the area: Nkandabwe (Fig. 2.2a), Siankondobo (Fig. 2.2b), Sinakumbe-Maze (Fig. 2.2c) and Mulungwa (Fig. 2.2d). The sedimentary succession in the study area has a general regional southeasterly dip from nearly horizontal to 45°, with Karoo sediments in part down-faulted against the Precambrian gneisses and schists, thus steepening the dip.

2.2.3.1 Nkandabwe map area

The Sinakumbe and Karoo groups occur in two northeasterly-trending outcrop belts (Fig. 2.2a), a smaller belt toward the northwest (containing the Nkandabwe coalfield), and a larger belt across the southeastern part of the map area.

The smaller belt extends northeastward from the Muzuma River to beyond the Kasika River. Faults in this belt are generally subparallel to the strike of the sedimentary succession, although the succession is also offset by several NW-trending faults. The belt can be divided into two half-grabens, with the sedimentary succession resting unconformably on basement rocks to the NW and faulted to the SE, against the basement. The narrow, 4.5 km-long southwestern portion named the Muzuma-Sikalamba corridor in this study, contains only the older rocks of the Sinakumbe Group. The corridor opens northeastward into the main 10 km- long portion that incorporates the Lower Karoo Group as well, the site of the Nkandabwe Coal field. Minor faults have been recognised widely in the Karoo strata in the northwestern outcrop belt (e.g. Fig. 2.3a, p. 27). Zam-Anglo exploration geologists have shown that two east-trending faults displace the coal seam in the open pit area, and divide the coalfield into 3 blocks. Cornwall (1965) attributed the pronounced dip variation in the central block to rotational or hinge movement.

The larger outcrop belt to the southeast contains primarily Karoo Group strata that are partly faulted against the basement and in part rest unconformably on the basement

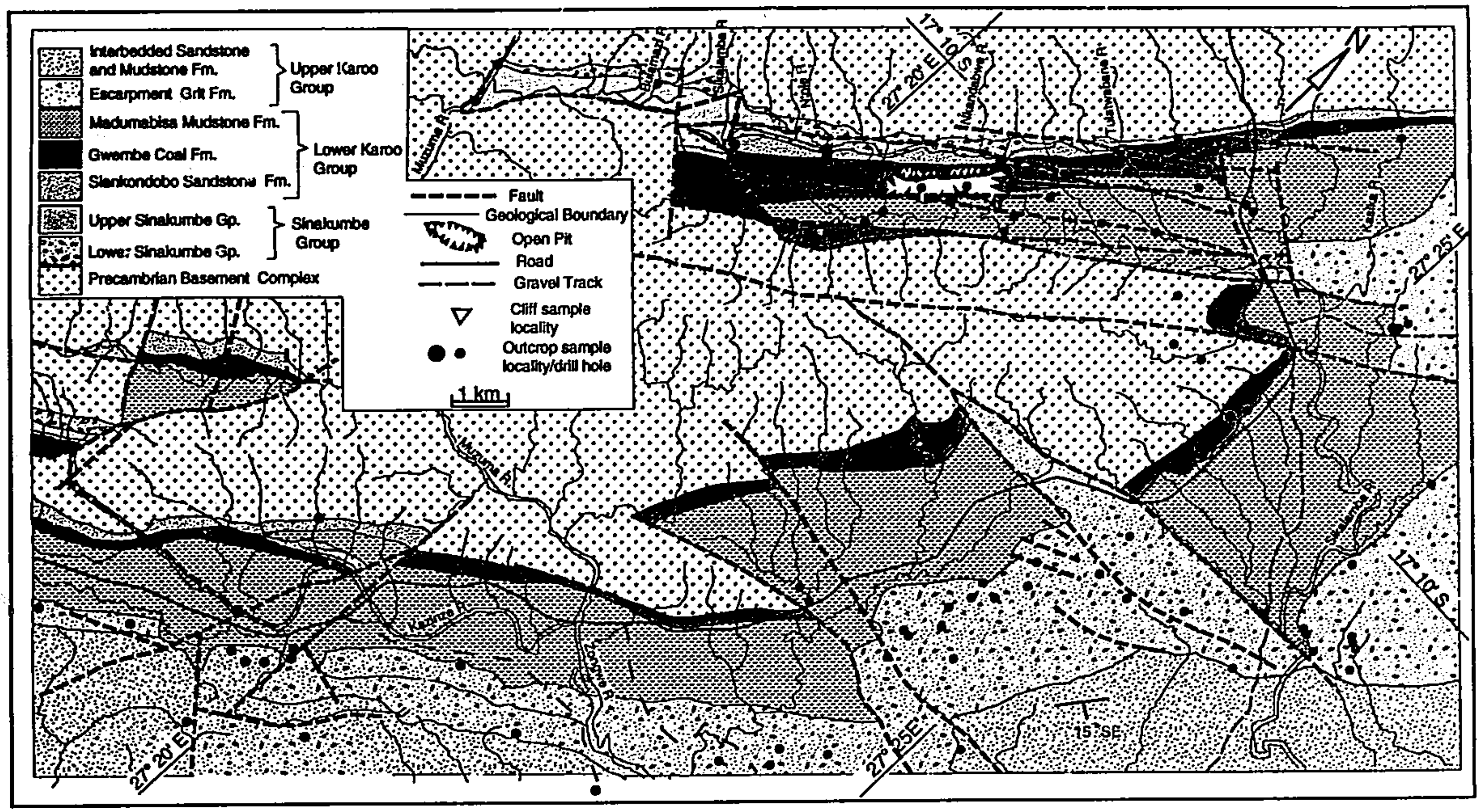


Fig. 2.2(a) Geology of the Nkandabwe area, mid-Zambezi Valley Basin, southern Zambia based on earlier work by Tavener Smith (1960) and Kotas (1977) with important modifications according to fieldwork carried out in this study. See Fig. 1.3 for general location in study area.

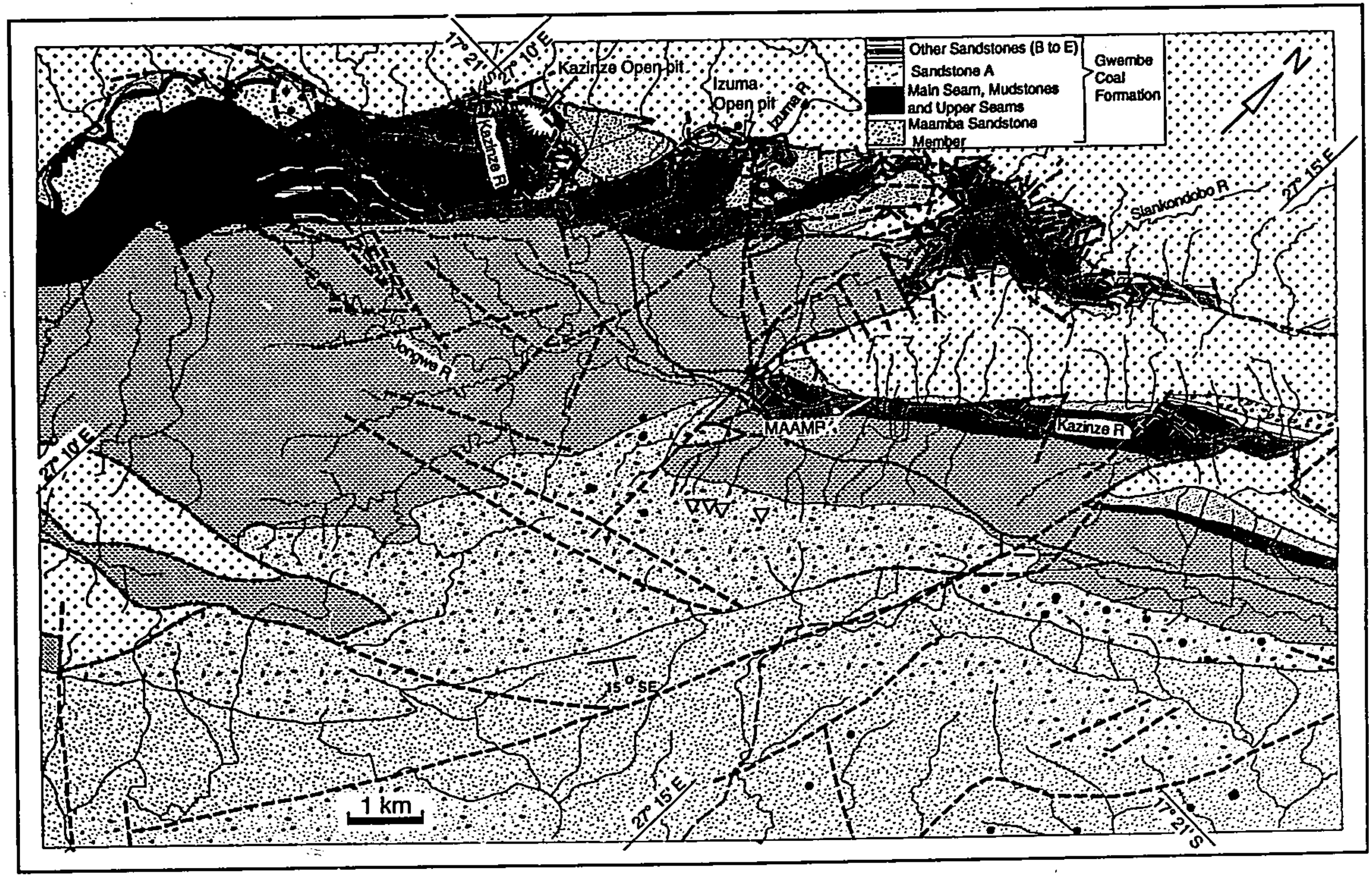


Fig. 2.2(b) Geology of the Siankondobo area, mid-Zambezi Valley Basin, southern Zambia, based on earlier work by Tavener Smith (1960) and various Geological Survey of Zambia reports in Siankondobo coalfield area with important modifications according to fieldwork carried out in this study. See Figs. 2.2(a) and 2.2(d) for legend of other formations. See Fig. 1.3 for general location in study area.

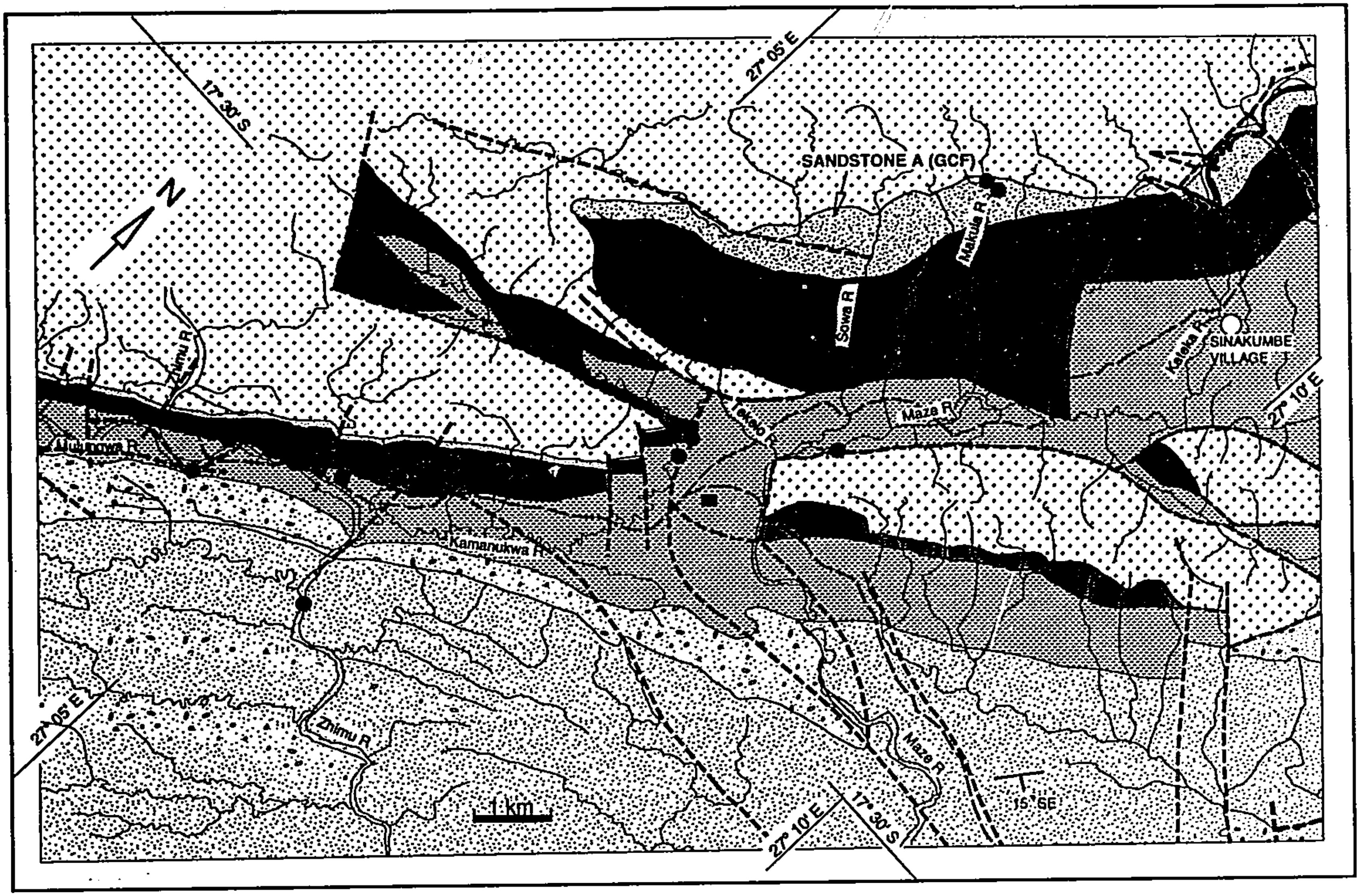


Fig. 2.2c Geology of the Maze-Sinakumbe area, mid-Zambezi Valley (Geology modified from Tavener-Smith (1960) according to fieldwork of this study). See Figs. 2.2(a), 2.2(b) and 2.2(d) for legend and Fig. 1.3 for general location in study area.

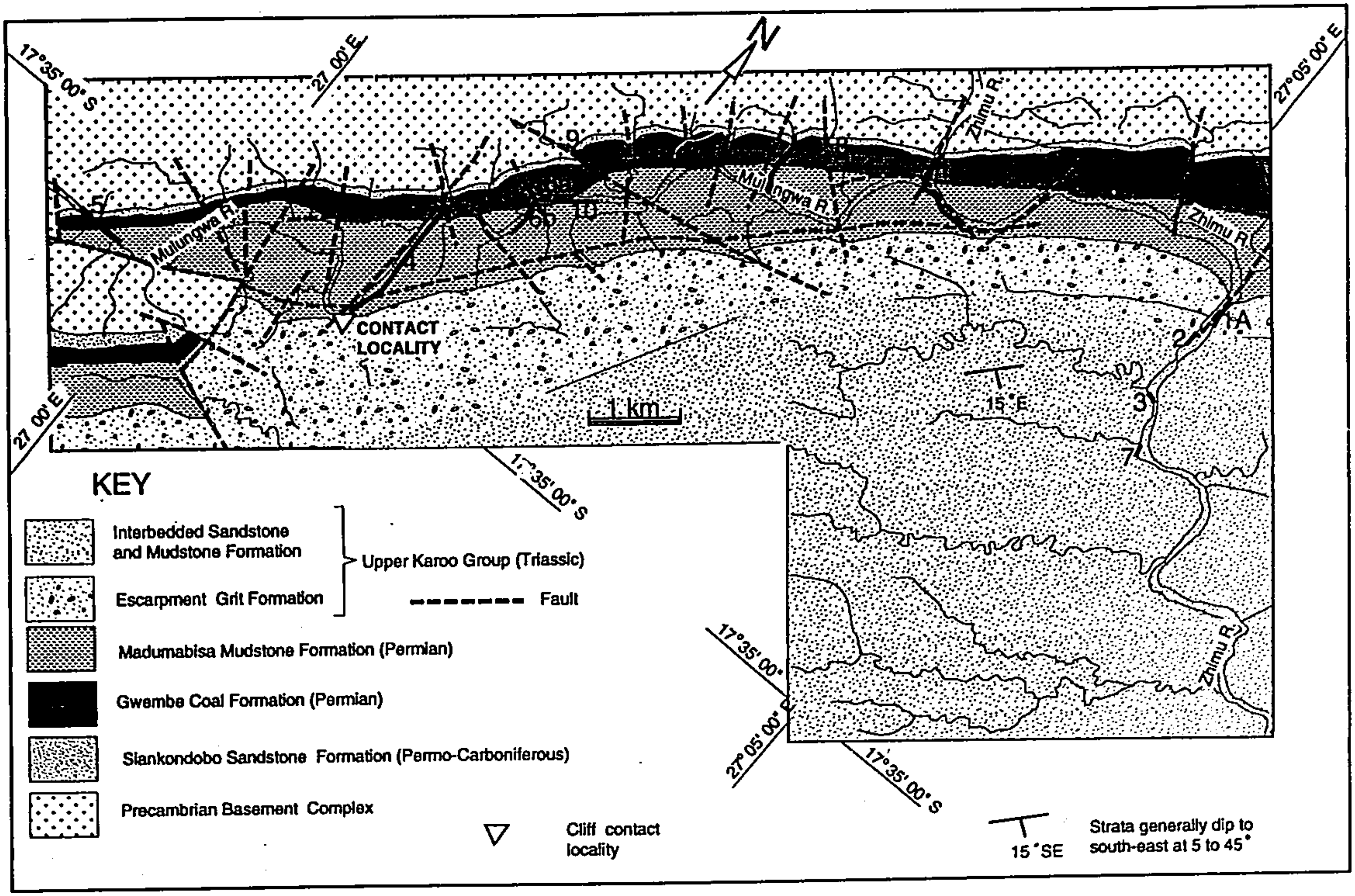


Fig. 2.2d Geology of the Mulungwa area, mid-Zambezi Valley (Geology modified from Radosevic (1968) and this study). See Fig. 1.3 for general location in study area. Numbers shown (e.g. 3, 6a) refer to sections measured (see Fig. 3.0d)

rocks. For example, along the Muzuma River, brecciated black argillite and abundant quartz veins mark a faulted contact between the Karoo coal sequence and basement rocks (Fig. 2.3b, c). The base of the sequence is largely concealed. Between the Zongwe and Sikalamba rivers, the succession is offset by several southeast- to east-trending faults. West of the Zongwe River the principal offsets are along several north-trending faults.

A small half graben with the sedimentary succession resting on basement rocks to the NW and faulted against the basement to the SE occurs in the west-central portion of the map area. This is connected to another small half graben described below. Basement hill remnants within the Karoo floor are common.

2.2.3.2 Siankondobo map area

Strata of the Lower Karoo Group are widely exposed across the northwestern half of the Siankondobo map area and Upper Karoo Group strata to the southeast (Fig. 2.2b). The outcrop of the Lower Karoo Group is largely in fault contact with basement rocks to the northwest. The succession is offset up to 3 km to the northwest of the margin of the Zambezi trough by several major north- to northeast-trending faults. These divide the coalfield into three main areas, named after Kazinze River, Izuma River, and Maamba Township. Smaller faults, parallel to and at various angles to the major faults, occur throughout the coalfield region, and have displacements of 1 to 10 m. The Kazinze area to the southwest (containing the Kazinze Open-pit) contains the largest block of coal measures, involved in a southwestward-plunging syncline (Money et al., 1974). The southeastern margin of the Kazinze area is the Izuma-Kazinze fault, with sinistral offset resulting from relative downthrow of the adjacent Izuma area (Fig.2.2b). The southeastern margin of the Izuma area is in part faulted, with dextral offset resulting from downthrow of the Izuma area relative to the Maamba area, and in part lies along the mapped boundary between the Gwembe Coal and Madumabisa Mudstone formations. Another major northwest trending fault, that marks the northeast margin of the Izuma area, cuts across the Lower Karoo succession in the eastern part of the map area, with dextral offset resulting from relative downthrow of the Maamba area.

The Izuma-Kazinze fault brings the Gwembe Coal Formation against the

Fig. 2.3 Faulting and Precambrian Basement Complex

Faulting

a: Fault scarps (arrows) in the Karoo Supergroup, Lower Karoo Group, Nkandabwe Open pit, Nkandabwe area. Person for scale.

b: Gwembe Coal Formation faulted against the Basement Complex, showing abundant quartz veins and the deformation of the coal sequence, Muzuma River Section 5, Nkandabwe map area. Hammer is 34 cm long.

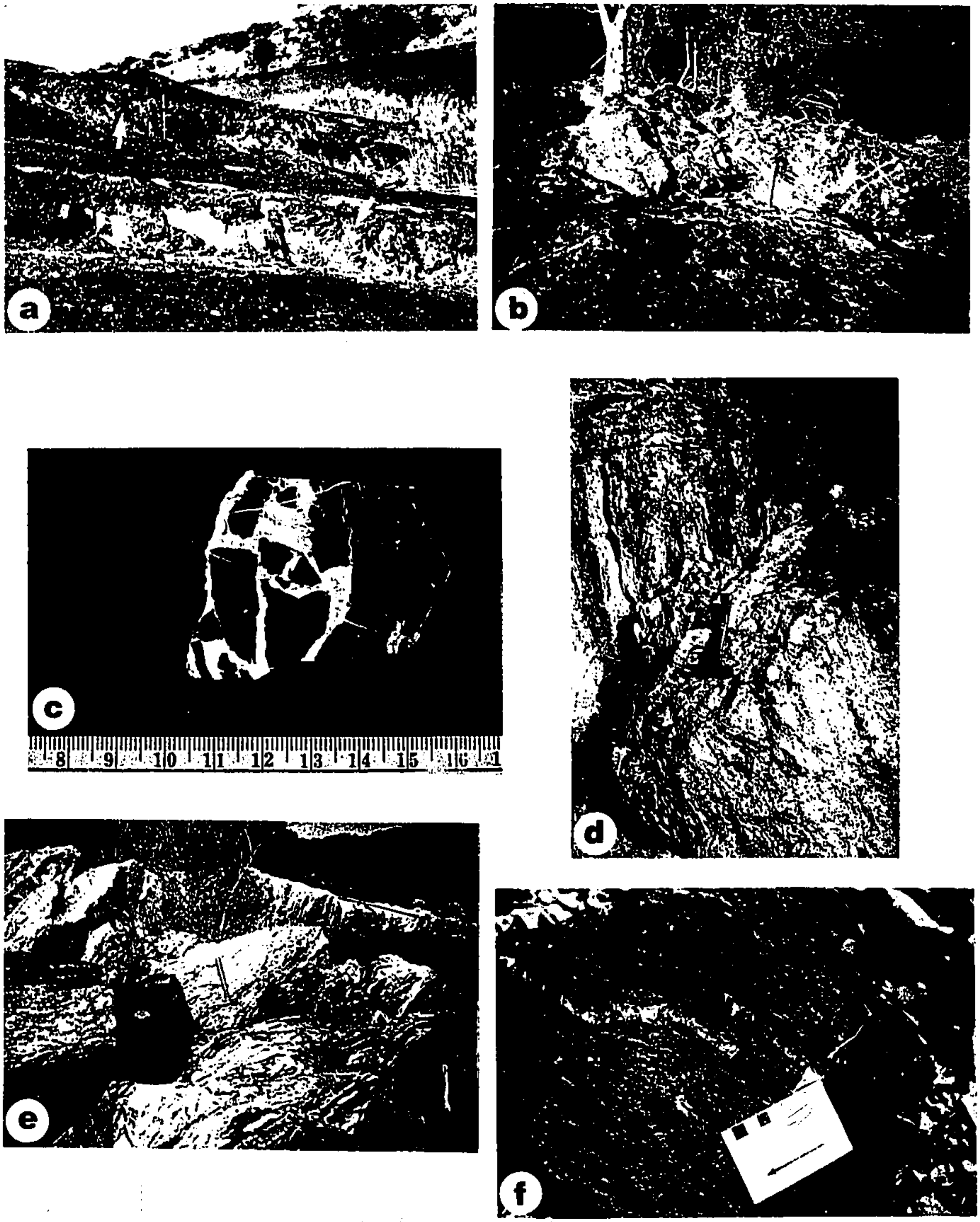
c: Polished slab from (b), above, showing the brecciated argillite. The breccia fragments are carbonaceous argillite. Notice the quartz veins (white) and hematite staining (reddish). Scale in cm.

Precambrian Basement Complex

d: Steeply dipping schist, Kazinze Open pit area, Siankondobo map area.

e: Gneiss with quartz-feldspar segregations (light coloured) and migmatitic rock (dark coloured). Muzuma River, Nkandabwe area.

f: Minor folding (phase F_2 ?) indicated by vein and highlight, Sikalamba stream section 6, Nkandabwe map area. Scale in cm


a
b
c
8 9 10 11 12 13 14 15 16 1
d
e
f

Siankondobo Sandstone Formation and basement rocks. As a consequence, the Main Seam does not crop out along the greater part of the northeast margin of the Kazinze area. In the mining cut NE 6/7 in the open pit area, Money et al. (1974) reports twenty faults in a distance of 750 m (see also Fig. 4.60a, this study).

The Maamba Township area occupies the northeastern Siankondobo map area separated from central Izuma area by a major northwest-trending fault. The area consists essentially of two sub-parallel, north-northeasterly-trending grabens containing Lower Karoo sediments separated by a horst of basement schists.

The northeastern part of Siankondobo map area shows offset of the succession by a northeast-trending fault that cuts across the Lower and Upper Karoo strata. A small half-graben in this area contains Sinakumbe strata resting unconformably on the basement rocks to the NW, and is in fault contact with the basement to the SE.

Much of the Upper Karoo strata in the southeast have been affected by east- , southeast- and northeast-trending faults. Some have thrown the Lower and Upper Karoo strata on to the horst basement rock in the southwest-central part of the map area.

2.2.3.3 Maze-Sinakumbe map area

The northeasterly-striking Karoo Supergroup strata are widely exposed across the map area; the Lower Karoo occupies the northwest and the Upper Karoo is exposed to the southeast. Although, Sinakumbe Group strata are not exposed, they were recorded in Geological Survey Borehole (GS 96) drilled in the vicinity of the Sinakumbe Village. The Lower Karoo occurs in three northeasterly-trending outcrop belts designated: northern, central and southern (Fig. 2.2c).

The northern belt is the largest (~7 km strike length), and is separated from the central belt by a narrow horst of basement rocks. The belt continues northeastwards into the Siankondobo coalfield area (Fig. 2.2b). The belt forms a shallow synclinal structural basin plunging gently northeast, and probably joins to the Kazinze syncline in the Siankondobo area (Fig. 2.2b). The Karoo and basement contact is concealed and largely suspected to be faulted against the basement. In the southeastern part of the belt, the Lower Karoo is faulted against the broad horst of basement rock. Minor east-trending faults are locally present.

The central belt is centred on the headwaters of the Kamanukwa River, forming the Kamanukwa half-graben (~5 km), with the sedimentary succession faulted against basement rocks to the SE. The half-graben opens northeastwards to a narrow area that connects the three belts.

The southern belt incorporates the Lower and Upper Karoo succession (to the southeast). It extends southwestwards into the Mulungwa map area. The sedimentary succession rests on the basement unconformably and has been offset by east-, northeast-, and northwest-trending faults.

2.2.3.4 Mulungwa map area

The northeastly-striking Karoo Supergroup strata are exposed in the Mulungwa area, with a general southeasterly dip of up to 50°. The succession has been offset by north-, northeast- , east- and southeast-trending faults. Some faults have throws up to 50 m (Money et al., 1974). Marginal faulting causing down-throw of Karoo sediments against the basement rocks, as in the Siankondobo map area (Fig. 2.2b), is not common, except for sliding along the plane of unconformity (Karoo and basement) reported by Radosevic (1968), which the present author has not observed. Brecciation of Madumabisa Mudstone and gneisses/schists occurs in the west of the map area where the former is faulted against the horst basement rocks.

2.3 REGIONAL GEOLOGY AND STRATIGRAPHIC FRAMEWORK

2.3.1 GENERAL REMARKS

This section summarises the general geology and stratigraphy of the mid-Zambezi Valley Basin and the study area. The sedimentary succession (Table 2.0) in the basin overlies the basement rocks and comprises the Sinakumbe Group and overlying Karoo Supergroup.

The **Karoo Supergroup** forms over 95 % of the outcrop in the basin, with the Sinakumbe Group occurring locally to the northwest, mainly in the Nkandabwe map area

Table 2.0 Stratigraphy of selected Karoo Basins in southern Africa. Numbers at head refer to main sources, viz. 1. Harland et al. (1982); 2. Kogbe and Burollet (1990); Hammerbeck and Allcock (1985); 3. Gair (1959); Tavener Smith (1960), Denman et al. (1968), Denman and Money (1970); 4. Bond (1967), Stagman et al. (1978); 5. Utting (1970); 6. Money (1972); 7. Habgood (1963), Thatcher (1974); 8. Quenell et al. (1956), Haughton (1963).

Ma	PERIOD [1]	SUPER GROUP	SOUTH AFRICA [2] GROUP	/FORMATION	GROUP	MID-ZAMBEZI ZAMBIA [3]	MID-ZAMBEZI ZIMBABWE [4]	LUANGWA [5]	BAROTSE [6]	MALAWI [7]	S. W. [8] TANZANIA
	QUATERNARY TERTIARY		KALAHARI GP			KALAHARI GP	KALAHARI GP	KALAHARI GP	KALAHARI GP	Various beds	Various beds
65	CRETACEOUS		ZULULAND GP				Malvernian Fm.			Dinosaur Beds	
144	EARLY JURASSIC (LIAS)		Drakensberg			Batoka Basalt Fm.	Batoka Basalt Fm.	Dolerite Dykes	Batoka Basalt with sediment interbeds	Basalt Lavas	
213	LATE TRIASSIC				UPPER	Red Sandstone Fm.	Forest Sandstone Pebbly Arkose	Upper Grit	Luena Sdst Kato Sdst	Red Sdst	K8 Manda Beds U Bone Bed
	EARLY TRIASSIC	KAROO	Stormberg	Clarens Fm Elliot Fm Molten Fm.	KAROO	Interbedded Sandstone and Mudstone Fm.	Red Marly Sandstone Ripple marked Flagstone	Red Marl Ntawere	Nkoya Grit Kahare Slst	Upp Sdst	
						Escarpment Grit Fm.	Escarpment Grit	Escarpment Grit	Machili Sdst	K7 Chiweta Grits	K7 Kingori Sdst
248	LATE PERMIAN		Beaufort	Tarkastad Subgroup Adelaide Subgroup	LOWER	Madumabisa Mudstone Fm.	Upper /K5 Madumabisa Mudstone Middle /K5 Lower /K5	Madumabisa Mudstone	Variegated Mudstone	K6 Chiweta Beds K5 Mwesia Beds	K6 L. Bone Bed K5 Ruhuhu Beds
258	EARLY PERMIAN		Ecca	Volksrust Fm. Vryheid Fm Pietermaritzberg Fm.	KAROO	Gwembe Coal Fm.	K4 Upper Wankie Sdst K2-3 Black Shale and Coal Group K1 Lower Wankie Sdst	Luwumbu Coal Fimba and Mpwashi members	Luampa Coal Carbonaceuos Mudstone, U. Luampa, Coal, & L. Luampa, B. Cgl. members	Rukuru Sdst and Shale Fm Coal Measures	K3 Intermediate Mdsts & Sdsts K2 L. Coal Measures
286	CARBONIFEROUS		Dwyka Formation			Siankondobo Sandstone Fm.	K0 Dwyka Glacial Beds	Basal Beds	Kado Sdst.	K1 Basal Beds	K1 Basal Beds
	DEVONIAN		Witterberg								
	SILURIAN	CAPE	Bokkeveld		SINAKUMBE	Upper Sinakumbe Group*- Quartzite Fm	SIJARIRA GROUP		Likupekupe Arkose Beds		
	ORDOVICIAN		Table Mountain			Lower Sinakumbe Gp* -U. Cgl Fm Sdst Fm L. Cgl Fm					

(Fig. 2.2a) and in a small half-graben in the northeast part of the Siankondobo map area (Fig. 2.2b). The supergroup has a maximum estimated thickness of 4.6 km and is divided into Lower and Upper Karoo at the sharp disconformable contact between the Madumabisa Mudstone Formation and the Escarpment Grit Formation (Table 2.0, Fig. 2.4a). Each group comprises several formations (Table 2.0; Fig. 2.4a, d-f). In Zambia, the subdivision into formations is essentially based on lithological grounds and inferred palaeontological evidence from other localities, particularly in Zimbabwe and South Africa. The formations are bounded by either a disconformity or gradational contacts. The K symbols (Table 2.0) introduced by Lightfoot (1929) for Karoo subdivisions at Wankie, and expanded by Bond (1952, 1967), were introduced to the Zambian coalfield succession by Denman and Money (1970). Owing to the paucity of palaeontological information, there appears to be no grounds for applying this strict subdivision to the Zambian succession, and it is therefore not used in the thesis.

2.3.2 BASEMENT COMPLEX

The basement rocks (pre-Karoo) are mainly Precambrian metasediments (>1 Ga) that occur as structurally alternating belts of schist (Fig. 2.3d, p.27) and gneiss (Fig. 2.3e, p.27) intruded by granitic plutons. Granitic intrusions occur to the northwest of the northeast-trending metamorphic belt, while the Karoo sediments and volcanic rocks occur to the south and southeast. Two distinct sequences are recognized, an older arkosic sequence with carbonate units (gneisses and marbles) and a younger schist sequence. Mafic rocks (now amphibolites) and pegmatites intruded the older arkosic succession before the argillaceous sediments (now schists) were deposited (Matheson, 1972; Legg, 1972; and Stillman, 1967).

These basement rocks were subjected to two phases of intense folding designated as F_1 and F_2 (Fig. 2.3f, p.27). The F_1 phase resulted in gently inclined axes and the F_2 resulted in steeply inclined tight folds with shallow, variable plunges on northeast-trending axes.

All major basement rock types are exposed in the so-called 'escarpment zone' bordering the Nkandabwe-Siankondobo-Mulungwa coalfields. The dominant structural

Fig. 2.4 Contacts between formations or with basement rocks

a: A sharp disconformable contact (near top of hammer handle) between the Lower Karoo (Madumabisa Mudstone Formation) and Upper Karoo (Escarpment Grit Formation) groups. This also defines the base of the Escarpment Grit Formation. Uphill Section, Mulungwa map area.

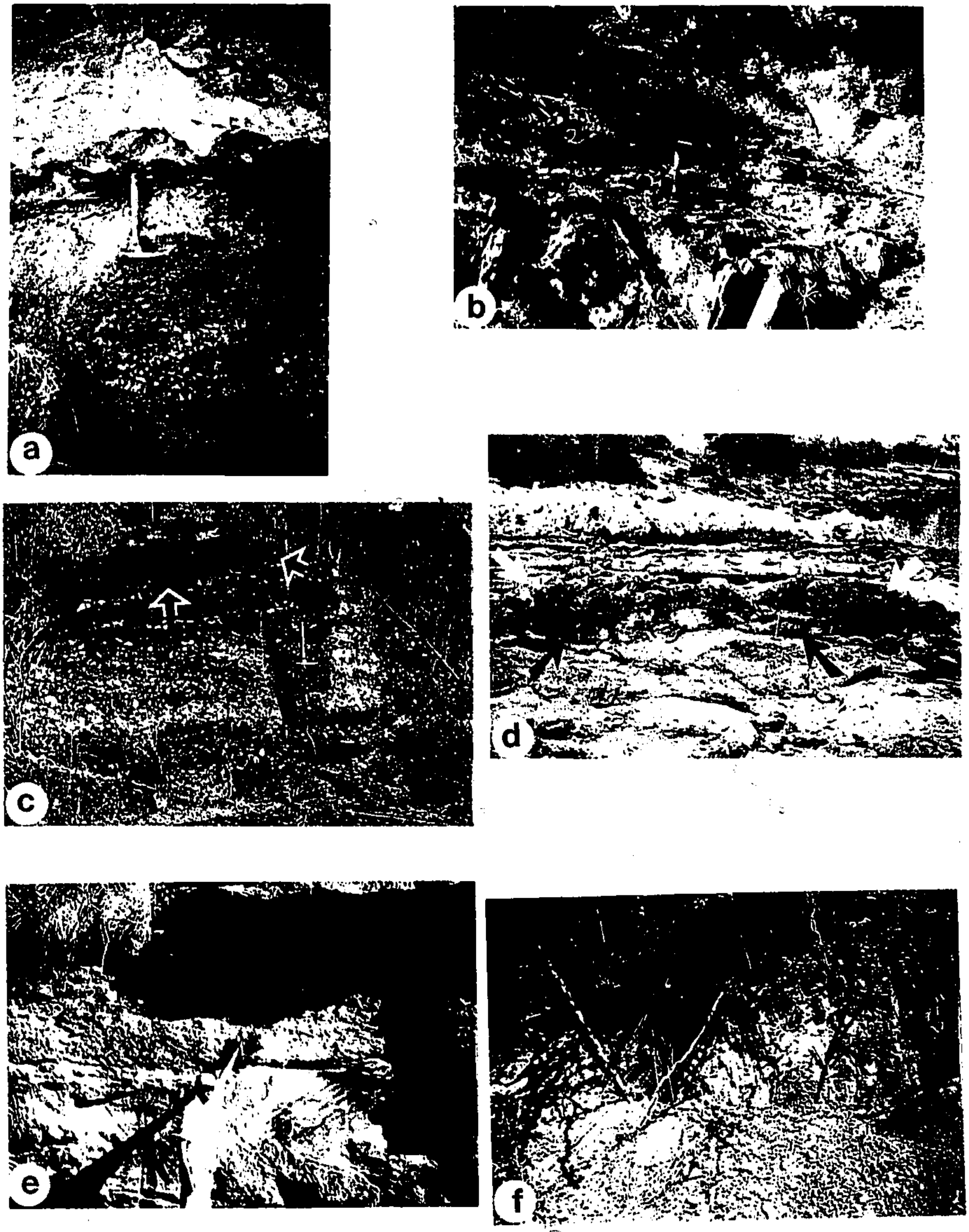
b: Unconformable contact between the Lower Sinakumbe Group and basement rocks. The crystalline basement rocks are overlain by red mudrock, then stratified pebbly sandstone and conglomerate. Ntole River Section 2. Hammer is 34 cm.

c: A sharp discomformable contact (arrowed) between matrix-supported conglomerate of the Lower Sinakumbe Group (below) and quartz arenite of the Upper Sinakumbe Group (above). Note interbedded pebbly sandstones in matrix-supported conglomerate lithofacies. Type section, Muzuma River Section 4, Nkandabwe map area.

d: Siankondobo Sandstone Formation resting unconformably on basement rocks. Notice the limited lateral extent of conglomerate overlain by siltstone/sandstone. Zhimu River Section 1, Mulungwa area. Hammer is 34 cm long.

e: Base of the Gwembe Coal Formation, resting conformably on the Siankondobo Sandstone Formation. Contact at hammer head. Izuma waterfall area, Siankondobo map area.

f: Base of Madumabisa Mudstone Formation (MMF) resting gradationally on the Gwembe Coal Formation (GCF) showing a change from brownish grey (GCF; hammer) to green/grey (MMF; metre scale) generally massive mudstone. Zhimu River, Section 1, Mulungwa map area. Hammer is 34 cm long.


a
b
c
d
e
f

trend is northeast, with the earlier fold phase (F_1) preserved only as minor structures. The gneisses are composed of quartz, feldspar, biotite and hornblende, with quartzo-feldspathic segregations occurring in the migmatitic varieties (Fig. 2.3c, p.27). The schists are composed of muscovite, quartz and biotite (Fig. 2.3d, p.27), commonly with garnet and sillimanite and more rarely staurolite. Granite and pegmatite intrusions form post-tectonic dykes and plutons. Some of the pegmatites are cassiterite-bearing, for example in the Masuku area (Legg, 1972; Newman and Drysdall, 1964). Amethyst veins occur sporadically as fracture fillings in the granulitic gneiss. The amethyst is usually associated with white crystalline quartz, and in places with calcite.

Late cataclasis on a northeast trend, accompanied by downgrading, resulted in the formation of several well-defined zones of mylonite. Finely banded mylonite consisting of translucent, non-micaceous, quartzose rock is the most common rock type.

2.3.3 SINAKUMBE GROUP

The Sinakumbe Group is the oldest sedimentary succession in the area, and was formerly designated a formation (Sinakumbe) by Denman (1969) on the basis of Geological Survey borehole GS96, drilled in the Maze area between the Mulungwa and Siankondobo coalfield areas. The group crops out extensively on the northwestern margin of the Nkandabwe map area (Fig. 2.2a) and in a small portion centred on an unnamed stream that enters the Kazinze River in the northeastern part of the Siankondobo map area (Fig. 2.2b). The Muzuma River section of the Nkandabwe map area gives a fairly good exposure of the group, with the maximum thickness of 176 m. However, in the Muzuma-Sikalamba corridor (Fig. 2.2b), the group is likely to be over 210 m thick.

The Sinakumbe Group was described by Denman and Money (1970) as 61 m of well-lithified, brightly coloured sediments occurring below the Lower Karoo Siankondobo Sandstone Formation. Further work by Denman and Money (1970) and Harper (1970, as quoted in Money et al., 1974) divided the 61 m sequence into three formations (Table 2.0): the Lower Conglomerate Formation, the Sandstone Formation and the Upper Conglomerate Formation. Each of the three formations was said to consist of a series of "fining-upward cycles". A fourth formation, the Quartzite Formation, was not intersected in the borehole, but described from derived pebble detritus in the lower beds of the Siankondobo Sandstone Formation. The Sinakumbe Group has been correlated to the Sijarira Group of Zimbabwe (Denman and Money, 1970). The type area for the group is the Maze-Sinakumbe area and the Geological Survey drillhole GS96 the type-log section.

The four formations are not well defined in the study area outcrops. The Middle Sandstone Formation is absent. Instead, the sandstone occurs mainly as amalgamated intercalations and irregular interbeds within the conglomerate. The division into lower, middle and upper is not practical, and therefore the group is here defined, based on sedimentological differences (lithology and association), as comprising two units which are readily distinguished in the field: the Lower Sinakumbe Group and the Upper Sinakumbe Group. The **Lower Sinakumbe Group** (Table 2.0), is equivalent to the Lower Conglomerate, Middle Sandstone and Upper Conglomerate formations of Denman and Money (1970). The unit, about 60 m thick, directly overlies the basement complex (Fig. 2.4b) and consists mainly of conglomerates and pebbly sandstones with subordinate mudrocks and fine-grained sandstones. The **Upper Sinakumbe Group** (equivalent to Quartzite Formation) is 150+ m thick, and comprises mainly quartz arenite with subordinate mudclast breccia. The contact between the two units (lower and upper) is a sharp disconformity (Fig. 2.4c). This new division is followed in the thesis. However, brief descriptions of the four formations defined in borehole GS 96 by Denman and Money (1970) are given below.

2.3.3.1 Lower Conglomerate Formation

The formation (Table 2.0), which is 21 m thick, comprises five cycles of fining-upward units that rest with angular unconformity on mica schists of the Precambrian basement. The basal cycle consists of coarse polymictic conglomerate that grades upwards into fine sandstone and siltstone; no mudstones are present. The beds are structureless, except for flute casts and horizontal lamination in finer-grained beds, poorly sorted and essentially red, though upper cycles are greyish-green and white in places.

The phenoclasts of the conglomerate consist mainly of metaquartzite, gneiss, sandstone and mudstone with diameters ranging from 15 cm at the base of lowest cycle to

3 cm in the upper cycle. The rocks are essentially matrix-supported (mud, sand and gravel matrix) with silica and carbonate cement, and are submature to immature, belonging to litharenites and lithwackes (Dott, 1964; McBride, 1963). The formation is correlated to the Mongolohwe Formation of the Sijarira Group of Zimbabwe (Harper 1970, as quoted in Money et al., 1974).

2.3.3.2 Sandstone Formation

The formation (Table 2.0), which consists of fifteen graded cycles of immature, greyish-green sandstones (lithic sub-arkose and feldspathic lithicwacke), is 30 m thick. Each cycle begins with an eroded basal surface followed by coarse sandstone that grades into siltstone, and in one place, mudstone (cycle 9). The rocks become cleaner (increased sand:shale ratio) and better sorted in the upper cycles. The finer clastics within the cycles show flaser bedding, parallel and wavy laminations, silt-sand lenses and flame structures.

The formation is correlatable to marginal facies resting above the red Mongolohwe Formation of the Sijarira Group of Zimbabwe (Harper, 1970, as quoted in Money et al., 1974).

2.3.3.3 Upper Conglomerate Formation

The formation (Table 2.0) is 10 m thick and consists of four poorly-defined fining-upward units that begin with a conglomeratic member. The conglomeratic unit has an open framework structure that is better sorted and cleaner than the Lower Conglomerate Formation. The upper cycles are composed almost entirely of clean, medium-grained, moderately well sorted, greyish-green to white sandstones that show small-scale cross-bedding, irregular bedding, and horizontal lamination.

The rocks are quartz arenites containing 90% quartz, with small amounts of feldspar and rock fragments, although some layers are subarkosic.

2.3.3.4 Quartzite Formation

The formation was originally described from pebbles and cobbles incorporated in basal Lower Karoo conglomerates. The quartzite pebbles, cobbles and boulders are pinkish to greyish-white, subrounded to well-rounded and in places are parallel- and cross-laminated (see Fig. 4.18a, Chapter 4), and very similar to quartzite pebbles collected in the Maze area (Denman and Money, 1970). The rocks are quartz arenite to subarkose, with silica as the main cement, and generally are matrix-free, although few specimens contain up to 10% matrix. The formation contains mainly clean, well sorted quartz sands with subordinate feldspar.

The wide occurrence of these clasts in the basal Karoo rocks and their non-intersection in the GS96 borehole led Denman and Money (1970) to conclude that these clasts are younger than the three formations intersected in GS96, but older than the basal Karoo rocks.

2.3.4 LOWER KAROO GROUP

The Lower Karoo Group, Permo-Carboniferous to Permian in age, is over 1 km thick and consists of three formations: the basal Siankondobo Sandstone, and overlying Gwembe Coal and Madumabisa Mudstone (Table 2.0). These three formations are exposed along the margins of the mid-Zambezi Valley basin.

2.3.4.1 Siankondobo Sandstone Formation

The Siankondobo Sandstone is the oldest Karoo formation in the mid-Zambezi Valley and is defined as predominantly arenaceous, non-carbonaceous beds resting unconformably on the basement (Fig.2.4d) or on the Sinakumbe Group or faulted against the basement. The formation has a maximum thickness of 90 m intersected in drill holes, but only about 30 m measured in exposures in the study area. Detailed mapping and diamond drilling in the Siankondobo area have shown that the single major arenaceous unit in the Lower Karoo Group recorded by Gair (1959), Tavener-Smith (1960), and Pagella and Drysdall (1966) can be subdivided into two major units, the Siankondobo Sandstone and the Maamba Sandstone, based on lithology, sedimentary structures and organic content. The formation was defined in the area on sedimentological grounds, and Siankondobo is regarded as the type area. The Maamba Sandstone, once part of the Siankondobo Sandstone Formation, is now considered to be the basal member of the

Gwembe Coal Formation.

On lithostratigraphic criteria, the formation has generally been designated a Late Carboniferous (Dwyka-Ecca) age (Denman and Money, 1970), and correlates with the Lower Wankie Sandstone of Zimbabwe. The formation shows considerable variation in thickness in the area, with an average thickness of 10-20 m, and thicker units in the region south of Siankondobo.

The formation has been divided into three conformable members: a Lower Member of diamictite and/or conglomerate, and glacial varves, a Middle Member of laminated fine-grained sandstone and an Upper Member of massive, fine to medium-grained sandstone (Denman et al., 1968). The Lower Member is 3-9 m thick. The Middle Member ranges from 3 m to over 20 m thick. The Upper Member is over 80 m thick in the Siankondobo area (Beacon Hill and Izuma), and is estimated to be 30 m thick in the Nkandabwe area (Tavener-Smith, 1960). There is no surface of erosion and no conglomerate between the middle and upper members; however, fragments from the Middle Member occur in the basal bed of the Upper Member in a few localities.

2.3.4.2 Gwembe Coal Formation

The Permian Gwembe Coal Formation, is a succession of carbonaceous, silty mudstones and siltstones with interbedded coal seams and sandstones overlying the Siankondobo Sandstone Formation disconformably and locally unconformably (Fig. 2.4e). The formation attains its maximum thickness, in excess of 280 m, in the Siankondobo coalfield area (borehole GS70). In the Mulungwa area, it is between 100 and 150 m thick. The formation was previously divided into three units (Denman et al., 1968), but since the basal sandstone occasionally interdigitates with the overlying coal, a two-fold division into Lower and Upper units, with a boundary at the base of Sandstone A, is more applicable (Money et al., 1968; this study). The Lower Unit attains its maximum thickness of over 60 m in the Maze area, and contains the coal seams. The Upper Unit is up to 250 m thick, and is characterised by five sandstone units designated A (oldest) to E (youngest). The coaly and carbonaceous mudstone units occur mainly in the lower Gwembe Coal Formation (Lower Unit) and the grey and silty mudstone units in the upper Gwembe Coal

Formation (Upper Unit). The formation also consists of several distinct lithological units, more variable in extent locally: the Maamba Sandstone Member at the base, Main Seam, Interseam Sandstone, upper seams/carbonaceous mudstone, five-sandstones (A to E) alternating with carbonaceous/silty mudstones, and transitional beds (known as the Izuma beds) at the top.

The **Maamba Sandstone Member**, was previously known as the Transition Beds (Pagella and Drysdall, 1966), and was subsequently renamed (Denman, Money and Radosevic, 1968). The sandstone is mainly buff, coarse-grained, and in many places with a basal conglomerate grading upwards to fine-grained sandstone, siltstone and mudstones, and locally coal. It varies in thickness from 0.3 to 30 m. The member can be subdivided into a lower conglomeratic unit generally 2-3 m thick and an upper fining-upwards (or graded sequence) unit. The latter comprises mainly alternating sandstone and mudstone with thin, coaly mudstones and coal seams that are frequently terminated by wash outs (Money et al., 1974).

The **Main Seam** conformably overlies the Maamba Sandstone in the lower Gwembe Coal Formation, or rests directly on the Siankondobo Sandstone Formation or on basement rocks (F147). The Main Seam (currently exploited) interdigitates with sandstone units (Interseam Sandstone) such that as many as four seams have been recorded from A to D, starting with the youngest (e.g. in the Kazinze Open pit). A and B seams are usually present (Money and Drysdall, 1975). The Main Seam grades upwards and laterally into carbonaceous mudstone that progressively becomes lighter grey and more silty (silty mudstone) incorporating coaly mudstone, the Upper Seams and thin siltstone and sandstone units. The Main Seam varies from 1 to 12 m thick. Individual seams can reach a maximum of 4 m thick and a minimum of less than a metre. Together with the Interseam Sandstone, the seam attains a maximum of 15 m thickness in the Siankondobo map area (Fig. 2.2a). At Nkandabwe to the north, it ranges from 1 to 7 m, with an average of 3.7 m (Tavener Smith, 1960; Cornwall, 1965), whereas in the Mulungwa coalfield area, the seam is between 5 m and 9 m thick (Radosevic, 1968; this study). The Main Seam can be best studied in the Kazinze and Izuma open pits (Fig. 2.5a and b), and Nkandabwe open pit (Fig. 2.5c). The Izuma open pit, adjacent to the Kazinze, is exploited whenever there are

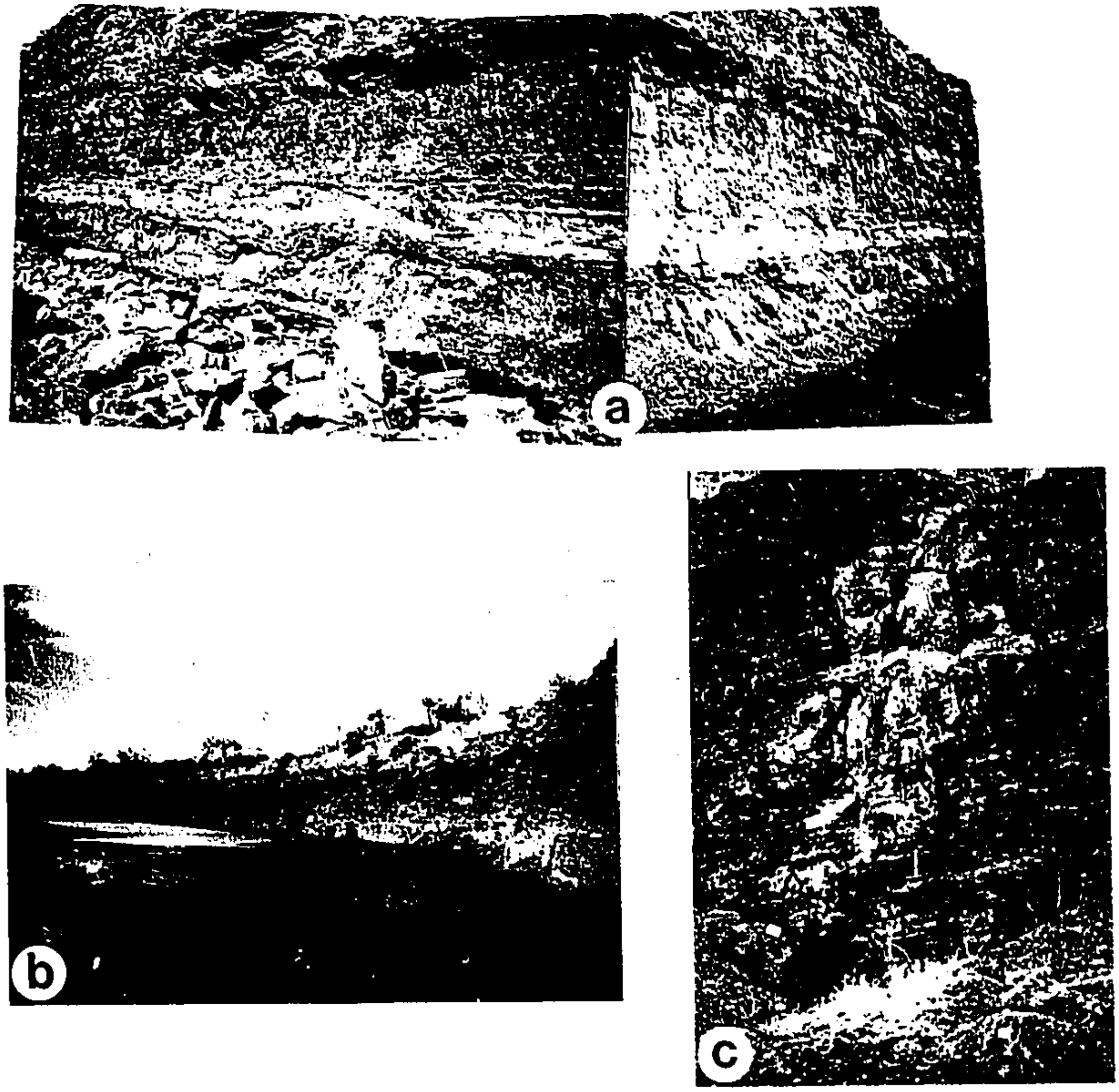


Fig. 2.5 Open Pits, Mid-Zambezi Valley Basin

a: Kazinze Open pit showing two seams (Main Seam; A and B) split by the Interseam Sandstone (whitish, behind the 2.1 m scale). As many as four seams have been mined (from oldest D, C, B and A).

b: Izuma Open pit showing one coal seam (Main Seam) intercalated with coaly, carbonaceous, silty and sideritic mudstones. Person for scale (see arrow).

c: Southwest part of Nkandabwe Open pit, showing one coal seam (Main Seam). Notice the coal is layered. Hammer is 34 cm.

mining problems at the latter. However, the exposure there does not allow easy stratigraphic positioning. The abandoned Nkandabwe open pit has been affected by recent weathering, and most exposures are covered by sand and vegetation, thus making the Kazinze Open-pit the best locality for study.

The **Upper seams** occur in the upper part of the Maamba Sandstone and in the Upper Gwembe Coal Formation. In the latter, together with the mudstone, the seams alternate with the sandstones. The seams are usually thin (≤50 cm, commonly 1 to 30 cm) and occur cyclically in gradational contact with coaly and carbonaceous mudstones (Tavener-Smith, 1960). Thin and isolated beds of fireclay occur in the Maamba open-pit area, and in the Mulungwa and Maze areas. For example, a 15 cm thick fireclay occurs above the Main Seam in borehole GS102. In boreholes F122 and F140, five unstratified, creamish-white to grey beds 2-17 cm thick, having all the attributes of tonstein, have been recorded from the dark grey upper Gwembe mudstones.

The **Interseam Sandstone**, up to 4 m thick, is petrologically similar to the Maamba Sandstone underlying the Main Seam, and this led Radosevic (1968) to include it in the estimated thickness (~30 m) of the Maamba Sandstone in the Mulungwa area.

The five sandstones are best exposed in the Kazinze area of the Siankondobo map area. In the Mulungwa area, sandstones A, B, C and D have been recognised, but only muddy feldspathic, medium-grained sandstone units up to 1 m thick, grading into siltstones, are recognised in the Nkandabwe area. Two coarse-grained, feldspathic sandstone bodies (A1 and A2) occur between the Main Seam and sandstone B in the Mulungwa area. In the Siankondobo area, the sandstones occur approximately 90 m, 120 and 180 m, respectively, above the base of the Main Seam and are separated by carbonaceous and silty mudstone.
The sandstones are 5 to 7 m thick (maximum 11 m for sandstone D in the Mulungwa area).

Sandstone A is the most widely developed and readily recognizable unit in the formation with a maximum thickness of over 30 m in the Siankondobo and Maze-Sinakumbe map areas, and up to 20 m thick in the Mulungwa map area.

Sandstone B is blue-grey to purple-grey, highly sideritic and ranges from muddy silt, to fine- to coarse-grained sand. It is generally 1 to 8 m thick (maximum 10 m), with type outcrop exposed near borehole GS50 in the Siankondobo area. It is separated from sandstone A by 40-50 m of carbonaceous mudstone. The sideritic sandstones in the Kazinze River have a characteristic hard, 'ironstone' coating, with a nodular or concretionary appearance and vary in thickness from 5 cm to 1 m, with lateral extents of no more than 15 m.

Sandstone C consists of medium- to fine-grained, non-ferruginous sandstone and greenish grey sideritic sandstone.

Sandstone D is a medium-grained, white sandstone with occasional dark siltstone bands and carbonaceous partings, and interbedded flaggy mudstone and silty mudstone. Conglomerate lenses up to 60 cm may be present in some outcrops.

Sandstone E is not well exposed, and at one outcrop in the Siankondobo area, it consists of an upper layer of coarse-grained, pebbly, arkose up to 5 m thick, overlying fine- to medium-grained sandstone.

Alternating dark, carbonaceous and pale, non-carbonaceous mudstone and siltstone beds, up to 20 m thick conformably overlain by Madumabisa Mudstone Formation, were named the **Izuma Beds** in the Izuma River type area by Denman et al. (1968).

2.3.4.3 Madumabisa Mudstone Formation

The Madumabisa Mudstone Formation overlies the Gwembe Coal Formation (GCF) conformably and gradationally (Fig. 2.4f). The formation is a uniform succession of massive, grey-green, non-carbonaceous, silty mudstone with a few thin sandstone and calcilutite layers, 200 to 700 m thick. In places, the grey-green colour is replaced by a striking khaki-brown, whereas near the contact with upper Karoo, the mudstone is tinged red, presumably due to weathering and oxidation before deposition of the Upper Karoo rocks. The formation crops out in the low-lying areas in the mid-Zambezi Valley between the Gwembe Coal Formation and the Escarpment Grit Formation of the Upper Karoo Group. The formation ranges in outcrop width from 2 to 4 km, and is of low relief, except for low ridges of calcilutite and sandstone. It was divided into three units, Lower, Middle and Upper, by Tavener-Smith (1960, 1962) and Gair (1960). The lower and upper units are homogeneous and poorly stratified compared to the middle division, which contains numerous calcilutite layers and concretions that contain fossils.

Feldspathic sandstone beds are generally 4 to 5 m thick. The beds may be traced up to 3 km along strike. In the Mulungwa area, graded sandstone units less than 50 cm thick commonly show all or part of the Bouma sequence.

2.3.5 UPPER KAROO GROUP

The Upper Karoo Group consists of red, buff and pink feldspathic grits and sandstone, with minor siltstone, mudstone and conglomerate, and basalts overlying the Madumabisa Mudstone Formation (Fig. 2.4a) or basement rocks. Its estimated thickness of over 2200 m may include units repeated by faulting parallel to strike. The group is exposed to the southeast/south of the Lower Karoo Group in the mid- Zambezi Valley. As a result, from the lowlands of the Madumabisa Mudstone Formation of the Lower Karoo Group southeastwards, one ascends into an area of generally northeast-trending ridges of Escarpment Grit Formation of the Upper Karoo Group. It is divided into four informal formations: the Escarpment Grit, Interbedded Sandstone and Mudstone, Red Sandstone, and Batoka Basalt formations (Power Nuclear Corporation of Japan (PNC), 1987). In the study area, the main lithostratigraphic units of the group exposed are the Escarpment Grit and Interbedded Sandstone and Mudstone formations. These two are therefore described in more detail here.

2.3.5.1 Escarpment Grit Formation

The contact between the Madumabisa Mudstone and Escarpment Grit formations is not well exposed, except for an abrupt change from mudstone to grit seen along the Chezya River near Jumbo and along the Chilola River. An unconformity occurs in the cliffs along the Gwemanji River, where the formation rests directly on basement gneisses, pegmatites and amphibolites (Gair, 1959; Tavener-Smith, 1960). In the Mulungwa map area, the contact between the two formations is a sharp irregular to undulatory disconformity (Fig. 2.4a).

The formation is approximately 350 m thick and consists essentially of variable thicknesses of purplish red, medium- to coarse-grained feldspathic sandstones and numerous 2 to 3 m-thick units of conglomerate containing quartz and feldspar pebbles. The maximum thickness estimated by PNC is 800 m, and 400 to 500 m by AGIP in the Kariba Lake area. Beds of green and reddish mudstone 4 to 5 m thick are abundant in the lower part of the Escarpment Grit.

2.3.5.2 Interbedded Sandstone and Mudstone Formation

The base of Interbedded Sandstone and Mudstone Formation is generally taken where the sandstone becomes predominantly medium- to coarse-grained and below the first appearance of mudstone interbeds. The formation consists of medium- to coarse-grained, feldspathic, gritty, and locally flaggy sandstone with minor intercalations of brownish-red calcareous mudstone, siltstone and conglomerate. Owing to warping and faulting, thickness estimates are difficult, but Malamphy and Company (Malamphy, 1950), and Tavener-Smith (1960) estimated 1750 m and 1900 m thick respectively. In recent work, the thickness of the formation was estimated to be in the order of 2000+ m (by PNC), and 250 to 1500 m (by AGIP) in the Lake Kariba area.

In areas where interbedded mudstone is well developed, numerous parallel sandstone ridges having steep scarp faces are separated by a fairly flat belt underlain by mudstone. The sandstone scarps are up to 75 m in height, with backslopes that dip from 15 to 20° to the southeast in general. Carbonaceous mudstone units (up to 50 cm) locally containing thin beds of dirty coal (10 cm thick max.) have been observed in the Mwenda River area and a cliff section at the Lusitu River (Gair, 1959).

2.3.5.3 Red Sandstone Formation

The formation overlies the Interbedded Mudstone and Sandstone Formation and consists of red sandstone with a distinctive homogeneous appearance due to uniform composition and sorting of grains. It has an estimated thickness of 200-500 m. The sandstone is composed mainly of quartz grains and subordinate feldspar, cemented by a fine mosaic of secondary silica and locally calcite. Up-sequence, the sandstone becomes brighter red, even-grained and homogeneous, commonly showing high-angle cross-bedding, and is rarely interbedded with mudstone. The sand grains are opaque, frosted, and highly spherical. The term "millet-seed sandstone" has been used previously to describe the rocks of this unit, and an aeolian origin has been attributed to them.

The Red Sandstone does not outcrop in the study area, and is not discussed in later parts of the thesis.

2.3.5.4 Batoka Basalt Formation

Outpourings of basaltic flows in the Early Jurassic terminated Karoo deposition. The basic volcanic rocks of the Batoka Basalt Formation crop out extensively to the south and southwest of the study area. In the study area, isolated outcrops of basalt overlain by sandstones occur along a stream close to the airstrip southwest of Maamba (Money et al., 1974). The formation has an estimated thickness of over 400 m, and is made up of separate basaltic to andesitic flows from 3 to over 30 m thick, with vesicular upper surfaces. Agglomeratic intercalations up to 7 m thick are present locally, near the top of the sequence. The basalt dips at a lower angle than the underlying sandstones, and the contact may be unconformable. On fresh surfaces, the basalt is generally black, or partly greenish to dark greyish-green and reddish-purple. It weathers to a reddish-brown clay and contains abundant calcareous concretions and agates. Pyroclastic units containing 'bombs' of vesicular and more massive lava up to several centimetres in diameter are present. The pyroclastic materials consist mainly of small fragments of vesicular and massive lava in a fine-grained, brownish, glassy matrix containing abundant zeolites. The basalt is composed mainly of individual or clustered phenocrysts of feldspar (labradorite-andesine) set in a groundmass of unoriented plagioclase laths, augite, subhedral grains of magnetite, and small amounts of acicular apatite and aggregates of serpentine pseudomorphing olivine. Scolecite, mesolite and agate occupy fractures and amygdules. In general, the basalt is tholeiitic.

The Batoka Basalt outcrops only rarely in the study area and is not considered further in this thesis.

2.4 CHRONOSTRATIGRAPHY

Most of the mid-Zambezi Valley stratigraphic succession outlined above is unfossiliferous. The ages listed in Table 2.0 and discussed below are based on information from the few units that do contain fossils, and from correlative lithostratigraphic units elsewhere in southern Africa.

No palynomorphs or other fossils have yet been recovered from the Sinakumbe Group and this has long led to uncertainty about its age. Some researchers argue that it forms the basal sequence of the Lower Karoo Group (Money, pers. comm., 1991). The group is considered to be older than the Karoo based on lithostratigraphy and on comparison with similar (Ordovician to Devonian) rocks in southern Africa, in particular the Sijarira Group in Zimbabwe, with which it is correlated. The latter is correlated in turn with the Cape Supergroup of South Africa (Table 2.0). It is therefore probable that only a small part of this age range is represented in the mid-Zambezi Valley Basin. This could also be the reason why the Sinakumbe strata are only 210 m thick in the basin. No marine conditions are indicated in pre-Karoo time in the mid-Zambezi Valley, except for equivalent clastic sediments to the Sinakumbe Group intersected in a borehole (GS108) in the western Zambia Karoo Basin (Money, 1972) that yielded acritarchs (Utting and Vavrdova, 1972) linked to marine conditions.

The Karoo Supergroup strata range in age from Permo-Carboniferous (280 Ma) to Early Jurassic (180 Ma), giving a depositional span of 100 m years. Plant remains are poorly preserved and have not been identified in the Siankondobo Sandstone Formation of the Lower Karoo Group. A Late Carboniferous age is interpreted from palynological data (Utting, 1978) and the occurrence of glacial units that are correlative to the Dwyka Group of South Africa.

The Gwembe Coal Formation is Lower Permian (mainly middle and upper Ecca) in age. Macerated plant fragments, often associated with pyrite blebs are present, but no large plant fossils have been observed. Thin calcilutite units in the Madumabisa Mudstone Formation have yielded a number of small, freshwater lamellibranchs, and plant remains. The study of fossils was pioneered by Molyneux, who described fish scales, lamellibranchs and plants (Molyneux, 1903). Fossils include *Palaeomutela neglecta* (Jones), *Palaeomutela rectodonta* (Amalitsky), *Palaeomutela rhomboidalis* (Sharpe), *Palaeonodonta caster* (Eichwald), *Palaeonodonta parallela* (Amalitsky), *Palaeonodonta* sp., *Kidodia coxi* (Bond), *Durwinula* sp., *Glossoptoria indica* (Sachimper), *Phyllotheca* sp. and some fish scales. Palynological data (this study) suggests that Madumabisa Mudstone Formation is Late Permian.

No fossils have been recovered from the Upper Karoo, except for fossilised wood. However, one sample in this study from the Interbedded Sandstone and Mudstone Formation yielded palynomorphs that indicate an age of Early to Middle (?) Triassic.

CHAPTER III

STUDY METHODS

3.1 GENERAL REMARKS

This study is based largely on field data collected in the mid-Zambezi Valley, Sinazongwe District, Southern Province, Zambia (Fig. 1.2) over seven months during two field seasons (April to September, 1990 and June to August, 1991). Most fieldwork required field camps set close to a school or village for use of the water wells and vehicle track (4WD) and the PNC camp. From these camps, foot traverses were made to outcrop areas, most requiring walking distances of over 10 km. Accommodation for mapping in the vicinity of the Maamba Mine area was generously provided by Maamba Mine Management. Another large set of data from 1000 boreholes, in the form of core descriptions, analyses of ash content and some analyses of sulphur content and volatile matter were also available. Full consideration of the borehole data has been deferred because of time constraints; post doctoral study of this additional data is planned, utilising the Geomodel System developed at the Institute of Sedimentary Petroleum Geology (ISPG) in Calgary, Canada. This chapter outlines the field and laboratory techniques used in the project.

3.2 FIELD WORK

Field work involved recording detailed sedimentological profiles, photographing more continuous exposures (mainly along river and stream courses) to provide photomosaics, and collection of representative samples throughout the study area (Fig. 3.0a, b, c, d). Vertical and lateral relationships between facies were established by plotting details of field observations onto photomosaics. Altogether, 48 profiles and 15 photomosaics were made. Most of the profiles (sections) are 20 to 100 m thick, but a few are over 200 m and the largest 750 m thick. The photomosaics commonly cover distances of 10 to 50 m laterally and the largest is 320 m. Fifteen boreholes were logged. Eight outcrop sections of the Sinakumbe Group were measured in the Nkandabwe area, and one

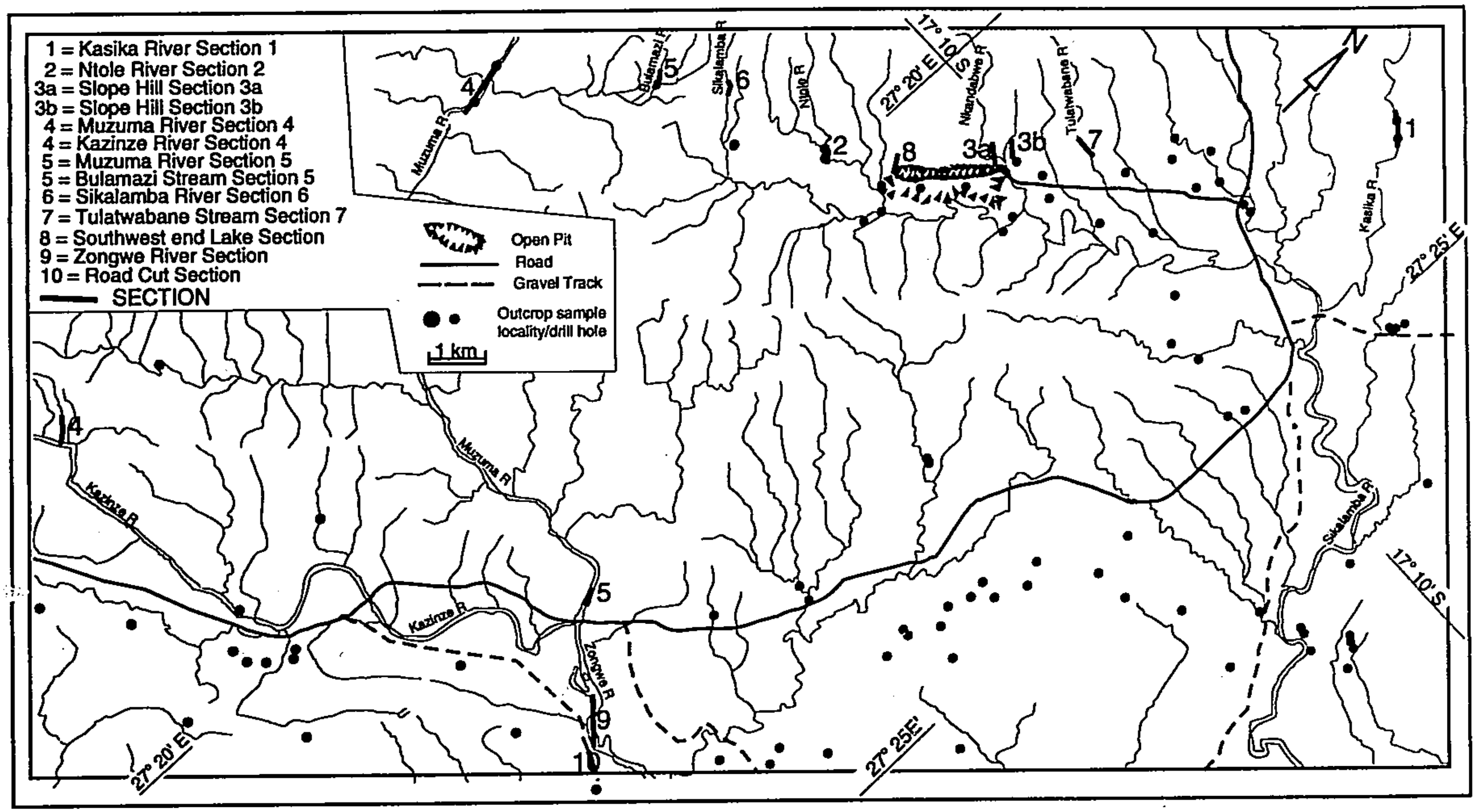


Fig. 3.0a Location of sections, samples and drill holes in Nkandabwe map area. See Fig. 1.3 for general location in study area.

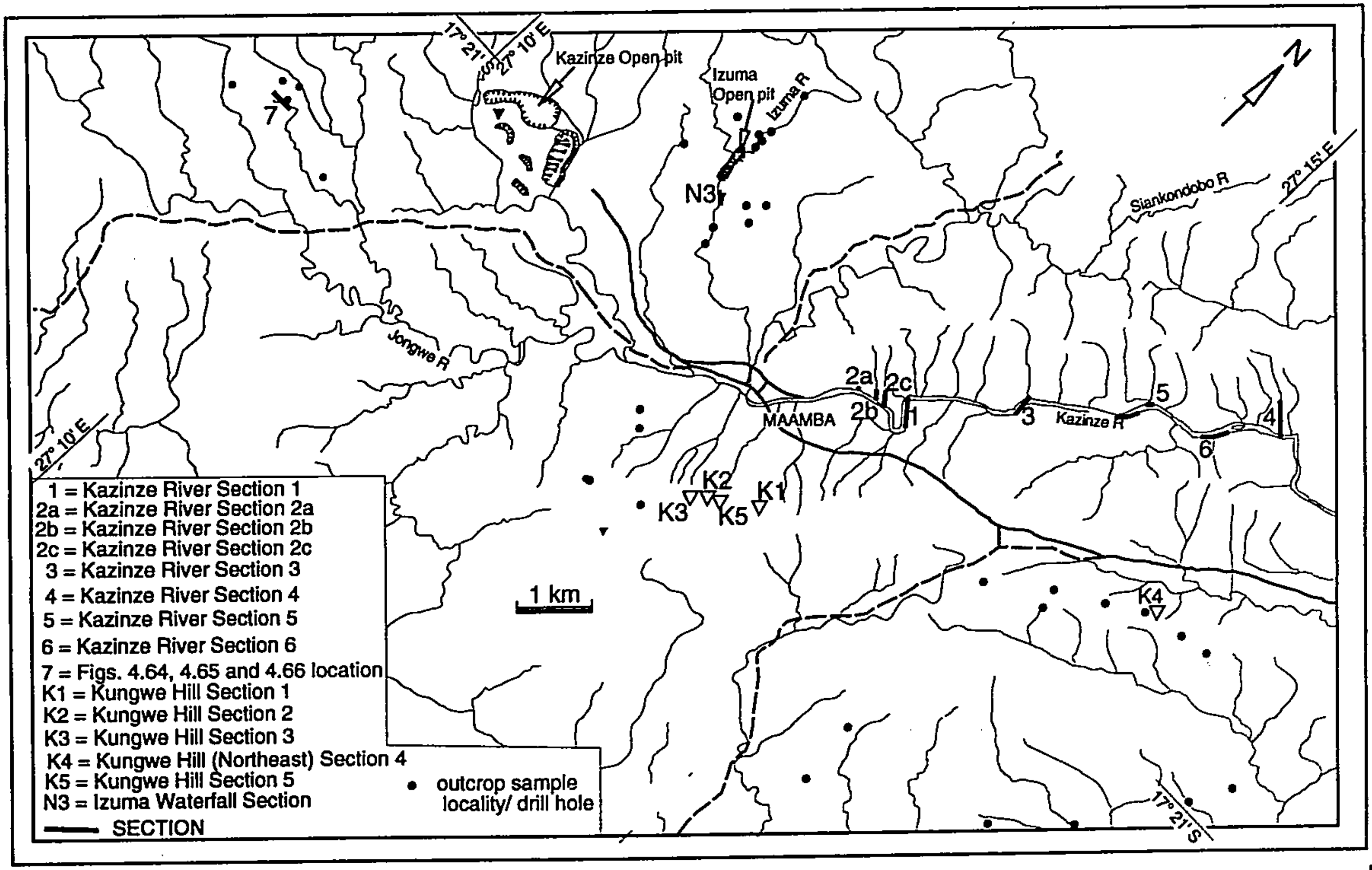


Fig. 3.0b Section localities, samples and drill holes in Siankondobo map area. See Fig. 1.3 for general location in study area.

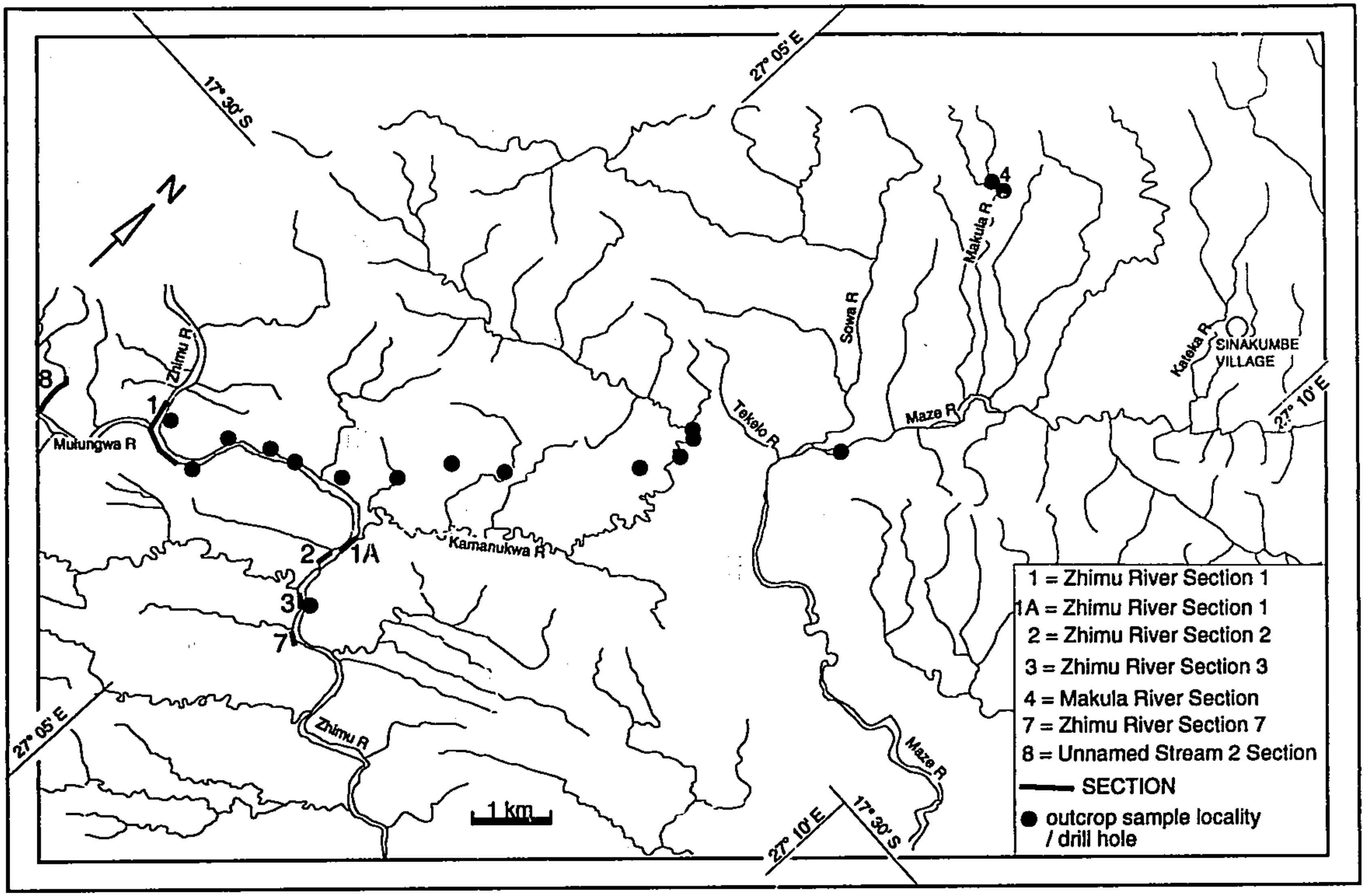


Fig. 3.0c Location of sections, samples and drill holes in Maze-Sinakumbe map area. See Fig. 1.3 for general location in study area.

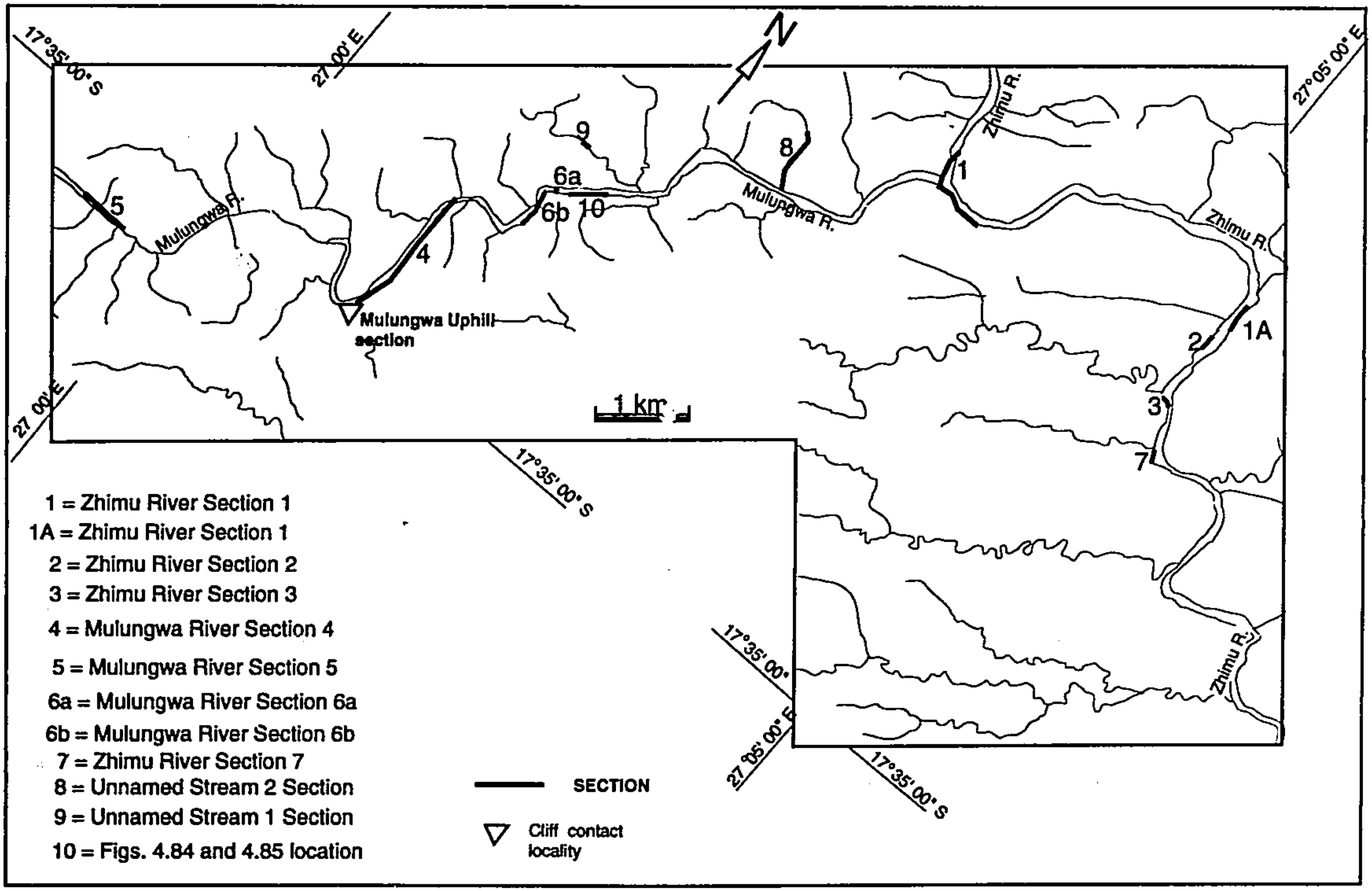


Fig. 3.0d Location of sections in Mulungwa map area. See Fig. 1.3 for general location in study area.

in the Siankondobo area. Also measured were twenty outcrop sections of the Siankondobo Sandstone Formation, 18 of the Gwembe Coal Formation, 7 of the Madumabisa Formation, and 8 of the Upper Karoo formations.

Palaeocurrents were measured mainly from unidirectional sedimentary structures, with axes of trough cross-strata being considered the most reliable unidirectional palaeocurrent indicator (Potter and Pettijohn, 1963). Some bidirectional features such as orientations of tree (plant) stem impressions were measured as well. Other directional features measured included planar cross-strata, ripple mark crests and cross-laminae, and aligned plant stems (medium to large sized). For all sections, a total of 750 measurements from cross-beds (trough) and ripple-foresets, and 190 plant stems orientations were recorded. Methods used in this study for the processing, plotting and interpretation of palaeocurrent data are those outlined by Curray, 1956; Collinson, 1971; Allen, 1966; Cant and Walker, 1976; Potter and Pettijohn, 1977; and Miall, 1974, 1976, 1990. Corrections for tectonic dip were not necessary, because dips of 25° or less do not affect orientations significantly (Potter and Pettijohn, 1963, 1977).

3.3 LABORATORY WORK

3.3.1 STRATIGRAPHIC-SEDIMENTOLOGIC AND COMPUTER METHODS

The profiles and drill-logs were re-drawn using the Macintosh Adobe Illustrator software computer program. Various symbols and patterns were used to represent lithology, sedimentary structures and other features in the resulting graphic logs. Line drawings from the photomosaics were scanned in, and redrawn and filled with the appropriate symbols. Other drawings in this thesis were prepared in a similar manner. Palaeocurrent data were plotted using the Rosy Software program for Macintosh computers. This is a two-dimensional orientation analysis program, that reads azimuth data from a text file and draws full rose, half-rose and histogram graphs. Data can be either unidirectional or bidirectional and can be plotted using 5, 10, 15, 20, 25 or 30 degree sectors; 10° was used for this study. Statistical parameters computed include total number of points, maximum percentage, mean percentage, standard deviation, vector mean, standard error of the mean and the Rayleigh probability distribution (McEachran, 1986-1990).

3.3.2 PETROGRAPHIC METHODS

3.3.2.1 Thin sections

Sedimentologic, economic and provenance studies commonly involve establishment of mineralogical composition. Petrographic assessments were carried out for more than 500 thin sections using a standard optical microscope. For determining grain size and sorting, comparators provided by Beard and Weyl (1973) were used because measurements of true grain-diameter distributions along traverse lines in thin sections are inaccurate owing to the infrequency of intersection of grains at their maximum diameter in thin-section (Beard and Weyl, 1973). For sphericity, visual comparators of Rittenhouse (1943) were used. Modal compositions were obtained by visual estimates. Some polished slabs were stained to provide visual estimates of percent feldspar in the rocks. Mineral identification in fine-grained sediments (mudrocks of the Karoo succession) is difficult to impossible (e.g. the distinction between untwinned feldspar and quartz) as is the establishment by conventional methods of diagenetic features, heavy mineral distribution and matrix composition; consequently polished sections were studied using the scanning electron microscope. Owing to weathering effects and alteration, identification of some rock fragments in thin section was difficult.

3.3.2.2 Scanning electronic microscopy (SEM)

Fifty-six polished sections were prepared, coated with a thin layer of carbon and examined using the backscattered electron detector (BSE) of a JEOL JSM 6400 scanning electron microscope at Carleton University. Use of the BSE mode of scanning electron microscope (SEM) operation for mineralogical and earth science applications is detailed in Robinson and Nikel (1979), and Hall and Lloyd (1981). The minerals appear in different shades of grey, and each spectrum obtained shows the elemental composition of the mineral, from which the name of the mineral can be determined, using publications such as the SEM Petrology Atlas (Welton, 1984). The heavy and opaque minerals, clays, cements and diagenetic features, some of which are difficult to determine in thin section, can easily be determined this way. Another important aspect of the SEM is the ability to collect digital element distribution maps. The maps were collected at 128x128 pixel resolution and required approximately 10 minutes collection time. The maps are useful in determining the composition of rocks, visual estimates and interpreting diagenetic processes (e.g. replacement textures). Clay mineral identification can be cumbersome where more than one clay is present because of interference in the spectrum from elements belonging to different clays. In such cases, clays are best determined by X-Ray diffraction after separation from the coarser fraction.

3.3.3 GEOCHEMICAL METHODS

3.3.3.1 X-Ray diffraction (XRD)

Clay mineralogy was analysed by XRD to determine the clay composition of the rocks of the Sinakumbe and Karoo groups, and thus provide the complete mineralogy. Clay minerals can be used for sedimentary process determination, and for climatic studies. Clays were separated from the coarser fraction by the procedure outlined by Higgins (1982). In this procedure, which is followed by Geological Survey of Canada, a 300-400 gm of broken sample is washed three times in approximately 200 ml (total 600 ml) of metaphosphate solution in a milkshake mixer. After each washing, the suspension is allowed to settle for 5 seconds and then decanted into a 1000 ml centrifuge bottle. Coarse material remaining in the mixer bucket is washed and retained for other tests. Then four opposing centrifuge bottles are balanced to within 1 g, shaken, and then spun for 3 minutes at 750 RPM on the centrifuge. The supernatant suspension (<2 mm) is decanted into a second series of centrifuge bottles, balanced, and spun at 2800 RPM for 14 minutes. The suspension is discarded, and the clay is scraped by stainless steel spatula with the aid of distilled water into nalgene cups. Clay-mounted disks (30 mm in diameter) are made from this solution and are ready for XRD when dry. The clay can also be dried overnight in the oven, and ground or disaggregated to a powder with an agate mortar and pestle.

Mineral abundances were estimated semiquantitatively using the peak height multiplied by the width at half height as a measure of quantity (Dypvik, 1977). Illite was recognised by a 10 A° XRD peak that stays constant throughout the three treatments (normal, ethylene glycol, and heating to 550°C for 1 hr). Kaolinite was recognised by well- developed 7.2 A° and 5.8 A° peaks that collapsed after heating. Smectite was recognised by a well-developed 14 A° peak that expanded to 17 A° after ethylene glycol treatment and collapsed to 10A° after heat treatment. The mixed-layer clay minerals display 12-11.5A° peaks on untreated runs. Traces of super lattice structures have been seen (26 A°) and indicate, together with the asymmetrical appearances of the 001/002 peak and split of the 5A° and 5.2A° peaks, the presence of regular illite-smectite mixed-layer clay minerals that contain possibly 20 to 30% smectitic layers (Brindley and Brown, 1980; Velde, 1985).

3.3.3.2 Geochemistry

Element analysis by X-ray fluorescence involved initial loss on ignition before final preparation of disks. For loss on ignition, 2 g samples were heated in an oven at 120°C for 2 hours, cooled in the desiccator and weighed (loss of hydroscopic or absorbed water - H_20-). The crucible was then fired at 1050°C for one hour (2 hours for coal samples), cooled in the desiccator, and weighed (loss on ignition - H_2O+). This loss in weight (LOS) is attributed mainly to water (H_2O+) and elemental loss (alkali metals, fluorine and sulphur oxide), whereas a gain in weight is likely to be due to oxidation of iron.

One gram of sample was weighed and used for fusion (mixture) into a disk by adding: 0.30 g of lithium fluoride (LiF), 5.00 g of lithium tetraborate (anhydrous - $Li_2B_4O_7$), a pinch of ammonium iodide and a pinch of ammonium nitrate. These were then fused in crucibles and the resulting disks were submitted to the Geological Survey of Canada for element analysis.

3.3.4 PALYNOLOGICAL METHODS

For palynological analysis, good recovery of palynomorphs is generally associated with dark coloured to greyish green unoxidized sediments. Because of tropical weathering, fresh unoxidized outcrops are rare in most parts of central Africa, and therefore some excavation is necessary in order to expose fresh rock surfaces.

Four natural outcrop sections and the Kazinze Open-pit section were sampled. The outcrop sections are cliffs along the Mulungwa and Zhimu rivers in the Mulungwa map area. These include the gradational contact between the Gwembe Coal and Madumabisa Mudstone formations, the middle (approximately) and the top part of the Madumabisa Mudstone Formation, and the Interbedded Mudstone and Sandstone Formation. The fresh exposure of the open pit provided samples of the Gwembe Coal Formation. Samples from the base and the top of the Madumabisa Mudstone Formation sections did not contain palynomorphs, and therefore are not considered further in this thesis. A total of 158 (59*[1]) samples from 9 sections in the entire succession were submitted to Dr. J. Utting of the Institute of Sedimentary and Petroleum Geology, Calgary, Canada for palynomorph identifications. These included 118 (32*) from Gwembe Coal Formation, 31 (22*) from Madumabisa Mudstone Formation, 5 (5*) from the Interbedded Sandstone and Mudstone Formation and 4 (0*) from the Sinakumbe Group.

[1] *the numbers in parentheses represent the number of samples analysed out of the samples submitted.

CHAPTER IV

SEDIMENTOLOGY: LITHOFACIES AND FACIES ASSEMBLAGES

4.1 GENERAL REMARKS

4.1.1 NATURE OF FACIES

A facies is the product of a depositional environment. Because of this, systematic studies of sedimentary deposits are generally based on the identification of major and minor lithofacies components, the determination of lithofacies assemblages (or associations), and the documentation of sedimentary structures, fossils, textures, internal relationships, geometry and orientation of the depositional units (Miall, 1981a).

Facies may be considered to be basic building blocks in these studies. Facies are defined as units of rock that differ from vertically and laterally adjacent bodies of rock by their physical, biological and chemical characteristics. Most alluvial deposits can be satisfactorily described using a set of approximately twenty standard lithofacies types (Miall, 1977, 1978, 1985; Rust, 1978a; Cant and Walker, 1976; McLean and Jerzykiewicz, 1978; Boothroyd and Nummedal, 1978). However, these lithofacies types should be used with caution for descriptive purposes, because several can occur in more than one depositional environment within a river system. Therefore, details of scale, grain size, internal structures, orientation and facies associations should be determined to ensure that units of dissimilar origin are not grouped together under one descriptive code (Miall, 1981a).

4.1.2 LITHOTYPE CONSTITUENTS AND CLASSIFICATION

The Sinakumbe and Karoo groups contain a wide variety of clastic rocks that are best classified according to grain size and composition. Grain diameters range from less than 2 microns for the mudrock (claystone, mudstone and siltstone) to more than a metre for the conglomerates. Extrabasinal rock fragments (igneous and metamorphic rock types) are locally less abundant than intrabasinal sedimentary fragments. Plant fragments (including stems) are considered to be rock fragments, following the definition of 'rock' by Bates and Jackson (1987, p. 542). The fragments are assumed to be of intrabasinal origin and are more abundant in the coarse siliciclastics (conglomerate, sandstone) and coal. The sandstones are made up of quartz, feldspar, lithic fragments (mainly derived from phyllites, schists, gneisses, cherts and mudrock), carbonaceous material (organic) including plant stems and leaves, accessory minerals (e.g. mica), heavy and opaque minerals, matrix and cements. Composition determination in the field indicated that the sandstones vary from litharenite, to feldspathic arenite, arkose, quartz arenite and carbonaceous arenite.

For a rock to be classified as a rudite, there is no universal agreement on the percentage of clasts above 2 mm (-1ø) which must be present (Pettijohn, 1975, p. 154). However, Folk (1954, 1980) and Collinson and Thompson (1989) recommend that the rock should contain more than 30% clasts larger than 2 mm before terms gravel (for unconsolidated material), conglomerate and breccia are used. Lindholm (1987) indicates that even a trace (0.01%) gravel should be recorded when naming a rock, and 'slightly gravelly' can be added as part of the name. The naming of rudites in this thesis follows that of Folk (1954, 1980) which utilizes a ternary diagram with three end-member classes (gravel, sand and mud) and the terms conglomerate and breccia applied to subangular and better-rounded materials, and angular fragments, respectively. The cutoff for differentiating clasts from matrix is set at 2 mm in accordance with the grain size classification for sediment and sedimentary rocks. In addition, the descriptive features for conglomerates outlined by Harms et al. (1975, 1982; Fig. 6.1) are used. The types of clasts present and the texture of the rock are important in the classification of rudites; for example, the Lower Sinakumbe Group conglomerates are polymictic (different types of clast; Pettijohn, 1975, p. 164) and range from matrix- to clast-supported in texture (Harms et al., 1982).

For rudites, very little theoretical or experimental work has been done that gives an understanding of sedimentary structures (Harms et al. 1982). Yet, these 'structures' may provide useful information concerning the provenance (e.g. properties i & ii below), transportation, history and the understanding of the processes and environments of deposition (properties ii to vi below). Consequently, sedimentary structures in rudites are interpreted broadly to include such characteristics as: (i) differences in composition, (ii) differences in shape, roundness and surface morphology of the constituent clasts, (iii) differences in fabric, packing and porosity, (iv) stratification and cross-stratification, and (v) the presence and type of graded bedding (Collinson and Thompson, 1989).

For mudrocks, the Brown and Harrell (1991) classification is followed, in which mudrock encompasses lithotypes ranging from essentially pure claystone, to mudstone and siltstone. The mudrock contains abundant silt-size quartz, feldspar, mica, heavy and opaque minerals, and clay minerals (e.g. kaolinite, illite, smectite, chlorite and mixed-layer clays).

Whilst lithofacies valid in local areas are less easily applied on a regional scale, designation of lithofacies in facies assemblages/associations within each formation may clearly lead to interpretation of facies distributions and tectonic evolution within depositional basins.

4.1.3 COLOUR

Rock colour depends on the colour of the rock-forming minerals present, on grain size, on the amount and oxidation state of elements present (e.g. iron), and on the amount and type of organic material present (Lindholm, 1987, p. 231). Iron-rich minerals and organic carbon are the most important colouring agents in sedimentary rocks. Levels of organic carbon in a sediment are controlled mainly by:- (i) sedimentation rate, (ii) rate of supply of organic matter and (iii) rate of decay of organics in the upper few centimetres of the sediment column, which is closely tied to oxygen levels (Potter et al., 1980), and different levels will impart greenish grey to black colours. The colour of the conglomerates is dependent on the clasts and matrix/cement. The predominant colours are brownish pink and creamish (whitish) grey clasts and greenish grey matrix.

The sandstones show various colours from pale grey, greenish grey (shades of grey) to white, dark grey to black, pink and red to shades of yellowish brown/brown. The colour of sandstones with no iron oxide is dependent on the framework grains and organic matter. The grey to white colours are associated with the quartz arenites, while the K-feldspar rich-varieties are usually pink. The shades of grey are associated with the litharenites and the carbonaceous sandstones.

Mudrocks in the Lower Karoo Group are black to dark grey and are very rich in organic matter. They weather to pink and red, and shades of yellowish brown/brown, whereas those in the Sinakumbe Group are pale brown to red, and in the Upper Karoo are greenish grey to purplish green, and purplish brown. Most coal is black, but lower ranks (e.g. lignite) commonly are pale yellow, pale brown or dark brown (Bustin et al., 1983). Two distinct colour spectra are exhibited by mudrocks and shales (Myrow, 1990): green-purple-red controlled by the ratio of ferrous iron to ferric iron (Fe^{+3}/Fe^{+2}) and green-grey-black controlled by total organic carbon content. Diagenetic changes in the oxidation state of iron are responsible for the green-purple-red spectrum in sediments as the sediment is buried below the water table. The other distinct colour sequence from greenish grey to black is imparted by organic content, independent of the oxidation state of iron, and is solely dependent on percent of organic carbon (Potter et al., 1980). Total organic content also determines the green to red sequence, because the quantity of organic matter controls the Fe^{+3}/Fe^{+2} ratio by oxidation-reduction reactions (Potter et al., 1980; McPherson, 1980).

In this thesis, the Munsell colour chart (GSA, 1990) has been widely used to assign colours to the rocks.

4.1.4 FACIES ASSEMBLAGES (ASSOCIATIONS)

Lithofacies are rock units with distinctive lithologic features, including composition, grain size, bedding characteristics, and sedimentary structures, that collectively represent the results of different environmental processes (Miall, 1990). Though lithofacies represent individual depositional events and have specific bedding styles and suites of sedimentary structures, they can be formed by various processes in different environments (e.g. horizontally laminated siltstone can accumulate both in fluvial overbank environments and lacustrine basins). Consequently, lithofacies associations (assemblages) are important, because distinctive lithofacies associations can characterize depositional environments, and in particular, many vertical lithofacies associations (vertical profiles) are diagnostic. Facies assemblages represent specific depositional settings arranged laterally and vertically within the basin during the phase of basin evolution.

Fluvial sediments are strongly cyclic, showing characteristics that reflect processes of autocyclic (originating within the depositional environment) and/or allocyclic (external to depositional environment) origin. The contacts between lithofacies are especially important: gradational contacts indicate gradual change in depositional environment; erosional contacts indicate rapid change, and commonly, the initiation of a new cyclic sequence. Jackson (1978) listed several factors that are pertinent to the grouping of fluvial lithofacies into stacked sequences: (i) the rate and duration of basin subsidence, (ii) the rates and magnitudes of sea-level changes, irrespective of subsidence, (iii) the proximity to non-fluvial environments, (iv) short-term channel behaviour (e.g. stability of channel pattern and avulsion), (v) the number and width of meander belts (meandering streams), and (vi) tectonism during sediment accumulation.

Defining and describing lithofacies assemblages commonly involves the use of multivariate statistics such as cluster and factor analysis (to determine natural groupings of sedimentary attributes), and the consideration of order of occurrence of lithofacies in a sedimentary section, using Walther's Law, namely that conformable lithofacies must show similar lateral environmental associations. Semiquantitative techniques include the Markov chain analysis (Miall, 1984; 1990). For this thesis, the order of occurrence of lithofacies in a sedimentary section has been used to define facies assemblages.

4.1.5 PALAEOCURRENT ANALYSIS

Palaeocurrent analysis, introduced by Sorby (1852), is best applied in outcrop studies, although oriented core can also be used. As noted by Miall (1984), this analysis can provide information on four main aspects of basin development: (i) direction of local or regional palaeoslope, (ii) depositional environment, (iii) direction of sediment supply, and (iv) geometry and trend of lithologic units. Many sedimentary structures provide evidence of the direction of the current that formed them, supplementing data obtained from facies and isopach maps. The most useful structures for this purpose (Miall, 1981a, 1984) are: (i) large-scale foreset structures (trough and planar cross-bedding), (ii) ripples (crest and foreset orientation), (iii) channels and scours, (iv) parting lineation, (v) sole marks (e.g. flute marks, tool marks), (vi) grain imbrication, (vii) oriented plants, bones, shells etc., and (viii) slump structures that are generated on depositional slopes and contain overfolds aligned parallel to strike. Slumps can be variably aligned relative to slopes, however, and their interpretation is controversial.

In fluvial deposits such as some of the Karoo units, these data can assist in two ways. Firstly, they provide evidence for determining sinuosity, as an aid to determining river type (Miall, 1976). Secondly, relative orientations of the various sedimentary structures can help in interpreting bedform dynamics (Cant and Walker, 1976). However, divergence between flow direction and cross-bed dip can occur. For example, Smith (1972, Fig. 11) showed that flow over transverse bars may diverge as much as 90 degrees from the direction of foreset dip measured immediately below. Nevertheless, the mean foreset dip azimuth generally corresponds very closely to mean channel direction.

Detailed palaeocurrent analysis can also assist in prospecting a coal- or mineral-bearing unit, where it can yield information about the internal geometry of fluvial deposits. For example, both placer and epigenetic ores (e.g. uranium) tend to follow channels, which contain the coarsest and most porous units (Miall, 1984). This can be significant for the Karoo in the mid-Zambezi Valley Basin, where coal seams and uranium mineralization are known to occur in the Lower Karoo and Upper Karoo groups respectively.

Procedures for palaeocurrent analysis are not discussed here, as they are well summarized in many publications such as Potter and Pettijohn (1977) and Miall (1981a, 1984). Information on techniques and interpretations is given by Allen (1966), Potter and Pettijohn (1977) and Miall (1974, 1984). In addition, Potter and Pettijohn (1977) described several distinctive palaeocurrent indicators, including sand-grain orientation and magnetic anisotropy. Palaeocurrent data from specific stratigraphic units can be plotted geographically as current rose diagrams, or by constructing moving averages or trend maps that portray regional transport patterns and basin palaeogeography. The absence of suitable exposures made such analysis difficult in most parts of this study area. However, palaeocurrent data were measured wherever there were suitable outcrops, and they have been plotted geographically in rose diagrams, and in vertical sections.

4.1.6 GENERAL SCHEME OF DESCRIPTION

Extensive use is made of vertical profiles in the thesis. Visher (1965) emphasized the importance of the profiles as indicators of general historic development and of local and/or transient modifications (interruptions, repetitions etc.) of the idealised depositional sequence. However, vertical profiles should not be considered alone unless the outcrops do not permit lateral comparisons. Facies repetition is indicative of a vertical repetition of hydrodynamic conditions (Miall, 1977). In this regard, sedimentary sequences may be recognised by physical sedimentary aspects (bedding, grain size and sorting, and sedimentary structures), biological aspects (associations of biota), and the presence and significance of sedimentary breaks. As a result, lithofacies are grouped into facies assemblages on the basis of genesis as inferred from characteristics of particular depositional environments.

The Sinakumbe and Karoo strata comprise a large variety of rock types, showing a large range of grain sizes, colours, textures, sedimentary structures and contact relationships. Some lithologies occur throughout the mid-Zambezi Valley Basin, and therefore are important for tectono-sedimentary analysis; others have much more local extent. Available methods of descriptions usually depend on the researcher and the ultimate aim of the study. Many people group their lithologies into major rock types such as sandstone lithofacies or conglomerate lithofacies etc. To facilitate description, the lithologic variability in the area had to be generalized, categorized and simplified. This was achieved by recognizing associations of attributes that are repeated in the outcrop sections and drill holes in the basin. Definition of the various lithofacies in measured sections and drill cores made use of field information on the nature and occurrence of sedimentary structures and contacts, and subsequent study of 1500 hand samples, thin sections and polished sections. Where applicable, facies codes following those of Miall (1978) and Rust (1978a) have been used, of which there are twenty-one recognized (Table 4.0). Bedding styles were distinguished by differences in composition, texture (grain size, sorting, etc.), internal structures and colour (Collinson and Thompson, 1989; Lindholm, 1987). The bedding terminology used in this thesis (Table 4.1) is adapted from Collinson and Thompson (1989).

Table 4.0 Lithofacies and sedimentary structures of fluvial deposits (from Miall, 1978)

FACIES CODE	LITHOFACIES	SEDIMENTARY STRUCTURES	INTERPRETATION
Gms	massive, matrix supported gravel	grading	debris flow deposits
Gm	massive or crudely bedded gravel	horizontal bedding, imbrication	longitudinal bars, lag deposits, sieve deposits
Gt	gravel stratified	trough crossbeds	minor channel fills
Gp	gravel stratified	planar crossbeds	linguoid bars or deltaic growths from older bar remnants
St	sand, medium to v. coarse, may be pebbly	solitary (theta) or grouped (pi) trough crossbeds	dunes (lower flow regime)
Sp	sand, medium to v. coarse, may be pebbly	solitary (alpha) or grouped (omikron) planar crossbeds	linguoid, transverse bars, sand waves (lower flow regime)
Sr	sand, very fine to coarse	ripple marks of all types	ripples (lower flow regime)
Sh	sand, very fine to very coarse, may be pebbly	horizontal lamination, parting or streaming lineation	planar bed flow (l. and u. flow regime)
Sl	sand, fine	low angle (<10°) crossbeds	scour fills, crevasse splays, antidunes
Se	erosional scours with intraclasts	crude crossbedding	scour fills
Ss	sand, fine to coarse, may be pebbly	broad, shallow scours including eta cross-stratification	scour fills
Sse, She, Spe	sand	analogous to Ss, Sh, Sp	eolian deposits
Fl	sand, silt, mud	fine lamination, very small ripples	overbank or waning flood deposits
Fsc	silt, mud	laminated to massive	backswamp deposits
Fcf	mud	massive, with freshwater molluscs	backswamp pond deposits
Fm	mud, silt	massive, desiccation cracks	overbank or drape deposits
Fr	silt, mud	rootlets	seatearth
C	coal, carbonaceous mud	plants, mud films	swamp deposits
P	carbonate	pedogenic features	soil

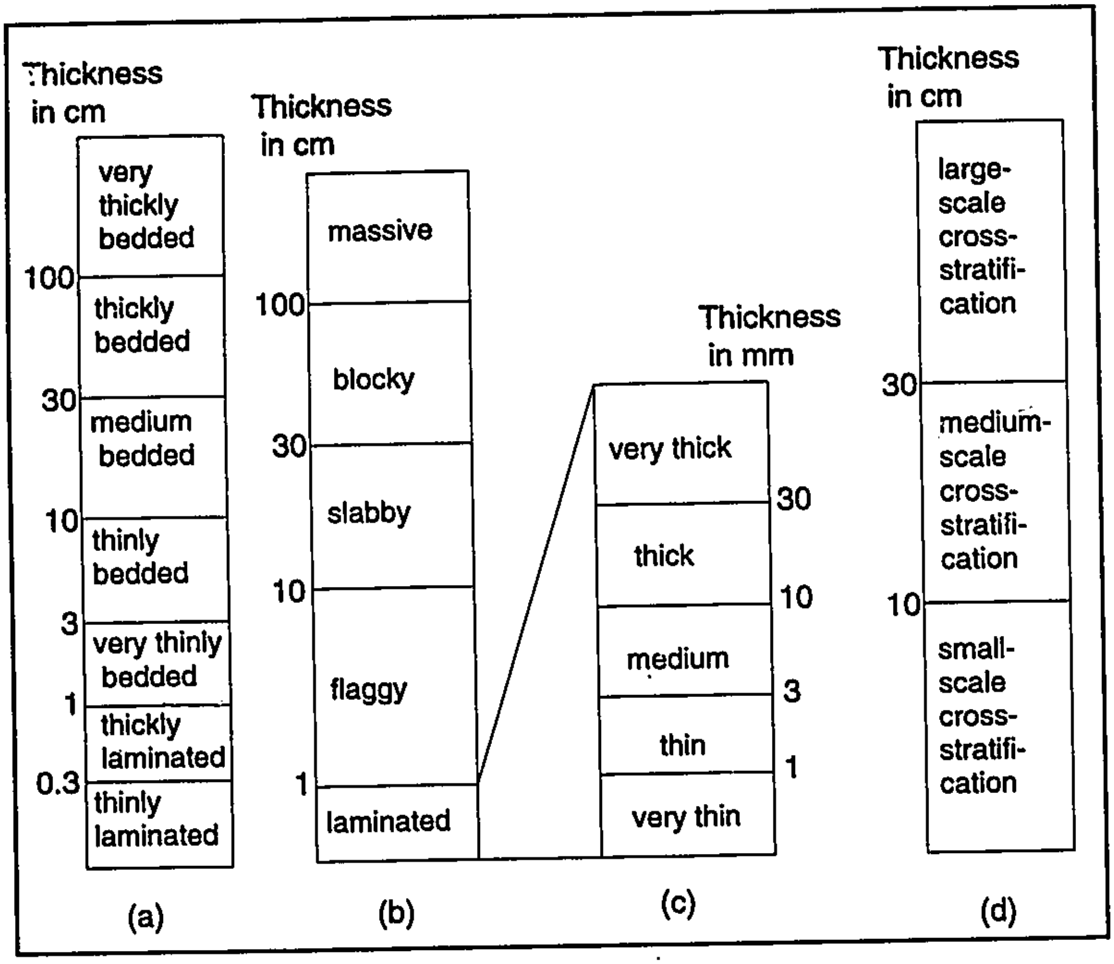


Table 4.1 Descriptive terminology for thickness of beds and units within beds (a to c from Collinson and Thompson, 1989). a = terminology for stratification thickness; b = terms to describe splitting or parting units within beds; c = terms to describe laminae within beds; d = arbitrary division of cross-stratification according to thickness, used in the thesis.

Geological mapping and coal exploration in the mid-Zambezi Valley by the Geological Survey of Zambia (Tavener Smith, 1960; Money et al., 1974) provided a stratigraphic framework for the sedimentological study of these sediments. The stratigraphic units defined by Tavener-Smith (1960) and modified by several workers (for example, Money and Drysdall, 1975), can be recognized in most outcrops and drill cores in the area (Table 2.0). However, some difficulties were experienced in applying this subdivision regionally, where outcrops are limited and some lithologies occur only sporadically. To avoid grouping units of dissimilar origin under one descriptive code (e.g. mudrocks of the Sinakumbe Group and of the Madumabisa Mudstone Formation), the lithofacies have been grouped and considered separately according to the revised, generalized composite stratigraphic column developed in this study (Fig. 4.0). The 37 lithofacies recognised and described below (Table 4.2) are grouped by formation, from oldest to youngest, i.e. from Lower Sinakumbe Group to Interbedded Sandstone and Mudstone Formation. Sedimentary structures are significant in the designation of the depositional facies and therefore are listed with the lithofacies and facies assemblages in tables and figures. In addition, letter symbols (Table 4.2) are used to denote the lithofacies (i.e. as an abbreviation) and have no interpretative connotation in contrast to those of Miall (1977). The Red Sandstone and Batoka Basalt formations are not considered here because they outcrop rarely in the study area. Following the lithofacies descriptions and interpretations, facies assemblages are defined.

4.2. SINAKUMBE GROUP

4.2.1 GENERAL REMARKS

The group is divided into two units, the Lower Sinakumbe Group and the Upper Sinakumbe Group (Figs. 4.1 and 4.0), based on sedimentological differences observed both in the field and in the laboratory.

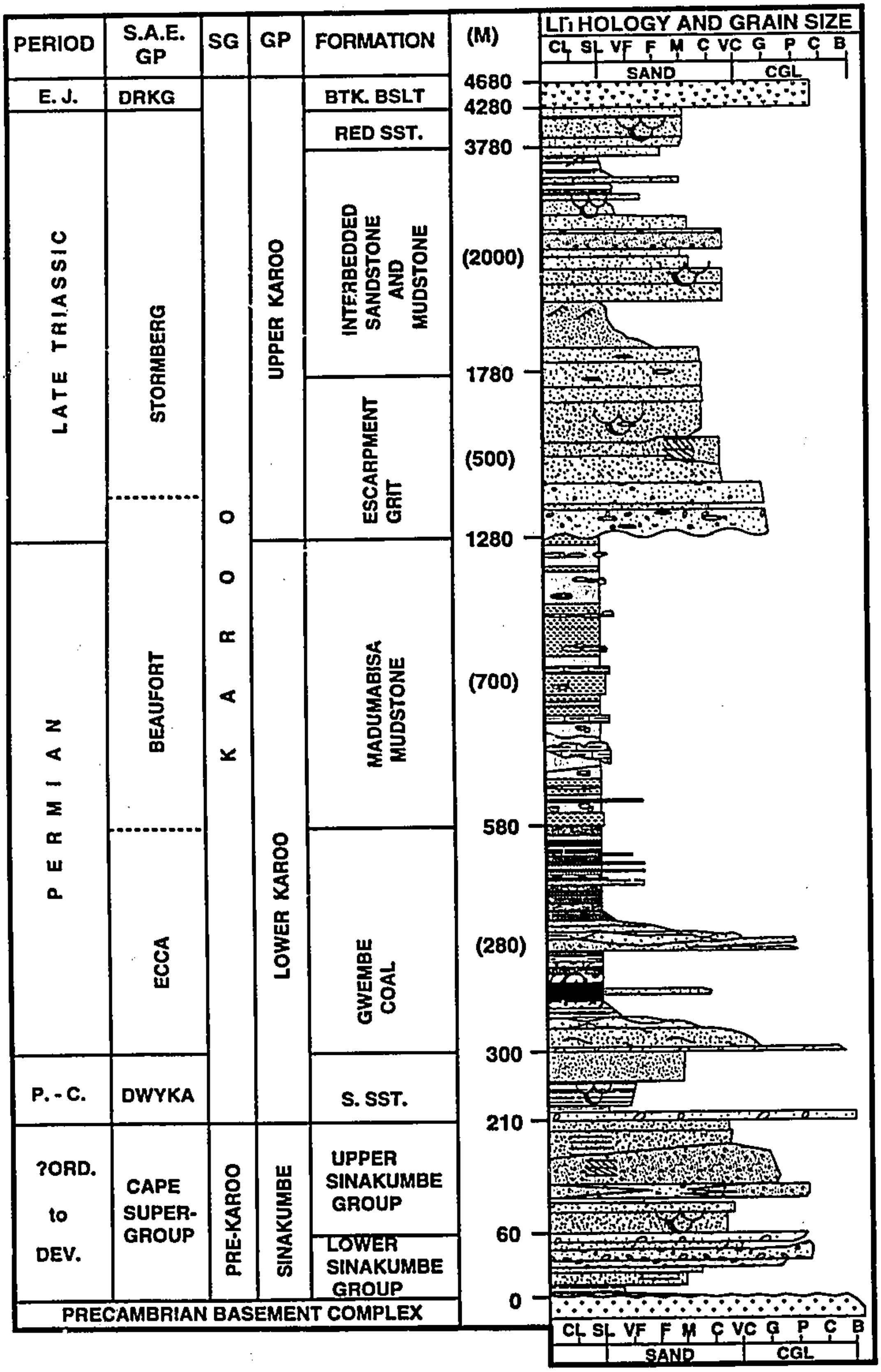
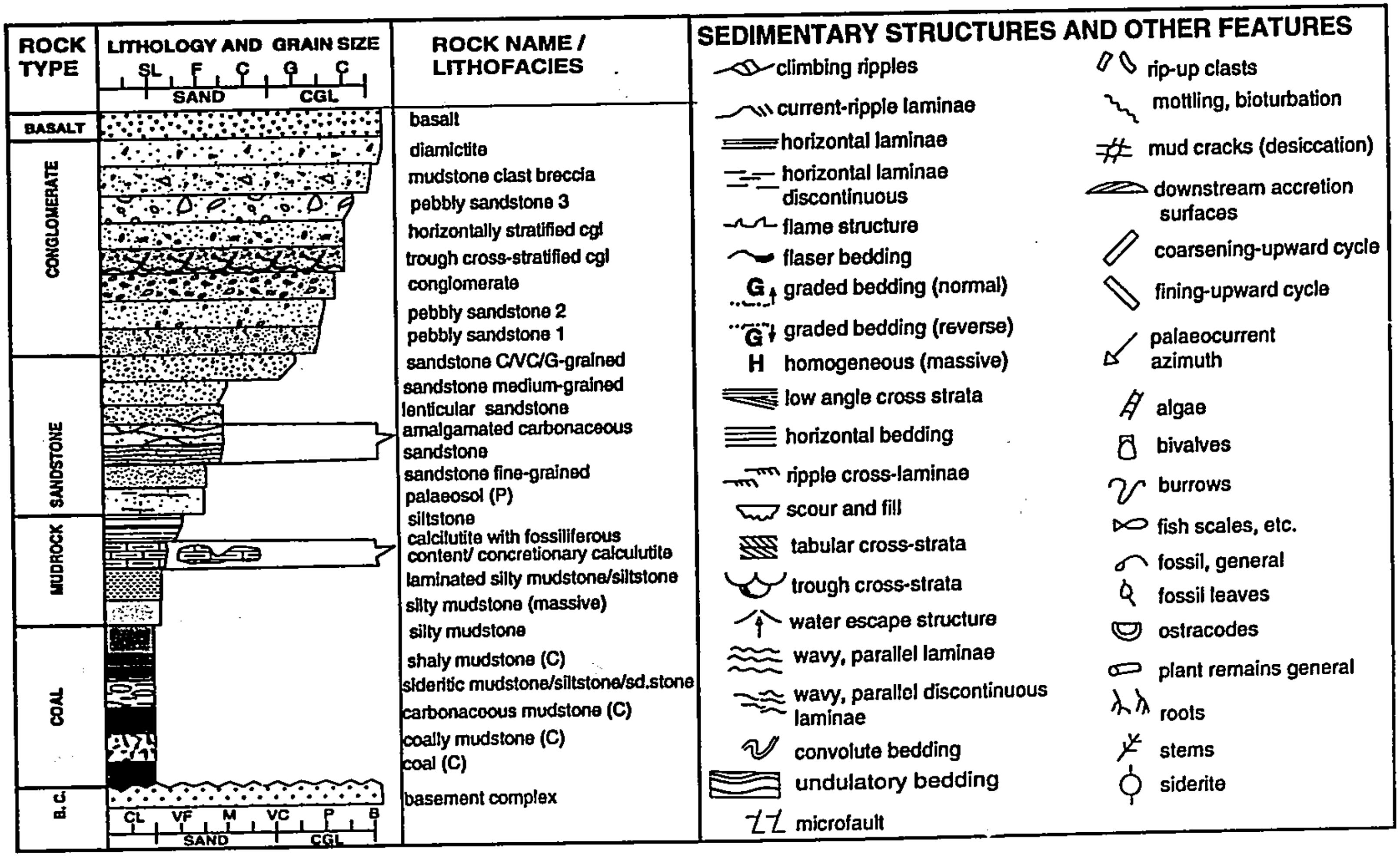


Fig. 4.0 General stratigraphy of Sinakumbe and Karoo groups, mid-Zambezi Valley Basin, southern Zambia (not to scale). See opposite page for explanation of symbols and abbreviations.



KEY TO ABBREVIATIONS

GRAIN SIZE

CL = Clay
SL = Silt
VF = Very fine-grained
F = Fine-grained
M = Medium-grained
C = Coarse-grained
VC = Very coarse-grained
G = Granules
P = Pebbles
C = Cobbles
B = Boulders
CGL = Conglomerate

SUCCESSION

BTK. BSLT = Batoka Basalt	SG = Supergroup
B. C. = Basement Complex	LKG = Lower Karoo Group
CGL = Conglomerate	UKG = Upper Karoo Group
DRKG = Drakensberg	S. SST. = Siankondobo Sandstone
GP = Group	Fm = Formation
E. J. = Early Jurassic	SSF = Siankondobo Sandstone Formation
P.- C. = Permo-Carboniferous	GCF = Gwembe Coal Formation
RED SST. = Red Sandstone	MMF = Madumabisa Mudstone Formation
S.A.E. GP = South African Equivalent Group	EGF = Escarpment Grit Formation
	ISMF = Interbedded Sandstone and Mudstone Formation

Legend for Fig. 4.0, and for all subsequent stratigraphic sections. C = coal, roots and other plants remains, sd.stone = sandstone. M = Metres.

Table 4.2 Recognized lithofacies in the Sinakumbe and Karoo groups, mid-Zambezi Valley Basin, southern Zambia

LITHOFACIES	FACIES ASSEMBLAGE	FORMATION	GROUP
Mudrock (M_{sm})	Mudrock	Lower Sinakumbe Group	Sinakumbe Group
Sandstone (S_{vf-m})			
Sandstone (S_{c-p})	Conglomerate		
Conglomerate (C_{ms})			
Conglomerate (C_{fs})			
Quartz arenite (A_q)	Quartz Arenite	Upper Sinakumbe Group	
Mudclast breccia (B_m)			
Diamictite (D)	Diamictite	Siankondobo Sandstone	Lower Karoo Group
Conglomerate (C_{ms})			
Mudstone/Siltstone (VM_{sm})	Siltstone		
Siltstone/Sandstone (SS_{cl})			
Sandstone (S_m)	Sandstone		
Sandstone/ Conglomerate (SC_{p-c})	Maamba Sandstone	Gwembe Coal	
Sandstone (S_{vf-vc})			
Coal (C)	Coal		
Sandstone (S_{sis})			
Sandstone (S_{lis})			
Mudstone (M_{cl})	Mudrock		
Mudstone (M_{ca})			
Mudstone (M_{sl})			
Sideritic Mudstone / Siltstone / Sandstone (MSS_{sd})			
Other Sandstones (LOS)			
Izuma Beds (LIB)			
Conglomerate/ Sandstone (CS_{g-vc})	Sandstone A		
Sandstone (S_{vf-c})			
Mudrock (M_{sm})			
Mudstone (M_m)	Massive Mudrock	Madumabisa Mudstone	
Calcilutite (C_c)			
Mudstone/Siltstone (MS_l)	Laminated Mudrock		
Calcilutite (C_l)			
Sandstone (S_{vf-vc})			
Sandstone (S_{c-g})	Sandtone/Mudrock	Escarpment Grit	Upper Karoo Group
Sandstone (S_{vf-m})			
Mudrocks (M_{m-s})			
Sandstone (S_{c-g})	Mudrock/Sandstone	Interbedded Sandstone and Mudstone	
Sandstone (S_{vf-m})			
Mudrocks (M_{m-s})			

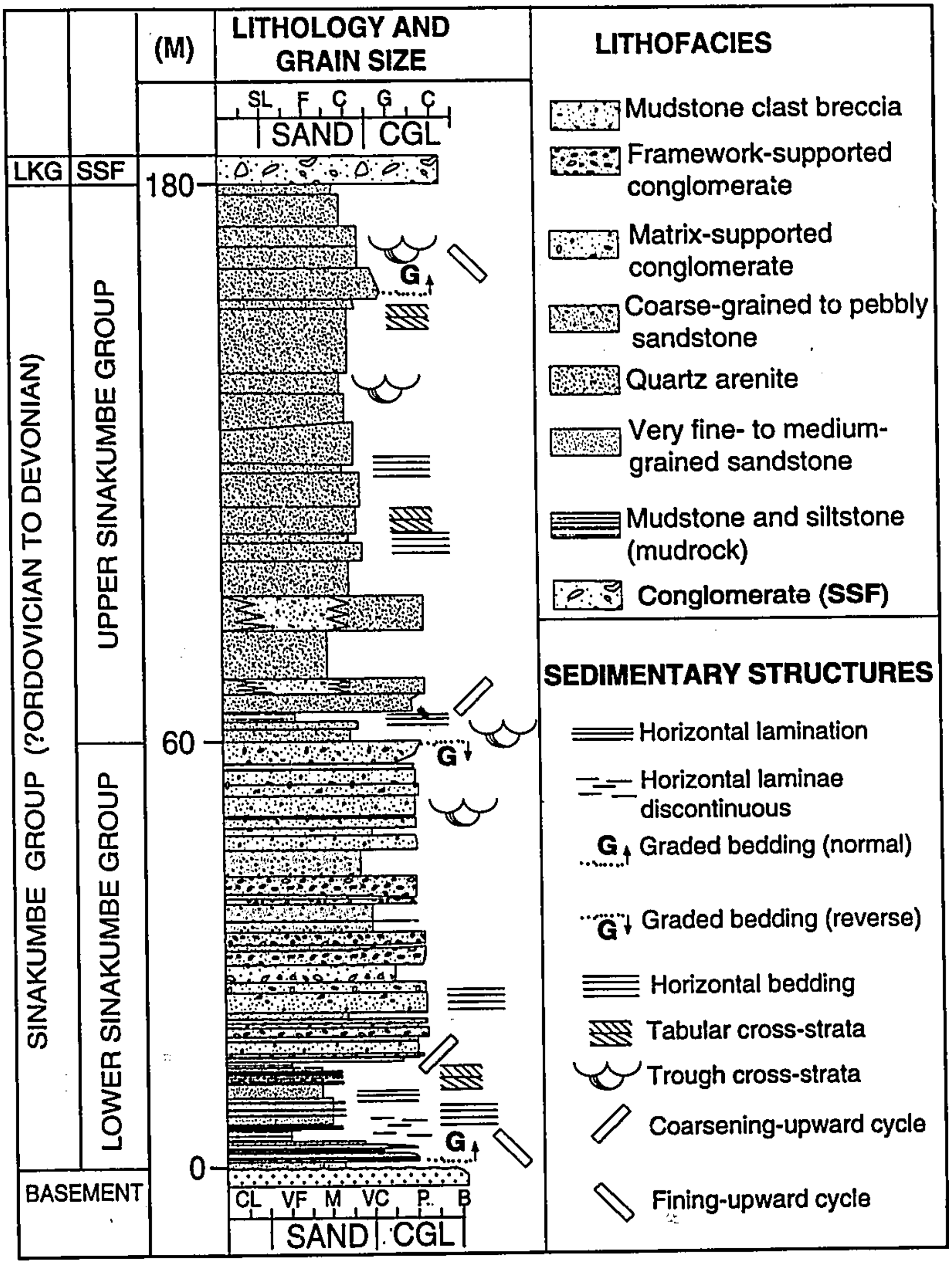


Fig. 4.1 **Generalized stratigraphic column of the Lower Sinakumbe Group and Upper Sinakumbe Group of the Sinakumbe Group (not to scale). For abbreviations see Fig. 4.0.**

4.2.2 LOWER SINAKUMBE GROUP

4.2.2.1 General remarks

The Lower Sinakumbe Group consists mainly of conglomerates and pebbly sandstones with subordinate siltstone, mudstone and fine-grained sandstones (Fig. 4.1). Siltstone and mudstone are grouped into mudrock lithofacies because a distinction between the two is difficult in the field. The predominant mudrock lithology is siltstone, which grades upward into sandstone. Mudrocks form about 10% of the Lower Sinakumbe Group. They are generally reddish (pale brown to red) characteristic of iron-rich mineral content. Depositional facies using the type codes of Miall (1977) and Rust (1978a) are indicated where possible.

The sandstone encompasses the entire sand size range from very fine (63 microns) to very coarse sand (2 mm), and up to pebbly. It is one of the main components (30%, mainly as pebbly sandstone) of the Lower Sinakumbe Group (Fig. 4.1). Sandstone directly overlies the basement complex, and is common at the base of the Lower Sinakumbe Group and also occurs as intercalations and interbeds within conglomerate in the upper parts of the subgroup. It varies from whitish grey, to pink, red and shades of yellowish brown and brown. Much of the whitish grey sandstone is mottled red or stained yellowish brown. The sandstone is made up of quartz, feldspar, lithic fragments (mainly phyllite, schist, chert and mudrocks), accessory minerals (e.g. mica), heavy minerals, matrix and cements. The principal varieties are litharenite, feldspathic arenite and arkose. The sandstone beds are tabular and internally stratified, or massive with subordinate normal grading. The sandstone units range from less than 10 cm to over 14 m thick. The units are stacked in an overall coarsening-upward sequence, with subordinate fining-upward cycles. The basal parts of these beds are granular to pebbly, with locally derived granules and pebbles. On the basis of grain size, two lithofacies are recognized: very fine- to medium-grained sandstone, and coarse-grained to pebbly sandstone. In places the subdivision is arbitrary due to poor exposure. Nevertheless, a description based on this rough subdivision is attempted.

Conglomerate forms 60 % of the Lower Sinakumbe Group (Fig. 4.1).

Stratigraphically, it occupies the upper part of the formation. The conglomerate generally consists of brownish pink/grey extra- and intra-basinal clasts in greenish grey sandy to conglomeratic matrix. The clasts consist mainly of rounded to subangular quartz, vein quartz, subangular K-feldspar and rock fragments (schists, quartzite, gneisses and some granites).

The conglomerate beds are continuous in the Sikalamba-Muzuma corridor in the Nkandabwe map area (Fig. 2.2a), even though for the most part they are obscured by thickets of vegetation. Bed geometries are complex and include lenticular, wedge and tabular varieties. Convex upward tops with irregular bases are common. Amalgamation of beds within a distance of less than 5 m laterally also makes identification, stratigraphic positioning and correlation from section to section rather difficult. On the basis of texture, the conglomerate consists of two lithofacies (Table 4.2): matrix-supported and framework-supported conglomerates. In addition, three depositional facies are recognised and include massive (Gmm), horizontally bedded (Gh) and trough cross-bedded facies (Gt). Interbedded pebbly sandstone, which is commonly crudely laminated, is present within the conglomerate facies. Normal and reverse grading are locally present.

Altogether, five lithofacies (Table 4.2) are recognised in the formation: (i) siltstone and mudstone (mudrock- M_{sm}), (ii) very fine- to medium-grained sandstone (S_{vf-m}), (iii) coarse to pebbly sandstone (S_{c-p}), (iv) matrix-supported conglomerate (C_{ms}), and (v) framework-supported conglomerate (C_{fs}).

4.2.2.2 Siltstone and mudstone (Mudrock) lithofacies (M_{sm})

The M_{sm} lithofacies is made up of homogeneous mudstones and siltstones interbedded with very fine- to fine-grained, red sandstones (Fig. 4.2a-c). The mudstones and siltstones are generally dull red (greyish red to dusky red) on fresh surfaces, weathering to pale brown. Sand-sized particles of mica, quartz, feldspar and rock fragments are common. The red sandstones are mottled white and pitted (Fig. 4.2d), owing to the removal of labile minerals (mainly calcite).

In outcrop, the maximum thickness of the mudrock units is at least 2.3 m, as in Kazinze Section 4, Siankondobo area, where they consist of beds 3 mm to just over 5 cm

Fig. 4.2 Mudrock Lithofacies

Lower Sinakumbe Group

a: Mudrocks (dark red) alternating with pebbly sandstone and matrix-supported conglomerate lithofacies. The tabular conglomerate units can be followed for the entire length of outcrops. Note that some of the thin beds wedge out, for example above the thickest bed behind hammer. Kazinze River Section 4, Siankondobo map area. Hammer is 34 cm.

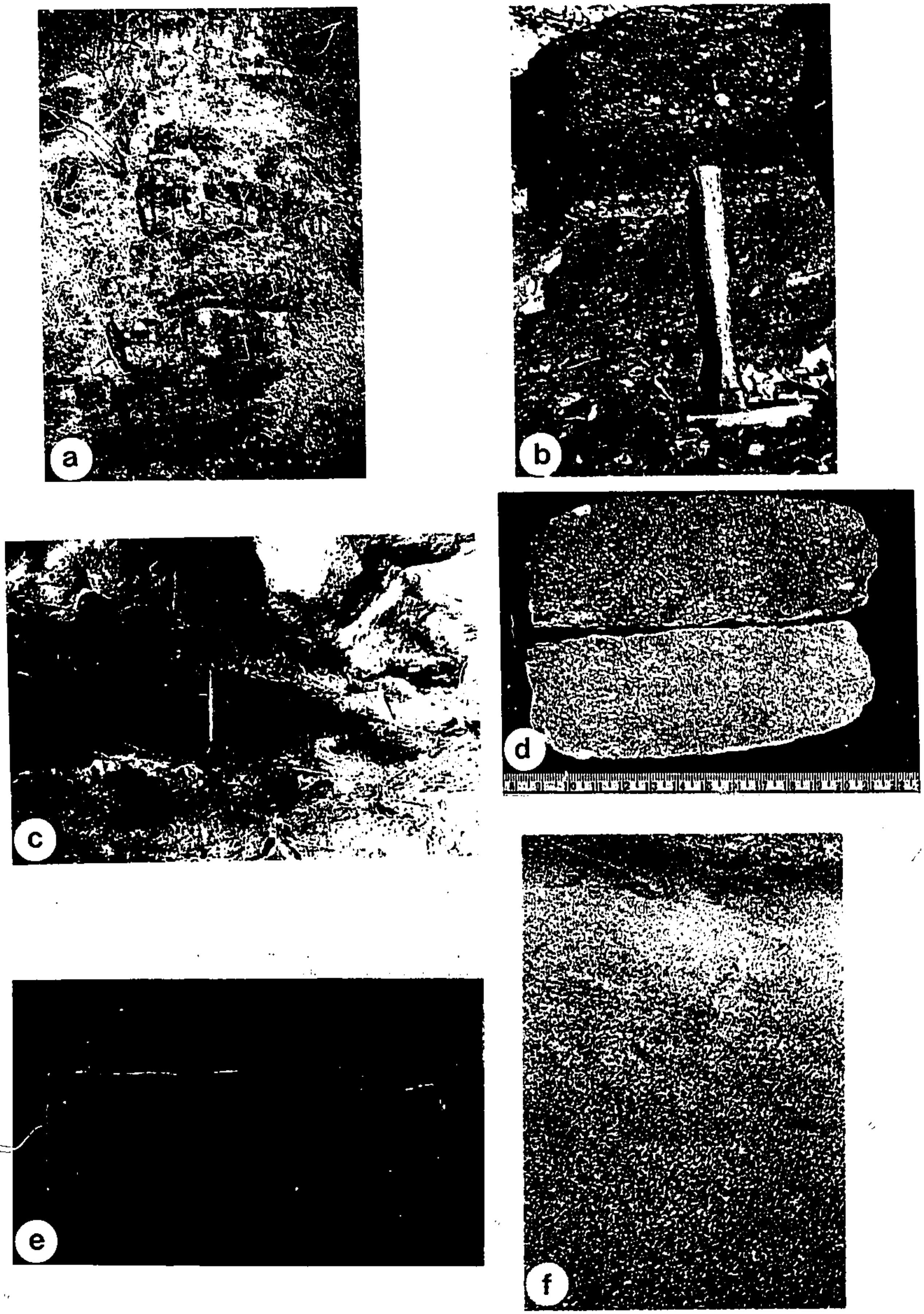
b: Mudrock lithofacies overlain sharply by matrix-supported conglomerate. Notice the fracture pattern in the mudrock and its internally massive character. Kazinze River Section 4, Siankondobo map area.

c: Mudrock lithofacies with pebbly interbeds at base, overlying basement schist. Ntole River Section 2, Nkandabwe map area.

d: Two polished slabs of the mudrock from (c), showing calcareous white patches and spots. The stained slab below shows some yellow detrital feldspar grains. Scale in cm.

e: Polished slab of the mudrock showing normal grading. Northern Slope Section 3b, Nkandabwe map area. Scale in cm.

f: Photomicrograph of (e) showing normal grading. The pinkish grains are mainly quartz, some feldspar whereas the greenish are mica. Notice some rip-up clay clasts at the top overlain by coarser layer. Long side of photograph is 15 mm.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thick (Fig. 4.2a). Outcrops have lateral limited extent (usually 5 m to 10 m) except for the northern side Nkandabwe Section 3b, where the exposure extends for 40 m laterally. However, the presence of this lithofacies in basal beds of the formation, in all eight stream sections examined, indicates that at least one unit of mudrock is continuous laterally. The absence of marker beds renders correlation difficult. The mudstones and siltstones are plane bedded and generally +massive (Fm; Fig. 4.2b, d), or locally normally graded (Fig. 4.2e) from coarse silt (.05 mm) up to mud. These beds show both horizontal lamination (Fl) and small-scale cross-lamination. Fm facies are predominant, with Fl closely associated. Bedding surfaces are planar and parallel, with subordinate undulatory to rippled surfaces. The rock breaks into lenses and flat slabs, giving the poorly exposed outcrops a fragmented appearance (Fig. 4.2b, c). Because of this, the maximum thickness of units of this lithofacies is likely to be more than 2.3 m. In the more sandy beds, as in Ntole Section 2, bed thicknesses are up to 10 cm (Fig. 4.2c). The sediments are commonly mottled white, and typically calcareous (Fig. 4.2d); parting surfaces and bedding planes in fissile mudstone show concentrations of mica (up to 50%) that are coarser than the general grain size of the rock. The mudrocks are interbedded with the sandstone and conglomerate lithofacies (Fig. 4.2a, b). The interbedded sandstones are usually thin (about 10 cm) and, in sequences transitional from mudstone to sandstone lithofacies, become progressively thicker as the mudstones and siltstones decrease in thickness. Interbeds of mudrock less than 50 cm thick occur in the conglomerate lithofacies (Fig. 4.1).

In thin sections (8 studied), the mudrocks range from clayey to sandy mudstones that are either internally massive, or normally graded (Fig. 4.2f) or parallel to crudely horizontally laminated with the irregular laminae defined by clayey and muddy films (0.6 mm; Fig. 4.3a). Minor scours infilled with coarse detritus are common in the normally graded mudrocks. The sandy mudstones contain scattered coarser grains, mainly of quartz (up to 0.4 mm in diameter) embedded in hematite-rich clay matrix (Fig. 4.3e), in some places apparently deforming (pushing aside) the laminae, suggesting dropgrains (Fig. 4.3c). Deformation is also indicated by bent muscovite laths (Fig. 4.3d). Elongate, lenticular sand-sized wedges are locally present. Muscovite and quartz are the predominant minerals of the lithofacies, with subordinate feldspar, mainly untwinned plagioclase, but locally

Fig. 4.3 Mudrock lithofacies, Lower Sinakumbe Group

a: Photomicrograph (crossed nicols) showing parallel to undulating laminae defined by composition and grain size. Very thin laminae consist of hematite stained clay (mainly sericite); the broad laminae are mainly, mica and quartz. Detrital grains (quartz, feldspar and calcite) are abundant in a layer at top of photograph. Type section, Muzuma River Section 4, Nkandabwe map area. Long side of photograph is 11 mm.

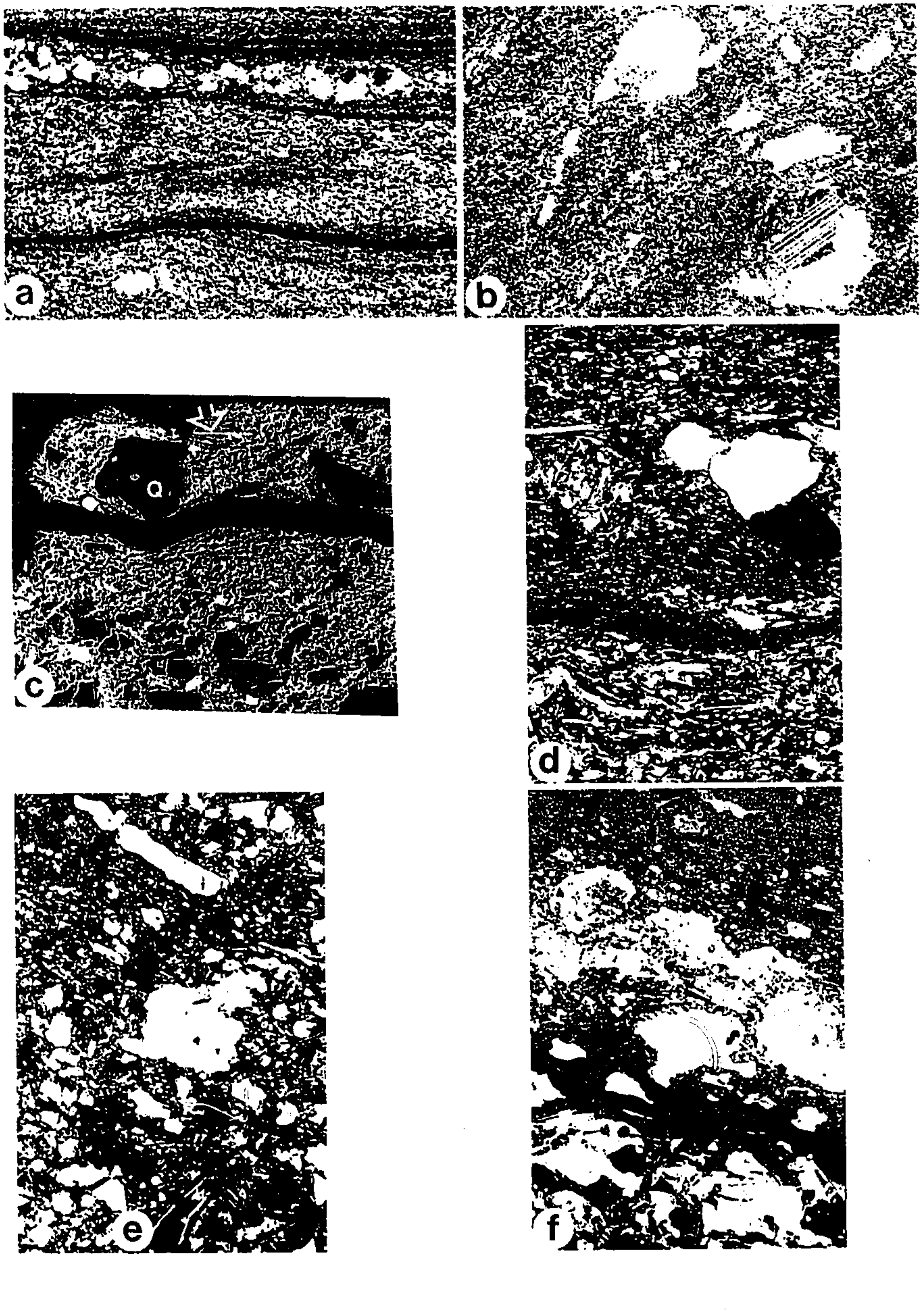
b: Photomicrograph (crossed nicols) showing detrital plagioclase grains replaced by calcite in a mica-rich matrix showing preferred orientation of grains. Ntole River Section 2, Nkandabwe map area. Long side of photograph is 4 mm.

c: Photomicrograph from SEM showing lamina deformed by quartz (Q) dropgrain in the mudrocks. Notice there is more quartz than feldspar (light grey). The white grains are heavy minerals; a zircon (bright white) grain is to the lower left of Q. Ntole River Section 2, Nkandabwe map area. White line = 100 µm (arrow).

d: Photomicrograph (crossed nicols) showing detrital quartz and feldspar in mica and hematite-rich matrix. Notice the bent muscovite grains below hematite-rich clayey lamina suggesting deformation. Type section, Muzuma River Section 4, Nkandabwe map area. Long side of photograph is 2.5 mm.

e: Photomicrograph showing the texture of the silty mudstone in Fig. 4.2d consisting mainly of detrital grains of quartz, feldspar and muscovite in hematite-rich matrix. Ntole River Section 2, Nkandabwe map area. Long side of photograph is 7 mm.

f: Photomicrograph (crossed nicols) showing aggregates of calcite rhombs, in places associated with feldspar grains in mica/hematite-rich matrix. Ntole River Section 2, Nkandabwe map area. Long side of photograph is 12 mm.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twinned (Fig. 4.3b). Coarse subangular to angular quartz grains are both monocrystalline and polycrystalline, with the latter showing planar to concavo-convex contacts. Some rip-up brick-red clasts are elongate parallel to bedding. Carbonate in the silty mudstones and siltstones is mixed with the detrital fraction as well as occurring as cement and as a replacement of detrital grains (probably feldspar). In the massive units, the calcite cement has pushed the matrix aside to form elongate aggregates (up to 10 crystals or more) parallel to bedding, or randomly oriented aggregates of equant calcite rhombs up to 0.8 mm across (Fig. 4.3f).

In modal composition, the mudrocks contain 20-30% quartz, 1-2% feldspar, and less than 0.1% of rock fragments, 50-60% matrix (30-35% sericite and muscovite) and 5% calcite cement. SEM analyses, represented on elemental maps, confirm these estimates and show that the feldspar is mainly K-feldspar, that quartz is the dominant clastic mineral (Fig. 4.3c), followed by K-feldspar, and that the mudrocks contain a substantial amount of calcite cement (Fig. 4.3c). Heavy minerals observed are zircon, apatite, epidote and iron oxides (including hematite and ilmenite). XRD analysis showed abundant illite and trace to minor amounts of chlorite as the clay minerals. Other clay-sized minerals in minor amounts include quartz and hematite, the latter interspersed with clays, and in places outlining grains.

The mudrock lithofacies is commonly transitional upward into sandstone lithofacies.

4.2.2.3 Very fine- to medium-grained sandstone lithofacies (S_{vf-m})

This sandstone forms a major part of the Lower Sinakumbe Group (Fig. 4.1). The S_{vf-m} lithofacies is well exposed along the Sikalamba stream, and on the slopes of hills that are separated by an unnamed stream that enters Nkandabwe River (Northern and Southern Slope Sections 3a and 3b, respectively). It attains a maximum thickness of 7 m in the Southern Section 3b, Nkandabwe area.

In outcrop, the sandstone weathers into flags with colours varying from pale red (greyish red) to greyish orange, pink, pale yellowish brown and dark reddish brown. Fresh surfaces are rare, but cream whitish grey appears to have been the original colour of these rocks. The sandstone forms thin sheets about 1 cm to 15 cm thick (Fig. 4.4a). Bed

Fig. 4.4 Very fine- to medium-grained sandstone lithofacies

Lower Sinakumbe Group

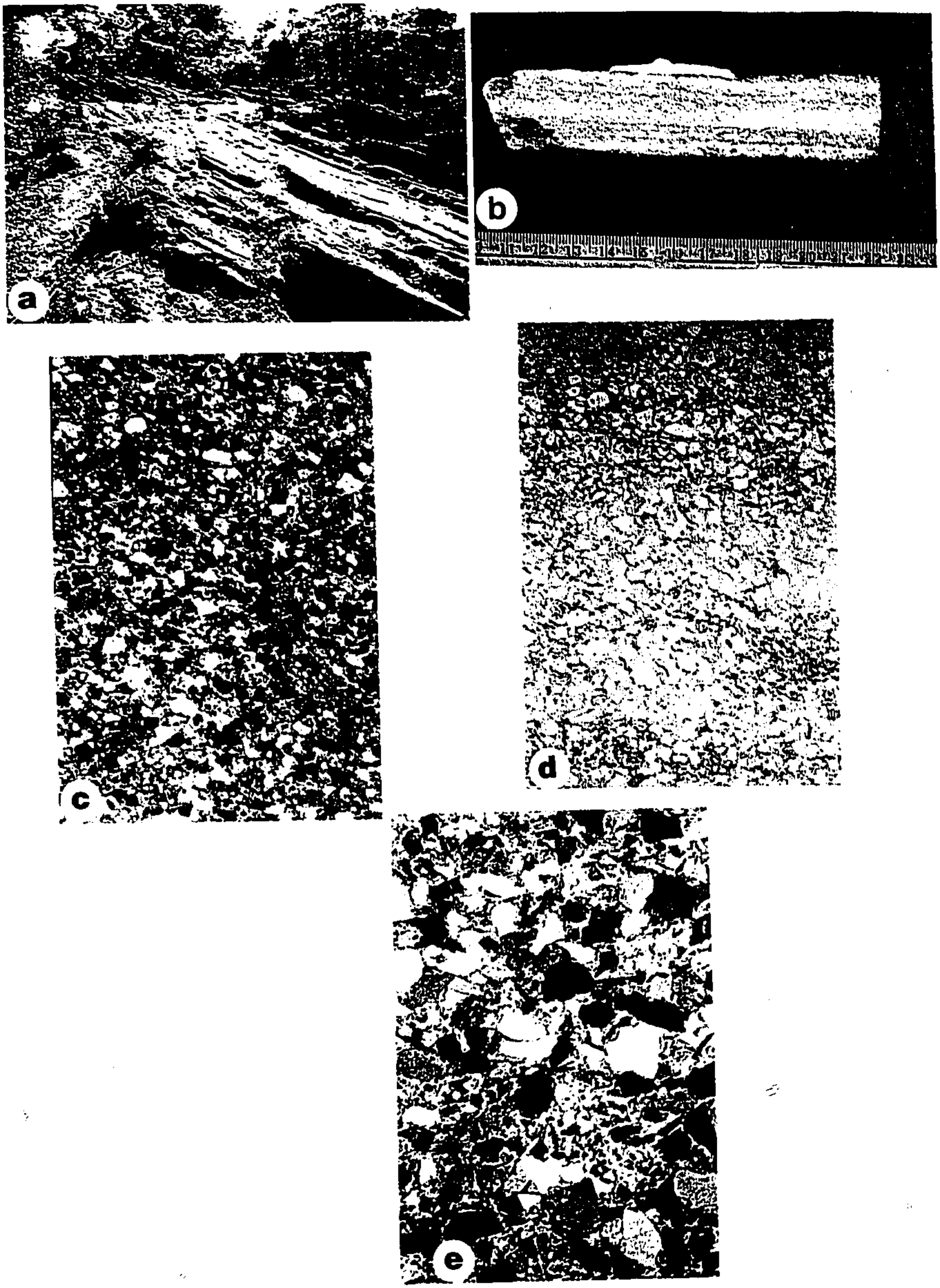
a: Sheets of very fine- to medium-grained sandstone lithofacies intercalated with mudrock lithofacies. Northern Slope Section 3b, Nkandabwe map area. Carrying sack (arrow) is ~ 35 cm.

b: Polished slab from (a), showing horizontal laminae defined by variation in grain size and composition. The thin red laminae accentuated by hematite contain abundant mud and clay. The thick whitish laminae are coarser and contain abundant detrital quartz and feldspar grains. Scale in cm.

c: Photomicrograph (crossed nicols) showing texture of the sandstone in (b), consisting of quartz, feldspar, opaque iron oxides and other heavy minerals cemented by sericite and calcite. Long side of photograph is 15 mm.

d: Photomicrograph showing texture of the sandstone as in (c), in plane polarised light. The black material filling spaces is hematite-coated clay. Long side of photograph is 15 mm.

e: Photomicrograph (crossed nicols) showing moderately sorted sandstone consisting of predominant quartz grains, altered feldspars and muscovite laths. Most feldspars have disintegrated into finer grains that form the matrix. Some of the small grains and clay probably resulted from disintegration of rock fragments. Northern Slope Section 3b, Nkandabwe map area. Long side of photograph is 3.5 mm.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contacts and contacts with underlying and overlying lithofacies are sharp. Most of the sandstone beds are horizontally laminated (Sh, Fig. 4.4b); tabular massive beds (Sm) and beds showing crude normal grading are subordinate. Laminae defined by hematite are evident in places. Alternating reddish pink and cream to whitish grey (thicker) laminae are accentuated by weathering.

The sandstone is generally moderately sorted, with predominantly subrounded to subangular grains (Fig. 4.4c, d). Cementation is generally moderate, so that the sandstone easily disintegrates without breaking grains, but is more complete in the fine-grained varieties, which fracture across the grains. Muscovite is abundant, usually concentrated along bedding planes. In thin section, the sandstone framework consists of quartz, feldspar and minor rock fragments in a matrix of hematite-rich clay and calcite cement. The framework grains are subrounded to subangular, with highly variable sphericity in the range of 0.50 to 0.80 (Fig. 4.4d). Grain contacts are planar to slightly concavo-convex. Bedding is defined by grain size, with thin fine-grained laminae containing abundant hematite-rich clay matrix, alternating with thick coarser laminae containing less clay matrix. Mica grains are oriented parallel to bedding, but where these are rare, laminae are not obvious owing to the equidimensional nature of the grains. Deformation of rock fragments (mostly mudrock) and alteration of feldspar has contributed to the clay matrix, which has intruded the pore space and surrounds competent framework grains, thereby reducing the porosity (1-5%) (Fig. 4.4d). Most porosity is in the form of oversized pores, suggesting leaching of labile minerals and fragments. The calcite cement consists of large crystals (sparite) that usually enclose a number of framework grains, resulting in a 'poikilotopic' texture.

Quartz is the predominant mineral, occurring mainly as monocrystalline grains (65-75%) that show undulose extinction, as polycrystalline grains with sutured contacts, and as stretched polycrystalline quartzite grains (<1%). Mica inclusions and vacuoles are common in all of the quartz types, as is fracturing similar to that of vein quartz (cf. Folk, 1980, p. 69). Chert is rare. Feldspars are represented by microcline, orthoclase and plagioclase. Most of the microcline grains are altered and replaced by calcite. Most of the orthoclase is untwinned, but can be distinguished from quartz by its alteration and interference figure. Muscovite is the dominant mica, with minor biotite and chlorite. Some biotite has altered to chlorite; many flakes of these minerals have been bent by compaction between quartz grains. Mica flakes are abundant in the hematite-rich clay partings or laminae, and are oriented parallel to bedding. Heavy minerals include garnet, epidote, apatite, tourmaline and zircon.

On the basis of sorting and roundness, the sandstone is texturally submature.

4.2.2.4 Coarse-grained to pebbly sandstone lithofacies (S_{c-p})

This sandstone lithofacies is more abundant in the basal part of the Sinakumbe Group, but it also occurs as intercalations within the middle conglomeratic part of the formation (Fig. 4.1).

In outcrop, the sandstone is extensively weathered; fresh exposures are extremely rare. Colours vary from light brownish pink to pale red, dark pinkish/reddish brown and yellowish brown (Fig. 4.5a, b), with brownish-black coatings obscuring structures. The freshest sandstones are the light creamy grey, probably close to the original colour. Most beds are tabular and bed thicknesses range from 5 cm to 1.4 m (Fig. 4.5a, b). Most beds are massive (Fig. 4.5c), but some show normal grading. In the Sikalamba Section up to 3 m of planar cross-stratification is exposed, consisting of 5 cm- to 30-cm thick cosets with foresets dipping 3-15° (Fig. 4.5d). Following the classification of Miall (1978), three depositional facies can be recognized: massive sandstone (Sm), planar cross-bedded sandstone (Sp) and normally graded sandstone (Sg). The Sp facies is medium brown with pale olive mottling. Stratification is defined by alternating coarse- to very coarse-grained laminae and medium- to fine-grained laminae (Fig. 4.5d, e). Some laminae show a concentration of hematite-rich clay (Fig. 4.5d). Most hand specimens are crumbly, suggesting poor cementation. Grains are subrounded to subangular. The few pebbles present are generally less than 6 mm in diameter. Pink feldspar is abundant; a stained sample from this group contains 10% K-feldspar (Fig. 4.5c).

Eight thin sections studied showed most of these sandstones to be framework-supported, with hematite-coated quartz, feldspar, and rock fragments mostly having concavo-convex to planar contacts (Fig. 4.5f). Deformation of altered rock fragments and

Fig. 4.5 Coarse-grained to pebbly sandstone lithofacies

Lower Sinakumbe Group

a: Tabular, yellowish brown, massive to crudely stratified, coarse-grained to pebbly sandstone lithofacies. Muzuma River Section 4, Nkandabwe map area. Hammer is 34 cm.

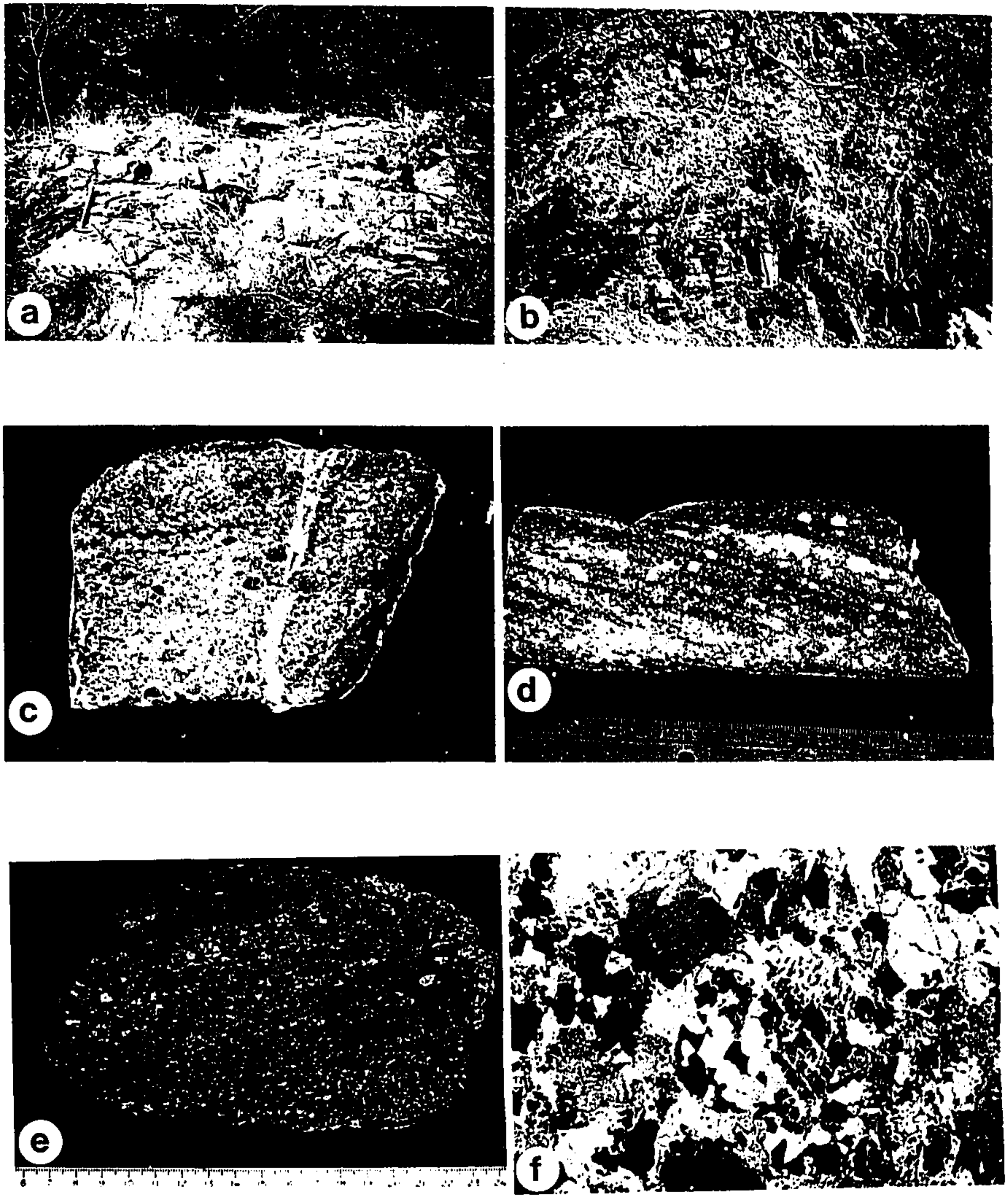
b: Tabular to lenticular, brownish pink, coarse-grained to pebbly sandstone lithofacies alternating with very fine- to medium-grained sandstone and mudrock lithofacies. The mudrocks have been weathered and fragmented. Kazinze River Section 4, Nkandabwe map area.

c: Polished slab from (a) showing internally massive sandstone with crude stratification. Feldspar content is shown by yellow staining. The fracture is filled by quartz. Scale in cm.

d: Planar cross-bedding defined by coarse- to very coarse-grained sandstone layers and medium- to fine-grained, hematitic clay-rich laminae. Sikalamba River Section 6 northeast side, Nkandabwe map area. Scale in cm.

e: Polished slab of sandstone showing crude stratification defined by differences in grain size. Northern Slope Section 3b, Nkandabwe map area. Scale in cm.

f: Photomicrograph (crossed nicols) from (c), showing a rock fragment consisting of polycrystalline quartz (embayed contacts) and feldspar undergoing sericitization; sericitization preferentially occurring along twin planes. Quartz is predominant mineral overall and some grains are fractured. Long side of photograph is 6 mm.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feldspars has resulted in abundant sericite-rich clay matrix that has intruded pore space and surrounds competent framework grains, considerably reducing the primary porosity. However, dissolution of both feldspar and rock fragments (Fig. 4.5f) has also given rise to oversized pores, considerably enhancing the secondary porosity (5-10%). Fracture porosity seen in the section has been filled by quartz. Grain size ranges from 0.02-5 mm, averaging 0.4-0.5 mm. Small grains are generally sub-angular; larger ones are subrounded to rounded. Sphericity varies from 0.50-0.75. Compaction is indicated by bent muscovite grains and fractured plagioclase (displacement of twinned zones). The predominant mineral is strained and fractured monocrystalline quartz with inclusions (e.g. biotite); less abundant is polycrystalline quartz (equant crystals with planar or undulatory contacts and subordinate triple junctions. Drusy, mosaic vein quartz filling fractures is present. Feldspars (both twinned and untwinned) include microcline (predominant), orthoclase and plagioclase. Large microcline grains and other feldspar grains show different stages of post-depositional alteration, with sericite as the end product (Fig. 4.5f). There are fewer rock fragments than expected (~ 5%) partly because altered feldspar and rock fragments can be difficult to distinguish if the fragments lack outlines. Rock fragments were very likely more abundant initially but have since been broken down into individual grains.

Muscovite forms less than 2% of the rock. Biotite is less abundant; chlorite is present in trace amounts. Matrix consists mainly of sericite, silt-size grains (from disintegration of rock fragments) and clay. These have been identified (XRD) as illite (abundant), smectite (minor to trace) and mixed-layer clays (I/S) in trace amounts, with quartz as the only clay-sized mineral recovered. Hematite coating is probably a weathering product; red to brick red stains and crystals are likely to be hematite. Calcite cement was observed in one section in the Sp depositional facies. Heavy minerals are mainly garnet (up to 0.5%) and epidote (up to 1% in one section L2). Epidote also occurs as clusters of minute, rounded to lath-shaped crystals associated with feldspar. Opaque minerals include iron oxides (ilmenite and rutile).

4.2.2.5 Matrix-supported conglomerate lithofacies (C_{ms})

The matrix-supported conglomerates show various colours including pale yellowish brown, dusky brown, dusky yellowish brown, pale brown to light brownish grey, and moderate red to dusky red. Yellowish, orangish and whitish mottling is common. The matrix is typically light olive grey (greenish grey), whereas clasts (granules to cobbles) are pink, red and brown. This lithofacies incorporates rocks that in the Miall (1978) and Rust (1978) classifications would be considered as three depositional facies: massive matrix-supported or crudely bedded gravel (Gmm), horizontally stratified gravel (Gh) and trough-stratified gravel (Gt).

In outcrop, units of the C_{ms} lithofacies range from 20 cm to over 5 m thick (Fig. 4.6a, b) with generally convex-upwards bed tops. Bed contacts are generally sharp, but locally gradational. Basal lags, and intercalations of this lithofacies in others (e.g. in coarse-grained to pebbly sandstone) can be as thin as 10-15 cm. Beds of Gmm range from 20 cm to 2.1 m (Fig. 4.6a), Gh from 20 cm to 5.1 m (Fig. 4.6b) and Gt from 30 cm to 1.3 m thick (Fig. 4.6c). In the Gmm, the conglomerate is poorly sorted, with grain size generally ranging up to pebble size, and local outsized clasts up to cobble size (Fig. 4.6d, e). The cobbles are up to 20 cm in diameter in Muzuma River Section 4, and along Bulamazi Stream (Fig. 4.6d, e). Coarse-grained to pebbly sandstone interbeds are common in the facies (Figs. 4.6f and 4.7a, b). Some of the interbeds are massive (Fig. 4.6f) or show crude stratification (Fig. 4.7a, b). In the Gh depositional facies (Fig. 4.6b), the pebbles define the bedding, but imbrication is rare. In the Kazinze River Section, the conglomerate units alternate with pebbly sandstone (Fig. 4.7c). Bed thickness is variable, and some lateral facies changes are abrupt. Normal and reverse grading are present, and in the latter (Fig. 4.7d) pebble size usually increases with no apparent grain size increase in the sandy matrix , e.g. in Muzuma River Section 4. In the Gt facies, both at Ntole River, Section 2 and in the Slope Hill Sections (3a and 3b), pebbles increase in amount upwards. In the Slope Sections, troughs decrease in thickness and width upwards. The overlying tabular pebbly sandstone shows some crude normal grading. Pebbles and cobbles in these beds are mostly quartz (over 70 %) and feldspar (Fig. 4.7f) and minor rock fragments. Quartz grains are usually subrounded to rounded, whereas the feldspar is subangular to subrounded (Fig. 4.7f). Estimates from field observations and stained slabs show that K-feldspar accounts for 15-25% of the conglomerates (Figs. 4.7f and 4.8a).

Fig. 4.6 Matrix-supported conglomerate lithofacies

Lower Sinakumbe Group

a: Matrix-supported conglomerate facies (Gmm) behind the hammer and framework-supported facies (Gmms) at the top of photograph. Muzuma River Section 4, Nkandabwe map area. Hammer is 34 cm.

b: Horizontally stratified gravel facies (Gh) with pebble layers defining bedding. Sikalamba River Section 6 southwest side, Nkandabwe map area.

c: Trough cross-stratified pebbly sandstone and conglomerate with structure almost obscured by weathering (brownish coating). Northern Slope Section 3b, Nkandabwe map area

d: Oversized angular quartz-vein clasts in conglomeratic matrix (matrix-supported conglomerate lithofacies). Muzuma River Section 4, Nkandabwe map area. Marker pen is 13 cm.

e: Oversized subangular quartzite clasts in conglomeratic matrix. Bulamazi stream Section 5, Nkandabwe map area. Lens cap is 5 cm diameter.

f: Conglomerate facies, (matrix-supported (below) and framework-supported (above), with sheet-like, coarse to pebbly, massive sandstone interbed (below hammer head). Muzuma River Section 4, Nkandabwe map area. Hammer for scale.

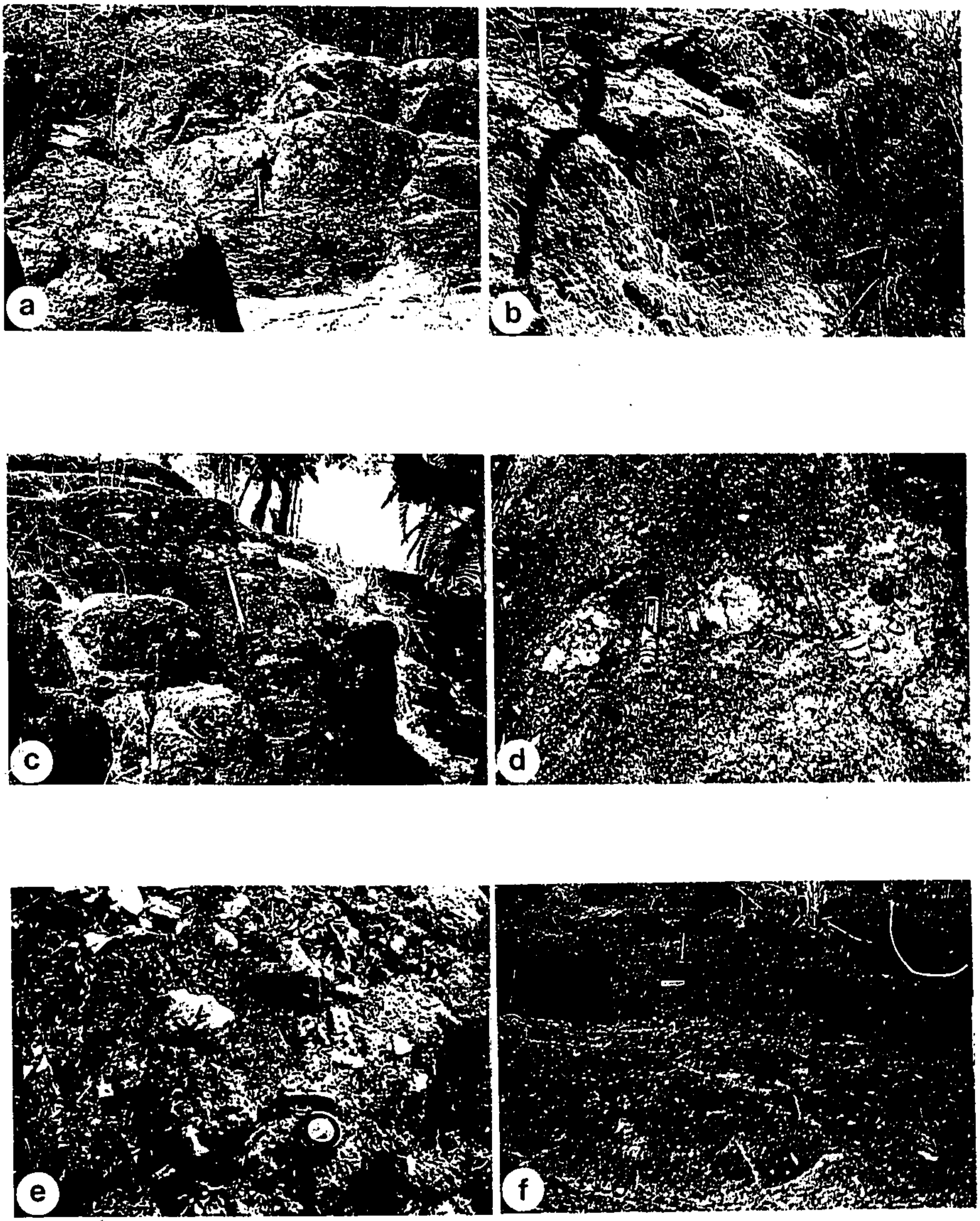
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Fig. 4.7 Matrix-supported conglomerate lithofacies

Lower Sinakumbe Group

a: Irregular, poorly defined complex bedforms, in mainly matrix-supported conglomerate lithofacies with interbedded horizontally stratified pebbly sandstone, and framework-supported conglomerate towards the top. Type section, Muzuma River Section 4, Nkandabwe map area. Hammer is 34 cm.

b: Interbedded conglomerate and pebbly sandstone in (a) showing internal horizontal to low-angle stratification.

c: Alternating pebbly sandstone and conglomerate lithofacies. Kazinze River Section 4, Nkandabwe map area.

d: Normal grading in bed below hammer overlain by crudely stratified bed in the conglomerate lithofacies. An alternating sequence of framework-supported conglomerate (F) and matrix-supported conglomerate (M) is evident. Muzuma River Section 4, Nkandabwe map area.

e: Feldspar-rich matrix-supported conglomerate lithofacies. Notice that the feldspar clasts are more angular than the quartz and quartzite pebbles. Sikalamba River Section 6, Nkandabwe map area. Pen is 14.4 cm long.

f: Polished slabs of the conglomerate in (a). Feldspars are stained yellow in slab to the right. Scale in cm.

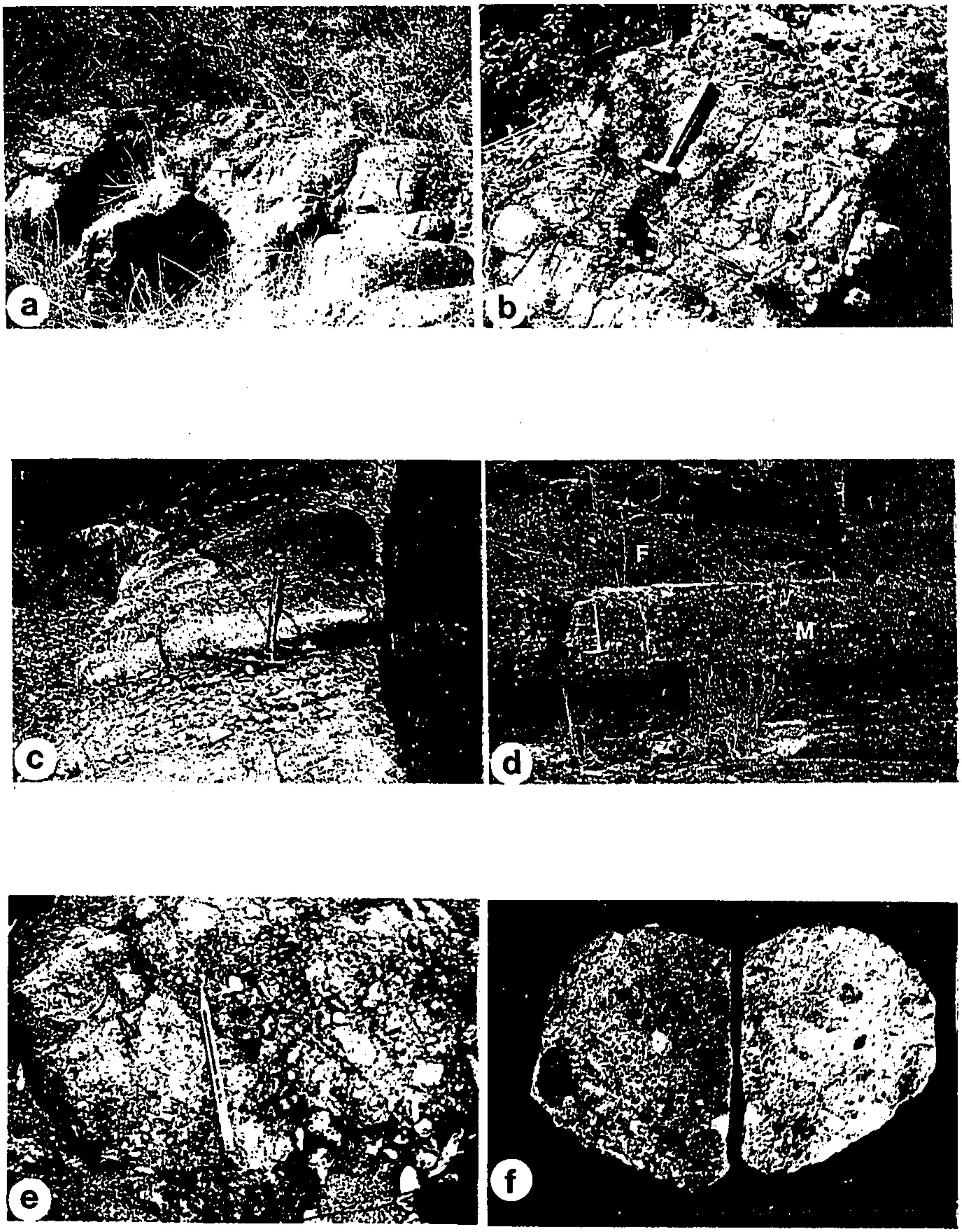
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Fig. 4.8 Matrix-supported conglomerate lithofacies

Lower Sinakumbe Group

a: Photomicrograph (crossed nicols) showing large microcline crystals, and muscovite grain bent as a result of compaction. Type section, Muzuma River Section 4, Nkandabwe map area. Long side of photograph is 6 mm.

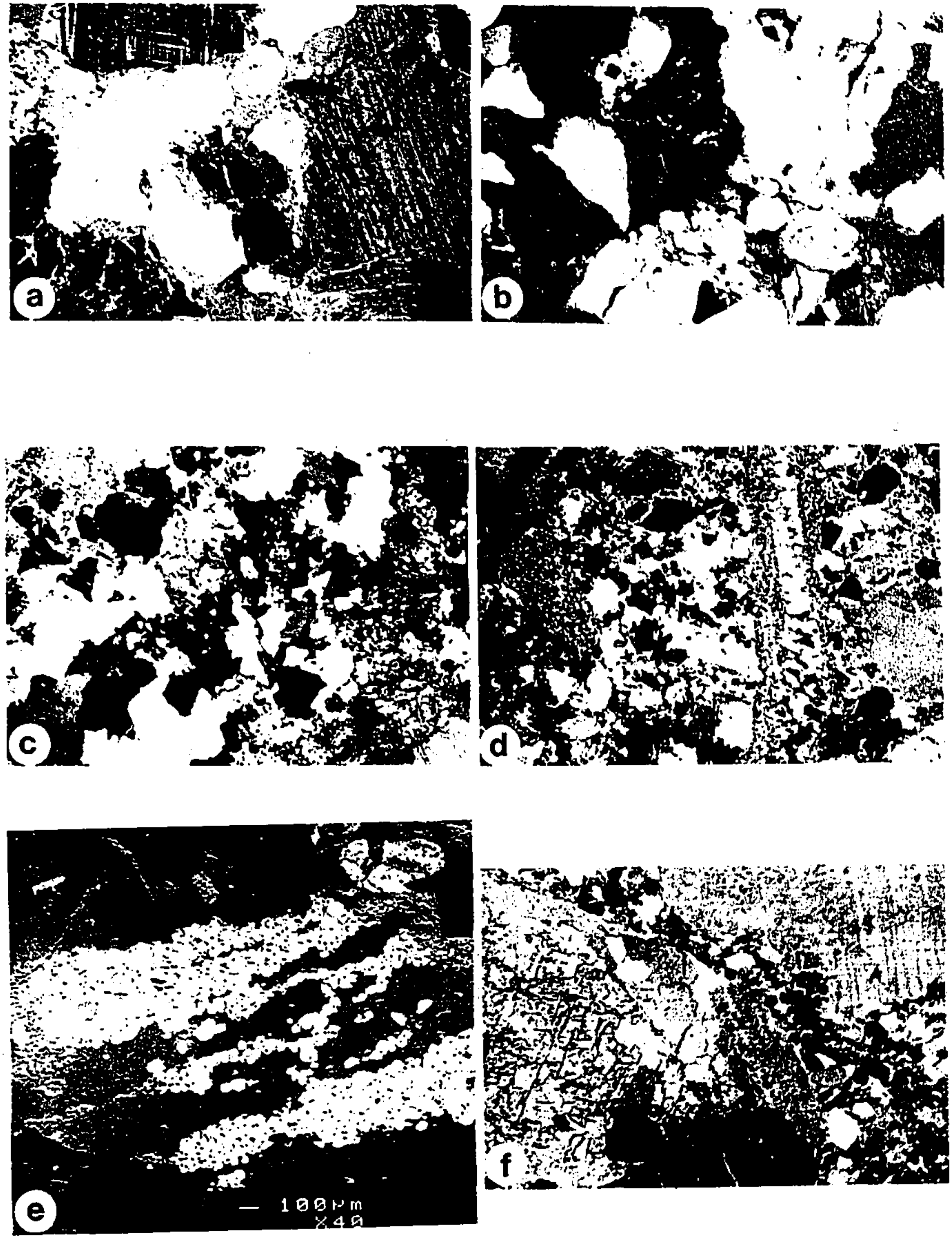
b: Photomicrograph (crossed nicols) showing hematite-coated sericite/calcite clay matrix filling voids between quartz and feldspar grains. Ntole River Section 2, Nkandabwe map area. Long side of photograph is 2.5 mm.

c: Photomicrograph (crossed nicols) showing polycrystalline quartz grains with bluish small grains probably of garnet. Clay is mainly sericite. Type section, Muzuma River Section 4, Nkandabwe map area. Long side of photograph is 13.5 mm.

d: Photomicrograph (crossed nicols) showing fracture filled by drusy mosaic quartz. Notice siltstone fragment at left centre. Type section, Muzuma River Section 4, Nkandabwe map area. Long side of photograph is 13.5 mm.

e: SEM photomicrograph showing large feldspar grain partly replaced by epidote. The epidote is concentrated along twin lamellae. Type section, Muzuma River Section 4, Nkandabwe map area.

f: Photomicrograph (crossed nicols) showing large microcline and well rounded rock fragments separated by small grains of quartz, feldspar, heavy minerals and sericite matrix. Notice the dark grey/black sericitised feldspar in the rock fragment. Type section, Muzuma River Section 4, Nkandabwe map area. Long side of photograph is 4.4 mm.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100µm
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In thin section, pebble-size clasts are seen to be poorly sorted and scattered in a sandy matrix of mainly quartz and feldspar. Rock fragments are minor. Quartz pebbles are fractured and some are hematite coated and others outlined. Microcline pebbles show various degrees of alteration.

The sandy matrix consists of coarse to very coarse grain-supported framework or the grains are commonly held together by hematite and sericite-rich clay matrix (Fig. 4.8b). The grains are subrounded to subangular with sphericity varying from 0.50 - 0.75, and are moderately well sorted. Grains show planar to concavo-convex contacts. Interpenetrating, undulatory and embayed contacts are also evident. Mechanical compaction is indicated by bent, squeezed and broken muscovite grains, and shattered and bent feldspars. Primary porosity is occluded by the matrix; however, dissolution of grains (secondary porosity) has slightly increased the porosity. Quartz is the predominant mineral (60-75%), with both monocrystalline and polycrystalline varieties (2-5%) present (Fig. 4.8c). The polycrystalline grains show sutured, interpenetrating and planar contacts, suggesting metamorphic and recrystallized metamorphic origins. Undulose extinction is common in the monocrystalline variety. 'Boehm' lamellae are present in some quartz grains. Some monocrystalline grains are fractured and contain abundant vacuoles indicative of vein quartz (Folk, 1980, p.69). Drusy, mosaic vein quartz with typical void-filling morphology of equant crystals increasing in size away from the fracture walls (Fig. 4.8d) is also present (cf. Adams et al., 1984, p. 57). Feldspars (5-20%) include microcline, orthoclase and plagioclase (Fig. 4.8a). The larger grains are mainly microcline; the smaller ones are plagioclase. The feldspars are altered to sericite and epidote. SEM studies confirmed that the K-feldspars are partially altered to sericite and epidotised (Fig. 4.8e), and that some are partly replaced by albite. The matrix contains a substantial amount of epidote (Fig. 4.8c), with some as inclusions in the feldspar. Fresh feldspars are common only in the finer-grained matrix.

Rock fragments are minor (~ 3%) (Fig. 4.8e), but are likely to have been the major original contributors to the sandy matrix. Muscovite is the common mica, but biotite is also present. Chlorite is also present. Sericite and muscovite wrap around the large grains. Heavy minerals include garnet, epidote (Fig. 4.8c, d), sphene, zircon, apatite and pyrite. Some rounded garnets occur in quartz clasts, and a spectrum taken in one of them indicated that they belong to the almandine group. Opaque minerals are mostly iron oxides (rutile and probably magnetite) some of them are localised in the matrix. Rutile intergrown with magnetite and a thorium-rich mineral were observed.

XRD analysis indicates that illite (sericite) with traces of smectite is the predominant clay mineral. Chlorite was only identified by SEM. The other clay-sized mineral observed is quartz and probably occurs as silica cement as observed in SEM. Calcite cement was observed (SEM) in the pinkish red conglomerate. Overall (i.e. together with pebbles), the C_{ms} lithofacies is a poorly sorted conglomerate and the abundance of feldspars indicates immaturity.

4.2.2.6 Framework-supported conglomerate lithofacies (C_{fs})

The framework-supported conglomerates show various colours, but yellowish, greenish brown to light greenish grey, pinkish red to very dusky red are most common. Greyish-black coatings are characteristic of these conglomerates. The C_{fs} lithofacies is not common, having been recorded only in the type locality (Muzuma River Section 4) with certainty, though it may be present in Kazinze River Section 4 and other localities.

The conglomerates occur in medium to thick bedded internally massive units with moderately well sorted clasts (Gmms; Fig. 4.9a-d). The beds are irregular and commonly wedge shaped, 20 cm to 2 m thick, with basal lags of about 10 cm thick. However, in the type locality a tabular persistent C_{fs} bed (60 cm) occurs, though with smaller pebble size (Fig. 4.6f). Gravel size is mostly in the pebble to cobble range, with an average of 3-5 cm (Fig. 4.9a-d) and a maximum cobble-size of 7.5 cm. Intercalations of pebbly sandstone are common, and matrix-supported conglomerate occurs locally in the framework-supported conglomerate (Fig. 4.9a, c). Fig. 4.9 (a) and (d) show the C_{fs} lithofacies overlain by irregular units of matrix-supported conglomerate and sandstone. The conglomerate is polymodal and clast-supported with a poorly-sorted matrix (Harms et al., 1975 terminology). Rounded quartz pebbles and minor cobbles are the predominant clasts, followed by subangular pink feldspar (Fig. 4.9b, e). Sphericity of pebbles and cobbles is high (0.65-0.85). The poorly sorted matrix consists of quartz and feldspar ranging from

Fig. 4.9 Framework-supported conglomerate lithofacies

Lower Sinakumbe Group

a: Framework-supported conglomerate lithofacies showing irregular commonly sharp contacts. Internally the conglomerate is massive (Gmms). Type section, Muzuma River Section 4, Nkandabwe map area. Hammer is 34 cm.

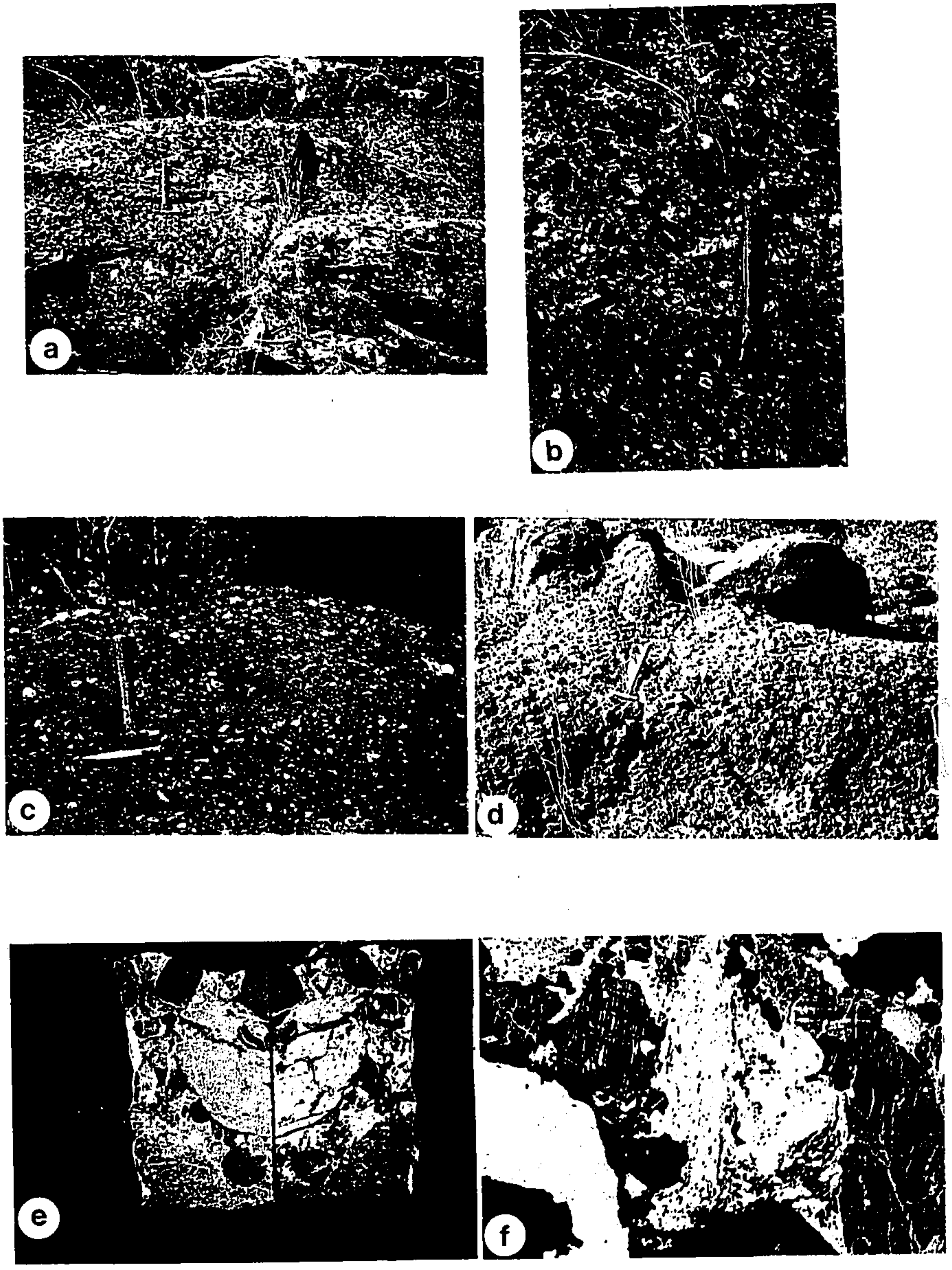
b: Close-up view of framework-supported conglomerate lithofacies in (a), showing well rounded moderately sorted clasts in greenish grey and red conglomeratic matrix. Type section, Muzuma River Section 4, Nkandabwe map area.

c: Framework-supported conglomerate lithofacies intercalated with pebbly sandstone. Type section, Muzuma River Section 4, Nkandabwe map area.

d: Internally massive, framework-supported conglomerate lithofacies (Gmms) exhibiting moderately well-sorted clasts, overlain by irregular-shaped, massive matrix-supported conglomerate and sandstone. Type section, Muzuma River Section 4, Nkandabwe map area.

e: Conglomerate lithofacies from (a), with stained slab (left) showing high amounts of K-feldspar (yellow). Scale in cm.

f: Photomicrograph (crossed nicols) showing microcline and quartz grains with a deformed rock fragment that contains bent muscovites. Kazinze River Section 4, Nkandabwe map area. Long side of photograph is 1cm.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coarse sand to granules (even small pebbles). Mica flakes are also common.

The conglomerates are usually massive (Gmms); grading is not common. In thin section, pebbles occur mainly as fractured polycrystalline quartz with locally sutured planar to concavo-convex contacts. They also show undulose extinction, indicating that the grains underwent straining. 'Boehm' lamellae are present. Cleaved garnets occupy the fracture spaces within quartz crystals. Other clasts include feldspars and rock fragments (Fig. 4.9f). Feldspars occur mainly as microcline, plagioclase and orthoclase. Some large microcline clasts contain quartz inclusions and twinned plagioclase along fractures and cleavage planes. Epidote and hematite coating is present. Rock fragments are not well-defined (outlines absent) (Fig. 4.9f), but some elongate polycrystalline quartz clasts with smooth, crenulated or granulated borders, a few plutonic fragments and traces of intrabasinal sedimentary fragments can be recognized.

The gravelly matrix shows a grain size range of 0.1 mm to over 3 mm. Grain contacts are planar to concavo-convex. Intergranular porosity has been occluded by matrix, and some secondary porosity has been created by dissolution of feldspar and along fractures. The matrix grains are loosely packed, and some are highly deformed (e.g. bent mica grains) reflecting compaction.

Muscovite predominates over biotite. Heavy minerals include epidote (most abundant), garnet, sphene and opaque minerals which are associated with fracture zones. Sericite-rich clay matrix, and hematite coating of grains are common and all account for 2-5% of the gravelly matrix. XRD confirmed illite to be the most abundant clay mineral, followed by smectite. Other clay-sized minerals are quartz and potassium feldspar indicating the predominance of the two minerals in the framework clasts. Overall, the framework-supported conglomerate is well sorted, tightly packed with no visible imbrication.

4.2.2.7 Lithofacies interpretation

The general characteristics of the Lower Sinakumbe Group lithofacies and their interpretation are given in Table 4.3. From the lithofacies association, the Lower Sinakumbe Group is regarded as an alluvial fan deposit. The presence of graded bedding,

Table 4.3 Summary of characteristics and interpretation of Lower Sinakumbe Group lithofacies

LITHOFACIES	GRAIN SIZE / SORTING	TEXTURE	MINERALOGY AND OTHER COMPONENTS	BEDDING AND SEDIMENTARY STRUCTURES	GEOMETRY / NATURE OF BOUNDING SURFACES / THICKNESS	DEPOSITIONAL ENVIRONMENT
Mudrock (M_{sm}) mudstone/siltstone/sandstone	silt to fine sand; moderately well sorted to well sorted		Detrital grains: quartz (20-30%), feldspar (1-2%), rock fragments (<0.1%). Heavy minerals: zircon, apatite, epidote, ilmenite. Matrix: sericite (illite) and muscovite (30-35%), chlorite. Cement: calcite (5%), hematite	massive (abundant) Fm horizontal laminae Fl beds may be normally graded	tabular, generally flat base and top (irregular surfaces present); beds up to 5cm thick, unit 2.3m.	mudflat at basin margin
Sandstone (S_{vf-m})	very fine to medium sand; moderately well sorted	matrix- to framework-supported	Detrital grains: quartz (65-75%), feldspar (microcline, orthoclase, plagioclase), rock fragments (rare), muscovite, biotite, chlorite. Heavy minerals: garnet, epidote, apatite, tourmaline, zircon. Clay minerals: illite. Cement: calcite	horizontal bedding (Sh) massive (Sm)	tabular, irregular base and top; beds up to 15cm thick, units 7m.	sandflat at basin margin
Sandstone (S_{c-p})	medium to pebbly sand; poorly sorted	matrix- to framework-supported	Detrital grains: quartz (70-75%), feldspar (microcline, orthoclase, plagioclase -5-20%), rock fragments (~5%), muscovite, biotite, chlorite. Heavy minerals: garnet, epidote, ilmenite, rutile. Clay minerals: illite, smectite, mixed layer clays (I/S), calcite, hematite	massive (Sm); may show normal/ reverse grading, horizontal bedding, solitary or group planar cross-beds (Sp) coarsening-upward sequence	tabular to lenticular concave-up bases to irregular, lenticular? flat tops and bases; may be irregular; bed thickness from 5cm to 1.4m.	rapidly deposited or destratification in various environments: linguoid bars and bar-edge sandwaves of braided streams
Conglomerate (C_{ms})	Matrix: medium sand to pebbles; poorly sorted Coarse fraction (clastics): granules to cobbles; poorly sorted	matrix-supported pebbles and cobbles	Detrital grains: quartz (60-75%), feldspar (microcline, orthoclase, plagioclase -15-25%), rock fragments (~3%), muscovite, biotite, chlorite. Heavy and opaque minerals: garnet, epidote, sphene, apatite, pyrite, ilmenite, rutile, magnetite. Clay minerals: illite, smectite. Cement: calcite, hematite.	trough cross-beds (Gt) Horizontal bedding (Gh) massive; some crude bedding (Gm)	lenticular, concave-up bases and poorly defined tops; tabular, poorly defined surfaces; units range from 20cm to 5m thick	braided streams on alluvial fans longitudinal bars debris flow deposit on alluvial fans
Conglomerate (C_{fs})	Matrix: fine sand to pebbles; poorly sorted Coarse fraction (clasts): pebbles; well sorted	clast-supported pebbles	Detrital grains: quartz, feldspar (microcline, orthoclase, plagioclase), rock fragments, muscovite, biotite, chlorite. Heavy minerals: epidote, garnet, sphene. Clay minerals: illite, smectite. Cement: hematite.	clast-supported, sandy to conglomeratic martrix, no imbrication or internal stratification (Gms)	Complex: bedforms of several shapes including lenticular, wedges and tabular sheets. convex-upward tops with irregular base; gradational contacts common between Gms and Gm; Beds 20cm to 2m thick	sheetflood deposit on alluvial fans

horizontal lamination, crude cross-lamination and massive bedding in the **siltstone and mudstone (mudrock) lithofacies (M_{sm})** indicates current deposition, and the diversity in structures indicates fluctuations in current flow. The horizontal laminae represent deposition under upper flow regime plane-bed conditions with subsequent rapid deceleration of the transporting current resulting in deposition from suspension to form normal grading. Current-rippled tops suggest reworking by decelerating flood currents (cf. Hardie et al., 1978 and Smoot, 1983). Normal grading indicates gradual change in sediment distribution, involving a shift in the modal size or an upward decrease in the abundance (or size) of the coarsest size fraction (coarse-tail grading), with little change in the rest of the distribution. Such beds occur in a wide range of depositional settings (Collinson and Thompson, 1989). However, the most notable occurrence is in turbidite deposits that form the A part of the Bouma sequence (Collinson and Thompson, 1989). The units are laterally persistent and in common association with fine-grained sandstone lithofacies, suggesting traction deposition from sheetfloods on mudflats.

The sheet geometry, with generally flat bases and tops and horizontal lamination (Table 4.3) and the lithofacies association suggest that the **very fine- to medium-grained sandstone lithofacies (S_{vf-m})** are sheetflood deposits that accumulated on sand flats at the basin margin. Hartley et al. (1992) interpreted sandstones with sheet geometry, large lateral extent, uniform thickness and horizontal lamination to represent deposition by unconfined tractional sheetfloods under upper flow regime conditions.

Tabular and internally massive units of **coarse-grained to pebbly sandstone lithofacies (S_{c-p})** are also interpreted as sheetflood deposits, and the normally graded beds are thought to have resulted from waning currents, i.e. deposition from loss of flow competence. The planar cross-bedded units of the lithofacies are interpreted as deposits of longitudinal bars of the braided-stream system. The red and reddish mottling in the S_{vf-m} and S_{c-p} lithofacies are due to the presence of ferric iron oxides (Fe_2O_3), whereas the yellowish brown and brown colours represent hydrous alteration products.

The **matrix-supported, massive conglomerate lithofacies** is interpreted as an assemblage of debris flow deposits; this is substantiated by the presence of poorly sorted, oversized clasts. Scattered very large clasts are typical of debris flow deposits (Middleton and Hampton, 1973, p.25). Horizontally stratified conglomerate (Gh) and trough cross-stratified conglomerate (Gt) depositional facies are regarded as stream flow deposits. Horizontally bedded gravel accumulates on longitudinal bars that originate as primary bedforms of high stage flows (Rust, 1978a). The erosive bases of trough beds and the general decrease of bed thickness and abundance of cosets upwards suggests channel filling. Some trough cross-beds could have resulted from transverse bars. Williams (1971) indicated that pebble-cobble conglomerates and crudely stratified granular sandstone result from deposition of longitudinal bars under rapid flow conditions. The commonly massive interbedded sandstones could be ascribed to rapid deposition (Arnott and Hand, 1989). Grading within this lithofacies suggests a turbulent sediment gravity flow process, in which decrease in velocity resulted in grain settling. Reverse grading in the pebbly sandstone and matrix-supported conglomerate lithofacies are possibly due to generation of considerable amounts of dispersive pressure in headward parts of turbidity currents where coarser grains are concentrated and maintained (Bagnold, 1954; Middleton, 1970) or related to a traction carpet.

The massive, **framework-supported conglomerate lithofacies** with pebbly sandy matrix may have been produced by an alternation of high- and low-discharge events (cf. Smith, 1974, Ramos et al., 1986) with the pebbly sand that was in suspension filling the pores in the gravel framework as the flow decreased and the gravel stopped moving (cf. Rust, 1984). Overall, the conglomerate records deposition from poorly confined sheet flows in which traction bedload transport predominated and was followed by turbulent flow laden by pebbly sand (cf. Todd, 1989; Hartley, et al., 1992). The sheet-like to lenticular geometry of the lithofacies indicates that these are high-energy sheetflood deposits on alluvial fans.

4.2.2.8 Facies analysis

The Lower Sinakumbe Group is a generally coarsening-upward sequence in which two lithofacies assemblages can be recognized. The close vertical and lateral association of siltstone and mudstone (mudrock- M_{sm}) lithofacies and very fine- to medium-grained sandstone (S_{vf-m}) lithofacies (Fig. 4.10), particularly in the lower part of the sequence, is

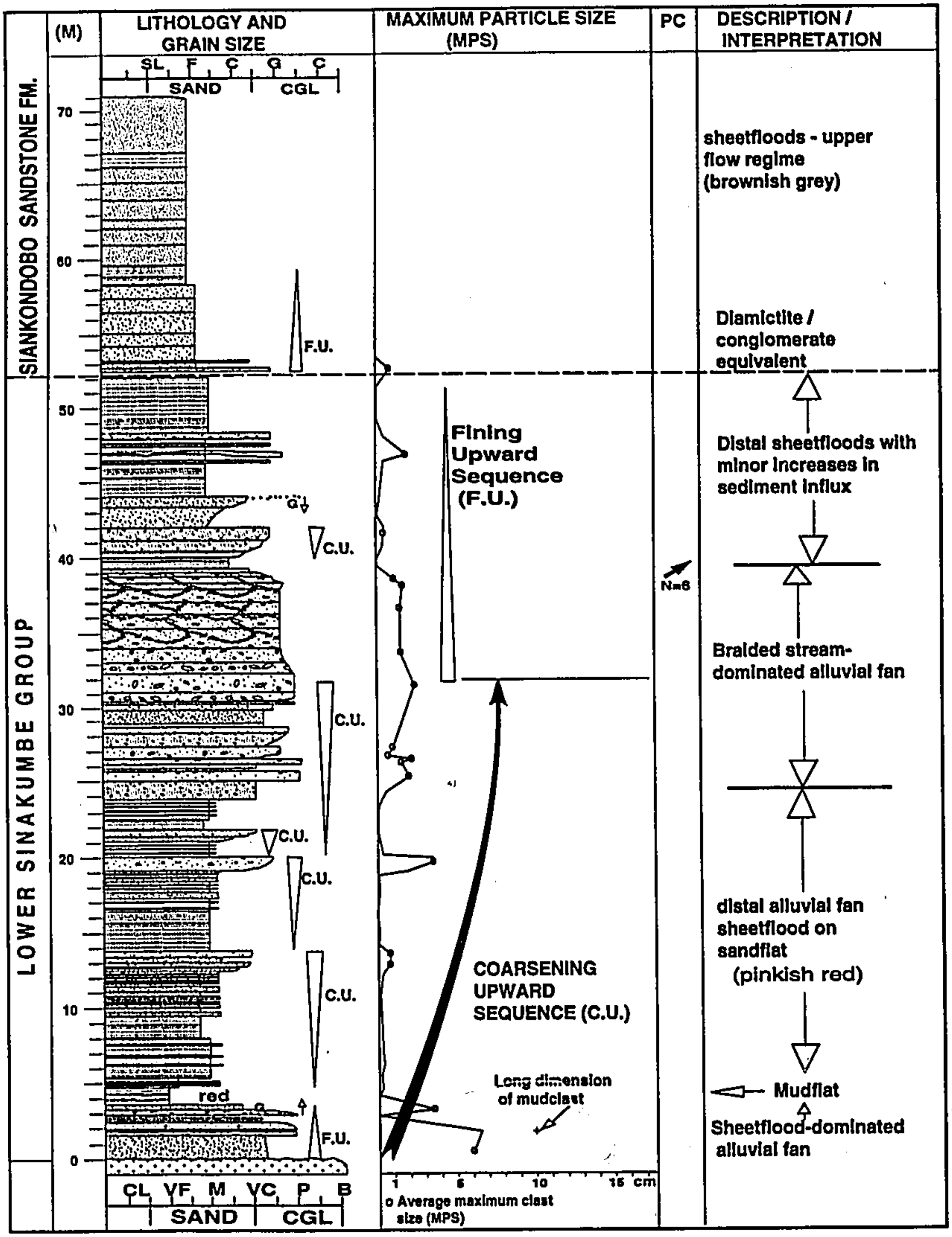

Fig. 4.10 Representative detailed log of the Lower Sinakumbe Group overlain by Siankondobo Sandstone Formation (Lower Karoo Group), Northern Slope Section 3b, mid-Zambezi Valley Basin, Nkandabwe area. PC = palaeocurrent, N = number of readings, FM = Formation, M = Metres.

the basis for recognizing the **mudrock-sandstone facies assemblage**. Similarly, the association of coarse-grained to pebbly sandstone ($S_{c\text{-}p}$) lithofacies, matrix-supported, massive conglomerate lithofacies and framework-supported conglomerate lithofacies is the basis for identifying the **conglomerate facies assemblage** (Fig. 4.11). Both are widely developed in the Nkandabwe map area, although the latter is common in the Sinakumbe-Muzuma corridor, whereas the former is more common northeast of the corridor (northeast of Sikalamba River). Bulamazi Stream Section 5 exhibits a maximum thickness in the conglomerate assemblage of ~45 m. The mudrock-sandstone assemblage is prominent in the Northern Slope Hill Section 3b (Fig. 4.10).

In the Nkandabwe type area (Fig. 2.2a), the base of the Lower Sinakumbe Group is marked by the appearance of red siltstone and mudstone with subordinate medium- to very coarse-grained, locally pebbly sandstone resting unconformably on basement rocks. The mudrocks are interbedded with sandstones, which are succeeded upward by conglomerates interbedded with sandstone. Throughout the eight examined sections in the Sinakumbe Group, a generally coarsening-upward sequence is apparent. The red mudrock and very fine- to medium-grained sandstone lithofacies are vertically and laterally associated (Fig. 4.10), and both are inferred to be products of sheetfloods across mudflat and sandflat environments at the basin margin. They therefore are grouped in the mudrock-sandstone facies assemblage. The close association of coarse-grained to pebbly sandstone, matrix- and framework-supported conglomerate lithofacies vertically and laterally means that these can be grouped in the conglomerate facies assemblage.

This **mudrock-sandstone facies assemblage** is prominent in the lower part of the Lower Sinakumbe Group, forming laterally extensive tabular sheets with generally flat tops and bases. In the Slope Hills Section (Fig. 4.10) in the vicinity of Nkandabwe River, the assemblage is up to 20 m thick. The lateral persistence of units in the mudrock-sandstone facies assemblage suggests sheetfloods, probably on mudflats and sandflats that were periodically flooded. The occurrence of mudrocks stratigraphically higher within the conglomerate facies assemblage, further attests to periodic flooding. The assemblage is therefore interpreted as distal sheetflood deposits on abandoned, distal segments of a fan during major floods. The absence of desiccation cracks and evaporitic minerals,

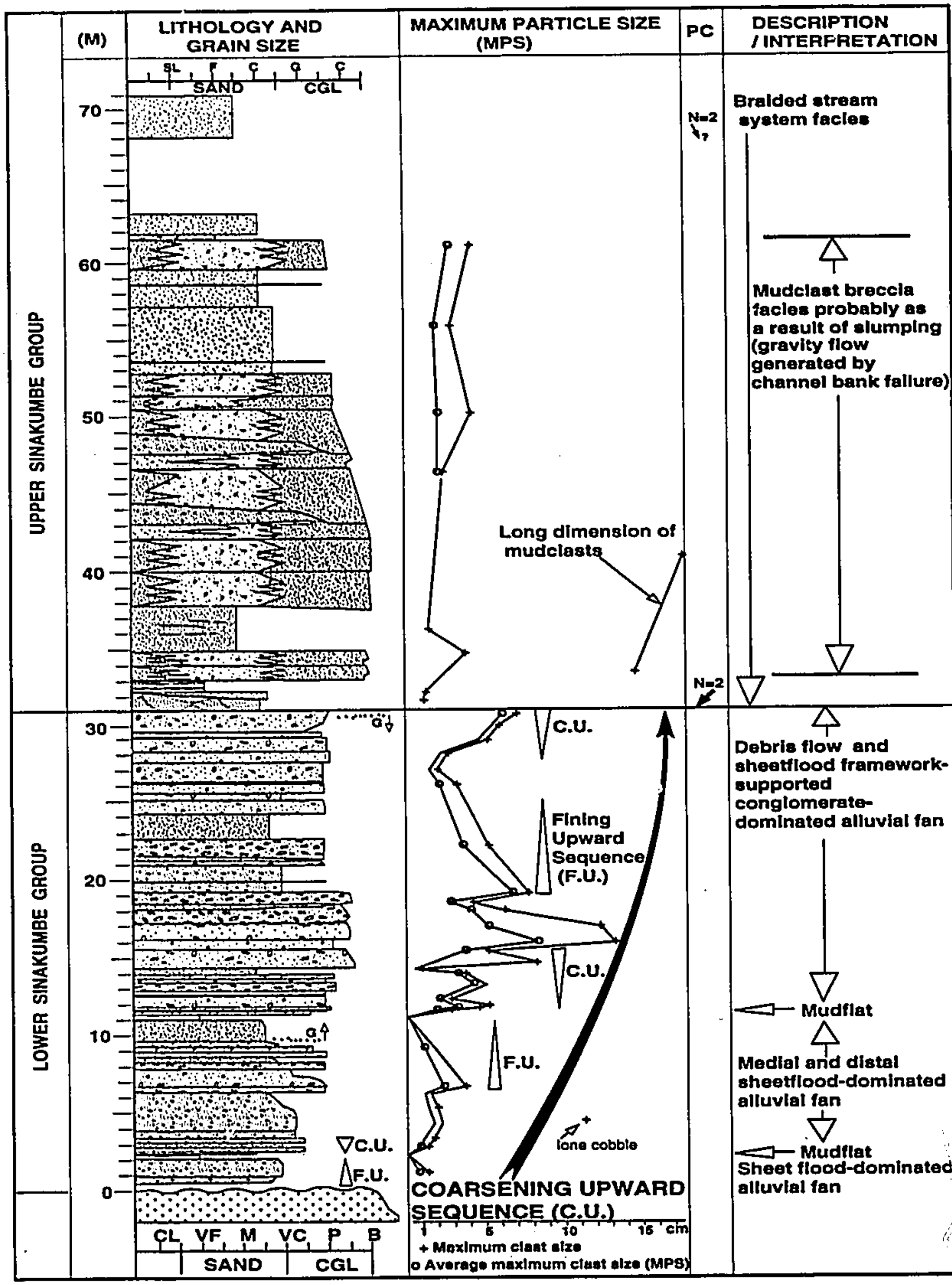

Fig. 4.11 Representative detailed log of the Lower Sinakumbe Group overlain sharply by Upper Sinakumbe Group, type section, Muzuma River Section 4, Nkandabwe area. PC = palaeocurrent, N = number of readings, M = Metres.

commonly associated with playa lake environments, suggests that wetting and drying (ponding) were minimal, although such absence could also reflect a low preservation potential for fine-grained sediments in such environments, as well as poor outcrop exposure. The distinct reddening of the mudrock-sandstone facies assemblage indicates aridity (cf. Hartley et al., 1992). All features (sheet geometry, etc.) indicate deposition by rapid ephemeral flood events, probably in a semi-arid environment (cf. Ballance, 1984; Flint and Turner, 1988).

The **conglomerate facies assemblage** forms 90% of the Lower Sinakumbe Group, consisting predominantly of medium- to very coarse-grained (pebbly) sandstone and matrix-supported conglomerate arranged in a coarsening-upward sequence overall (Figs. 4.10 and 4.11). The coarsening upward units begin with the red mudrock-sandstone assemblage, grading up into the pebbly sandstones and conglomerates of the conglomerate assemblage, which usually are massive or show internal grading, horizontal stratification, or planar and trough cross-stratification (facies Gmm, Gms, Gt, Sp, Sh, Sm and Sg of Miall, 1978, Rust, 1978a). The poor to moderate sorting of immature sediments suggests proximity to a comparatively high relief source area, where mechanical weathering and rapid transport were important. The textures (e.g. Fig. 4.8), complex bedforms (poorly defined bed bases) and abrupt changes in lithology (Figs. 4.12 and 4.13, Table 4.3), together with poorly sorted clasts (up to cobble size), indicate deposition by a highly cohesive debris flow process in which clasts were supported during transport by the cohesive strength of the matrix (Lowe, 1982; Hartley et al., 1992). The crude horizontal to low-angle (<10°) stratification in associated sandstone interbeds (Fig. 4.7b) indicates fluctuations in flow competence in upper flow regime plane-bed conditions. The debris flow deposits are widely developed in the Nkandabwe area and form the predominant component of the Lower Sinakumbe Group. The deposits are commonly made of matrix-supported, ungraded conglomerates that are interbedded with coarse-grained to pebbly sandstone, horizontally stratified gravel (Gh) and framework-supported conglomerate. The absence of planar cross-bedded gravel facies indicates that water depths were insufficient to allow transverse bars to form (Eyles and Kocsis, 1988), or flow velocity was too high for dunes to form.

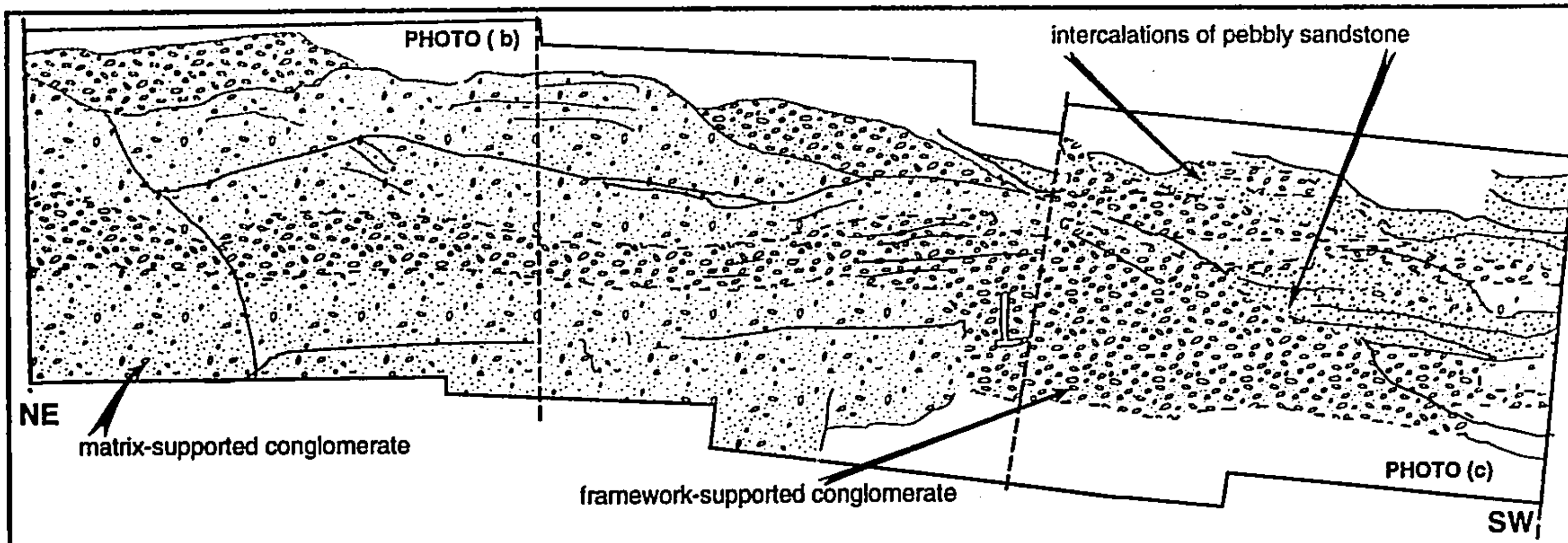

Fig. 4.12 Lateral variation of lithofacies within the conglomerate facies assemblage of the Lower Sinakumbe Group, type section, Muzuma River Section 4, Nkandabwe map area.

a) Profile drawn from photomosaic shows interbedded matrix- and framework-supported conglomerate lithofacies with pebbly sandstone intercalations. Notice how irregular the bed geometries are. Hammer outline is 34 cm long.

b) Representative photograph showing interbedded matrix- and framework-supported conglomerate lithofacies. Notice the convex-upwards tops.

c) Representative photograph showing interbedded matrix- and framework-supported conglomerate lithofacies with pebbly sandstone intercalations. Notice that in the two photographs some beds are missing mainly due to recent erosion.

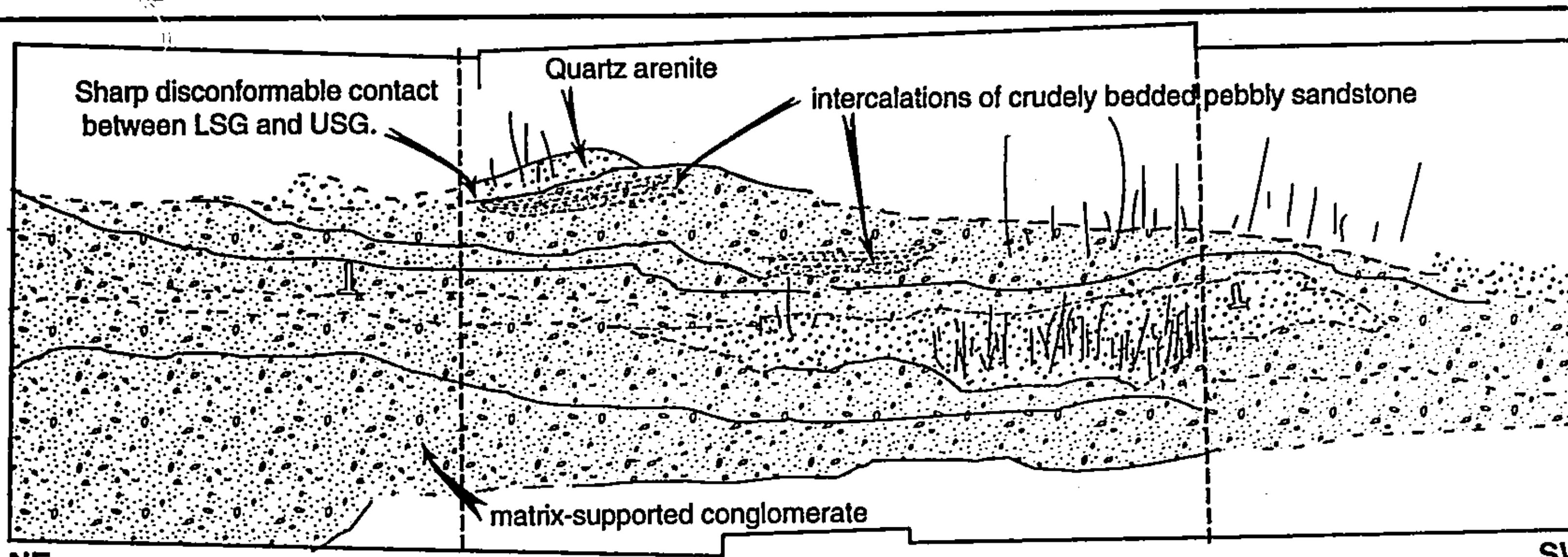

Fig. 4.13 Lateral variation of lithofacies within the conglomerate facies assemblage of the upper part of Lower Sinakumbe Group (LSG), type section, Muzuma River Section 4, Nkandabwe map area.

a) Profile drawn from photomosaic shows matrix-supported conglomerate lithofacies with pebbly sandstone intercalations, overlain by the Upper Sinakumbe Group (USG). Hammer outlines are 34 cm long.

b) General photograph between dashed lines in profile A showing matrix-supported conglomerate lithofacies with pebbly sandstone interbeds. Note the sharp disconformable contact (arrows) between LSG and USG.

c) Detail of (b) showing matrix-supported conglomerate lithofacies with pebbly sandstone interbeds.

The stream flow deposits occur only rarely in the type section (Muzuma River Section 4), but occur extensively in the Slope Hills Section (northern and southern sections 3a and 3b) and also in Ntole Section 2, overlying massive pebbly sandstone and matrix-supported conglomerate (Gmm). In these sections, the matrix-supported conglomerate is less well developed, and framework-supported conglomerate is not present. In their place is the pebbly sandstone. In addition, the clast sizes are much smaller compared to the Sikalamba-Muzuma corridor. The presence of trough cross-bedded units in these localities differentiates these sediments from those in the Sikalamba-Muzuma corridor. Massive conglomerate (pebbly sandstone) predominates, possibly because of shallow water depths, the low relief of bars, and the restricted depths of associated channels (cf. Eyles et al., 1988). The stacked nature of the trough cross-beds, erosive bases and geometry of the units suggest deposition by stream flow processes in braided stream systems.

Trough cross-beds form as dune bedforms and migrate along the channel floor during intermittent high water (Allen, 1963a, 1964; Harms and Fahnestock, 1965; Williams, 1968, 1969, 1971). They reflect the development of sinuous-crested in-channel dunes. The association of this facies with the less common matrix-supported conglomerate and the underlying mudrock-sandstone assemblage suggests that the trough cross-strata represent alluvial braided channel deposits that succeeded the mud- and sand-flat environment. Thick (2 m) sets of cross-bedded gravelly sandstone in other ancient alluvial-fan sequences are interpreted to have resulted from streamflood deposition in fanhead channels (Bluck, 1965; Steel, 1974; Brookfield, 1980).

Two types of sheetflood deposits are evident: proximal sheetfloods represented by the framework-supported conglomerate, and medial to distal sheetfloods represented by coarse-grained to pebbly sandstone with interbedded finer grained sandstone. The interbedded sediments of the mudrock-sandstone assemblage locally form laterally persistent sheets, and together with this assemblage, they support the interpretation that the Lower Sinakumbe Group was deposited in an alluvial fan setting.

4.2.3 THE UPPER SINAKUMBE GROUP

4.2.3.1 General Remarks

The upper part of the Sinakumbe Group (Fig. 4.1) was not intersected in the type locality (Borehole GS96) of the group; however, there is an extensive outcrop in the southwestern part of the Nkandabwe map area and northeastern part of Siankondobo map area (Fig. 2.2a, b). Lack of continuous exposure of the Upper Sinakumbe Group perpendicular to strike makes its thickness difficult to determine. However, in the Muzuma River Section 4, where the river runs approximately perpendicular to strike, the subgroup has an estimated maximum thickness of 150 m. Brownish grey, stratified arenite (trough cross-bedded) of the subgroup sharply overlies the Lower Sinakumbe Group.

The unit consists almost entirely of quartz-rich sandstone, mostly quartz arenite, with subordinate mudclast breccia. However, in outcrop, the sandstone has the appearance of a quartzite, which led Denman and Money (1970) to name the formation 'Quartzite Formation'. "Quartzite" is a long-standing field term for a metamorphosed siliceous sediment, so well cemented by silica that it breaks across quartz grains. The terms orthoquartzite and metaquartzite have been used for unmetamorphosed and metamorphosed quartz-rich sandstones, respectively (Pettijohn et al., 1972). The term quartz arenite is preferred here to quartzite because it is now widely used in the sedimentological literature (Chandler, 1988). Quartz arenite, is composed of 80% or more quartz, chert and quartzite grains and is usually almost devoid of muddy matrix (Chandler, 1988). However, most authors restrict the term to 95% or more of quartz (e.g. Pettijohn et al. 1972). In places, the arenite is arkosic. The mudclast breccia is dominated by intrabasinal fragments, i.e. the mudclasts that are similar to mudrock lithofacies of the Lower Sinakumbe Group. The formation consists of two lithofacies: quartz arenite predominates and mudclast breccia occurs locally (Table 4.2).

4.2.3.2 Quartz arenite (Quartzose sandstone) lithofacies (A_q)

The A_q lithofacies is generally medium light grey with variations to light olive grey, greenish grey, brownish grey, pinkish grey and pale brown. Pale red and pinkish brown mottling due to the presence of feldspar is common throughout. Weathered surfaces are yellowish brown to blackish red.

The lithofacies occurs as lenticular (Fig. 4.14a), tabular (Fig. 4.14b, c) and amalgamated beds ranging from 5 cm to over 5 m thick (Fig. 4.14a, c, d, e). Some of the units are sheared and commonly are associated with the mudclast lithofacies (Fig. 4.14e). Some of the lenticular beds (up to 80 cm thick) show spheroidal weathering (Fig. 4.14f). It is thinly to very thickly bedded and internally massive or stratified. On this basis, the predominant depositional facies (in Miall's 1978, terminology) is massive sandstone (Sm, Fig. 4.14d-f) with subordinate trough cross-stratified sandstone (St, Fig. 4.15a, b), horizontally bedded sandstone (Sh, Fig. 4.15c) and planar cross-stratified sandstone (Sp, Fig. 4.15d) units. St, Sh and Sp are usually poorly defined, mainly due to poor outcrop exposure. Normally graded sandstone units (Sg) are also present. The arenite is generally medium to very coarse-grained and commonly granular to pebbly (up to 7 mm) and locally conglomeratic. However, some very fine- to fine-grained arenite is present as well-sorted beds from less than a centimetre up to 15 cm thick, in units with a maximum thickness of 0.8 m. A typical exposure shows a sharp contact overlain by pebbly or very coarse-grained, massive arenite that grades into well developed or crudely stratified beds that are in turn overlain by horizontally stratified beds. These units usually occur in poorly developed fining upward cycles. Soft sediment deformation is uncommon, but flexures have been observed in the quartz arenite.

Hand specimens show a compact, strongly indurated rock that is composed of moderately sorted (coarser varieties, Fig. 4.15e) to well sorted (finer varieties, Fig. 4.15f) subrounded to subangular grains. The larger grains are more rounded. Low matrix (<5 %) and abundant quartz (>80%) qualifies the rock as a quartz arenite. The main cement appears to be silica (recrystallisation) though brown hematite grain coatings are present. Sedimentary structures visible in hand specimens include normal grading and horizontal lamination (Fig. 4.15f). Feldspar, mainly pink-feldspar (8-15 %, Fig. 4.15e, f), and dark grey mudrock fragments are present.

In thin section, the quartz arenite generally consists of framework-supported quartz and feldspar grains and minor rock fragments (Fig. 4.16a, b, c, d). The framework grains

Fig. 4.14 Quartz arenite lithofacies

Upper Sinakumbe Group

a: Lenticular, trough cross-bedded quartz arenite beds that amalgamate laterally. The arenite of the Upper Sinakumbe Group sharply (arrow) overlies Lower Sinakumbe Group. Type section, Muzuma River Section 4, Nkandabwe map area. Person for scale.

b: Sharp disconformable contact (hammer head) between tabular, generally massive quartz arenite lithofacies and matrix-supported, crudely bedded conglomerate of the Lower Sinakumbe Group, Sikalamba River Section 6, Nkandabwe map area. Hammer is 34 cm.

c: Tabular to lenticular, thinly to thickly bedded, jointed quartz arenite. Muzuma River Section 4, Nkandabwe map area.

d: Typical massive quartz arenite lithofacies, commonly occurring as amalgamated to irregular units. Muzuma River Section 4, Nkandabwe map area.

e: Sheared and deformed quartz arenite in irregular beds, usually associated with mudclast lithofacies. Muzuma River Section 4, Nkandabwe map area.

f: Thickly bedded massive quartz arenite. Splitting at edges of beds resembles spheroidal weathering. Kazinze River Section 4, Nkandabwe map area.

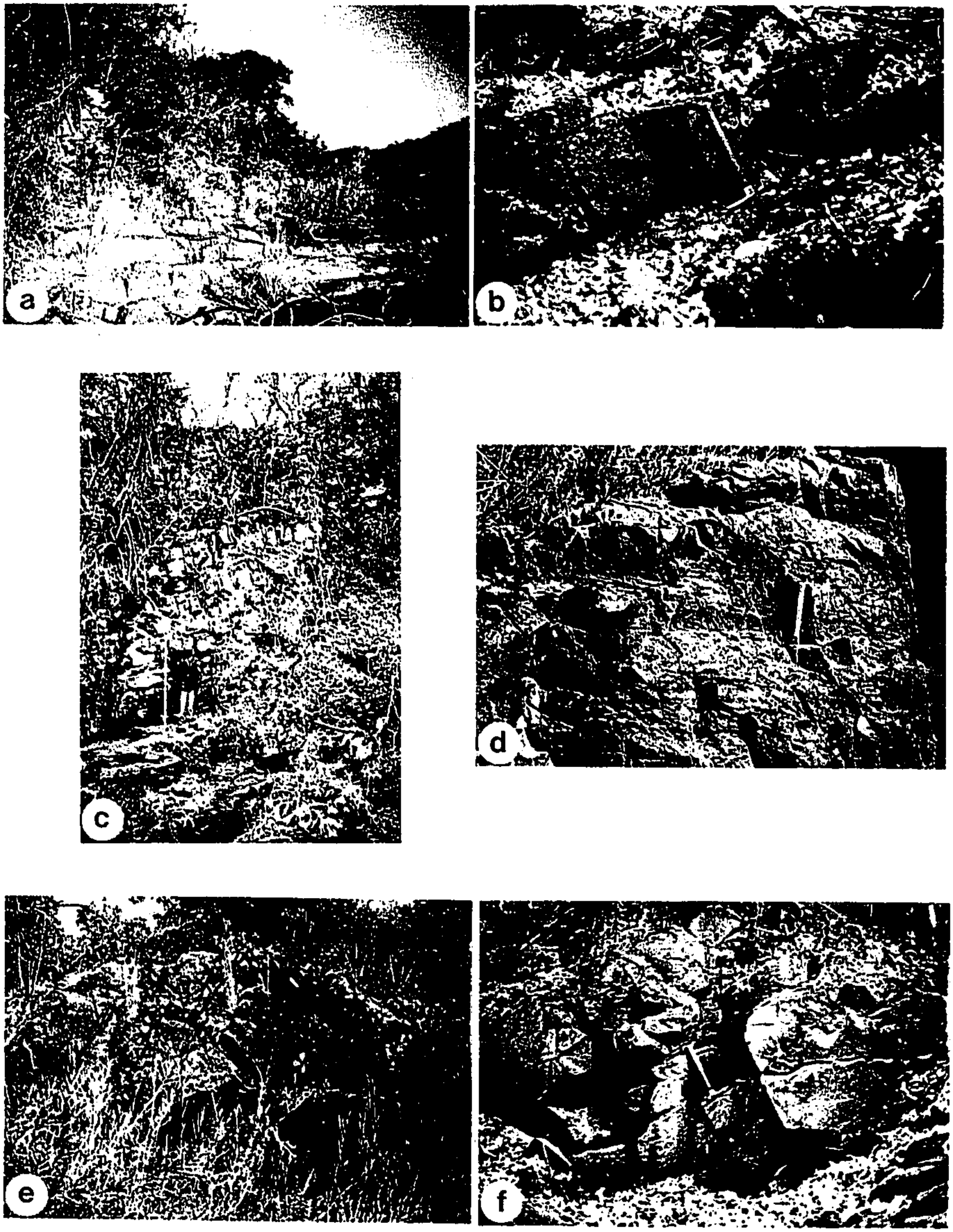
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Fig. 4.15 Quartz arenite lithofacies. Type section,
Muzuma River Section 4, Nkandabwe map area

Upper Sinakumbe Group

a: Large-scale trough cross-beds in feldspathic arenite, with stratification defined by grain size variation. Hammer is 34 cm.

b: Medium to small trough cross-beds, quartz arenite lithofacies. Marker pen is 13.7 cm.

c: Horizontally laminated, quartz arenite lithofacies.

d: Planar cross-beds, quartz arenite lithofacies.

e: Polished slabs of massive quartz arenite. Feldspar (yellow) comprises up to 15% of the stained slab. Scale in cm.

f: Polished slabs of very fine-grained, horizontally to small-scale cross-laminated quartz arenite; the bright patch towards top of right sample is calcareous. Notice feldspar grains (yellow) in the patch and to the right. Scale in cm.

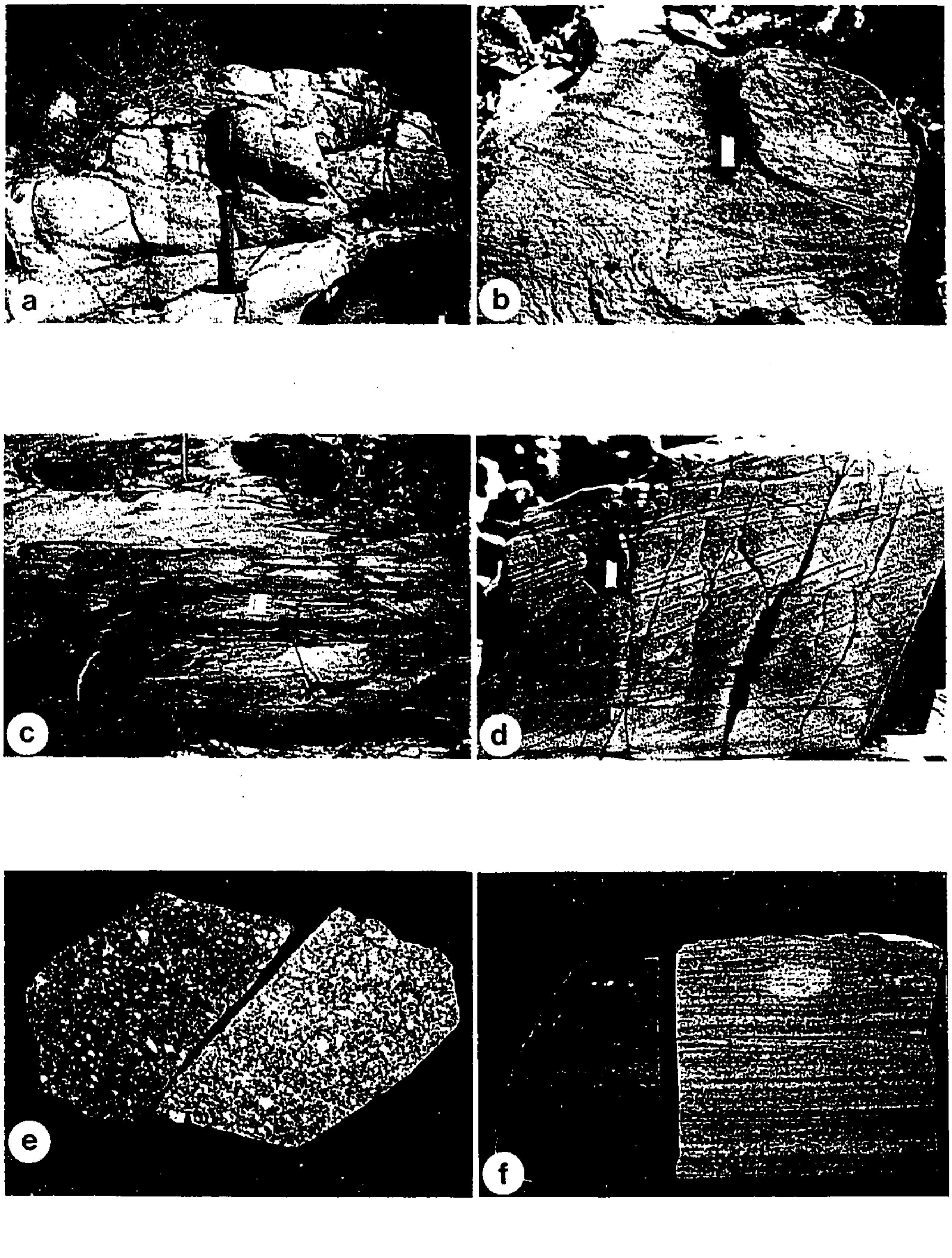
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Fig. 4.16 Quartz arenite lithofacies

Upper Sinakumbe Group

a: Photomicrograph (crossed nicols) showing quartz-feldspar-rock fragment-supported quartz arenite from Fig. 4.13e. The mottled grains are mainly sericitised feldspar (e.g. the large grain) and minor siltstone fragments. Type section, Muzuma River Section 4, Nkandabwe map area. Long side of photograph is 4.5 mm.

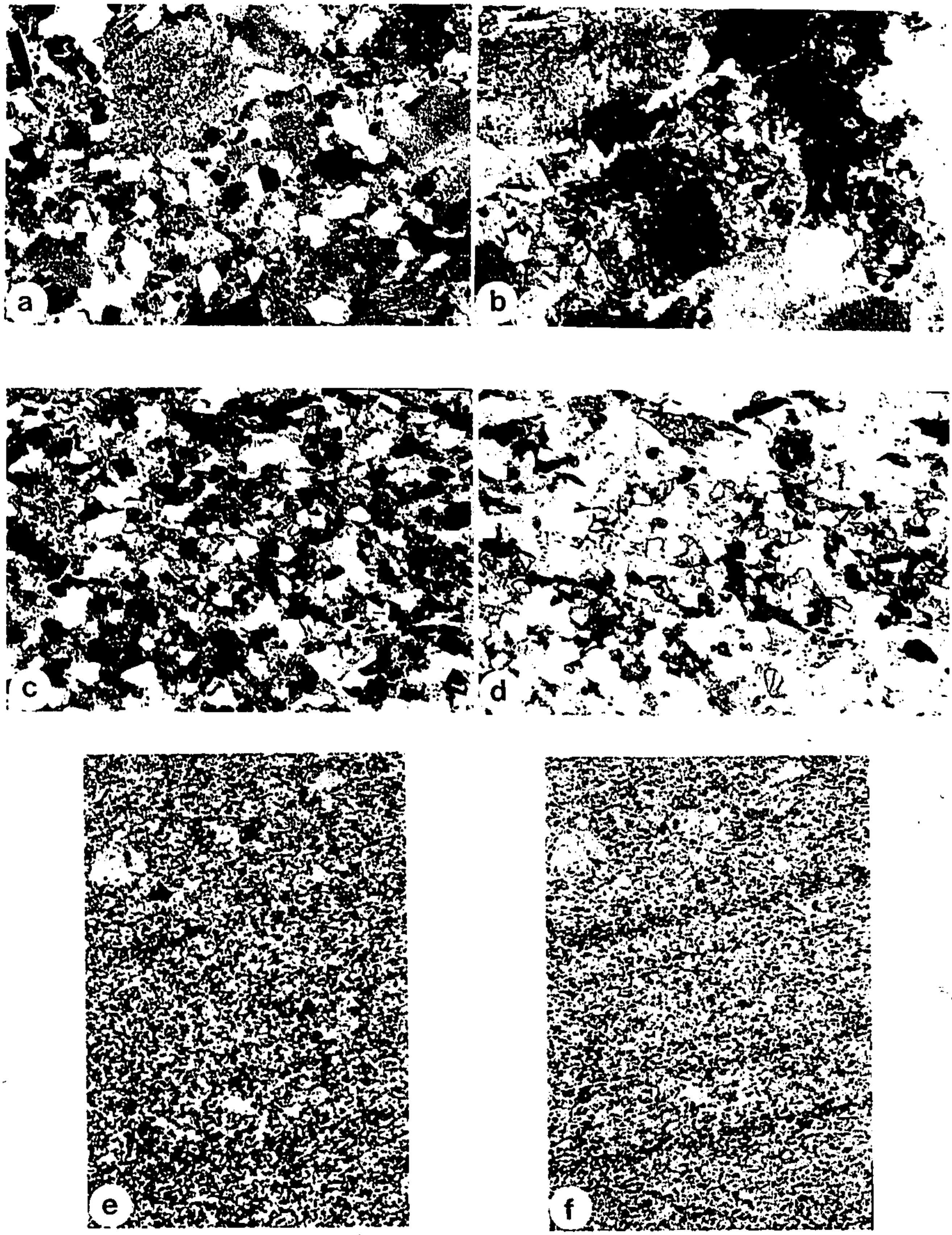
b: Photomicrograph (crossed nicols) showing microcline partly epidotised (yellowish orange/pink); above is another partly sericitised. Type section, Muzuma River Section 4, Nkandabwe map area. Long side of photograph is 0.8 mm.

c: Photomicrograph (crossed nicols) showing texture of the fine- to medium-grained quartz arenite. The opaque minerals are mostly heavy minerals, and the yellowish orange/pink is epidote. Type section, Muzuma River Section 4, Nkandabwe map area. Long side of photograph is 2.1 mm.

d: Same area shown in (c), in plane polarized light. Notice that one of the heavy minerals is garnet (e.g. arrow).

e: Photomicrograph (crossed nicols) of quartz arenite showing lamination defined by concentration of heavy minerals. Type section, Muzuma River Section 4, Nkandabwe map area. Long side of photograph is 11 mm.

f: Same area shown in (e), in plane polarized light. Type section, Muzuma River Section 4, Nkandabwe map area. Long side of photograph is 11 mm.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are subrounded to subangular and the larger ones are more rounded. The arenite is moderately well sorted with sphericity between 0.50 and 0.85. Grains show sutured to concavo-convex contacts. The equidimensional nature of the grains precludes expression of oriented fabric (Fig. 4.16c, d). Compaction is indicated by sutured contacts and bent micas (muscovites). Clay matrix from squashed rock fragments and altered feldspar is present in trace to minor amounts. Calcite cement is present locally.

Monocrystalline and polycrystalline quartz grains predominate (>80%). Grains of quartzite, stretched polycrystalline quartz and recrystallized quartz with planar contacts are also present. The quartz is commonly strained, with numerous vacuoles and strongly undulose extinction. The polycrystalline quartz shows sutured contacts. Feldspar is the second most abundant mineral (1-15%) (Fig. 4.16b), occurring as twinned and untwinned orthoclase, microcline, microperthite, perthite and plagioclase. Microcline with characteristic hatched twinning is the most abundant, and occurs as large subangular pebbles and granules, some with quartz and mica (biotite) inclusions. Plagioclase grains are usually smaller, and show both albite and Carlsbad twinning. Some of the feldspars are altered to sericite (Fig. 4.16a, b). One microcline grain showed concentration of epidote crystals along twin lamellae, suggesting that it was partly epidotised (Fig. 4.16b).

Quartz-rich (>95 %) quartzite and mudrock are the predominant rock fragments, but together form less than 5 % of the rock. Most of the fragments have been altered and disintegrated, giving a pseudo-matrix that occludes porosity adjacent to the original fragments. The predominant mica is muscovite (< 1%); biotite and chlorite occur in trace amounts. Chlorite in places appears to be an alteration product of biotite. The heavy mineral suite includes garnet (predominant), epidote (Fig. 4.16c, d), zircon, sphene and iron oxides (e.g. ilmenite). The matrix (< 5%) consists mostly of decomposed rock fragments and feldspar, resulting in pseudo- and epi-matrix, respectively, and with calcite cement making up to 4% of the rock. The feldspar contribution to the matrix appears to exceed that of the rock fragments. If this is typical, the amount of rock fragments in this lithotype is minimal. Quartz overgrowths are minor and are seen in close association with calcite cement where they appear to have been terminated by calcite cementation. Calcite forms 'poikilotopic' texture and replaces feldspar, and seems to replace some quartz grains.

Iron oxide coating is also common. These have reduced interparticle porosity considerably (<2 %). Some dissolution of feldspar has increased the secondary porosity slightly.

Illite and chlorite, the only clay minerals (XRD), occur in minor or equal amounts relative to other clay-sized minerals such as quartz (abundant) and potassium feldspar (minor). In the fine-grained and horizontally laminated quartz arenite (Fig. 4.16e, f), illite is the major clay mineral, with minor amounts of chlorite. Quartz (minor to abundant), albite (minor) and potassium feldspar (minor) are also present. Calcite occurs in trace amounts.

Overall, the quartz arenite is texturally submature to mature, as indicated by sorting and roundness. The high quartz content (80-98 %) qualifies the sandstone as a quartz arenite with subordinate arkoses and litharenites.

4.2.3.3 Mudclast breccia lithofacies (B_m)

This lithofacies consists of intrabasinal, elongate, angular mudrock clasts embedded in gritty to pebbly quartz arenite. The mudrock clasts are similar to the mudrock lithofacies described earlier in the Lower Sinakumbe Group. The clasts can be over 20 cm long. Other fragments include fine-grained quartz arenite.

The lithofacies is exposed in Muzuma River Section 4 and Kazinze (Unnamed Stream) Section 4. In both sections the breccia occurs as very irregular amalgamated beds that intertongue with the massive gritty quartz arenite and wedge out laterally. Together with the enclosing quartz arenite, the unit reaches a maximum thickness of 15 m in the Muzuma River but only 70 cm are recorded in the Unnamed Stream Section off the Kazinze River. In the former, the unit extends over 30 m along strike before wedging out in opposite directions. A 1.7 m unit at the base of the 15 m mudclast breccia has a lateral extent of 11 m. The mudclast breccia is crudely horizontally stratified, with clasts parallel to bedding, or massive, with the mudclasts randomly oriented in pebbly quartz arenite (Fig. 4.17a, b). Some of the mudclasts are horizontally laminated (Fig. 4.17c). The matrix shows crude inverse grading from very fine-grained to very coarse-grained (pebbly) at the top and the mudclasts increase from <30 to over 60 % from base to top.

In hand specimen (Fig. 4.17d, e), both poorly sorted and well sorted matrix are

Fig. 4.17 Mudclast breccia lithofacies. Type section, Muzuma River Section 4, Nkandabwe map area

Upper Sinakumbe Group

a: Mudclast breccia lithofacies, sheared and deformed. Hammer is 34 cm.

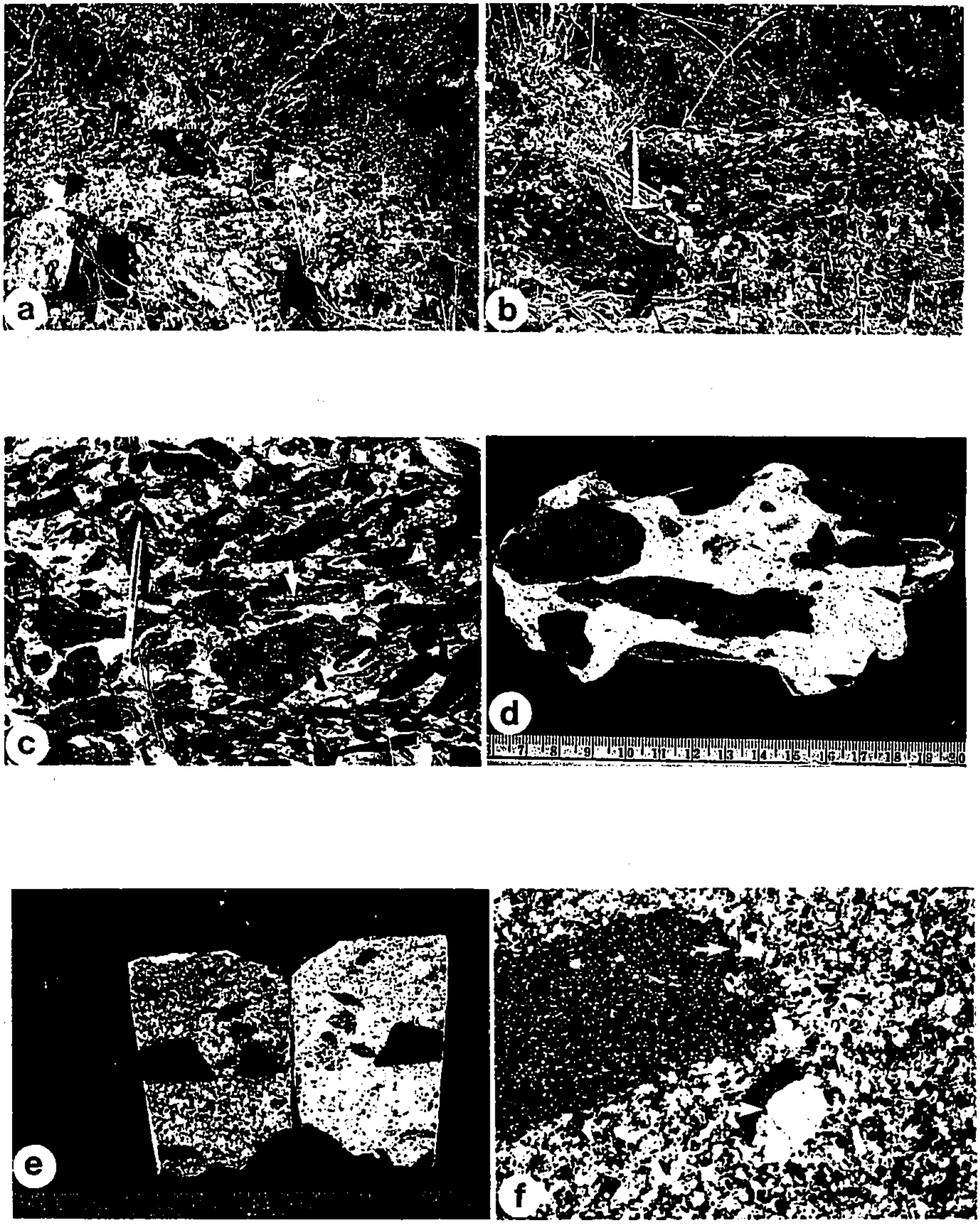
b: Close-up view of mudclast breccia lithofacies in (a) above, showing an irregular bed, of limited extent, embedded in quartz arenite lithofacies.

c: Detail of (b) above. Notice the lamination within the mudclast (arrow) indicating that the mudclasts were well consolidated before transport. Pen is 14 cm.

d: Polished sample showing irregular, elongate, massive mudclasts in quartz arenite matrix. Scale in cm.

e: Polished and stained sample showing mudclasts (large one angular) in K-feldspar-rich quartz arenite. Scale in cm.

f: Photomicrograph (crossed nicols) showing silty mudstone fragment in sericite-rich matrix. A fracture (arrow) divides this zone from the calcite-cemented zone to the right. Long side of photograph is 13.3 mm.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evident. The former consists of very fine sand to pebbles, whereas the latter is fine- to medium-grained sand. In one specimen, the elongate large and small mudclasts show preferred orientation parallel to bedding. Pebbles in the matrix consist of subrounded to rounded quartz, pink-feldspar, and mudstone and sandstone fragments.

In thin section, the poorly sorted matrix consists mainly of subangular to subrounded (and some angular) quartz, feldspar and rock fragments (mudstone and fine-grained sandstone) (Fig. 4.17f). Granules are predominant (~ 2 to 3 mm up to 20%) set in a framework-supported (concavo-convex grain contacts) quartz-rich (80%) sandstone with grain size averaging 0.2 mm. Sericite and epidote, resulting from feldspar alteration, as well as squashed rock fragments occupy the interparticle porosity. The moderately well-sorted matrix consists of quartz, feldspar and minor rock fragments set in either calcite-rich or sericite-, hematite- and epidote-rich clay matrix. In the calcite-rich zones, grains appear to float, giving a 'poikilotopic' texture. In one thin section a fracture that post-dates sedimentation controlled the calcite cementation as it separates the calcite zone and the sericite zone (Fig. 4.17f). As epidote and sericite are also present in calcite zones, it seems reasonable that calcite was a later diagenetic feature.

The mudrock clasts are the predominant fragments (5-80%). The clasts are randomly oriented in the quartz arenite, but some show a preferred orientation, with long axes parallel to or oblique to bedding. The dusky brown to blackish red mudrock clasts consist of clay to coarse silt (0.05 mm) with scattered quartz and feldspar grains up to 0.2 mm in diameter and averaging 0.02 mm. Internally, the clasts are either massive or horizontally laminated with elongate grains (micas especially) aligned parallel to bedding. The clay matrix contains hematite.

Quartz occurs as monocrystalline and polycrystalline grains in the quartz arenite. The polycrystalline grains show undulatory to concavo-convex contacts, suggesting recrystallized metamorphic and/or stretched metamorphic source rocks. The presence of chert fragments was confirmed by SEM. Feldspars include microcline, orthoclase and plagioclase.

Heavy minerals present are epidote, zircon and apatite. Epidote occurs in association with albite and potassium feldspar. Aggregates of epidote in feldspar clasts are common. Iron oxides are titanium-rich, and are probably rutile or ilmenite.

XRD analysis indicates that kaolinite and illite are predominant, with traces of mixed-layer clays (illite/smectite and probably chlorite/smectite). Also present are clay-sized grains of quartz (minor), plagioclase (minor) and potassium feldspar (trace to minor).

In modal composition, the mudclast breccia lithofacies contains 5-80% mudclasts in a matrix composed of 60-65% quartz, 10-15% feldspar, 5-15% rock fragments, 2-3% mica, 15-20% sericite, 2-5% epidote, hematite, and calcite cement.

4.2.3.4 Lithofacies interpretation

The **quartz arenite lithofacies** shows a wide variety of sedimentary structures and bedding, which is an indication of variability in the environment of deposition (Table 4.4). The characteristics of the lithofacies suggest that the Upper Sinakumbe Group is a braided river deposit. The range of sedimentary structures may be present within individual exposures, reflecting the changes in depositional facies, and hence local complexity in fluviatile style. The trough cross-stratified units are interpreted as sinuous crested dunes, whereas the overlying horizontally stratified beds are interpreted as upper flow regime plane beds. The small-scale trough cross-strata reflect the development of sinuous-crested in-channel dunes formed at a subsequent lower flood stage (cf. Hartley et al., 1992). The coarse nature of the lithofacies, and low content of fine sediments, suggest that they were deposited in braided streams. Minor occurrences of fine-grained sediments reflect the very low preservation potential of such sediments in braided-stream depositional environments (Cant, 1978; Smith, 1980; Miall, 1982).

The **mudclast breccia lithofacies** is a product of penecontemporaneous erosion. Its local occurrence suggests stream bank failure and slumping (Table 4.4) in a manner similar to that described by Rust and Jones (1987). Bank failure is a common phenomenon in rivers, and is generally initiated by subaqueous flow at the base of an oversteepened bank, followed by complete bank failure by shear along one or more discrete curved failure surfaces (Turnbull et al., 1966). Failure occurs mainly at flood stage, because of bank steepening by river-bed scour and because water saturation of the bank sediments increases their density and decreases the shear strength, due to elevated pore pressure (Laury, 1971).

Table 4.4 Summary of characteristics and interpretation of Upper Sinakumbe Group lithofacies

LITHOFACIES	GRAIN SIZE / SORTING	TEXTURE	MINERALOGY AND OTHER COMPONENTS	BEDDING AND SEDIMENTARY STRUCTURES	GEOMETRY / NATURE OF BOUNDING SURFACES / THICKNESS	DEPOSITIONAL ENVIRONMENT
Quartz arenite (A_g)	fine to pebbly sand; poorly sorted	matrix- to framework -supported	Detrital grains: quartz (80-98%), feldspar (microcline, orthoclase, plagioclase, microperthite, perthite -5-20%), rock fragments (~5%), muscovite, biotite, chlorite. Heavy and opaque minerals: garnet, epidote, zircon, sphene, iron oxides (e.g. ilmenite). Clay minerals: illite. Cement: calcite, hematite	massive (Sm) with irregular beds/ amalgamated beds; may be graded, small- to medium-scale trough cross-stratified cosets and isolated bed forms (St), reactivation surfaces with minor bedforms, beds may be graded, horizontally stratified (Sh)	wedges/tabular, poorly defined surfaces lenticular, concave-up bases and poorly defined tops; tabular, generally flat surfaces (top and base); beds 5cm to over 5m thick	in-channel braided stream deposit in-channel dunes of braided streams longitudinal bars of braided streams
Mudclast breccia (B_m)	Matrix: fine sand to pebbles; poorly sorted Coarse fraction (Clasts): granules to cobbles; poorly sorted	matrix-supported pebbles and cobbles	Detrital grains: rock fragments (mudrock and finer-grained sandstone - 5-80%), quartz, feldspar (microcline, orthoclase, plagioclase), muscovite, biotite, chlorite. Heavy and opaque minerals: garnet, epidote, ilmenite, rutile. Clay minerals: kaolinite, illite, mixed layer clays (I/S & C/S). Cement: calcite, hematite; see text for matrix composition, p. 107	massive; bedding crude chaotic	wedge? very irregular beds; units up 15m thick	bank failure of braided stream (slump deposit)

The falling flood stage exacerbates this situation by withdrawing the support of water in the channel, and by concentrating bank seepage along potential surfaces of failure (Costa and Baker, 1981).

4.2.3.5 Facies analysis

The quartz arenite lithofacies is an important component of the Upper Sinakumbe Group (over 90%), consisting of medium-grained to pebbly sandstone beds that are generally olive grey and associated with subordinate fine-grained lithotypes. The poor exposure does not allow detailed analysis of facies assemblages, and hence no unique general sequence for the subgroup is apparent. However, many authors have also pointed out the difficulty in establishing a characteristic sequence for braided-stream systems (Ramos et al., 1986). The mudclast breccia, interpreted as slump deposits due to overbank failure, occurs within the braided stream quartz arenite. On this basis, the two lithofacies are grouped together as the **quartz arenite facies assemblage.**

The quartz arenite facies assemblage occurs widely in the Muzuma-Sikalamba Corridor, and in the southwestern part of the Nkandabwe map area (see Fig. 5.1, p. 302), but is rare in the main basin (Fig. 2.2a, b, c, d) In the corridor, the assemblage is over 150 m thick (Fig. 4.18), but less than 25 m thick in the southwestern part. The facies changes are not abrupt as in the Lower Sinakumbe Group, but units are laterally persistent, continuous and commonly in the form of amalgamated beds and units (Fig. 4.19). Palaeocurrents directed to the southwest (e.g. Fig. 4.18, 4.19d) suggest that palaeoslope was generally perpendicular to the palaeoslope of the alluvial fan system of the Lower Sinakumbe Group. The depositional facies (massive arenites (Sm), trough cross-stratified arenite (St), horizontally bedded arenite (Sh) with subordinate normal graded arenite (Sg) and poorly defined planar cross-bedded arenite (Sp)), general coarseness and immaturity (locally arkosic arenite), and minor fine-grained sediments in the assemblage are consistent with braided stream deposition. The 15-metre-thick sequence of mudclast breccia lithofacies is easily accommodated in a braided system as a result of bank failure, which is a common feature in braided streams.

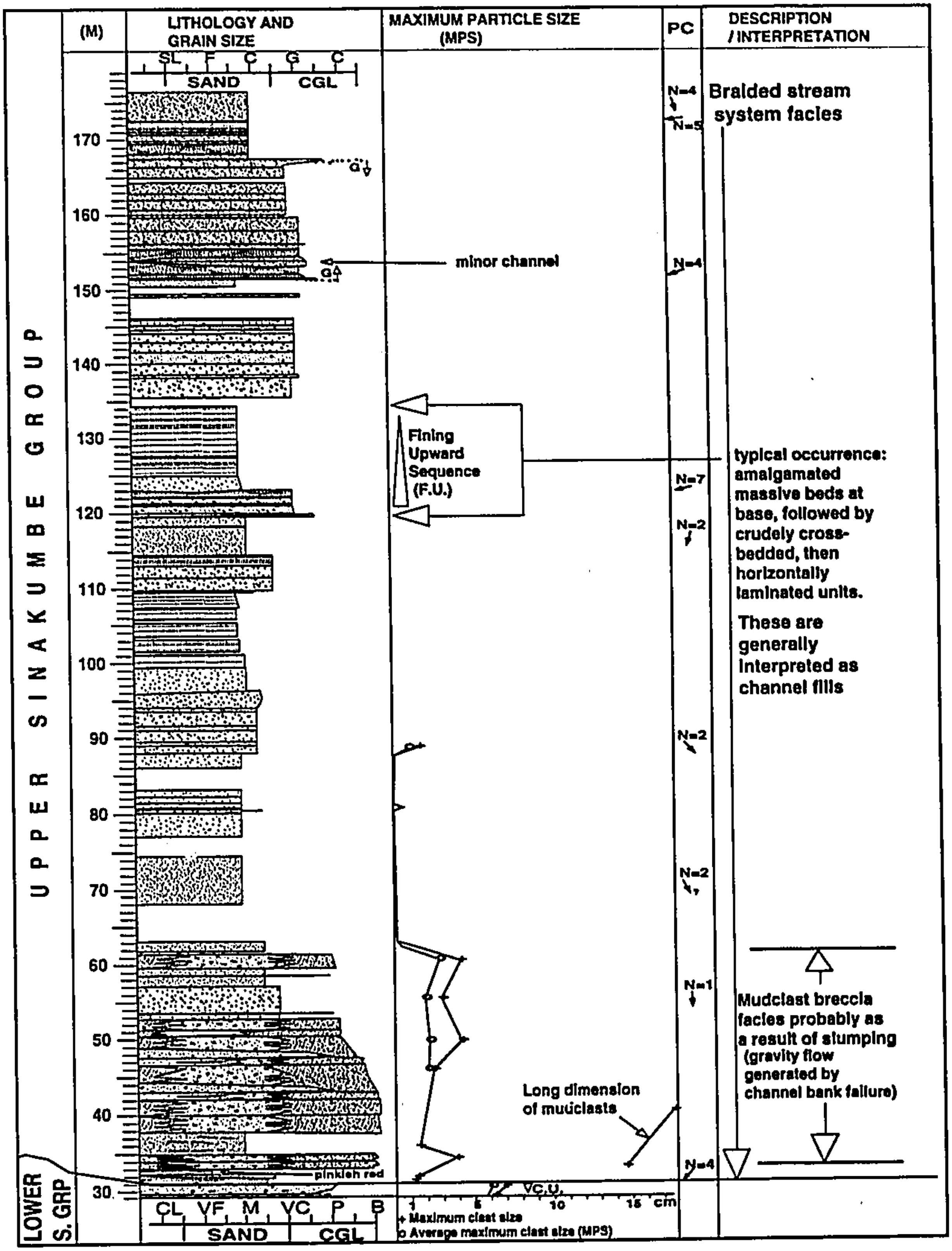


Fig. 4.18 Representative detailed log of the Upper Sinakumbe Group underlain sharply by Lower Sinakumbe Group, type section, Muzuma River Section 4, Nkandabwe area, mid-Zambezi Valley Basin. PC = palaeocurrent, N = number of readings, M = Metres. See Fig. 4.0 for abbreviations.

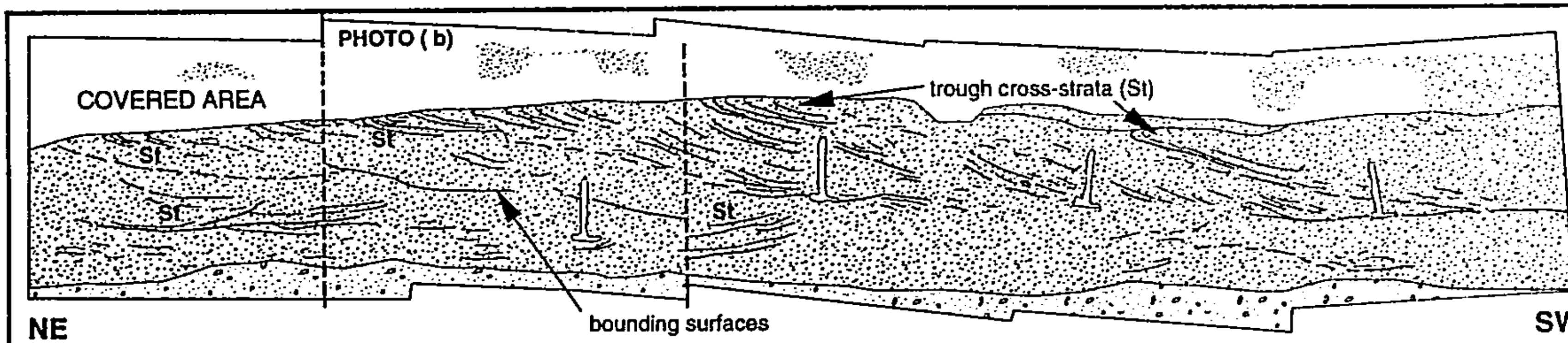
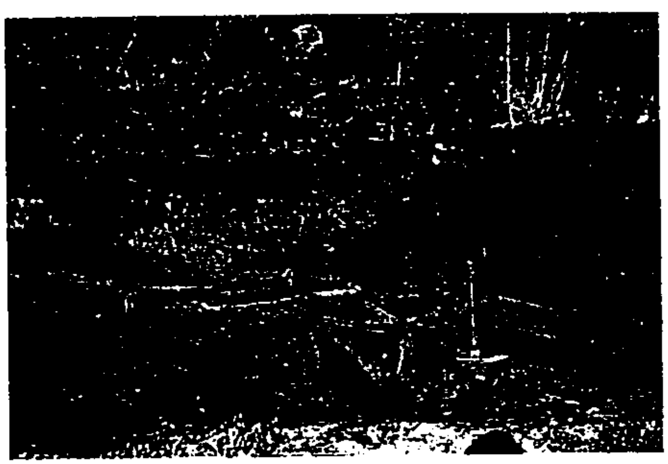


Fig. 4.19 Lateral variation in sedimentary structures in the Upper Sinakumbe Group, type area, Muzuma River Section 4, Nkandabwe map area.

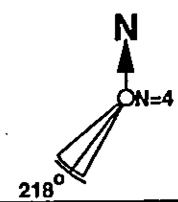
a) Profile drawn from photomosaic shows quartz arenite lithofacies of the Upper Sinakumbe Group (USG) sharply underlain by matrix-supported conglomerate lithofacies of the Lower Sinakumbe Group (LSG). Hammer outlines are 34 cm long.

QUARTZ ARENITE (USG) MATRIX-SUPPORTED CONGLOMERATE (LSG)



b) Representative photograph showing the trough cross-stratified coarse- to very coarse-grained (locally pebbly) quartz arenite. Hammer is 34 m long.

c) Distance view of laterally continuous, lenticular, massive, coarse-grained to pebbly quartz arenite.



d) Paleocurrent measurements from (a) indicate transport towards the southwest (4 readings)

4.3 LOWER KAROO GROUP

The Lower Karoo Group consists mainly of fine-grained sediments (mudstones, siltstones and sandstones) with subordinate conglomerates and calcilutites. The group consists of three formations; the Siankondobo Sandstone, Gwembe Coal and the Madumabisa Mudstone (Fig. 4.0).

4.3.1 SIANKONDOBO SANDSTONE FORMATION

4.3.1.1 General Remarks

The formation is represented by a succession of diamictite/conglomerate, varve-like sediments, and horizontally stratified, fine-grained light greyish white sandstone and cross-laminated, grey siltstone (brown weathered surfaces). These are overlain by fine- to medium-grained buff to white, massive feldspathic sandstone that occurs widely in the Nkandabwe map area, and constitutes the major part of the Siankondobo Sandstone Formation. Petrologically, Siankondobo Sandstone beds represent immature to sub-mature wacke-type sandstones with the framework grains generally constituting less than 75% of the rock.

The generalised stratigraphic column of the formation is shown in Fig. 4.20. Five lithofacies (Table 4.2) are distinguished on the bases of lithology and sedimentary structures, namely (i) diamictite, (ii) conglomerate, (iii) silty mudstone and siltstone, (iv) cross-laminated siltstone and sandstone, and (v) massive sandstone.

4.3.1.2 Diamictite lithofacies (D)

As indicated in Chapter II, previous workers regarded tillite to be the basal unit of the Siankondobo Sandstone Formation. However, features indicative of a "tillite" are absent and therefore a non-genetic term is more appropriate. Although terms such as mixtite have been used, diamictite is appropriate and used here because it has been used more commonly in recent sedimentological literature (Eyles and Eyles, 1992).

The diamictite lithofacies directly overlies the basement complex (Fig. 4.21a-f). However, in the Nkandabwe area at Ntole River Section 2, although the actual contact is

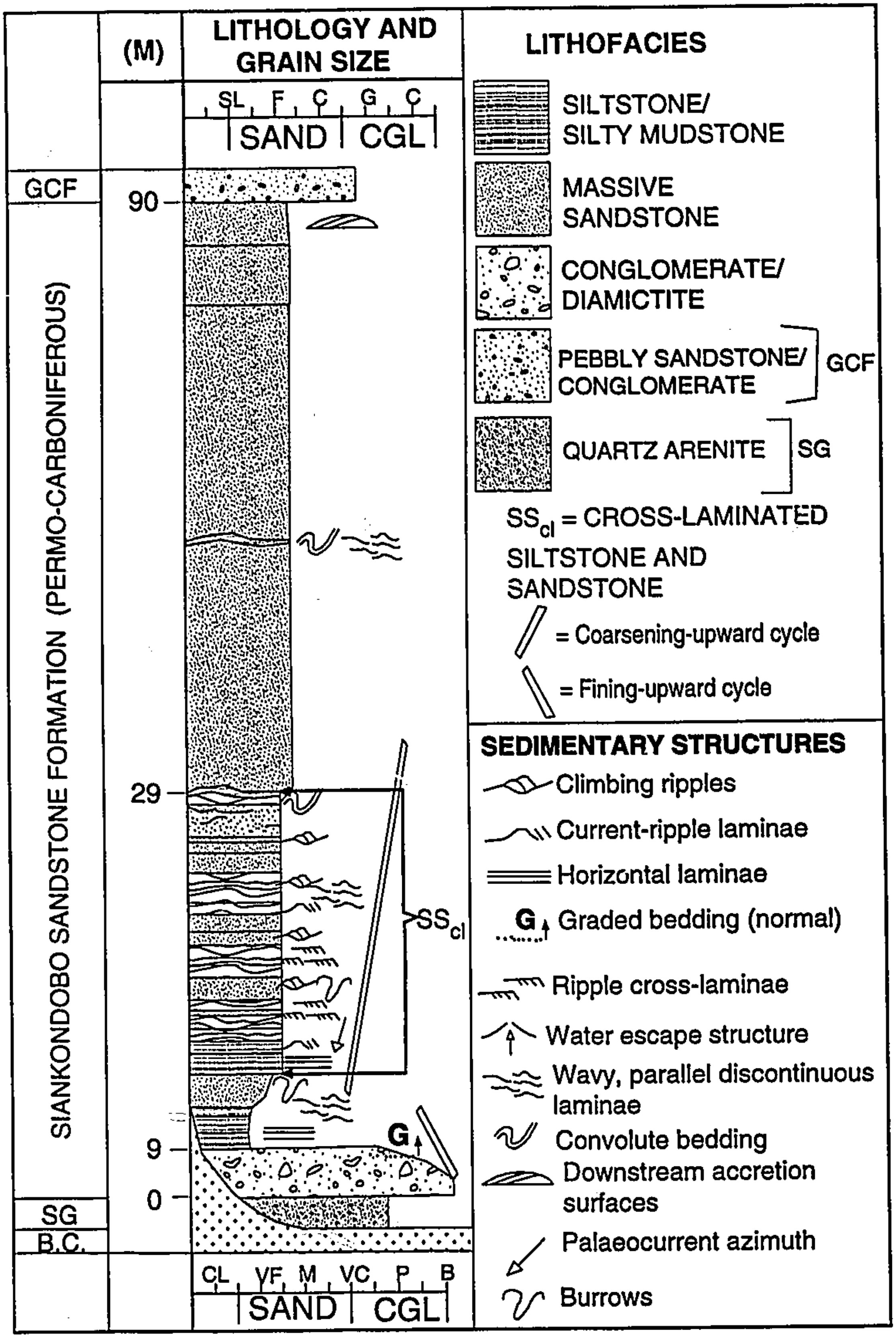


Fig. 4.20 Generalized stratigraphic column of Siankondobo Sandstone Formation, mid-Zambezi Valley, southern Zambia (variable scale). See Fig. 4.0 for abbreviations.

Fig. 4.21 Diamictite lithofacies

Siankondobo Sandstone Formation

a: Subrounded lithic fragment in laminated siltstone/sandstone. Kazinze River Section 2c, Siankondobo map area.

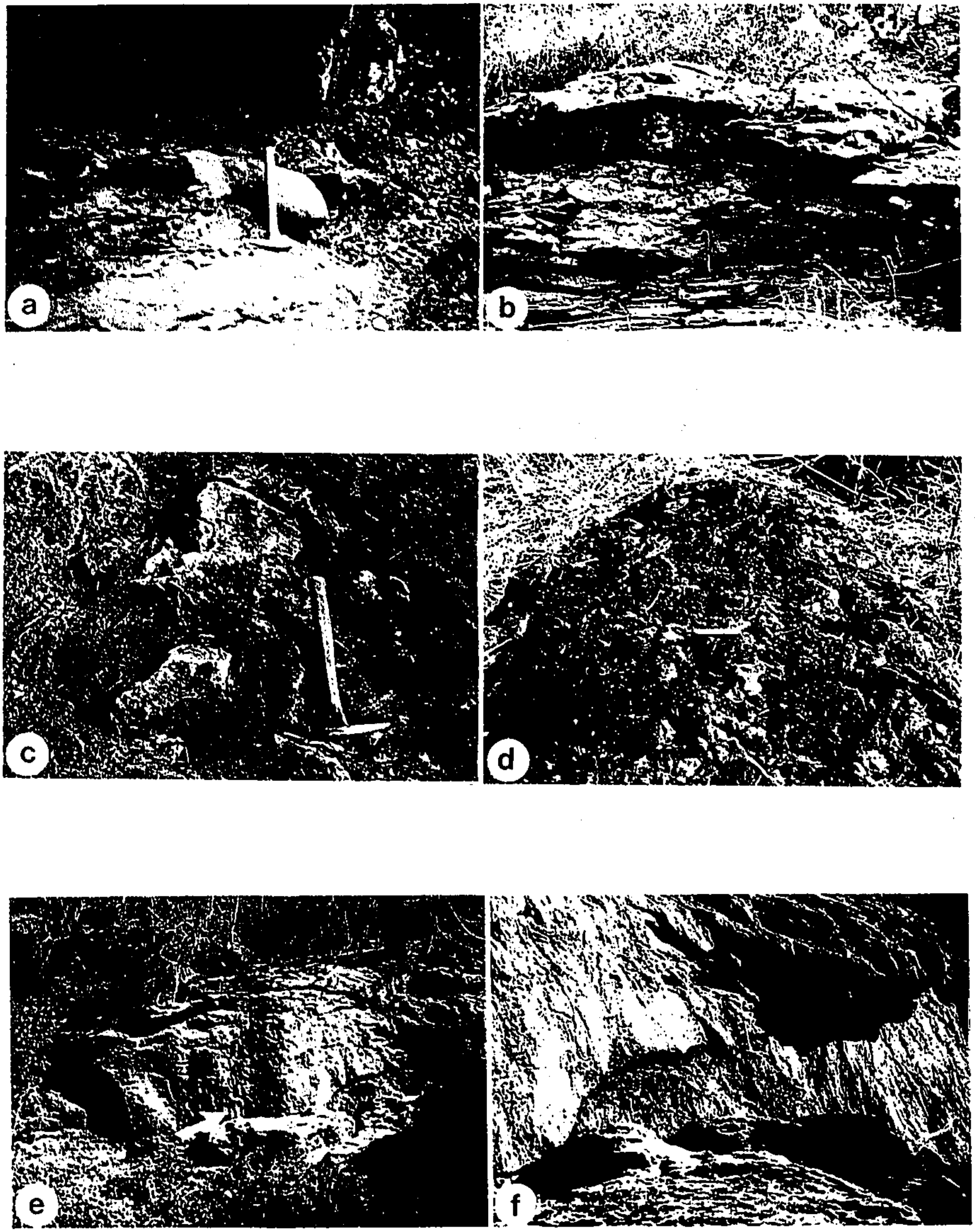
b: Irregular diamictite bed (0-80 cm) unconformably overlying the basement schist (contact at hammer). Kazinze River Section 3, Siankondobo map area. Hammer is 34 cm.

c: Angular quartz vein fragments in diamictite matrix, surface of diamictite bed in (b) above.

d: Angular quartz vein fragments (mostly) in more schistose (deformed) diamictitic matrix. Floor of Kazinze River, Siankondobo map area. Pen is 16 cm.

e: Diamictite in channelized body up to 6 m thick, containing cobbles. Along Kazinze River, Siankondobo map area. Hammer (arrow) for scale.

f: Irregular unconformity (at hammer) between the diamictite unit and the basement schist; basement surface shows no glacial effects. Along Kazinze River, Siankondobo map area.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concealed, the diamictite overlies the Sinakumbe Group. In a small stream entering Kazinze River (Kazinze Section 2c), Siankondobo area, a 0.6 m thick unit of internally thinly laminated siltstone and very fine-grained sandstone contains scattered rounded fragments up to boulder-size (Fig. 4.21a). The clasts are mainly extrabasinal in origin. The enclosing layers are bent down beneath the clasts. This unit is overlain by cross-laminated siltstone and sandstone lithofacies (Fig. 4.21a). About 500 m to the northeast, at an equivalent stratigraphic level, is a thick to very thick unit (0.2 to 1.1 m) that contains scattered angular vein quartz fragments (pebbles to boulders) in a mica-rich fine-grained sandstone to diamictitic matrix (Fig. 4.21b, c). Because of their stratigraphic positions, these units are presumed to be equivalent and are included in the Siankondobo Sandstone Formation in this thesis. The only difference is that the 1.1 m unit appears to have been faulted against the basement and is overlain by Gwembe Coal Formation strata. On the floor of the Kazinze River, is a flat-lying outcrop (Fig. 4.21d) that belongs to the 1.1 m unit above. This locality has been referred to as one of the 'tillite' sites in the mid-Zambezi Valley Basin in previous literature of the geological survey. The outcrop was recently considered to be the basal part of the Maamba Sandstone Member of the Gwembe Coal Formation (Money et al., 1974), with two types of mixtite; a sand-matrix, micaceous, non-carbonaceous mixtite with subangular schist fragments (~ 25 cm in diameter) and a carbonaceous mixtite with subangular sparse quartz pebbles above (i.e. the 1.1 m unit). The unit is underlain by deformed and folded phyllite, in places grading into schist, with abundant quartz veins. The phyllite is compositionally similar to the silty mudstone and siltstone lithofacies of the Siankondobo Sandstone Formation and appears to have resulted from faulting of the formation against the basement. This was the main reason for previously assigning it to the basal Gwembe Coal Formation; however, the general setting suggests that it belongs instead to the Siankondobo Sandstone Formation and is described here as the basal part of the latter. The quartz veins in the phyllite are elongate parallel to the foliation. The 1.1 m unit wedges out to the northeast and then reappears with a maximum thickness of up to 6 m (Fig. 4.21e-f). The thickest part forms a channelized body (Fig. 4.21d) that rests on steeply dipping basement schist and wedges out laterally in opposite directions. The basal contact is sharp and irregular (Fig. 4.21f). According to

Rust (1990, pers. comm.), there is no evidence on the basement surface beneath the 6 m unit to suggest glacial activity.

In the Nkandabwe area, the Southwest Section exposes two units of diamictite (0.5 m and 2.2 m thick) that are separated by 6 m of fine-grained sandstone. Ntole River Section 2, exposes a massive (chaotic) diamictite up to 8 m thick (Fig. 4.22a-b). The diamictite consists of polymictic pebbles to boulders (to over 1 m in diameter) including basement rock types (schist, gneiss, etc.), quartz vein and quartz arenite of the Sinakumbe Group, in a fine-to very coarse-grained matrix of quartz, feldspar, and mica (diamictitic matrix; Figs. 4.21; 4.22a-c). Some cobbles and pebbles are internally horizontally laminated (Fig. 4.22a).

In thin section (Fig. 4.22c), the framework grains of quartz (predominant), feldspar and rock fragments are loosely held together by sericite-rich matrix. Muscovite is also abundant. Large fragments of vein quartz are commonly polycrystalline (Fig. 4.22c). Deformation is indicated by bent muscovite grains. Feldspar, mainly plagioclase, is locally replaced by calcite. Modal composition shows quartz to be up to 50%, feldspar 5 to 25% and rock fragments can be over 50%. Porosity is poor except near weathered surfaces where leaching of unstable minerals (e.g. calcite) has created secondary porosity. The diamictite is poorly sorted and texturally and mineralogically immature.

4.3.1.3 Matrix-supported conglomerate lithofacies (C_{ms})

This lithofacies is exposed in the Zhimu River, Mulungwa area. It forms a 1 m-thick lenticular body (Fig. 4.22d) of limited lateral extent, consisting of subrounded to rounded pebbles to boulders of quartzite, schist, gneiss, amphibolite, vein quartz (angular) and pink feldspar in a conglomeratic matrix (Fig. 4.22e) cemented mostly by silica and minor calcite. Similar exposures in the Siankondobo area are lenticular and also of limited extent (not more than 10 m wide) (Money et al., 1974).

The pebbles and boulders show their a-axes generally aligned parallel to the strike of the bed. The maximum diameter of the largest boulder is 1.1 m. Some well-defined imbrication in borehole samples and medium-scale cross-bedding have been reported (Money et al., 1974). In thin sections, rock fragments form over 50% of the matrix (Fig.

Fig. 4.22 Diamictite and conglomerate lithofacies

Siankondobo Sandstone Formation

a: Diamictite lithofacies overlying Sinakumbe Group. Notice lamination in the quartzitic cobbles and pebbles (arrowed). Ntole River Section 2, Nkandabwe map area. Pen is 13 cm.

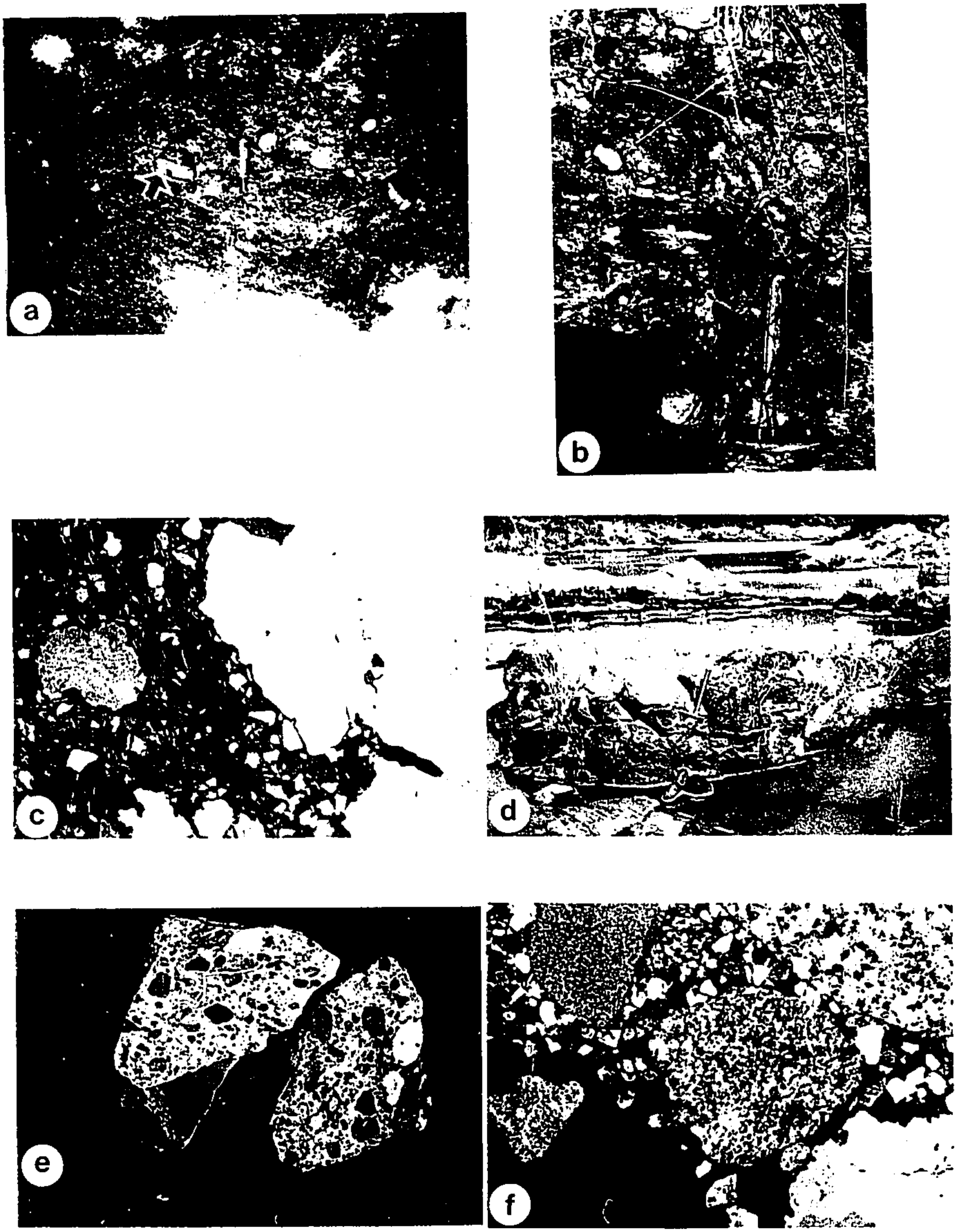
b: Diamictite lithofacies, in weathered outcrop. Notice the weathered subrounded fragments. Southwest End lake Section, Nkandabwe map area. Hammer is 34 cm.

c: Photomicrograph (crossed nicols) from Fig. 4.17c showing large polycrystalline quartz fragment with planar and sutured contacts, in sandy matrix of mainly quartz and mica. Long side of photograph is 5.4 mm.

d: Conglomerate lithofacies, exposed in Zhimu River, Mulungwa area. Note the limited extent of the outcrop and large boulders of quartzite and schist behind hammer.

e: Polished and stained slab from (d), showing dominance of quartzitic fragments Notice K-feldspar (yellow), including one large grain at top in contact with a schist fragment. Scale in cm.

f: Photomicrograph (crossed nicols) from (e), showing rounded rock fragments in quartz-rich matrix cemented by silica and calcite. Note the deflection of laminae in silica cement around the rock fragment in bottom left corner of photograph. Zhimu River Section 1, Siankondobo map area. Long side of photograph is 8.5 mm.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4.22f), followed by quartz (20%) and alkali feldspar. The cement is mostly silica, but calcite is also present in places. Laminae in silica cement appear to be draped around the clasts (Fig. 4.22f). The feldspars and some rock fragments are altered to sericite. Heavy minerals identified both in thin section and by SEM form less than 1% of the rock, and include garnet (predominant), zircon and apatite. Clay mineralogy analysis (XRD) showed kaolinite to be the dominant clay, followed by illite, with trace amounts of mixed-layer clays (illite and smectite - I/S). Other clay-sized minerals are quartz (abundant), potassium feldspar (minor), calcite (trace) and albite (trace).

According to Money et al. (1974) the conglomerate/diamictite ranges from orthoconglomerate (Pettijohn, 1957, p. 256), mainly petromictic conglomerate, to muddy-silty sandstone with clasts up to 40 cm in diameter (paraconglomerate of Pettijohn, 1957 p. 261, or mixtite of Schermerhorn, 1966).

4.3.1.4 Varve-like silty mudstone and siltstone lithofacies (VM_{sm})

Varve-like silty mudstone and siltstone lithofacies overlie the diamictite and/or conglomerate lithofacies, or lie directly on the basement complex. Good examples are in Kazinze River Section 2 (Fig. 4.23a, b) and in borehole GS 277 (Fig. 4.23c). In Fig. 4.23b, the medium brown laminae are thicker (1 - 3 mm) than the dark coloured laminae (< 1 mm). In thin section, lamination is defined by compositional and grain size differences where the thick laminae are composed of coarser quartz-rich grains and the thin laminae of hematite- stained clay (Fig. 4.23d). Black ferruginous impressions on bedding planes are common and faintly resemble carbonaceous matter. Dendrites are also present (Fig. 4.23b). In Mulungwa River Section 5, in the northwestern part of the study area, 24 m of the Siankondobo Sandstone Formation are exposed directly overlying the basement complex. At this locality, the poorly exposed contact between varve-like sediments and overlying cross-laminated siltstone and sandstone lithofacies is tentatively placed 4 m above the basement. The basal sequence consists of thinly bedded (<10 cm) units that are commonly weathered and fragmented, and become progressively thicker upward to a maximum of 25 cm (Fig. 4.23e). Horizontal lamination is characteristic, particularly in lower parts of the sequence, but in thick beds (≥10 cm) small scale cross-lamination

Fig. 4.23 Varve-like silty mudstone and siltstone lithofacies

Siankondobo Sandstone Formation

a: Varve-like silty mudstone and siltstone, consisting mainly of parallel-laminated beds up to 5cm thick. Kazinze River Section 2, Siankondobo map area. Hammer is 34 cm.

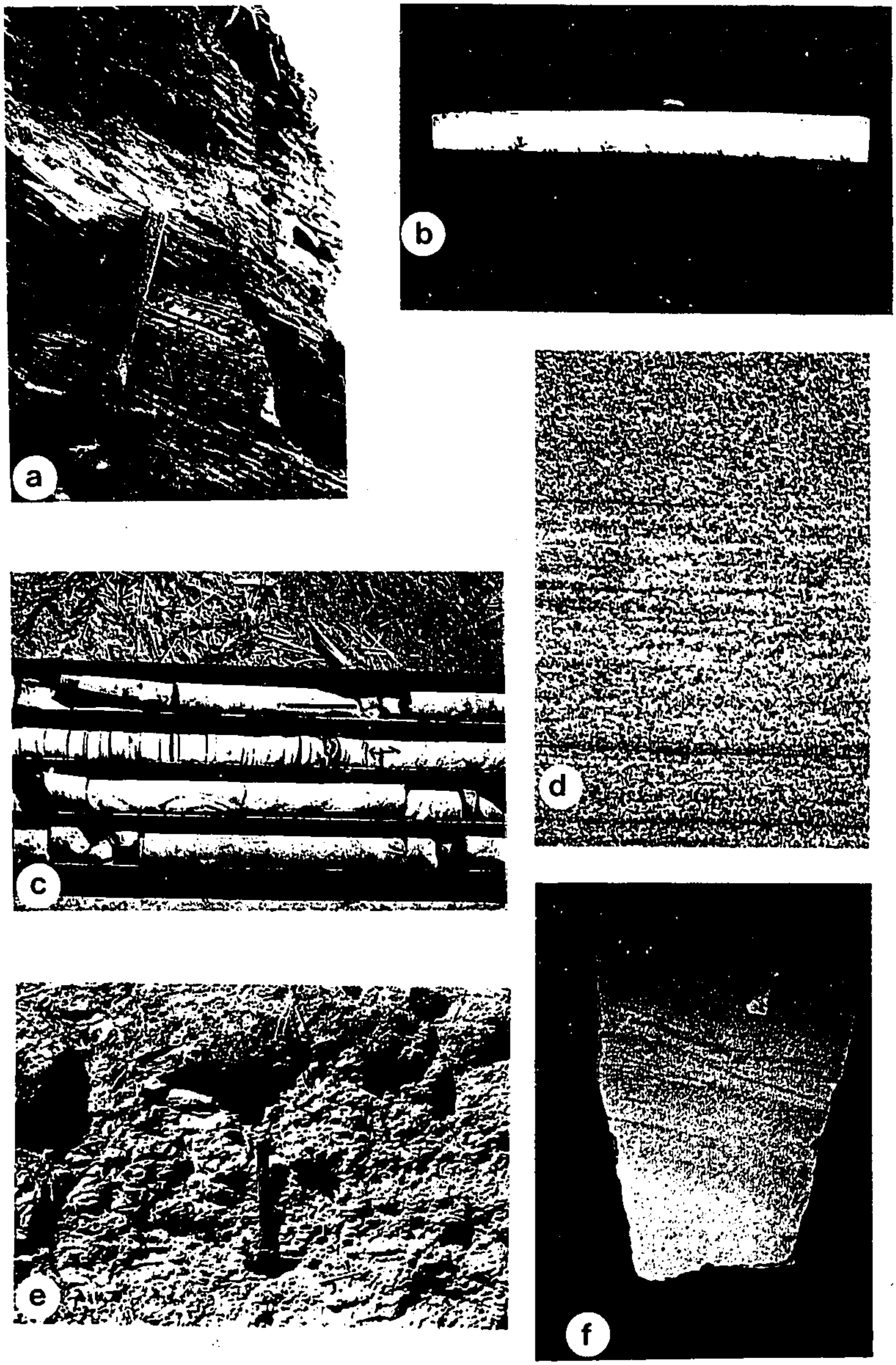
b: Polished slab showing internal laminae. The flower-like features (greyish black) at the bottom are manganiferous dendrites. Kazinze River Section 2, Siankondobo map area. Scale in cm.

c: Varve-like sediments (arrow) overlying basement rocks. Drill hole GS 277, Maze-Sinakumbe area. Core 7 cm in diameter. Black line on core is 13 cm.

d: Photomicrograph (crossed nicols) of (b) above showing horizontally laminated silty mudstone. Laminae are defined by composition and grain size differences (thinner ones are more clay-rich). The pinkish white grains are mainly quartz. Long side of photograph is 7.8 mm.

e: Thinly bedded (up to 25 cm), laminated to massive siltstones, fragmented to lensoids. Mulungwa River, Section 5, Mulungwa map area.

f: Polished slab showing an upward change in stratification, from massive to thinly horizontally- and cross-laminated. Kasika River Section 1, Nkandabwe map area. Scale in cm.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predominates. At Kasika River Section 1, generally horizontally laminated beds (varve-like sediments) at the base are separated from cross-laminated units by medium- to fine-grained, homogeneous, massive sandstone facies up to 7 m thick. An 8 cm-thick sample of the horizontally laminated beds showed a massive basal portion and a horizontally to small-scale cross-laminated upper portion (Fig. 4.23f).

In summary, the varve-like sediments consist of beds of silty mudstone generally less than 5 cm thick which internally show alternating medium and dark brown, continuous to discontinuous horizontal laminae. The sediments pass upwards into light creamy grey, small-scale, cross-laminated siltstone and very fine- to fine-grained sandstone.

4.3.1.5 Cross-laminated siltstone and sandstone lithofacies (SS_{cl})

This lithofacies, light creamy grey on fresh surfaces, yellowish brown and medium brown weathering, is composed predominantly of siltstone and very fine- to fine-grained sandstone containing abundant small-scale cross-lamination. The lithofacies is exposed along stream cliffs in units up to 20 m (e.g. along the Mulungwa River Section 5), consisting of beds one centimetre to 0.9 m thick. However, the vertical and lateral associations are difficult to determine because of the lack of continuous fresh outcrops. Massive interbeds are minor components.

In the Zhimu River Section 1, a 10 m-thick sequence shows amalgamated beds that are horizontally laminated to predominantly cross-laminated towards the top (Fig. 4.24a). A similar sequence is exposed in Unnamed Stream Section 2 (Fig. 4.24b). It is composed of alternating cross-laminae that are light-coloured (1 - 3 mm) and dark-coloured (< 1 mm) (Fig. 4.24c-f). Fig. 4.24f shows erosional type bounding surfaces at the base that grade upwards into sinusoidal type bounding surfaces. Well-developed small-scale cross-lamination is common throughout the study area, and includes types ranging from type A to sinusoidal of Jopling and Walker (1968). Well-preserved ripple morphology is associated with these internal structures in the Kasika River Section 1, Nkandabwe area (Fig. 4.25b-d), Kazinze River Section 2c, Siankondobo area (Figs. 4.25e, f; 4.26a, p. 125) and Zhimu River Section 1, Mulungwa area. In the Kasika Section (Fig. 4.25a-d) most of the 12 m thick unit shows sinusoidal climbing ripple drift lamination, with bed thicknesses

Fig. 4.24 Cross-laminated siltstone and sandstone lithofacies

Siankondobo Sandstone Formation

a: Thinly to thickly bedded, small-scale cross-laminated siltstone, fractured and jointed. Zhimu River, Section 1, Mulungwa map area. Hammer is 34 cm long.

b: Thin to medium bedded, small-scale cross-laminated siltstone. Notice the lenticular beds. Unnamed stream Section 2, Mulungwa map area.

c: Detail of (a), showing small-scale ripple drift cross-lamination. Pen is 14 cm.

d: Polished slab showing internal cross-lamination, from (a). Scale in cm.

e: Polished slab from (b), showing the erosional ripple drift cross-lamination. Scale in cm.

f: Polished slab from (b), showing erosional ripple drift cross-lamination becoming sinusoidal towards top. Scale in cm.

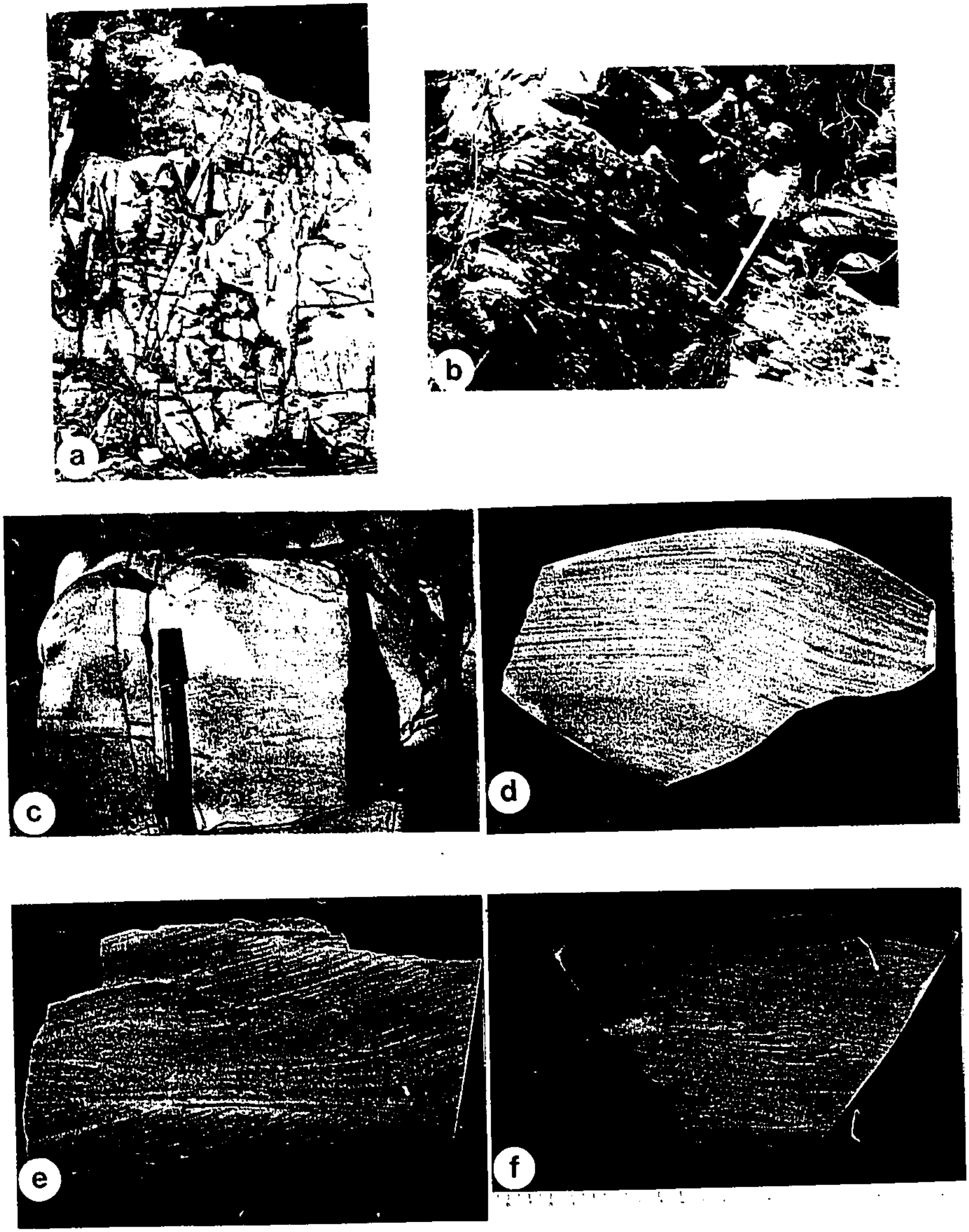
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Fig. 4.25 Cross-laminated siltstone and sandstone lithofacies

Siankondobo Sandstone Formation

a: Thickly bedded cross-laminated siltstone and sandstone. Kasika River Section 1, Nkandabwe map area. Hammer is 34 cm long.

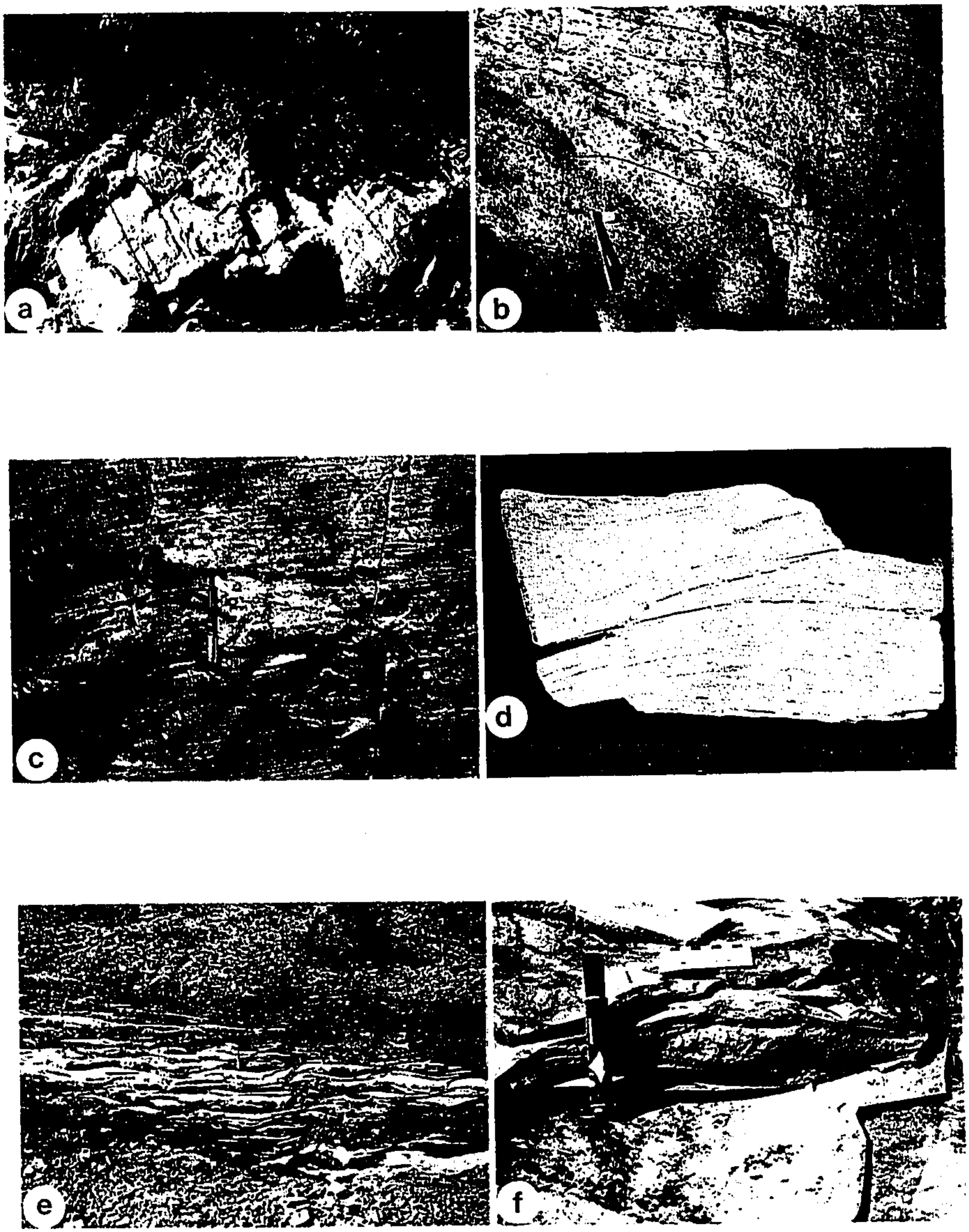
b: Detail of (a) showing climbing ripples (high-lighted; see arrow)

c: Climbing ripple siltstone and sandstone. Kasika River Section 1, southern side, Nkandabwe map area. Pen is 14 cm.

d: Polished slab showing laminae in climbing ripples from (a). Scale in cm.

e: Well preserved ripple-form sets (topography) in the small-scale cross-laminated siltstone and sandstone lithofacies. Kazinze River Section 2c, Siankondobo map area. Marker pen is 13 cm long.

f: Detail of (e), showing foresets in the lenticular bed to the right of the marker. Marker pen is 13 cm long.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from 0.4 to 0.9 m. Sinusoidal ripple lamination is also exposed elsewhere, notably in Kazinze River Section 2c (Fig. 4.26a) and Zhimu River Section 1. The climbing ripple foreset angles are in the order of 15-25° (Fig. 4.25b) and foreset laminae dip downflow with no reversals (Fig. 4.25f). Palaeocurrent measurements in the Kazinze River Section 2 indicate palaeocurrent flow to the southeast.

Soft-sediment deformation (water escape structures) have been observed in borehole cores (Fig. 4.26b). Money et al. (1974) reported sliding along pelitic laminae, which locally produced recumbent and primary contorted structural features. In places, grey siltstone laminae occur in which burrows have been recognised (GS51 and GS34)

In thin sections, grain size ranges from silt to fine sand, with an estimated mean grain size between 0.02-0.05 mm, and a maximum of less than 0.1 mm. The sediment consists of well-sorted, elongate, subangular, monocrystalline quartz and feldspar grains in a clay matrix (Fig. 4.26c, d, e). Much of the feldspar has been altered to clay minerals. Sphericity is between 0.55 and 0.70. Small-scale cross-lamination is characteristic throughout, and a few samples are massive. The lamination reflects both compositional and grain-size variations. The lighter-coloured laminae are made up mainly of subangular quartz with minor clay matrix; the darker laminae contain more clay matrix and finer grains (mainly quartz). Modal estimates show a content of: quartz (70-75%), feldspar (5-8%), mica (muscovite) (1-2%) and clay-rich matrix (10-20%) (Fig. 4.26e). The matrix contains abundant kaolinite in well-preserved books that are commonly coarser than the associated clastic quartz, feldspar and mica. This is in contrast to the chlorite-rich matrix previously reported in the literature. The kaolinite makes up to 5% of the rock. These estimates are confirmed by visual estimates from elemental map images made from SEM (Fig. 4.26f) which showed that quartz is the predominant mineral (70-75 %) followed by feldspar (2-5 %), mostly K feldspar, and clay-rich matrix (15-20 %). Plagioclase is less than 1% of the rock. Calcite and heavy minerals were identified by SEM. Calcite cement does not exceed 1% of the rock. However, Money et al. (1974) have reported spherulites of siderite as the main carbonate, with impregnations and laminae of hematite and limonite common. Heavy minerals include zircon (abundant) and apatite, which together do not exceed 0.1 % of the rock, but no garnets were observed.

Fig. 4.26 Cross-laminated siltstone and sandstone lithofacies

Siankondobo Sandstone Formation

a: Preserved ripple morphology in cross-section. Kazinze River Section 1, Siankondobo map area. Marker pen 16 cm long.

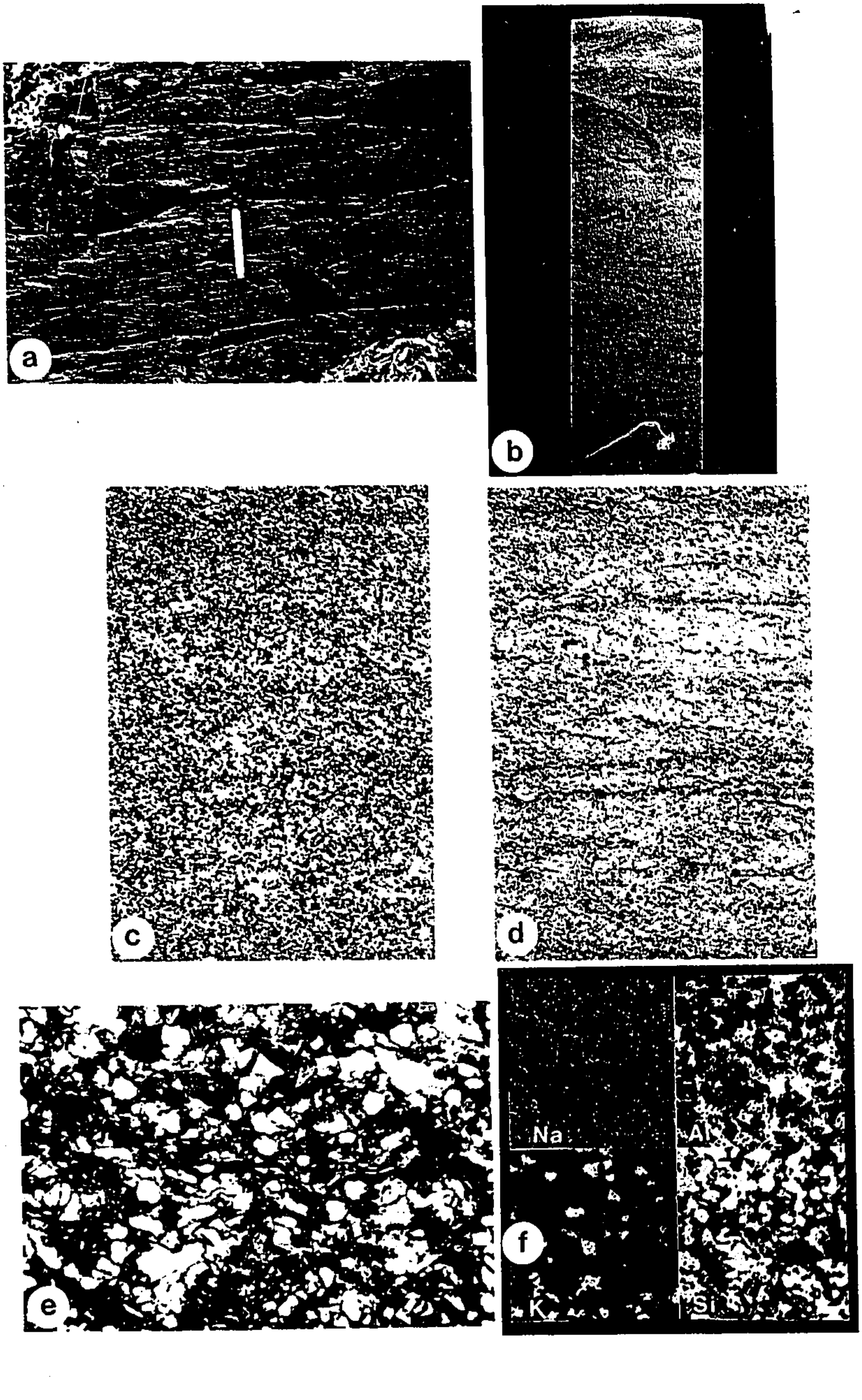
b: Soft-sediment deformation (water escape structures) in siltstone in 7 cm diameter core.

c: Photomicrograph (crossed nicols) of Fig. 4.25d showing the well sorted texture of the siltstone. Laminae are defined by composition and grain size differences (thinner ones are more clay-rich). The pinkish white grains are mainly quartz. Long side of photograph is 7.8 mm.

d: Same area shown in (c) above, in plane polarized light. Notice that the thin clay-rich laminae are accentuated by hematite coatings. Long side of photograph is 7.8 mm.

e: Photomicrograph (crossed nicols) showing detail of (c) above showing quartz as the predominant mineral and the undulating hematite-rich laminae. Long side of photograph is 1.4 mm.

f: Photomicrograph of a map image prepared by SEM showing distributions of elements Na, Al, K and Si (labelled). The element distribution is related to their corresponding major rock-forming minerals in clastic sediments. Notice that the siltstone is poor in Na, but richer in Si and Al, and with intermediate K, suggesting quartz is predominant followed by K-feldspar with a substantial amount of clay. Zhimu River Section 1, Mulungwa map area. Scale indicated on photograph.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Na
Al
K
Si

4.3.1.6 Massive sandstone lithofacies (S_m)

This lithofacies consists of massive, medium- to fine-grained, buff sandstone. The lithofacies crops out as thinly to thickly bedded or more commonly as very thickly bedded units over 30 m (Fig. 4.27a-f) and is extensively exposed in a series of northeast-trending elongate bodies separated by present-day stream valleys in the Nkandabwe area. The sandstone beds range from less 0.2 m to over 10 m thick (Fig. 4.27). In the thinly to thickly bedded units, bed contacts are sharp and beds usually tabular (Fig. 4.27a, c). In the thinly bedded varieties, some crude lamination is evident. In very thickly bedded units, bed contacts are not well defined, and beds commonly tend to be amalgamated (Fig. 4.27d-f). Elongate pits developed on surface exposures are artifacts of weathering, most likely due to removal of labile minerals. The sandstone is creamy whitish grey, homogeneous and internally massive (Fig. 4.28a), and usually has a dark brown to black coating and is locally pitted on weathered surfaces (Fig. 4.27). Denman and Money (1970) reported that nodular and dendritic pyrite is common and that the oxidation of pyrite has given rise to a characteristic pink and buff staining of the sandstone. Minor interbeds of horizontally to undulatory laminated, recessive siltstone and very fine- to fine-grained sandstone (Fig. 4.28b) occur within and at the bases of the massive sandstone units. Some of the interbeds are soft-sediment deformed (contorted), and appear folded and even overturned (Fig. 4.28c). The interbeds are generally 5-15 cm thick or amalgamated to 1.6 m, and similar to the cross-laminated siltstone and sandstone lithofacies. In Kasika River Section 1, a 7 m-thick lenticular, medium- to fine-grained, massive, buff sandstone similar to these thick massive sandstone bodies occurs between the varve-like sediments and the cross-laminated siltstone and sandstone lithofacies.

Thin sections show the sandstone to be mainly matrix-supported, with subangular to subrounded quartz and feldspar grains (Fig. 4.28d, e). Grain size averages 0.3 mm with a maximum of 0.7 mm. Where grains are in contact, planar to concavo-convex contacts have been observed. Quartz grains predominate (75-80%) (Fig. 4.28d, e), and are mainly subrounded (equigranular) and monocrystalline, with only trace amounts of elongate polycrystalline grains. Some grains contain muscovite inclusions; most grains are fractured. Feldspars are minor and have disintegrated, with authigenic kaolinite filling the

Fig. 4.27 Massive sandstone lithofacies

Siankondobo Sandstone Formation

a: Thinly to very thickly bedded, commonly internally massive sandstone. Bed geometry tabular. Kazinze River, Siankondobo map area. Scale 2.1 m.

b: Very thickly bedded (~25+ m) massive sandstone. Complex bedforms show undulatory tops. Tulatwabane Stream Section 7, Nkandabwe map area.

c: Detail of (a) above. Notice sharp contacts and the tendency for beds to become amalgamated to the left of the hammer. Hammer is 34 cm long.

d: Detail of extreme left (b) above. Notice complex bedforms that appear deformed. unrolled tape is ~ 25 m.

e: Detail of (b) above. Notice that beds amalgamate laterally. Elongate pits are due to weathering of labile material. Hammer for scale.

f: Very thickly bedded (~10 +m) massive sandstone. Beds show convex-upward tops. Notice black weathered surface is vertically interrupted by rainwash. Hill Slope Section 3b, Nkandabwe map area. Hammer for scale.

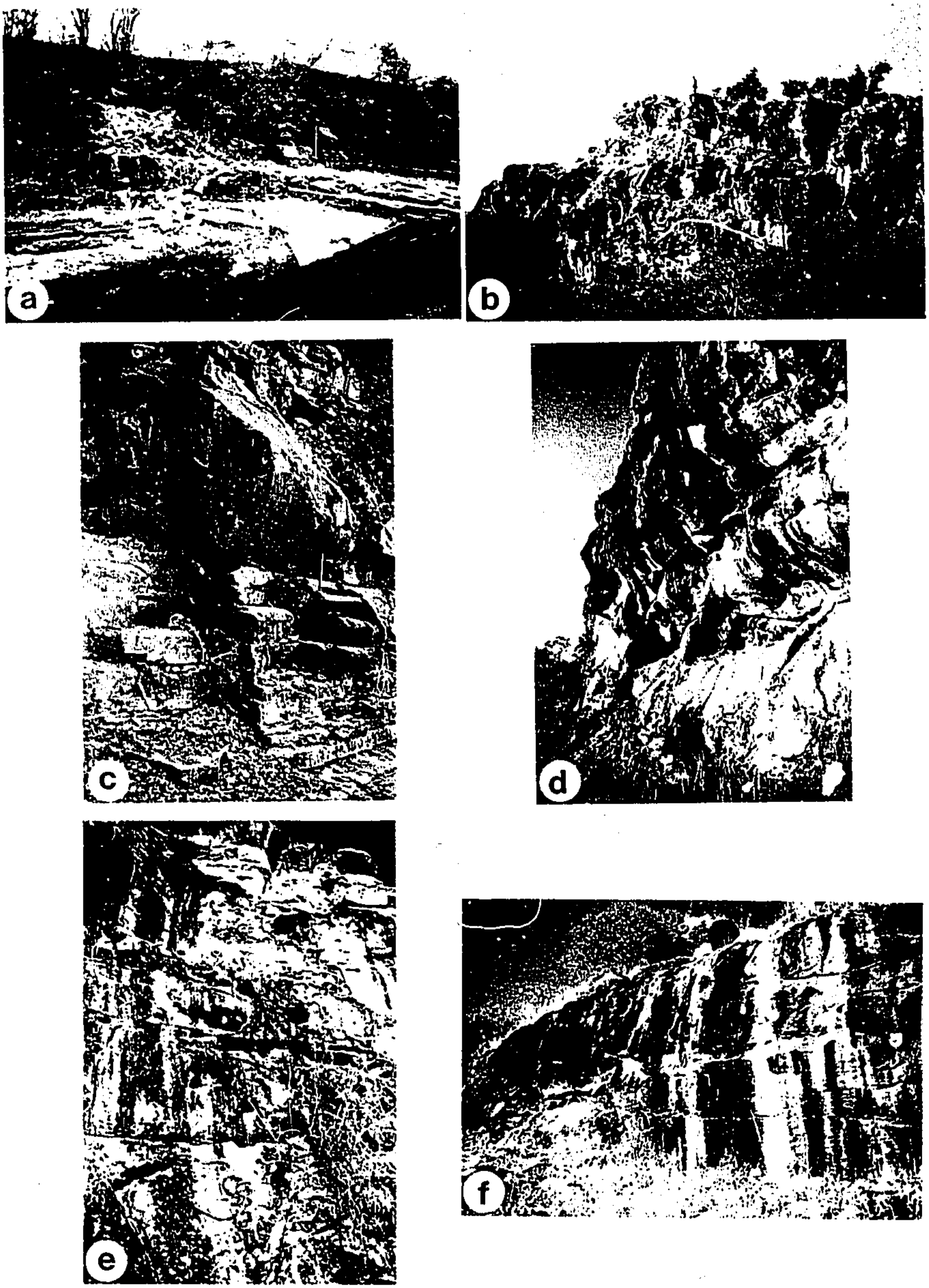

a
b
c
d
e
f

Fig. 4.28 Massive sandstone lithofacies

Siankondobo Sandstone Formation

a: Polished slab of homogeneous, structureless sandstone. Tulatwabane stream Section 7, Nkandabwe map area. Scale in cm.

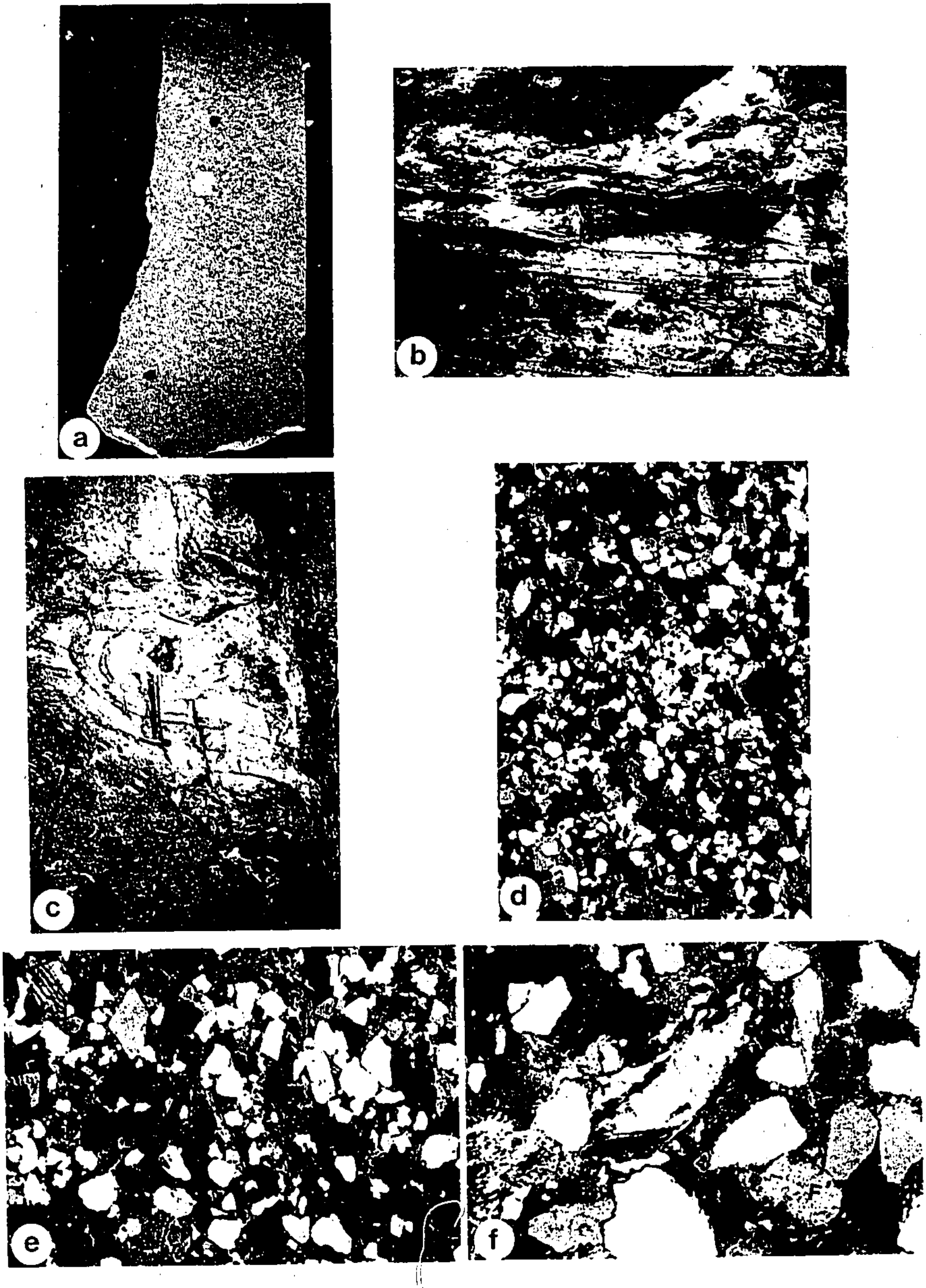
b: Interbeds of small-scale laminated, undulatory siltstone within the massive sandstone lithofacies. Tulatwabane Stream Section 7, Nkandabwe map area. Pen is 14.4 cm long.

c: Detail of intraformational folding in the massive sandstone. Tulatwabane Stream Section 7, Nkandabwe map area. Hammer is 34cm long.

d: Photomicrograph (crossed nicols) showing the homogeneous texture of the sandstone. It consists mainly of quartz, feldspar, minor muscovite, and generally less than 5% clay matrix. Tulatwabane Stream Section 7, Nkandabwe map area. Long side of photograph is 4.8 mm.

e: Photomicrograph (crossed nicols) showing framework-supported quartz (minor) and minor feldspar. Black is either void or heavy minerals (mainly zircon and sphene), with clay minerals of mainly kaolinite. Kasika River Section 1, Nkandabwe map area. Long side of photograph is 5.4 mm.

f: Photomicrograph (crossed nicols) showing kaolinite 'verm' in centre. Notice a feldspar (F) grain altered to sericite. Long side of photograph is 1.4 mm.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secondary voids (Fig. 4.28f). Minor muscovite makes up less than 1% of the rock. Heavy minerals (0.5 to 2.5%) include zircon (abundant) and epidote. Tourmaline has been reported by previous workers; the opaque minerals are rutile and iron oxides.

The matrix (5-10%) consists mainly of clay minerals shown by XRD to be mostly kaolinite with trace amounts of illite and mixed-layer clays (illite and smectite ~ I/S). In the thinly bedded units, illite occurs in minor amounts. However, kaolinite books (Fig. 4.28f) are significantly minor in comparison to the cross-laminated siltstone and sandstone lithofacies. Quartz is the only non-clay mineral identified in the clay-size particles. Calcite cement is lacking.

At the top of the massive sandstone units, for example at Izuma waterfall, lateral accretion surfaces (large cross-bedding) are well preserved, with dips between 15 and 30°. (Fig. 4.29). Similar, but less well-developed large-scale structures are evident in the top units of the massive sandstone in the Nkandabwe area. These units are conformably overlain by the Maamba Sandstone unit of the Gwembe Coal Formation.

4.3.1.7 Lithofacies interpretation

The characteristics and interpretation of the lithofacies in the Siankondobo Sandstone Formation are given in Table 4.5. Taken collectively, the lithofacies indicate that the formation was deposited subaqueously from a retreating continental ice sheet. The lithofacies association (diamictite, varve-like sediments, laminated and massive silty mudstone /siltstone /sandstone), the suite of sedimentary structures (climbing ripples, etc.), the occurrence of varves outside the study area (Tavener-Smith, 1960), and the direct evidence of probable glacial activity in the mid-Zambezi Valley in Zimbabwe and other Karoo basins at the same stratigraphic position support a glacial interpretation for the Siankondobo Sandstone Formation. The chaotic nature of the **diamictite lithofacies** suggests that the constituent units were deposited as debris flows from a retreating glacier. The diamictite lithofacies in the Nkandabwe area (Fig. 4.22a, b), in particular, is massive and chaotic, with large fragments indicating deposition close to a coarse-grained and heterogeneous sediment source prone to downslope resedimentation. These grade upwards into massive sandstone with scattered pebbles (~ 1 cm) which are probably dropstones

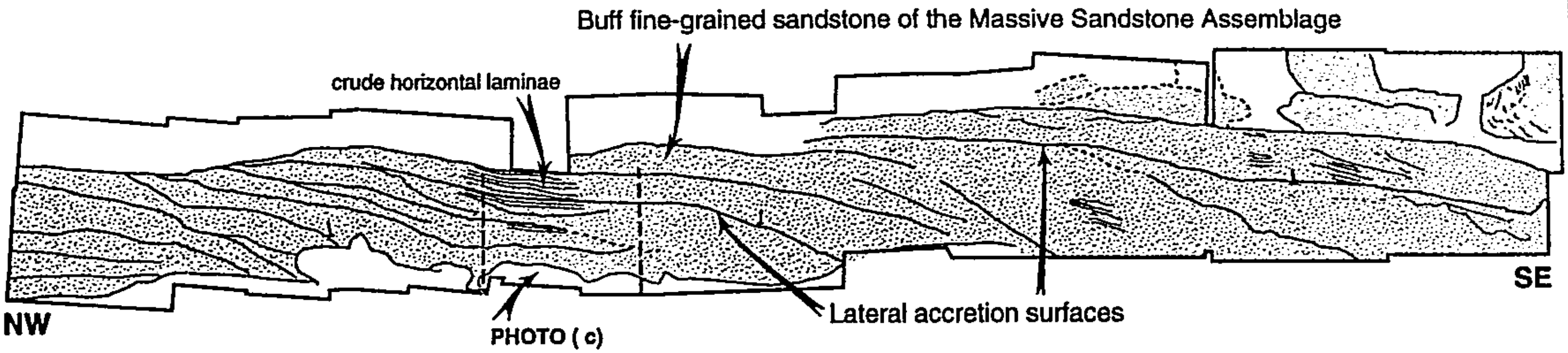


Fig. 4.29 Downstream accretion surfaces in the massive sandstone facies assemblage of the Siankondobo Sandstone Formation, Izuma Waterfall, Siankondobo map area.

a) Profile drawn from photomosaic shows lateral accretion surfaces at the top of the massive sandstone assemblage with crude horizontal laminae locally present. Hammer outlines are 34 cm long.

b) General photograph showing the laterally accreted beds for most of the profile in (a) taken at an oblique angle facing to the northeast. Person for scale.

c) Representative photograph showing detail of the beds exposing some crude horizontal laminae parallel to bounding surfaces.

Table 4.5 Summary of characteristics and interpretation of the lithofacies in the Siankondobo Sandstone Formation, mid-Zambezi Valley, southern Zambia

LITHO-FACIES	GRAIN SIZE / SORTING	TEXTURE	MINERALOGY AND OTHER COMPONENTS	BEDDING AND SEDIMENTARY STRUCTURES	THICK-NESS (m)	GEOMETRY/NATURE OF BOUNDING SURFACES	DEPOSITIONAL PROCESS	DEPOSITIONAL ENVIRONMENT
Silty mudstone/ siltstone (VM_{sm})	mud to silt			horizontal lamination (varve-like)	~ 4 m max.	sheet-like	settling from suspension and density underflow	glacial lake bottom
Siltstone/ Sandstone (SS_{cl})	silty to fine sand; moderately to well sorted	grain-supported	Detrital grains: quartz (70-75%), feldspar (5-8%), muscovite (1-2%). Heavy minerals: zircon, apatite. Clay minerals: kaolinite (up to 5%). Cement: calcite, hematite	small-scale ripple cross lamination (Sr); horizontal lamination (Fl); undulatory bedding; beds may be normal graded; soft sediment deformation	24 m max	tabular, generally flat base and top (wavy and undulatory surfaces locally); sharp contacts	density underflow	glacial outwash
Sandstone (S_m)	fine to medium sand; moderately well sorted to well sorted	grain-supported	Detrital grains: quartz (75-80%), feldspar (5-15%), muscovite. Heavy minerals: zircon, epidote. Clay minerals: kaolinite, illite, mixed layer clays (I/S)	massive (Sm); some normally or reverse grading; horizontal bedding; soft sediment deformation	80 m max. 25 m expo-sed	generally tabular convex-upwards to flat tops; base often concealed	rapid deposition or destratificat-ion; various sediment gravity flows	channel
Conglom-erate (SC_{D-C})	Matrix: medium sand to pebbles; poorly sorted. Coarse fraction (clasts): granules to boulders; poorly sorted	matrix-supported pebbles, cobbles and boulders	Detrital grains: rock fragments (> 50%), quartz (20%), alkali feldspar. Heavy minerals: garnet, zircon, apatite. Clay minerals: kaolinite, illite, mixed layer clays (I/S). Cement: silica, calcite	massive (Gmm)	9 m max.	lenticular, convex-down bases and poorly defined tops; deformed and folded	debris flow	braided glacio-fluvial
Diamictite (D)	angular quartz fragments in diamictic matrix; pebbles to boulders	matrix-supported pebbles, cobbles	Detrital grains: quartz up to 50%, feldspar (5-25%), rock fragments (basement rocks, quartz arenites etc. - > 50%)	massive (Dmm) and locally chaotic diamictite (Dms)	1 m to 6m expo-sed	diamictite with poorly defined bases and tops	debris flow	glacio-fluvial

released from minor icebergs. Some of the textures are similar to those described by Rust (1988) for the Ottawa area. Rust (1988) interpreted a diamict unit in the Ottawa area as probably deposited by a debris flow, possibly triggered by storm action. The channelised bodies (e.g. exposed along Kazinze River) represent the development of channels on a glacial outwash plain.

The **conglomerate lithofacies** is interpreted as deposits formed at the proximal margins of the basin in small streams probably related to glacial retreat. They probably resulted from high concentration turbidity currents localised in braided streams, as indicated by the body geometry and large clast sizes. Denman and Money (1970) suggested that the diamictite at the Zhimu River Section 1, Mulungwa map area, is a landslide or a mudflow deposit. Saltation and/or suspension are the suggested transport mechanisms for the gravel.

The **varve-like silty mudstone and siltstone lithofacies** has been interpreted by previous workers as varves. A varve is defined as a sedimentary bed or lamina deposited in a body of still water within one year, specifically a thin pair of graded glaciolacustrine layers seasonally deposited from meltwater streams in a glacial lake or other body of still water in front of a glacier (Bates and Jackson, 1987). However, rhythmic bedding can also represent more frequent events and in summer, for example, could result from pulses in a single under flow (minutes), slump-generated surge currents (minutes), diurnal discharge fluctuations (hours) or normal weather variations (days) (Smith and Ashley, 1985). The thicker silt-rich layers are deposited during summer and the thinner clayey layers in winter. A lack of lateral continuity of the layers in varve-like sediments within the study area suggests that "true" varves are not present, even in stream sections previously reported to contain them. However, outside the study area, glacial varves have been recognised by Tavener-Smith (1956a, 1957, 1960) on the Lusengesi River (16° 20' S and 28° 17' E), a tributary of Lufua River. The sediments in these thick, multilaminated, varve-like silt layers were likely carried directly to the site of deposition by underflows with minor overflows and interflows (cf. Ashley, 1972). A lack of evidence of bedload transport indicates that the varve-like sediments were deposited predominantly from suspension. Dropstones in the laminated siltstone confirm a subaqueous environment of deposition.

The ripple-drift **cross-laminated siltstone/ sandstone lithofacies** appears to represent deposition as subaqueous outwash from density underflows. The climbing ripples with two end-member types (Type A, with eroded stoss-side laminae; Type B, with stoss-side laminae preserved; Jopling and Walker, 1968) represent a shift during waning flow from rapidly migrating ripples with low vertical aggradation rates to slowly migrating ripples with high vertical aggradation rates (Smith and Ashley, 1985). Rust (1988) attributed similar ripple-drift cross-laminated units to waning density underflows on distal parts of a fan complex, perhaps representing seasonal cycles. Deposition of draped laminae (sediment from suspension) terminated ripple migration.

The medium-grained, remarkably homogeneous **massive sandstone lithofacies** is ascribed to rapid deposition involving one or more processes. Rust (1988) attributed massive appearing sandstone either to rapid deposition of well-sorted sediment from suspension or to fluidization of the sediment soon after deposition. Other mechanisms suggested are "modified" grain flow maintained by dense interstitial fluid, excess pore-fluid pressure, or shear stress applied by the superjacent current (Lowe, 1976a, b, 1982; Middleton and Hampton, 1976; Nemec et al., 1984) or turbidity current (Hiscott and Middleton, 1979). Lowe (1982) indicated that liquefied flows may evolve into high-density turbidity currents from which the coarser load is commonly deposited as thick units lacking current structures (i.e. massive sandstones). Rust (1988) interpreted massive sands in horizontally bounded units in two ways: as sediment gravity flow (mass flow) deposits or as 'rain-out' of sand from suspension, in both cases not allowing the development of bed-forms. Similar processes are suggested for the massive sandstone lithofacies with rapid deposition as the most probable mechanism (cf. Arnott and Hand, 1989).

4.3.1.8 Facies analysis

From the lithofacies descriptions, field occurrences and associations, the diamictite and conglomerate lithofacies are grouped into a diamictite facies assemblage; the varve-like sediments and cross-laminated siltstone and sandstone lithofacies into a siltstone facies assemblage; and the massive sandstone and recessive interbedded siltstone/sandstone lithofacies into a sandstone facies assemblage. These assemblages correspond roughly to the three members (lower, middle and upper) recognised in the formation by Denman et al. (1968), except that the varve-like sediments are included here in the siltstone assemblage with which they are closely associated, rather than in the diamictite assemblage. The three assemblages are rarely present in a single section; the diamictite assemblage is only locally present; the other two assemblages form the major part of the formation. The siltstone assemblage is present throughout the study area; the sandstone assemblage predominates in the Nkandabwe and Siankondobo map areas, but is absent from the Maze-Sinakumbe and Mulungwa areas.

The **diamictite facies assemblage** forms about 5% of the formation, occurring only locally in the study area, with a maximum thickness of 9 m (intersected in drillholes) in the Siankondobo area, 8 m in the Nkandabwe area and only 2.5 m in the Mulungwa area. Commonly, the assemblage is of limited extent laterally (e.g. Fig. 4.22d), suggesting that the lithofacies were confined to minor gullies where they were preserved. The sheet-like deposit with locally channelized bodies along the Kazinze River probably represents deposition on an outwash plain. The variable thickness of the diamictite assemblage is a function of the underlying topography. Eyles and Eyles (1992) emphasized the importance of sediment body geometry, lateral and vertical associations and overall basinal context as the key to elucidation of the depositional environment. The Kazinze deformed diamictite with characteristic vein quartz fragments in silt-sand-size matrix (Fig 4.21) is an extensive blanket-like unit that indicates supply of abundant fine-grained sediment to the basin, probably from meltwater sources, with the quartz fragments and others as debris from icebergs (cf. Eyles et al., 1993). However, a massive diamictite facies can be deposited in a wide range of glacigenic environments, as a result of subglacial deformation and lodgement, subaqueous 'rain-out' of suspended sediment and settling of ice-rafted debris (Eyles et al., 1993). The locally overlying varve-like sediments imply a subaqueous setting for the Kazinze diamictite, whereas the absence of such sediments above other diamictites (e.g. Nkandabwe diamictite) suggests a subaerial setting.

In the Nkandabwe area , the second and third stratigraphically higher diamictite units (Fig. 4.30) are indicative of a second and a third glacial retreat. Smith and Ericksson (1979) interpreted the massive diamictite facies to represent glacial moraines deposited at

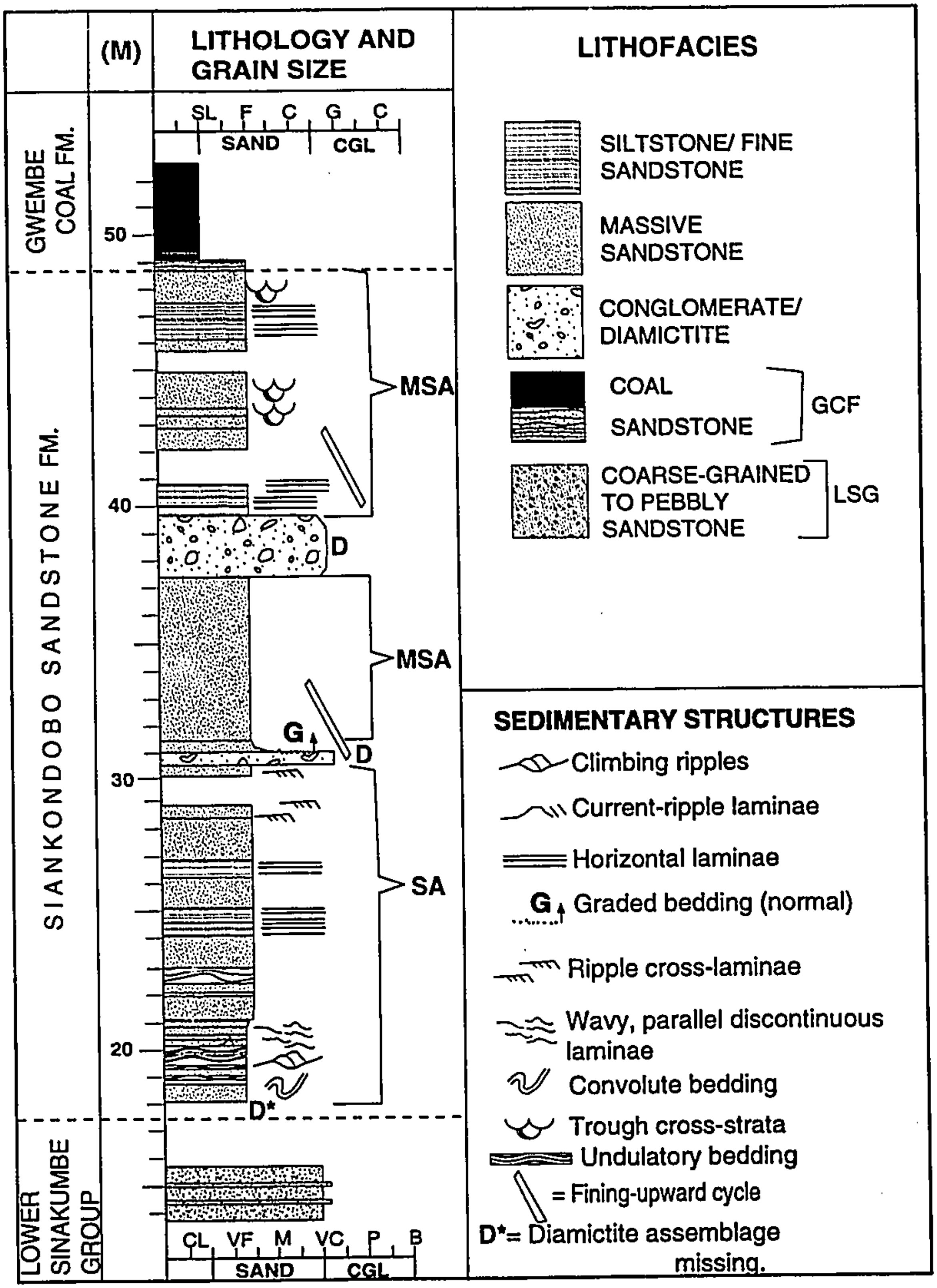


Fig. 4.30 Representative log of the Siankondobo Sandstone Formation showing the three facies assemblages (**D** = Diamictite Assemblage; **MSA** = Sandstone Assemblage; **SA** = Siltstone Assemblage). Southwest End Lake section, Nkandabwe area, mid-Zambezi Valley Basin, southern Zambia.

the base and in front of the northward-retreating ice-sheet that covered most of Gondwana.

Collectively, the features of the diamictite assemblage are indicative of subaqueous flow and glacial melt-out.

The **siltstone facies assemblage** occurs throughout the study area, but is more abundant and better preserved in the Mulungwa map area (Fig. 4.31), with a maximum thickness of 24 m. The association of varve-like sediments with the cross-laminated siltstones and sandstones, and the absence of sharp-based, normally graded sequences with sedimentary structures indicative of gradual deceleration, alternating with fines, rules out a true turbidity current origin (cf. Jopling and Walker, 1968). Instead, the sedimentary structure suite of the cross-laminated siltstone/sandstone is similar to subaqueous glacial outwash deposits of the Ottawa Valley (Rust and Romanelli, 1975) and the late Wisconsinan Kame delta deposits near Concord, Massachusetts (Jopling and Walker, 1968). Undulations and local soft-sediment deformation in the beds are attributed to differential compaction. The variation noted above in climbing ripple style indicates changes in the ratio of suspended load to bedload, as well as changes in current velocities (Gustavon et al., 1975). Jopling and Walker (1968) attributed these variations to deposition from density underflows of sediment-laden meltwater flowing into a glacial lake. Absence of features indicative of turbidity currents, such as graded bedding and erosional features (flutes, etc.,) fits the underflow model of Jopling and Walker (1968). This is further strengthened by the facies association (diamictite facies, varve-like sediments, cross-laminated siltstone/sandstone and massive sandstone). The massive sandstone bodies between the varve-like sediment and cross-laminated siltstone and sandstone in Kasika River Section 1 are interpreted as channel-fill sandstone.

The **sandstone facies assemblage** forms thick sandstone bodies that attain a maximum thickness of 80 m in the Siankondobo area (Beacon Hill and Izuma- borehole data), and is relatively well exposed (sections up to 30 m) in the Nkandabwe map area (Fig. 4.32).

Massive sandstone bodies represent rapidly emplaced sand that was not sorted by hydraulic processes during deposition. Various studies have proposed that they can be a product of upper flow regime currents (Collinson, 1966, 1970; Conaghan and Jones, 1975;

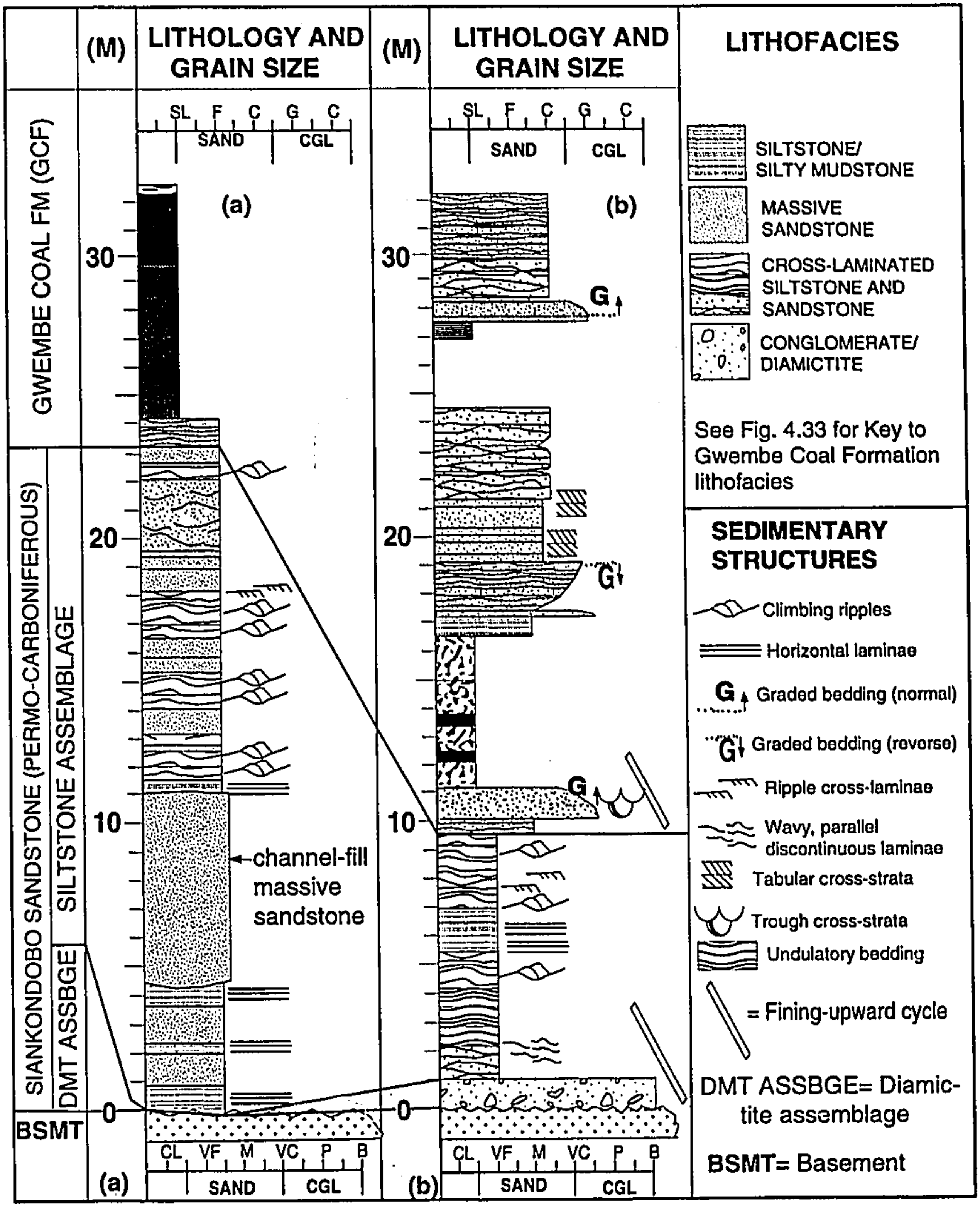


Fig. 4.31 Graphic logs showing lateral variation of the siltstone facies assemblage: (a) Kasika River Section 1, Nkandabwe map area and (b) Zhimu River Section 1, Mulungwa map area, southern Zambia. Note massive sandstone unit in (a) interpreted as channel-fill. Overlying the siltstone facies assemblage is the Gwembe Coal Formation.

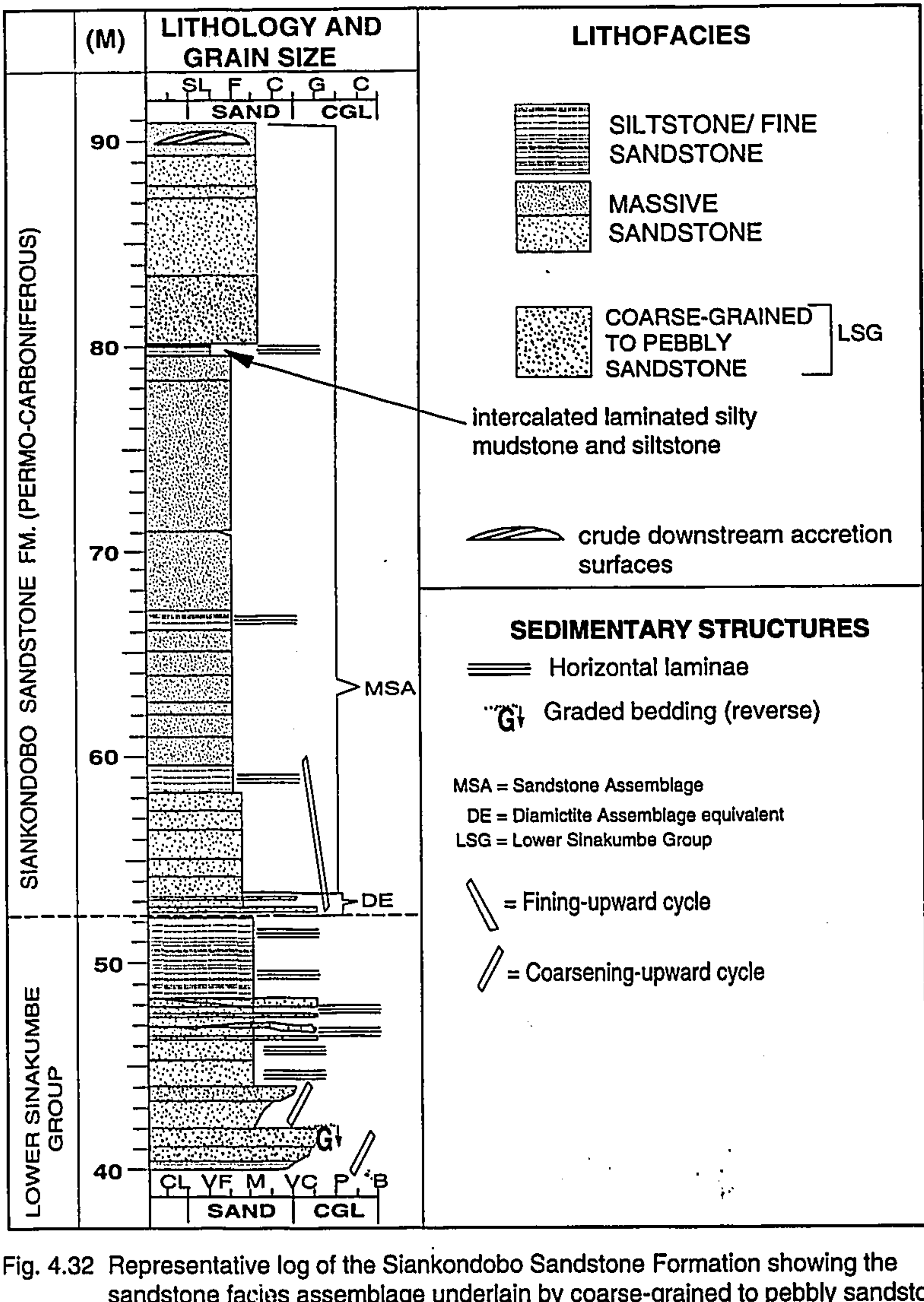


Fig. 4.32 Representative log of the Siankondobo Sandstone Formation showing the sandstone facies assemblage underlain by coarse-grained to pebbly sandstone that is stratigraphically equivalent to the diamictite facies assemblage. Northern Slope Section 3b, Nkandabwe area, mid-Zambezi Valley Basin, southern Zambia.

Conaghan, 1980), or subaqueous gravity flows (Jones and Rust, 1983; Rust and Jones, 1987; Turner and Monro, 1987) or braid-channel processes (Hodgson, 1978). The formation of massive channel fills on transverse fluvial bars during the falling stage, that were deposited as the (secondary) channel flow was rapidly cut off (as proposed by Hodgson, 1978) cannot apply to the massive sandstone of the Siankondobo Sandstone, because flow within a channel rarely contains enough sediment to fill it completely by rapid loss of carrying capacity. The massive sandstone is well sorted and lacks silt, indicating that it was not derived from within the braided channel system, but must have come from a more proximal location, such as deglaciated areas, during the increasing-flow stage. Smith (1985) indicated that meltwater streams that issue from glacial snouts carry enormous quantities of detrital sediment away from the ice margin to be deposited in various environments that include fluvial, lacustrine, eolian and marine settings. Such a supply of sand was likely, following retreat of the Gondwana icesheet, and the sands may have been deposited by one or more of the processes proposed above.

The facies, including the deformation of the sediments (Fig. 4.28c) within the assemblage, shows similarities to the subaqueous outwash described by Rust and Romanelli (1975). Although the downstream accretion bodies (Fig. 4.29) lack shale layers and scour-and-fill structures reminiscent of fluvial origin (cf. Smith and Ericksson, 1979), their persistence favours fluvial deposition in a deltaic setting.

Overall, the initiation, transport, and deposition of the Siankondobo sandstone facies assemblage involved a combination of processes and a variety of grain-support mechanisms. Gradation from the diamictite facies assemblage, to varve-like sediments overlain by cross-laminated siltstones/sandstones of the siltstone facies assemblage, followed by massive sediments, suggests a change from glacio-fluvial to glacio-lacustrine deposition for the Siankondobo Sandstone Formation.

4.3.2 GWEMBE COAL FORMATION

4.3.2.1 General remarks

The Gwembe Coal Formation (Fig. 4.33) consists mainly of carbonaceous/silty

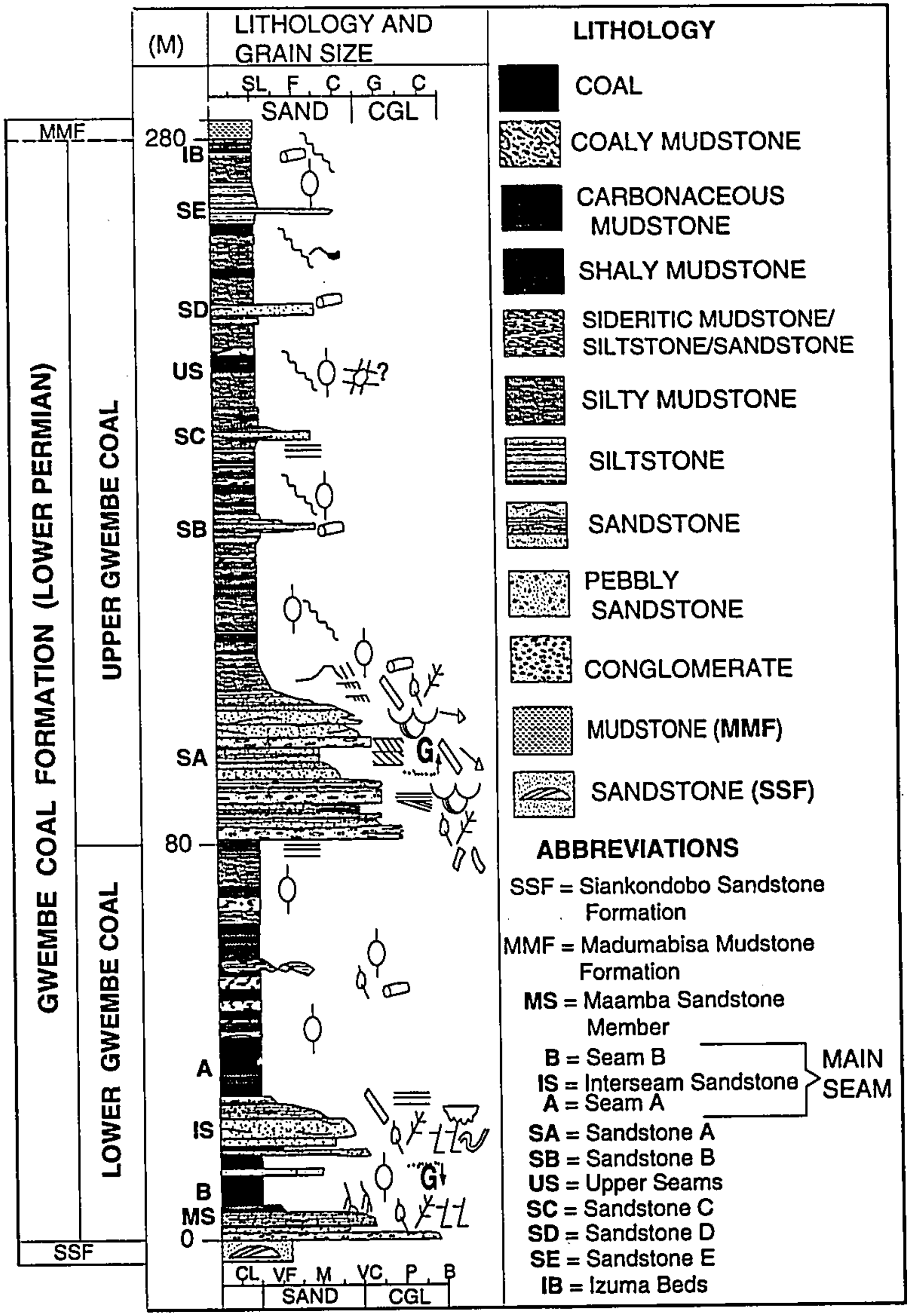


Fig. 4.33 Generalised stratigraphic column of Gwembe Coal Formation, mid-Zambezi Valley Basin, southern Zambia (not to scale). See Fig. 4.0 (p.67) for key to sedimentary structures & other features.

mudstones and siltstones (mudrocks) with interbedded coal seams and sandstones. A number of formal and informal stratigraphic names have been applied to portions of the formation (see Chapter 2), as a result of the detailed work carried out during exploitation of this coal-bearing succession. Briefly, these are the Maamba Sandstone Member, Main Seam, Interseam Sandstone, five sandstone units designated A to E, that alternate with mudstone, and the Izuma Beds. Fourteen lithofacies (Table 4.2) have been defined in this study on the bases of lithology, grain size, sedimentary structures, and rock composition.

The **Maamba Sandstone** is composed mainly of units of buff, coarse-grained to pebbly, slightly feldspathic and micaceous sandstone, in many places with a basal conglomerate grading upwards through carbonaceous fine-grained sandstone and siltstone into carbonaceous and coaly mudstones, and some coal. Sedimentary structures include cross-bedding, current scours, ripple lamination, pinch and swell, flaser bedding and disturbed bedding (Money et al., 1968). Macerated plant fragments, impressions and vitrain shards are the characteristic features of the Maamba Sandstone. The Maamba Sandstone contains two broad lithofacies, namely conglomerate and sandstone. The lower member, which is equivalent to the conglomerate lithofacies, consists of coarse, massive, poorly to moderate-sorted conglomerate units, generally 2-3 m thick with pebbles and cobbles (up to 20 cm in diameter) of basement rocks, quartz and Siankondobo Sandstone, and a pebbly sandstone (0.5 to 2 m thick) that fines upwards into the upper member. The upper member, which is equivalent to the sandstone lithofacies, comprises mainly alternating sandstone and mudstone with thin, coaly mudstones and coal seams frequently terminated by wash outs (Money et al., 1974).

The **Main Seam** is almost entirely coal containing only subordinate intercalated mudstone and therefore only a coal lithofacies has been designated. Argillaceous laminae, specks of siderite (roses and spherulites) oxidised to limonite, marcasite 'flowers', barite on joint and bedding planes, and layers of pyrite nodules occur locally in the Main Seam (Money et al., 1968). The seam grades laterally and vertically into more carbonaceous mudstone that contains impersistent closely spaced vitrain laminae. The **Upper seams** are impersistent, thin coals. Those in the upper part of the Maamba Sandstone member are similar in composition to the Main Seam; those in the upper Gwembe Coal Formation are slightly different in composition.

The **Interseam Sandstone** shows various colours from all shades of grey (very light to greyish black) with subordinate whitish mottling, to whitish grey (cream white), and weathers yellowish brown/brownish black. It is a very fine- to very coarse-grained sandstone with subordinate conglomerate lags, and intercalated siltstone and mudstone. The sandstone varies in thickness (up to 4 m thick), with well-developed cross-bedding and fining-upward sequences, usually with basal pebbly lag conglomerates. Plant fragments and stem impressions over 1 m in length, and fragments of siltstone, mudstone and coal are also present. Two lithofacies are recognised based on geometry, namely sheet and lenticular sandstone.

Mudrock forms about 70% of the Gwembe Coal Formation. It is black to dark grey and very rich in organic matter. Mudstone is the predominant lithology of the mudrock of the Gwembe Coal Formation. Money et al. (1974) recognized four types of mudstone in the formation, i.e. coaly mudstone, carbonaceous mudstone, sideritic mudstone, and dark grey mudstone with gradational to sharp contacts. The coaly and carbonaceous mudstone units occur mainly in the lower Gwembe Coal Formation and the grey and silty mudstone members in the upper Gwembe Coal Formation. In the Kazinze open pit section, sideritic mudstone occurs within coaly and carbonaceous mudstones and siderite is common in silty mudstone and carbonaceous sandstone. Pale coloured laminae of siderite are common in banded coaly mudstone, in argillaceous laminae of the coal seams and in silty mudstone. In other words, in fresh outcrops the distinction between sideritic mudstone and other mudstones can be difficult. However, in weathered outcrops the sideritic units are easy to distinguish because siderite is oxidised to iron oxides. Three mudstone lithofacies, namely coaly, carbonaceous and silty (slightly carbonaceous) mudstones, have been distinguished on the basis of different carbon content. The three lithofacies are usually massive, but where mica flakes are abundant, their alignment results in shaly and fissile mudstone. A fourth lithofacies defined on the basis of high siderite content also includes siltstone and sandstone and is termed sideritic mudstone, siltstone and sandstone. The lithofacies occurs in very thinly to very thickly bedded alternating units (cycles). Seventeen cyclic units in a 12 m sequence, involving bright laminated coal, coaly mudstone and carbonaceous mudstone were recorded by Tavener-Smith (1960). Carbonaceous matter occurs mainly as fine disseminations, stringers, streaks and impersistent laminae of vitrain as well as plant fragments. Films associated with marcasite occur locally (Money et al., 1974). Pyrite 'flowers' occur on joint and bedding planes. Mudstone pellet breccia and conglomerate units overlain by dark carbonaceous mudstone with scattered pellets of paler mudstone define fining-upward units and cycles in the mudstone (Money et al., 1974). Symmetrical sand and silt lenses (a centimetre in length), small-scale symmetrical folds and loading and the resultant flame structures are apparent in the mudstones (Money et al., 1974).

Mine geologists use a knife blade for quick distinction between the three mudstones during core logging: coaly mudstone has no streak (sooty) and the knife slides; carbonaceous mudstone has a slight fine black streak; and silty mudstone has a lighter streak (soot) and a deep cut (Ngwata, pers. comm., 1990). This technique can be applied in natural exposures, but in weathered surfaces, the three mudstones are easily distinguished without the knife test.

Sandstone A is well developed throughout the study area; the others (B to E) are minor and have not been located in surface exposures in their type locality (Maamba Mine Licence area) during the present field work. Because of this, only Sandstone A is fully covered in this section, and the other sandstones measured are described under the general heading "**Lithofacies of Other Sandstones**". The interpretation of these will combine descriptions from old literature with this study's observations. Outcrops of Sandstone A are confined to river and stream sections; however, in the Siankondobo and Sinakumbe areas, the sandstone forms ridges and hills (e.g. in Fig. 2.2b). Eight sections were studied. The sandstone varies in thickness from 0 to over 30 m. The maximum thicknesses measured are 6 m in the Nkandabwe area, Kasika River Section 1, 30 m in the Siankondobo area, 30 m in the Makula Stream Section, Sinakumbe area and slightly over 20 m in the Unnamed Stream Section 2, Mulungwa area. Dips are generally less than 12°. In areas between streams and rivers, the sandstone is presumably continuous along strike, as is evident from some of the drill cores. However, wedging out of these sandstone bodies is also common. Sandstone A is composed mainly of medium- to very coarse-grained sandstone, pebbly sandstone, quartz microconglomerate and subordinate siltstone and mudstone. The coarser siliciclastics are more abundant at the base, and grade upwards into very fine clastics. The sandstone is generally whitish grey (cream) in the coarser-grained units, varying to greenish grey (shades of grey) in the finer grained units. Pinkish red and shades of yellowish brown are typical colours of some altered zones. Sandstone A is almost invariably cross-bedded. The cross-bedding (both planar and trough) is defined by bands of small pebbles in basal sections of units, and by bands with plant fragments towards the top. Other structures include massive bedding, graded bedding, horizontal bedding, scour and fill, erosional truncation planes and minor parting lineation. Three lithofacies are recognised, namely microconglomerate to very coarse-grained sandstone, very fine- to coarse-grained sandstone, and mudrocks (siltstone and mudstone). Seven depositional facies (Miall, 1977; 1978; Rust, 1978a) recognised in the lithofacies are trough cross-stratified sandstone (St), massive sandstone (Sm), planar cross-stratified sandstone (Sp), low angle cross-bedded and tangential scoop-shaped cross-bedded sandstone (Sl), ripple cross-laminated sandstone (Sr), horizontally stratified sandstone (Sh), and planar bedded mudrock (mainly siltstone), with fine lamination and very small ripples (Fl), in decreasing order of abundance. Erosional scours with intraclasts (Se) are present locally, whereas massive mudrocks (Fm) are rare.

The **Izuma Beds** consist of a carbonaceous and a silty mudstone lithofacies.

For convenient cross-reference, the headings used for the lithofacies below incorporate the stratigraphic occurrence of each within the formation.

4.3.2.2 Conglomerate lithofacies (SC_{p-c}) (Maamba Sandstone Member)

This lithofacies directly overlies the Siankondobo Sandstone Formation (Figs. 4.34a; 4.0) or rests directly on the basement where the Gwembe Coal Formation oversteps the Siankondobo Sandstone or where the latter is absent. The conglomerate (Figs. 4.34a, b, c) is well exposed at the Izuma waterfall, where it is up 6 m thick and shows characteristics of a channelized body that fines upward into carbonaceous coarse-grained sandstone, and eventually to coal (Fig. 4.34a). In Fig. 4.34c, a fining-upward unit shows a conglomerate at the base overlain by low-angle stratified pebbly sandstone which is in turn overlain by

Fig. 4.34 Lithofacies of the Maamba Sandstone Member Gwembe Coal Formation

a: Sharp contact (lower 2 arrows) between the Siankondobo Sandstone Formation and the Maamba Sandstone member of the Gwembe Coal Formation. Some cobbles occur in the conglomerate at the base of the Maamba Sandstone Member which is in turn overlain (2 upper arrows) by pebbly to fine-grained sandstone. The conglomerate increases in thickness to the left. Izuma Waterfall, Siankondobo area. Outcrop is 12 m thick.

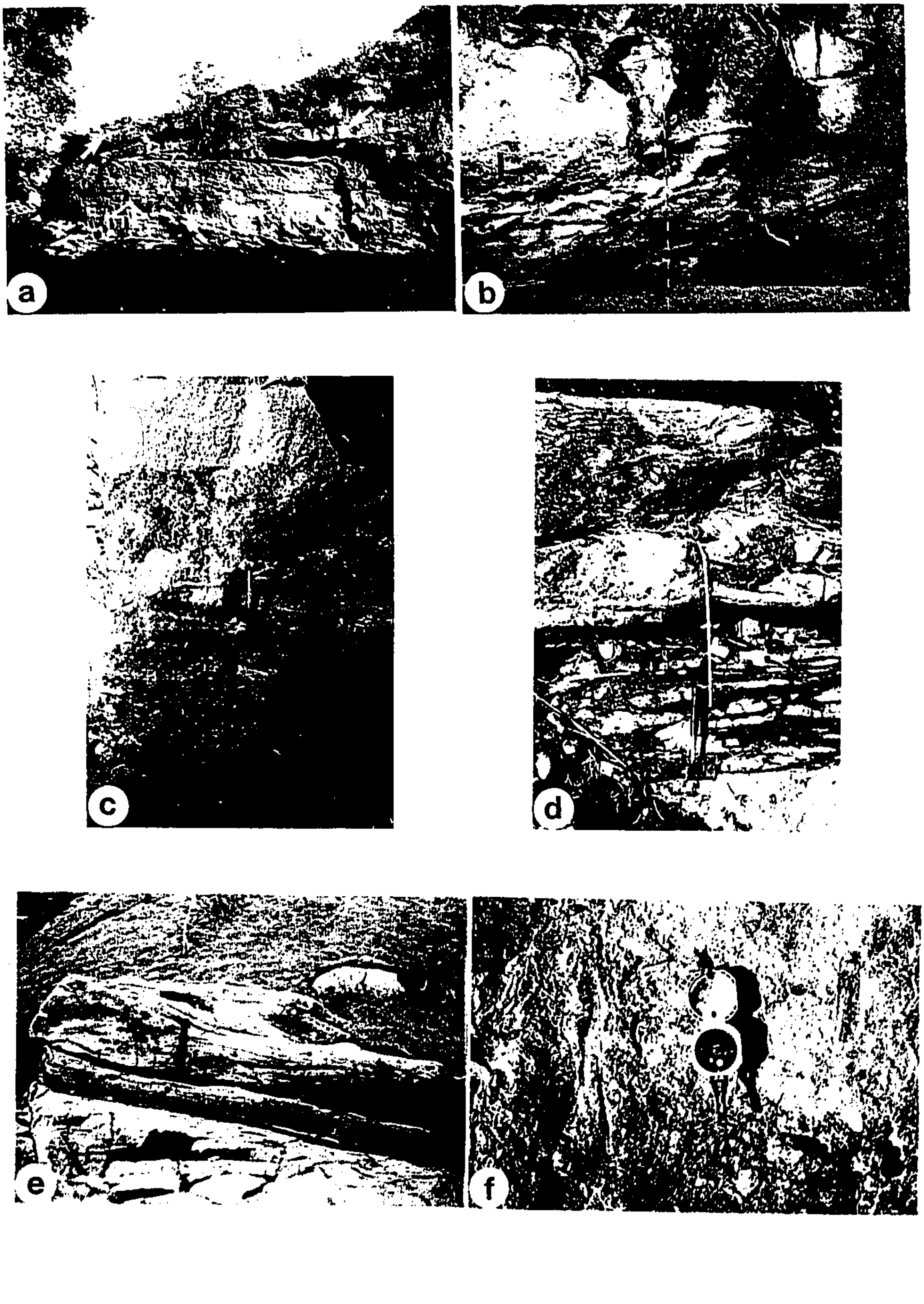
b: Detail of (a) above showing conglomerate lithofacies. Generally, the clasts are scattered, and pebbles are commonly concentrated locally (L-lags). Alternating red and white marks represent 10 cm intervals.

c: Typical fining-upward unit with conglomerate at base overlain by low-angle cross stratified pebbly sandstone, in turn overlain by generally massive, coarse- to medium-grained sandstone. Izuma Waterfall, Siankondobo map area. Pen is 15 cm long.

d: Maamba Sandstone Member in sharp contact (at axe head) with non-carbonaceous sandstone of underlying Siankondobo Sandstone Formation. Maamba Sandstone here consists of amalgamated medium- to coarse-grained sandstone with carbonaceous siltstone to silty mudstone intercalations, overlain by stratified very coarse-grained to microconglomeratic sandstone. Zhimu River Section 1, Mulungwa area. Axe is 34 cm long.

e: Medium- to coarse-grained sandstone of the Maamba Sandstone Member directly overlying the Siankondobo Sandstone Formation. Notice the irregular carbonaceous laminae outlining small channels. Zhimu River Section 1, Mulungwa area. Hammer is 34 cm long.

f: Large plant (tree?) stem impressions on bedding plane in fine- to medium-grained sandstone lithofacies, Nkandabwe Open pit, Nkandabwe area.


a
b
c
d
e
f

massive sandstone. The lithofacies, together with overlying sandstone, has been intersected in drill holes in the Siankondobo area (GS 84 -13 m; GS 59 - 17 m) and in the Mulungwa area (GS 100 - 9 m; GS 94 - 9 m). At the Izuma waterfall, the conglomerate consists of scattered pebbles and cobbles in a pebbly sandstone matrix. It is polymictic and consists mainly of subangular to subrounded clasts of greyish white sandstone (Siankondobo Sandstone Formation), quartz, quartzite (probably Sinakumbe Group), and basement rocks (mainly schists). The quartz and quartzite cobbles are up to 20 cm in diameter. At the base the pebbles and cobbles are scattered and in places, they define bedding and/or form lags (Fig. 4.34b). Pebble size decreases from base to top and the unit increases in thickness down- gradient (Fig. 4.34a). The gradient is indicated by the downstream accretion beds of the upper part of the sandstone assemblage of the Siankondobo Sandstone Formation (Fig. 4.29) on the northeastern side of the Izuma Waterfall Section. The conglomerate is overlain by irregular, amalgamated, lenticular, pebbly sandstone beds with recessive carbonaceous sandstone and mudrock intercalations (Fig. 4.34a). The pebbly sandstone grades upwards into finer sandstone, carbonaceous siltstone and mudstone or the Main Seam.

The conglomeratic unit is absent from the Zhimu River Section 1, where medium- to coarse-grained carbonaceous sandstone directly overlies the Siankondobo Sandstone Formation (Fig. 4.34d, e).

4.3.2.3 Very fine-grained to very-coarse grained sandstone lithofacies (S_{vf-vc}) (Maamba Sandstone Member)

This sandstone lithofacies overlies the conglomerate lithofacies or lies directly on the Siankondobo Sandstone Formation (Fig. 4.34a, d, e). The lithofacies is also exposed in the Unnamed Stream 2 Section, Mulungwa River Sections 4 and 5, Mulungwa area, and Kasika River Section 1 in the Nkandabwe area. The outcrop in the Zhimu River Section 1 (Fig. 4.34d) shows alternating amalgamated beds of crudely stratified sandstone (stratification defined by irregular, horizontal laminae) and thin coaly, carbonaceous mudstone/coal layers. The alternating beds are succeeded by fining upward, trough cross-bedded, very coarse-grained sandstone (Fig. 4.34d) which locally has undergone soft-sediment deformation. Ten metres to the northeast of this locality, the sandstone shows numerous carbonaceous stringers and laminae and minor small-scale channels (Fig. 4.34e). A cyclic sequence of sandstone, carbonaceous sandstone, siltstone, mudstone and coaly mudstone, muddy coal and coal occurs at many localities. In Mulungwa River Section 5, herringbone cross-bedding is apparent. Weathered surfaces show numerous, shallow, sub-circular pits averaging 1 cm across, resulting from the weathering out of carbonaceous fragments (Money et al., 1974).

No *in situ* plant trunks and stems have been observed in the Maamba Sandstone Member lithofacies, even though the member directly underlies the Main Seam. However, plant stem impressions of various sizes (Figs. 4.34f, 4.35a), some over 1 m in length, fossil leaves and other plant remains are common. Money et al. (1968) reported tree stem impressions up to 2 m in length. The large stems do not show any preferred orientation. Other features include microfaulting (See Fig. 4.60, p. 199).

In thin section the sandstone is composed of quartz (predominant, Fig. 4.35b), feldspar, rock fragments, and muscovite (biotite is uncommon) in a matrix of limonite, sericite and subordinate chlorite. Some of the quartz is fractured (Fig. 4.35b). Heavy minerals include zircon, epidote, sphene, metallic minerals, rutile and tourmaline (Radosevic et al., 1968). The overlying sandstone/siltstone is highly carbonaceous and consists of quartz, feldspar, and minor rock fragments. Kaolinite is the predominant clay mineral (XRD) with trace amounts of illite. Quartz (abundant) and K-feldspar (trace) are the other clay-sized minerals.

4.3.2.4 Coal lithofacies (C)

Coal was defined by Schopf (1956) as "a readily combustible rock containing more than 50% by weight and more than 70% by volume of carbonaceous material, formed from compaction or induration of variously altered plant remains similar to those of peaty deposits". Coalification transforms peat through the progressive ranks of coal, with 'brown coal' a term used for lignite and sub-bituminous coals, and 'hard coal' used for higher rank coals (Bustin et al., 1983).

The coal lithofacies is defined in terms of the primary (genetic types of coal) and

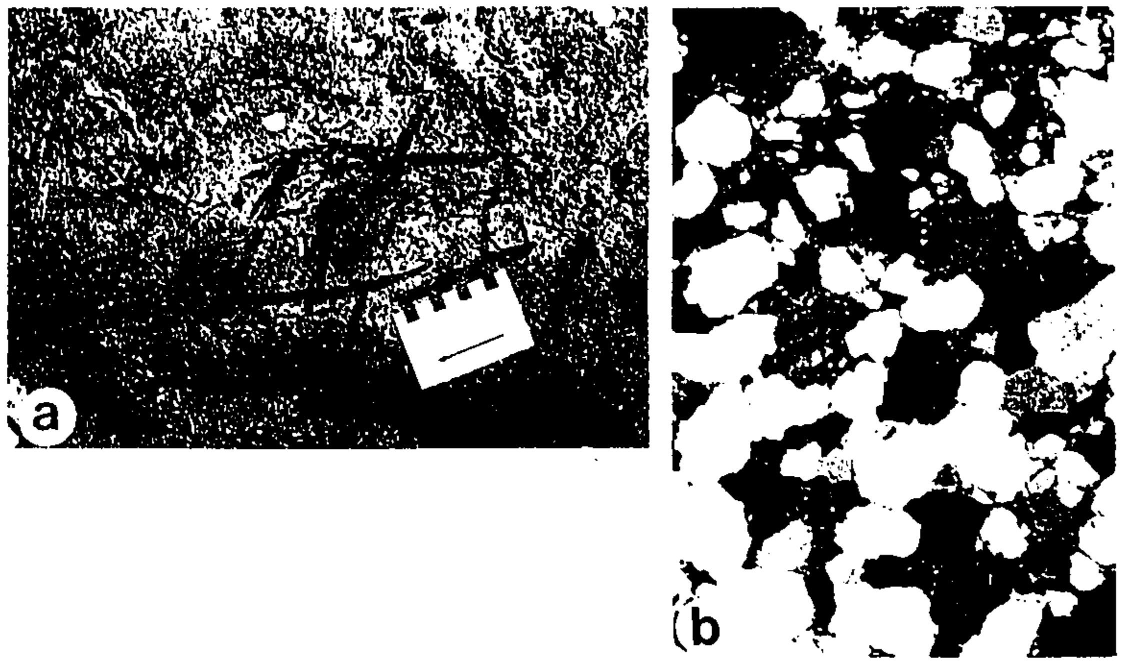


Fig. 4.35 Lithofacies of the Maamba Sandstone Member

Gwembe Coal Formation

a: Small plant stem impressions on bedding plane in fine- to medium-grained sandstone lithofacies, Nkandabwe Open pit, Nkandabwe area. Scale in cm.

b: Photomicrograph (crossed nicols) of the sandstone consisting mainly of quartz with planar to concave-convex contacts. The quartz is fractured and the black material is mainly carbonaceous matter. Zhimu River Section 1, Mulungwa map area. Long side of photograph is 2.5 mm.

the diagenetic characteristics that determine its mineral and organic composition. These include the mode of deposition (autochthonous, allochthonous), plant communities, depositional milieux (including pH, bacterial activity, and sulphur availability), and redox potential (Teichmuller and Teichmuller, 1982; Bustin et al., 1983, p. 19).

Coal is a heterogeneous rock composed of an organic fraction that can be split into a series of 'macerals' (organic equivalents of minerals) and an inorganic fraction. At the simplest level macerals are divided into three groups, namely vitrinite, inertinite and liptinite (exinite). This classification (Table 4.6) reflects either similar origin (liptinite group) or differences in preservation (macerals of vitrinite and inertinite groups) (Bustin et al., 1983). The inorganic fraction, basically various primary and secondary minerals, is known as ash (McCabe, 1984).

Macroscopically recognizable coal lithologies present in layers at least a few millimetres thick are termed lithotypes (Table 4.6). Two basic types of coal are known: humic coals (derived mainly from macroscopic plant parts), and sapropelic coals (derived from microscopic plant parts). The former are more abundant. Table 4.6 summarizes the two coals and their lithotypes.

Ash consists mainly of iron disulphides, quartz, carbonate and clay minerals; and a large suite of accessory minerals. The minerals are of three general types; detrital (transported), plant-derived (contained-in), and authigenic (introduced into peat during or after deposition) (McCabe, 1984).

In the mid-Zambezi Valley, the coal lithofacies is confined to the Main and Upper seams of the Gwembe Coal Formation of the Lower Karoo Group. The best locality to study the lithofacies is the Kazinze (Fig. 4.36a-d) Open pit (see Chapter 2), Siankondobo area (Fig. 2.2b). The lithofacies consists of thinly to very thickly bedded units (over 1 m) that contain argillaceous laminae mainly comprising carbonaceous and coaly mudstone with minor silty intercalations (Fig. 4.37a, b). Where the seam is plane bedded, it consists of thin laminae (< 1 cm) to medium beds (≤ 50 cm) (Fig. 4.37a). The Upper seams in the formation are usually thin (≤50 cm) and show predominant vitrain laminae. Spotting with siderite specks concentrated in the argillaceous layers (mudstone), and well-developed cleats occurring in the vitrain, the surfaces of which are usually coated with films of

Table 4.6 Coal macerals: group macerals, lithotypes and microlithotypes, their classification, origin, and properties (compiled from Davis et al., 1976; Stach et al., 1982 and McCabe, 1984).

MACERAL GROUP	MACERAL	MORPHOLOGY	ORIGIN		APPEARANCE		CHEMISTRY	CARBON-IZATION	LIQUEFACTION	LITHOTYPE	DESCRIPTION	COMPOS-ITION	MICRO-LITHO-TYPE	COMPOSITION
			SOURCE	PROCESS	colour in thin section	reflected light								
Vitrinite (Humin-ite)	Telinite	cellular structure	cell walls of trunks, branches, roots, leaves, bark, etc.	Mummi-fication			intermedi-ate	principal reactive		Vitrain	black, very bright lustre, thin layers break cubically, thick layers have conchoidal fracture	vitrinite macerals with < 20% exinite macerals	vitrite	>95% vitrinite
	Collinite	structureless	Reprecipitation of dissolved organic matter in a gel form		red-brown	inter-med-iate grey	hydrogen content and volatiles	constitu-ent in coking coal	susceptible to liquefaction	Clarain	finely stratified layers of vitrain, durain and, in some cases fusain; medium lustre	variable	Liptite	>95% exinite
	Vitrodetri-nite	fragments of vitrinite	very early degradation of plant and humic peat particles										Inertite	>95% inertinite
	Sporinite	fossil form	mega- and microspores							Durain	Black or grey, dull, rough fracture surfaces	mainly inertinite and exinite macerals	Fusite	inertite with no micrinite or macrinite
	Cutinite	bands which may have appendages	cuticles-- the outer layer of leaves, shoots and thin stems	Resistant									Clarite	>95% vitrinite and exinite
Liptinite (Exinite)	Resinite	cell filling, layers or dispersed	plant resins, waxes and other secretions		yellow	dark grey	higher hydrogen content and volatiles; more aliphatic	reactive during carboni-zation	susceptible to liquefaction	Fusain	Black, silky lustre, friable and soft.	mainly fusinite	Durite	>95% exinite and inertinite
	Alginite	fossil form	algae										Vitrin-ertite	>95% vitrinite and inertinite
	Liptode-trinite	fragments of exinite	degradation residues											

Table continued on the next page

Table 4.6 continued

Inertinite	Fusinite	empty or mineral filled cellular structure. Cell structure usually well preserved	oxidized plant material (biochemical oxidation) -- mostly charcoal due to burning of vegetation		opaque	white, yellowish light grey	Lower hydrogen content and volatiles; more aromatic	inert during carbonization	resistant to liquefaction	Cannel coal	Black, dull, lustre may be 'greasy', breaks with conchoidal fracture	fine maceral particles, usually dominated by sporinite	Trimacerite	vitrinite, exinite and inertinite each >5%
	Semifusinite	cellular structure	partly oxidized plant material	Intermediate between vitrinite and fusinte						Boghead coal	Black or brown, dull, homogeneous, breaks with conchoidal fracture, lustre may be 'greasy'	dominated by alginite		
	Macrinite	amorphous 'cement'	oxidized gel material											
	Inertodetrinite	small particles of fusinite, semifusinite and/or macrinite	redeposited inertinites											
	Micrinite		degradation of macerals, especially exinites, during coalification											
	Sclerotinite		mainly fungal remains	Resistant remains										

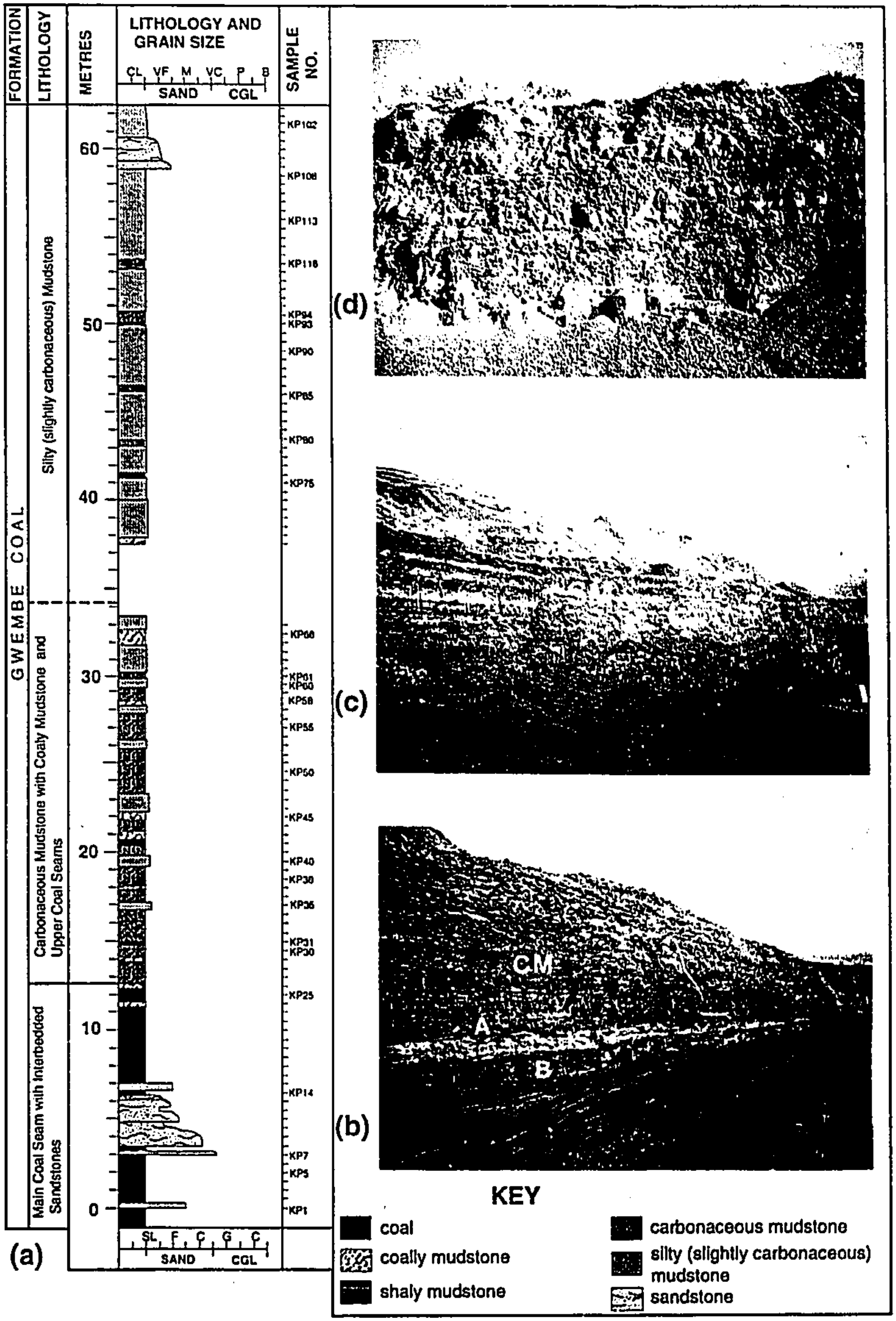
Fig. 4.36 Stratigraphy and photographs of the lower Gwembe Coal Formation in the Kazinze Open pit, Maamba Mine, Siankondobo area.

a: Stratigraphic log of the open pit shows the lithofacies of the lower Gwembe Coal Formation.

b: Western part of the open pit, exposing the Maamba Sandstone Member on the floor, overlain by Main Seam (B, locally C), Interseam Sandstone (IS), Main Seam (A) and mainly carbonaceous mudstone (CM). Person (left of centre, near cliff base) for scale.

c: Middle part of sequence, showing persistent beds of silty mudstone/siltstone (SM) lithofacies (whitish) interbedded with darker, more carbonaceous mudstone. Offset in beds is due to faulting. Person (base of cliff at centre) for scale.

d: Top part of the sequence, showing mainly silty mudstone alternating with thin beds of carbonaceous mudstone. Hammer (arrow) is 34 cm long.



FORMATION
LITHOLOGY
METRES
LITHOLOGY AND GRAIN SIZE
CL VF M VC P B
SAND CGL
SAMPLE NO.
GWEMBE COAL
Silty (slightly carbonaceous) Mudstone
Carbonaceous Mudstone with Coaly Mudstone and Upper Coal Seams
Main Coal Seam with Interbedded Sandstones
60
50
40
30
20
10
0
KP102
KP108
KP113
KP118
KP94
KP93
KP90
KP85
KP80
KP75
KP68
KP61
KP60
KP58
KP55
KP50
KP45
KP40
KP38
KP35
KP31
KP30
KP25
KP14
KP7
KP5
KP1
SL F C G C
SAND CGL
(a)
(b)
(c)
(d)
CM
A
S
B
KEY
coal
coaly mudstone
shaly mudstone
carbonaceous mudstone
silty (slightly carbonaceous) mudstone
sandstone

Fig. 4.37 Lithofacies of the Main Seam, Kazinze Open Pit

Gwembe Coal Formation

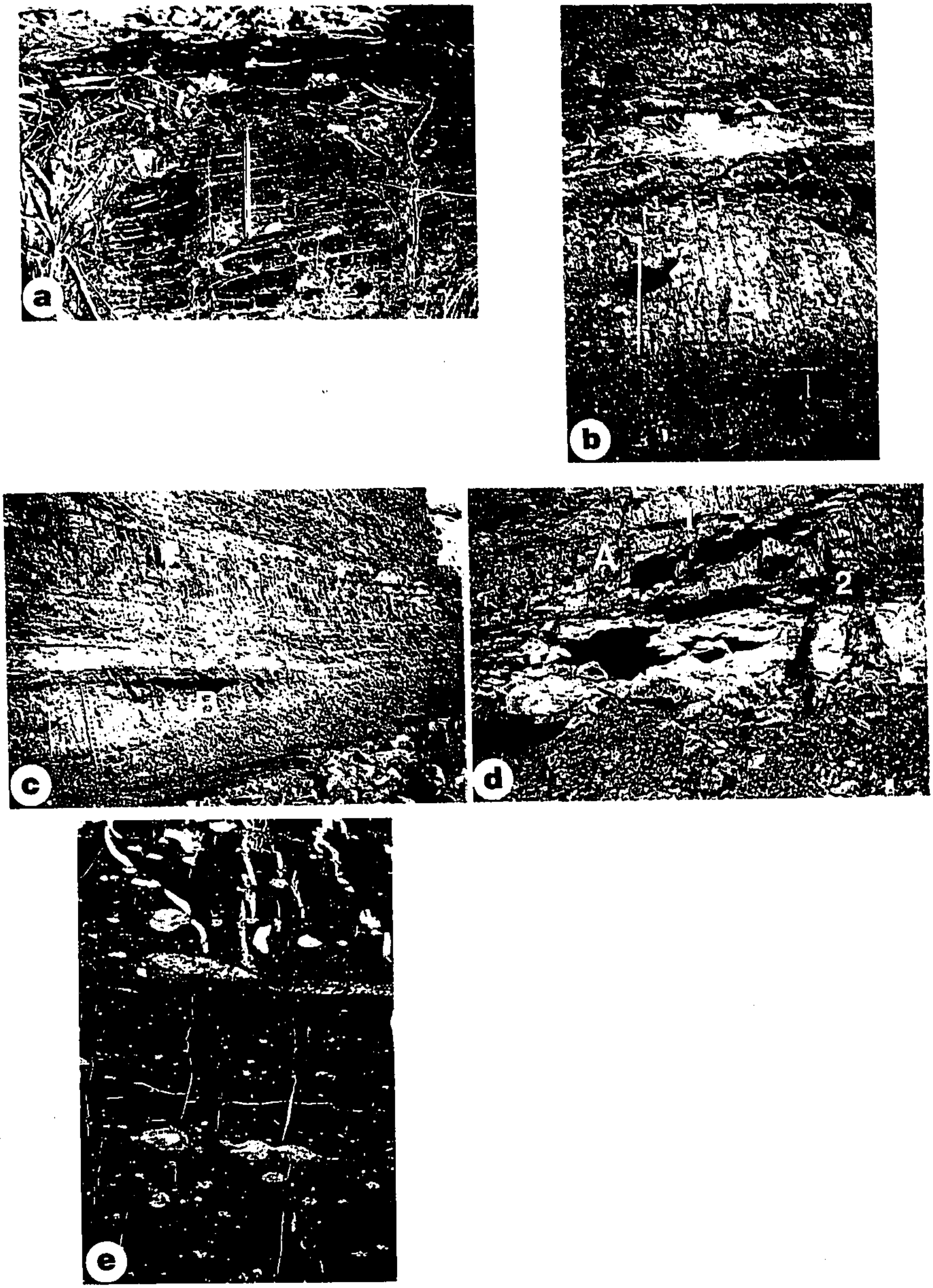
a: Horizontally laminated coal, with abundant cleats. Pen is 14 cm long.

b: Generally massive coal (B Seam) behind scale, overlain by Interseam Sandstone. C Seam (~ 50cm thick) is below hammer. Scale 2.1 m.

c: Main Seam (A and B) separated by Interseam Sandstone. Scale 2.1 m.

d: Detail of A Seam (A) showing conchoidal fracturing. Notice lighter intercalation of carbonaceous mudstone above the sandstone (2) and within the coal (1).

e: Photomicrograph (plane polarized light) of coal showing inert minerals, mainly siderite (altered to iron oxide), and ?calcite, infilling cleats (mainly vertical and subvertical). Also notice argillaceous lenses parallel to bedding. Long side of photograph is 15 mm.


a
b
A
1
2
c
d
e

carbonates, are some characteristic features of the upper seams.

The Main Seam consists of massive durain with a characteristic dull metallic lustre and conchoidal fracture (Fig. 4.37b, d). Banding (bright-dull alternations) is quite common on faces in the plane bedded units, and reflects interstratification of durain (semifusinite) and vitrain. Isolated lenses of mudstone, siltstone and sandstone occur in the Main Seam. The few thin sections examined showed that the coal is commonly laminated, with cleats filled by carbonates (calcite, ankerite and siderite revealed by SEM) and it contains blebs of siderite elongated parallel to bedding (Fig. 4.37e). In massive coals, blebs are more or less spherical, resembling spherulites. In hand specimen, many of the durain-rich coals contain elongate fragments and stringers of bright vitrain parallel to bedding. Clarain (finely stratified vitrain, durain and locally fusain) is also present, but less abundant. In the thinner seams, such as the Upper seams, vitrain laminae alternating with carbonaceous mudstone appear to be very important, and coaly mudstone is a characteristic lithofacies. The visible mineral matter consists mostly of pyrite, clay minerals, siderite (roses and spherulites) and quartz grains. These give a high ash content, suggesting that a considerable amount of detrital material entered the peat swamps. Pyrite occurs disseminated or as blebs (aggregates of pyrite grains) within the coal and along cleats. Calcite is common, occurring locally as coatings as well as thin plates and films in horizontal and vertical cleats. Siderite rosettes and spherulites, oxidized to limonite and other iron oxides, are also common.

Seven samples (three each from A and B seams, and one from an upper seam) were submitted to the Department of Energy, Mines and Resources - CANMET - Energy Research Laboratories for coal petrographic analysis (Price et al., 1992). In addition, three samples - a coal, a coaly mudstone and a carbonaceous mudstone, were also submitted for similar analysis.

Maceral analysis measures the proportion of the originally derived, microscopically recognizable components of coal which are defined by their morphology, colour and reflectances in reflected light (Hunt and Hobday, 1984). Petrographic properties of coal can be described by means of transmitted light or incident light microscopy. Incident light microscopy has the advantage of studying the entire range of coal rank (peat to anthracite and graphite) both qualitatively and quantitatively compared to transmitted light in which higher coal ranks appear opaque (Bustin et al., 1983).

Prepared disks and polished sections of coal were studied using incident light microscopy at a magnification of 625X. The main parameters used to distinguish the macerals included (i) reflectance and anisotropy, (ii) morphology, relief, and size, (iii) etching, and (iv) fluorescence. For example, three maceral groups can be distinguished in low to intermediate rank coals (lignite to low volatile bituminous) by different grey levels or reflectivity (Fig. 4.38a), as follows:

(i) liptinite (L) = dark grey, low reflecting

(ii) vitrinite (V) = medium grey, medium reflecting

(iii) inertinite (S) = light grey to white, high reflecting.

Shape, size, and internal structures are used to distinguish macerals where reflectance is similar but morphology is different, for example, the preservation of morphology in fusinite distinguishes it from semifusinite (Fig. 4.38b, c), and some macerals show differences in relief.

The main component of the Main Seam is inertinite, which represents oxidized and degraded plant remains that are divided principally into semifusinite (Fig. 4.38d, e) and inertodetrinite. Semifusinite is the main component, occurring in non-structured forms (e.g. Fig. 4.38a, c), but some shows botanical structure (Fig. 4.38d). Fusinite (Fig. 4.38b), micrinite (Fig. 4.39a) and macrinite (Figs. 4.38e, 4.39b) are usually present. Vitrinite (Fig. 4.39a) which originated mainly from humified 'woody' plant remains, rarely exceeds 10% in the Main Seam. Liptinite (Fig. 4.39b), which is composed mainly of spores, cuticles, resinite or locally algae, is normally less than 4% in the Zambian coal. Ash is commonly fine (< 5 mm) and occurs disseminated or as aggregates in clay-rich matrix. It is an important component (Fig. 4.39c, d) of the coal, consisting mainly of siderite roses and spherulites (usually altered to limonite and other iron oxides), clay minerals (predominantly kaolinite), quartz, and other carbonates (calcite and ankerite). Siderite, calcite and ankerite fill organic cellular cavities, or occur as tissue replacements and lenses alternating with coaly-rich layers. Siderite is pale creamy-brown where fresh, but on oxidation becomes red, giving the coal seam a mottled appearance (red and black).

Fig. 4.38 Coal lithofacies of the Main Seam, Kazinze Open Pit. All photomicrographs in incident light. Sample numbers (KP prefix) are shown on Fig. 4.36.

Gwembe Coal Formation

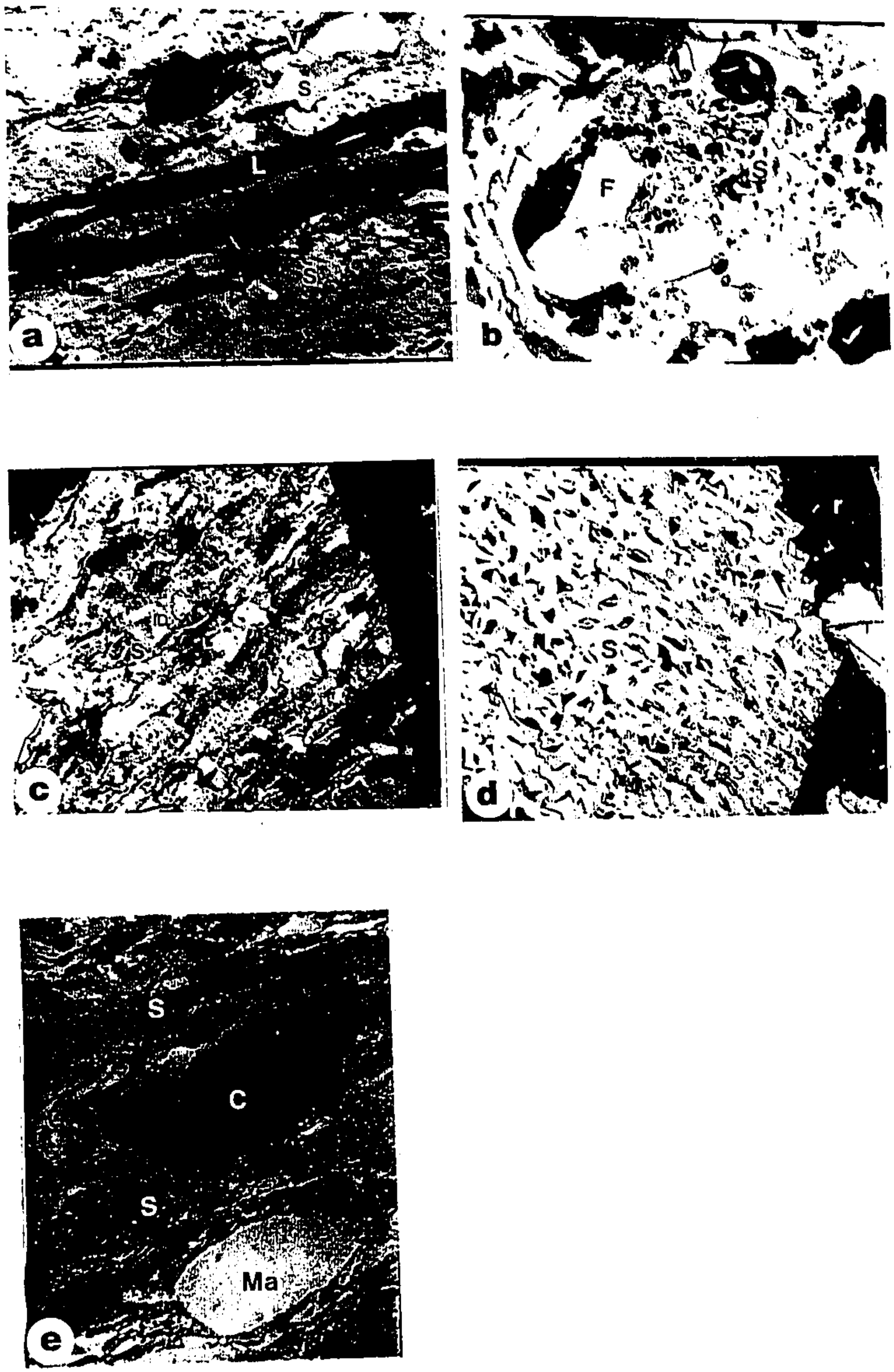
a: Alternating laminae of liptinite (L), semifusinite (S), and vitrinite (V). (KP2S). Long axis of photograph is 1.05mm.

b: Fusinite (F) with an inclusion of semifusinite (S). Notice some mineral matter filling rounded pores. (KP8S). Long axis of photograph is 1.05mm.

c: Discontinuous stringers of liptinite (L) in semifusinite (S). The bright small pieces are inertodetrinite (ID). (KP19C). Long axis of photograph is 1.05mm.

d: A large piece of semifusinite (S) with a cellular structure. Smaller pieces with no visible structure are also present. r is resin. (KP16C). Long axis of photograph is 1.05mm.

e: Corpocollinite (C) and macrinite (Ma) grains embedded in semifusinite (S). Notice that the semifusinite appears to be draped around C and Ma grains. (KP19S). Long axis of photograph is 1.05mm.



a
V
S
L
S
b
F
S
c
d
S
r
e
S
C
S
Ma

Fig. 4.39 Coal lithofacies of the Main Seam, Kazinze Open Pit. All photomicrographs in incident light. Sample numbers (KP prefix) are shown on Fig. 4.36.

Gwembe Coal Formation

a: Vitrinite (V) with lenses of micrinite (Mi); a characteristic feature of the Zambian coals, (KP8C). Long axis of photograph is 1.05mm.

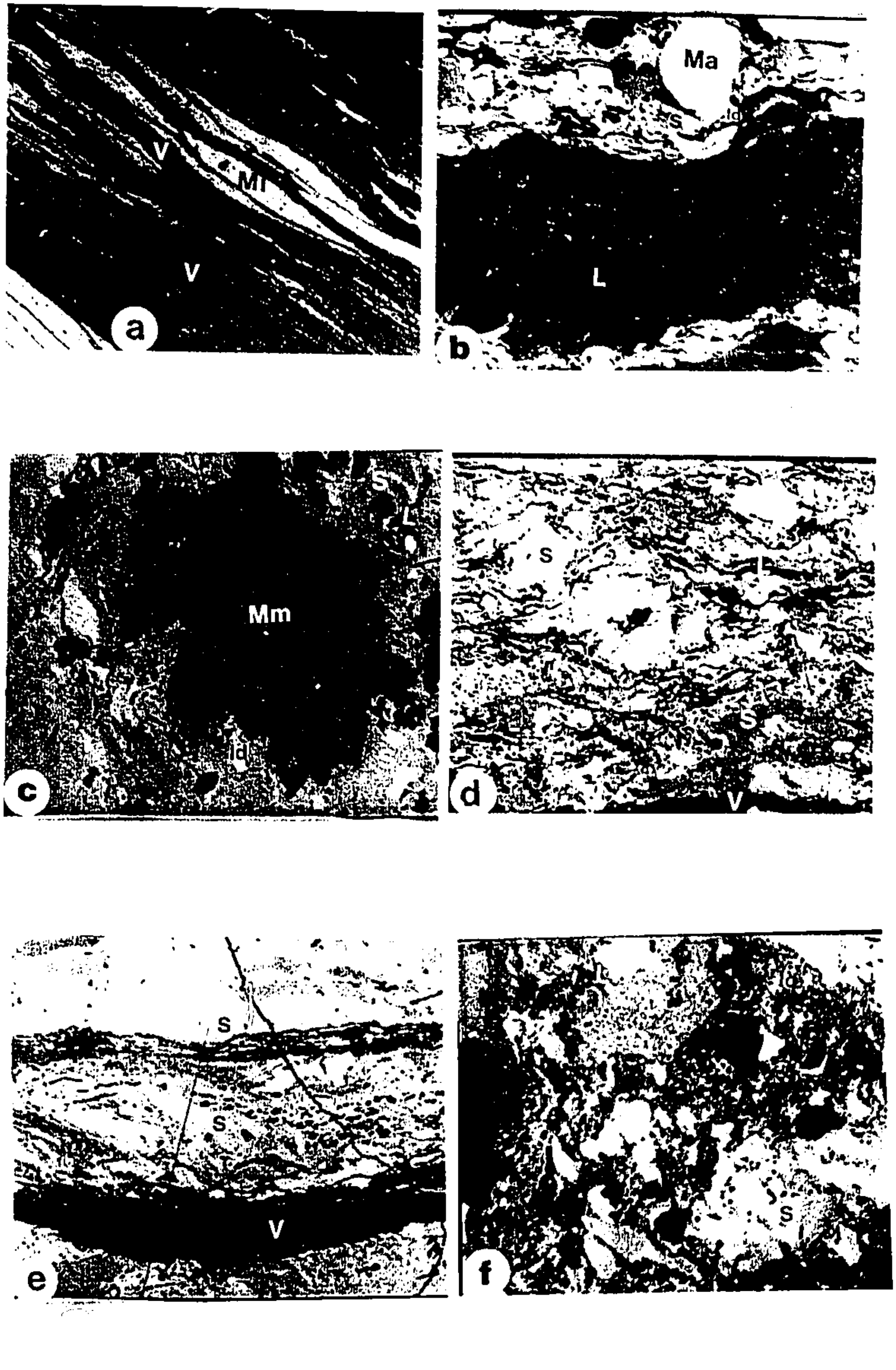
b: Characteristic structure of liptinite (L). Notice that semifusinite (S), liptinite and elongated bright inertodetrinite (Id) grain flow around the macrinite (Ma). (KP6C). Long axis of photograph is 1.05mm.

c: Irregularly rounded body of mineral matter (Mm) in semifusinite (S)-rich coal. The darker discontinuous stringers are liptinite (L). (KP19S). Long axis of photograph is 1.05mm.

d: Radial structure in siderite spherulite (white) in semifusinite (S)-rich coal with vitrinite (V) and liptinite (L) stringers. The small bright pieces are inertodetrinite. (KP200). Long axis of photograph is 1.05mm.

e: Interlaminated semifusinite (S) and vitrinite (V). The bright small pieces within vitrinite (forming discontinuous laminae) are inertodetrinite. (KP16S). Long axis of photograph is 1.05mm.

f: Brighter inertodetrinite (Id) pieces and semifusinite (S). Liptinite (L) is also present. (KP22S). Long axis of photograph is 1.05mm.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From microscopic features, the Main Seam consists of two characteristic coal types, banded (Fig. 4.39e) and non-banded (Fig. 4.39f). The massive (non-banded) type is composed largely of semifusinite associated with other macerals in minor amounts (Fig. 4.38d); the banded type consists of alternating thick semifusinite layers and thin vitrinite layers (Fig. 4.38a). Laminae and intercalations of other macerals (e.g liptinite) are present locally in association with the major ones (Figs. 4.38a and 4.39b). The two types are consistent with field observations in that the microscopically banded type is usually associated with the finely banded coals (lamina thickness from 1 mm to slightly more than 1cm) and the non-banded type is associated with the more coarsely banded (bed thickness over 1 cm) but internally massive coals.

Upper Seams are laminated with numerous vitrain laminae up to 1cm thick, separated by duller, fine-grained clarain-fusain laminae and locally thin, muddy partings of similar thickness. The Upper seams consist mainly of mineral matter alternating with vitrinite laminae (Fig. 4.40a-d). Although the Main Seam consists mainly of the inertinite maceral group, the single sample from the Upper seams has a high vitrinite content (60%). This value corresponds to high vitrinite content of the Main Seam obtained by Utting and Wielens (1992) from the mid-Zambezi Valley and other basins in Zambia.

In summary, the Zambian coal shows that all three maceral groups are present, with the inertinite (largely semifusinite) accounting for 84%, vitrinite 12% and liptinite 4% (Table 4.7). Similar results were reported by Alpern (1968, cited in Money and Drysdall, 1975), namely 95% inertinite, 3% vitrinite and 2% exinite (liptinite). In addition to the macerals listed in Table 4.7, the inertinite group includes macrinite and semiinertodetrinite, all of which have been observed in Zambian coal. The vitrinite maceral group recorded in Zambian coals includes collinite (most abundant) and tellinite, while the liptinite group comprises sporinite, cutinite and detritoliptinite. Alginite and resinite macerals have not been observed. Most of the lithotypes given in Table 4.6 have been identified in the coal fields in the study area as well. The durite microlithotype (semifusinite) is predominant, and is associated with lesser amounts of vitrite and liptite.

The ash content is relatively high, with an average of 22%, fixed carbon 54.7% (61.2%, this study), volatiles 18.6% (22%, this study), moisture 2.4% and combustible

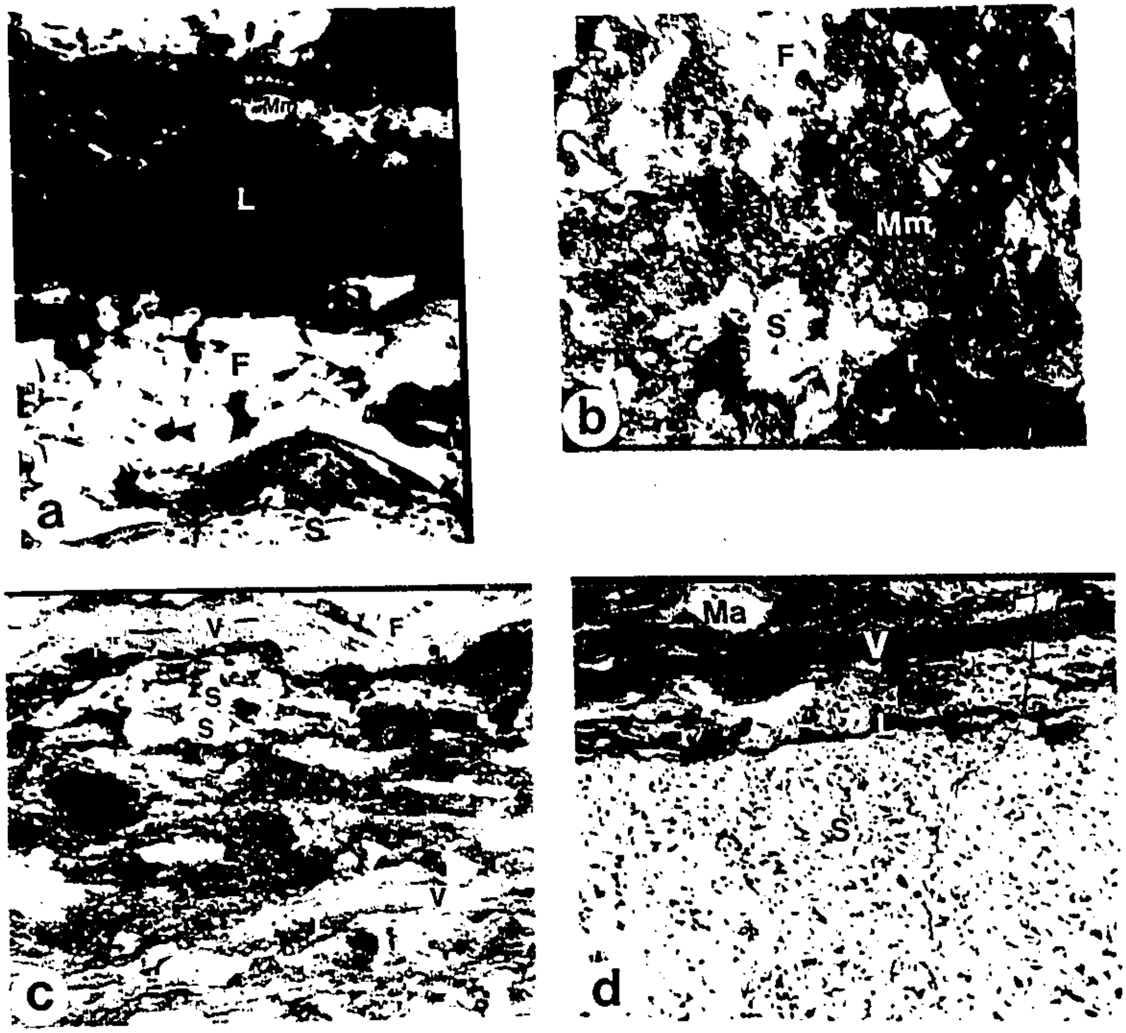

Fig. 4.40 Coal lithofacies of the Upper Seam, Gwembe Coal Formation, Kazinze Open Pit. All photomicrographs in incident light. Sample numbers (KP prefix) are shown on Fig. 4.36

a: Laminae of liptinite (L) with mineral matter (Mm), fusinite (F) and semifusinite (S). Notice liptinite just below fusinite (F). (KP66C). Long axis of photograph is 1.05mm.

b: Mineral matter (Mm) with pieces of fusinite (F), semifusinite (S) and inertodetrinite (small bright pieces). Mm may be associated with liptinite. r is resin. (KP66C). Long axis of photograph is 1.05mm.

c: Irregular laminae of vitrinite (V) and discontinuous pieces of semifusinite (S). Note liptinite (L) below vitrinite (V). Some liptinite is associated with mineral matter. (KP66S). Long axis of photograph is 1.05mm.

d: Large piece of semifusinite (S) with cellular structure. Notice laminae of vitrinite (V), liptinite (L) and a grain of macrinite (Ma). (KP66S). Long axis of photograph is 1.05mm.

Table 4.7 Characteristics of Coal from the Main Seam, Maamba Mine, Kazinze Open Pit.

Coal Petrography	Maceral	Intervals	Petrographic intervals present, indicating vertical changes in composition of seam
		Lithotypes	Durian greatly predominates in the Main Seam. Various amounts of vitrain, clarain and fusain.
		Amounts	Inertinite aleways more than 80%; vitrinite 12% or less; lipinite 4% or less.
		Dominant types	Inertinite occurs as semifusinite, micrinite inertodetrinite and fusinite; vitrinite mainly as collinite; and liptnite as liptite.
		Preservation	Good; preserved cellular structures in semifusinite and fusinite.
	Mineral Matter		Siderite (rosettes and spherulites) altered to limonite and other iron oxides; clay minerals and carbonates (calcite and ankerite); syngenetic pyrite mainly finely disseminated and as patches, clots, blebs and aggregates.
Proximate analysis of productive coals	Fixed Carbon Ash Volatile matter Rank		From 58% to 65% From 13% to 22% From 17% to 25% Low Volatile Bituminous.
Ultimate analysis of productive coals.	Carbon Hydrogen Nitrogen Sulphur Ash Oxygen (by difference)		From 68% to 75% From 2.5% to 4.0% From 1.4% to 1.6% From 0.35% to 3.25% From 13% to 22% From 4.4% to 6.3%

sulphur 1.5% (1.3%, this study) and the coals have a calorific value of 5933 kcal/kg (Money and Drysdall, 1975). Total sulphur, mainly from pyrites, is much higher (up to 3.25%) (Table 4.7) in the Kazinze Open pit than in the Mulungwa and Nkandabwe areas (0.77% and 1.1% respectively).

4.3.2.5 Sheet sandstone lithofacies (S_{shs}) (Interseam Sandstone)

This lithofacies occurs as thin sheets (up to 50 cm maximum) that are laterally persistent (Fig. 4.41a-c) and grade laterally and vertically into dark grey, carbonaceous sandstone and siltstone, and eventually mudstone and/or coal. Less commonly the sandstone grades laterally into small channel-form bodies. The lithofacies is internally massive, but normal or inverse grading and/or horizontal to low-angle stratification is locally present (Fig. 4.41a, b). Seatearths or underclays (palaeosols with rootlets) occur only rarely, which is anomalous for a seam (Main Seam) as thick as this. However, root traces were observed in a medium- to coarse-grained, whitish grey, sheet sandstone at the base of the B Seam (Fig. 4.41b). Where present, stratification is defined by carbonaceous detritus.

4.3.2.6 Lenticular sandstone lithofacies (S_{lls}) (Interseam Sandstone)

This lithofacies (Figs. 4.41d, 4.42) occurs as beds 0. 5 to 1.5 m thick. The thin beds grade into channel-form bodies up to 10 m wide and less than 2 m deep (Figs. 4.41d; 4.42a). The beds are either massive, or graded (normal or inverse). More commonly they have irregular continuous and discontinuous laminae (up to 3 mm thick), stringers and streaks of carbonaceous matter draping scour-and-fill lenses that show internal low-angle cross-stratification (Fig. 4.42b, c). These lensoids, up to 50 cm long and 15 cm thick, become smaller upward in the unit (Fig. 4.42c). Laminae are defined by carbonaceous material. Basal contacts between the sandstone and coal are usually sharp; however, the tops of the fining-upwards units commonly grade into mudstone or coal. Bedding is crudely defined by carbonaceous material and locally by alignment of coal clasts. Most of the sandstones occur in simple irregular beds or amalgamated beds, usually with erosional basal contacts overlain by dark grey, carbonaceous conglomeratic lag, and then by more

Fig. 4.41 Lithofacies of the Interseam Sandstone (Main Seam)

Gwembe Coal Formation

a: Sheet sandstone lithofacies. Very coarse-grained, generally massive sandstone becoming faintly stratified (horizontal to low-angle) towards top. Notice root traces. Kazinze Open pit. Pencil is16 cm.

b: Another part of sandstone bed in (a) showing root traces and coaly fragments. Pen is 13 cm long.

c: Lenticular sandstone lithofacies. Notice a dark grey carbonaceous lower portion, sharply overlain by cream whitish grey, massive sandstone (middle) and intercalated irregular carbonaceous/coaly mudstone towards top. Note also thin sheet sandstone bed below the lenticular sandstone. Kazinze Open pit. Dark grey bed (arrowed) is 12cm.

d: Lenticular sandstone lithofacies, in channel form. Notice other thinner sandstone bodies below the larger one. Kazinze River Section 3, Siankondobo area. Scale 2.1 m

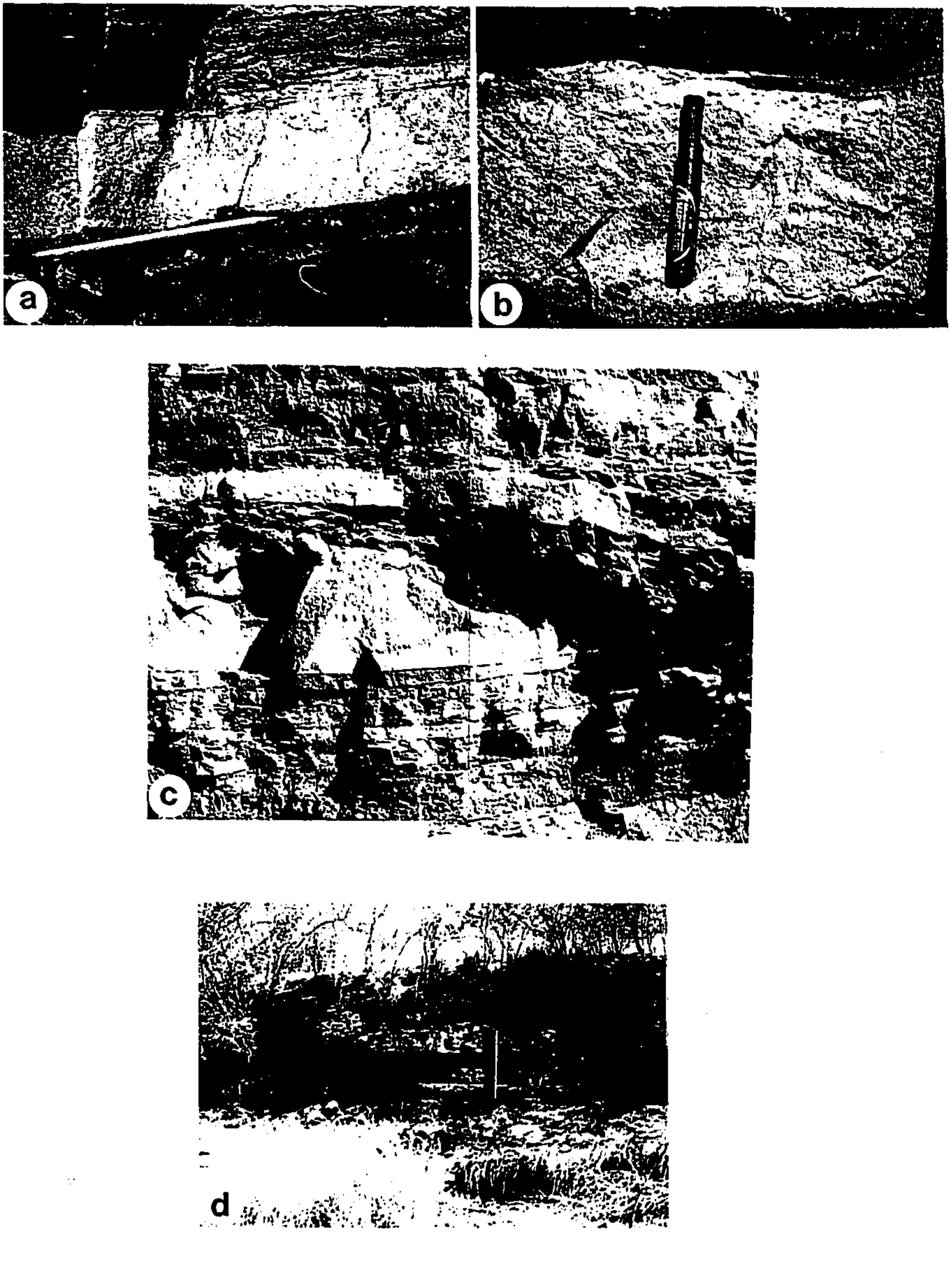
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Fig. 4.42 Lithofacies of the Interseam Sandstone (Main Seam)

Gwembe Coal Formation

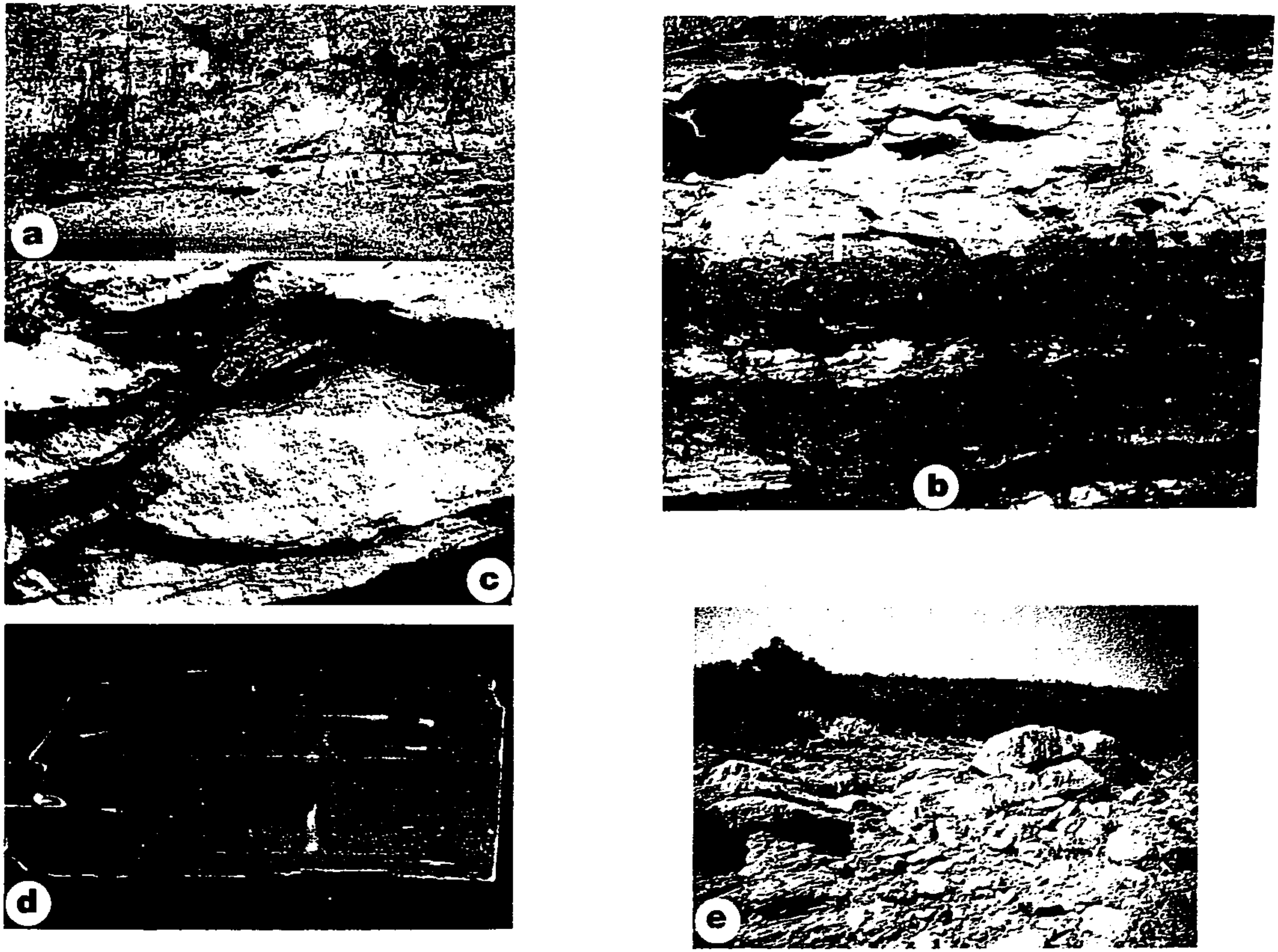
a: Lenticular sandstone lithofacies in channel-form (~10 m long and 1.5 m thick) sandstone body, in Kazinze Open pit, behind person.

b: Detail of the channel sandstone in (a) above showing lensoid bodies draped with coaly laminae. Notice thinner sandstone in the coal below. White line is 12 cm.

c: Detail of one of the lensoids in (b) above, showing cut-and-fill structure involving foreset laminae. Coal drapes common. Pen is 14 cm.

d: Polished slab of horizontally laminated siltstone from the upper part of the channel sandstone body in (b) above. Sample length is 20 cm.

e: Lenticular sandstone lithofacies consisting of coarse-grained amalgamated sandstone. Zhimu River Section 1, Mulungwa area. Hammer (arrow) for scale.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whitish grey, much cleaner, medium- to coarse-grained, slightly carbonaceous sandstone (Fig. 4.42b). This is in turn overlain by dark grey medium- to very fine-grained horizontal (Fig. 4.42d) to undulatory beds of carbonaceous sandstone/ siltstone which show small-scale ripple cross-lamination. Coaly intercalations are common throughout the lithofacies. In the Zhimu River Section, the Interseam Sandstone contains irregular amalgamated beds with abundant carbonaceous intercalations (Figs. 4.42e, 4.43a). Pyrite is common in the Interseam Sandstone.

Dewatering structures, slumps and folded sandstones (Sd) are also common in the lithofacies (Fig. 4.43b-d). These were observed in Mulungwa River Section 5, Mulungwa area, and occur locally elsewhere in the study area.

Study of 40 samples and thin sections from the sheet and lenticular sandstone lithofacies indicates grain size ranges from very fine sand to pebbles (1 cm maximum across). The sandstones show a framework of quartz, feldspar, minor rock fragments and muscovite (Fig. 4.43e). Grain contacts are planar to concavo-convex, with no preferred grain orientation due to the equidimensional nature of the grains. However, in the horizontally laminated fine-grained carbonaceous siltstone and sandstone (Fig. 4.43f), laminae are defined by composition and grain size differences commonly as alternating carbonaceous-rich and quartz-rich laminae (Fig. 4.43f). The grains are subangular to subrounded. Quartz is the predominant grain component with minor feldspar and rock fragments. Based on 20 samples, clay minerals are predominantly kaolinite, illite and smectite.

4.3.2.7 Coaly mudstone lithofacies (M_{cl})

This lithofacies consists of predominantly laminated and subordinate massive greyish black to black mudstone (Fig. 4.44a, b). Abundant coal fragments in carbonaceous mudstone qualifies the mudstone as coaly mudstone (Fig. 4.44c, d). The mudstone therefore contains coaly (up to 60%) and woody fragments, and exinous and finely dispersed organic debris. The lithofacies is intermediate in composition between coal and carbonaceous mudstone (Figs. 4.33 and 4.36a, b). Plant stem impressions and scattered leaf fragments form bright aggregates within the lithofacies. The mudstone is commonly

Fig. 4.43 Lithofacies of the Interseam Sandstone (Main Seam)

Gwembe Coal Formation

a: Lenticular sandstone lithofacies consisting of amalgamated sandstone with abundant carbonaceous intercalations. Zhimu River Section 1, Mulungwa area.

b: Very irregular sandstone body (soft-sediment deformation) of the lenticular sandstone lithofacies. Mulungwa River Section 5, Mulungwa area.

c: Deformed and contorted, highly carbonaceous sandstone of the lenticular sandstone lithofacies. Mulungwa River Section 5, Mulungwa area. Knife is 9.5 cm long.

d: Polished slab showing sandstone bodies modified by soft-sediment deformation. Mulungwa River Section 5, Mulungwa area. Scale in cm.

e: Photomicrograph (crossed nicols) showing the texture of the sandstone. It consists mainly of quartz and feldspar with minor muscovite. Kazinze Open pit. Long side of photograph is 3 mm.

f: Photomicrograph (crossed nicols) of Fig. 4.42d, showing parallel laminae rich in detrital minerals (mainly quartz) alternating with laminae rich in mica, kaolinite and carbonaceous matter. The yellowish orange laths are muscovite. Kazinze Open pit. Long side of photograph is 7.8 mm.

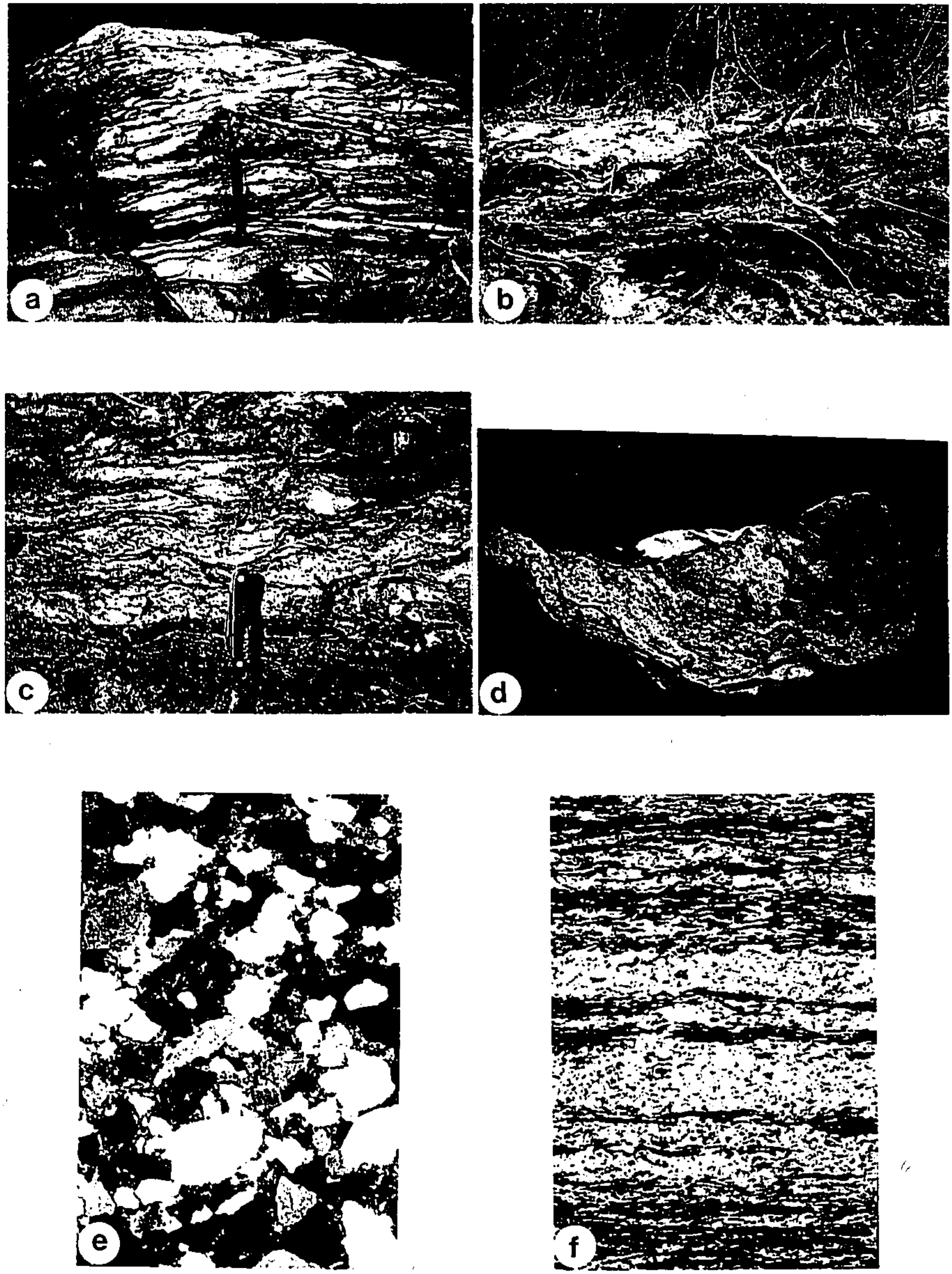
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Fig. 4.44 Coaly mudstone lithofacies

Gwembe Coal Formation

a: Polished slab showing massive coaly mudstone from Kazinze Open pit. Scale in cm.

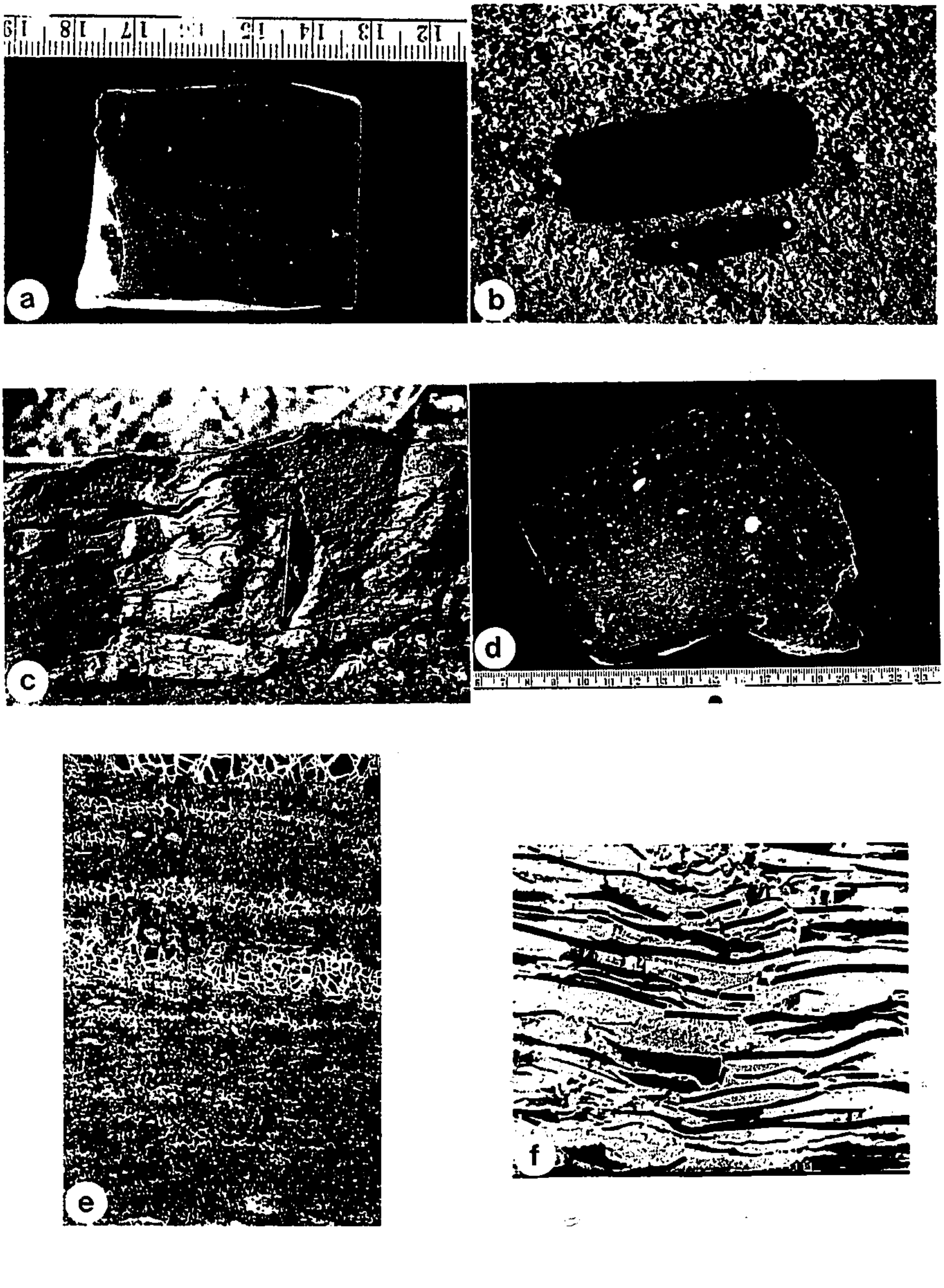
b: Polished slab (above knife) showing laminated coaly mudstone, with laminae of bright vitrinite (top), and carbonaceous and silty laminae. Mulungwa Section 6, Mulungwa map area. Knife is 9.5 cm long.

c: Greyish black coaly mudstone, weathering to yellowish orange with abundant irregular coal stringers and streaks. Notice mudstone lenses in places defined by coal drapes. Zhimu River Section 1, Mulungwa area. Pen is 14 cm long.

d: Polished slab from (c) above showing bright, silty mudstone clasts, black coal streaks and stringers. Scale in cm.

e: Photomicrograph (plane polarised light) of (b) above showing reddened elongate siderite spherulites distributed parallel to bedding in a matrix of carbonaceous matter. The wire mesh-like feature is associated with coal layers and filled by calcite/ankerite. Some argillaceous inclusions are also present, for example at the bottom of the photograph. Long side of photograph is 19.4 mm.

f: Photomicrograph (SEM) showing thin siderite laminae (white) in ankerite-filled mesh-like structures. Zhimu River Section 1, Mulungwa area. Long side of photograph is 1.4 mm.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spotted or contains stringers and streaks of coal that show blackish red to brick red iron oxide coloration, presumably an alteration of siderite.

In outcrops, the coaly mudstone forms units thicker than 7 m (e.g. in the Mulungwa River Section 5), that consist of beds 1-10 cm thick. Numerous intercalations of coal and subordinate carbonaceous, sideritic and silty mudstone interlayers and fragments are common throughout the lithofacies. Cream-white siderite spherulites, 2-3 mm across, are characteristic in the more argillaceous laminae and layers of coaly mudstone and coal. Horizontal lamination is defined by alternating dull and bright laminae (clarain and vitrain, respectively). In places, compaction of the laminae and streaks coupled with the presence of mica flakes and specks has resulted in shaly coaly mudstones that consist of beds usually less than 10 cm thick. The bright vitrain (< 1 mm) is commonly made of fossil leaves. However, massive blocks that contain abundant comminuted vitrain with an irregularly breaking habit are also present. Along bedding and joint planes, calcite and pyritiferous mineralisation is present.

In one hand specimen, the mudstone is spotted whitish grey with abundant black coaly stringers (Fig. 4.44d) and is weathered yellowish orange due oxidation. In thin sections, the whitish grey spots are seen to be silty mudstone intraclasts (Fig. 4.44e), and some clasts appear deformed. Fractures cut across the compacted coal fragments and are filled by fibres and radiating blades of 'beef' calcite, in places resulting in cone-in-cone structures. The cone-in-cone structures have incorporated fragments of the host material. This type of carbonate composes almost the entire (95-99%) thin section. However, the mudstone consists mainly of organic matter (60%), silt-size detrital grains, siderite and other mudrock intraclasts (Fig. 4.44e). The organic matter forms discontinuous irregular horizontal laminae and stringers with abundant siderite blebs (red, Fig. 4.44e). Vitrain layers with preserved cellular structure contain fractures filled by siderite and ankerite (SEM, Fig. 4.44f). The detrital grains (quartz, feldspar and mica) in organic matter- and clay-rich matrix form less than 10% of the rock, with quartz as the most abundant (up to 5%). The platy mica grains are oriented parallel to bedding, whereas the scattered quartz grains (up to 0.5 mm), have laminae deflected around them. Isolated blood-red cloudy masses of iron oxide (siderite originally) are present. In places a mineral with low birefringence, vermicular fibrous texture, and sweeping extinction, probably kaolinite, is common in the mudstone.

4.3.2.8 Carbonaceous mudstone lithofacies (M_{ca})

This lithofacies consists of mainly massive, dark grey/black, highly carbonaceous mudstone that weathers to reddish, yellowish, and orangish brown colours.

In outcrops, the lithofacies occurs as thinly to very thickly bedded units over 2 m thick (Fig. 4.45a) or as thin intercalations within other lithofacies (Fig. 4.45b). The mudstone units can be up to 17 m thick and are characterised by intercalations of light-coloured silty mudstone (Figs. 4.45a, c and 4.36a), bright black coaly mudstone and yellowish mottled sideritic mudstone. Coal beds are also present.

In hand specimens, the mudstone is made up of carbonaceous mud and clay, with scattered detrital grains. The mudstone is massive (Fig. 4.45d), but commonly contains irregular, usually discontinuous horizontal laminae and stringers of organic matter, some of which are separated by thin, light grey, silty mudstone intercalations (Fig. 4.45c). Coal (vitrinite) forms discontinuous horizontal and irregular bright laminae and stringers; silty intercalations and lenses are commonly draped by carbonaceous matter. Where strongly indurated, the mudstone breaks conchoidally or more commonly breaks down to irregular, massive lensoids (Fig. 4.45d). Poorly developed alternating bright and dull laminae forming clarain are present. The mudstone is rarely fissile. Plant stem and leaf fragments occur commonly as vitrain impressions.

In thin section, organic matter can be seen as disseminated material or as large clasts that form up to 50% of the mudstone. The detrital grains can be up to 25% in the silty intercalations, but are usually less than 15% in the lithofacies (SEM, Fig. 4.45e). The grains are mostly silt-size, rarely exceed 0.3 mm in diameter (maximum 0.5 mm) and are mainly quartz. However, subangular intraclasts of carbonaceous mudstone are present with coaly laminae bent around them. Some coaly fragments display poorly preserved cell-like structures. Laminae are bent around coarser grains (0.3 mm). Normal grading is present with some of the coaly fragments deformed (Fig. 4.45f). Cloudy masses of presumably carbonate minerals are disseminated in the mudstone, and are likely to be either sideritic or

Fig. 4.45 Carbonaceous mudstone lithofacies

Gwembe Coal Formation

a: Thinly to very thickly bedded, generally massive, fractured carbonaceous mudstone. Notice whitish grey silty intercalations, particularly towards top of photograph. Kazinze Open pit.

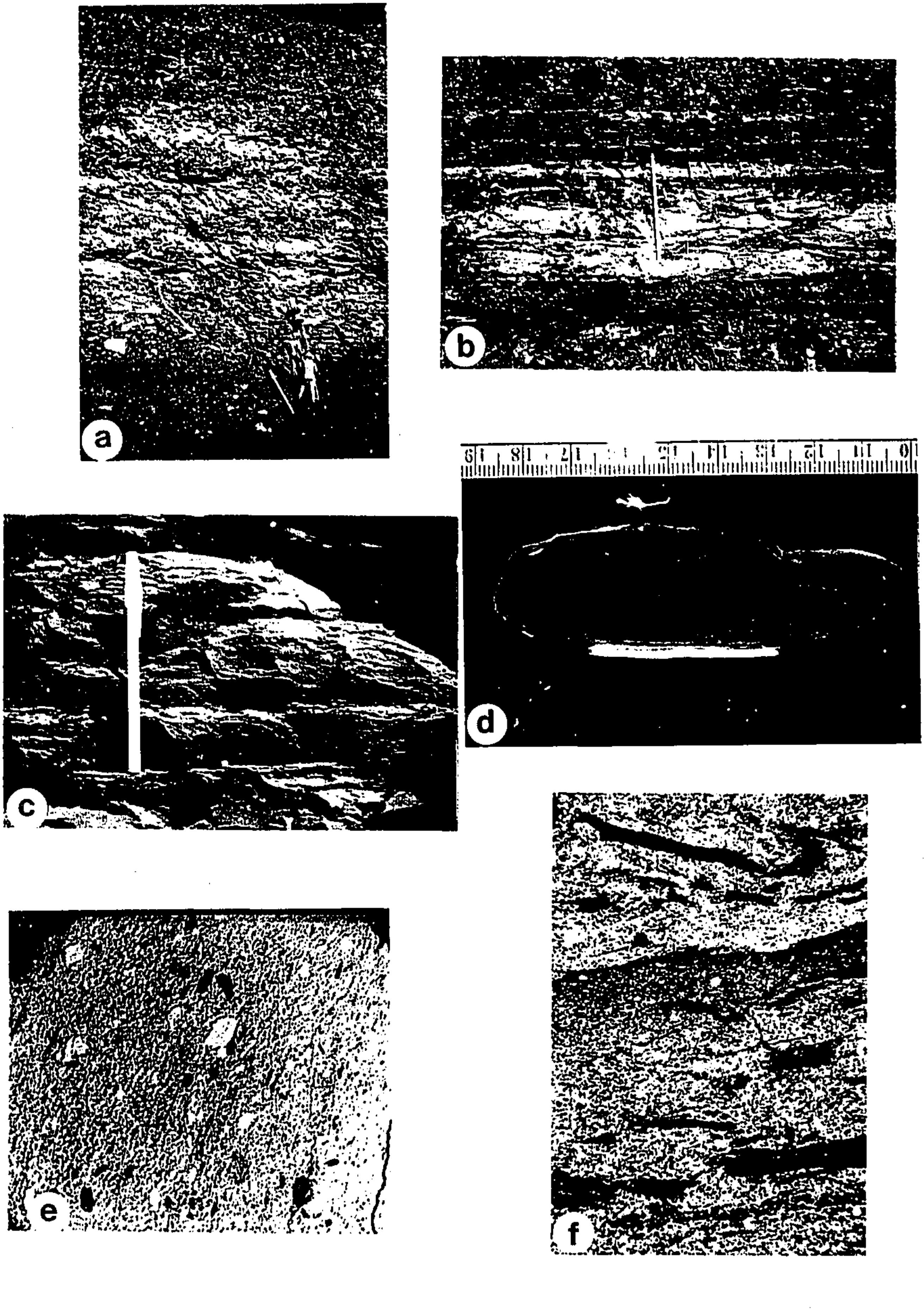
b: Carbonaceous mudstone/siltstone lithofacies intercalated with coal and lithofacies of the Interseam Sandstone (white). Scale 2.1 m.

c: Carbonaceous mudstone with silty mudstone intercalations (lighter coloured). Characteristic fracturing into lenses and small fragments. Izuma Open pit. Pen 15 cm long.

d: Polished slab of a lens of massive carbonaceous mudstone from (c) above. Scale in cm.

e: Photomicrograph (SEM) of (d), showing outsized angular quartz grains and black coaly clasts. Crude lamination is indicated by elongate grains and fine black (carbonaceous) striae. Izuma Open pit. Scale indicated on photograph.

f: Photomicrograph (crossed nicols) showing normal grading. Notice coaly fragments also decrease in size upwards. The base of the second graded unit contains coaly fragments that are deformed. The light pinkish grains are mainly quartz and the iron stained grains are siderite. Kazinze Open pit. Long side of photograph is 12 mm.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dolomitic.

4.3.2.9 Silty (slightly carbonaceous) mudstone lithofacies (M_s)

The silty mudstone lithofacies is the predominant component (over 70%) of the Upper Gwembe Coal Formation. In outcrops, the lithofacies occurs as very thinly to very thickly bedded units (cm to 10+ m) of massive silty mudstone and siltstone (Fig. 4.46a, b) with subordinate laminated silty mudstone. On fresh surfaces it is usually blocky (Fig. 4.46b) with a siliceous appearance and a conchoidal fracture. The mudstone is variegated, displaying all shades of grey (light olive grey, light, medium to dark grey, greyish black) with light olive grey predominant (Fig. 4.46c-e). For example, it is common to see medium to dark grey stringers, layers, patches, spots and elongate to sub-spherical clasts and flakes in light olive grey mudstone (Fig. 4.46c). In Fig. 4.46d, the orangish yellow elongate irregular intraclasts increase in proportion upwards, whereas in Fig. 4.46e, light grey elongate irregular intraclasts in greyish black matrix are brecciated and generally aligned parallel to bedding. The former also shows local black coloration that fades downwards (top left of photograph) and contains many dark grey traces, possibly rootlets or burrows. These form fining-upward units (observed in cores only) consisting of basal mudstone breccia with closely packed angular fragments (e.g. Fig. 4. 46e) overlain by matrix-supported mudclast conglomerate that grades upwards into dark carbonaceous mudstone with scattered intraclasts of silty mudstone; locally the units form cycles. In places, the mudstone consists of small carbonaceous lenses draped by darker organic matter. On weathered surfaces the mudstone is fragmented, yellowish and orangish brown (Fig. 4. 46a), brownish black, greyish red and brownish yellowish grey. Mottled combinations of these colours are common.

The laminated silty mudstone forms units up to 1.5 m thick, consisting of beds less than 10 cm thick (Fig. 4.46f). These are commonly horizontally laminated (Fig. 4.46f), and in one sample alternating whitish grey laminae (less than a millimetre) and medium-grey laminae (up to 2 mm), resemble varves (Fig. 4.47a, p. 173) and grade into undulatory laminae. Weathered exposures are commonly fractured into small lensoids and slabs (for thinly bedded mudstone), and where micas and clays are concentrated, the mudstone is

Fig. 4.46 Silty mudstone lithofacies

Gwembe Coal Formation

a: Massive, fractured reddish brown silty mudstone. Zhimu River Section 1, Mulungwa area. Lower portion of scale in black is 1 m long.

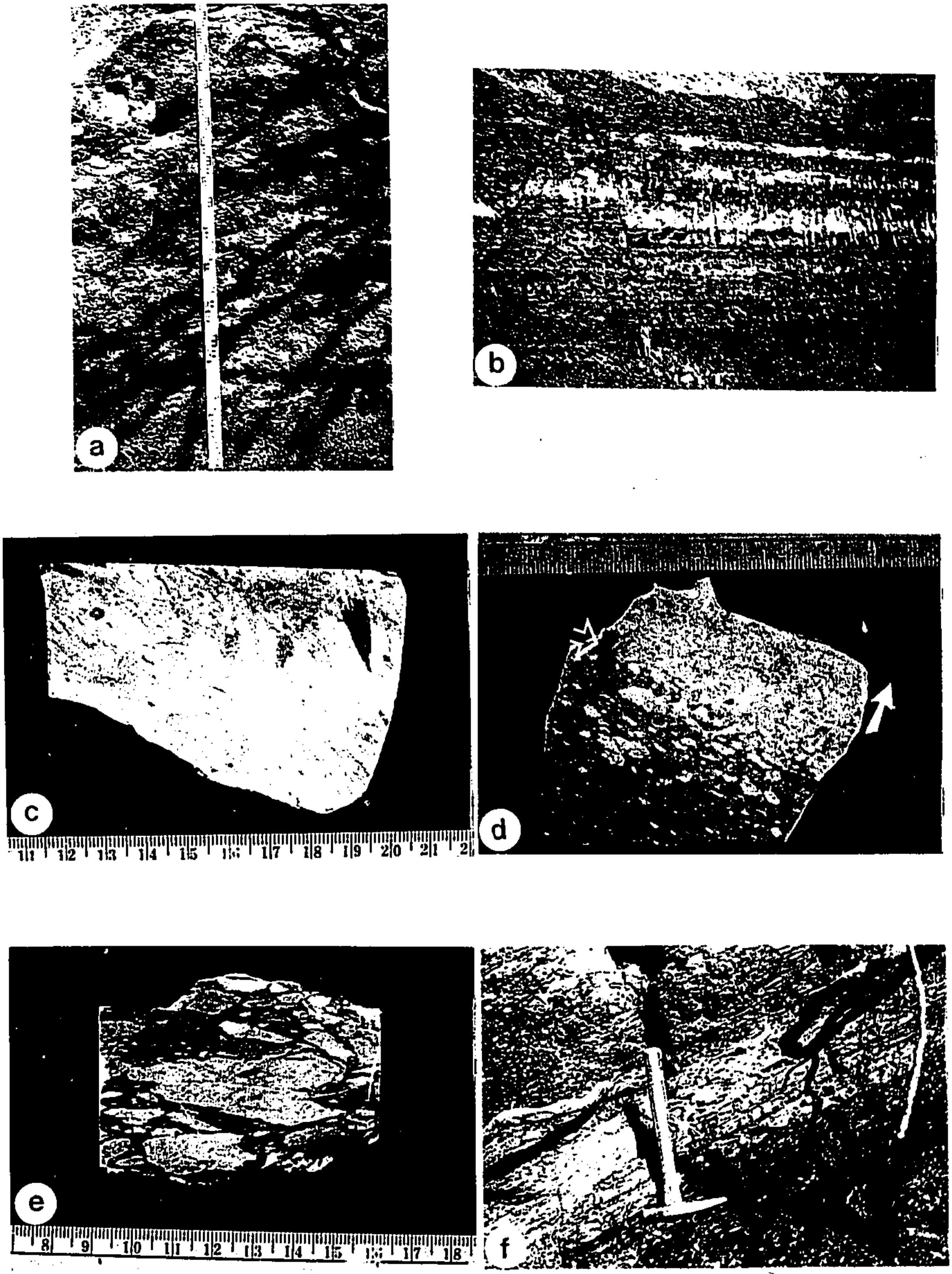
b: Laterally persistent, thinly to thickly bedded, massive, light grey to dark grey silty mudstone and siltstone. Beds offset by faults. Kazinze Open Pit.

c: Polished slab of light to medium grey silty mudstone from (b), made up of diffuse elongate to sub-spherical intraclasts with diffuse margins. Scale in cm.

d: Polished slab of silty mudstone strongly bioturbated towards top (arrow). Orangish yellow alteration due to weathering. Notice area of black coloration (open arrow) that fades downwards and many dark grey traces, probably representing rootlets or burrows. Kazinze Open pit. Scale in cm.

e: Polished core sample, showing light grey intraclasts of silty mudstone in greyish black, more carbonaceous, silty mudstone. Disruption of the mudstone is probably due to bioturbation. Core is 7 cm in diameter (see scale at bottom).

f: Horizontally laminated, yellowish brown, silty mudstone, overlying dark brown to black carbonaceous to coaly mudstone, Zhimu River Section 1, Mulungwa area..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fissile. The silty and coarser-grained, sandy mudstone that grades into siltstone contains small-scale lamination. Small-scale sigmoidal lamination is also present (Fig. 4.47b). In places, lamination is defined by concentrations of organic matter and black, elongate irregular, carbonaceous mudstone intraclasts. Amalgamated yellowish brown sandy mudstone layers (1 to over 10 mm thick) are commonly intercalated with medium brown mud layers 1 mm thick. Lenticular bedding, flaser bedding and small-scale cross-lamination are locally well developed. Irregularly deformed laminae are present in places. Some bright areas represent black vitrain fossil leaves, but most is disseminated as comminuted plant material. Calcite fills joint planes, and slickensides have been observed in the Kazinze Open pit. Rootlets have been observed in the mudstone in the Kazinze Open pit (Fig. 4.47c). Sideritic beds within the mudstone lithofacies show joint patterns that locally resemble polygonal shrinkage cracks, (Fig. 4.47d) but are apparently not desiccation cracks.

In thin section, the mudstone is seen to consist mainly of siliciclastic detrital grains (up to 50%) with subordinate carbonaceous mudstone intraclasts, and carbonaceous matter (5-10%) dispersed in the clay-carbonate matrix (30-60%) (Fig. 4.47e, f). Grains are mainly of silt size, with outsized quartz and muscovite up to 0.2 mm. Poorly preserved cellular structures are cut by calcite veinlets. Differences in colour, lamination, etc. in the lithofacies are mainly due to differences in composition, as follows:-

i. the dark greyish brown carbonaceous intraclasts contain < 20% detrital material, and pale brown silty intraclasts contain ~55% detrital material in darkish brown clay-rich matrix (50-60%).

ii. the darker patches, spots, streaks, stringers and laminae contain more carbonaceous material.

iii. the darker and lighter laminae in the varve-like mudstone reflect alternating clay/organic matter-rich laminae and clay-poor laminae. In the crudely laminated mudstone, micaceous (platy) minerals define the laminae.

iv. some thick silty layers contain mainly monocrystalline quartz (grains up to 0.08 mm in diameter), feldspar (plagioclase mainly), detrital muscovite, and coaly mudstone intraclasts in clay matrix and calcite cement, alternating with poorly preserved plant

Fig. 4.47 Silty mudstone lithofacies

Gwembe Coal Formation

a: Polished slab showing horizontally laminated silty mudstone. Zhimu River Section 1, Mulungwa area. Scale in cm.

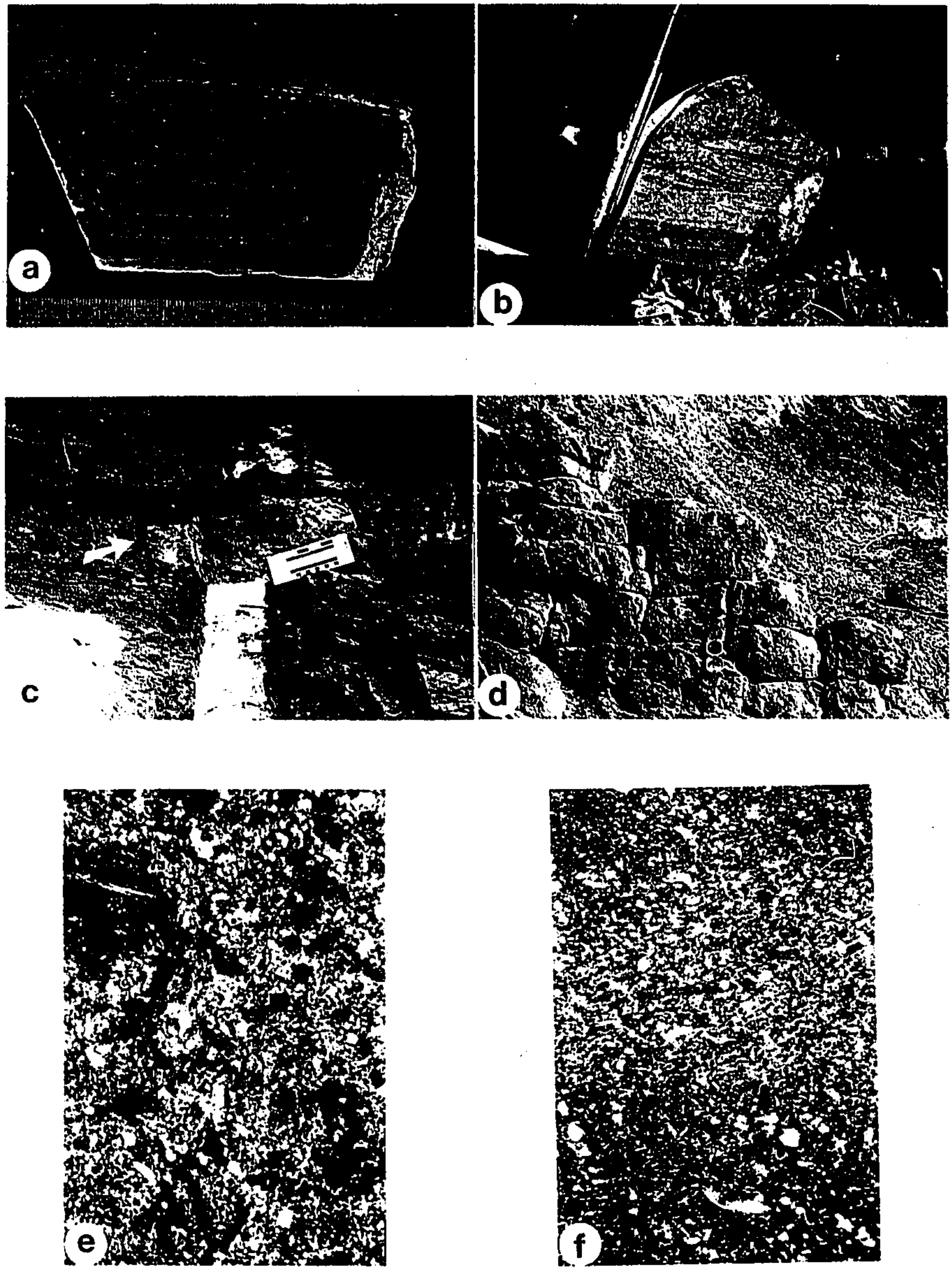
b: Small-scale sigmoidal lamination in light grey silty mudstone, Zhimu River Section 1, Mulungwa area. Pen is 14 cm long.

c: Roots (e.g. arrow) in silty (slightly carbonaceous) mudstone. Kazinze Open pit. Lower scale in cm.

d: Sideritic bed in silty mudstone lithofacies showing jointing locally resembling polygonal shrinkage cracks, with cracks filled by finer material (in contrast to desiccation cracks, that are commonly filled by coarser material). Zhimu River Section 1, Mulungwa area. Brunton compass for scale

e: Photomicrograph (crossed nicols) showing cloudy masses (blebs) in argillaceous matrix. The white grains are quartz and black areas are coaly stringers and fragments. Kazinze Open pit. Long side of photograph is 1.4 mm.

f: Photomicrograph (crossed nicols) of general texture of silty mudstone lithofacies, showing scattered quartz and minor feldspar grains in matrix rich in mica (illite) and kaolinite (e.g. arrow). Calcite is also present. Kazinze Open pit. Long side of photograph is 1.4 mm.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cell laminae and streaks.

Quartz is the predominant detrital mineral (mainly monocrystalline and few polycrystalline crystals), followed by feldspar and muscovite. Chlorite is present in trace amounts. Common heavy minerals are tourmaline and epidote. Carbonate (siderite, dolomite?) occurs as disseminated, cloudy blebs and aggregates in the matrix and can form up to 20% of the rock. Siderite spherulites have been stained by iron oxides, possibly hematite. Calcite cement occurs as sparite, some forming a poikilotopic texture, or more commonly as disseminated micrite and microspar.

4.3.2.10 Sideritic mudstone, siltstone and sandstone lithofacies (MSS_{sd})

The isolated sideritic concretions and concretionary beds are easily distinguished in weathered outcrops due to alteration of the main constituent, siderite, to iron oxides. The host lithology is commonly mudstone (e.g. in the Kazinze open pit), but sideritic bodies also occur in sandstone and siltstone as for example, in Mulungwa River Section 6, where sandstone is the host lithology to sideritic beds. It is therefore practical to include all of the sideritic occurrences in this lithofacies. Siderite occurs also as thin, pale beds, some showing complex convolute structures, and is especially abundant between sandstones A and C (Money et al., 1974).

The sideritic lithofacies occurs in both concretionary and tabular (sheet) forms. Both are common throughout the Gwembe Coal Formation. On fresh surfaces the rocks are light olive grey, blue-grey to purple-grey, weathering to various shades of purple, pink and red with a characteristic hardened rusty brown 'ironstone' coating. Mottled combinations of fresh and weathered colour are usually common.

The concretionary form of the lithofacies is best exposed in the Kazinze River, Section 2c (Fig. 4.48a) and is considered to be equivalent to Sandstone B as defined by Radosevic et al. (1968) in the Kazinze mining area. However, Money et al. (1974) considered these units to be stratigraphically slightly higher than Sandstone B. The units consist of impersistent, irregular concretionary beds 0 to 1.4 m thick within coaly and carbonaceous mudstone lithofacies. The beds consist of individual concretions that have coalesced laterally to form impersistent but extensive irregular bodies up to 15 m long

Fig. 4.48 Sideritic mudstone, siltstone and sandstone lithofacies

Gwembe Coal Formation

a: Discontinuous concretionary beds in coaly to carbonaceous mudstone lithofacies, Kazinze River Section 2c, Siankondobo area. Hammer is 34 cm long.

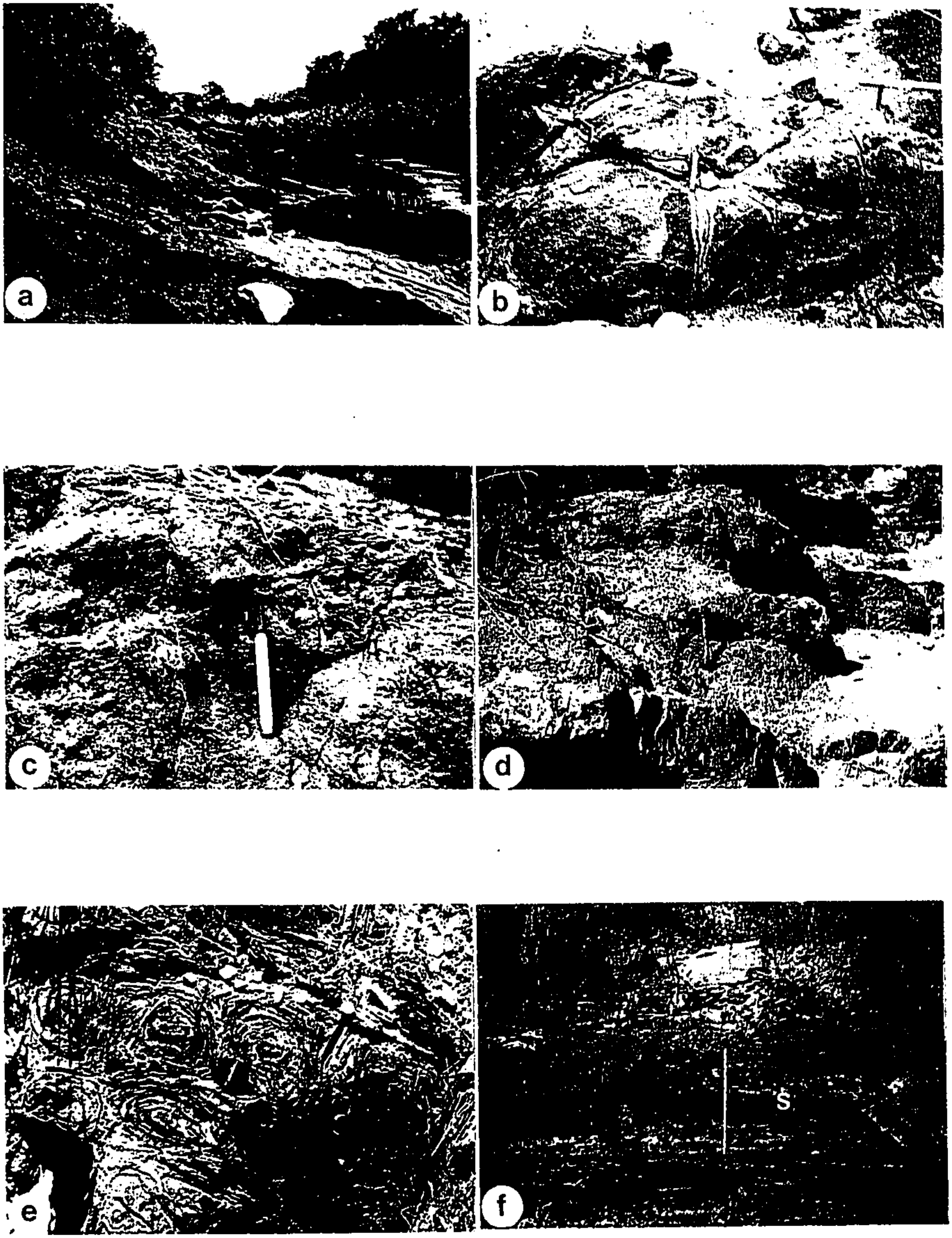
b: Detail of (a), showing beds consisting of coalesced concretions. Pen is 16 cm long.

c: Detail of (a), showing massive mudstone with root tubules highlighted by bluish grey coloration. Pen is 16 cm long.

d: Massive, irregular concretionary beds within silty mudstone lithofacies. Mulungwa River Section 6, Mulungwa area.

e: "Box-wood" concretions with convex-upward tops and irregular and sharp bases. One extracted from bottom left corner of photograph has centre filled by sand. Above Sandstone A (not directly), Maamba Mine Licence area, Siankondobo area. Lens cap is 5 cm in diameter.

f: Brick-red sideritic bed (S) parallel to bedding, in places contorted within carbonaceous sandstone. The bases of the coalesced concretions are convex downward. Notice isolated concretions below the main one (S) left of scale. Mulungwa River Section 6, Mulungwa area. Scale is 2.1 m.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(Fig. 4.48b). They contain numerous, bluish grey, branching, vertical structures indicative of root tubules (Fig. 4.48c). The bases of the beds are irregular and sharp, whereas the tops are fairly smooth and sharp, with convex-upward bulges defining concretions. The concretions are coarse-grained and massive, with a characteristic appearance reflecting the spherulitic structure of the oxidised siderite spherulites and aggregates. Because of this, Radoscevic et al. (1968) referred to Sandstone B as 'apparently oolitic'. The spherulites are colourless to faint yellow when fresh, but are generally stained yellow to brown round the margins, probably due to oxidation (Radosevic et al., 1968). Similar beds exposed in the Mulungwa River, Section 6 are up to 2.2 m thick and are enclosed by fragmented silty mudstone lithofacies (Fig. 4.48d). However, in Unnamed Stream Section 2, Mulungwa area, brownish red concretionary beds (~35 cm maximum) alternate with massive silty mudstone through an interval of 6 m. In the Maamba Mine Licence area, Siankondobo area, the concretionary beds a short distance above Sandstone A are arranged in a "box-wood" structure with convex-upwards tops (Fig. 4.48e). The bases are irregular and sharp, and the centres of the concretions are filled by sand. Where sandstone is the host lithology, e.g. Mulungwa River Section 6, the sideritic beds are continuous and parallel to bedding (Fig. 4.48f), in places are contorted, and can be up to 80 cm thick (Fig. 4.48f). The bases of individual concretions are convex downwards.

In hand specimens, the concretionary structures in the sideritic lithofacies appear shiny and metallic, strongly indurated (heavy) and weather rusty red to brick red, or dusky yellowish brown (buff) to dusky brown. Fresh and/or slightly weathered sideritic units consist largely of spherulites of siderite (up to 95%) in a clay-rich matrix. These spherulites give the rock a grain size generally from fine- to coarse-grained, with an average of medium-to coarse-grained. In completely altered rocks, the brick red to blood-red iron oxides can occur as layers of coarse sand- to granule-size grains where concentrated and continuous.

The siderite lithofacies (Fig. 4.49a, b) occurs as continuous tabular beds up to 30 cm thick that persist along strike for distances of at least 50 m. These beds are commonly associated with the coaly to carbonaceous mudstones. On fresh surfaces, they are difficult to distinguish from the other mudstones but commonly show yellowish white and dark

Fig. 4.49 Tabular sideritic lithofacies

Gwembe Coal Formation

a: Cyclic alternation of tabular sideritic lithofacies (T) and coaly and carbonaceous mudstones. Kazinze River Section 1, Siankondobo area. Scale 2.1 m.

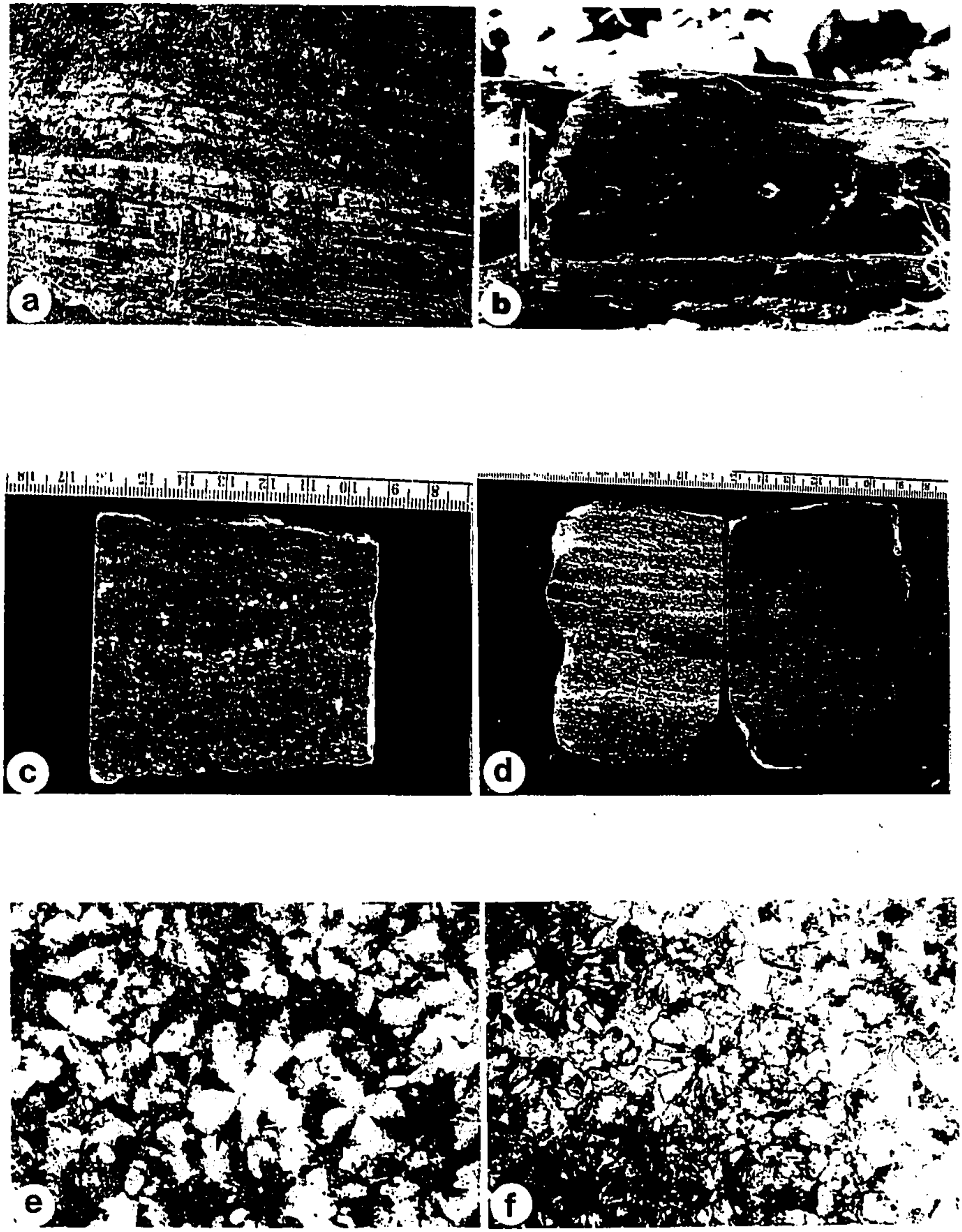
b: Detail from (a), showing brick red to brownish black sideritic mudstone. Notice that the mudstone is horizontally laminated with coal streaks and laminae. Pen is 14 cm.

c: Polished core sample of sideritic mudstone showing yellowish white (siderite) and dark grey/black (carbonaceous matter) mottling. Drill Hole, E183, Kazinze Open pit area. Scale in cm.

d: Polished slab of horizontally laminated sideritic mudstone showing brick-red (siderite altered to iron oxide) and dark grey/black mottling. Kazinze River Section 2, Siankondobo map area. Scale in cm.

e: Photomicrograph (crossed nicols) showing siderite spherulites (petals), locally with iron stained centres. Spaces in between spherulites are filled by clay, mainly kaolinite. Zhimu River Section 1, Mulungwa map area. Long side of photograph is 1.4 mm.

f: Photomicrograph (crossed nicols) showing altered of siderite spherulites. Alteration seems to have started from the centres of spherulites; the right half of the photograph has not been altered. Kazinze River Section 2. Siankondobo map area. Long side of photograph is 4.4 mm.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grey/black mottling (Fig. 4.49c). On weathered surfaces, alteration of siderite to iron oxides reveals the nature of the beds (Fig. 4.49b). Commonly, the siderite beds consist of alternating thin irregular coaly laminae and thicker siderite-rich (mottled) laminae (Fig. 4.49c, d). In hand specimens, the sheet-form sideritic mudstones are generally mottled brick red (blood-red spheres) and dark grey/black and laminated (Fig. 4.49d).

In thin section, the lithofacies is seen to consist mainly of siderite (~95%) in a clay matrix (Fig. 4.49e, f). Widespread alteration of the siderite to iron oxides makes thin section study rather difficult (Fig. 4.50). The siderite occurs as spherulites with broad blades or slender fibres (crystals) radiating from cores that are filled by clay, organic matter and scattered inclusions of an opaque mineral which is probably pyrite (Fig. 4.50a). Without interference, the spherulites are spherical. Coaly laminae commonly show cell-like structures (probably plant cells) and lenses of organic matter. A yellowish brown coating around the crystals is common throughout. In altered rocks the iron oxides (30-95%) occur as patches or interconnected stringers associated with siderite in a clay-rich matrix (Fig. 4.50a, b). The matrix consists mainly of quartz grains (up to 0.06 mm across), locally up to 20%, some feldspar (both twinned and untwinned) and mica. Quartz occurs as monocrystalline (predominant), polycrystalline and recrystallized (metamorphic) crystals. The monocrystalline quartz shows undulose extinction and vacuoles. Muscovite appears to be altered to chlorite. The matrix (5-60%) occurs as interparticle fillings locally forming brownish coloured, irregular stringers and streaks.

In Mulungwa River Section 6, the blood-red unit contains calcite instead of siderite. The calcite occurs in spherical, prismatic, ellipsoidal and irregular shapes up to 0.05 mm across (Fig. 4.50c, d). Flower-like clusters of calcite crystals (Fig. 4.50c, d) up to 0.3 mm across also occur. The flower-like clusters are commonly interconnected and vermiform (Fig. 4.50c, d). These textures fit the description of *Microcodium* (Fig. 4.50c, d), which has been described as elongate, petal-shaped calcite prisms or ellipsoids, 1 mm or less in length and grouped in spherical, sheet- or bell-like clusters (Esteban, 1974). The presence of *Microcodium* in these rocks has been confirmed by Morin (pers. comm., 1992). *Microcodium* was long thought to be algal, inorganic bacterial or actinomycete in origin, but is now considered to represent calcified mycorhizae, a symbiotic association between

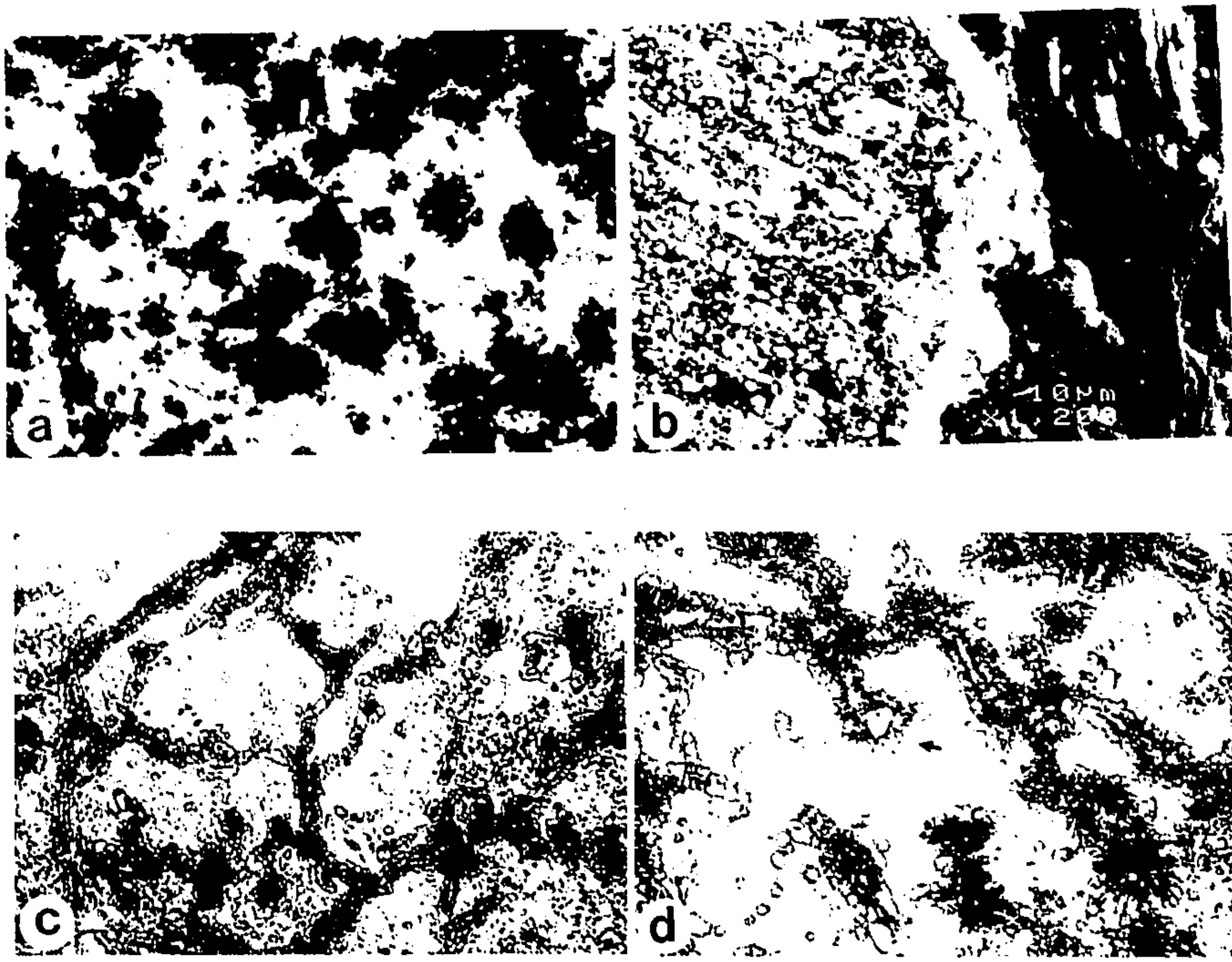


Fig. 4.50 Sideritic mudstone, siltstone and sandstone lithofacies
Gwembe Coal Formation

a: Photomicrograph (plane polarized light) showing completely altered siderite (black) leaving argillaceous material (mainly clay) that filled the voids. Kazinze River Section 2, Siankondobo map area. Long side of photograph is 2.5 mm.

b: Photomicrograph (SEM) showing the texture of the iron oxide after complete siderite replacement. Kazinze River Section 2, Siankondobo map area. Scale indicated on photograph.

c: Photomicrograph (plane polarized light) showing network of *Microcodium* in calcite-rich argillaceous matrix. Mulungwa River Section 6, Mulungwa map area. Long side of photograph is 1.4 mm.

d: Photomicrograph (plane polarized light) showing detail of *Microcodium*. Notice petal-shaped calcite crystals (arrow). Mulungwa River Section 6, Mulungwa map area. Long side of photograph is 1.4 mm.

soil fungi and cortical cells of roots of higher plants (Klappa, 1978).

Analysis by SEM and XRD indicates that kaolinite is the main clay mineral of the matrix. It occurs finely disseminated in vertical desiccation cracks in vitrain laminae, cavities in fusain laminae, along cleats in association with carbonates, and as horizontal partings or laminae. Money et al. (1974) indicated that the kaolinite in the cracks is opaque and white, and has a porcellaneous lustre.

4.3.2.11 Microconglomerate to very coarse sandstone lithofacies ($CS_{g\text{-}vc}$) (Sandstone A)

This is the most abundant lithofacies of Sandstone A, and is exposed in all the stream and river sections, ridges and hills where Sandstone A outcrops. The lithofacies is cream whitish grey and some exposures have dark brown coatings. In the northwestern part of the Siankondobo area, Sandstone A occupies the ridges and hills as large areas of almost flat-lying sandstone and numerous protruding blocks. These outcrops form excellent areas for measuring palaeocurrents, although stratigraphic position is difficult to determine.

The lithofacies is associated with minor intercalations of medium to coarse-grained sandstone. Mudrocks are rare, occurring as thinly to very thickly bedded units that commonly are cross-stratified, with both trough (St- predominant) and planar (Sp) cross-beds present. Massive (Sm) and normal graded beds are also present. Reverse-grading is common. In the Makula stream, Sinakumbe area, Sandstone A is exposed (Fig. 4.51a), overlying laminated carbonaceous, coaly and silty mudstone (Fig. 4.51b). The basal part of the section starts with an erosional sharp contact, followed by 15 m of amalgamated, massive microconglomerate (Fig. 4.51a). This is in turn overlain by channel-like bodies (Fig. 4.51a). The lithofacies consists mostly of moderately to well-sorted quartz granules and pebbles (up to 95%) with little sandy matrix (Fig. 4.51b-d) and hence is a microconglomerate. Medium-grained intercalations are present (Fig. 4.51c). In the Mulungwa River Section 5, Mulungwa area, 15 m thick fining-upward units of Sandstone A with interbeds of finer-grained sandstone are exposed. The basal parts of these units are made up of this lithofacies (see section on profiles under Sandstone A assemblage).

In the northwestern part of the Siankondobo area, the lithofacies consists of beds

Fig. 4.51 Lithofacies of Sandstone A

Gwembe Coal Formation

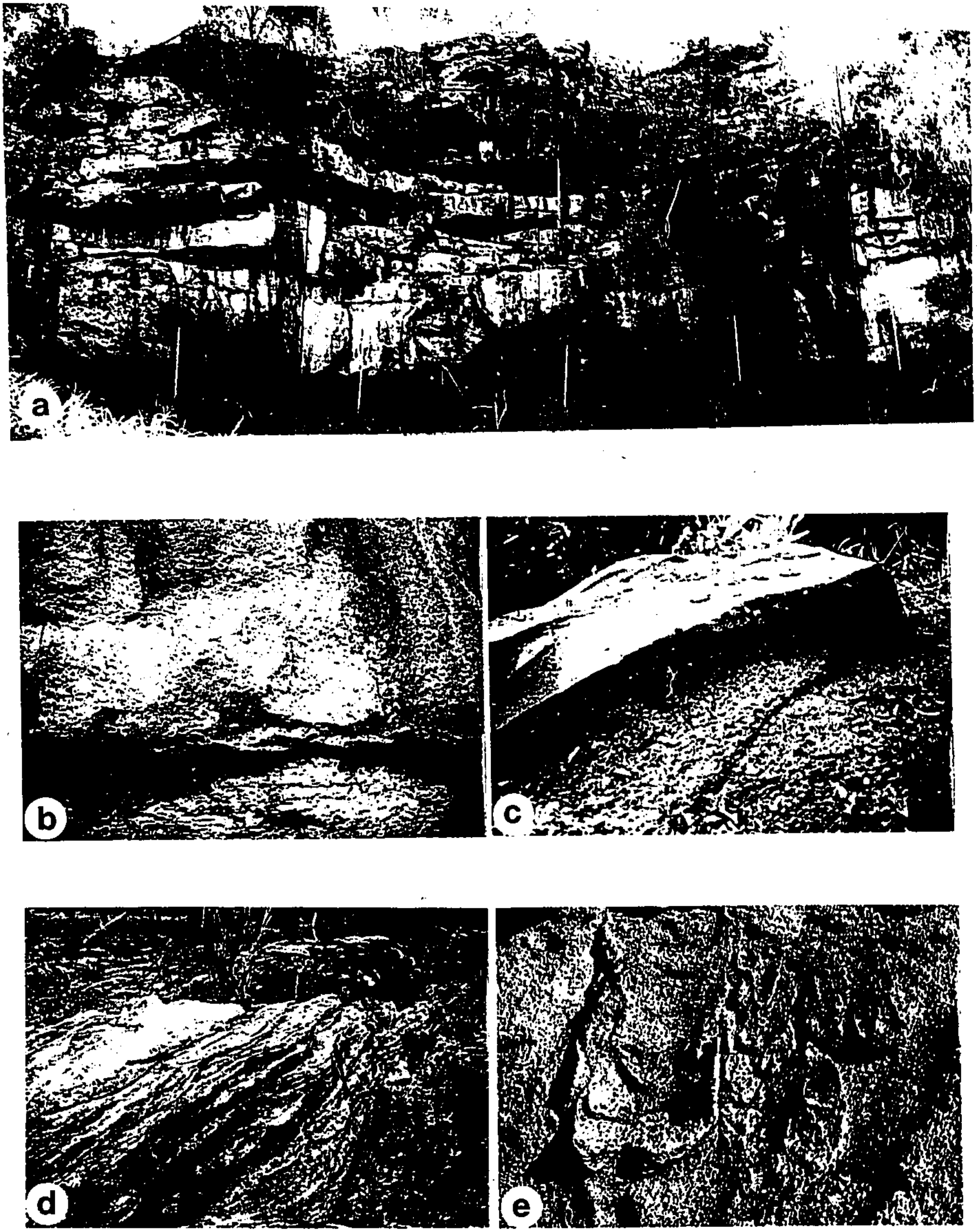
a: Photomosaic showing lithofacies of Sandstone A sharply overlying carbonaceous and coaly mudstone lithofacies, Mukula stream, Maze-Sinakumbe area. Notice amalgamated beds, and channel-like structures towards top. Scale is 2.1 m.

b: Detail of (a), showing very coarse-grained sandstone i.e. microconglomerate lithofacies. Notice horizontal lamination in the underlying mudstone. Pen is 13 cm long.

c: Microconglomerate exposed on a bedding plane with intercalated coarse-grained sandstone lithofacies. Mukula stream, Maze-Sinakumbe area. Pen is 13 cm long.

d: Large exposure of microconglomerate with trough cross-bedding well developed at the top. Siankondobo area. Hammer is 34 cm.

e: Trough cross-sets on a bedding plane in microconglomerate, Siankondobo area. Pen is 13 cm.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ranging from 30 cm to over 2 m. Most of the protruding blocks are over 1 m thick and are either trough cross-bedded or planar cross-bedded. Some blocks form large flat-lying outcrops up to 30 m wide, with trough cross-beds (St) up to 2.5 m wide (Fig. Fig. 4.51e, f); others show low angle cross-bedding and sets of tangential scoop-shaped cross-bedding (Sl) over 10 m wide (Fig. 4.52a, b). Foreset laminae are commonly defined by concentrations of granules and pebbles (Fig. 4.52b) or by discontinuous stringers and intercalations of mainly carbonaceous and silty material in the finer interbeds within the lithofacies. Palaeocurrent orientations measured from the troughs (e.g. Fig. 4.51f) exposed on the bedding planes of the flat-lying outcrops (144 readings) indicated an average palaeocurrent direction of 121° (southeast) with a spread from northeast to southwest. Similar sandstone beds with numerous fine-grained sandstone intercalations are evident in the Zhimu River (Fig. 4.52c) and the Unnamed Stream Section 2, Mulungwa area. At these localities the sandstone is thinner, but commonly the lithofacies occupies the basal position and fining-upward is characteristic.

In hand specimen, the sandstone comprises mainly quartz with little matrix (< 5%) (Fig. 4.52d). In thin section, the microconglomerate varies from grain-supported to matrix-supported, consisting mainly of polycrystalline and monocrystalline quartz (over 90%), minor feldspar, rock fragments and mica (Fig. 4.52e). The matrix (2-4%) consists of silica, chlorite and sericite, with chalcedony as cement. It generally lacks plant remains. Radosevic et al. (1968) indicated that zircon, epidote, tourmaline and rutile are the common heavy minerals.

The microconglomerate lithofacies grades upwards into very fine- to coarse-grained sandstones lithofacies that become increasingly carbonaceous (Fig. 4.52f). In thin section, a change is observed from the polycrystalline quartz grains to predominantly smaller monocrystalline quartz grains (Fig. 4.53a).

4.3.2.12 Very fine- to coarse-grained sandstone lithofacies (S_{vf-c}) (Sandstone A)

The sandstone is whitish grey or dark grey where carbonaceous material is present. Units of the lithofacies range from 10 cm to 5 m thick and commonly occur as irregular and amalgamated beds (Fig. 4.53b) except in Mulungwa River Section 5, where trough

Fig. 4.52 Microconglomerate to very coarse-grained sandstone lithofacies, Sandstone A

Gwembe Coal Formation

a: Large exposure of microconglomerate exposing low angle cross-bedding and tangential scoop-shaped cross-bedding (Sl), Siankondobo area. Hammer for scale.

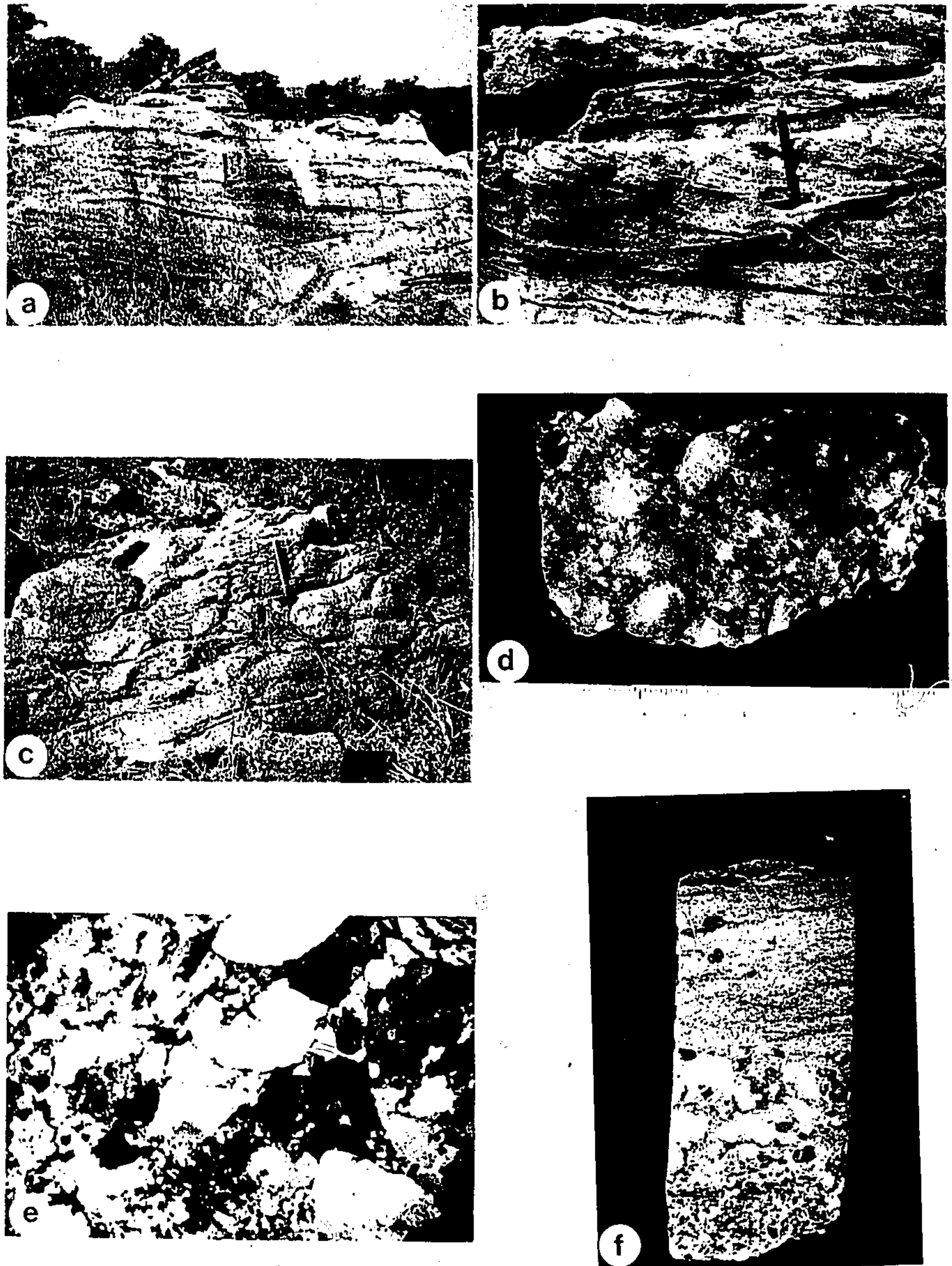
b: Trough cross-bedded microconglomerate with stratification defined by concentration of pebbles. Siankondobo area. Hammer for scale.

c: Microconglomerate intercalated with discontinuous, locally laminated, medium- to coarse-grained sandstone. Zhimu River Section 1, Mulungwa area. Hammer for scale.

d: Polished slab of microconglomerate with over 95 % quartz. Zhimu River Section 1, Mulungwa map area. Scale in cm.

e: Photomicrograph (crossed nicols) of (d) showing polycrystalline quartz grains with small grains forming the matrix. Zhimu River Section 1, Mulungwa map area. Long side of photograph is 23.3 mm.

f: Polished core slab showing normal grading, from conglomeratic sandstone at base to medium-grained sandstone at the top. Borehole GS271 (C10), Mulungwa map area. Scale in cm.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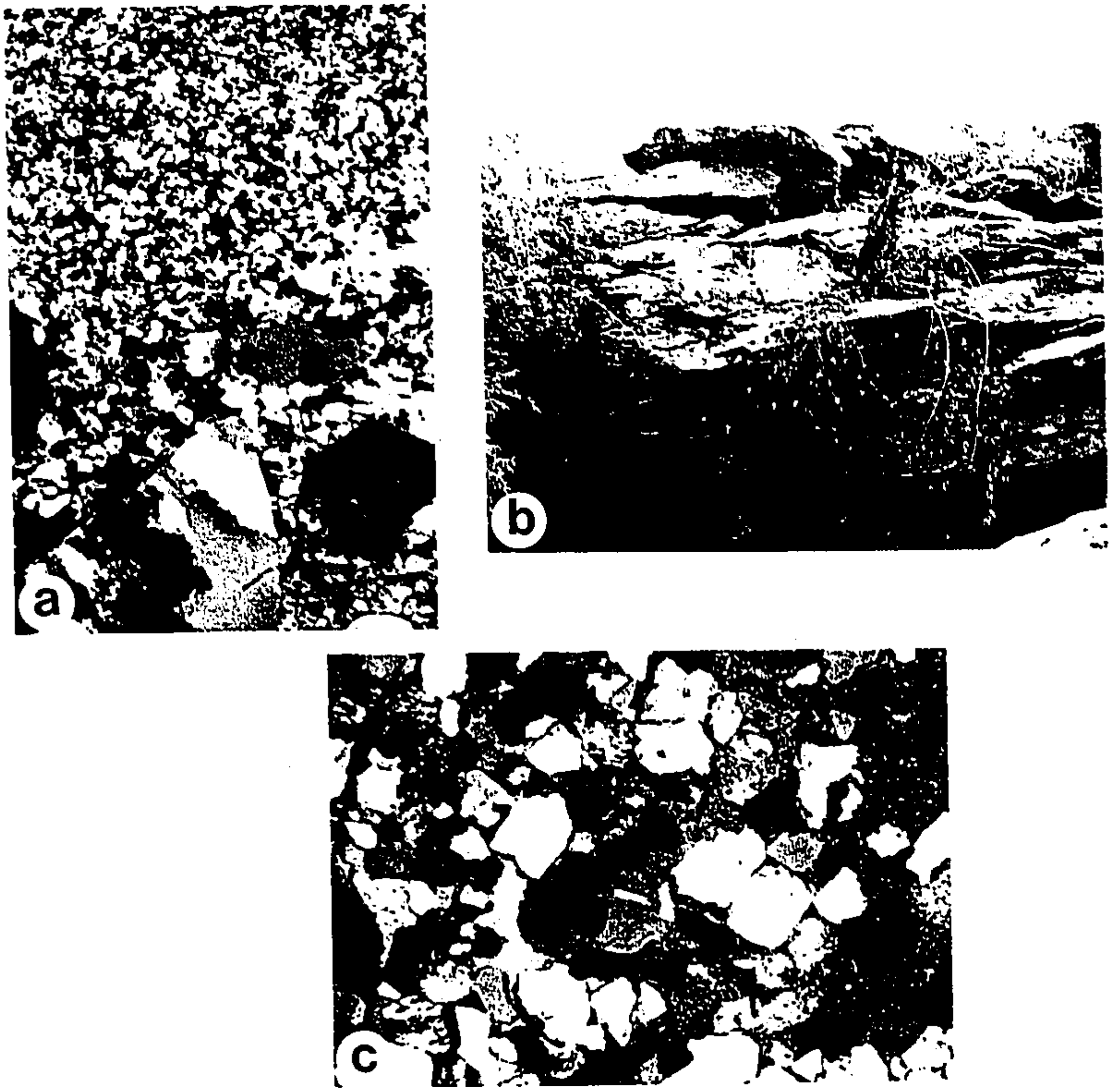


Fig. 4.53 Lithofacies of Sandstone A, Gwembe Coal Formation

a: Photomicrograph (crossed nicols) of sandstone in Fig. 4.52f showing normal grading with polycrystalline quartz grains at base grading into small monocrystalline quartz grains. Feldspar and muscovite are also present. Long side of photograph is 15 mm.

b: Amalgamated medium- to coarse-grained sandstone beds. Izuma River, Siankondobo area. Outcrop is 2.4 m thick.

c: Photomicrograph (crossed nicols) of medium- to coarse-grained sandstone showing quartz and feldspar (some altered) in clay matrix and calcite cement. Black areas are void spaces. Oversized matrix-filled area at top right corner probably represents altered mudrock fragment. Unnamed Stream Section 2, Mulungwa map area. Long side of photograph is 4.4 mm.

cross-beds are well developed. The amalgamated beds are commonly massive. In Mulungwa River Section 5, the change in grain size from microconglomerate at the base to very fine sandstone is accompanied by a change in size of sedimentary structures from large trough-cross beds at the base to small-scale trough-cross beds at the top (see section on profiles under Sandstone A facies assemblage). Horizontal bedding is also present. Most contacts are gradational, although some sharp contacts have been observed in the northwestern part of the Siankondobo area. In the Mulungwa map area, a thin section made from a greenish grey sample taken from the top of the fining upward unit, Mulungwa River Section 5 (see Fig. 4.55, p. 192 at ~ 90 m) indicate the presence of calcite and a yellowish brown clay mineral (probably chlorite) and abundant porosity (Fig. 4.53c)

Sideritic concretions have not been observed in the lithofacies. Fossil plant stems and leaf impressions are common. These units are gradational into mudrocks.

4.3.2.13 Mudrock lithofacies (M_{sm}) (Sandstone A)

Mudrock lithofacies are rare in Sandstone A, and are commonly confined to the top part, particularly in the fining-upward sequences as at Mulungwa River Section 5 and Zhimu River Section 1. However, mudrocks commonly occur as minor intercalations in the microconglomerate and sandstone lithofacies described above. The lithofacies consists mainly of carbonaceous siltstone and mudstone. Plant debris is abundant in the mudrocks. The mudrock in Sandstone A has siltstone as the predominant lithology, in comparison to the other lithofacies previously described.

4.3.2.14 Lithofacies of the Other Sandstones (LOS) (B, C, D, E)

Sandstone B is blue-grey to purple-grey and varies from a fine-grained, muddy siltstone to a coarse-grained, muddy sandstone and is highly sideritic. The sandstone is deep red where weathered, due to oxidation of the ferruginous minerals, but grey to speckled pale greenish-brown where fresh, due to numerous, closely packed, radial growths of siderite in a fine-grained matrix consisting predominantly of quartz (Radosevic et al., 1968). It is similar to the sideritic lithofacies, and is therefore described under that section.

Sandstone C consists of medium- to fine-grained, non-ferruginous sandstone and greenish grey sideritic sandstones. Sandstone C is generally feldspathic, with potash feldspar predominant. Grain-support is common in the coarser varieties and matrix-support in the finer with a matrix of silica, sericite and chlorite. Heavy minerals include pyroxene (28%), sphene (18%), zircon (16%) and epidote (10%). Small tree trunk impressions (up to 20 cm long) and fragments of siltstone and fine sandstone occur frequently (Radosevic et al., 1968).

Sandstone D is a medium-grained, white sandstone with occasional dark siltstone beds and carbonaceous partings, and interbedded flaggy mudstones and silty mudstones. Small- to medium-scale cross-bedding with a lag conglomerate at the base are common sedimentary structures. Conglomerate lenses up to 60 cm are locally present in some outcrops with subangular to sub-rounded quartz (5 mm in diameter), homogeneous grey-green siltstone fragments (2 cm in diameter) and smaller fresh feldspar grains. Epidote (70%), zircon (10%) and amphibole (10%) are the main heavy minerals. The sandstone is classified as a quartz wacke (Radosevic et al., 1968).

Sandstone E is not well exposed, and at one outcrop in the Siankondobo area, it consists of an upper unit of coarse-grained, pebbly arkose up to 5 m thick, overlying fine- to medium-grained sandstone. Medium-scale low angle cross-bedding with thin whitish to pink feldspar lag conglomerate at the base is evident in Sandstone E. The grain-supported fabric consists of feldspar (over 25%), quartz and some biotite. Heavy minerals include zircon (40%), sphene (18%), epidote (13%) and garnet (12%). The rock is poorly to moderately sorted arkose (Radosevic et al., 1968).

In summary, sandstone/siltstone units (Fig. 4.54a, b) have been observed in the Gwembe Coal Formation, but their correlation to the above sandstones (C to E) is difficult as the author did not see the latter in their type locality in the Siankondobo map area. The units form fining-upward sequences up to 4 m thick, commonly with a basal conglomerate containing mud intraclasts, quartz pebbles (1.2 cm across) and abundant plant fragments and impressions. The conglomerate is overlain by stratified to massive carbonaceous sandstone and siltstone (Fig. 4.54a). Most of the units are wedge-shaped, consisting mainly of lenticular beds. Horizontal and small-scale cross-lamination (Fig. 4.54c) is

Fig. 4.54 Lithofacies of the "Other Sandstones" and Izuma Beds

Gwembe Coal Formation

a: Generally cross-stratified fining-upward sandstone (from mudclast conglomerate at hammer head to silty mudstone at the top). The red overlying beds are sideritic. Mulangwa River Section 6c, Mulungwa map area.

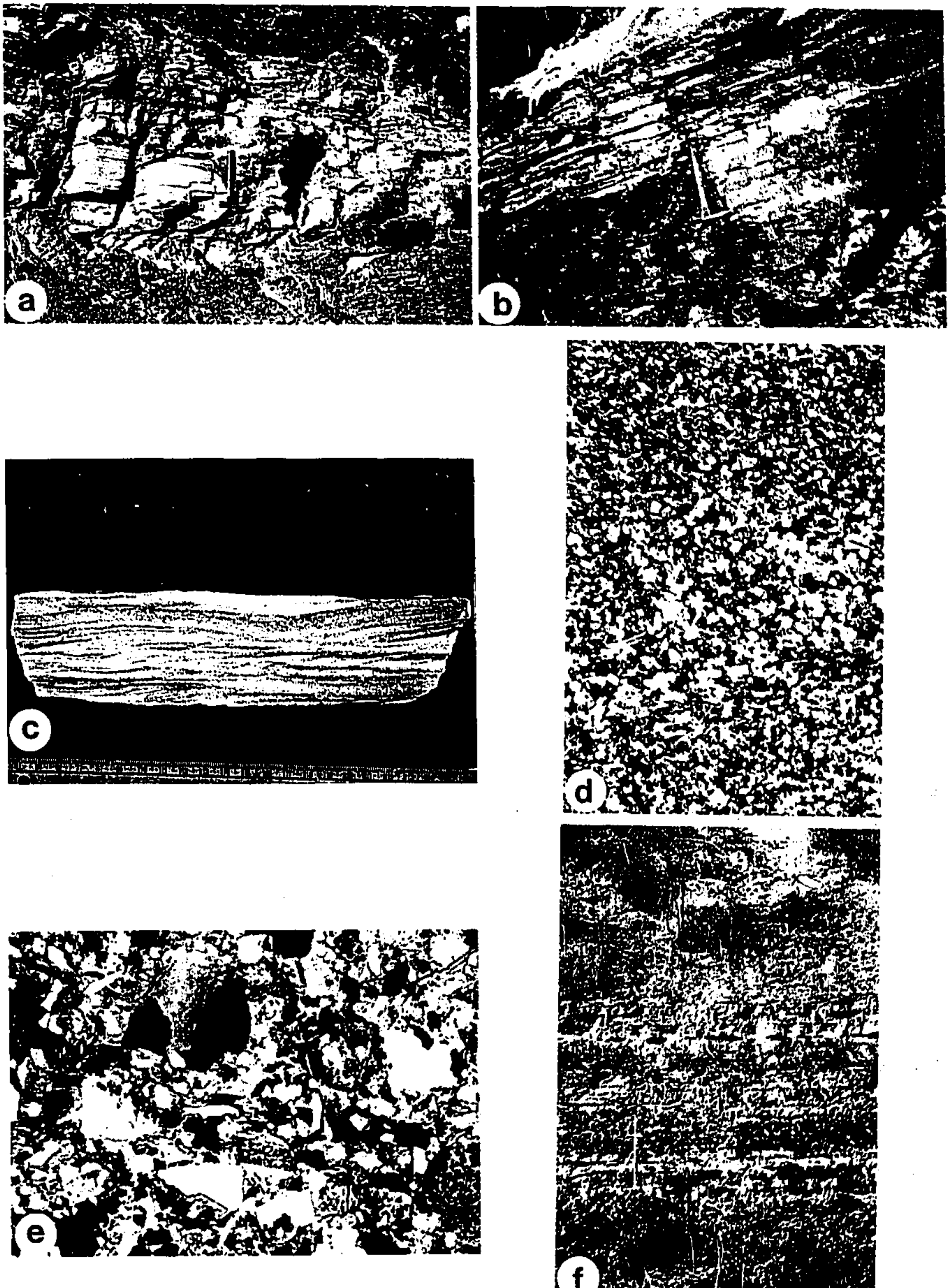
b: Parallel to lenticular bedded siltstone; more sandy at base and locally containing mud intraclasts, grading upwards into silty mudstone. Ntole River Section 2, Nkandabwe map area.

c: Polished slab of very fine grained sandstone showing ripple cross-lamination. Scale in cm.

d: Photomicrograph (crossed nicols) showing texture of "other sandstone" lithofacies consisting of abundant quartz and some feldspar and muscovite in clay-rich matrix. Mulungwa River Section 5, Mulungwa map area. Long side of photograph is 6 mm.

e: Photomicrograph (crossed nicols) showing texture of a sandstone consisting mainly of quartz, feldspar and minor muscovite. Some plagioclase has been sericitized. Clay minerals identified include kaolinite and illite. Calcite cement is present, locally forming poikilotopic texture. Zhimu River Section 1, Mulungwa map area. Long side of photograph is 4.4 mm.

f: Izuma Beds consisting of alternating recessive more carbonaceous mudstone (darker) lithofacies and resistant silty mudstone/siltstone (lighter) lithofacies at the type locality. Izuma River, Siankondobo area. The beds eventually grade into the Madumabisa Mudstone Formation. Scale is 2.1 m.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common in the units. In thin section, the sandstone/siltstone consists of quartz (predominant), feldspar (some altered), muscovite and minor intraclasts (rock fragments) in clay-rich matrix and calcite cement (Fig. 4.54d, e). The main clay minerals are kaolinite and illite.

4.3.2.15 Lithofacies of the Izuma Beds (LIB)

The carbonaceous and silty mudstone/siltstone lithofacies of the Izuma Beds are similar to the lithofacies described in section 4.3.2.8 and 4.3.2.9, respectively. The lithofacies are illustrated in Fig. 4.54f, and occur as alternating beds of carbonaceous mudstone and silty mudstone /siltstone.

4.3.2.16 Lithofacies interpretation

The general characteristics of the Gwembe Coal Formation lithofacies and their interpretation are given in Table 4.8. The coarseness and sedimentary structures (mainly cross-stratification) indicate that the **conglomerate and sandstone lithofacies** of the Maamba Sandstone can be interpreted as high-energy fluvial deposits. The fining-upward sequences (e.g. Fig. 4.31a) are interpreted as point bars of a meandering river channel system. The Izuma Waterfall conglomerate /sandstone outcrop indicates a former channel with palaeo-flow approximately to the south-east.

The **coal lithofacies** formed by accumulation of peat in relatively shallow swamps on an alluvial flood plain. Peat accumulation was interrupted periodically by introduction of crevasse deposits (Interseam Sandstone). Extensive calcite lenses possibly resulted from evaporation in small pans or open-water areas (cf. Falcon, 1989). Iron sulphide minerals (e.g. pyrite), such as those found in the coal lithofacies, are known to occur in reducing environments, usually in humic-rich waters (Berner, 1971).

The **lenticular sandstone lithofacies** of the Interseam Sandstone is interpreted mainly as crevasse channel deposits, and the **sheet sandstone lithofacies** as crevasse splay deposits. The thickness of the fining-upwards units (< 2 m) of the lenticular sandstone lithofacies and the paucity of low-angle stratification characteristic in many fluvial point bars indicate that these are minor channels, probably crevasse channels. The low-angle

Table 4.8 Summary of characteristics and interpretation of Gwembe Coal Formation lithofacies

LITHOFACIES	GRAIN SIZE/SORTING	TEXTURE	MINERALOGY AND OTHER COMPONENTS	BEDDING AND SEDIMENTARY STRUCTURES	GEOMETRY / NATURE OF BOUNDING SURFACES / THICKNESS	DEPOSITIONAL ENVIRONMENT
Sandstone/ Conglomerate (SC_{p-c})	Matrix: fine to conglomeratic sand; poorly sorted Coarse fraction (clasts): granules to cobbles; poorly sorted	matrix-supported	rock fragments (quartz, quartzite, sandstone, schists)	massive, some show crude stratification	irregular bases; fining-upward sequences; units up 17 m thick including the overlying S_{vf-vc} lithofacies	fluvial: point bars of meandering river channel system
Sandstone (S_{vf-vc})	very fine to very coarse sand; moderately well sorted	matrix- to framework-supported	Grains: quartz, feldspar, rock fragments, muscovite. Matrix: limonite, sericite and chlorite. Heavy minerals: zircon, epidote, sphene, metallic minerals, tourmaline, rutile	horizontal bedding (Sh); massive (Sm); trough cross-bedding (St); soft sediment deformation; plant stem impressions.	tabular and amalgamated; irregular bases and tops; fining-upward units; minor small scale channels	
Coal (C)	not applicable (see Table 4.7)	see Table 4.7	see Table 4.7	massive and horizontal lamination	tabular: generally irregular bases and flat tops with overlying sandstones; up to 12 m thick	alluvial: swamp
Sandstone (S_{sis})	very fine sand to pebbles	generally framework-supported; moderately well sorted.	Grains: quartz, feldspar, rock fragments, muscovite. Clay minerals: kaolinite, illite, and smectite	massive; locally normal or reverse grading; horizontal to low-angle stratification; root traces	tabular (sheets) up to 50 cm thick	alluvial: crevasse splay deposits
Sandstone (S_{lis})				massive, or graded (normal or reverse); scour and fill lenses	irregular beds or amalgamated beds; erosional basal contacts; beds up to 1.5m thick in units up to 4m.	alluvial: crevasse channel deposits
Mudstone (M_{cl})	abundant coal fragments in carbonaceous mud		coaly (60%) and woody fragments, exinous, organic debris; quartz, feldspar, mica, mudrock intraclasts, siderite, kaolinite	laminated and massive plant stem impressions and leaf fragments	generally tabular beds with sharp contacts beds 1-10cm thick, units over 7m.	alluvial: flood plain and swamp
Mudstone (M_{ca})	carbonaceous mud		organic matter (50%), quartz, feldspar, siderite	massive; normal grading noted at thin section scale	commonly gradational contacts; units up to 17m thick	alluvial: flood plain and swamp

Table continued on next page

Table 4.8 continued

Mudstone (M_{sl})	silty mud; local poorly sorted mudclast breccias and conglomerates		Detrital grains (up to 50%): quartz, feldspar, muscovite and mudrock intraclasts, siderite, calcite, tourmaline, epidote	massive (predominant) and laminated; lenticular and flaser bedding; small-scale cross-lamination; rootlet casts	blocky, tabular; sharp and gradational contacts; units over 10m thick; fining-upward units	alluvial: levees, channel and floodplain distal crevasse splays
Sideritic Mudstone/ Siltstone/ Sandstone (MSS_{sd})	mud to medium sand	diagenetic concentrat-ion of siderite	siderite (up to 95%) in matrix of clay, quartz, muscovite; siderite altered to iron oxide	massive	concretionary and tabular siderite; generally irregular sharp bases and sharp convex-upward tops; beds up to 2.2m thick	originally alluvial, diagenetically altered by siderite cementation
Conglomerate/ Sandstone ($CS_{g\text{-}vc}$)	granules and pebbles (up to 95%); little sandy matrix, moderately to well sorted	framework-supported	Grains: quartz (>90%), feldspar, rock fragments, mica, rutile. Matrix (2-4%): silica, chlorite, sericite. Heavy minerals: zircon, epidote, tourmaline	trough (St) and planar (Sp) cross-beds; massive (Sm) or graded (normal and reverse); low angle and tangential scoop-shaped cross-bedding (Sl)	erosional sharp basal contacts; amalgamated beds; beds over 2m thick in units up to 25m including overlying $S_{vf\text{-}c}$ and M_{sm} lithofacies; locally fining-upward units	fluvial: various dune forms in braided streams (see text)
Sandstone ($S_{vf\text{-}c}$)	very fine to coarse sand; moderately well sorted	matrix- to framework-supported	quartz, feldspar, mica	massive, trough cross-bedding; horizontal bedding	fining-upward units common; amalgamated beds; contacts commonly gradational; units up to 5m thick	
Mudrock (M_{sm})	mud and silt; moderately well sorted		quartz, feldspar, mica	massive and small -scale cross-lamination	poorly defined units (i.e. poor exposure); occupy top portions of fining-upwards units	
Other Sandstones (LOS)	fine sand to pebbles; poorly to moderately well sorted	matrix- to framework-supported	quartz, feldspar, rock fragments, mica, siderite, zircon, sphene, epidote, garnet, amphibole, pyroxene, calcite, kaolinite and illite in various proportions in the sandstones (see text).	massive (Sm), horizontal and small-scale cross-lamination, low angle cross-bedding	mainly wedge-shaped, lenticular beds; units up to 10m; fining-upward units common	fluvial: crevasse channel and splay from avulsion of the main channel on the flood plain
Izuma Beds (LIB)	similar to (M_{ca}) and (M_{sl}) lithofacies above	similar to (M_{ca}) and (M_{sl}) lithofacies above	similar to (M_{ca}) and (M_{sl}) lithofacies above	similar to (M_{ca}) and (M_{sl}) lithofacies above	similar to (M_{ca}) and (M_{sl}) lithofacies above; unit up to 20m thick	similar to (M_{ca}) and (M_{sl}) lithofacies above

stratification in the sheet sandstone lithofacies probably represents crevasse splay deposits (cf. Rust, 1978a) and the rootlet structures (therefore palaeosol) in this lithofacies indicate an *in situ* origin of at least the Main Seam.

The **coaly mudstone lithofacies** is interpreted as overbank fines that settled from suspension on the flood plain. The silty mudstone clasts in the coaly mudstone lithofacies (e.g. Fig. 4.44d) resemble the diamictite texture in some Karoo sequences in South America (N. Eyles, per. comm., 1992). If this is true for the Gwembe Coal Formation, it indicates that short-lived periods of glaciation still occurred from time to time in the mid-Zambezi Valley. Another possible interpretation is that the clasts were blown in by wind. The cone-in-cone structures formed by diagenesis during compaction.

The **carbonaceous mudstone lithofacies** are also thought to represent overbank fines deposited from suspension during floods on the flood plain and in swamps. The normal grading observed in some beds suggests deposition by waning flow during falling flood stage. Laminae bent around small grains suggest that these are dropgrains blown by wind.

The **silty mudstone lithofacies** is interpreted as mainly overbank fines deposited in levees and in fining-upward units in channels. The mudclast breccias and conglomerates in the fining-upward cycles suggests reworking during flood events, followed by waning currents. The coarser varieties of the lithofacies (siltstone) are interpreted as distal crevasse splays and channel deposits. Rootlets in some beds (Fig. 4.47c) indicate subaerial exposure and that plants flourished on the flood plain.

The **sideritic mudstone, siltstone and sandstone lithofacies** indicates siderite cementation beneath a high water table during diagenesis. The concretions are characteristic of waterlogged soils that are neutral to alkaline, occurring where the surface of the floodplain is continuously saturated (Retallack, 1988). It is suggested that in extensive areas where the floodplain was saturated, and in ox-bow lakes, the siderite developed a tabular form, and where the floodplain was locally saturated, the siderite was in concretionary form. This depended on the supply of both iron and carbonate, and on the duration of saturation. The tabular beds may have formed in saturated areas over long periods of time. Postma (1982) confirmed that siderite is dominant in freshwater sediments with pore waters containing little chloride or dissolved sulphide, and that are supersaturated with ferrous iron. Although the root traces suggest subaerial exposure, grey colour and high organic content indicate accumulation in a reducing environment. In short, the occurrence of siderite is consistent with an alluvial floodplain origin for the Gwembe Coal Formation.

The **microconglomerate to very coarse sandstone lithofacies** of Sandstone A suggests deposition in a high-energy environment. Large trough cross-beds are interpreted as dune bedforms of the lower flow regime, whereas planar cross-beds likely resulted from migration of linguoid and transverse bars (Miall, 1977; Bluck, 1979). Reverse grading indicates progradation of channels during floods and normal grading represents settling of grains during waning current flow.

The **"other sandstone" lithofacies** are interpreted as crevasse channel and splay deposits resulting from avulsion of the main channel on the flood plain. Money and Drysdall (1975) indicated that the succeeding Gwembe sandstones (B, C, D, and E) marked the periodic re-establishment of a complex river system. However, the localised occurrence and thinness (< 10 m thick) of these lithofacies suggest deposition in crevasse channels and splays during episodic flooding.

4.3.2.17 Facies analysis

On a regional scale, the facies associations observed indicate alternating coarse-grained facies (sandstone) and fine-grained facies (mudstone) (Figs. 4.55, 4.56, and 4.57). For example, coaly mudstone is associated with coal, and carbonaceous mudstone occupies an intermediate position between the underlying coaly mudstone and the overlying grey silty mudstone. In general, a progressive, upward decrease in carbonaceous matter from the Main Seam is observed as the mudstone becomes greyer and siltier (Figs. 4.33, 4.36a, 4.55 and 4.57). The contacts between the lithofacies are commonly gradational, with subordinate sharp contacts particularly between coaly mudstone and the other mudstone lithofacies, and between sideritic lithofacies and the host rock type. These lithofacies are cyclic in nature. Because, the coal lithofacies of the Main Seam is *in situ*, whereas the mudstones (coaly, carbonaceous and silty) are transported, the former has been grouped with the intervening sandstones (Interseam Sandstone) as the coal facies assemblage, and

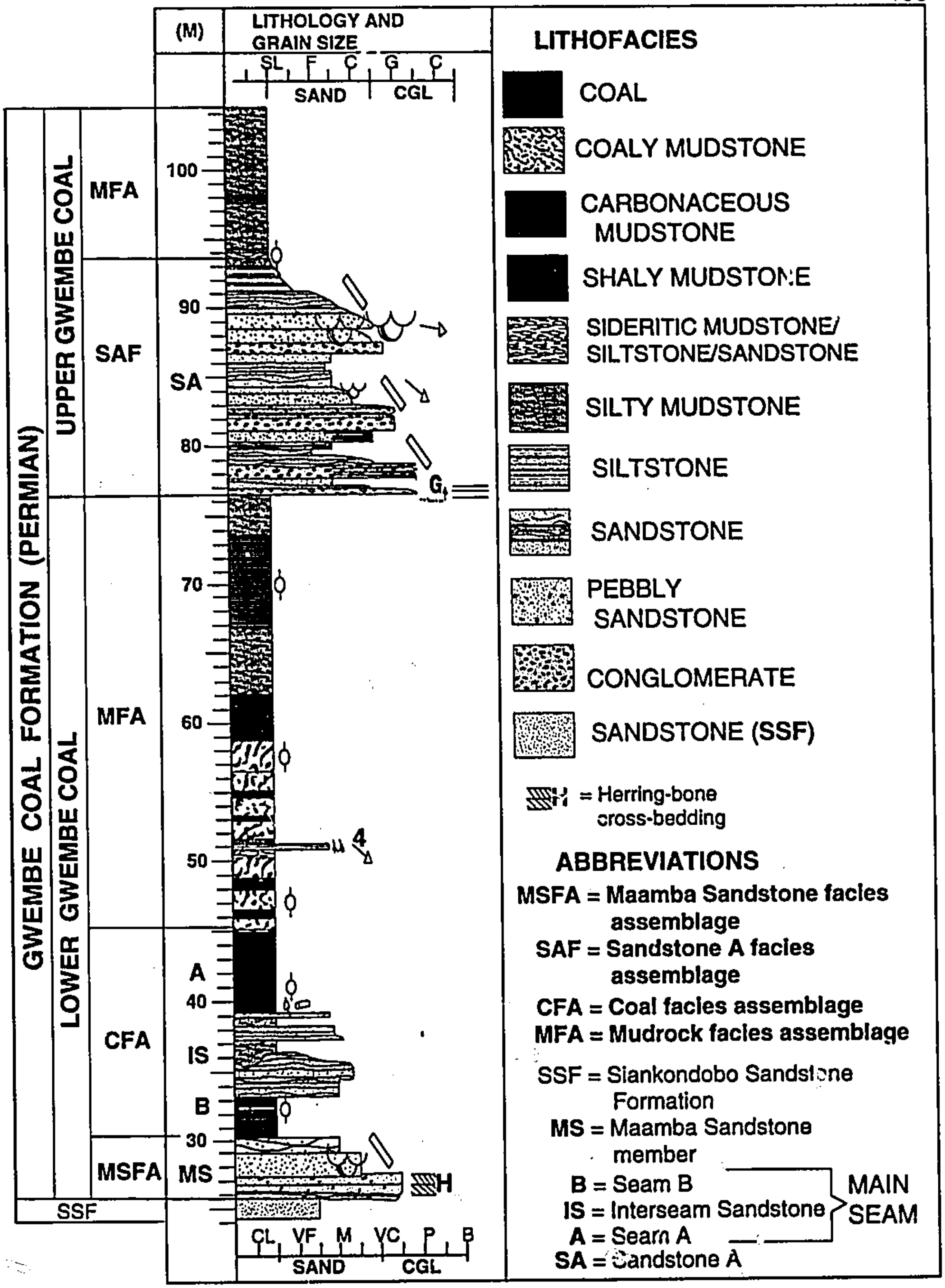


Fig. 4.55 Graphic log showing the facies assemblages in the Gwembe Coal Formation, Mulungwa River section 5, Mulungwa map area, mid- Zambezi Valley Basin, southern Zambia. Note that SAF is thicker at this locality in contrast to locality in Fig. 4.56. For key to sedimentary structures and features, see Figs. 4.0 and 4.33.

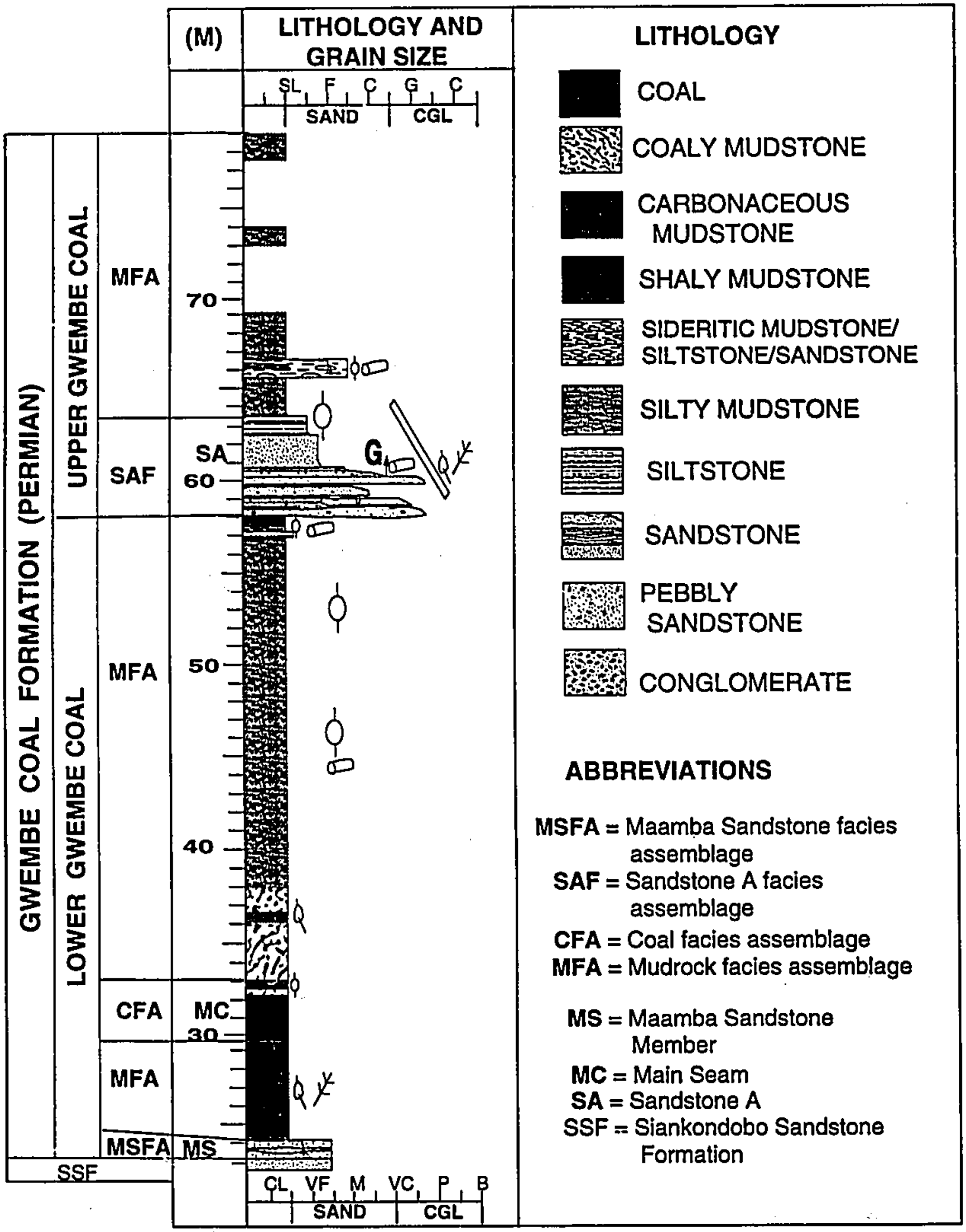


Fig. 4.56 Graphic log showing the assemblages in the Gwembe Coal Formation, Kasika River section 1, Nkandabwe map area, mid- Zambezi Valley Basin, southern Zambia. Note that SAF is thinner at this locality in contrast to locality in Fig. 4.55. For key to sedimentary structures and features, see Figs. 4.0 and 4.33.

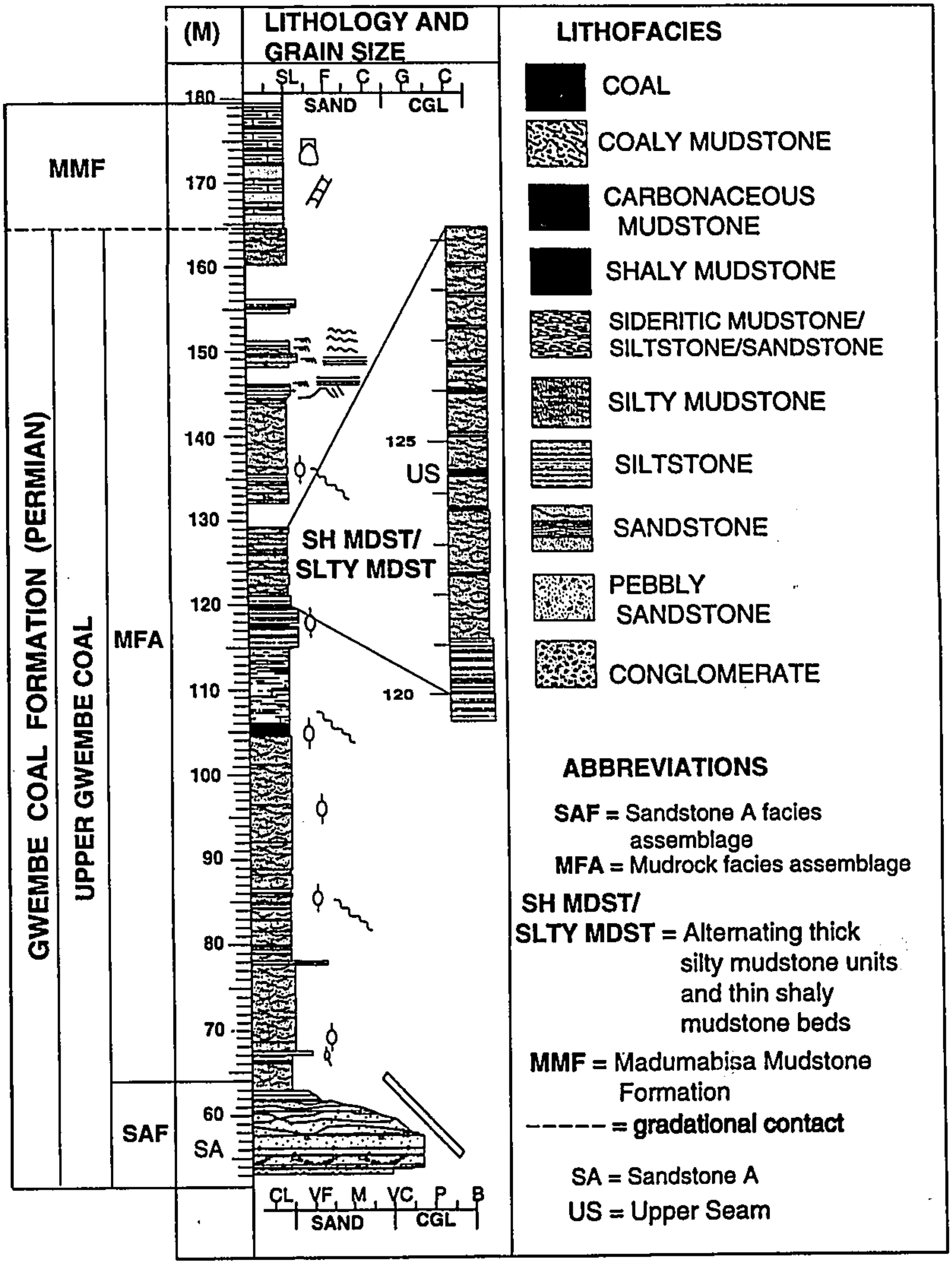


Fig. 4.57 Graphic log showing the facies assemblages in the Upper Gwembe Coal Formation, Zhimu River section 1, Mulungwa map area, mid- Zambezi Valley Basin, southern Zambia. For key to sedimentary structures and features, see Figs. 4.0 4.33 and 4.67.

the mudstones (coaly, carbonaceous and silty), sideritic lithofacies, the lithofacies of the "Other Sandstones" and Izuma Beds lithofacies are grouped as the mudrock facies assemblage. Therefore, four facies assemblages are identified in the formation: Maamba Sandstone, coal, mudrock and Sandstone A (Figs. 4.55 and 4.56).

The **Maamba Sandstone facies assemblage** comprises the conglomerate and sandstone lithofacies interbedded with subordinate coaly, carbonaceous and silty mudstones, and coal. The assemblage forms a fining-upward sequence (≤18 m thick) that grades into the Main Seam. The thickness, geometry and sedimentary structures suggest that the assemblage represents a channelized sandstone body deposited on an alluvial plain by a high sinuosity stream. Money et al. (1968) suggested that coarse-grained basal sediments of the Maamba Sandstone were probably formed by slumping in an unstable environment along the delta front, and that such instability was in part a result of episodic isostatic readjustment after the retreat of the Dwyka ice sheet. The alternating sandstone and carbonaceous (silty) mudstone lithologies in the assemblage indicate rapid changes in current flow.

The sheet sandstone and lenticular sandstone lithofacies of the Interseam Sandstone belong to the **coal facies assemblage** (Figs. 4.56 and 4.58). In Figs. 4.58, 4.59 and 4.60, the lateral and vertical variation of the Interseam Sandstone, coal and mudrock bodies indicate the widespread occurrence of the assemblages, with the variable geometry reflecting local changes in depositional environment. Some coal beds grade laterally into coaly mudstone and then into silty mudstone, and some lenticular sandstone bodies grade into channel-form bodies. These features indicate variation in sediment supply. The Interseam Sandstone shows variable thicknesses (≤ 4 m) and consists of generally fining-upwards bodies with subordinate coarsening-upwards units that divide the Main Seam into four seams (A, B, C, D). These fining-upwards units fill channels that are generally shallow (≤ 2 m) and wide (10 to 20 m). Channel filling was not continuous, as indicated by carbonaceous/coal-draped surfaces and small, cross-cutting channels within the sandstone body.

The variation in microlithotype (largely fusite to clarite), maceral and mineral content of the mid-Zambezi Valley coal indicates that the coals formed under variable conditions.

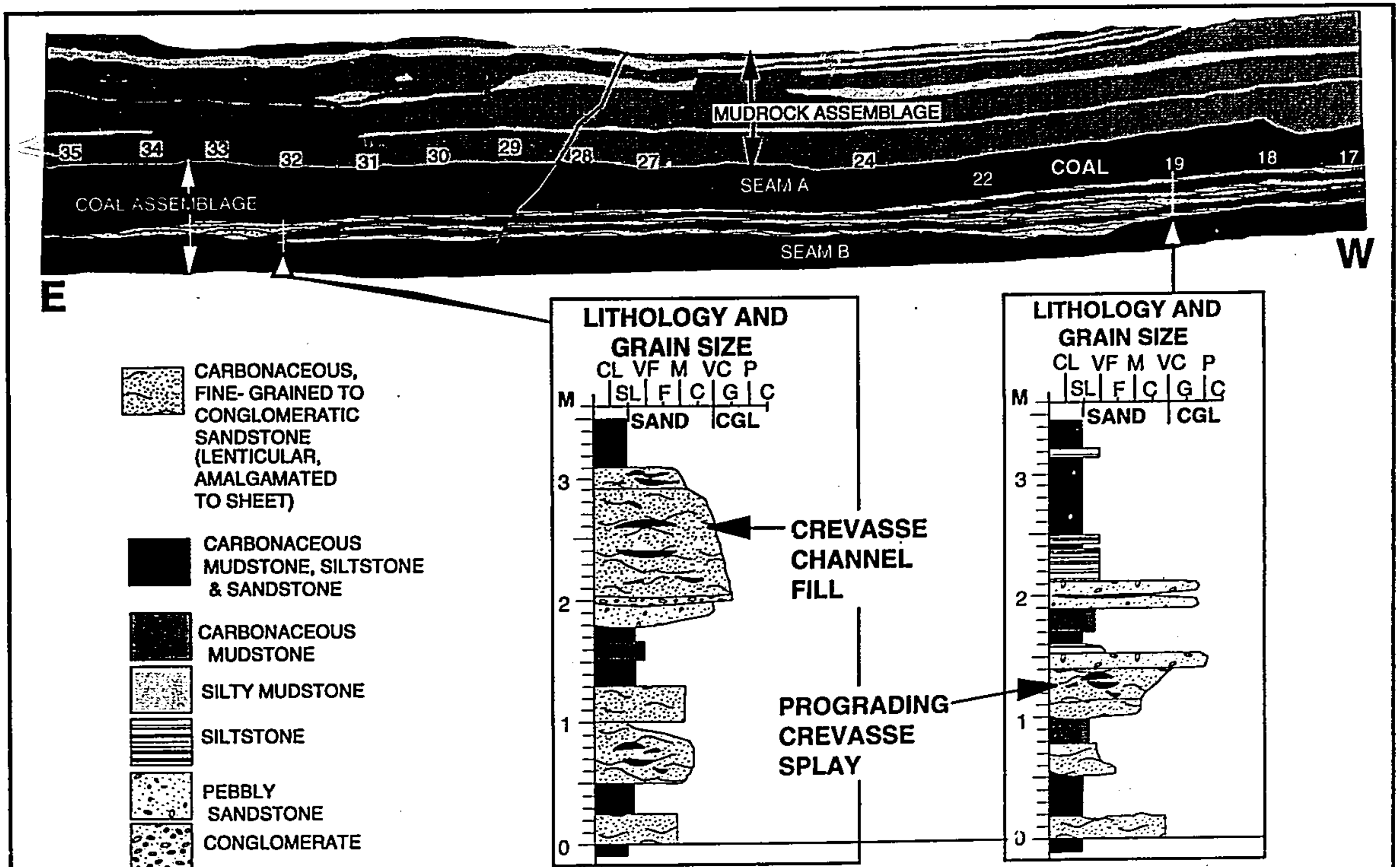


Fig. 4.58 Lateral variation in the coal and mudrock facies assemblages of the Gwembe Coal Formation, Kazinze Open Pit, Siankondobo map area.

a) Profile drawn from photomosaic shows lateral pinchout of siltstone and sandstone beds in the coal facies assemblage and mudrock facies assemblage; continuation to west in Fig. 4.59a). (b) and (c) are representative vertical profiles and interpretations of the Interseam Sandstone at the indicated sampling points. Some photographs taken within the Interseam Sandstone here are shown in Figs. 4.59 and 4.60.

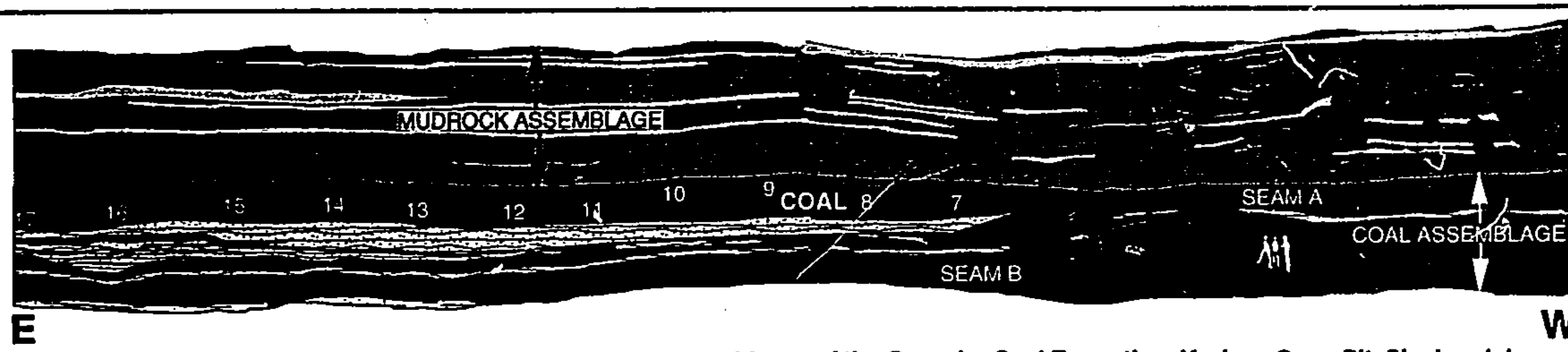
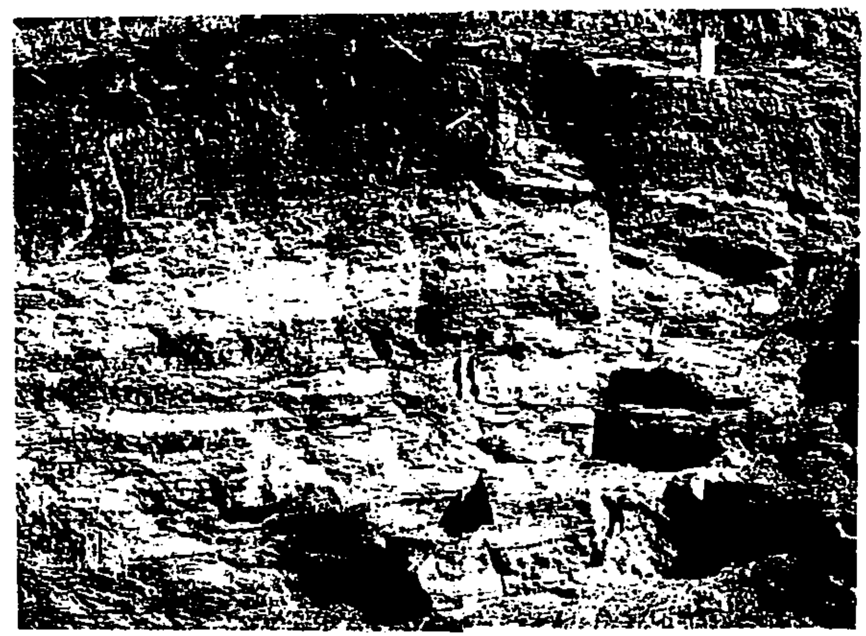


Fig. 4.59 Lateral variation in the coal and mudrock facies assemblages of the Gwembe Coal Formation, Kazinze Open Pit, Siankondobo map area.

a) Profile drawn from photomosaic shows lateral pinchout of siltstone and sandstone beds in the coal facies assemblage and mudrock facies assemblage; continuation to east in Fig. 4.58a) and to west in Fig. 4.60a). Outlines of human figures for scale. For Key, see Fig. 4.58.

b) Close-up view taken from sampling point 14 showing trough cross-bedded sandstone of lenticular sandstone lithofacies enclosed in carbonaceous mudstone/siltstone. Pen is 14 cm.



c) Photograph from sampling point 11 showing lenticular sandstone lithofacies (light coloured) of the Interseam Sandstone within carbonaceous mudstone/siltstone. Notice sandstone lenses (light coloured). White line is 6 cm long.

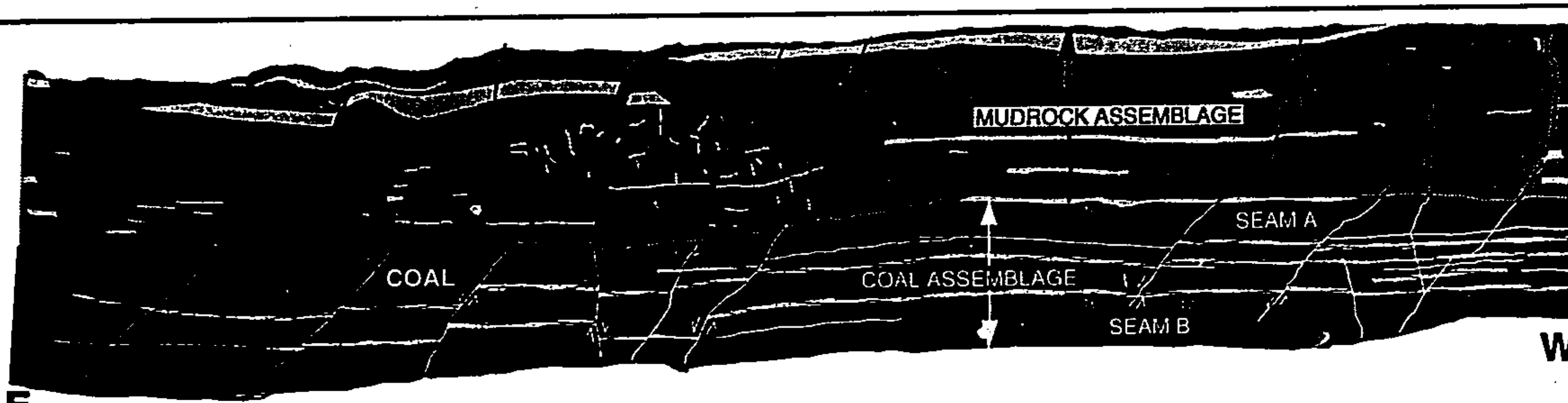
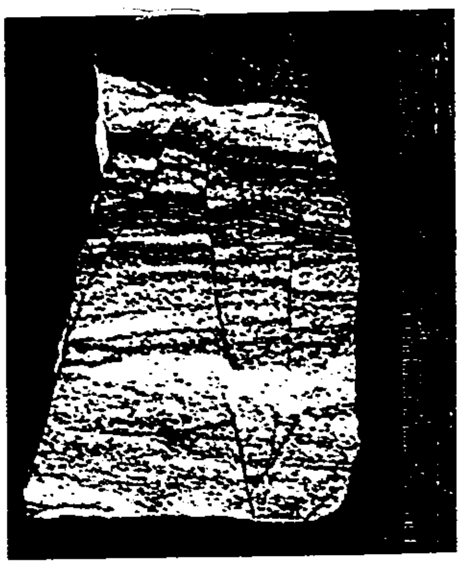
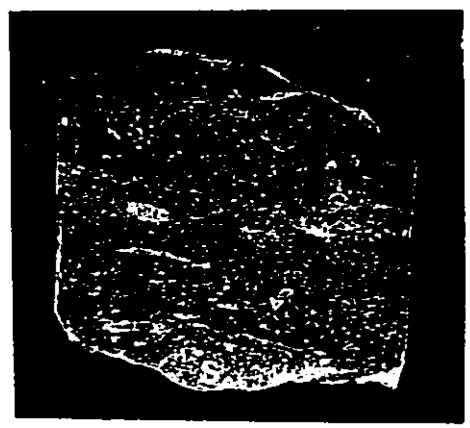


Fig. 4.60 Lateral variation in the coal and mudrock facies assemblages of the Gwembe Coal Formation, Kazinze Open Pit, Siankondobo map area.

a) Profile drawn from photomosaic shows lateral pinchout of siltstone and sandstone beds in the coal facies assemblage and mudrock facies assemblage; continuation to east in Fig. 4.59a). Faults post-date the formation. For Key, see Fig. 4.58.



b) Photograph taken from sampling point 32 (Fig. 4.58a) showing microfaults in the lithofacies of the Interseam sandstone. Scale in cm.



c) Photograph taken from sampling point 32 (Fig. 4.58a) showing carbonaceous siltstone/ mudstone with elongate fragments of silty mudstone and fine-grained sandstone (S) from the mudrock assemblage. Sample is 11 cm wide.

d) Photograph showing cylindrical body of carbonaceous/ coaly mudstone, probably fossil root. Lens cap is 5 cm in diameter.

These variations may represent periods of reworking, local flooding or rising ground-water levels, and/or changing geochemical conditions. Such factors likely varied between areas depending on the proximity to river channels and valley flanks, the degree of subsidence and compaction, and the length of time under specific conditions. Studies of microlithotype distribution suggest that this is an indication of the time spent in a particular palaeoenvironment or under certain geochemical conditions (Hagelskamp and Snyman, 1988; Hagelskamp et al., 1988). These studies have shown that a vitrite (vitrinite) layer indicates plant matter accumulating in relatively quiet, reducing, water-logged conditions; a semifusinite layer (inertite) indicates plant material accumulating *in situ* in exposed semioxidizing to oxidising conditions; an inertodetrite layer (inertite) indicates either decomposition of cellulose-rich plant matter (herbaceous forms) *in situ*, in oxidising and semiaqueous conditions to form fine, granular gel-like material, or the removal of a variety of plant material from its original site of accumulation and partial gelification, followed by re-deposition in a water-borne detrital form.

The common occurrence of quartz and clay minerals associated with abundant inertodetrites is considered to be indicative of relatively high-energy, fresh-water flood deposits, whereas clays, which appear to have flocculated in coal-forming environments, may indicate the existence of specific and different geochemical conditions in standing peat-swamp waters. The abundance of pyrite within the Interseam Sandstone and Coal seams of the Gwembe Coal Formation suggests reducing conditions; its formation is favoured by the presence of dissolved sulphide. Freshwater contains some sulphate, which in the reduced zone will inevitably result in the formation of some sulphide together with siderite. Postma (1982) concluded that it formed through the reduction of ferric oxyhydroxides by organic matter. This provides a source of both Fe^{2+} and carbonate for siderite formation. This was initially demonstrated theoretically by Berner (1964, 1971) who showed that siderite is not stable in marine environments, because it is only stable at extremely low dissolved sulphide activities, lower than in seawater. In Late Pleistocene and Recent deposits of northern Lake Tanganyika (East Africa rift), Baltzer (1991) indicated that pyrite is associated with layers in which sulphur is a direct function of iron and that siderite is typical of layers in which sulphur occurs in minor amounts and is distributed independently from iron. However, although siderite is common in ancient non-marine sediments, it has not been observed precipitating today (Kelts and Hsu, 1978).

The **mudrock facies assemblage** (coaly, carbonaceous and silty mudstone lithofacies, sideritic lithofacies, "other sandstone" lithofacies and Izuma Beds lithofacies) are generally massive, with minor lamination. Alternation of lithofacies has given rise to cyclothems (Figs. 4.36a, 4.57 and 4.61). Massive, fine-grained sediments have long been interpreted as suspension deposits resulting from waning currents (Collinson and Thompson, 1989). Abundant intraformational fragments commonly elongate parallel to lamination suggest current activity. The mudrocks of the mid-Zambezi Valley are therefore interpreted as overbank fines that accreted vertically from suspension during episodic flooding of the floodplain. The coarser, horizontally- to small-scale cross-laminated sediments (silty mudstone, siltstone and very fine-grained sandstone) are interpreted as distal deposits of crevasse channels, splays and levees. Silt-dominated overbank fines were likely deposited in splays and channels, with peat accumulating in the swamps to form coaly and carbonaceous mudstones, depending on the ratio of mud to organic matter. Away from the swamps, non-carbonaceous silt accumulated to form the silty mudstones. Pedogenesis, particularly in the mudrock assemblage, is expressed by the occurrence of root tubules in the sideritic concretionary facies and by mottling of the mudrock. Mottling in the massive mudstone, particularly in the silty mudstone lithofacies, is interpreted as resulting from seasonally oscillating water tables, and may have developed during pedogenesis either as a result of fluctuating Eh-pH conditions or through redistribution of iron oxide/hydroxide particles (Buurman, 1980; Platt and Keller, 1992).

The colour of sediments is generally considered to be an early diagenetic phenomenon controlled by geochemical conditions (Eh) and biological activity (Downing and Squirrell, 1965; Walker, T. R, 1967; Thompson, 1970; McBride, 1974; McPherson, 1980 and Myrow, 1990). Redox reactions result in green-grey to red coloration. As the Fe^{+3}/Fe^{+2} ratio in a rock decreases, the resulting colours can range from red through purple to grey (McBride, 1974). Yellow coloration is imparted by limonite, brown results from goethite, and red and reddish mottling from hematite (ferric-Fe_2O_3) (Myrow, 1990). Yellowish brown/brown colours are thus alteration products. The laterally persistent brick red (blood-

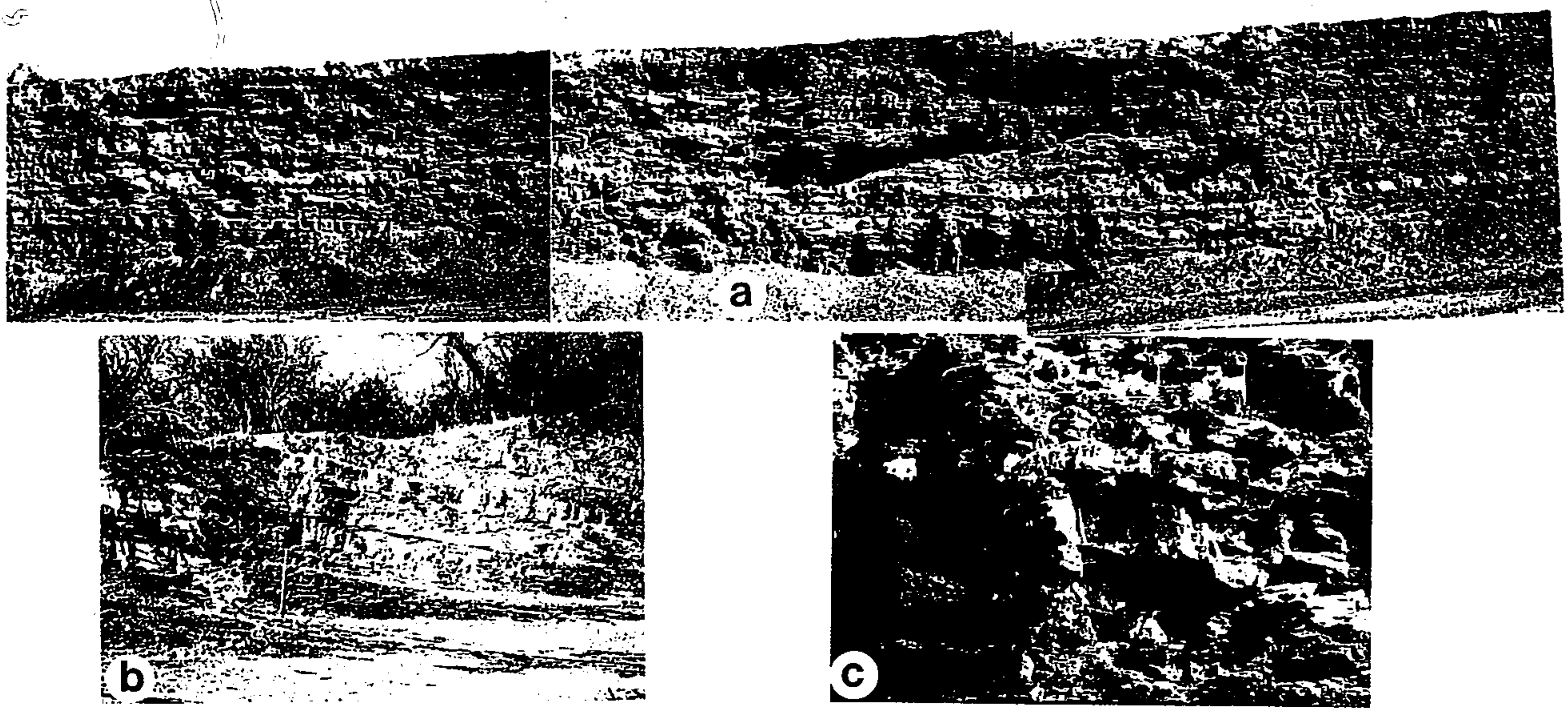


Fig. 4.61 Mudrock Facies Assemblage, Gwembe Coal Formation

a: The uppermost part of the Kazinze Open pit showing thinly to thickly bedded silty mudstone intercalated with coaly (white-burned) and darker carbonaceous mudstone. Person for scale.

b: Cyclothem defined by alternating silty mudstone (more resistant) and carbonaceous/coaly mudstone, Kazinze River Section 3, Siankondobo area. Scale 2.1 cm.

c: Alternating silty mudstone and carbonaceous (coaly) mudstone. Hammer head rests on base of a channel. Kazinze Open pit.

red) siderite beds indicate that the mudrock assemblage was deposited on a broad alluvial plain. The abundance of siderite suggests a fresh-water floodplain environment. Ankerite is probably a late diagenetic cement (Boles, 1978). In summary, crevasse channel and splay deposits, swamp deposits and high-sinuosity meandering channels and the cyclic nature of lithofacies indicate that the Gwembe Coal Formation was deposited on an alluvial flood plain.

The **Sandstone A assemblage** (Figs. 4.33, 4.55 and 4.56) marked a re-establishment of more active fluvial conditions on the floodplain. Two photomosaic profiles were made of Sandstone A, one in the Mulungwa Section 5 (Figs. 4.62 and 4.63), the other in the northwestern part of the Siankondobo area (Figs. 4.64, 4.65 and 4.66). In the former area the mosaic was taken in the top part of a 15 m fining-upward unit of Sandstone A. The base of microconglomerate that starts the fining upward unit is poorly defined, because isolated discontinuous layers of microconglomerate are in places sandwiched within fine to coarse-grained sandstone (Fig. 4.62a-c), and together they have been contorted (Fig. 4.62c). However, to the northeast of the profile, a bounding surface is overlain by large-scale trough cross-beds (3.2 m wide and 2 m thick) that become crudely stratified to massive laterally to the southwest (Fig. 4.62b). These microconglomerate layers locally contain intercalations of distorted finer sediments and coal fragments. The trough cross-beds and the equivalent massive bed are succeeded by medium- to small-scale trough cross-beds (Fig.4.63a, b), which grade upward into mudstone. The lithofacies commonly contain intraclasts, mainly of coal and coaly fragments, and fossil plant stem impressions. Measurement of trough cross-bed orientations (7 readings) showed a palaeocurrent direction to the southeast (Fig. 4.63c).

Figs. 4.64, 4.65 and 4.66 represent a 171 m long downdip profile from the Siankondobo area. The profile shows downstream accretion surfaces with a down-current change in grain size from granular (microconglomerate), to fine- to medium-grained sandstone. Sedimentary structures are obscured by weathering, but in places horizontal bedding parallel to bounding surfaces is present as well as crude trough cross sets. The included photographs illustrate some of the features observed in the sandstone. Orientations of the ribs and furrows (156 readings) exposed on bedding surfaces within the

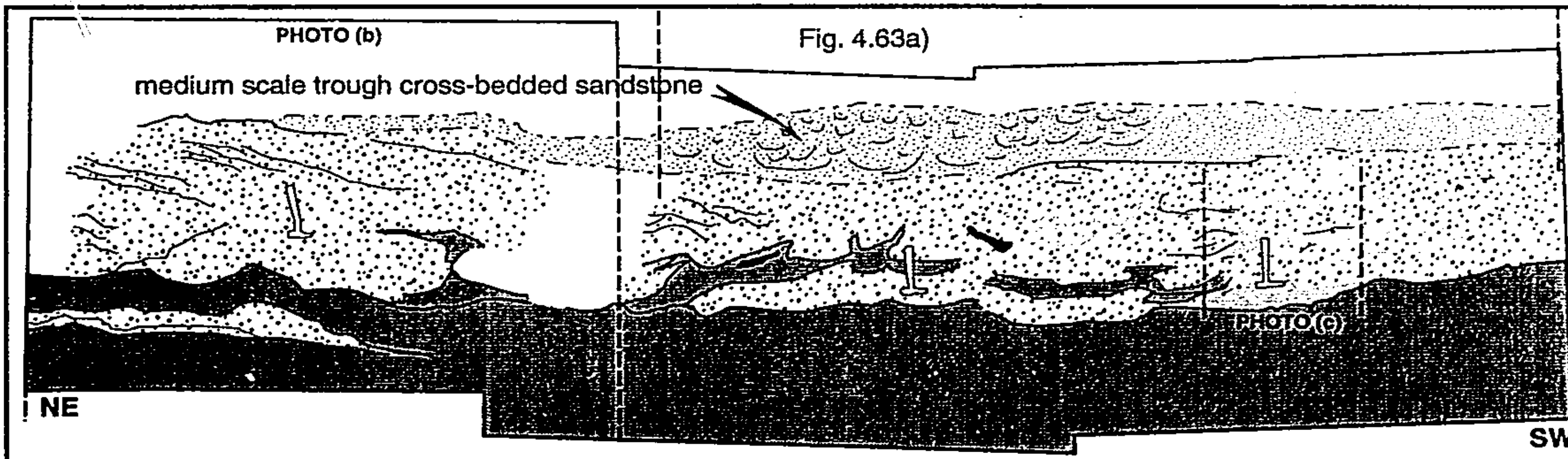
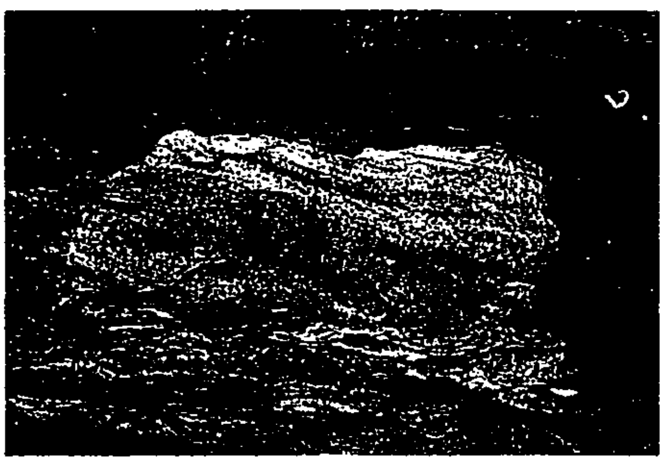


Fig. 4.62 Fining-upward unit (point bar) in Sandstone A Facies Assemblage of the Gwembe Coal Formation, Mulungwa River Section 5, Mulungwa map area.

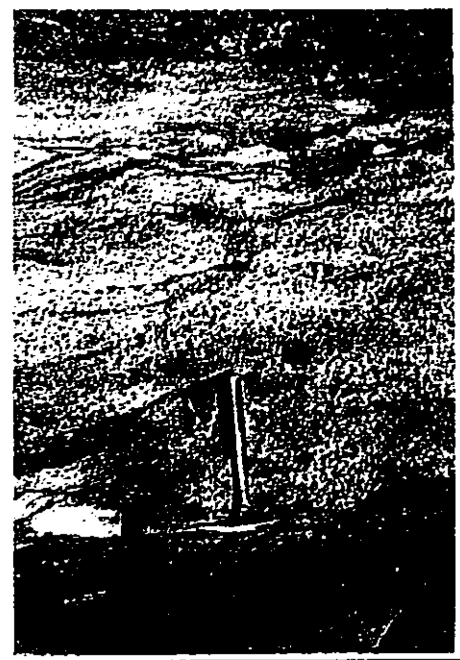
a) Profile drawn from photomosaic shows a fining-upward unit from basal conglomeratic sandstone to very fine-grained sandstone with abundant intercalations of medium- to very coarse-grained sandstone and siltstone/mudstone. Coal fragments are also present. For detail of upper part, see Fig. 4.63a). Hammer outlines are 34 cm long.



b) Representative photograph showing microconglomerate with contorted carbonaceous, medium- to coarse-grained sandstone. Hammer for scale.

KEY

- COAL FRAGMENTS
- SILTY MUDSTONE/ SILTSTONE
- VERY FINE- TO MEDIUM-GRAINED SANDSTONE
- MEDIUM- TO VERY COARSE -GRAINED SANDSTONE
- CONGLOMERATIC SANDSTONE



c) Close-up photograph showing microconglomerate intercalated with irregular beds and stringers of medium- to very coarse-grained sandstone.

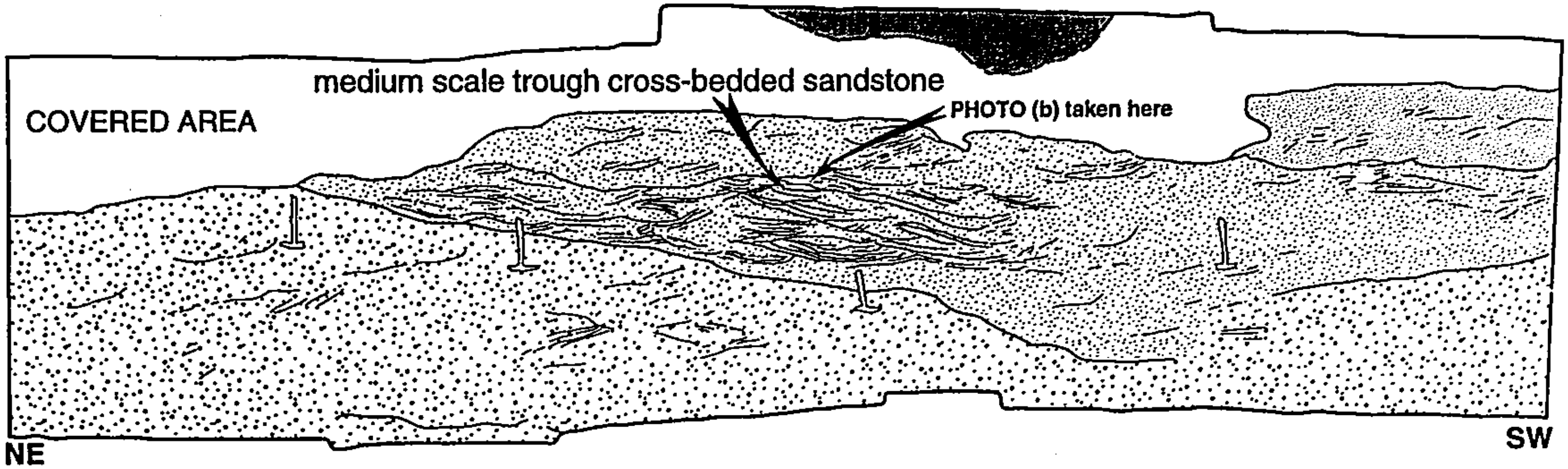
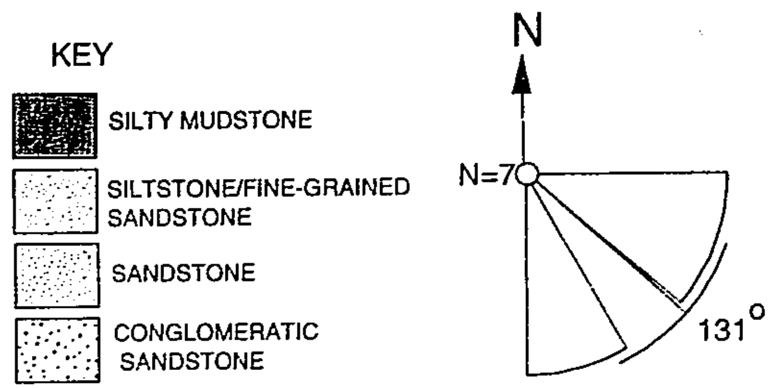


Fig. 4.63 Fining-upward unit (point bar) in Sandstone A Facies Assemblage of the Gwembe Coal Formation, Mulungwa River Section 5, Mulungwa map area.

a) Profile drawn from photomosaic shows a typical fining-upward unit (point bar) from basal conglomeratic sandstone to silty mudstone; profile represents enlargement of the upper right part of Fig. 4.62a (between dashed lines). Hammer outlines are 34 cm long.

b) Close-up photograph showing detail of medium scale trough cross-bedded cosets in fine- to coarse-grained sandstone lithofacies. Hammer for scale.



(c) General Palaeocurrent direction to the Southeast

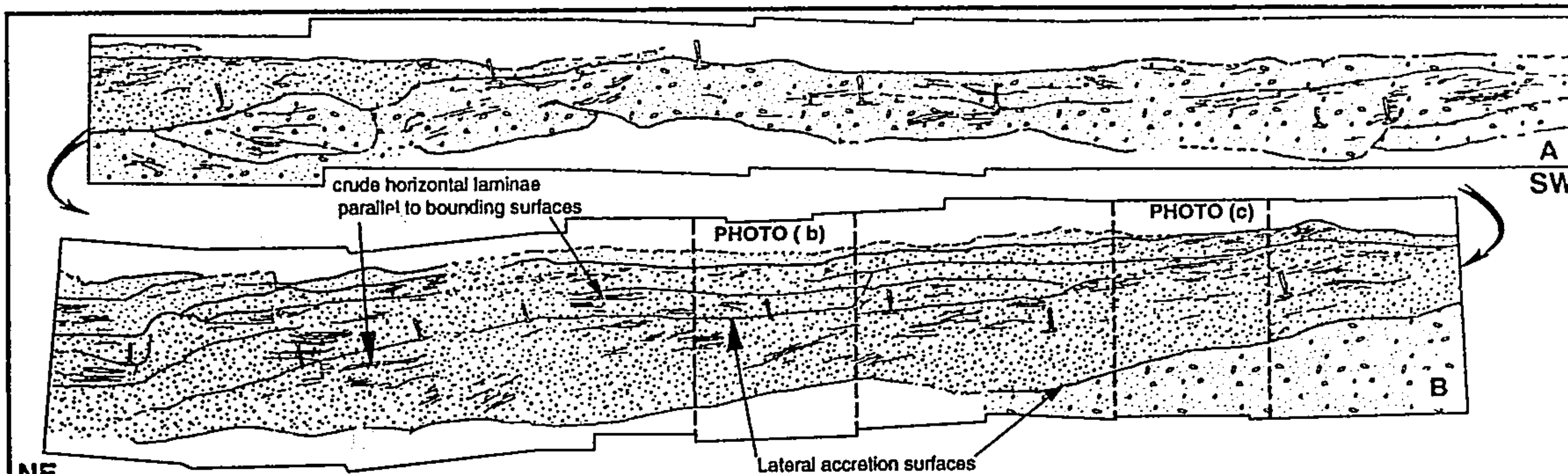
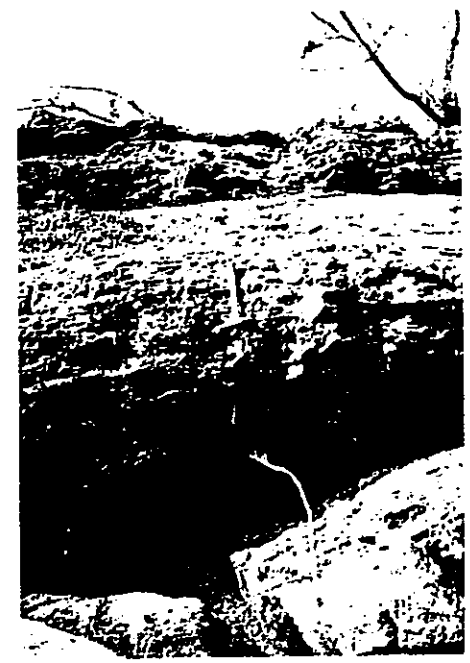


Fig. 4.64 Downstream accretion surfaces and grain size reduction in Sandstone A Facies Assemblage of the Gwembe Coal Formation, northwestern part of Siankondobo map area.

a) Profiles A and B drawn from photomosaic show downstream accretion surfaces with crude stratification; continuation of profile B after a gap, to northeast in profile C of Fig. 4.65a). Hammer outlines are 34 cm long. For key to lithology, see Fig. 4.65a).

b) Representative photograph showing crude low-angle cross-stratification in pebbly sandstone. Hammer for scale.



c) Representative photograph showing microconglomerate overlain by crudely stratified pebbly sandstone. Hammer for scale.

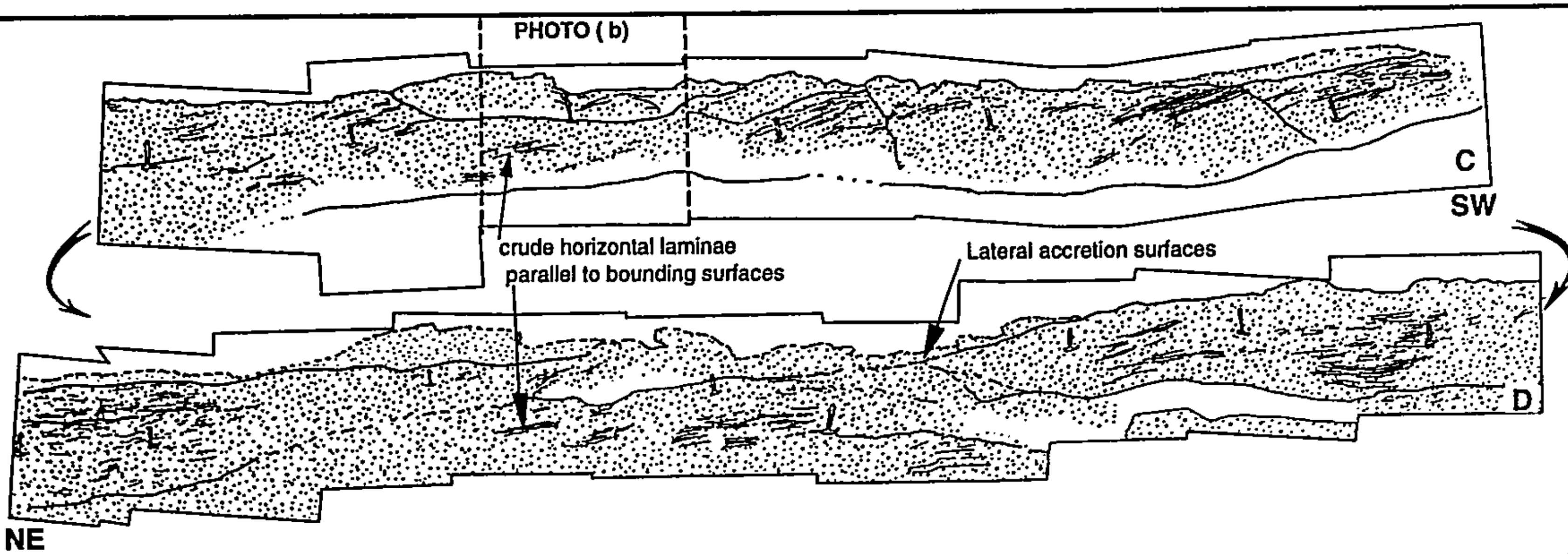
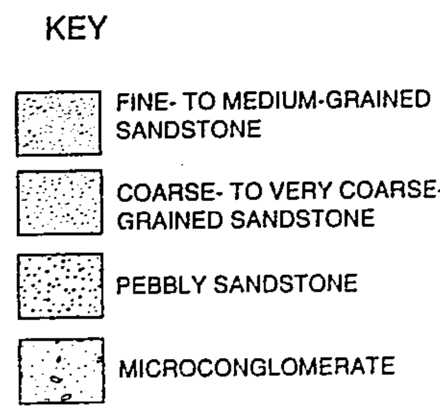


Fig. 4.65 Downstream accretion surfaces and grain size reduction in Sandstone A Facies Assemblage of the Gwembe Coal Formation, northwestern part of Siankondobo map area.

a) Profiles C and D drawn from photomosaic show downstream accretion surfaces with crude stratification; continuations after a gap, to southwest on profile B of Fig. 4.64a) and to northeast on profile E of Fig. 4.66a). Hammer outlines are 34 cm long.



b) Representative photograph showing faintly horizontally and cross-stratified pebbly sandstone. Stratification has been obscured by weathering. Hammer for scale.

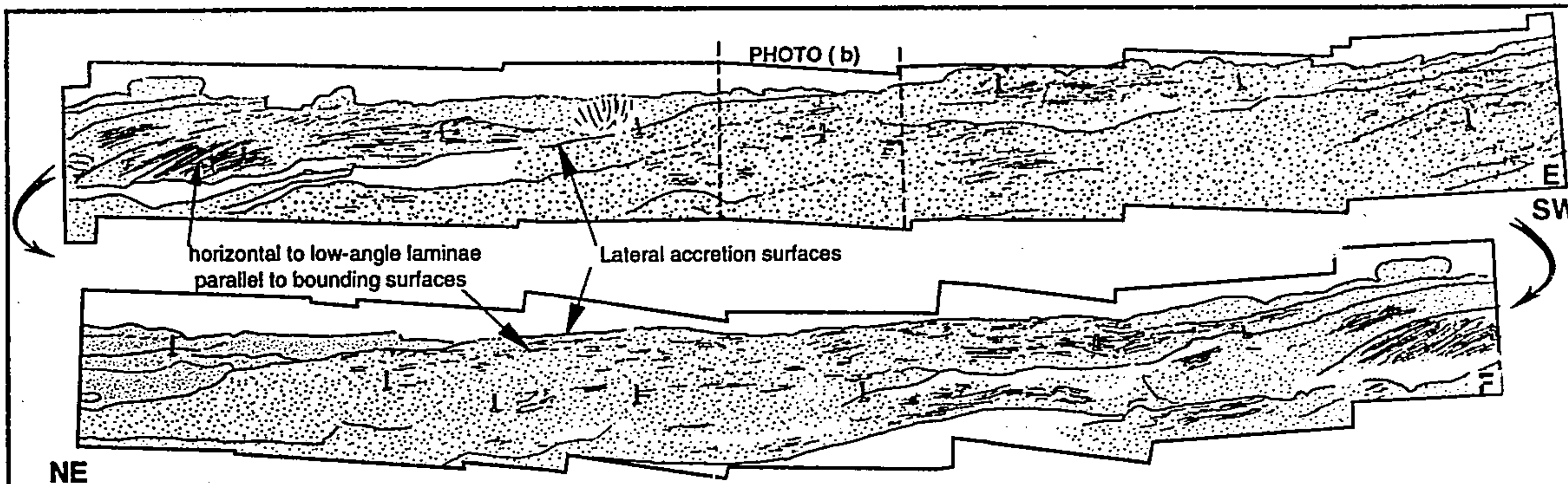
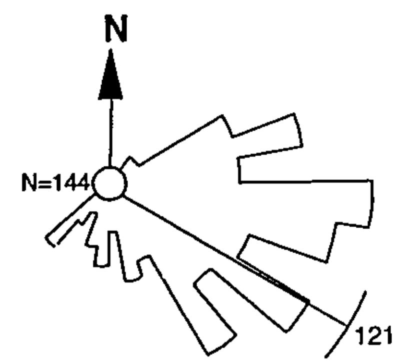


Fig. 4.66 Downstream accretion surfaces and grain size reduction in Sandstone A Facies Assemblage of the Gwembe Coal Formation, northwestern part of Siankondobo map area.

a) Profiles E and F drawn from photomosaic show downstream accretion surfaces with crude stratification; continuation of profile E to northeast on profile D of Fig. 4.65a). Total distance (profiles A, B, gap, C to F) is 171 m. For key to lithology, see Fig. 4.65a). Hammer outlines are 34 cm long.

b) Representative photograph showing faintly stratified coarse- to very coarse-grained (locally pebbly) sandstone. Stratification has been obscured by weathering. Hammer for scale.



(c) General palaeocurrent direction to the southeast. Readings taken from bedding surfaces exposing rib and furrow (trough) within the vicinity of the profiles (A to F).

vicinity of the profile showed a palaeocurrent direction to the southeast (Fig. 4.66c).

Thicker Sandstone A units in the northwestern part of Siankondobo map area and the northern part of the Maze-Sinakumbe map area (Fig. 4.51) reflect active subsidence with a lateral transition from dominantly low-sinuosity channels deposits to dominantly high-sinuosity channel deposits. Money and Drysdall (1975) interpreted Sandstone A as a lateral accretion deposit of a meandering channel on the floodplain. However, the very coarse-grained nature (e.g. Fig. 4.52d, e), the large-scale cross-bedding (trough and planar; e.g. Figs. 4.51d, e and 4.52a, b), and the paucity of mudrocks in the microconglomerate to very coarse sandstone lithofacies of Sandstone A indicate that the sandstone was probably deposited in a proximal braided stream system at the margin of the basin. Rust (1978a) pointed out that gravel in braided systems is distinguished from that in meandering systems by the dominance of framework-support and that sand in braided systems is distinguished by the presence of suspension-deposited intraclasts as opposed to bedload. The framework-supported grains of the microconglomerate lithofacies and coaly intraclasts (likely to have been moved in suspension) in the lithofacies suggest a braided influence. Presence of downstream accretion surfaces, common in braided streams, further supports the braided-stream interpretation. These streams probably fed a high sinuosity river running parallel to the basin axis that produced lateral accretion bodies of the meandering type. Rust (pers. comm., 1990) compared Sandstone A to the Triassic Hawkesbury Sandstone of Australia, which is interpreted as a braided river system deposit.

4.3.3 MADUMABISA MUDSTONE FORMATION

4.3.3.1 General Remarks

The formation is formed by up to 700 m of monotonous grey-green, non-carbonaceous, silty mudstone and siltstone (mudrocks - Brown and Harrell, 1991) with minor interbedded calcilutite, irregular concretionary and nodular calcilutite, claystone, sandstone and muddy conglomerate (Fig. 4.67). The mudrocks form over 95 % of the formation, are calcareous and contain subordinate marls. A generalised stratigraphic column for Madumabisa Mudstone Formation is given in Fig. 4.67.

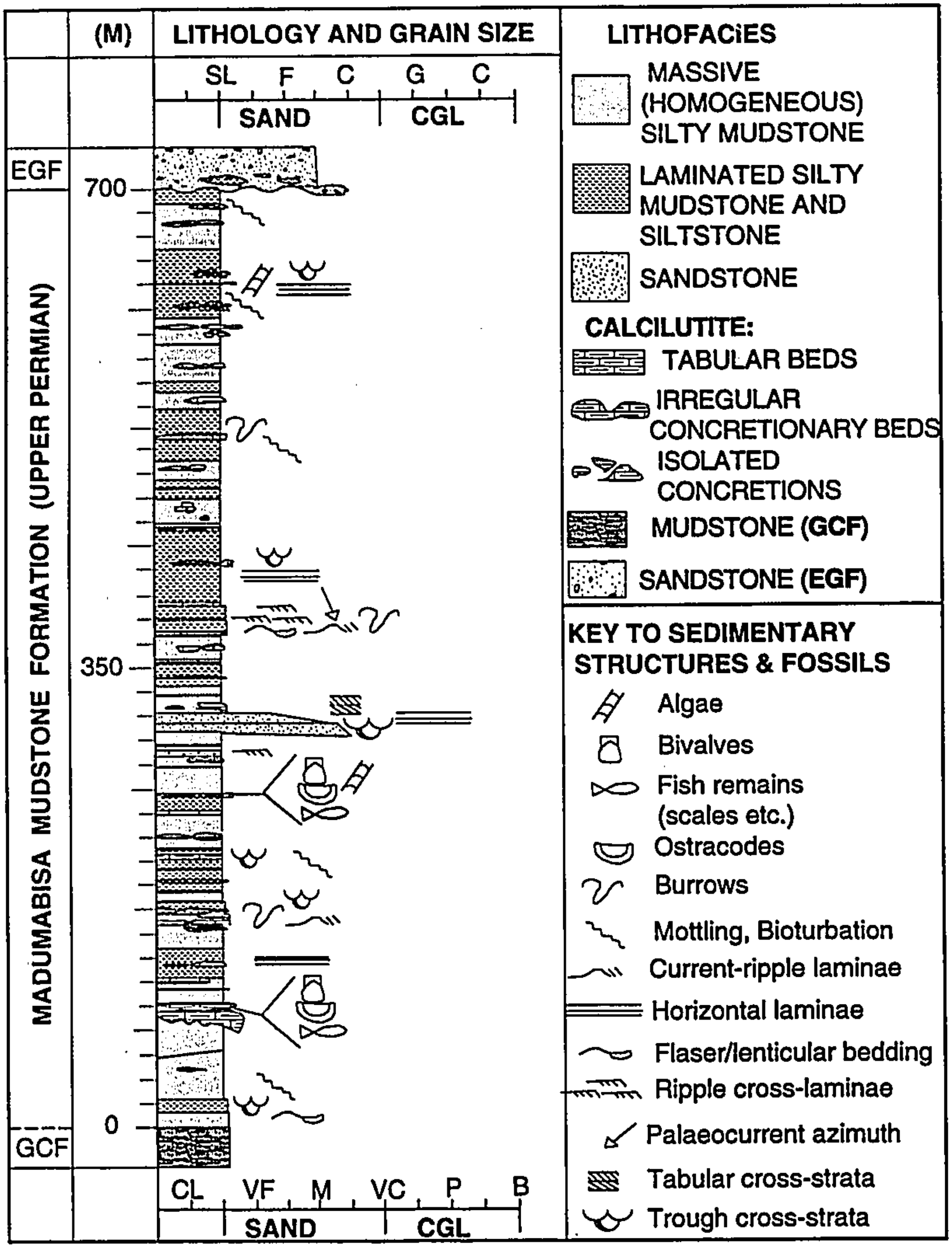


Fig. 4.67 Generalized stratigraphic column of the Madumabisa Mudstone Formation, mid-Zambezi Valley, southern Zambia (not to scale). For abbreviations see Fig. 4.0. ---- = Gradational contact.

Weathering and erosion has resulted in the removal and covering of the mudrocks in low-lying areas. However, some good outcrops are exposed along creeks, streams and rivers. In the study area, the best place to study the formation is in the Mulungwa area, where the present Mulungwa River meanders across the formation, giving measurable sections approximately perpendicular to the strike of the formation at certain locales. Seven sections about 100 m or more thick were measured in the area; one is in the Siankondobo area (Kazinze Section 1) and one in the Nkandabwe area (Kasika Section 1). Elsewhere, stream sections are limited, and the difficulties of stratigraphic positioning make measurement impracticable.

Depositional and diagenetic factors have contributed to the heterogeneity of the mudrocks.

Most of the Madumabisa mudrock is green/grey, but other colours ranging from grey (all shades of grey), brownish grey, greenish grey or dark green and red to pale brown on fresh surfaces are also present. On weathered surfaces, the colours range from greenish and greyish and yellowish brown to dark brown, purplish brown and brick red. Khaki colours are also present. The green coloration reflects the presence of iron-bearing phyllosilicates such as chlorite and illite.

The finer end-members of the mudrock, both mudstone and claystone, are usually massive with subordinate crude lamination. The coarser types (silty mudstone and siltstone) tend to show tabular bedding. The characteristic structures are small-scale cross-lamination, graded bedding, lenticular, flaser and wavy bedding. The lamination in these beds is attributed to subtle variations in grain size, composition (mineralogy), or colour. On weathered surfaces, the laminae are accentuated by colour changes due to leaching of carbonates (mainly calcite) and finer material (e.g. clay). Bioturbation has resulted in the destruction of sedimentary structures, some completely.

The Madumabisa Mudstone Formation consists mainly of alternating poorly stratified (massive) homogeneous mudstone and stratified (laminated) silty mudstone and siltstone units with subordinate calcilutite, sandstone and conglomerate beds. Tavener-Smith (1960, 1962) and Gair (1960) divided the formation into lower, middle and upper units, considering that the lower and upper units are more homogeneous and poorly stratified. This subdivision is not easily applied to small isolated outcrops, and is generally not practicable, as stratification was observed throughout the formation. However, on the basis of distinctive sedimentary structures, geometry and lithology, four lithofacies are defined here: (i) massive, silty mudstone, (ii) concretionary calcilutite, (iii) laminated silty mudstone and siltstone, and (iv) sandstone. Lateral continuity of the mudrock lithofacies can be up to 500 m where the present streams and rivers meander through the strata parallel to the depositional strike (for example, along the Mulungwa River); otherwise, the outcrops are of limited lateral extent, usually within 5-10 m. The absence of marker beds makes correlation difficult.

4.3.3.2 Massive silty mudstone lithofacies (M_m)

The massive silty mudstone lithofacies has a hackly conchoidal fracture and comprises predominantly grey to green, massive (non-laminated) silty mudstone. It is associated with minor but common concretionary calcilutite lithofacies (Fig. 4.68).

In outcrops, the lithofacies forms units ranging from less than a metre to over 30 m thick (Fig. 4.68a, c). The mudstone is characterized by fragmental weathering (Fig. 4.68a-d) that obscures the structural and biological (burrowing) features. It is variously coloured and usually mottled in all shades of grey, but is commonly light olive grey (mainly greenish grey) to brownish grey. Mottling is common towards the top of the formation, particularly in the 20 m interval beneath the Escarpment Grit Formation, where green and red mottling predominates. Some units weather yellowish orange. The brownish grey mudstone has a siliceous appearance.

The silty mudstone breaks or peels spheroidally into small lensoids, usually less than 1cm in diameter, that fracture conchoidally. In places, the mudstone is fragile. Fine quartz grains have been noted locally and scattered mica specks are common. Calcite veinlets are present locally. Black and reddish brown intraclasts, disseminated black material and streaks are common. Overall, the fragmentary nature of the weathered silty mudstone makes sample collection difficult.

In thin section, the silty mudstone consists mainly of subangular quartz (20-60%), minor feldspar (plagioclase common), muscovite, mudstone clasts, and bioclasts embedded in calcite cement and clay-rich matrix. Trace amounts of microcline and orthoclase are

Fig. 4.68 Massive silty mudstone lithofacies

Madumabisa Mudstone Formation

a: Massive mudstone showing characteristic isolated and aggregated concretions and concretionary calcilutite. Notice that bedding is crudely expressed. Mulungwa River Section 4, Mulungwa map area. Outcrop ~ 15 m thick.

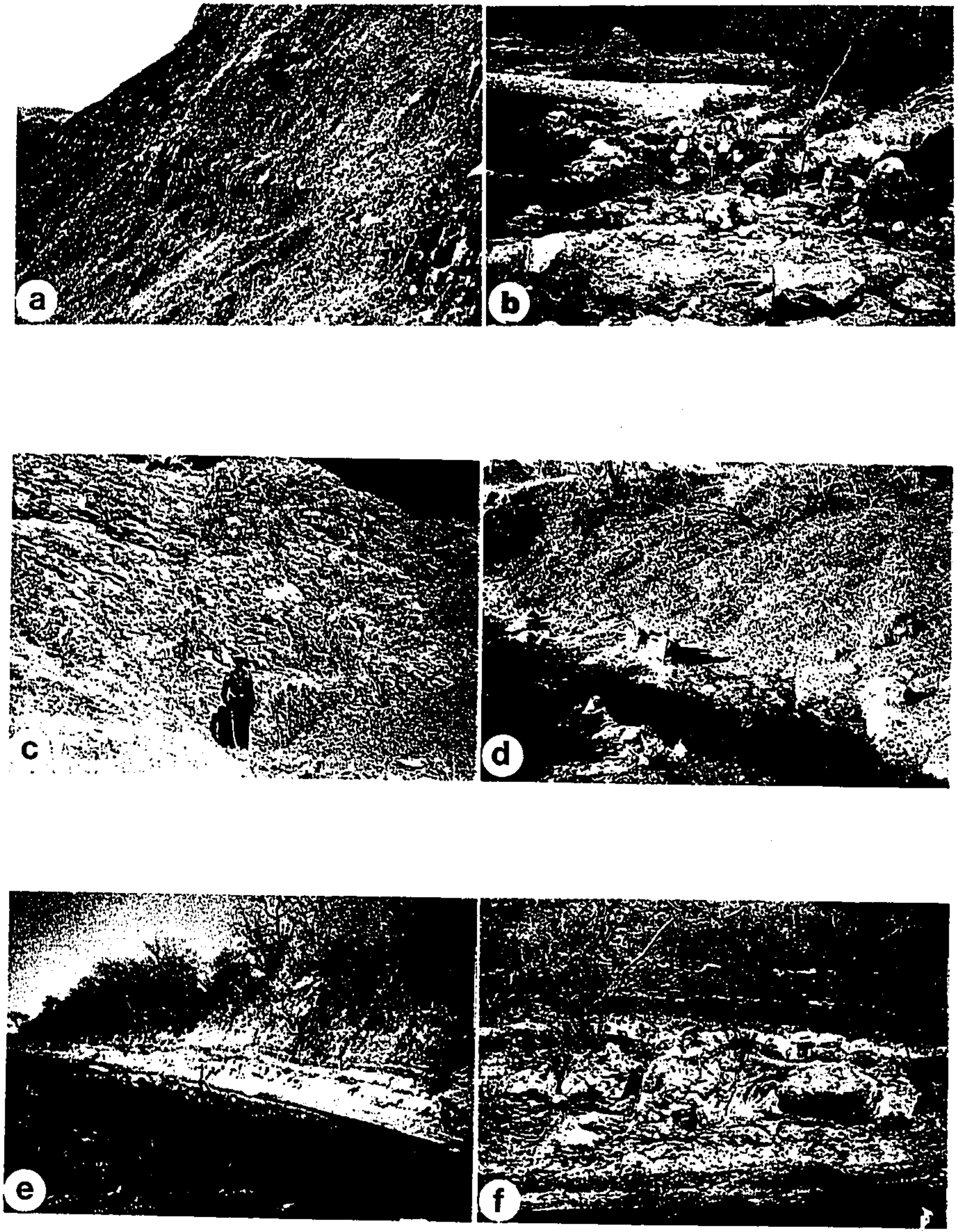
b: Large (up to .8 m thick) calcilutite concretions and concretionary beds in massive silty mudstones. Zhimu River Section 1, Mulungwa map area. Hammer is 34 cm.

c: Massive silty mudstone with conchoidal fractures related to weathering. Notice absence of calcilutite concretions. Mulungwa River Section 4, Mulungwa map area. Person for scale.

d: Massive silty mudstone with scattered isolated concretions. Mulungwa River Section 4, Mulungwa map area. Hammer for scale.

e: Massive silty mudstone with concretionary calcilutite interbeds succeeded by crudely laminated silty mudstone lithofacies. Mulungwa River Section 6, Mulungwa map area.

f: Detail of (e). Notice irregular basal contacts, but flattened convex tops of the concretionary calcilutite interbeds.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also present. Some quartz overgrowths are present in the calcite-poor mudstone. The cement consists of micrite (dominant) and microspar. The mudstone is generally structureless, but locally is crudely laminated. Intraformational micrite mudclasts, clay-rich (illite/smectite) mudclasts and brownish/reddish black, irregular, elongate to sub-spherical clasts are common throughout the mudstone. The maximum grain diameter is 0.05 mm, with an average of 0.01-0.02 mm. Discontinuous irregular clay-rich stringers and streaks in the mudstone attest to bioturbation. This is further expressed by some elongate grains that show preferred orientation parallel to bedding. Irregular sparite-filled cavities probably represent burrows. Alternation of darker (comprising organic matter and clay) and lighter laminae is common in the mudstone. The mudstones also contain skeletal fragments, mainly ostracods and minor bivalves. The bioclasts are associated with scattered micrite-rich and/or clay-rich mudclasts. The ostracod shells are commonly replaced by sparite or microspar, and locally show geopetal infilling.

The modal composition of the silty mudstone is: quartz (30-60%), feldspar (0.1-10%), mica (muscovite mainly, <0.5%), calcite (10-60%), clay (illite and smectite 5-30%), and heavy minerals (epidote, sphene and garnet). The silty mudstone, with more than 30% detrital grains (20-65%) that are clay- and micrite-supported, is classified as wackestone (Dunham, 1962).

4.3.3.3 Concretionary calcilutite lithofacies (C_t)

This lithofacies is commonly associated with the silty mudstone lithofacies, occurring as irregular isolated concretions (Fig. 4.68b, d) or more commonly as aggregates and beds (Fig. 4.68e, f). The rocks are whitish grey, light olive grey to brownish grey and weather yellowish orange and yellowish brown. Black to dark brown coatings are common on surface exposures.

Aggregates of coalesced concretions (Fig. 4.68f) form very irregular beds of concretionary calcilutite up to 1.2 m thick. Scattered, isolated spherical to ellipsoidal septarian concretions (millimetres to 50+ cm in diameter) are abundant (Fig. 4.68). The thick concretions and concretionary beds are mostly confined to the basal part of the formation. Some beds contain discontinuous, contorted laminae. Aggregates of fist size and larger concretions are common (Fig. 4.69a, b), but most aggregates occur along the same horizons, probably following bedding planes (Fig. 4.69a). The concretions break conchoidally, forming very sharp edges. Some large concretions appear to have resulted from cementation of individual concretions by calcite (Fig. 4.69b); some are septarian (Fig. 4.69c) but commonly the septarian structure is only observed when broken (4.69d); some show numerous calcareous veinlets which probably were pre-existing calcareous algae (Fig. 4.69d, top of photo) or due to fracturing. A mesh-work defined by very light (whitish) grey calcareous veinlets was observed in one bed. Internally, some fist-size concretions show irregular creamy brown veins and veinlets (Fig. 4.69e). Mudstone intraclasts averaging 1cm in diameter (up to 5 cm), dark brown/black and green filaments, and disseminated black to dark brown and reddish brown material (probably organic) are common. Ellipsoidal to subspherical whitish grey (khaki) algal lumps (Fig. 4.69f, identified by Rust, 1990 pers. comm.) and brownish grey, greenish grey to dark grey, rounded to elongate, argillaceous and micritic intraclasts (Fig. 4.70a, b) occur in some beds. In others, fragments appear diffuse (Fig 4.70c), with evidence of brecciation expressed by stylolites. On a small scale, some of these beds display boudinage-like features (Fig. 4.70a), whereas some larger scale examples resemble ball and pillow structures. Cone-in-cone structures are developed in some beds (Fig. 4.70d), but are less well developed than examples in the literature (Pettijohn, 1975; Fig. 12.8). Along the Mulungwa River, near Section 6, the concretionary beds show a peculiar surface feature consisting of crests and troughs resembling shrinkage cracks (Fig. 4.70e). Internally, where the structure is preserved (Fig. 4.70f) it appears to reflect differences in grain size rather than composition. Slickensides (Fig. 4.71a) and fenestra-like-structures (Fig. 4.71b) occur locally. Some concretionary beds and concretions contain abundant bioclasts consisting mainly of ostracods and minor bivalves (Fig. 4.71c, d). Fish scales, bones and teeth are also common and are deep blue in colour. Subaerial exposure in these units is indicated by rhizoconcretions which have been highlighted by greenish white coloration root tubules (Fig. 4.71e). More typical pinkish to purplish red coloration is indicative of oxidation reactions at shallow burial depth.

The concretionary calcilutites show evidence of bioturbation ranging from distinct

Fig 4.69 Concretionary calcilutite lithofacies

Madumabisa Mudstone Formation

a: Exposure of massive silty mudstone with isolated and clustered calcilutite concretions. Along Mulungwa River, Mulungwa map area. Hammer is 34 cm.

b: Aggregate of calcilutite concretions cemented together in massive silty mudstone. Notice knob-like feature in the concretions (arrow). Along Mulungwa River, Mulungwa map area. Lens cap is 5 cm in diameter.

c: Septarian calcilutite concretions with fractures filled by calcite. Zhimu River Section 1, Mulungwa map area. Lens cap is 5 cm in diameter.

d: Polished slab of septarian calcilutite concretion. Notice branching filaments (?) at the top in a mesh like-network. Zhimu River Section 1, Mulungwa map area. Scale in cm.

e: Calcilutite concretion exposing calcite core with cream-coloured barite in veinlets. Mulungwa River Section 6, Mulungwa map area. Scale in cm.

f: Algal lumps (skeletal algae?; Rust, personal comm., 1990) in calcilutite bed. Mulungwa River Section 4, Mulungwa map area. Marker pen is 16.4 cm long.

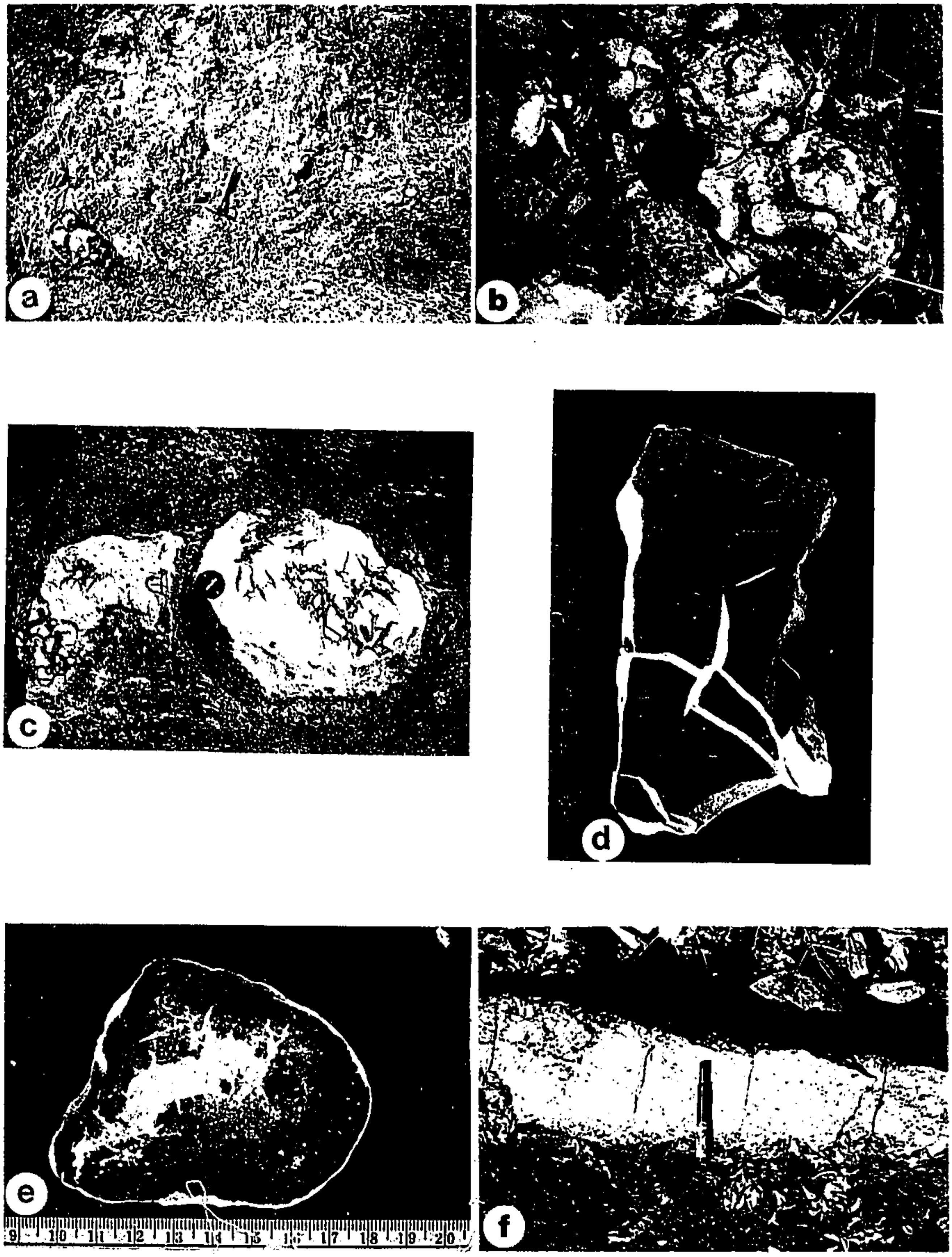

Fig 4.70 Concretionary calcilutite lithofacies

Madumabisa Mudstone Formation

a: Part of a bed showing concretions that have coalesced parallel to bedding, enclosing rounded to elongate mudclasts, in concretionary calcilutite. Some clasts show diffuse boundaries. Mulungwa River Section 6b, Mulungwa map area. Pen is 15 cm long.

b: Polished slab showing variegated subrounded to rounded intraclasts of various types in a calcilutite concretion. The intraclasts are calcareous mudstone. Notice predominance of smaller green intraclasts (less calcareous, more argillaceous) in the lower half. Stylolites impart a brecciated appearance to the calcilutite especially in the upper part of the specimen. Mulungwa River Section 4, Mulungwa map area. Scale in cm.

c: Polished slab showing subrounded elongate intraclasts and intraclasts with diffuse boundaries in a calcilutite concretion. Notice horizontal and subhorizontal burrows in the darker brown clast and in most parts of the lighter area. Burrows are also present in other parts of the slab. The green clasts are argillaceous (less calcareous). Along Mulungwa River, Mulungwa map area. Scale in cm.

d: Cone-in-cone structure in a concretionary calcilutite bed. Mulungwa River Section 6. Mulungwa map area. Pen is 15 cm long.

e: Bedding surface showing possible shrinkage cracks in concretionary calcilutite. Along Mulungwa River, Mulungwa map area. Lens cap is 5 cm in diameter.

f: Internal appearance of (e), cut horizontally. The narrow, lighter areas are made up of finer dense micrite with fewer detrital grains and clay clasts and the intervening areas have coarser micrite (approaching microspar) with more clay clasts and detrital grains. Scale in cm.

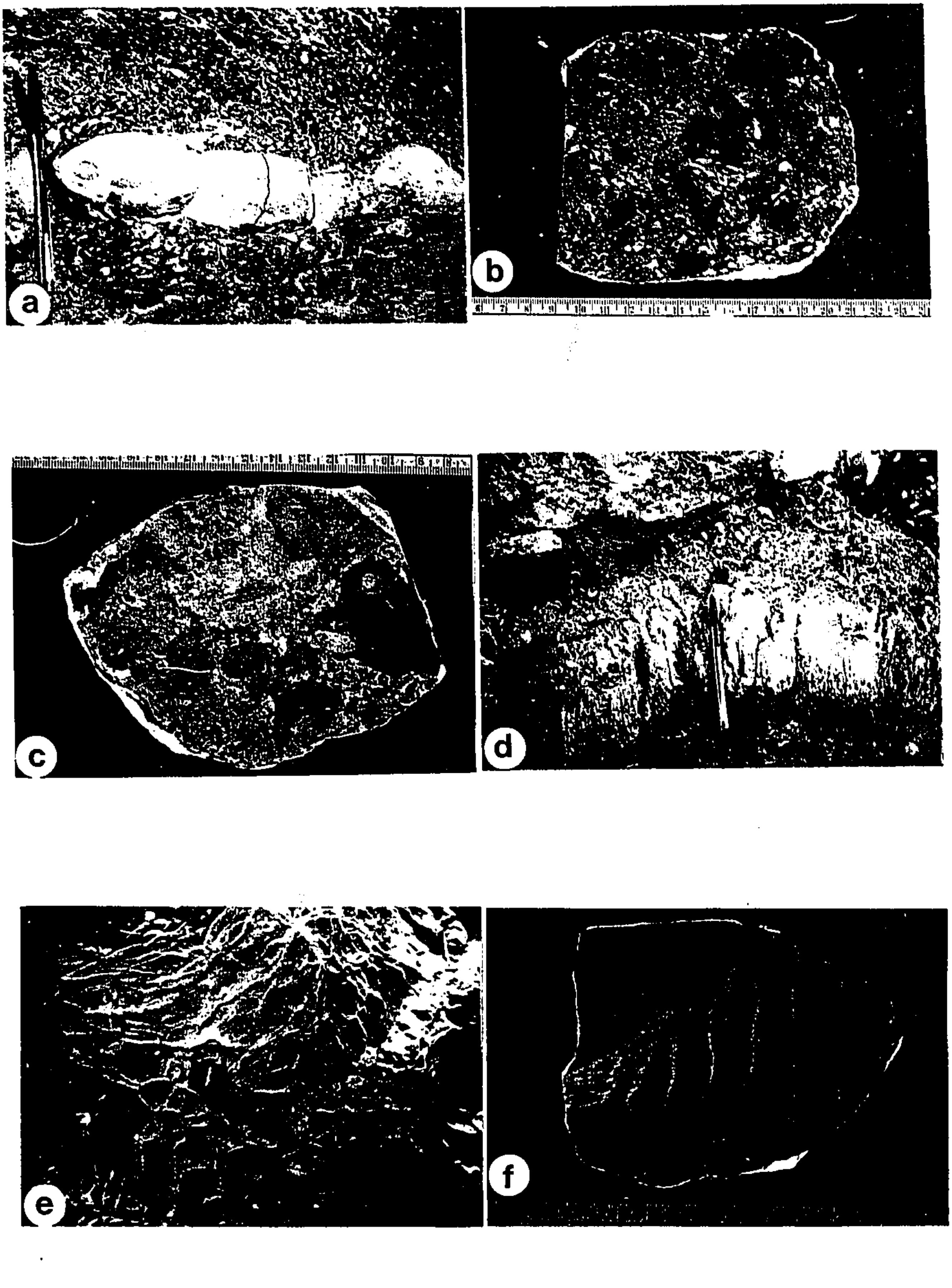
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Fig. 4.71 Concretionary calcilutite lithofacies

Madumabisa Mudstone Formation

a: Slickensides in the concretionary calcilutite beds. Mulungwa River Section 6c, Mulungwa map area. Scale in cm.

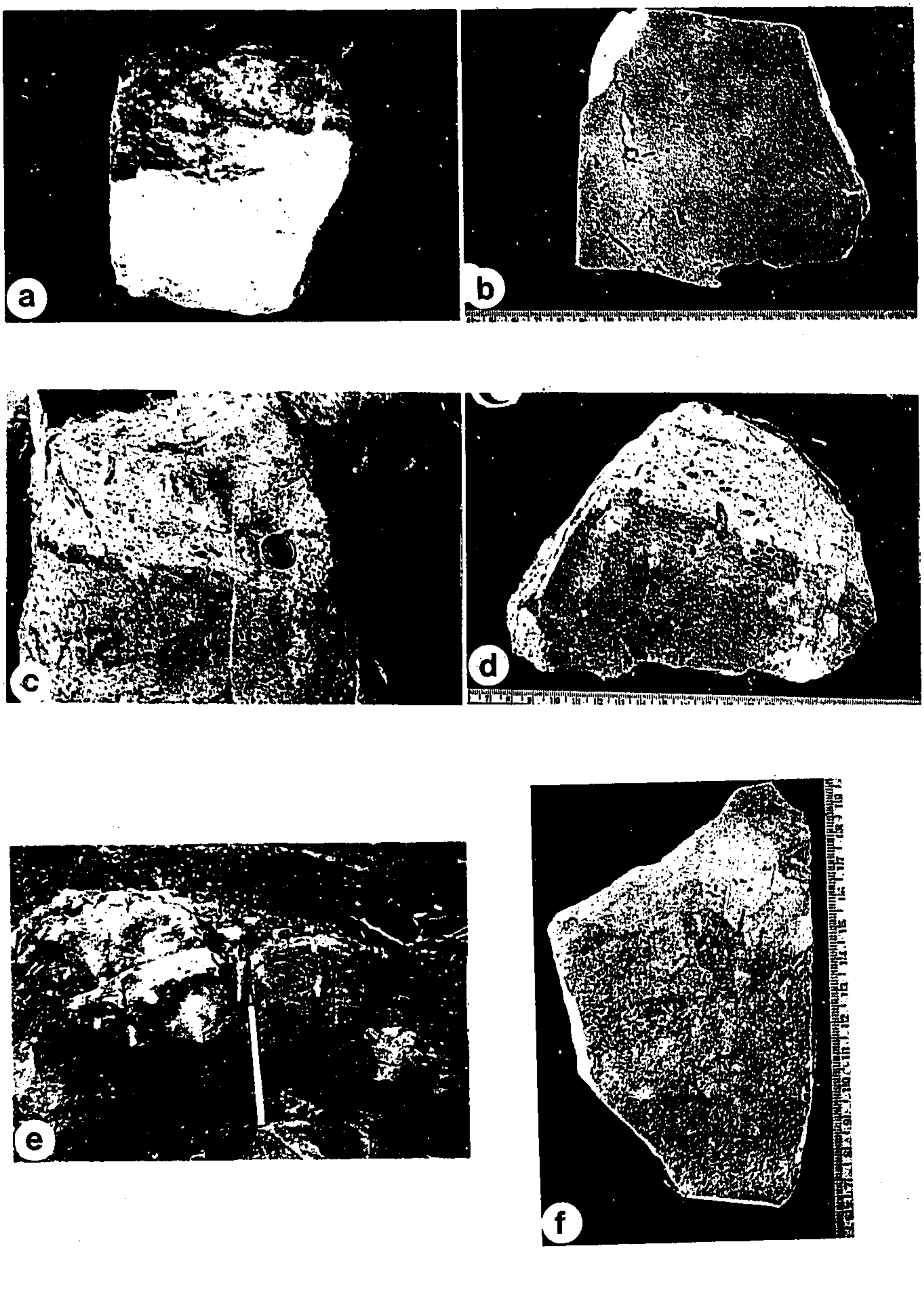
b: Polished slab showing structures resembling fenestrae. The whitish cream filling mineral is barite. Mulungwa River Section 6c, Mulungwa map area. Scale in cm.

c: Abundant ostracods and bivalve bioclasts in concretionary calcilutite beds. Gastropods are also present. Notice crude lamination where ostracods are concentrated at level of the coin. Mulungwa River Section 6c, Mulungwa map area.

d: Polished slab of calcilutite containing abundant ostracods. Notice change in colour from bottom to top. The dark brown lines oblique to stratification are probably stylolites, as burrows such as the vertical burrow at the left of the photograph are not lined. Horizontal burrows are present in the darker layer to the right of photograph. Mulungwa River Section 6c, Mulungwa map area. Scale in cm.

e: Greyish red mudstone with roots and reduction cylinders. Along Zhimu River, Mulungwa map area. Pen is 14 cm long.

f: Light brown calcilutite, containing medium brown intraclasts with diffuse boundaries and filaments that penetrate the calcilutite. Note dark brown rims on light brown intraclasts and probable skeletal debris (arrow) near the top right of photograph. Scale in cm.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burrows to chaotic textures (Figs. 4.71f, 4.72a-d). These are commonly highlighted by different coloration reflecting compositional and grain size differences (Fig. 4.72a-d). Infiltration of overlying lighter sediments into the generally darker sediment beneath is common (e.g. Fig. 4.72a). Burrows range from vertical to subvertical, oblique, subhorizontal and horizontal (Figs. 4.71f, 4.72a-c). Some burrows show crude spreiten (Fig. 4.72b), whereas others contain inclusions of different colours. Stylolite-like features are common, mostly terminating at or following burrow borders (Figs. 4.71f, 4.72b). Fish remains and other bioclasts are abundant in some of the burrowed sediments (Fig. 4.72a). Commonly the intraclasts are diffuse and compositionally range from argillaceous mud, to micritic mud to organic-rich mud.

In thin section, the concretionary beds and concretions consist almost entirely of micrite (90-99%) with minor microspar, sparite, siliciclastics (Fig. 4.72e), intraformational clasts of micrite and silty mudstone (Fig. 4.72f), and bioclasts (Fig. 4.73a). Generally, the siliciclastic material in these rocks is less than 0.1%. Microspar and sparite are usually confined to bioturbated areas and veins. Burrows are common and are reflected by coarser sparite/microspar burrow infillings. Both walled and unwalled (common) calci-ellipsoids and spheres occur in micrite mudstones. The former are possibly of ostracodal or algal origin and are associated with micritized and spar-filled skeletal debris; the latter likely represent burrow infillings or possibly alteration of radiolarians. The dense micrite walls (envelopes) form an irregular zone enclosing sparite or void. In some of the bioturbated areas, oolith-like masses of calcite occur. The non-collapse of some of the burrows (borings?) suggests that the sediment was partly lithified when the burrow was made. Small-scale spreiten are locally well preserved (Fig. 4.73b). In large clasts, sparite-filled burrows are common, and veinlets are commonly filled with fibrous calcite.

Stylolite solution zones (solution interfaces) characterised by dark brown lines with concentration of insoluble minerals (especially clays and iron minerals) are well developed (Fig. 4.73c). On a smaller scale, stylolites are commonly characterized by hematitic coating (brownish to reddish stained) on clay-rich seams in micritic mudstone. Some stylolites terminate in cemented voids and bioturbated areas after passing through the host lithology. One section shows anastomosing fibrous (beef) calcite veins and veinlets (Fig.

Fig. 4.72 Concretionary calcilutite lithofacies

Madumabisa Mudstone Formation

a: Greyish green silty mudstone overlain by buff bioturbated mudstone rich in dark fragments including fish remains, organic matter, ostracods and bivalves. Contact is a hard ground. Unnamed Stream Section 2, Mulungwa map area. Scale in cm.

b: Dark grey calcilutite, containing vertical and oblique burrows filled by lighter grey calcilutite, some showing spretien (right), others containing intraclasts. Notice abundant stylolite-like vertical structures, some outlining or terminating in burrows, and a sharp change in colour from darker base to lighter top. Along Mulungwa River, Mulungwa map area. Scale in cm.

c: Medium grey calcilutite containing slightly oblique to vertical burrow filled by dark grey, less calcareous mudstone. Horizontal darker grey laminae at the top of photograph terminate at the burrow and re-appear on the other side. Black material is probably organic matter. Mulungwa River Section 6c, Mulungwa map area. Scale in cm.

d: Disrupted and diffuse boundaries probably related to bioturbation, in bioclast-rich layers in laminated calcilutite. Mulungwa River Section 4, Mulungwa map area. Scale in cm.

e: Photomicrograph (crossed nicols) from Fig. 4.70(f) showing generally massive micrite/ microspar calcilutite. The lighter zone that cuts the photograph obliquely (L) consists mainly of finer micrite, corresponding to the narrow lighter areas in Fig. 4.70(f). Some of the white scattered grains are quartz. Long side of photograph is 7.8 mm.

f: Photomicrograph (crossed nicols) showing rounded micrite intraclasts; some are brecciated especially at edges with hematite staining. The small green intraclasts are mainly argillaceous. The light pink patches and veinlets in the intraclasts and in the matrix are mainly sparite and minor quartz. Mulungwa River Section 4, Mulungwa map area. Long side of photograph is 29.7 mm.

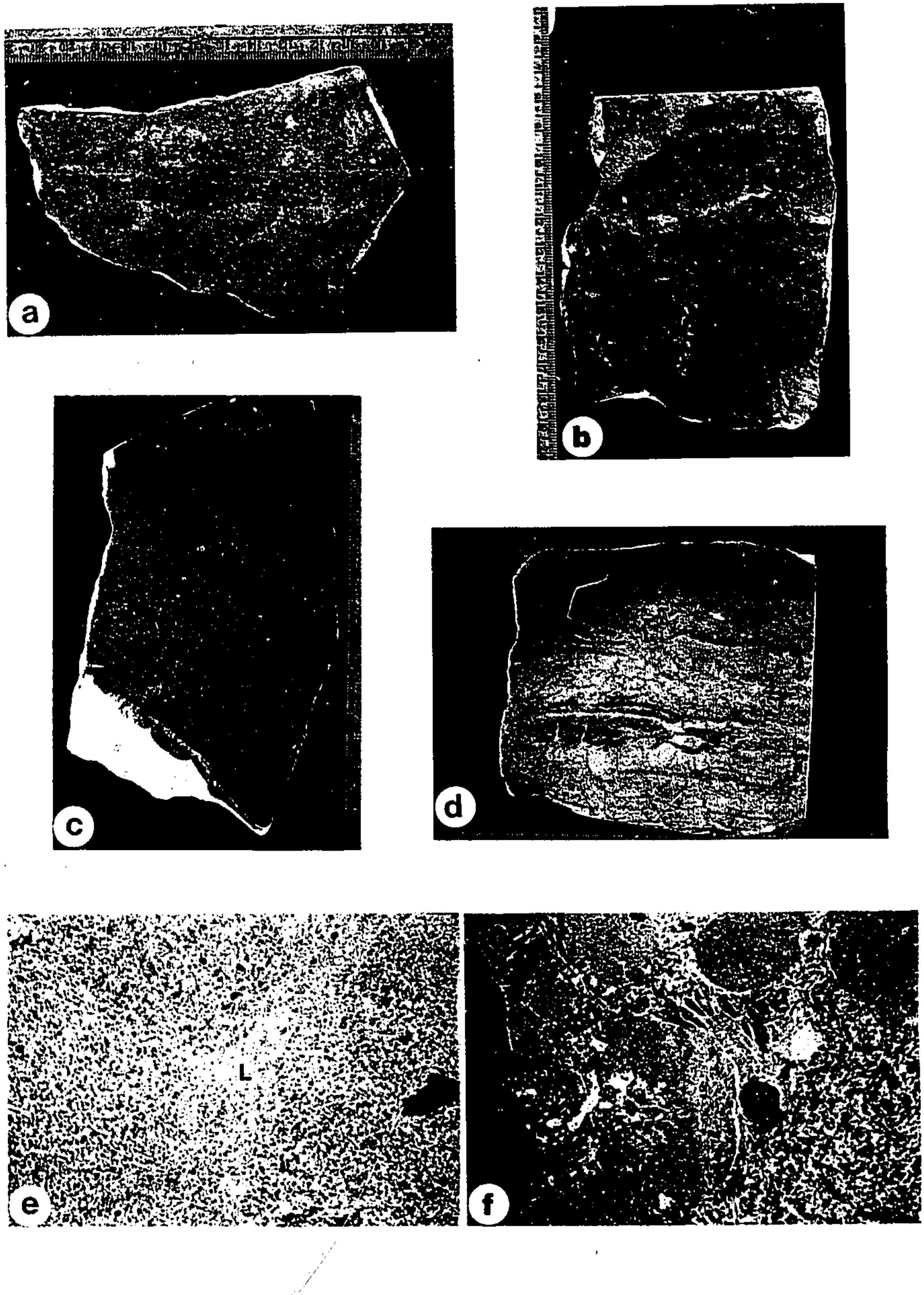
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Fig. 4.73 Massive silty mudstone, and concretionary calcilutite lithofacies

Madumabisa Mudstone Formation

a: Photomicrograph (crossed nicols) showing a concentration of ostracods with substantial clastic material in contrast to the surrounding micrite with fewer ostracods fragments. The outsized whitish grains are quartz. Mulungwa River Section 6c, Mulungwa map area. Long side of photograph is 15 mm.

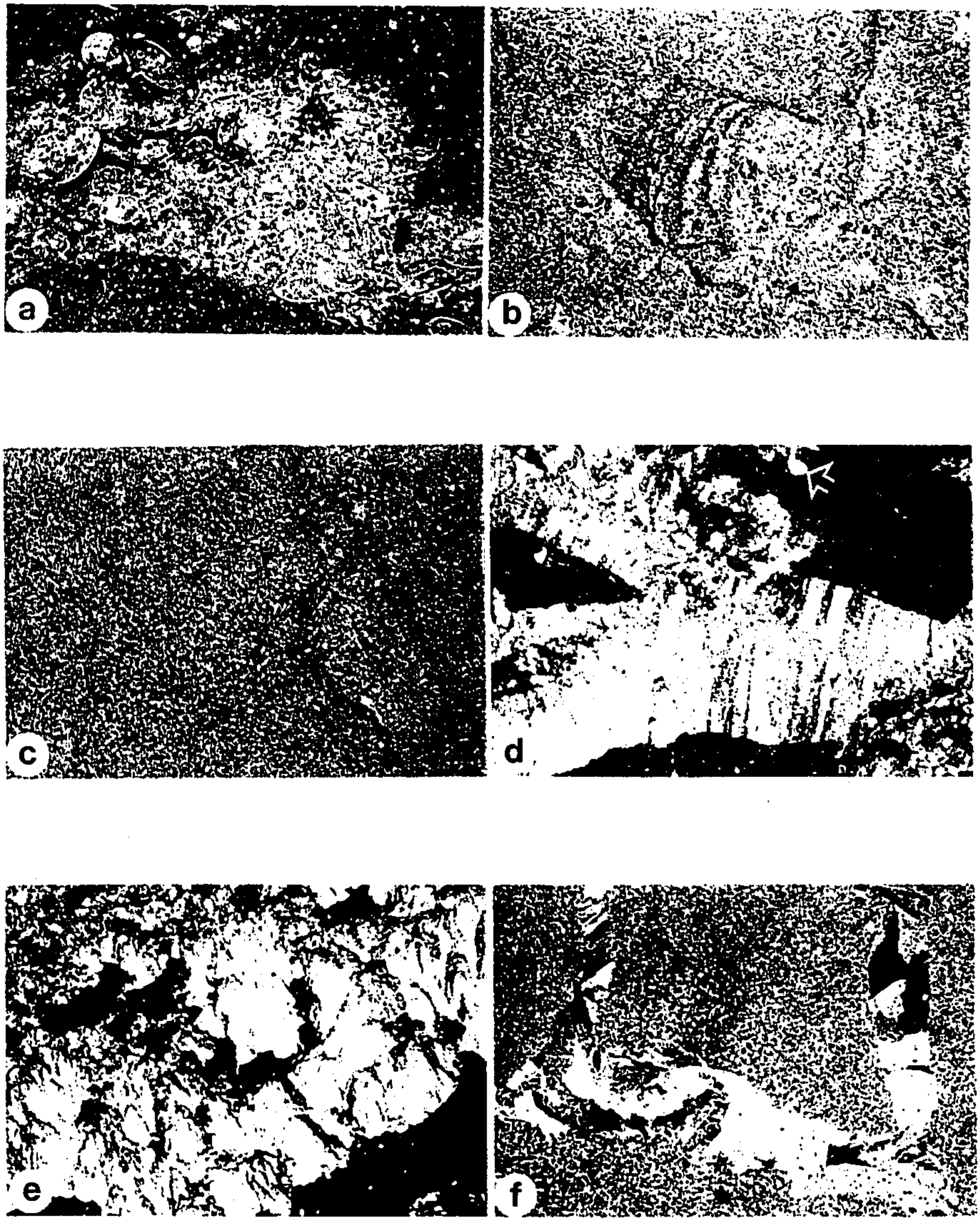
b: Photomicrograph (crossed nicols) showing spreiten defined by thin laminae of argillaceous material/micrite separated by sparite (light pink). Mulungwa River Section 4, Mulungwa map area. Long side of photograph is 12 mm.

c: Photomicrograph (crossed nicols) showing stylolites defined by hematite staining, clay and small detrital grains, mainly quartz, in micrite-rich calcilutite. Mulungwa River Section 4, Mulungwa map area. Long side of photograph is 7.8 mm.

d: Photomicrograph (crossed nicols) showing fibrous (beef) calcite in the same thin section as (a). Quartz grain marked by arrow. Long side of photograph is 0.8 mm.

e: Photomicrograph (crossed nicols) showing calcite cone-in-cone structure. The dark green material is micrite. Zhimu River Section 1, Mulungwa map area. Long side of photograph is 3 mm.

f: Photomicrograph (crossed nicols) from Fig. 4.69(e) showing calcite and barite (shades of grey) infilling vein. The matrix is micrite-rich. Long side of photograph is 7.8 mm.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4.73d) with well-developed small-scale cone-in-cone structure (Fig. 4.73e). The cone-in-cone structure is formed by stacks of mutually interfering bundles of fibrous calcite crystals which become progressively more coarsely crystalline away from the apex (Fig. 4.73e). The fibrous calcite layers (Fig. 4.73d) are composed of coarse inward-growing bladed crystals that meet along central zones of dense intracrystalline microspar. Finer fibrous calcite layers cross-cut the primary argillaceous (clay-rich) mudstone. In one section, a pseudomorph network of calcite has infilled a cell-like structure (joined polygons) with the centres of the polygons being argillaceous (clay-rich) mudstone.

Calcilutite beds commonly have a dense, non-skeletal, micritic basal part that grades into, or is sharply overlain by, a lighter coloured siliciclastic-rich and bioclastic (ostracods) upper part. For example, the siliciclastic/bioclastic content might vary from 1-2% at the base to 5-10% at the top of the bed. Some of the micritic clasts appear brownish and possibly are dolomitic. In the structure resembling shrinkage cracks (Fig. 4.72e) the crest-like parts are made up of finer dense micrite with fewer detrital grains and clay clasts, and the intervening hollows have coarser micrite (approaching microspar) with more clay clasts and detrital grains. The lighter and darker grey diffuse patches and fragments are made up of clay-rich organic matter and coarser micrite (microspar), respectively.

In the calcilutite with a clast framework (Fig. 4.72f), the subrounded and elongate clasts include micritic mudstone and silty mudstone intraclasts and phosphatic bioclasts (fish scales, bones and teeth), cemented by sparite. Some of the fragments are fractured with the overall texture of a brecciated rock. Bioturbation and erosion have led to the production of intraformational micrite clasts up to 2 cm across. Some of the large clasts have developed septaria filled by sparite. In some of the fist-size concretions, the inner irregular veins and veinlets are filled by calcite spar and barite (Figs. 4.73f, 4.74a), the latter distinguished by its characteristic discoidal crystal shapes (locally rhomboidal shaped, Fig. 4.74a), calcite-inclusions and low birefringence. Some barite occurs as large crystals (0.6 mm across and 2 mm in length). The calcite spar associated with the barite crystals appears to be pseudomorphic after barite, as some crystals have the original barite crystal form. Rosettes of barite, and radiating-upward to fan-shaped clusters (Fig. 4.74b), were

Fig. 4.74 Massive silty mudstone, and concretionary calcilutite lithofacies

Madumabisa Mudstone Formation

a: Photomicrograph (crossed nicols) from Fig. 4.69(e), showing a rhomboidal cross-section through barite. Some of the light pink grains in the micrite matrix are quartz. Long side of photograph is 3.4 mm.

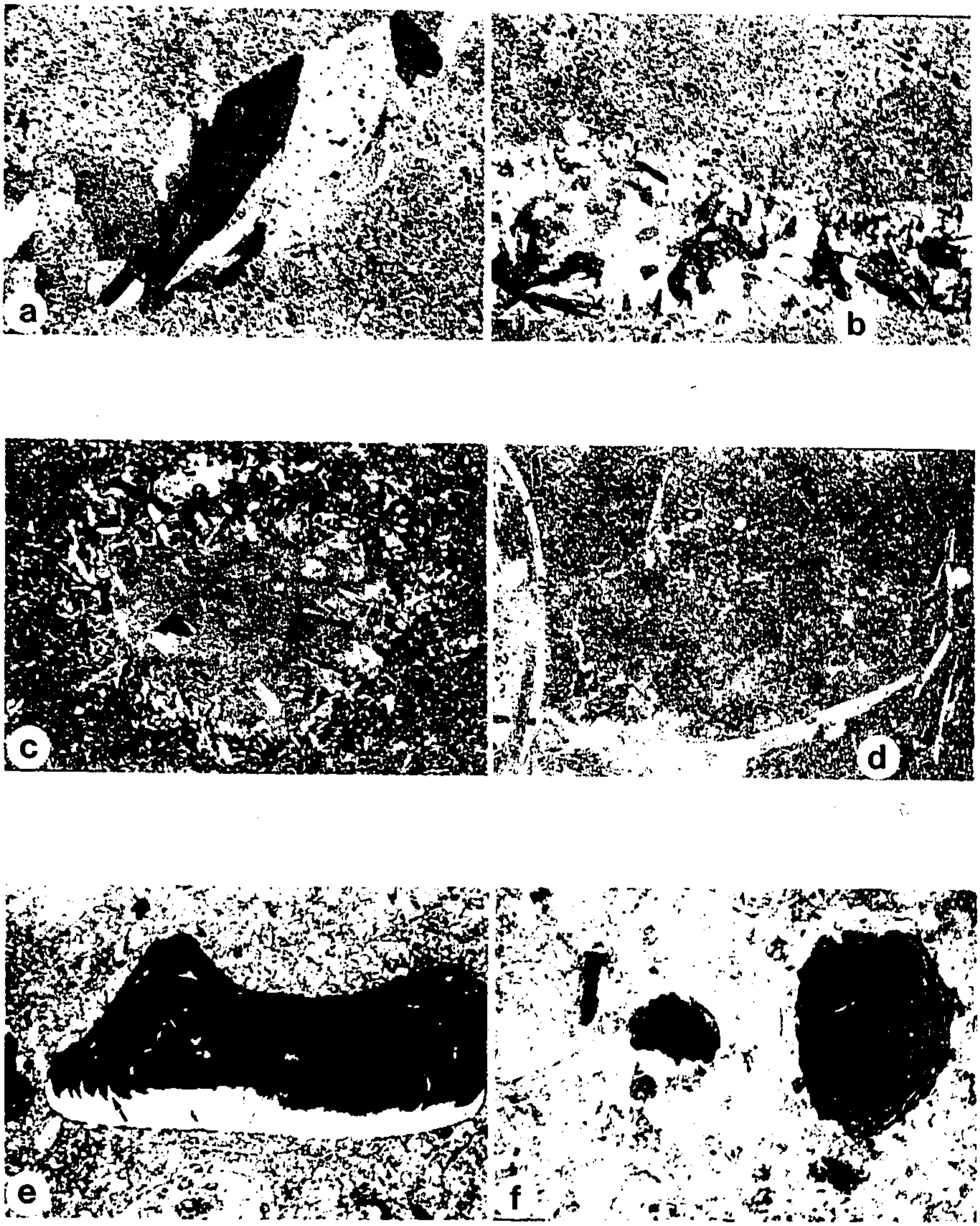
b: Photomicrograph (crossed nicols) showing a ?vein infilled with calcite spar and rosettes of barite (arrow) after gypsum in micrite-rich calcilutite. Zhimu River Section 1, Mulungwa map area. Long side of photograph is 1.8 mm.

c: Photomicrograph (crossed nicols) showing laths of albite (identified by SEM but resembling gypsum in crystal form) associated with micrite intraclasts in microspar/argillaceous matrix. Notice that some ghosts of laths within micrite mimic gypsum. Long side of photograph is 1.4 mm.

d: Photomicrograph (crossed nicols) showing large ostracod fragments. Some rounded patches (arrow) are unwalled burrows infilled with sparite. Long side of photograph is 7.8 mm.

e: Photomicrograph (plane polarized light) from Fig. 4.72(a), showing fish bone, probably part of a jaw, in micrite/microspar-rich matrix. Notice sharp curved protrusions (arrow) in dark brown (phosphate) material. Long side of photograph is 1.5 mm.

f: Photomicrograph (plane polarized light) from Fig. 4.72(a), showing fish scale and other phosphatic fragments. Ostracod fragments are also abundant. Long side of photograph is 1.5 mm.



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observed in a sparite-filled vein. Some rosettes and clusters have petrographic characteristics typical of gypsum (selenite) with interference colours up to first-order pale grey. The fenestrae-like structures seen in hand specimens are filled with sparite or consist of dense micritic calcite. The micritic calcite shows some encrustations (outlines) of dark brown fibrous material, probably dolomitic in composition, and usually does not contain detrital grains. The micritic calcite locally contains well-developed lath-shaped crystals (some twinned, others clearly six-sided prisms) (Fig. 4.74c) that appear to be pseudomorphs of gypsum, although SEM has identified albite as the present constituent. The crystals are replacements of micritic calcite, as evident in other examples where the micrite has been incompletely replaced.

Terrigenous siliciclastic material, mainly angular quartz and minor feldspar (twinned plagioclase is common) and muscovite, is scattered in the micrite. The carbonate content is much higher in the calcilutite units (over 70%), than it is in the silty mudstone lithofacies (usually less than 30%). Calcite cement, where present, predominates over clay matrix. Although bioclasts are minor in the concretionary lithofacies, they appear to be present everywhere. By far, ostracods (Fig. 4.74d) are the major bioclasts (2-40%), followed by bivalved molluscs (<1%) and fish fossils, with trace amounts of gastropods. Together, these form up to 30% of the rock locally, with an average of less than 5%. The bioclasts are commonly associated with a high detrital clastic content. Phosphate is brownish to brownish black and occurs mainly as fragments of fish bones, teeth and scales (Fig. 4.74e, f), but also as secondary infilling of voids. The other brownish/reddish black, irregular, elongate to sub-spherical clasts are also probably phosphatic and usually have their voids infilled with calcite. Some black clasts may be organic matter. In places, radial and 'beef' fibrous calcite have nucleated on these phosphatic/organic substrates, in one instance forming structures that resemble small-scale cone-in-cone structures.

In summary, most of the calcilutite consists almost entirely of micrite (90-98%) with less than 5% detrital siliciclastic grains, and can therefore be classified as mudstone using Dunham's (1962) classification. Bioturbation has allowed significant clastic infiltration and infilling of bioturbated areas by microspar/sparite, whereas non-affected areas remained unchanged (micrite-rich). With bioclastic content up to 40%, some of the rocks can be classified as fossiliferous wackestone. Some of the mudstones contain mudstone clasts and are classified as intraclastic calcirudite wackestone.

4.3.3.4 Laminated silty mudstone and siltstone lithofacies (MS_l)

This lithofacies comprises green to grey (greyish-white, khaki upon weathering), very thinly to thickly bedded, horizontally laminated to small-scale cross-laminated, silty mudstone and siltstone (Fig. 4.75a-f). The medium to thickly bedded (coarser) units are commonly pinkish grey and the very thinly to thinly bedded (finer) units are dark grey. Alternating dark and light laminae are common. Most of the dark greenish grey, medium dark grey to black laminae are rich in organic matter. The lighter laminae are light olive grey to grey and greyish brown and contain minor organic matter. Burrows commonly disrupt the laminae.

The lithofacies forms very thin to thick (>10 m) sheet-like units (Fig. 4.75a, b, c) that are laterally persistent on outcrop scale (maximum 500 m), and commonly alternate with units of the massive silty mudstone lithofacies (Fig. 4.75d). Units typically grade upwards (or downward) from very thin beds (< 5 cm) into thick beds (up to 70 cm) forming thickening-upward sequences (Fig. 4.75a-c), and some are capped by a tabular concretionary calcilutite bed (Fig. 4.75b, d). Portions that are very thinly to thinly bedded are commonly strongly fractured and recessive and can be mistaken for massive mudrocks (Fig. 4.75e). However, the laminated mudstone breaks into slabs (Fig. 4.75f) in contrast to the conchoidal fracturing common in the massive mudrock (Fig. 4.76a). The presence of tabular, commonly continuous calcilutite interbeds (e.g. Fig. 4.75c) in the laminated lithofacies aids in distinguishing between the two lithofacies. Thin beds (< 5 cm) are usually horizontally laminated, with continuous laminae of varied thickness (Fig. 4.76b). In medium beds (5- 15 cm), small-scale cross-lamination (Fig. 4.76c), horizontal lamination (Fig. 4.76d), and flaser and lenticular bedding (Figs. 4.76e) are common. Flasers associated with current ripple cross-lamination are observed locally (Fig. 4.76c). Thick beds (> 15 cm, averaging 20-25 cm, maximum 70 cm) are generally lenticular and cross-laminated and also show a characteristic curved fracture (spheroidal weathering) (Fig. 4.76f).

Fig. 4.75 Laminated silty mudstone and siltstone lithofacies

Madumabisa Mudstone Formation

a: Very thinly to thickly bedded mudrocks showing thickening-upward units, some capped by concretionary calcilutite beds. Kazinze River Section 1, Siankondobo area. Person for scale. The capping by calcilutite beds suggests precipitation of calcite in shallow water.

b: Detail of (a), showing concretionary calcilutite beds alternating with laminated silty mudstone beds in the lower half, overlain by a coarsening-upward unit (recessive to resistant interval showing upward increase in bed thickness in the upper half of photograph). Hammer (below centre) is 34 cm.

c: Detail of the thickening-upward unit in (a), with horizontally laminated beds near the top up to 60 cm thick. Notice the beginning of another thickening-upward unit above.

d: Alternating units of laminated and massive mudrock lithofacies; unit behind scale is generally massive (crudely stratified). Mulungwa River Section 4, Mulungwa map area.

e: Very thinly to medium laminated mudrock. Notice that calcilutite beds define bedding. The recessive units are usually very thinly laminated (≤ 1 mm). Zhimu River Section 1, Mulungwa map area. Scale is 2.1 m long.

f: Fragmentation in laminated mudrocks commonly produces slabs in contrast to rugged appearance in massive silty mudstone lithofacies (e.g. Fig. 4.65a, c-d). Mulungwa River Section 4, Mulungwa map area. Hammer is 34 cm.

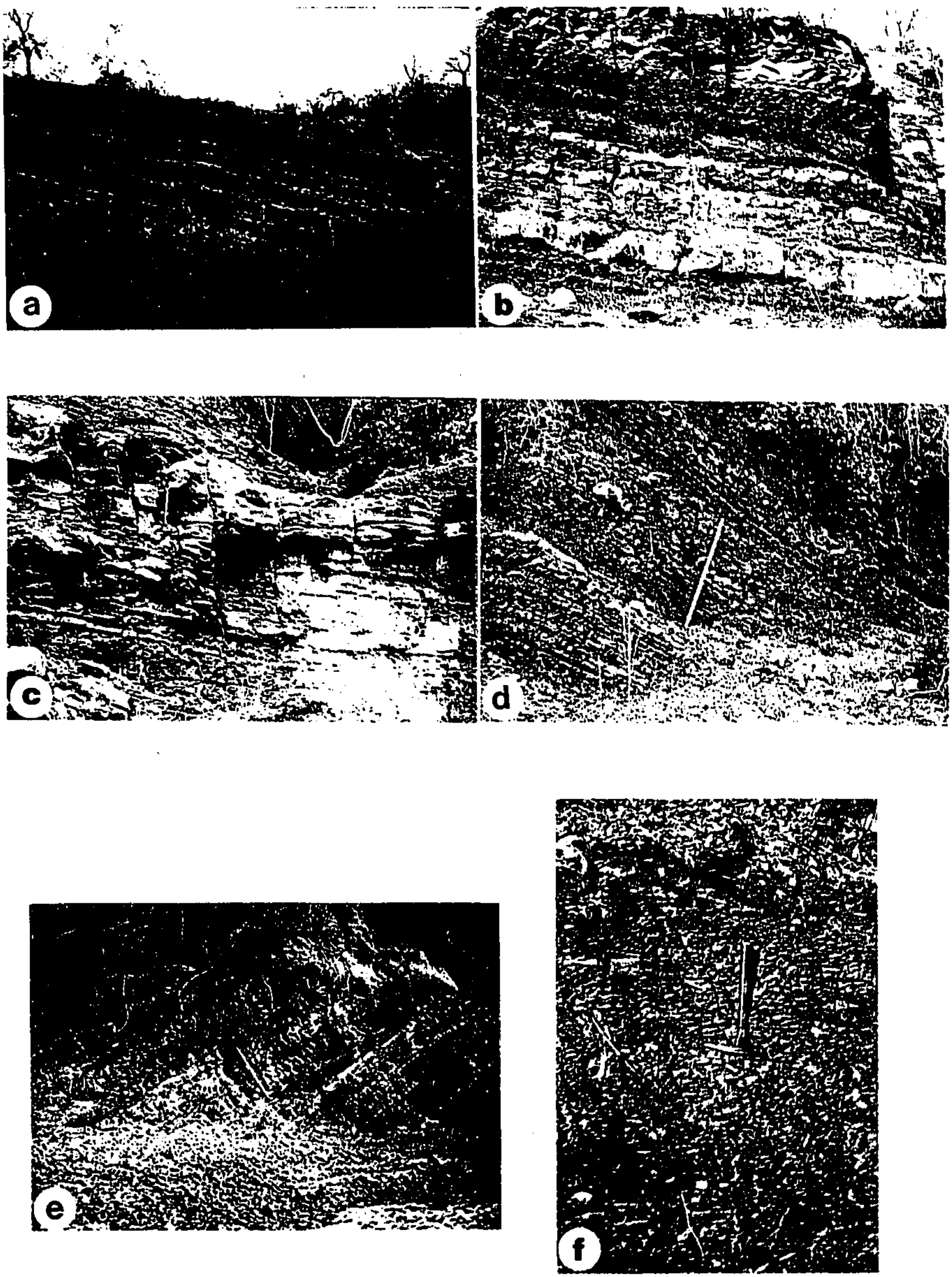
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Fig. 4.76 Laminated silty mudstone and siltstone lithofacies

Madumabisa Mudstone Formation

a: Recessive laminated unit of silty mudstone overlain by resistant, competent massive bed of silty mudstone/siltstone. Zhimu River Section 1, Mulungwa map area.

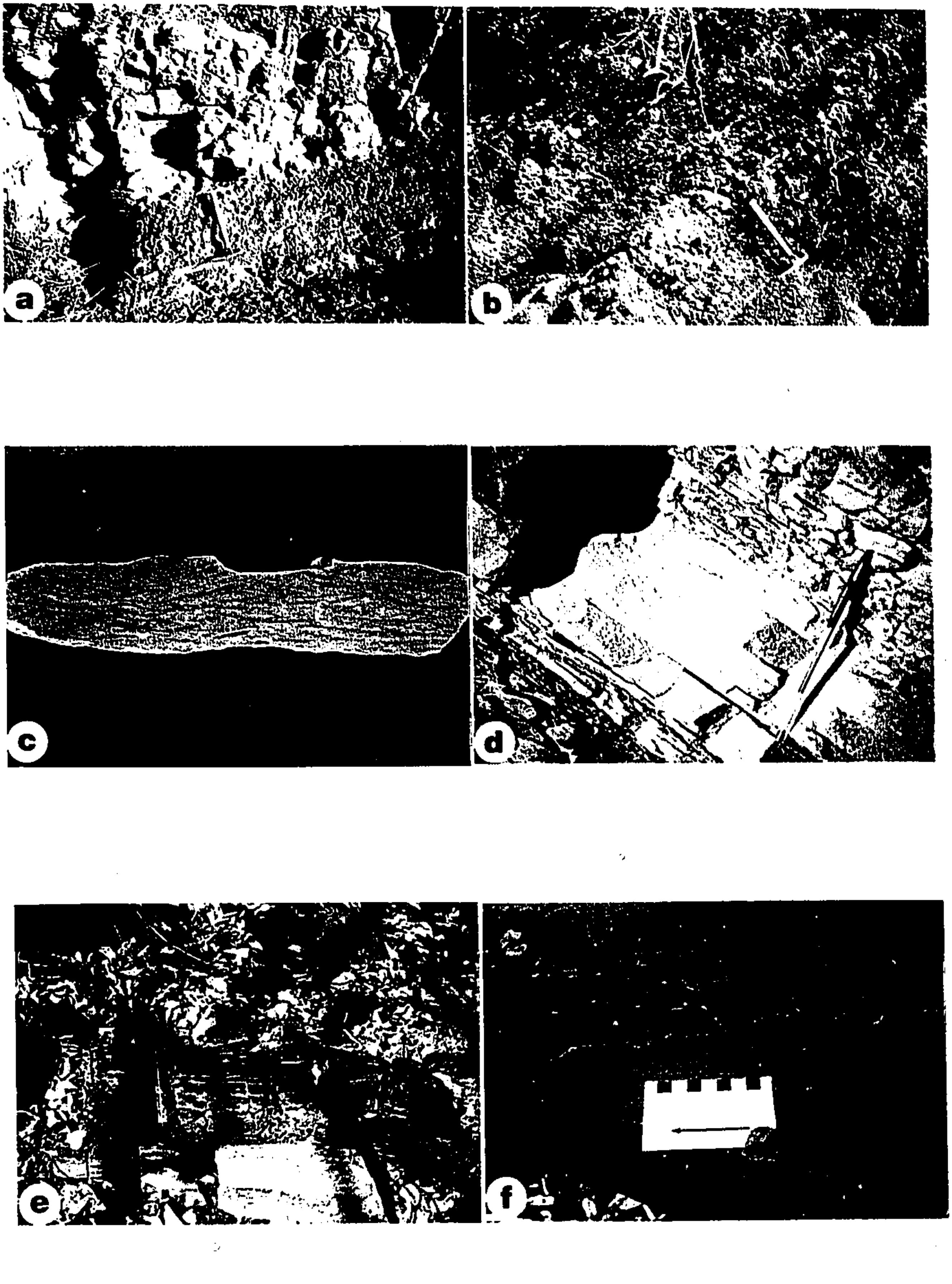
b: Very thinly laminated mudrock. Notice coarsening-upwards reflected by increase in bed thickness behind hammer and again towards upper left. Zhimu River Section 1, Mulungwa map area.

c: Polished slab of silty mudstone/siltstone showing flasers associated with small-scale ripple cross-lamination. Mulungwa River Section 4, Mulungwa map area. Scale in cm.

d: Horizontally laminated silty mudstone/siltstone (mudrock). Mulungwa River Section 6b, Mulungwa map area. Pen is 14.6 cm long.

e: Lenticular and flaser bedding in the silty mudstone/siltstone bed behind the marker; mainly lenticular in upper part and flaser in lower part. Mulungwa River Section 4, Mulungwa map area. Marker pen is 16.4 cm long.

f: Ripple cross-lamination in medium-bedded siltstone. The same beds also show ripple marks (see Fig. 4.77(a)). Mulungwa River Section 4, Mulungwa map area.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Organic matter in the form of dispersed plant remains, in beds not exceeding 30 cm, and thin coaly beds (up to 15 cm thick) characterised by vitrain laminae, siderite and general fissility (shale) occur locally (e.g. Kazinze River Section 1) in close association with the laminated mudstone lithofacies. The finely disseminated organic matter is common in the green/grey mudstone, but rare in the pinkish grey mudstone.

Structures useful for palaeocurrent measurements are rare. Most outcrops are two-dimensionally exposed such that even where small-scale cross-sets are present, the third dimension necessary to measure orientation is difficult to determine. However, in Mulungwa River Section 4, ripple marks (Fig. 4.77a) with flattened tops and broad troughs and internal structure characteristic of current ripples clearly indicate palaeocurrent flow to the southeast.

No evidence for subaerial exposure, such as desiccation cracks, was observed in the study area. However, it should be noted that joint patterns can locally produce polygonal structures that somewhat resemble shrinkage cracks (Fig. 4.77b, c).

Evidence of bioturbation is common (Fig. 4.77d), and in hand specimens, burrows that are vertical, slightly oblique to bedding, or horizontal commonly contain spreiten (Figs. 4.77e, f; 4.78a). Burrows are filled by detritus of either similar, or different, composition and colour than the enclosing material. In places, strong bioturbation has resulted in elongate dark grey and reddish brown areas within greenish-grey matrix, and these contain abundant black phosphatic fish skeletal fragments and ostracods elongated parallel to bedding (Fig. 4.78b). These bioturbated areas are disorganized and pass upward into brownish grey areas containing disseminated black material and clasts that in turn grade into light olive grey mudstone that is faintly laminated and finer in grain size (Fig. 4.78b). The overall view is that of a normal graded bed with a muddy conglomerate base that grades into a laminated upper portion. Thin, dark, bituminous calcilutite and muddy conglomerate are locally present. Burrows commonly disrupt lamination (Fig. 4.77e, f). As in the massive mudrock lithofacies, burrows are distinguished mainly by differences in colour (usually due to compositional and grain size differences) between the burrow infill and host sediment (Fig. 4.77d). Vertical burrows predominate over subvertical, oblique, subhorizontal and horizontal forms.

Fig. 4.77 Laminated silty mudstone and siltstone lithofacies

Madumabisa Mudstone Formation

a: Ripple marks on bedding surface of a siltstone bed. The ripple marks are flat-crested. Mulungwa River Section 4, Mulungwa map area. Knife is 9.5 cm long.

b: Two sets of joints trending northeast and southeast, resulting in a polygonal pattern on this bedding surface. Mulungwa River, Section 4, Mulungwa area. Hammer handle for scale.

c: Detail from (b) to show the polygonal pattern, that in places can resemble shrinkage cracks. Brunton compass for scale.

d: Ripple cross-laminated silty mudstone with back-filled burrows. Along Mulungwa river, Mulungwa map area. Part of the pen ~ 10 cm.

e: Polished slab of pinkish grey siltstone showing vertical burrows and subordinate horizontal burrows disrupting small-scale cross-lamination. Zhimu River Section 1, Mulungwa map area. Scale in cm.

f: Polished slab of light olive grey silty mudstone/siltstone showing vertical, subvertical and oblique burrows disrupting small-scale cross-lamination. Zhimu River Section 1, Mulungwa map area. Scale in cm.

In Figs. 4.77e, f and 4.78a, vertical burrows are generally more common than horizontal and oblique burrows.

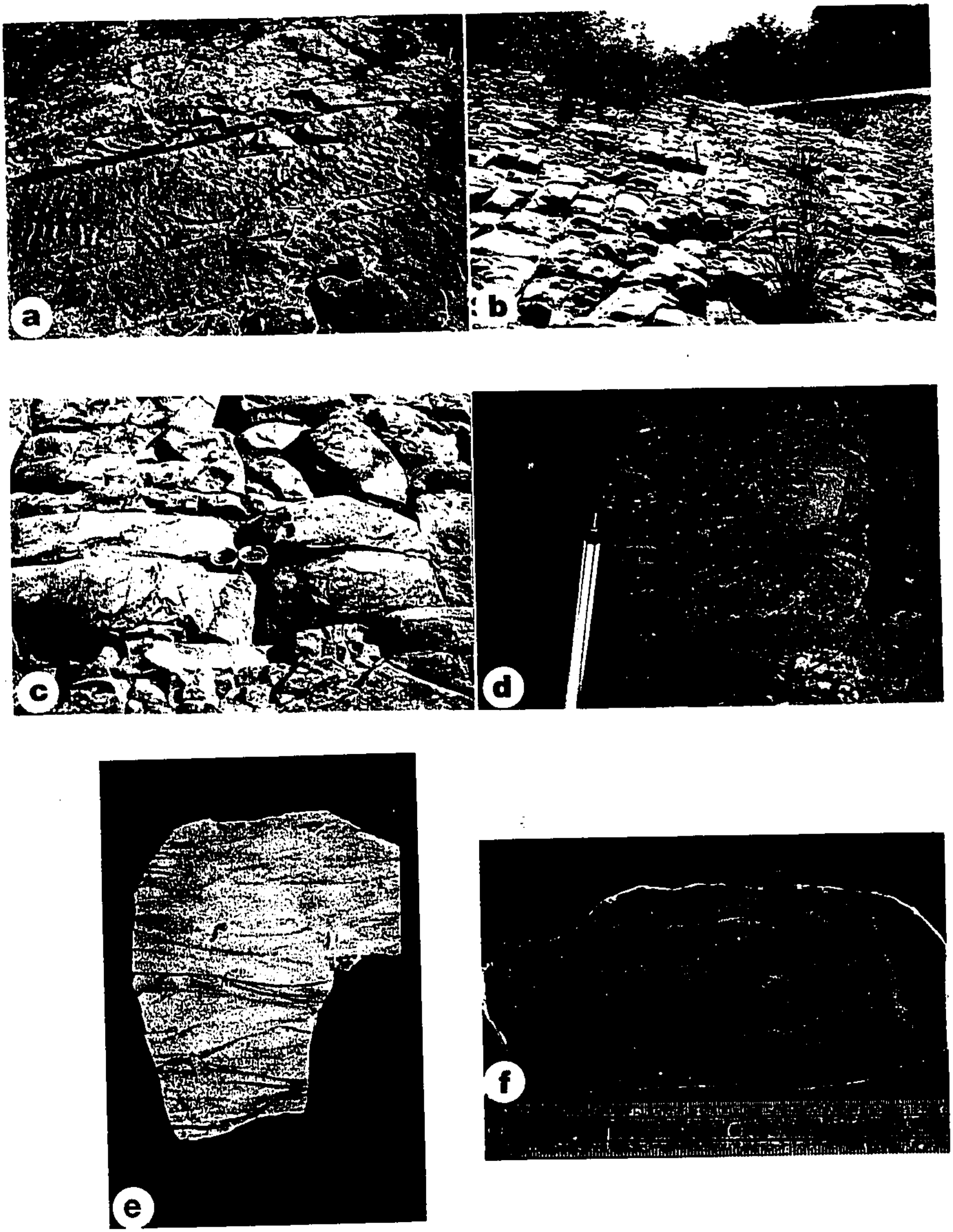
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Fig. 4.78 Laminated silty mudstone and siltstone lithofacies Madumabisa Mudstone Formation

a: Polished slab of light brownish grey silty mudstone showing vertical burrows disrupting the horizontal lamination. Mulungwa River Section 4, Mulungwa map area. Scale in cm.

b: Silty mudstone/siltstone polished slab showing bioturbated lower portion with abundant fish skeletal grains and ostracods in laminated mudstone showing slight grading. Mulungwa River Section 4, Mulungwa map area.

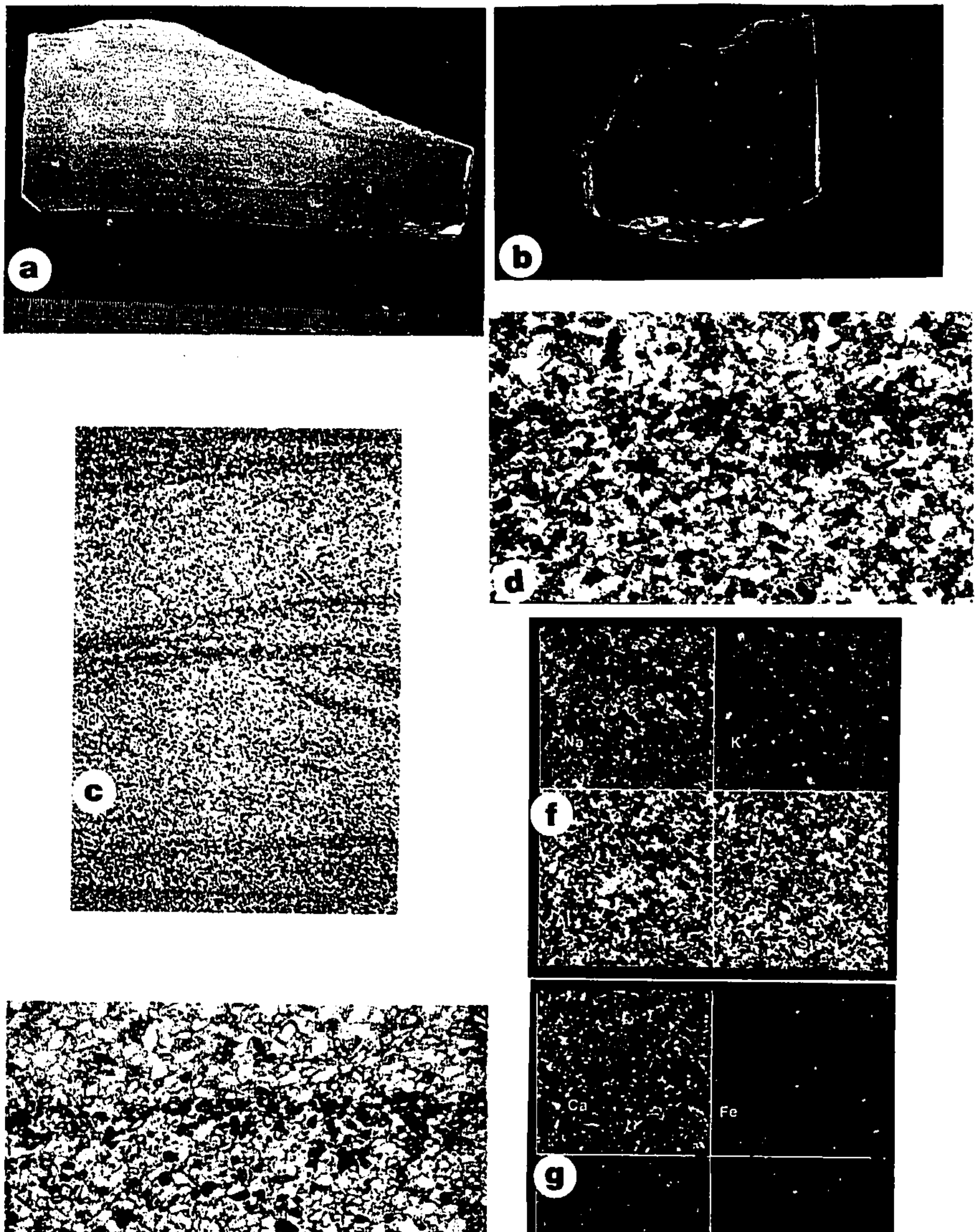
c: Photomicrograph (crossed nicols) of Fig. 4.73c showing cross-lamination with laminae defined by concentration of clay and micrite or concentration of heavy minerals (arrow). Mulungwa River Section 4, Mulungwa map area. Long side of photograph is 14.3 mm.

d: Photomicrograph (crossed nicols) showing detail of texture of the silty mudstone/siltstone in (c), consisting of predominant quartz and minor feldspar and mica in calcite cement and illite clay (SEM). Notice that heavy minerals define the laminae. Mulungwa River Section 4, Mulungwa map area. Long side of photograph is 1.8 mm.

e: Photomicrograph of (d) above in plane polarized light clearly showing heavy minerals defining laminae. Mulungwa River Section 4, Mulungwa map area. Long side of photograph is 1.8 mm.

f: Photomicrograph of map image prepared by SEM showing distributions of elements Na, Al, K and Si in silty mudstone. Notice that the silty mudstone/siltstone is poor in K, but richer in Si and Al. The substantial amount of Na suggests that Na-feldspar is next to quartz in abundance, followed by clay and calcite. The high Na in these rocks resulted in precipitation of albite laths in these rocks (e.g. Fig. 4.70e). Zhimu River Section 1, Mulungwa map area. Scale indicated on photograph.

g: Photomicrograph of map image prepared by SEM showing distributions of elements Ca, Fe, Mg and Ti in silty mudstone. The low Mg content suggests that dolomite is minimal.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Ca
Fe
g
Mg
Ti

In thin section, the lithofacies is characterised by horizontal to small-scale cross-lamination (Fig. 4.78c). It contains more terrigenous siliciclastic material than the massive silty mudstone lithofacies (Fig. 4.78d, e). Grain size is mainly silt-size with a maximum of 0.06 mm and an average of 0.02-0.03 mm. Elongate and platy grains (clasts) are oriented parallel to the laminae.

The silty mudstone/siltstone consists of a framework of quartz, feldspar, mica (muscovite) (Fig. 4.78d, e) and intraclasts of silty mudstone and micrite mud, in a clay-rich matrix with subordinate calcite cement. Bioclasts are also present. Quartz predominates (20-65%), followed by feldspar (plagioclase, orthoclase and microcline ~ 2-10%), mica (muscovite ~ 0.5-2%), clay-rich clasts (<1%) in clay matrix (20-40%) and micrite/microspar cement (5-30%). As in the concretionary lithofacies, albite laths occur at the edges of and within the dense micritic calcite and reddish brown, medium to dark grey silty mudstone clasts. Most mudstone clasts are outlined by dark brown rims which are either stylolitic or represent micrite envelopes. Chlorite is present in trace amounts. Heavy minerals include epidote, sphene, tourmaline and garnet (usually <0.1% of the rock). Opaque minerals include iron oxides, particularly ilmenite. Disseminated and fragmentary organic carbonaceous matter is present in minor amounts. Calcite cement occurs as micrite, microspar and sparite, the last of which is locally poikilotopic.

The horizontal and small-scale cross-laminae represent variations in composition and grain size. The thin dark laminae (~2 mm) are usually defined by concentrations of clay and the thick lighter laminae (up to 5 mm) have relatively less clay and are commonly calcite-cemented (poikilotopic). In several sections, very fine laminae (~0.2 mm thick) are defined by concentrations of heavy minerals (Fig. 4.78d, e), identified by SEM as mainly garnet, ilmenite, zircon and epidote. In layers where calcite has been removed by leaching, angular to subangular detrital grains are clay matrix-supported, indicating the predominance of clay throughout the mudrock. The laminae are commonly disrupted by burrows. Bioclasts are common and include phosphatic bones, teeth and scales of fish, and minor ostracods. Phosphatic matter also occurs as diagenetic pore fillings. Some intraclasts contain sparite-infilled voids. Stylolites are also present and are commonly reddish, probably representing hematite. Element map images from SEM (Fig. 4.78f, g) show that sodium is more common than potassium, suggesting that albite is abundant relative to K-feldspar, and that the lithofacies contains a substantial amount of calcite (Fig. 4.78g).

Trace fossils are common in the lithofacies. Dr. G.M. Narbonne of Queen's University, Canada, identified possible *Teichichnus, Zoophycos, Rhizocorallium, Skolithos* and *Planolites* in samples of this lithofacies (Fig. 4.77e, f). *Skolithos* and *Planolites* are known to occur in both marine and freshwater environments. However, the other three are usually associated with marine environments or environments having some marine influence. Because no modern animal in freshwater is known to make spreiten, the identification of *Teichichnus, Zoophycos* and *Rhizocorallium* in this lithofacies suggests a marine environment for the Madumabisa Mudstone Formation.

4.3.3.5 Tabular calcilutite lithofacies (C_t)

Tabular concretionary calcilutite beds are both laterally persistent and impersistent (Figs. 4.75a-e); they locally consist of coalesced ellipsoidal concretions, but isolated ellipsoidal concretions are also present. These beds have sharp basal contacts and convex-up tops, and range from zero to over 60 cm thick. As in the irregular concretionary calcilutite lithofacies, bioclasts including ostracods, bivalves and fish scales are present and form up to 30% of the calcilutite. Other features include deformed calcilutite layers and beds with small-scale contortions and bioturbated areas. Horizontal laminae are preserved in some layers.

4.3.3.6 Sandstone lithofacies ($S_{vf\text{-}m}$)

This lithofacies is exposed along Kazinze River Section 1 where a 2.3 m thick unit consists of massive to stratified (planar, trough and horizontal), thinly to thickly bedded, medium- to coarse-grained sandstone (Fig. 4.79a, b). Its contact with underlying mudstone is sharp. A basal 1.05 m massive sandstone is overlain in succession by trough cross-laminated (0.4 m), planar cross-laminated (0.12 m), horizontally laminated (0.16 m) and finally massive (0.6 m) sandstone. The sandstone lithofacies appears tabular, although it thins laterally down dip and likely wedges out.

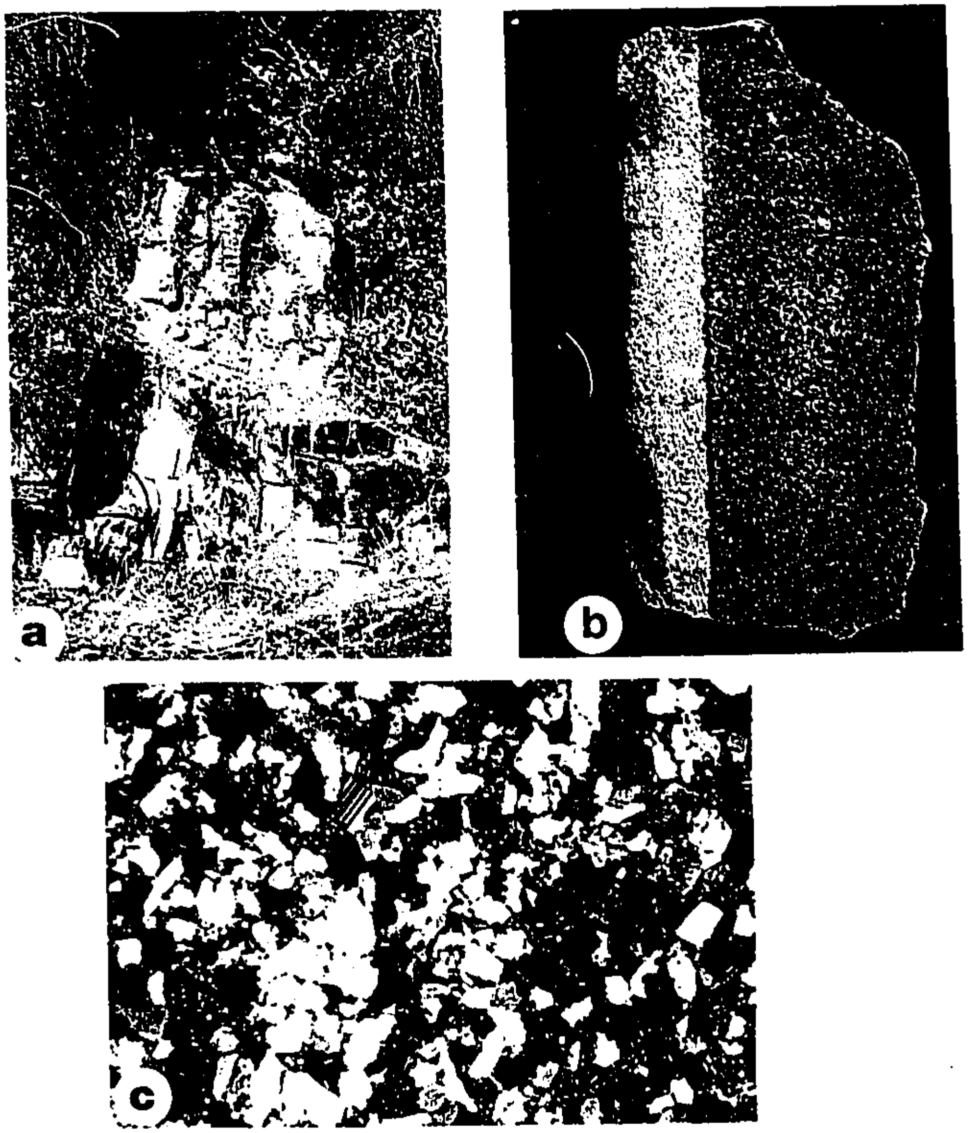


Fig. 4.79 Sandstone lithofacies, Madumabisa Mudstone Formation

a: Wedge-shaped stratified sandstone overlain by laminated silty mudstone lithofacies. Kazinze River Section 1, Siankondobo map area. Hammer for scale.

b: Polished slab from (a), showing crude lamination defined by concentration of mica and clay. Scale in cm.

c: Photomicrograph (crossed nicols) from (b), showing the texture of the sandstone consisting of quartz (predominant), feldspar and minor muscovite. Notice fresh twinned plagioclase grain. Matrix is mainly clay and minor calcite cement. Long side of photograph is 5.4 mm.

The sandstone is locally grain-supported, but is generally matrix-supported, containing quartz and feldspar grains and mudrock fragments in a clay matrix (Fig. 4.79c). Grain size averages 0.3 mm (maximum 0.7 mm). Grain contacts are planar, but where compaction was significant, concavo-convex contacts are apparent, and muscovite and twinned plagioclase are bent or broken. The clay matrix has a speckled yellowish orange and brown birefringence which is characteristic of illite/smectite mixed layer clays. The grains are moderately well sorted, with a sphericity of 0.51-0.75. A few quartz overgrowths are present. Mudrock fragments have disintegrated, filling some pores, but high porosity persists due to dissolution of fragments.

Modal composition shows quartz as the dominant mineral (60-85%), then feldspar (microcline, plagioclase, orthoclase; 5-10%), mudrock fragments (2-20%) and clay matrix that is derived mainly from the fragments. Most of the rocks are lithic-feldspathic arenites.

4.3.3.7 Clay mineralogy

Twenty-seven samples were analysed by XRD, and the strongly calcareous samples were treated with acid to remove calcite. The massive silty mudstone lithofacies showed illite to be the predominant clay, followed by smectite and chlorite. Mixed layer clays (illite/smectite - I/S) are present in minor to trace amounts. Kaolinite is absent, except for a minor amount in one sample at the Madumabisa Mudstone / Upper Karoo contact. The laminated mudrock lithofacies shows similar clay mineralogy, with illite predominant, followed by smectite. Chlorite occurs in minor to trace amounts; and kaolinite and mixed-layer clays (I/S) are present in trace amounts. In the concretionary calcilutite beds both illite and chlorite are present in minor amounts. Chlorite is predominant in the calcilutite, in contrast to its trace occurrence in the massive and laminated mudstone lithofacies. Mixed layer clays (I/S) are present in trace to minor amounts in the calcilutite, and kaolinite in trace amounts. Other clay-sized minerals are calcite (abundant), quartz (minor to abundant) and plagioclase (mainly albite). In contrast, in the laminated and massive mudstone lithofacies, clay-size quartz predominates over calcite and feldspar.

The thin section and XRD results were confirmed by SEM. In the laminated mudrock lithofacies, quartz ranges from 30-80%, with albite plagioclase from 3 to 10% and potassium feldspar up to 3%. However, in the pink-grey silty mudstone and siltstone, potassium feldspar almost equals the amount of albite. The abundance of calcite cement is up to 20%. Heavy minerals include garnet, zircon, ilmenite, epidote, rutile, barite, sphene(?) and pyrite. In the massive silty mudstone lithofacies, SEM results compare with the thin section data except XRD that showed calcium plagioclase to be common and illite as the predominant clay mineral. Barite, rutile and apatite (calcium phosphate, mostly fish skeletal material) were identified. In the concretionary beds, SEM results indicate that the discoidal mineral is barite, and that quartz (silica) does not exceed 5%. Albite is the common feldspar. Clays include chlorite, illite, mixed layer clays (I/S) and kaolinite.

4.3.3.8 Lithofacies interpretation

The general characteristics of the Madumabisa Mudstone Formation lithofacies and their interpretation are given in Table 4.9. The lithofacies association and the presence of non-marine fossils suggest that the formation is a lacustrine deposit. The **massive silty mudstone lithofacies** is interpreted as a deposit formed by suspension settling in areas of negligible traction current activity, at an indeterminate depth below effective wave base (cf. Dijk et al., 1978). The angular nature of the coarser grains in the mudstone suggests that they were wind-borne. The high amount of clastic material in bioturbated zones suggests significant biogenic displacement of grains from overlying beds.

The **concretionary calcilutite lithofacies** likely developed diagenetically through the mobilisation of Ca^+ and CO_3^{2-}. The abundant ostracod and bivalve fragments (Fig. 4.71c, d) and low detrital content in the micritic calcilutite indicate that they are low-energy lacustrine carbonates formed during shallowing of the Madumabisa Lake. The calcilutite beds represent freshwater lacustrine conditions when clastic input was limited and calcium carbonate was precipitated from a more permanent body of standing water (cf. Hartley et al., 1992). The clasts are mainly argillaceous (mudrocks) and were products of erosion, although some are well preserved bioclasts, indicating minimal agitation. The dense micrite walls (envelopes) acted as templates for internal and external sparry cementation. Pressure solution, indicated by stylolites, created fractures that were filled by calcite with a drusy mosaic texture, and some partly by poorly-developed geopetal structures. Stylolites

Table 4.9 Summary of characteristics and interpretation of Madumabisa Mudstone Formation lithofacies

LITHOFACIES	GRAIN SIZE/SORTING	TEXTURE	MINERALOGY AND OTHER COMPONENTS	BEDDING AND SEDIMENTARY STRUCTURES	GEOMETRY / NATURE OF BOUNDING SURFACES / THICKNESS	DEPOSITIONAL ENVIRONMENT
Mudstone (M_m)	mud and silt		Detrital grains: quartz (20-60%), feldspar (mainly plagioclase- up to 10%), muscovite, mudstone intraclasts. Cement: calcite (10-60%). Heavy minerals: epidote, sphene, garnet. Clay minerals: illite, smectite.	massive (abundant); conchoidal fracture; bioturbation	poorly exposed surfaces, but sharp contacts with (MS_l) lithofacies; irregular contacts with (C_c); units from less than a metre to over 30m thick	probably deep-water lacustrine deposit
Calcilutite (C_c)	generally micrite; also microsparite, sparite, detrital silt, intraclasts		calcite (micrite >70%). Grains: quartz, feldspar (plagioclase), muscovite, mudstone intraclasts, barite, pseudomorphs of gypsum. Organic components: algal lumps?, calcareous algae?, fish remains, phosphates, ostracods (2-40%), bivalves (<1%), gastropods. Clay minerals: chlorite, illite, mixed layer clays, kaolinite	massive; burrows, bioturbation; cone-in-cone, septarian and fenestrae-like structures, stylolites	irregular concretionary beds, aggregates, irregular isolated concretions; irregular bases and smooth tops; beds up to 1.2m thick	originally lacustrine, diagenetically altered by calcite cementation and concretionary development
Mudstone / Siltstone (MS_l)	mud, silt, very fine to fine sand; generally well sorted		Detrital grains: quartz (20-65%), feldspar (plagioclase, orthoclase, microcline ~ 2-10%), muscovite (up to 2%). Cement: micrite/microspar (5-30%). Heavy minerals: epidote, sphene, tourmaline, garnet, ilmenite, zircon, barite. Clay minerals: illite, chlorite. Organic components: ostracods, fish remains, burrows. Trace fossils: *Teichichnus*, *Zoophycos*, *Rhizocorallium*, *Skolithos* and *Planolites*	horizontal lamination to small-scale cross-lamination; flaser and lenticular bedding; ripple marks; burrows and bioturbation; stylolites	tabular sheets; generally flat base and top (irregular surfaces present); beds <5cm up to 70cm thick in units > 10m thick; thickening-upward sequences	ranging from deep water to lake margin settings; ripple bedforms in small channels, sheetfloods; thickening-upward cycles represent repeated deepening and shallowing.
Calcilutite (C_l)	generally micrite; also microsparite, sparite, detrital silt, intraclasts		similar to (C_c)	local horizontal lamination, small-scale soft-sediment contortions; bioturbation and burrows	tabular beds; sharp basal contacts and convex-up tops; beds to over 60 cm thick	see C_c lithofacies above
Sandstone (S_{vf-vc})	very fine to very coarse sand; poorly to moderately well sorted	matrix- to framework-supported	quartz (60-85%), feldspar (microcline, plagioclase, orthoclase - 5-10%), mudrock fragments (2-20%)	massive to stratified (planar, trough, horizontal)	wedge-shaped, lenticular beds; units up to 2.3m thick	lacustrine: channel deposition during low lake water levels

could have provided late diagenetic cement for voids such as burrows (Scholle, 1978, p. 206). Deformation during late diagenesis produced multiple fracture-forming veins (now filled by 'beef' fibrous calcite) which cross-cut some of the intraclasts and phosphatic clasts (cf. Scholle, 1978, p. 208). There is no evidence of subaerial exposure; this suggests deposition in perennial, rather than ephemeral lakes (cf. Platt, 1992, p. 89). Barite is a prominent vein mineral commonly associated with quartz and calcite. Minor amounts of barite are disseminated in the limestones and sandstones, and barite is abundant in some concretions, but is rare as a rock-forming mineral (Kerr, 1977). Barite pseudomorphs of gypsum rosettes in the concretionary calcilutite indicate late replacement of gypsum. The earlier presence of gypsum indicates arid climatic conditions.

Horizontal and small-scale cross-lamination in the **laminated silty mudstone and siltstone lithofacies** indicate current activity, probably in lake-marginal settings. The cross-laminae are interpreted as ripple bedforms in small channels (proximal reaches) that flowed in the lake. The current ripples indicate palaeocurrents to the southeast, suggesting the presence of streams transverse to a northeast-trending lake. Bedding planes acted as conduits for precipitation of calcite cement, resulting in tabular calcilutite bodies.

4.3.3.9 Facies Analysis

The predominant silty mudstone lithofacies and associated concretionary calcilutite are grouped as the massive mudrock facies assemblage (Fig. 4.80). The laminated silty mudstone and siltstone lithofacies, and associated tabular concretionary calcilutite and sandstone lithofacies are grouped as the laminated mudrock facies assemblage (Fig. 4.81). These two facies assemblages are more useful groupings in terms of environmental association than the three-fold subdivision of Tavener-Smith (1960, 1962) and Gair (1960). The two facies assemblages occur as alternating units forming cyclical sequences (Fig. 4.82). Within the assemblages, layering defined mainly by the resistant calcilutite beds is common throughout the Madumabisa Mudstone Formation (Fig. 4.83).

The **massive mudrock facies assemblage** was probably deposited from suspension from sediment-laden river water entering the lake. Sturm and Matter (1978) indicated that sediment-laden river water may be denser than the epilimnion but less dense than the

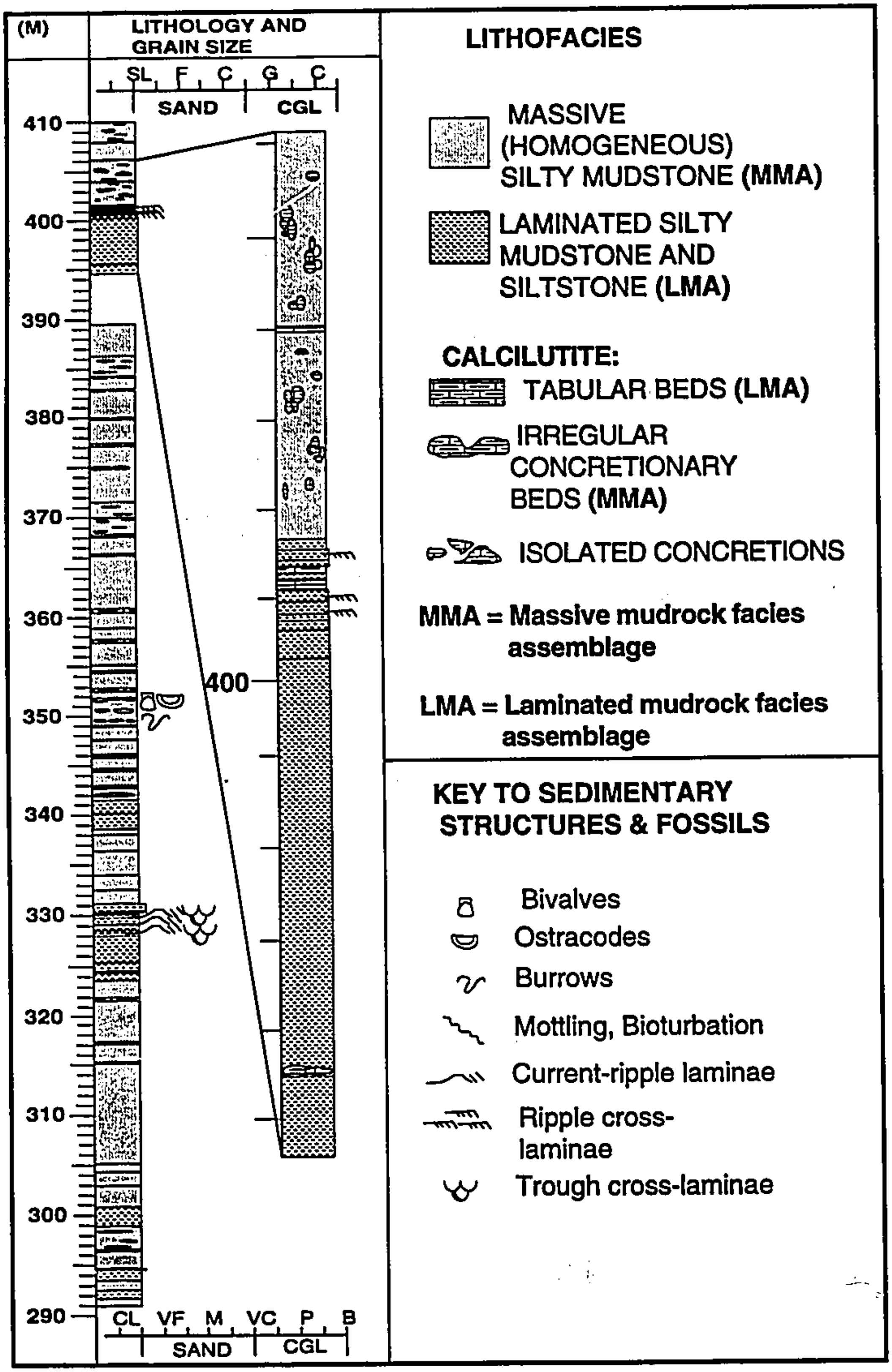


Fig. 4.80 Stratigraphic log of Madumabisa Mudstone Formation showing massive mudrock facies assemblage (typical example) predominant over laminated mudrock facies assemblage, Mulungwa River Section 4, Mulungwa map area, mid-Zambezi Valley Basin, southern Zambia.

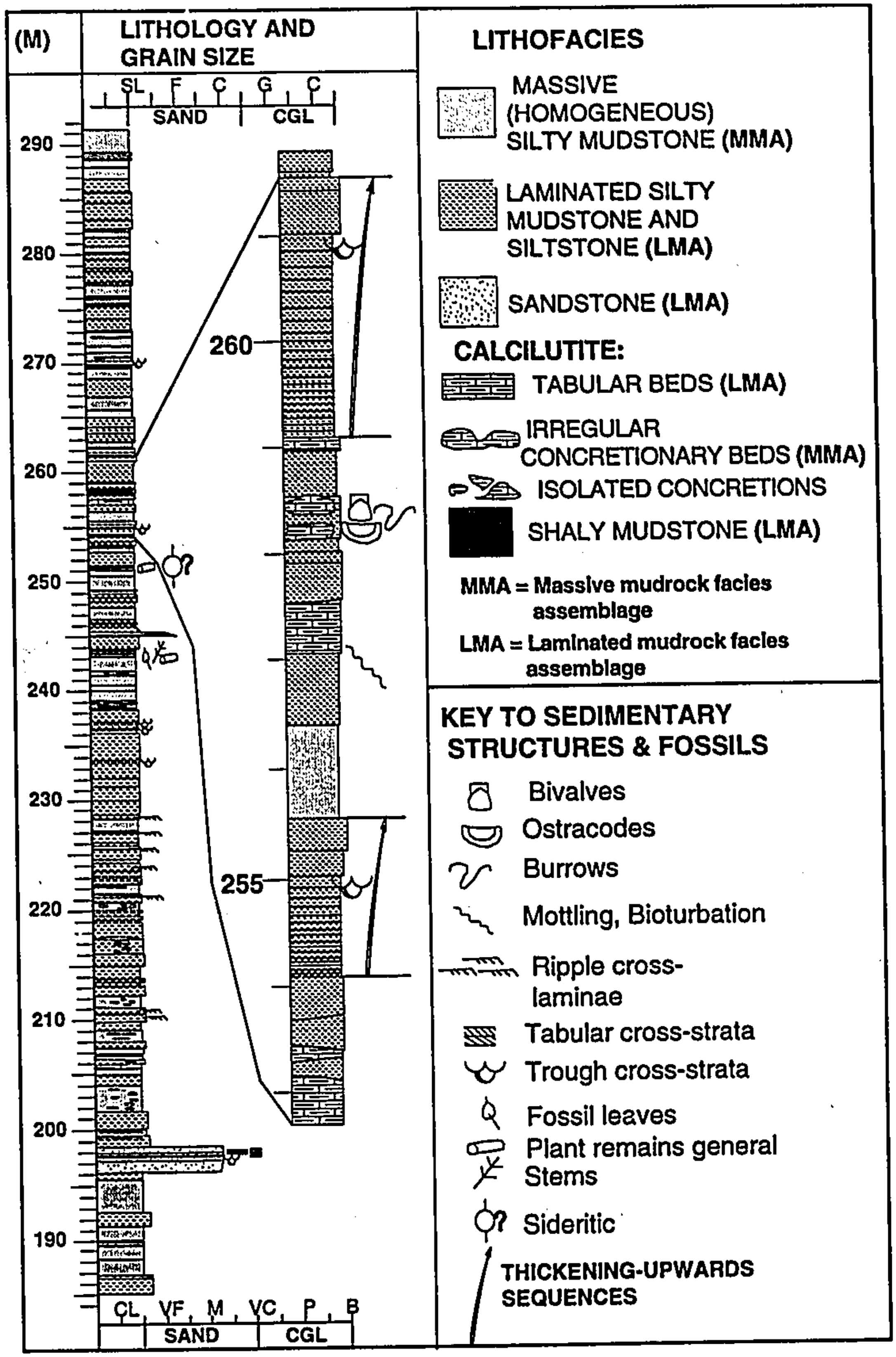


Fig. 4.81 Typical example of the laminated mudrock facies assemblage showing thickening-upward sequences, Madumabisa Mudstone Formation, Kazinze River Section 1, Siankondobo map area, mid-Zambezi Valley, southern Zambia.

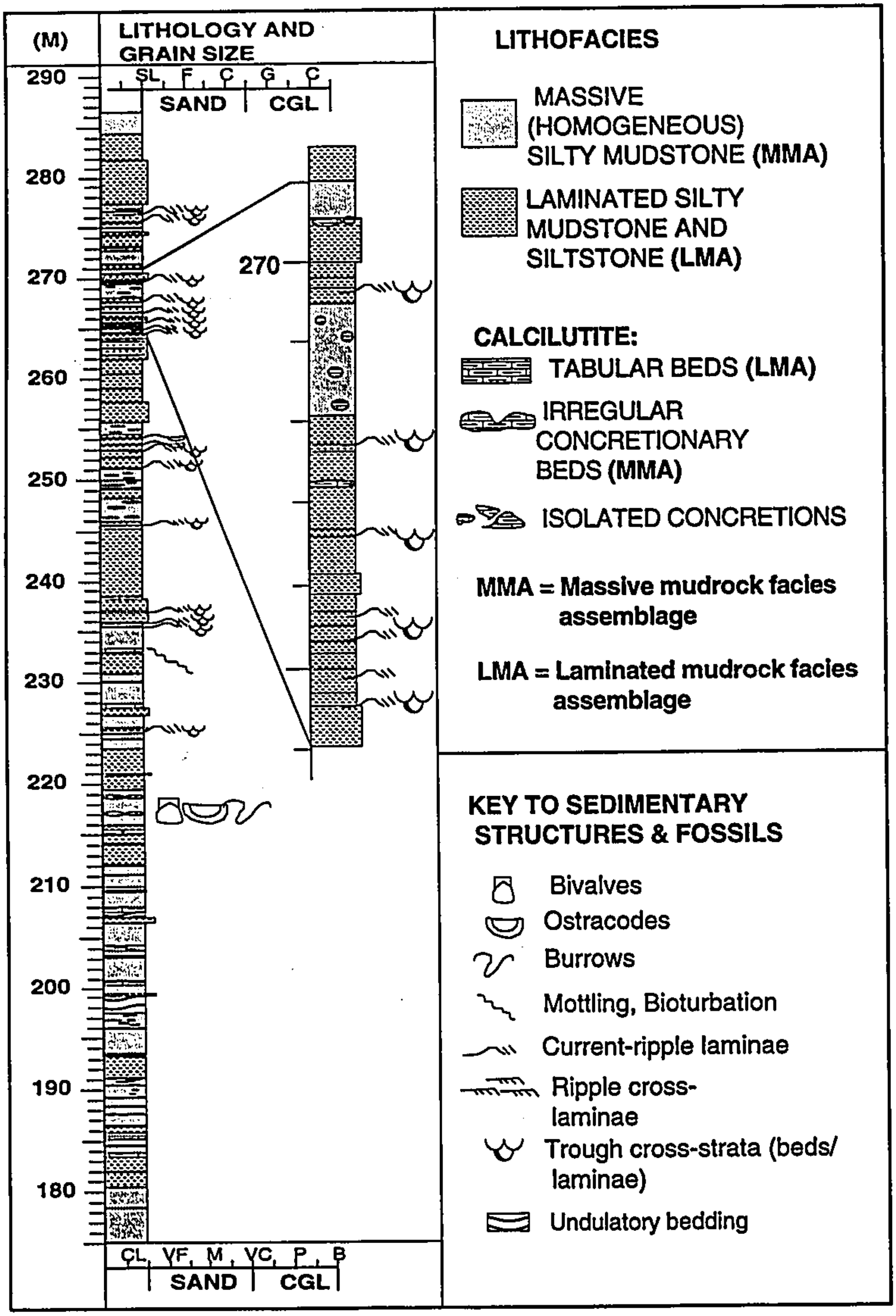
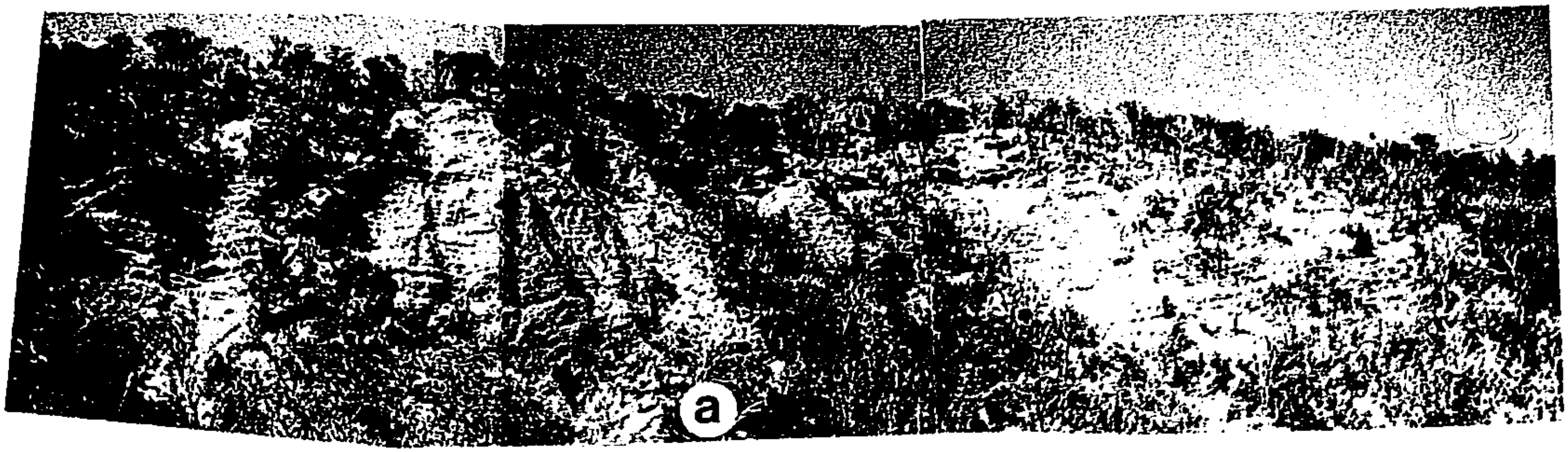


Fig. 4.82 Stratigraphic log of Madumabisa Mudstone Formation showing alternating laminated mudrock facies assemblage (predominant) and massive mudrock assemblage, Mulungwa River Section 4, Mulungwa map area, mid-Zambezi Valley Basin, southern Zambia.



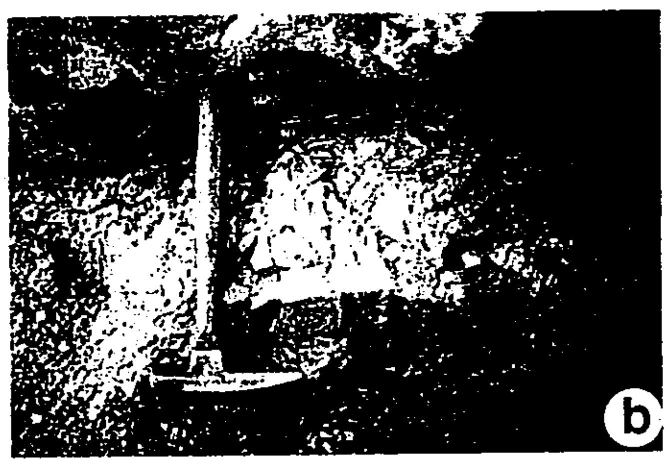


Fig. 4.83 Field exposure of upper Madumabisa Mudstone Formation

a: Photomosaic showing resistant concretionary calcilutite beds that define bedding. The sequence comprises alternating laminated and massive silty mudstone facies assemblages, and is overlain by Upper Karoo Group.

b: Close-up view at the contact (end of hammer handle) between Madumabisa Mudstone and Upper Karoo, showing green and red colours in the former.

hypolimnion, resulting in an interflow along the thermocline or chemocline. The coarser material would settle throughout the lake and the fines would remain in suspension until the lake waters overturned (Sturm and Matter, 1978). This may explain the coarser grains embedded in silty matrix; another possibility is that the grains were blown there by wind. The presence of burrows and rootmarks suggests that the massive character of these beds is due in part to bioturbation. A profile made from a photomosaic in the assemblage indicates that the concretionary calcilutite forms continuous beds in the massive silty mudstone lithofacies that can be followed for more than 300 m laterally (Figs. 4.84 and 4.85). These beds probably indicate palaeo-sediment/water interfaces where calcite precipitated to form concretions that coalesced to form continuous beds. These features together with rootlets, local reddening and reduction suggest shallowing and possible emergence. The associated fauna (e.g. ostracods) indicates shallow, oxygenated waters.

The thickness of the green grey laminated (dark grey in very thinly laminated) lithofacies (up to 4.5 m) of the **laminated mudrock facies assemblage** suggests that the lake water mass was stratified for long periods (meromictic lake). Rising water level would favour stratification of the bottom water mass and/or rising of the oxycline. The assemblage displays thickening-upward cycles (Fig. 4.81) that suggest alternating deepening (transgression) and shallowing (regression) of the lake. The very thinly laminated and graded mudstones were likely deposited from suspension. Laminated sediments commonly accumulate in stagnant stratified lakes, although they can form under oxygenated waters.

The medium bedded units of laminated and cross-laminated sandstone, siltstone, and mudstone lithofacies are interpreted as sheetflood deposits locally associated with shallow water lacustrine units near a source of terrigenous sediment. The cross-lamination and asymmetrical ripples suggest deposition from currents rather than waves. The sharp, planar and locally erosive bases of beds, and locally normally graded beds in the assemblage may be interpreted as the result of deposition by distal turbidity currents (cf. Lambert and Hsu, 1979; Kelts and Hsu, 1980). A stratified sandstone unit was probably fluvially deposited by inflowing streams during low lake water levels.

Bioturbation is common in the two assemblages, and burrows are commonly filled by

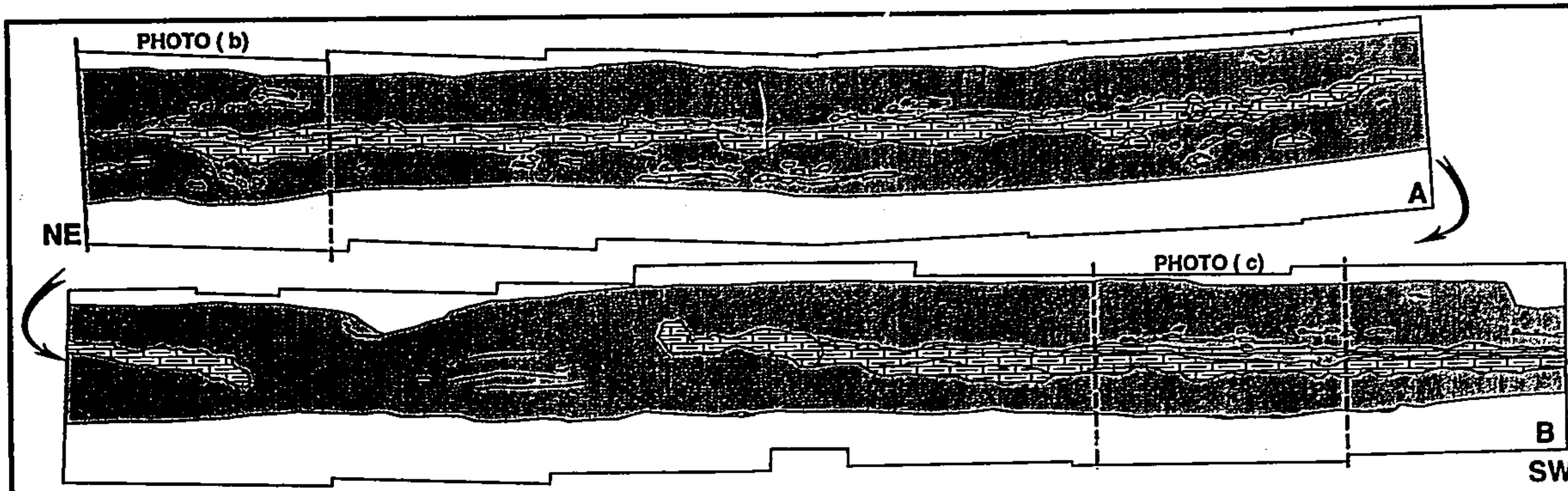
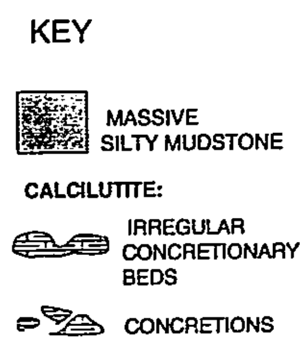


Fig. 4.84 Lateral variation of concretionary calcilutite lithofacies in the Madumabisa Mudstone Formation, Along Mulungwa River, Mulungwa map area.

a) Profiles A and B drawn from photomosaic show lateral variation of concretionary calcilutite beds and concretions in generally massive silty mudstone; profile B continues to the southwest into profile C of Fig. 4.85a). For scale, see representatative photographs.

b) Representative photograph showing concretions coalesced to form continuous irregular beds. Hammer (arrow) is 34 cm long.



c) Representative photograph showing concretions coalesced to form continuous irregular beds. Hammer (arrow) is 34 cm long.

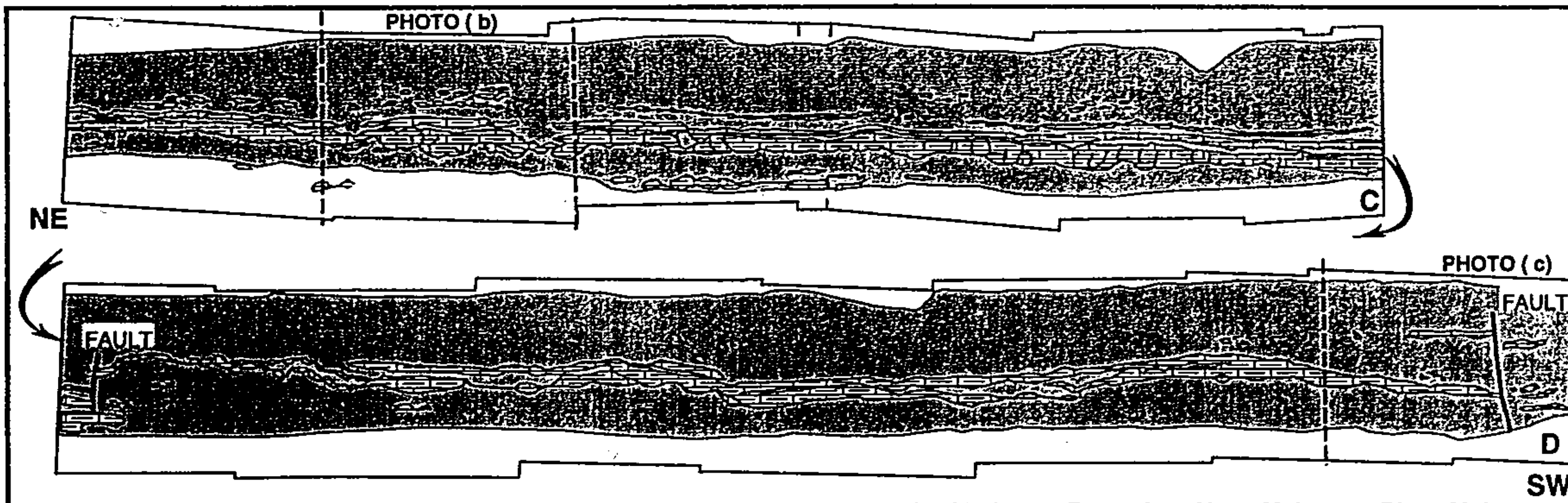
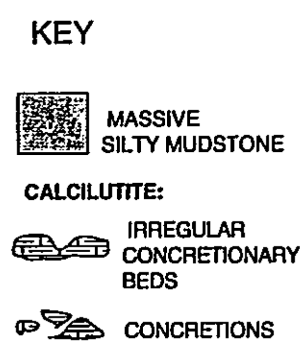


Fig. 4.85 Lateral variation of concretionary calcilutite lithofacies in the Madumabisa Mudstone Formation, Along Mulungwa River, Mulungwa map area.

a) Profiles C and D drawn from photomosaic show lateral variation of concretionary calcilutite beds and concretions in generally massive silty mudstone; profile C continues to the northeast into profile B of Fig. 4.84a). Total distance (profiles A to D) is 320 m. For scale, see representatative photographs.

b) Representative photograph showing concretions coalesced to form continuous irregular beds. Hammer (arrow) is 34 cm long.



c) Representative photograph showing concretions coalesced to form continuous irregular beds. Hammer (arrow) is 34.cm long.

green clays and display a high bioclastic content. The vertical variation in siliciclastic /bioclastic content within a bed indicates bioturbation in the upper part of the bed, caused by displacement of clastic material from the surface. To a depth of 10 m beneath the contact with the overlying Escarpment Grit Formation of the Upper Karoo Group, the mottled red and green colour in the Madumabisa Mudstone Formation (Fig. 4.83b) indicates a possible soil zone i.e. subaerial exposure or leaching by groundwater from the overlying sandstone.

4.4 UPPER KAROO GROUP

4.4.1 GENERAL REMARKS

The Upper Karoo Group (UKG) comprises four formations: the Escarpment Grit, Interbedded Sandstone and Mudstone, Red Sandstone, and Batoka Basalt (Fig. 4.0). The lithofacies of the first two formations are the only ones described here (see Chapter two).

Although exposures are of limited extent in the study area, three relatively good sections were measured, one in the Nkandabwe, and two in the Mulungwa map areas (Figs. 2.2a, d) and five short sections in the Siankondobo area (Fig. 2.2b). Two sections are over 400 m thick; the rest do not exceed 30 m. Drill holes in search for uranium by Power Nuclear Corporation of Japan (PNC) in the Upper Karoo were of little use for this sedimentological study, because the core was discarded and drill logs are in an abbreviated form.

Figure 4.86 summarizes the main characteristics of the Escarpment Grit and the Interbedded Sandstone and Mudstone formations; arenaceous lithotypes predominate (>70%), with minor mudrocks (siltstones and mudstones) and conglomerates. From field observations and laboratory study of 50 hand samples, and thin and polished sections including SEM and XRD analysis, three broad lithofacies are recognised in the two formations, based primarily on grain size:-

i. Coarse-grained to conglomeratic sandstone (S_{c-g}),

ii. Very fine- to medium-grained sandstone (S_{vf-m}), and

iii. Mudrocks (siltstone and mudstone-M_{m-s}).

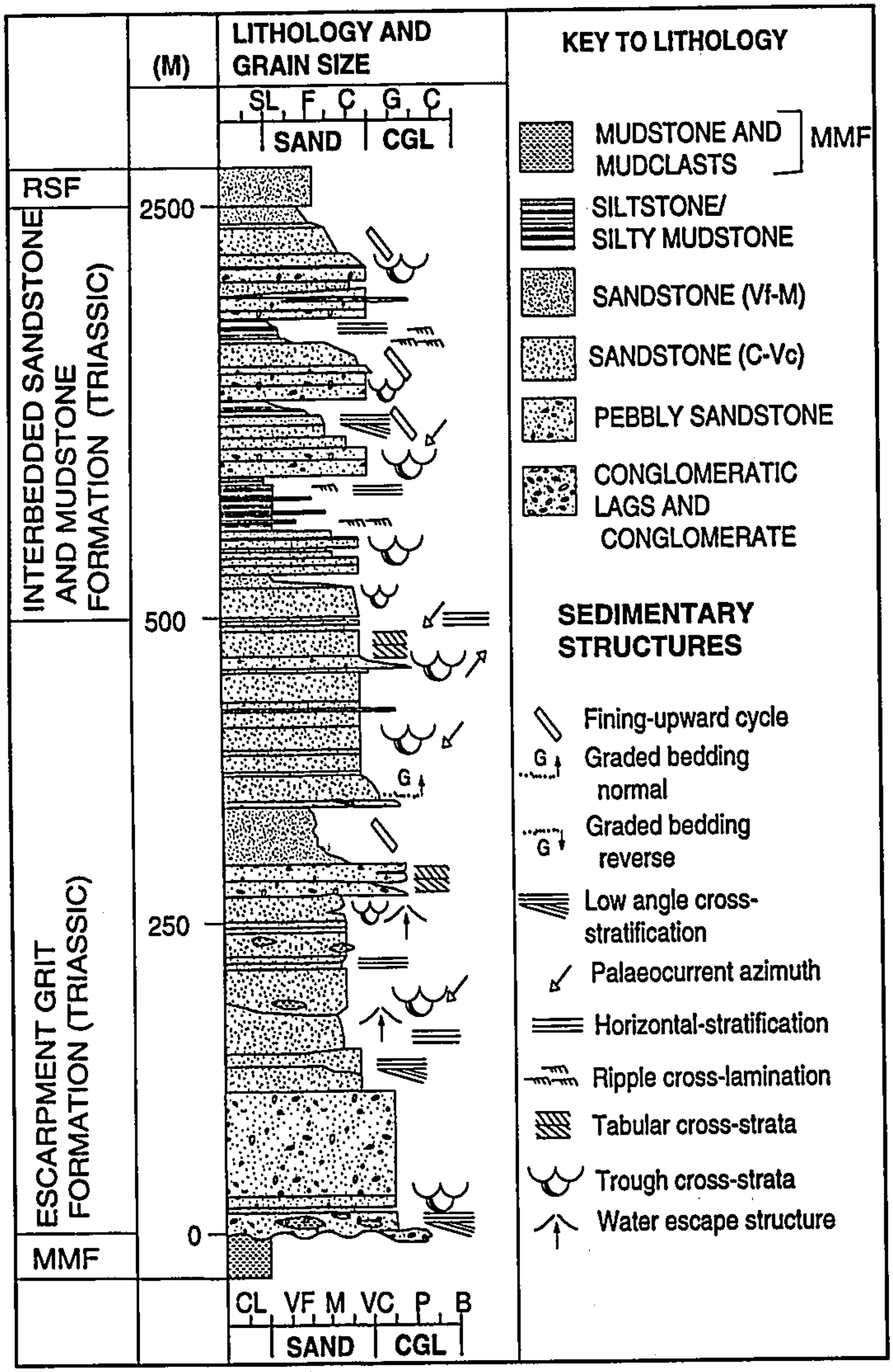


Fig. 4.86 Generalized stratigraphic column of the Escarpment Grit and Interbedded Sandstone and Mudstone formations of the Upper Karoo Group. Note change of scale at 500 m. MMF = Madumabisa Mudstone Formation; RSF = Red Sandstone Formation.

The coarser sandstone (S_{c-g}) lithofacies predominates in the Escarpment Grit Formation, but decreases in proportion stratigraphically upward and in the Interbedded Sandstone and Mudstone Formation where the finer sandstone lithofacies (S_{vf-m}) predominates. In general, the two formations consist internally of stratified fining-upwards sequences in which the following nine depositional facies (Miall, 1977; 1978; Rust, 1978a) are recognised:-

i. trough cross stratified sandstone (St)
ii. massive sandstone (Sm)
iii. low-angle cross-bedded and tangential scoop-shaped cross-bedded sandstone (Sl)
iv. horizontally stratified sandstone (Sh)
v. planar cross-stratified sandstone (Sp)
vi. ripple cross-lamination sandstone (Sr),
vii. sandstone with erosional scours and intraclasts (Se)
viii. massive mudrock (Fm) and
ix. plane-bedded, finely lamination mudrock, with very small ripples (Fl).

Fm and Fl are mostly confined to the mudrock lithofacies, the rest occur commonly in the sandstone and conglomeratic lithofacies; deformational facies are also present and are designated as Sd.

4.4.2 ESCARPMENT GRIT FORMATION

4.4.2.1 General remarks

The Escarpment Grit Formation (EGF) of the Upper Karoo Group disconformably overlies the Madumabisa Mudstone Formation of the Lower Karoo Group (Fig. 4.87a, b, d, e). However, northeast of Kasika River, in the Nkandabwe map area for example, the Escarpment Grit oversteps the Lower Karoo to rest directly on basement gneisses, pegmatites and amphibolites (Tavener-Smith, 1960). The formation consists of poorly sorted, coarse- to very coarse-grained sandstone (grit) with abundant locally conglomeratic sandstone lags that fine upwards into finer-grained sandstone and

Fig. 4.87 Coarse-grained to pebbly sandstone lithofacies, Uphill Section, Mulungwa map area

Escarpment Grit Formation

a: Resistant coarser sandstone lithofacies overlain by rubble-covered, finer-grained sandstone lithofacies.

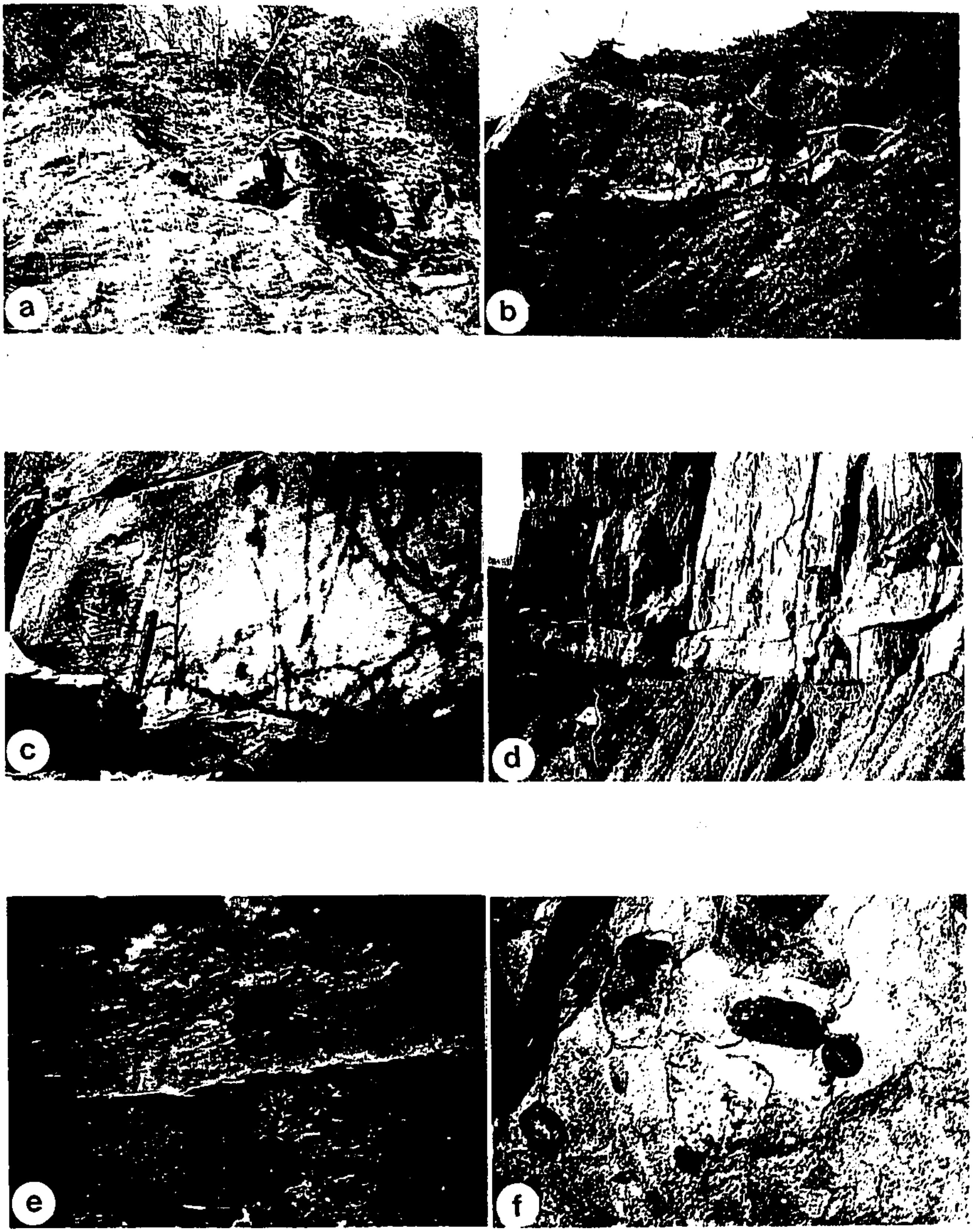
b: Detail of (a) above, showing the lateral persistence of coarser sandstone lithofacies, resting with sharp disconformity on the Madumabisa Mudstone Formation.

c: Downflow-dipping tangential and scoop-shaped cross sets in coarse-grained to pebbly sandstone overlying erosional scours with intraclasts.

d: Detail of (b), above, showing massive sandstone overlying the cross-sets in (c), above.

e: Detail of (d), above, showing extraformational mudclasts (derived from Madumabisa Mudstone Formation) and the sharp disconformable contact above the latter.

f: Elongate, subrounded Madumabisa Mudstone Formation mudclasts in a loose block of coarser sandstone of the Escarpment Grit Formation. Lens cap is 5 cm in diameter.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intercalated mudstone. The sandstone also contains intraformational mudflakes and mudballs. Huge blocky exposures of the EGF (up to 12 m thick) are commonly separated by rubble- and vegetation-covered areas (Fig. 4.87a). The covered areas conceal the finer sandstone (S_{vf-m}) lithofacies; the mudrock (M_{m-s}) lithofacies is minor (< 10%). The fining-upward units are typically stratified as expressed by predominant trough cross-bedding, planar cross-bedding, and low-angle to horizontal bedding. Small-scale cross-bedding is common in the finer grained sandstone and mudrocks. Extraformational Madumabisa Mudstone clasts are common in the formation (Fig. 4.87f). The formation is overlain conformably by the Interbedded Sandstone and Mudstone Formation.

4.4.2.2 Coarse-grained to pebbly sandstone lithofacies (S_{c-g})

This lithofacies consists of very coarse-grained to pebbly sandstone (abundant granules and scattered pebbles) and subordinate conglomeratic lags. Because of the coarseness of the sandstone, the term grit is appropriate and used in the name of the formation. In outcrops, the lithofacies ranges from light brownish to yellowish grey, and pale yellowish brown, to pale brown, greenish orange pink, pale reddish brown, and pale red. Brownish black and brick red mottling is common in the basal parts of the units.

The grain size is generally coarse- to very coarse sand with granules and subordinate pebbles. Intercalations of medium to fine sandstone are present. Commonly the pebbles and granules occur as scattered grains in the sandstone or define the laminae and bedding. Granules and pebbles are made of quartz, pink feldspar, vein quartz and minor rock fragments (e.g. brick red mudstone). The sand fraction is composed predominantly of quartz with subordinate feldspar and rock fragments. Extraformational mudrock fragments from the underlying Madumabisa Mudstone Formation are common and are up to 20 cm in length and 10 cm in width.

The S_{c-g} lithofacies occurs mainly in thick to very thick beds (0.15 m to 5 m, average of 0.5-0.8 m) forming stratified units over 25 m thick. Fining-upward cycles are common; coarsening-upward units are rare. In the Uphill Section, Mulungwa area (Fig. 4.87a-f), the fining-upward units start with erosional scours filled with crudely bedded (massive) or trough cross-stratified sets containing mudrock intraclasts, overlain by downflow-dipping low-angle (≤10°) cross sets that are commonly tangential and scoop-shaped (Sl; Fig. 4.87c). At this locality, Sl is 0.8 m thick overlain by 4.7 m massive sandstone (Sm; Fig. 4.87d). The unit contains elongate extraformational MMF mudstone clasts with long axes parallel to bedding (Figs. 4.87e, f). The unit is overlain by rubble with locally protruding tabular units of generally medium-grained massive sandstone. Towards the top of the section, medium- to small-scale trough cross-sets with intercalated conglomeratic lenses and finer sandstone (S_{vf-m}) lithofacies form a 2.3 m fining-upward unit in which the sizes of trough cosets decrease upwards (Fig. 4.88a).

The salient feature of the coarse-grained sandstone (S_{cg}) lithofacies and the Escarpment Grit Formation is the stacking of cosets of trough and planar cross-beds (Fig. 4.88b, c) with stratification accentuated by weathering. Trough cross-bedding is the predominant sedimentary structure, ranging from large-scale trough sets (> 1 m thick) to small-scale trough sets (<10 cm thick). On bedding surfaces, troughs are commonly exposed and are best for palaeocurrent measurement (Fig. 4.88d). These range from less than 20 cm to slightly more than 3 m wide. Planar cross-bedding is the next common sedimentary structure, occurring in beds ranging from 2 m to 4 m thick (Fig. 4.88e). In places, scour-and-fill structures are present (Fig. 4.88f). Other examples of the trough and planar cross-stratified units and beds are shown in Fig. 4.89a-d. In Fig. 4.89b, c, granules and pebbles are scattered throughout the lithofacies, but in a few places, concentration of granules and pebbles define bedding. Horizontally bedded coarse-grained sandstone (1.8 m thick) is exposed in the Road Cut Section, Nkandabwe area, as well as in the Kungwe Hill Sections (Fig. 4.89e). In the basal parts of the Road Cut Section, Nkandabwe map area, alternating units of cross-stratified and generally massive coarse- to very coarse-grained sandstone are present (Figs. 4.89f, 4.90a). The massive units are lenticular and wedge-shaped and consist of beds up to 5 m thick (Fig. 4.89f). The cross-stratified beds consist of cosets 0.14 to 0.7 m thick, of planar to low-angle cross-bedded sandstone with planar bases (Fig. 4.90a). In the Zhimu River Section 1, the lowest exposures of Escarpment Grit Formation (above a concealed basal contact) are brownish red medium- to coarse-grained sandstone grading upward into very thickly bedded coarse sandstone (S_{cg}) lithofacies. The units consist of trough and planar cross-bedded cosets. Bounding surfaces are reddish

Fig. 4.88 Coarse-grained to pebbly sandstone lithofacies

Escarpment Grit Formation

a: Medium- to small-scale trough cross-sets with intercalated conglomeratic pockets and finer-grained sandstone. Uphill Section, Mulungwa area.

b: Stacked sets of planar and trough cross-bedded sandstone. Notice erosional effect of weathering. Kungwe Hill, Siankondobo map area. Hammer is 34 cm long.

c: Detail of (b), above, showing trough cross-bed behind hammer overlain by planar cross-bed.

d: Bedding surface dipping to the southeast exposing troughs indicating general palaeocurrent flow to the northeast. Zhimu/Mulungwa Hill, Mulungwa map area.

e: Tabular, very thickly bedded, cross-stratified sandstone. Notice large planar set behind scale at the bottom. Zhimu River Section 1, Mulungwa map area. Marker pen is 13 cm long.

f: Scour-and-fill structures in coarser sandstone lithofacies. Zhimu River Section 1, Mulungwa map area. Hammer for scale.

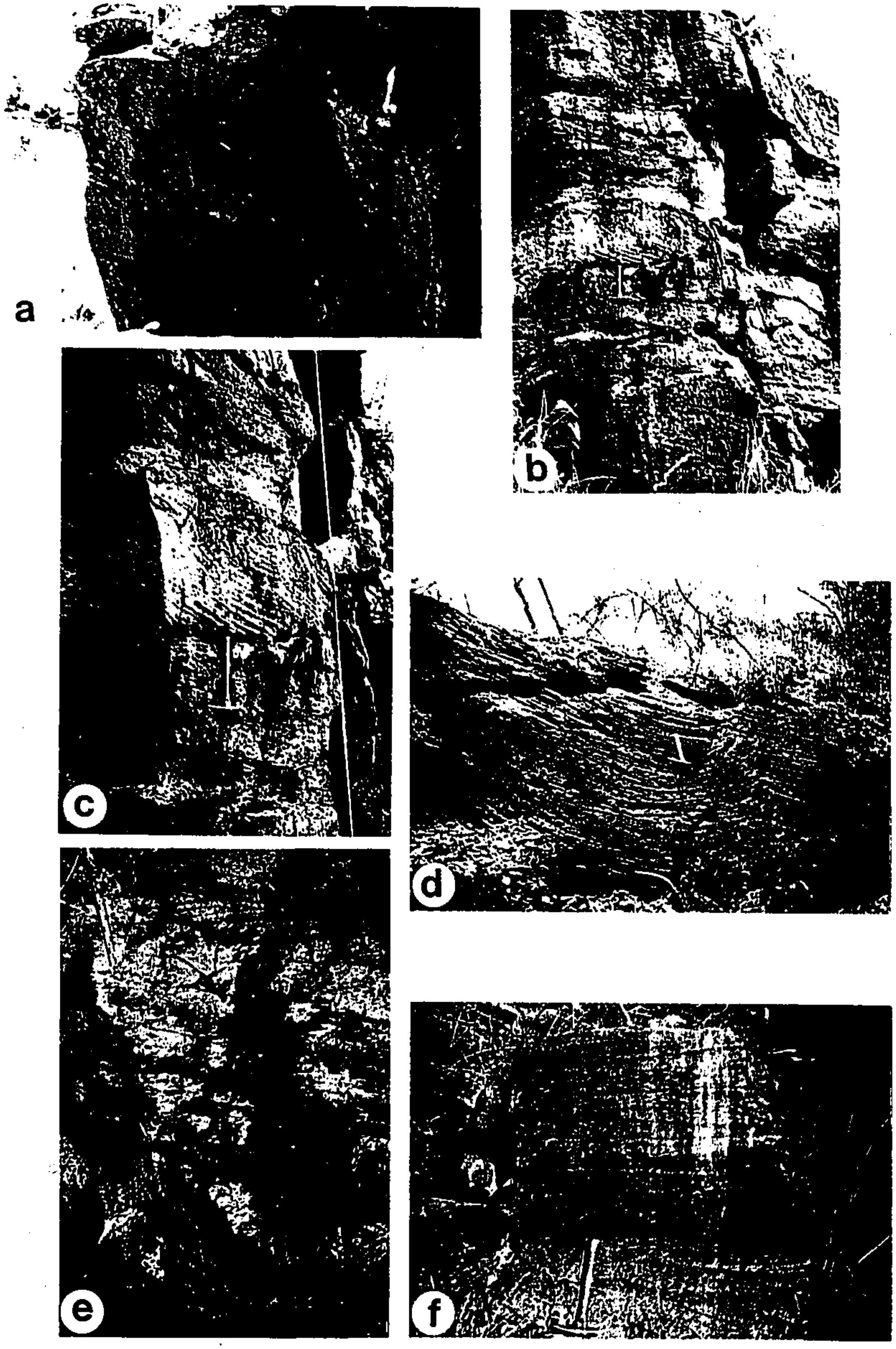
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Fig. 4.89 Coarse-grained to pebbly sandstones lithofacies

Escarpment Grit Formation

a: Cross-stratified sandstone with foresets showing tangential contacts. Zhimu/Mulungwa Hill, Mulungwa map area. Hammer is 34 cm.

b: Trough cross-bedding in pebbly sandstone. Zhimu River Section 1, Mulungwa map area. Hammer is 34 cm long.

c: Trough cross-bedding in pebbly sandstone with pebbles defining bedding. Northeast Kungwe Hill, Siankondobo map area. Marker pen is 16 cm long.

d: Planar cross-bedding sets in coarser sandstone, Zhimu River Section 1, Mulungwa map area.

e: Horizontally to low-angle (< 5°) cross-stratified, recessive, medium- to coarse-grained sandstone beds at bottom overlain by more resistant, trough and planar cross-stratified, slightly coarser sandstone. Kungwe Hill, Siankondobo map area.

f: Wedge-shaped amalgamated massive sandstone beds. Zongwe River/Road cut Section, Nkandabwe map area. Scale 2.1 m long.

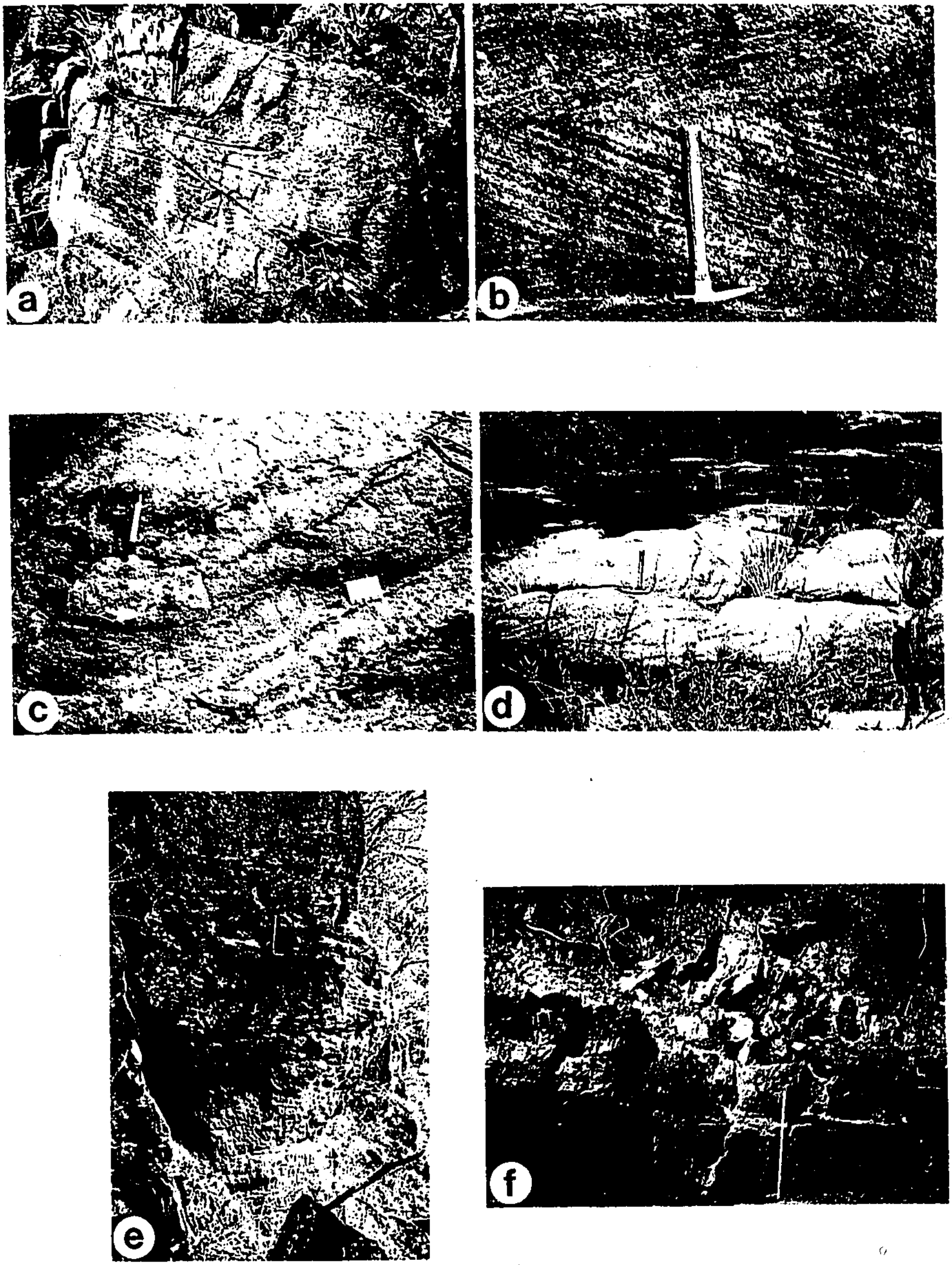
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Fig. 4.90 Coarse-grained to pebbly sandstone lithofacies

Escarpment Grit Formation

a: Planar cross-stratified sandstone between massive sandstone units. Notice tangential basal foreset contacts. Zongwe River/Road cut Section, Nkandabwe map area. Hammer for scale.

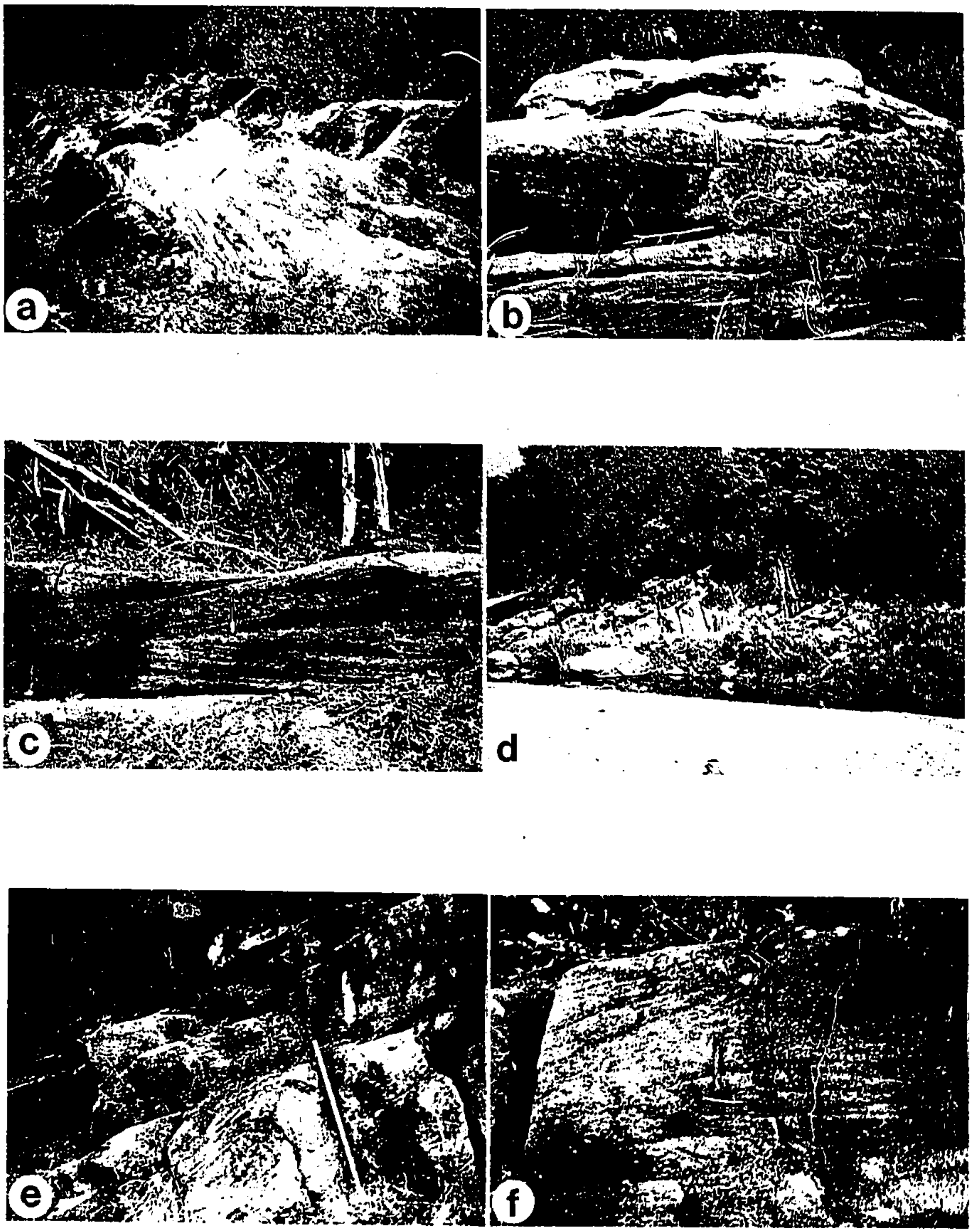
b: Amalgamated cross-stratified sandstone beds. Notice small-scale trough sets in the bottom bed. Zhimu River Section 1, Mulungwa map area. Hammer is 34 cm long.

c: Cosets of low-angle sigmoidal cross-bedding in coarser sandstone lithofacies. Zhimu River Section 1, Mulungwa map area. Marker pen is 16 cm long.

d: Zhimu River Section 2 exposing a fining-upward sequence grading from pebbly sandstone to medium-grained sandstone. Person for scale.

e: Detail of (d), above, showing tabular beds of cross-stratified, coarse-grained to pebbly sandstone. Scale is 2.1 m.

f: Detail of (d), above, showing trough cross-bedded sandstone. Notice the scattered pebbles in the sandstone.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stained and the finer-grained lithofacies (S_{vf-m} and M_{m-s}) intercalations have been weathered and eroded. Amalgamated cross-stratified units are present within the sequences (Fig. 4.90b) as well as cosets of low-angle, sigmoidal cross-stratified units (Fig. 4.90c). Stratigraphically higher (Section 2; Fig. 4.90d) the 17 m sequence exposed consists of a lower tabular stratified coarser sandstone (S_{c-g}) composed of beds 0.10-4 m thick, overlain by medium- to coarse-grained greenish grey sandstone with planar to trough cross-sets (Fig. 4.90e, f). Grading, normal (Fig.4.91a, b) and reverse, is present with grain size differences defining the bedding.

Other features in the coarser sandstone (S_{c-g}) lithofacies include deformation structures such as water-escape structures (Fig. 4.91c, d), and possible fossil logs (Fig. 4.91e). Gair (1959) reported the occurrence of small silicified logs with well-preserved annual rings and radial structures in the formation in the northeastern part of the mid-Zambezi Valley. Units of the deformational facies (sandstone with water-escape structures) range from 0.15 m to 2 m thick (Fig. 4.91c, d).

Lateral profiling in this lithofacies is hampered by lack of continuous accessible outcrops, but short profiles (<30 m laterally) are possible. Laterally, Figs. 4.92 and 4.93 show that different sedimentary structures occur in the same bed or unit within short distances.

In thin sections, rocks of this lithofacies are seen to be poorly to moderately well sorted and grain-supported, with quartz and feldspar predominating and rock fragments subordinate (Figs. 4.94a-c). Matrix-supported sandstones occur locally. Grains are equidimensional but grain size differences (very coarse versus medium coarse) locally produce a crude stratification. The coarser grains (granules and pebbles) are rounded; the finer grains are subangular to subrounded. Matrix occurs rarely and where the sandstone is matrix-supported, the matrix does not exceed 10% of the rock. Other intergranular space is occupied by quartz overgrowths and calcite cement. Hematitic grain outlines are present locally.

Quartz predominates, mainly as monocrystalline grains; polycrystalline grains, mostly recrystallized (Fig. 4.94a), rarely exceed 1% of the rock, and a few stretched polycrystalline grains were observed. Fractures are common in the quartz (Fig. 4.94b).

Fig. 4.91 Coarse-grained to pebbly sandstone lithofacies

Escarpment Grit Formation

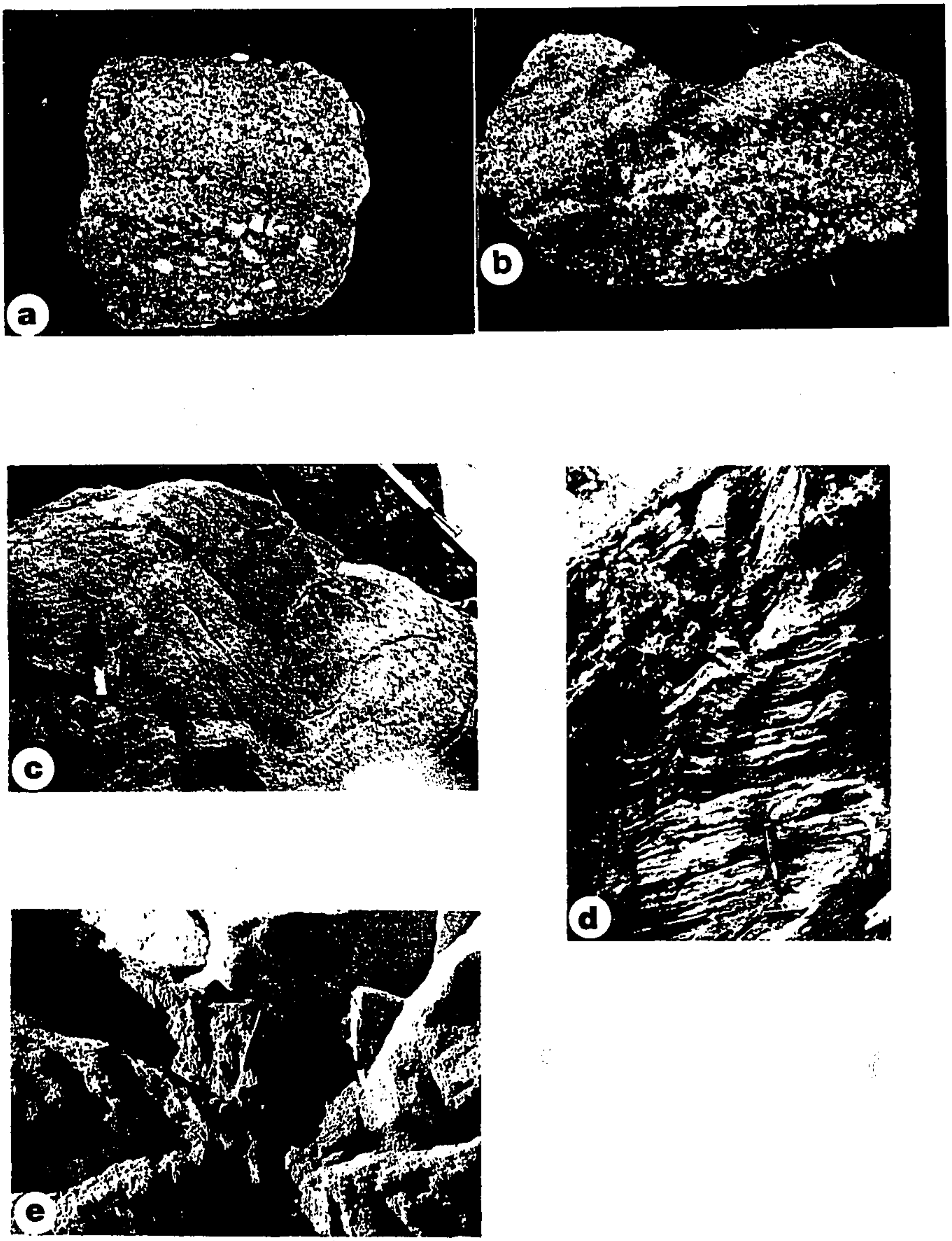
a: Polished slab of pebbly sandstone showing normal grading with stratification defined by grain size differences. Zhimu River Section 1, Mulungwa map area. Scale in cm.

b: Polished slab showing microconglomerate at base grading into coarse-grained sandstone. Notice local iron-staining. Kungwe Hill, Siankondobo map area. Scale in cm.

c: Water-escape structure in pebbly sandstone, Zhimu River Section 1, Mulungwa map area. Marker pen is 16 cm long.

d: Large-scale water-escape structure in coarser sandstone. Notice horizontal bedding at base grading into the dewatering structure. Kungwe Hill, Siankondobo map area. Hammer is 34 cm long.

e: Weathered, cylindrical body, probably a fossil log, in coarse-grained to pebbly sandstone, Road cut-Section, Nkandabwe area. Axe is 34 cm long.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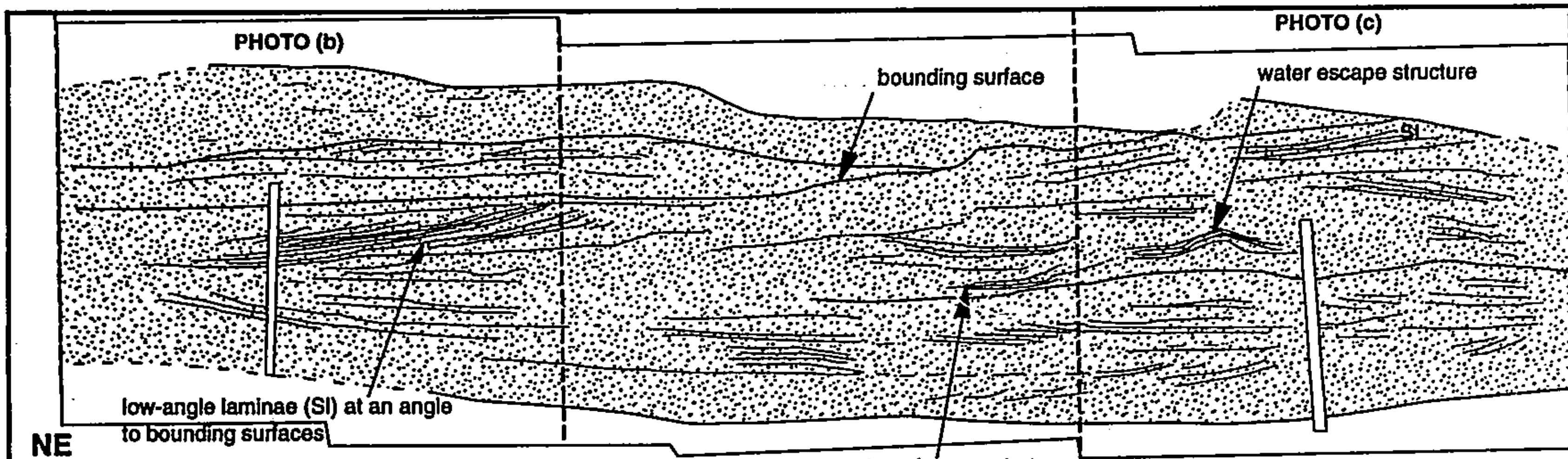


Fig. 4.92 Lateral variation in sedimentary structures and geometry of coarse-grained to pebbly sandstone lithofacies of the Escarpment Grit Formation. Zhimu River Section 1, Mulungwa map area.

a) Profile drawn from photomosaic shows amalgamated and wedging out beds of coarse-grained to pebbly sandstone lithofacies. Scale is 2.1 m.

b) Representative photograph showing cross-stratified coarse-grained to pebbly sandstone. The topmost bed is massive to crudely stratified. The recessive layers consist of finer sediments. Scale is 2.1 m.

KEY

COARSE-GRAINED TO PEBBLY SANDSTONE

c) Representative photograph showing trough cross-stratified coarse-grained to pebbly sandstone. Scale is 2.1 m.

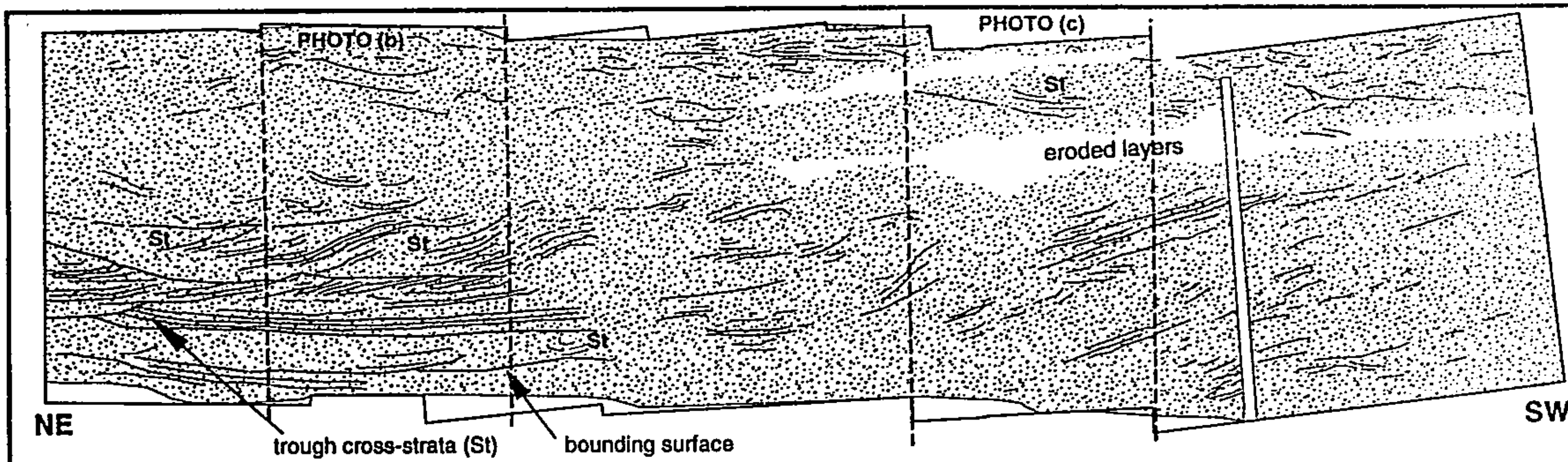
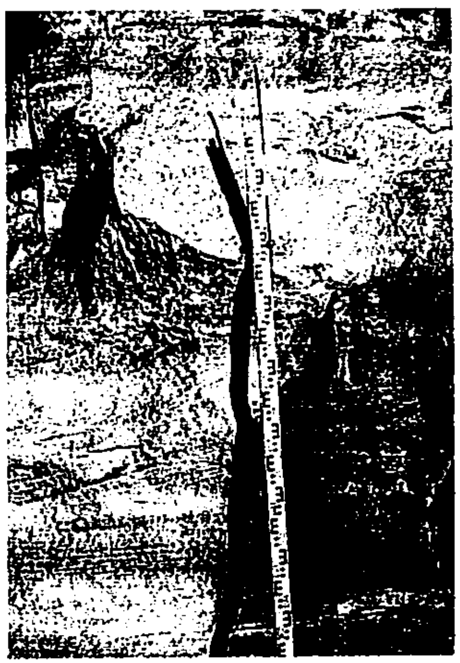


Fig. 4.93 Lateral variation in sedimentary structures of coarse-grained to pebbly sandstone lithofacies of the Escarpment Grit Formation. Zhimu River Section 1, Mulungwa map area.

a) Profile drawn from photomosaic shows abundance of trough cross-stratification in the coarse-grained to pebbly sandstone lithofacies. Scale is 2.1 m.

b) Representative photograph showing trough cross-stratified coarse- to very coarse-grained sandstone. Scale is 2.1 m.



KEY

COARSE- TO VERY COARSE-GRAINED SANDSTONE

c) Representative photograph showing cross-stratified coarse- to very coarse-grained sandstone. The recessive layers (eroded) consist of finer sediments. Scale is 2.1 m.

Fig. 4.94 Fine- to medium-grained sandstone lithofacies and coarse-grained to pebbly sandstone lithofacies

Escarpment Grit Formation

a: Photomicrograph (crossed nicols) showing quartz grains with planar to concavo-convex contacts. Zongwe River/Road cut Section. Nkandabwe map area. Long side of photograph is 2.5 mm.

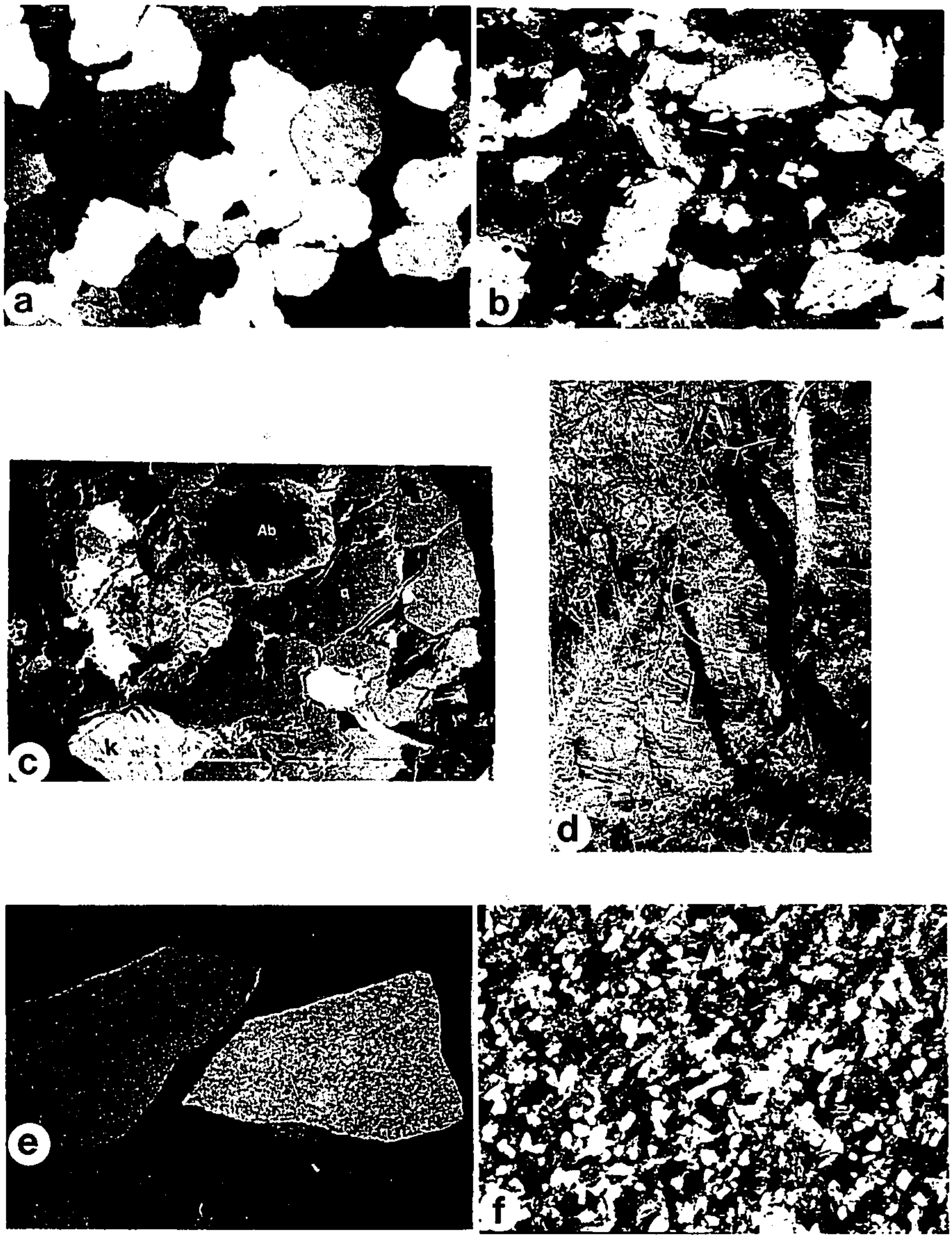
b: Photomicrograph (crossed nicols) showing fractured quartz and minor feldspar in clay matrix with abundant void space. Zhimu River Section 1. Mulungwa map area. Long side of photograph is 3.6 mm.

c: Photomicrograph (SEM) showing albite (Ab) partly altered to potassium feldspar (k) with clay, iron and calcite forming the matrix. Most of the grains are quartz (q) and the white mineral is iron oxide. Zhimu River Section 1. Mulungwa map area. Scale indicated on photograph.

d: Thinly bedded, fine- to medium-grained sandstone, generally internally massive, Kungwe Hill, Siankondobo map area.

e: Polished and stained samples of massive sandstone taken from (d) above. Scale in cm.

f: Photomicrograph (crossed nicols) showing the texture of (e). The elongate grains show preferred orientation. Quartz is predominant. Matrix is mainly illite clay and calcite cement. Long side of photograph is 2.5 mm.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Quartz forms over 80% of the sandstone, and is over 95% in some. Feldspar is second in abundance (2 to 15%, average 10%) and is mainly microcline with subordinate orthoclase and plagioclase, and minor perthite and microperthite. Locally potassium feldspar has replaced albite (Fig. 4.94c; SEM). Microcline is mainly fresh, but some grains are altered to sericite. The orthoclase is always inclusion-rich and brownish in section. Rock fragments include quartzite, mudstones and siltstones (mudrocks), sericite-rich quartzite, and chert, but overall, rock fragments do not exceed 5% of the rock. Basement gneiss, pegmatite and mylonite fragments have been reported by previous workers. Muscovite is more common than biotite, but together, they do not exceed 1% of the rock.

Matrix is made up of quartz and feldspar grains, sericite and minor clays. Calcite cement is present locally, some of it forming a poikilotopic texture. The cement is common in the matrix-supported sandstones. Quartz overgrowths, on the other hand, predominate in the framework-supported sandstone.

Heavy minerals occur rarely, and do not exceed 0.5% of rock composition and include epidote, zircon, sphene, tourmaline and rutile. K-feldspar, iron-rich clays, and calcite form the matrix (SEM). XRD shows that smectite and kaolinite are the abundant clay minerals. Others include illite in minor amounts and mixed-layer clays (Illite/Smectite) in trace amounts. Other clay-sized minerals are quartz, calcite and albite.

In terms of sorting and composition, the sandstone is submature to mature and is classified as feldspathic sandstone to quartz arenite.

4.4.2.3 Very fine- to medium-grained sandstone lithofacies (S_{vf-m})

This lithofacies forms a minor portion of the Escarpment Grit Formation. It consists of pale yellowish brown, greyish orange pink, greyish red to pale red, moderately well sorted to well sorted, very fine- to medium-grained sandstone. Good outcrops of the lithofacies are rare, and it is mostly covered by rubble and vegetation. Some exposures are flat lying, as along Zhimu River Section; in others such as the slopes of Kungwe Hill, a vertical section exposes pale red, thinly bedded, fine- to medium-grained sandstone (Fig. 4.94d).

In outcrop, the lithofacies is represented by thin beds rarely exceeding 10 cm which are internally horizontally laminated, small-scale cross-laminated or massive (Fig. 4.94e). The rock breaks into thin slabs. Along the Zhimu River Section, the small-scale cross-laminated sets showed elongate pebbles aligned along laminae. The rock weathers brick red with brownish black spots. Hand specimens show fine- to medium-grained, well-sorted sandstone (Fig. 4.94e) with local mica flakes.

In thin sections, rocks of this lithofacies are seen to consist mainly of subangular to subrounded grains of quartz and feldspar that are either framework-supported or matrix-supported (Fig. 4.94f). Where grains are in contact, planar to concavo-convex contacts are evident. Crude preferred orientation of the mica grains was observed locally.

Quartz is the predominant mineral (70-80%), followed by feldspar (microcline, plagioclase and orthoclase - 5-15%) and minor chert-like fragments. Most of the quartz is monocrystalline, and some is strained and contains inclusions (including sphene). Muscovite and sericite are the abundant micas (5-10%); flakes of the former are bent around quartz grains. The heavy minerals are epidote, zircon, sphene and rutile. SEM work showed that the matrix is made up of high-aluminum clays with minor magnesium and iron clay, confirmed by XRD to be illite with trace amounts of smectite. Other clay-size minerals include quartz and analcime.

4.4.2.4 Mudrock lithofacies (M_{m-s})

This lithofacies is not common in the Escarpment Grit Formation and is mainly covered by rubble and/or vegetation. The mudrock (M_{m-s}) lithofacies is known mainly from thin intercalations and extraformational mudstone clasts in the formation. The mudstone clasts are green, grey or red, resembling mudrocks of the underlying Madumabisa Mudstone Formation.

4.4.2.5 Lithofacies interpretation

The general characteristics of the Escarpment Grit Formation lithofacies and their interpretation are given in Table 4.10. From the lithofacies association, the formation is interpreted as a braided river deposit. The **coarse-grained to pebbly sandstone lithofacies** (S_{c-g}) contains a variety of sedimentary structures (e.g. trough and planar cross-

Table 4.10 Summary of characteristics and interpretation of Escarpment Grit Formation lithofacies

LITHOFACIES	GRAIN SIZE / SORTING	TEXTURE	MINERALOGY AND OTHER COMPONENTS	BEDDING AND SEDIMENTARY STRUCTURES	GEOMETRY / NATURE OF BOUNDING SURFACES / THICKNESS	DEPOSITIONAL ENVIRONMENT
Sandstone (S_{c-g})	coarse sand to pebbles; poorly to moderately well sorted	framework -supported, matrix-supported locally	Detrital grains: quartz (> 80%), feldspar (2-15%), rock fragments (<5%), mica, extraformational mudstone clasts. Heavy minerals: epidote, sphene, tourmaline, rutile. Cement: calcite. Clay minerals: illite, mixed-layer clays (I/S)	trough cross beds (St); massive (Sm); planar cross beds (Sp); low-angle and tangential scoop-shaped cross-bedding (Sl); horizontal bedding (Sh); normal and reverse grading; erosional scours and intraclasts (Se); deformation structures (Sd, e.g. water escape structure); stacked cosets of St and Sp.	tabular; generally flat base and top (irregular surfaces present); wedge-shaped and lenticular particularly (Sm); beds 0.15m to 5m thick in units up to 25m thick; fining-upward units	fluvial: dune, linguoid and transverse bar, and bar-edge sandwaves of braided streams; see text for details
Sandstone (S_{vf-m})	very fine to medium sand; moderately to well sorted	matrix- to framework -supported	Detrital grains: quartz (70- 80%), feldspar (microcline, plagioclase, orthoclase - 5-15%), chert-like fragments, muscovite and sericite (5-10%). Heavy minerals: epidote, sphene, zircon, rutile. Cement: calcite. Clay minerals: illite, smectite, analcime	massive; horizontal and small-scale cross-lamination	tabular; sharp bases and tops; beds rarely exceed 10 cm.	fluvial: upper flow regime plane beds, and lower flow regime ripple bedforms in channels
Mudrocks (M_{m-s}) lithofacies not common in EGF see Table 4.11	mud and silt		extraformational mudstone clasts from Madumabisa Mudstone Formation are common	see Table 4.11	see text	fluvial: bar top deposition during waning floods; see Table 4.11

bedding) reflecting changes in depositional environment. Miall (1977) interpreted medium-grained to pebbly sandstone with trough cross-bedding (St) to result from deposition by dune bedforms, and those with planar cross-bedding (Sp) from probably linguoid and transverse bars, and from sand waves. The massive sandstones are interpreted primarily as channel-fill deposits. Rust and Jones (1987) interpreted massive sandstones as either channel-base deposits formed by large-scale remobilization of cross-stratified sand or as deep, major channel complexes subjected to seasonal flooding and elevated pore-water pressures, the latter causing sand on channel banks and bedform foresets to liquefy and flow. Similar mechanisms of emplacement are envisaged for the massive sandstones. Their association with stratified units supports the channel-fill interpretation. Sandstone containing abundant low-angle and tangential scoop-shaped cross-beds (Sl) is interpreted as the result of shallow, high-velocity flow into low-relief scours (Rust, 1978a). The normal and reverse graded beds represent waning currents and increase in flow competence (progradation of bedforms), respectively. The change from one sedimentary structure to another indicates variation in current flow.

The deformation structures in the coarse-grained to pebbly sandstone (S_{c-g}) lithofacies are attributed to liquefaction. Liquefaction is a common phenomenon in rapidly deposited, loosely-packed sands in which the grains temporarily lose contact when disturbed and are supported by the fluid. Lowe (1976b) indicated that sediments in this state will flow on gentle slopes, but that coarse sand will quickly resediment. The water expelled during sedimentation of liquefied flows commonly generates water-escape structures (Fig. 4.91c, d) such as pillars and dishes (Rust and Jones, 1987).

Thin sheet units of the massive, **very fine- to medium-grained sandstone lithofacies** are attributed to upper flow regime under a "rheological bed" condition (Moss, 1972) or alternatively to deposits of sandy debris flows derived from bank collapse along a newly initiated channel (Rust and Jones, 1987). Small-scale cross-laminated beds probably resulted from the migration of current ripples during waning flow and channel abandonment. Horizontally-laminated beds probably represent upper flow regime plane beds.

Mudrock lithofacies probably formed mainly from suspension settling.

Williams and Rust (1969), and Rust (1972) indicated that silt and clay are deposited from suspension along bar tops or within cutoff secondary channels during waning flood stages and may be reworked by subsequent braided stream processes. Reworking may explain the scarcity of the mudrock lithofacies in the formation.

4.4.2.6 Facies analysis

Due to poor exposure, the lithofacies could not be grouped into different facies assemblages and are therefore considered as one, the **sandstone/mudrock facies assemblage**. The assemblage comprises poorly defined, fining-upward and rare, coarsening-upward sequences (Fig. 4.95), characteristic of a fluvial environment. Following deposition of a basal lag, a rapid decrease in both fluid and sediment discharge is required to generate cross-stratified pebbly sandstone bars (cf. Hein and Walker, 1977), which could be remobilised to deposit massive pebbly sandstone. Cosets of trough cross-strata were generated by migration of groups of more distinctly sinuous-crested dunes in relatively shallow water (cf. Rust and Jones, 1987) or by megaripple migration in channels (Boothroyd and Ashley, 1975) across which pebbly sandstone bars accreted during subsequent high discharge conditions. On the bar tops, mud accumulated and was subsequently reworked by migrating braided channels.

4.4.3 INTERBEDDED SANDSTONE AND MUDSTONE FORMATION

4.4.3.1 General remarks

The Interbedded Sandstone and Mudstone Formation (ISMF) consists generally of fining-upwards units of mainly coarse- to very fine-grained sandstone with minor conglomeratic sandstone and conglomerate alternating with mudrocks (Fig. 4.86). The finer portion consists predominantly of alternating beds of greenish grey to purplish green, and purplish brown, locally calcareous, massive mudstone and much finer-grained, brown to purplish brown sandstone. The contact between ISMF and the underlying Escarpment Grit Formation is gradational, and is placed at the base of the first sandstone unit that fines up to mudstone.

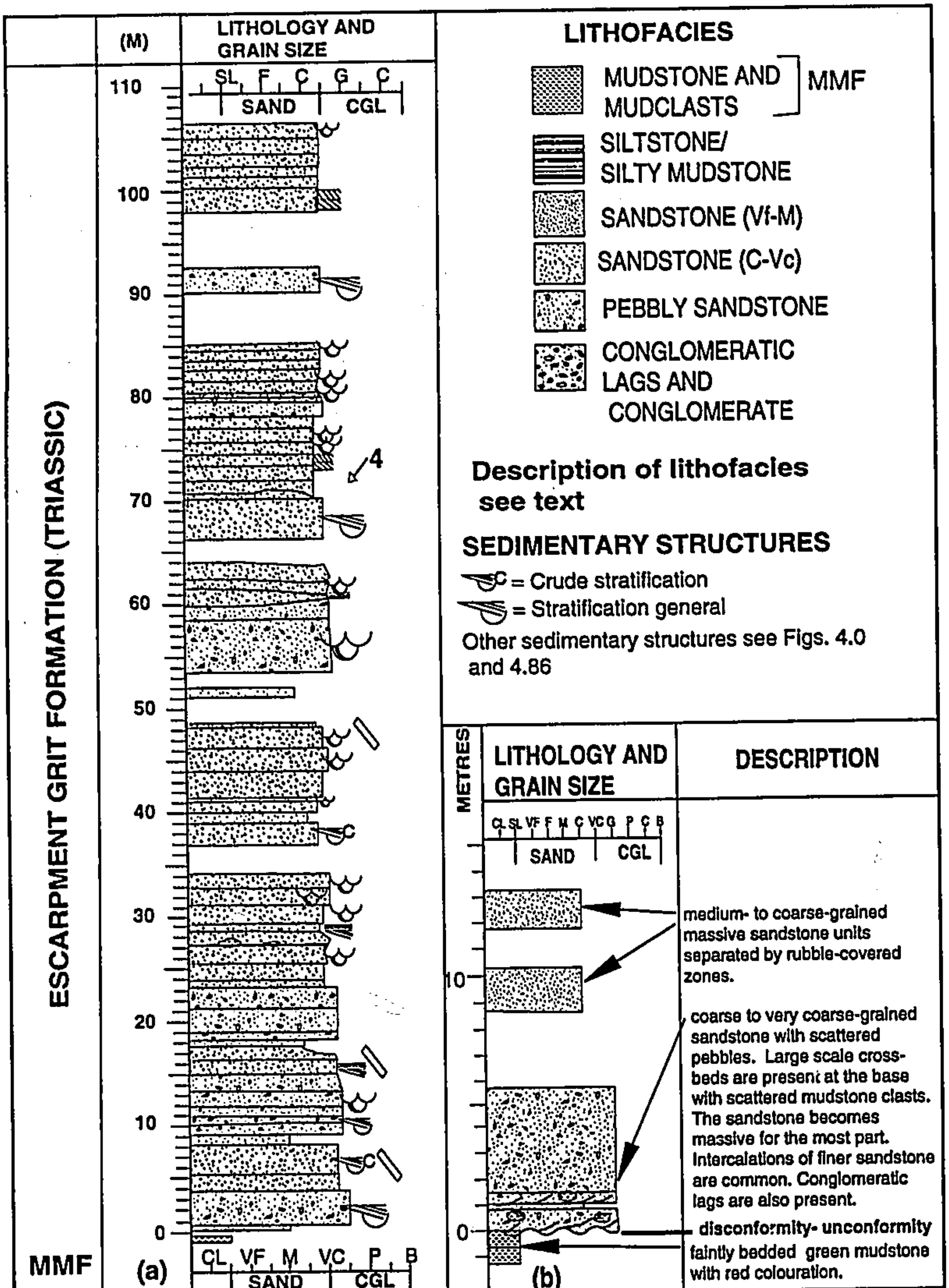


Fig 4.95 Typical sandstone/mudrock facies assemblage of the Escarpment Grit Formation, (a) Zongwe River Section, Nkandabwe map area, (b) Mulungwa Uphill Section, Mulungwa map area, mid-Zambezi Valley Basin, southern Zambia. Note different scales in (a) and (b).

A typical fining-upward sequence has a basal conglomerate that grades upwards into trough cross-bedded, coarse- to very coarse-grained sandstone and eventually into mudrocks. The fining upwards sequences range from less than 4 m to over 16 m (16.8 m maximum measured), with beds ranging from 10 cm to over 2 m thick. The sequence thickness is likely to be more, because the upper parts of the fining-upward sections are covered by rubble and vegetation. In the upper portions of the fining-upward sequences, the contacts between lithofacies are usually gradational. Bed thickness of the lithofacies range from 25 cm to 1.5 m, with stratification defined by grain size differences. Mudclasts are locally present in basal portions of the fining-upward units. Palaeocurrent indicators (57 readings) show current directions towards the southeast.

4.4.3.2 Coarse-grained to pebbly sandstone lithofacies (S_{c-g})

This lithofacies is confined strictly to the basal portions of fining-upwards sequences (Fig. 4.96a-c). Along the Zhimu River (Sections 3 and 7) two isolated outcrops containing fining-upwards sequences are separated by vegetation and sand cover. Section 3 exposes a very irregular to wedge-shaped amalgamated coarse sandstone body (S_{c-g}) containing irregular intercalations of finer material (very fine-grained sandstone and mudrocks), and overlying mudrock (M_{m-s}) (Fig. 4.96a). This suggests that the vegetation and sand-covered areas between these outcrops are largely underlain by mudrocks. The sandstone bodies are commonly massive or locally crudely stratified. Section 7 exposes irregular lenticular to wedge-shaped coarser sandstone (S_{c-g}) lithofacies with conglomerate wedges containing abundant elongate mudclasts (Fig. 4.96d). A typical sequence commonly starts with an erosional scoured contact overlain by intraclasts (Se) and/or a conglomeratic bed grading upwards into stratified (St common) and massive pebbly sandstone, then finer-grained sandstone, siltstone and mudstone (mudrock lithofacies) (Fig. 4.96a-c, e). Normal grading and horizontal bedding are locally present. The quartz pebble diameters rarely exceed 2 cm. Both the sedimentary structures and pebbles decrease in size upwards. The large trough sets are succeeded by medium cross-bedding and finally small-scale cross-lamination in the siltstones and mudstones. In places, large planar sets are present and these are succeeded by trough sets.

Fig. 4.96 Lithofacies of Coarse-grained to pebbly sandstone, very fine- to medium-grained sandstone and mudrock

Interbedded Sandstone and Mudstone Formation

a: Zhimu River Section 3 exposing mudrock at base overlain sharply by fining-upwards amalgamated beds of coarser sandstone with intercalated finer-grained sandstone.

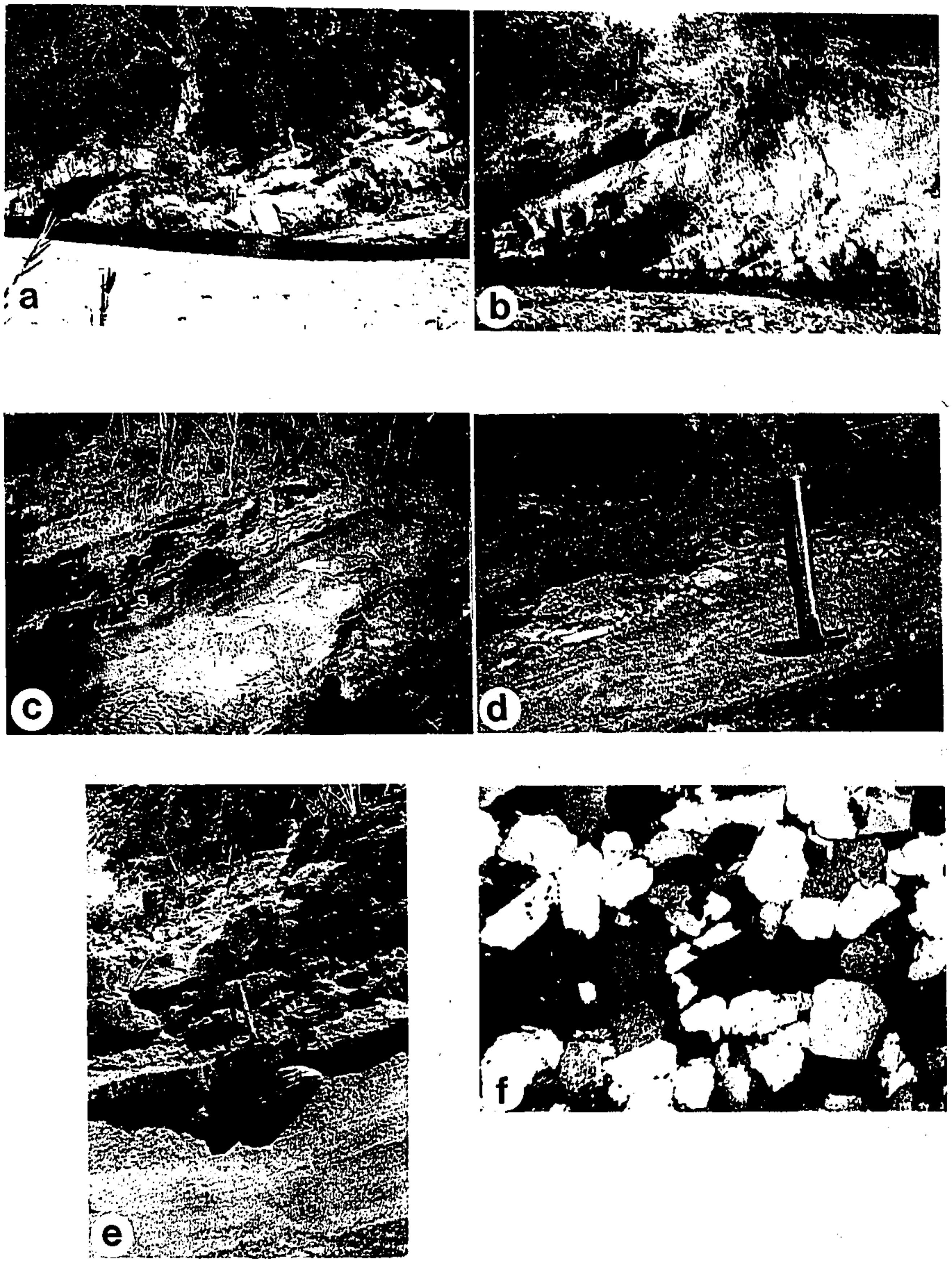
b: Alternating fining-upwards units; grading from conglomeratic base to mudrocks. Zhimu River Section 7, Mulungwa area. Person for scale.

c: Red, fine-grained sandstone and mudrocks overlain by resistant, coarse-grained to pebbly sandstone. Notice detached elongate sandstone fragment (S). Zhimu River Section 7, Mulungwa area. Hammer (arrow) is 34 cm long.

d: Detail of (c), showing conglomerate bed containing elongate mudclasts, grading upward into pebbly sandstone (black coated).

e: Close-up view in (c) above, showing a horizontally laminated, well rounded, elongate cobble of sandstone in fine-grained sandstone.

f: Photomicrograph (crossed nicols) showing predominant quartz with planar to concavo-convex contacts with some partly altered feldspar mottled grains. Black areas are void spaces (high porosity). Zhimu River Section 7, Mulungwa map area. Long side of photograph is 7 mm.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In thin section, rocks of this lithofacies are mainly framework-supported, with quartz and feldspar as the main grains (Fig. 4.96f). Grain contacts are concavo-convex, with no preferred grain orientation because of their equidimensional nature. The grains are mainly subrounded (larger grains better rounded) and moderately well sorted. Laminae are locally defined by grain size differences. The matrix contains sericite, and grains are locally hematite-coated. Calcite cement is common in the matrix-supported sandstone although quartz overgrowths are more common. The hematitic staining appears to be a later diagenetic feature related to calcite, as it invades calcite areas.

Quartz is the predominant component (over 80%), mainly as monocrystalline grains, locally polycrystalline. The monocrystalline grains are usually fractured, contain inclusions and vacuoles, and some show undulose extinction. The polycrystalline grains show embayed to sutured contacts. The feldspar (5-15%) is mainly microcline, with subordinate orthoclase and plagioclase and local perthite and microperthite. The microcline is generally fresh, but some large grains are altered to sericite. Some feldspars are replaced by calcite. Rock fragments present include mudrocks, quartzite and chert-like fragments, collectively less than 2% of the rock. Mica occurs relatively rarely except in the matrix-supported sandstone where it is a common matrix component. Muscovite predominates over biotite, but together, they rarely exceed 1% of the rock.

Heavy minerals (epidote, zircon and sphene) rarely exceed 0.1% of the rock.

4.4.3.3 Very fine- to medium-grained sandstone lithofacies ($S_{vf\text{-}m}$)

This lithofacies forms parts of the fining-upwards sequences in the Interbedded Sandstone and Mudstone Formation and commonly grades into underlying and overlying lithofacies. However, where it alternates with the mudrock lithofacies, sharp and erosional contacts are present.

In outcrop, the sandstone is red to greenish orange pink (Fig. 4.96b-e, 4.97a, b) and weathers to blackish red and very dark red. The lithofacies consists of thinly- to medium-bedded sandstone, in units ranging from less than a metre to approximately 10 m thick, with an average bed thicknesses of 15-25 cm. In general, the sandstone is well sorted. Three depositional facies (St, Sh and Sm) are recognised. Sandstone with trough

Fig. 4.97 Lithofacies of Coarse-grained to pebbly sandstone, very fine- to medium-grained sandstone and mudrock

Interbedded Sandstone and Mudstone Formation

a: Detail of Fig 4.96c, showing mudrock/fine-grained sandstone with horizontal to small-scale cross-lamination. Notice the tangential contacts of foresets. Marker pen is 13 cm long.

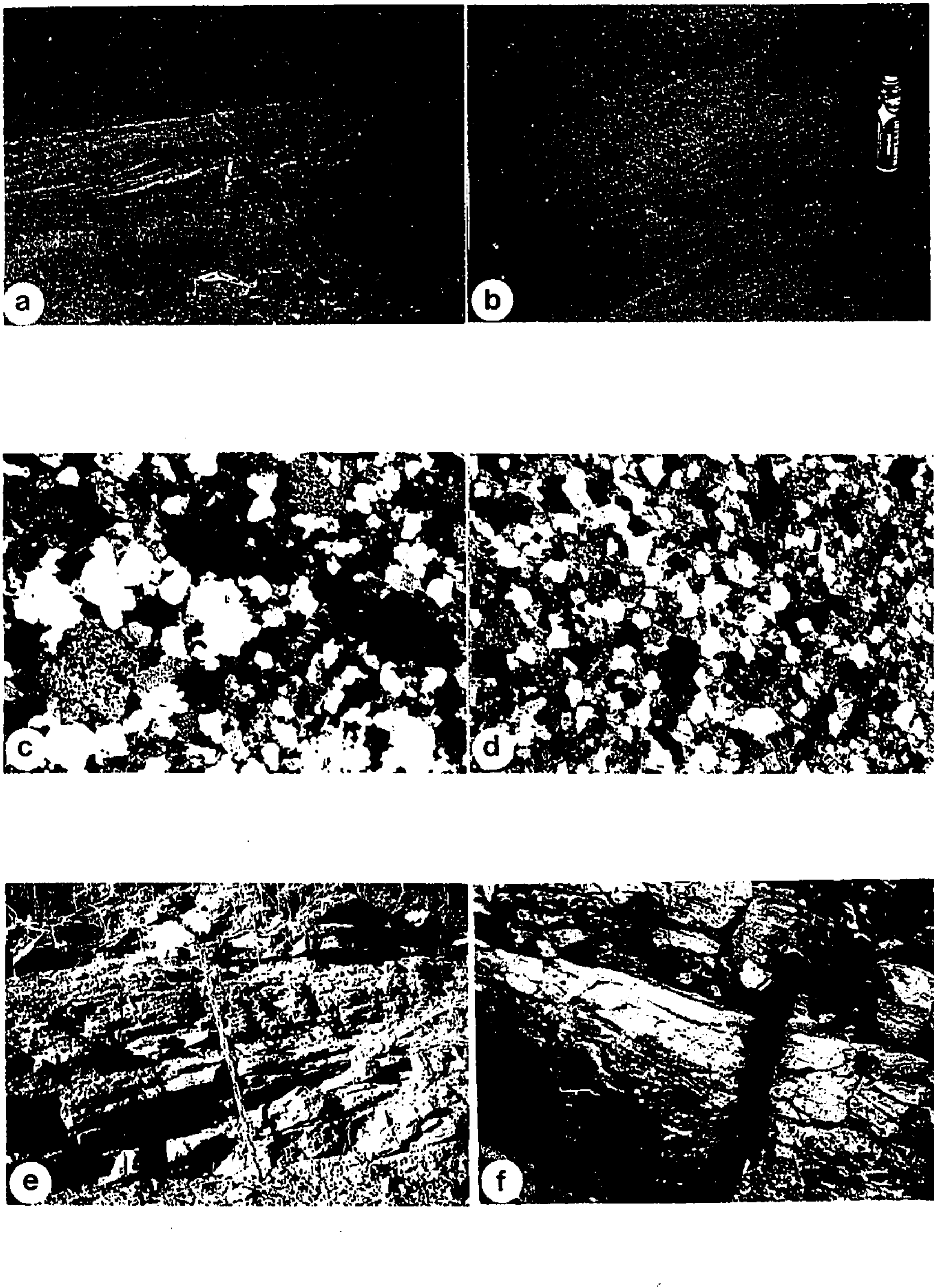
b: Small-scale trough cross-sets in well-sorted sandstone. Zhimu River Section 7, Mulungwa area. Marker pen is 13 cm long.

c: Photomicrograph (crossed nicols) showing polycrystalline quartz, altered feldspar and, silty mudstone fragments in quartz-rich matrix. Oversized black area is void space. Opaque minerals are also present. Zhimu River Section 7, Mulungwa map area. Long side of photograph is 15 mm.

d: Photomicrograph (crossed nicols) showing texture of medium- to coarse-grained sandstone consisting of quartz, feldspar, muscovite and traces of rock fragments in clay-rich matrix. Calcite cement is locally present. Zhimu River Section 7, Mulungwa map area. Long side of photograph is 6 mm.

e: Detail of the mudrock unit in Fig. 4.96a, showing massive to stratified (horizontal and cross-lamination) siltstone/fine-grained sandstone. Scale is 2.1 m long.

f: Detail of the mudrock unit in Fig. 4.102, showing internal small-scale ripple cross-lamination.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cross-bedding (St) predominates (Figs. 4.97a, b) in the lithofacies, followed by Sh facies (Fig. 4.97a). Sandstone with trough cross-bedding forms units up to 2.3 m thick, consisting of beds from 0.2 m to less than 0.9 m. As grain size decreases upwards, the cross sets decrease in thickness as well. The horizontally laminated sandstone beds (Sh) are usually thinner than the St beds. In Zhimu River Section 2, the thinly to medium-bedded, medium- to coarse-grained, greenish-grey sandstone unit (2.8 m thick) is horizontally bedded at the base, with beds ranging from 5 to 12 cm (1.4 m thick total), and overlain by a 90 cm bed with trough cross-sets approximately 2.8 m wide.

In thin section, the sandstones are seen to be matrix-supported (Fig. 4.97c, d), and where the grains are in contact, point and planar contacts are common. The grains are subrounded, moderately well sorted to well sorted quartz and minor feldspar. Unlike for the micas and clays, the quartz and feldspar grains are randomly oriented. The matrix consists of small grains of quartz, feldspar and iron-rich clay (Fig. 4.97d). Calcite cement is common throughout (Fig. 4.97d), some of it forming poikilotopic texture or replacing feldspar.

Quartz is the predominant component (70-75%) (Fig. 4.97c, d), with some grains fractured and strained (showing undulose extinction). Recrystallized quartz is locally present. Microcline, orthoclase, plagioclase and microperthite form 10-15% of the rock. Some feldspars are completely altered to calcite or partially to sericite (Fig. 4.97c). Rock fragments consist of chert-like fragments and silty mudstone (Fig. 4.97c). The removal of labile material has increased the porosity in these sandstones to 5-10%. Muscovite and biotite account for less than 2% of the rock.

The above mineralogy was confirmed by SEM work and rutile was one of the heavy minerals identified. Smectite and illite are the predominant clays, with trace to minor amounts of kaolinite, and traces of mixed-layer clays (I/S). Other clay-size minerals are quartz, plagioclase and hematite.

4.4.3.4 Mudrock lithofacies (M_{m-s})

The mudrock lithofacies is a substantial component (30%) of the Interbedded Sandstone and Mudstone Formation. The predominant lithologies are siltstone and mudstone but intercalated very fine grained sandstone is common.

The lithofacies is exposed at the Road Cut Section in the Nkandabwe area and the Zhimu River Section (Fig.4.96a-e; 4.97e, f) in the Mulungwa area. In the Road Cut Section, mudrock units range from 30 cm to 4 m thick, and up to 16 m in the Zhimu River Section 3. The maximum unit thickness is likely to be more if the entire covered areas are underlain by mudrocks. The mudrock facies is light olive grey (greenish grey) to pinkish red (Figs. 4.97e, f), with abundant mica flakes. The rocks are mainly thinly bedded with maximum bed thickness < 25 cm, and horizontally laminated, massive or contain small-scale cross-laminations (Fig. 4.97f, 4.98a). In the Zhimu River Section, the mudrock beds range from 8 to 12 cm thick and become thicker and cross-laminated towards the top (Fig. 4.97e). The thin beds are predominantly horizontally laminated, with small-scale ripple cross-lamination more developed in the thick beds towards the top of the unit. The laminated mudrocks are equivalent to Fl, and the massive to Fm of Miall (1978). The lithofacies contains thin intercalations of very fine-grained sandstone. The mudrocks are rarely bioturbated.

In thin section, the mudrocks are seen to consist of moderately to well sorted siltstone, mudstone and sandstone (Fig. 4.98b, c). They consist of subangular grains of quartz (mainly) and feldspar in clay-rich matrix (Fig. 4.98c). Micas and clays show preferred orientation parallel to bedding and cross-lamination. Laminae reflect grain size and compositional differences; for example, laminae that are well sorted and quartz-rich alternate with laminae that are clayey (Fig. 4.98b). Dissolution of labile material (feldspars included) has resulted in oversized pores that appear as pitted and leached zones in some samples. Calcite cement is usually present.

Quartz is the predominant grain component (75-80%) followed by feldspar, with rock fragments occurring only rarely. Muscovite is abundant (5-10%), with biotite locally present. Chlorite was rarely observed. SEM work shows that mudrocks contain more quartz grains (70-80%) than feldspar (10%). Epidote, apatite and rutile were identified by SEM. XRD showed kaolinite to be the predominant clay mineral, followed by illite, with mixed-layer clays (I/S) occurring in minor to trace amounts. Smectite is present in trace amounts. Quartz is the only non-clay mineral present in the clay-size fraction.

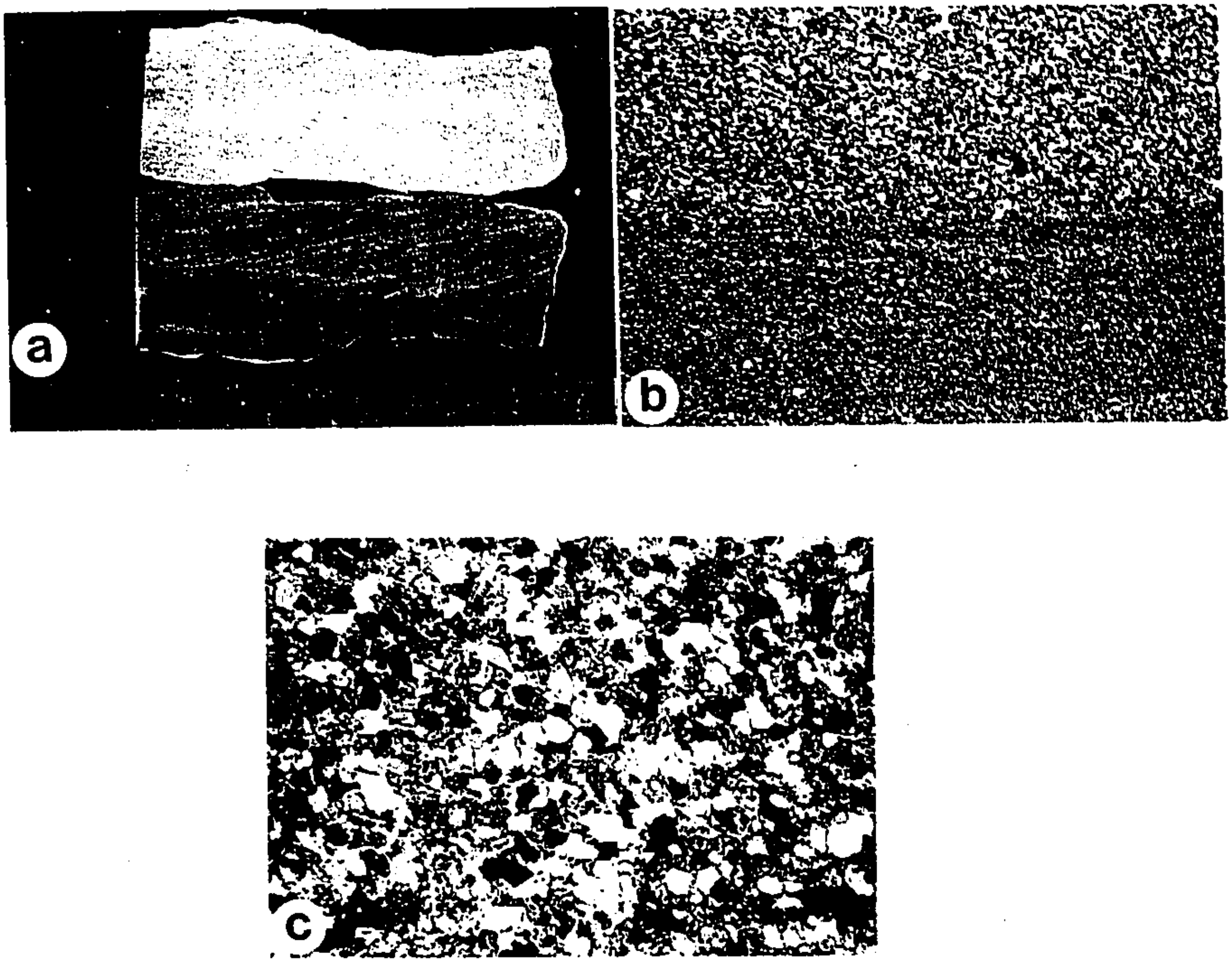


Fig. 4.98 Mudrock lithofacies, Interbedded Sandstone and Mudstone Formation

a: Polished slabs from Fig. 4.97d, showing small-scale cross-lamination in siltstone. Scale in cm.

b: Photomicrograph (crossed nicols) from thin section of (a) showing grain-rich and clay-rich laminae and lamination within the clay-rich portion. Grains are mainly quartz. Long side of photograph is 8.5 mm.

c: Photomicrograph (crossed nicols) showing texture of fine- to medium-grained sandstone lithofacies consisting mainly of quartz, feldspar (twinned, e.g. the fresh microcline grain at top centre, and untwinned) and muscovite in illite (XRD) and calcite cement matrix. Rock fragments are rare. Black areas are heavy minerals and the oversized ones are void spaces. Zhimu River Section 1. Mulungwa map area. Long side of photograph is 5 mm.

4.4.3.5 Lithofacies interpretation

The general characteristics of the Interbedded Sandstone and Mudstone Formation lithofacies and their interpretation are given in Table 4.11. From the characteristics of the lithofacies, the formation is regarded as a transitional, braided river to meandering river deposit. The suite of sedimentary structures in the **coarse-grained to pebbly sandstone lithofacies (S_{c-g})** suggest depositional processes similar to those in the Escarpment Grit Formation. However, this lithofacies appears to consist mainly of channel-fill deposits, given their position in the fining-upward cycles.

The medium- to small-scale trough cross-strata in the **very fine- to medium-grained sandstone lithofacies (S_{vf-m})** probably reflect the development of sinuous-crested in-channel dunes and ripple-forms created during subsequent lower flood stages (Hartley et al. 1992).

Red to maroon and olive grey, massive, small-scale cross-laminated, lenticular to planar siltstone, sandy micaceous mudstone and very fine-grained sandstone beds (**Mudrock lithofacies - M_{m-s}**) occupying the tops of fining upward sequences are interpreted as having formed by small-scale ripples during channel abandonment. The massive to poorly laminated mudrocks are probably local overbank sediments that accumulated between migrating braided channels during floods (cf. Anderson and Picard, 1974).

4.4.3.6 Facies analysis

The lithofacies of the Interbedded Sandstone and Mudstone Formation occur in fining-upward cycles (Figs. 4.99 and 4.100). The mudrocks probably represent channel fill as they are closely associated with the coarse-grained lithofacies, although overbank mudrocks may be abundant (rubble- and vegetation-covered areas). Because of their close association, the lithofacies are grouped into the mudrock-sandstone facies assemblage (Figs. 4.99 and 4.100).

The fining-upward cycles of the **mudrock-sandstone facies assemblage** (Figs. 4.99 and 4.100) can be explained either by channel meandering, as in the classical fining-upward point bar sequence, or temporal changes in flow conditions (cf. Shaw, 1985, p.

Table 4.11 Summary of characteristics and interpretation of Interbedded Sandstone and Mudstone Formation lithofacies

LITHOFACIES	GRAIN SIZE / SORTING	TEXTURE	MINERALOGY AND OTHER COMPONENTS	BEDDING AND SEDIMENTARY STRUCTURES	GEOMETRY / NATURE OF BOUNDING SURFACES / THICKNESS	DEPOSITIONAL ENVIRONMENT
Sandstone (S_{c-g})	coarse sand to pebbles; poorly to moderately well sorted	framework-supported, matrix-supported locally	Detrital grains: quartz (> 80%), feldspar (microcline, plagioclase, orthoclase, perthite and microperthite - 5-15%), rock fragments (mudrocks, quartzite, chert-like fragments <2%), mica (<1%). Heavy minerals: epidote, zircon, sphene, Cement: calcite. Clay minerals: illite	massive (Sm) or crude stratification; trough cross bedding (St); planar cross bedding (Sp); erosional scours and intraclasts (Se)	lenticular to wedge-shaped units in fining-upward sequences up to 16 m thick	fluvial: mainly channel-fill deposits; braided stream transitional to meandering stream
Sandstone (S_{vf-m})	very fine to medium sand; moderately to well sorted	matrix-supported, framework-supported locally	Detrital grains: quartz (70-75%), feldspar (microcline, plagioclase, orthoclase, microperthite - 10-15%), rock fragments (chert-like fragments, silty mudstone), muscovite and biotite (<2%), rutile. Cement: calcite. Clay minerals: smectite, illite, kaolinite, mixed-layer clays (I/S), hematite	massive (Sm); horizontal and small-scale cross-lamination; trough cross bedding (St); horizontal bedding (Sh)	tabular; sharp and erosional contacts; average bed thickness ~ 15-25cm; units up 16m.	fluvial: various bedforms in channels; braided stream transitional to meandering stream
Mudrocks (M_{m-s})	mud, silt, very fine to fine sand; moderately to well sorted		Detrital grains: quartz (75-80%), feldspar (10%), rare rock fragments, muscovite (5-10%) and biotite locally, epidote, apatite, rutile. Cement: calcite. Clay minerals: kaolinite, illite, chlorite, smectite, mixed-layer clays (I/S), hematite	massive (Fm); horizontal lamination (Fl); small-scale ripple cross-lamination (Sr)	tabular sheets, locally lenticular; units up to 16 m thick; bed thickness < 25 cm	alluvial: channel fills during abandonment; overbank fines during floods; braided stream transitional to meandering stream

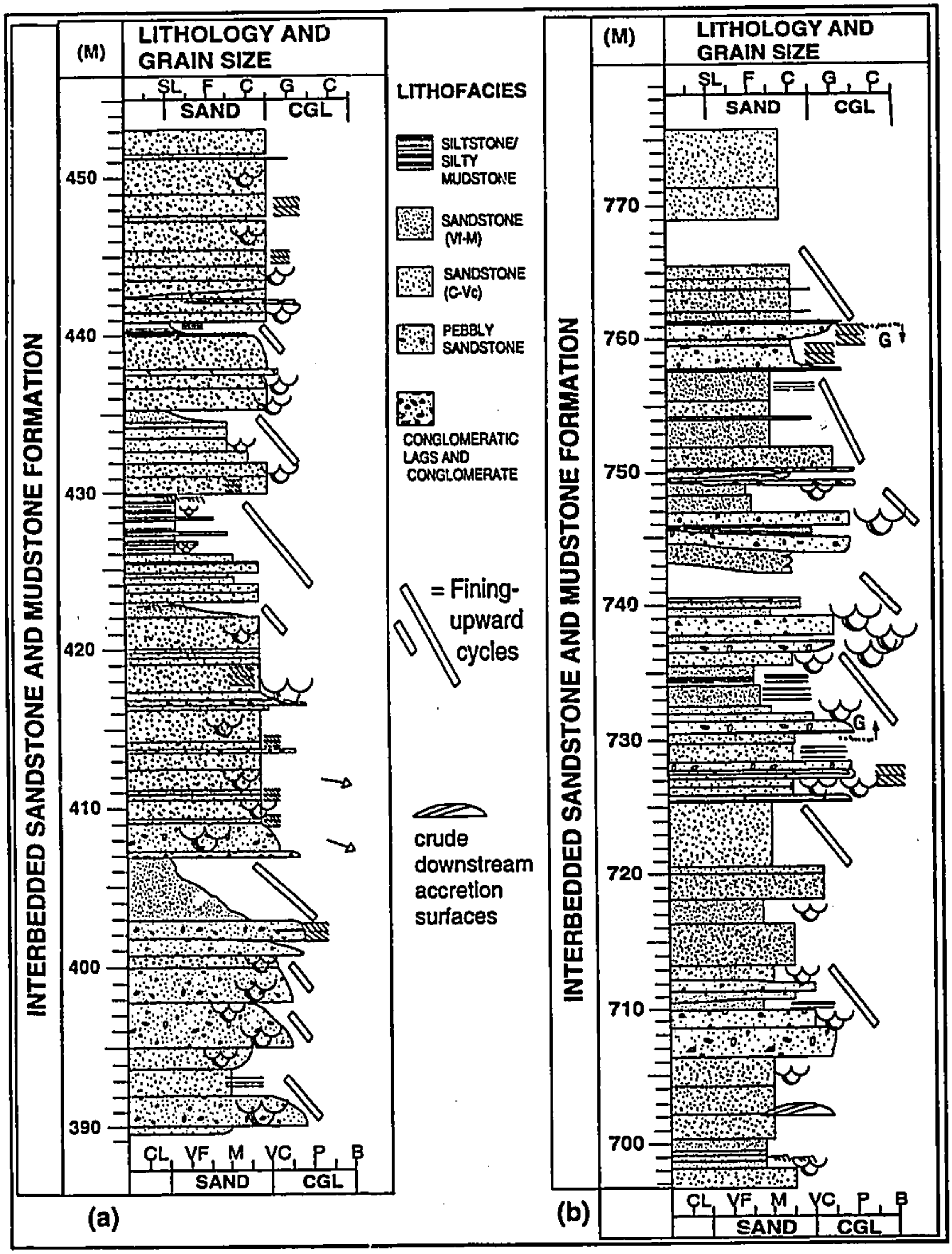


Fig. 4.99 Mudrock/sandstone facies assemblage of the Interbedded Sandstone and Mudstone Formation, containing fining-upward cycles. (a) Road Cut Section, Nkandabwe map area; (b) Zhimu River Section 7, Mulungwa map area, mid-Zambezi Valley Basin, southern Zambia. For key to sedimentary structures and features see Figs. 4.0 and 4.86.

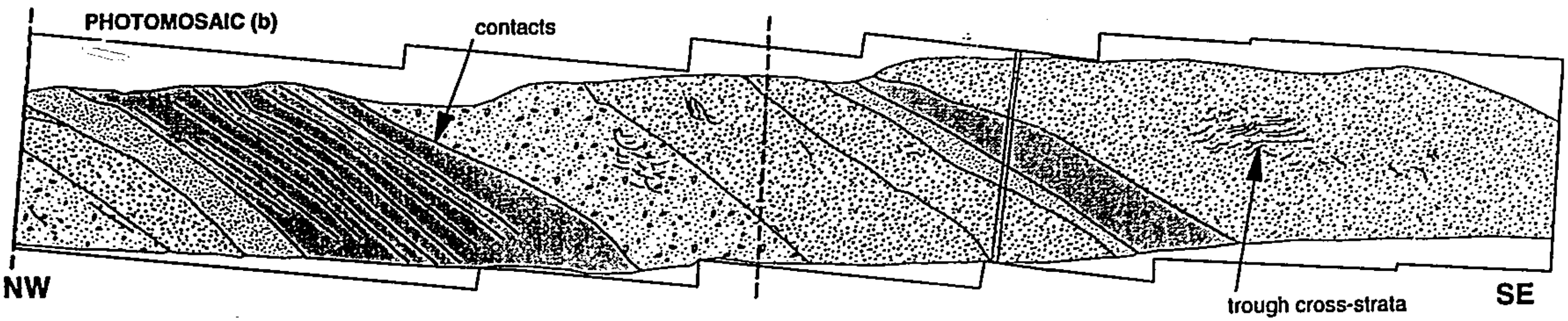


Fig. 4.100 Fining-upward cycles in the Interbedded Sandstone and Mudstone Formation, Road Cut Section, Nkandabwe map area.

a) Stratigraphic profile drawn from photomosaic shows repeated cyclic change in grain size from pebbly sandstone to mudstone. Scale is 5 m.

KEY

SILTSTONE/ SILTY MUDSTONE

SANDSTONE (C-Vc)

SANDSTONE (Vf-M)

PEBBLY SANDSTONE

b) Representative photographs showing one fining-upward cycle and the base of a second. The mudrock /very fine-grained sandstone occupies most of the centre photograph. Scale is 5 m.

62). The cross-laminated facies (Fl) and horizontally-laminated fine-grained sandstone, and siltstone, with minor mudstone, are interpreted primarily as abandoned channel fills (cf. Rust and Jones, 1987), but floodplain overbank fines are also present, probably occupying the present vegetated- and sand-covered flat areas. A profile drawn from a photomosaic (Fig. 4.101) shows variation in sedimentary structures, indicating changes in current strength. The horizontal bedding largely represents upper flow regime plane beds. During waning currents, dunes and ripples formed, producing trough and planar (minor) cross-strata. Orientation measurements (46) taken from ribs and furrows on bedding surfaces on and near the profile indicate flow to the southeast, which suggests sediment input from the northwest.

4.5 PALAEONTOLOGY

4.5.1 GENERAL REMARKS

A total of 59 palynological samples from 9 sections were studied by Dr. J. Utting of the Institute of Sedimentary and Petroleum Geology, Calgary, Canada. These included 32 from the Gwembe Coal Formation, 22 from the Madumabisa Mudstone Formation and 5 from the Interbedded Sandstone and Mudstone Formation. The primary aim of the study was to determine the ages of the formations, environments of deposition, probable palaeoclimates and thermal maturity levels (using thermal alteration index - TAI). Most samples from the Gwembe Coal Formation (Fig. 4.102) contained palynomorphs, but only three from the Madumabisa Mudstone Formation (Fig. 4.103) and one from the Interbedded Sandstone and Mudstone Formation (Fig. 4.104) were productive. Red (greenish grey locally) Sinakumbe Group material was not analysed because of the high level of oxidation.

4.5.2 PALYNOLOGY

Dr. Utting's findings (Palaeontology Subdivision Reports 4-JU-92 and 4-JU-93) integrated with sedimentological evidence are summarised as follows: The Gwembe Coal Formation contains (Fig. 4.102) mainly trilete spores (e.g. *Punctatisporites gretensis*,

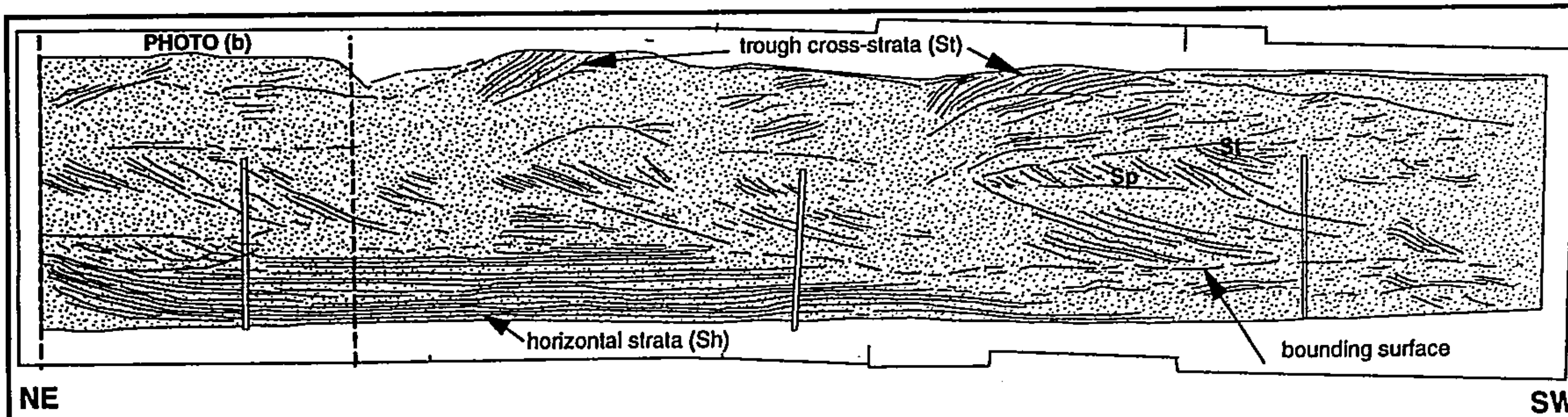
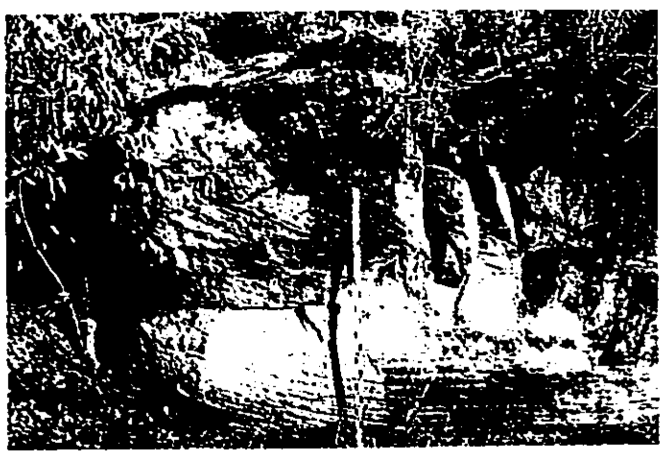


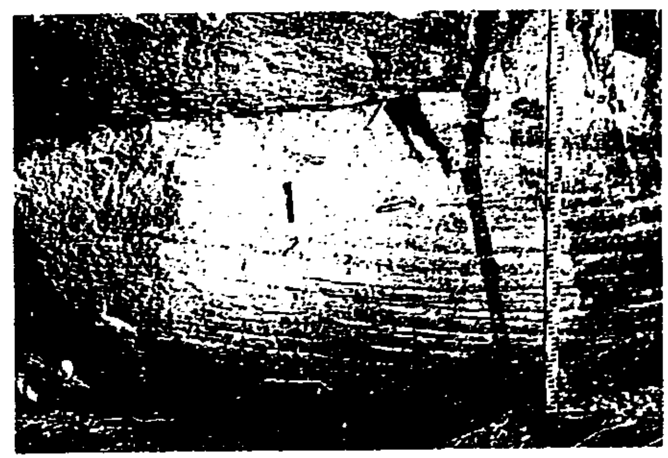
Fig. 4.101 Lateral variation in sedimentary structures in fine- to coarse-grained sandstone of the Interbedded Sandstone and Mudstone Formation.

a) Profile drawn from photomosaic shows locally low-angle to horizontal stratification grades upwards into trough cross-stratification. Exposure is 15 m to the southwest of Road Cut Section, Nkandabwe map area. Scale is 2.1 m. Lateral distance is 22 m.



KEY

SANDSTONE (F-Vc)



b) Representative photograph showing low-angle to horizontally stratified fine- to medium-grained sandstone overlain by trough/ planar cross-stratified coarse- to very coarse-grained sandstone. Scale is 2.1 m

c) Close-up photograph in (b) showing that the low-angle to horizontal stratification grades upwards into trough cross-stratification. Pen is 14 cm.

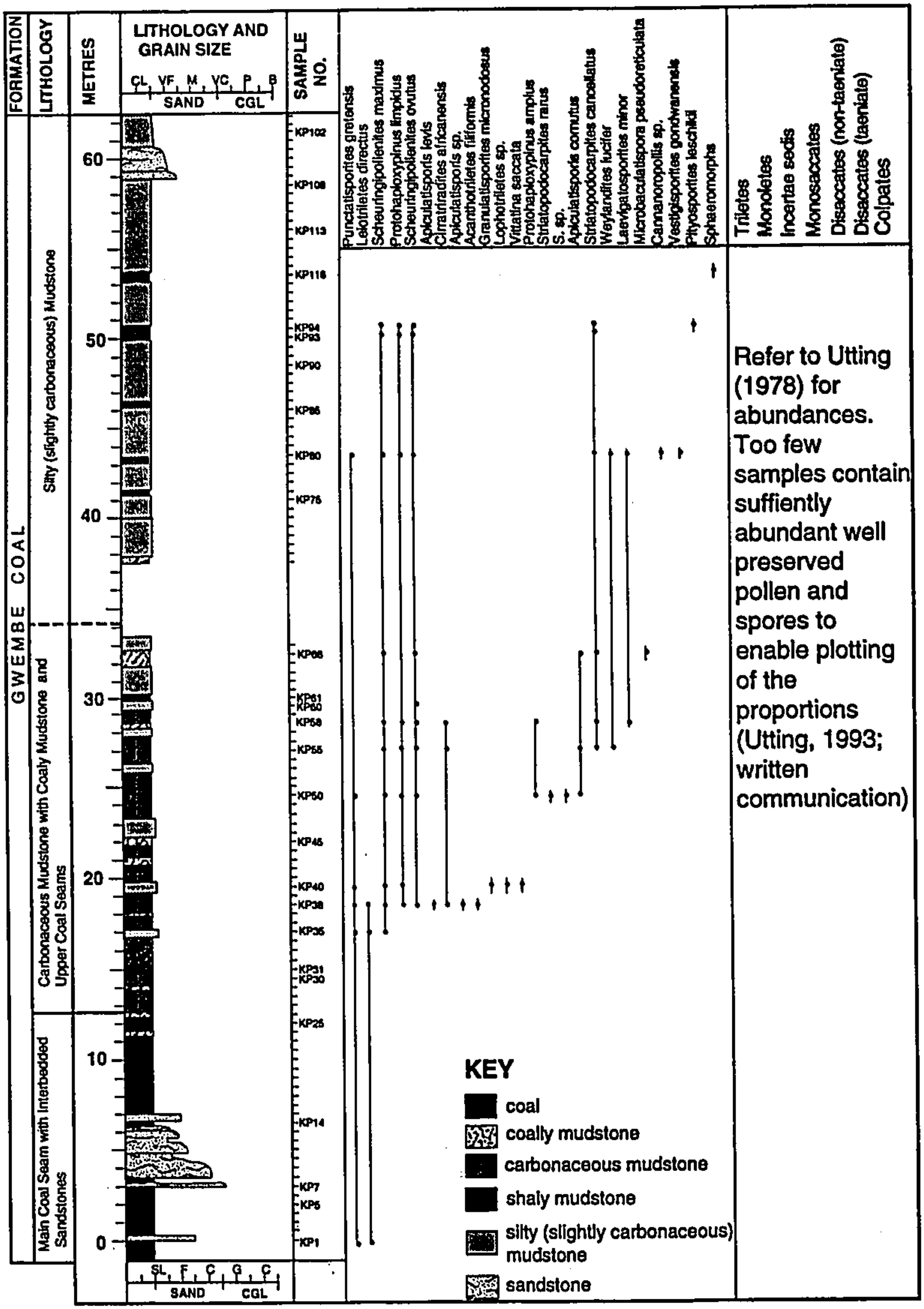


Fig. 4.102 Stratigraphic section and vertical distribution of palynomorphs in Gwembe Coal Formation, Kazinze Open Pit, Maamba Mine, Siankondobo area, mid-Zambezi Valley, southern Zambia.

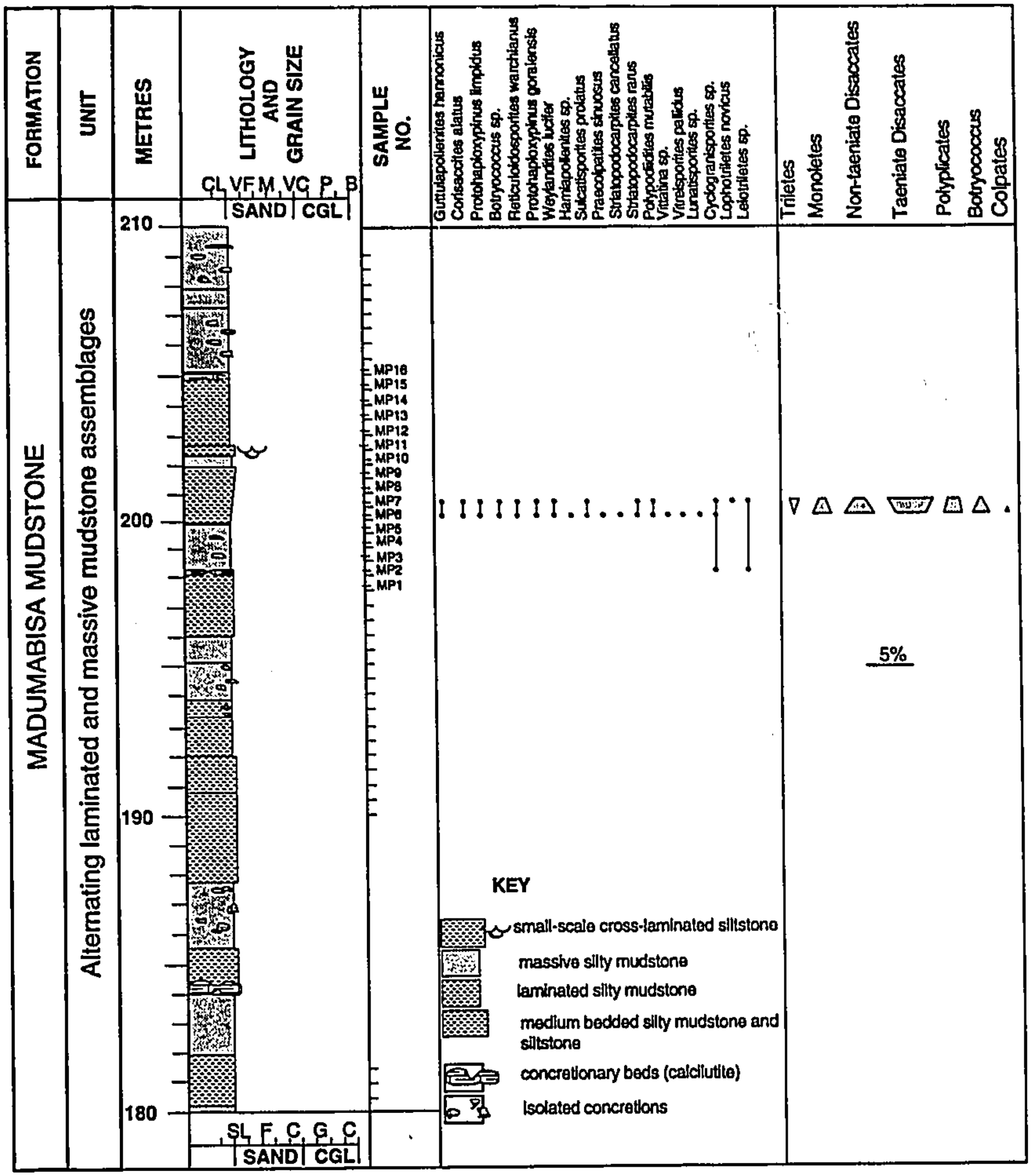


Fig. 4.103 Stratigraphic log of Madumabisa Mudstone Formation showing recovered palynomorphs, Mulungwa River Section 6, Mulungwa area, mid-Zambezi Valley Basin, southern Zambia.

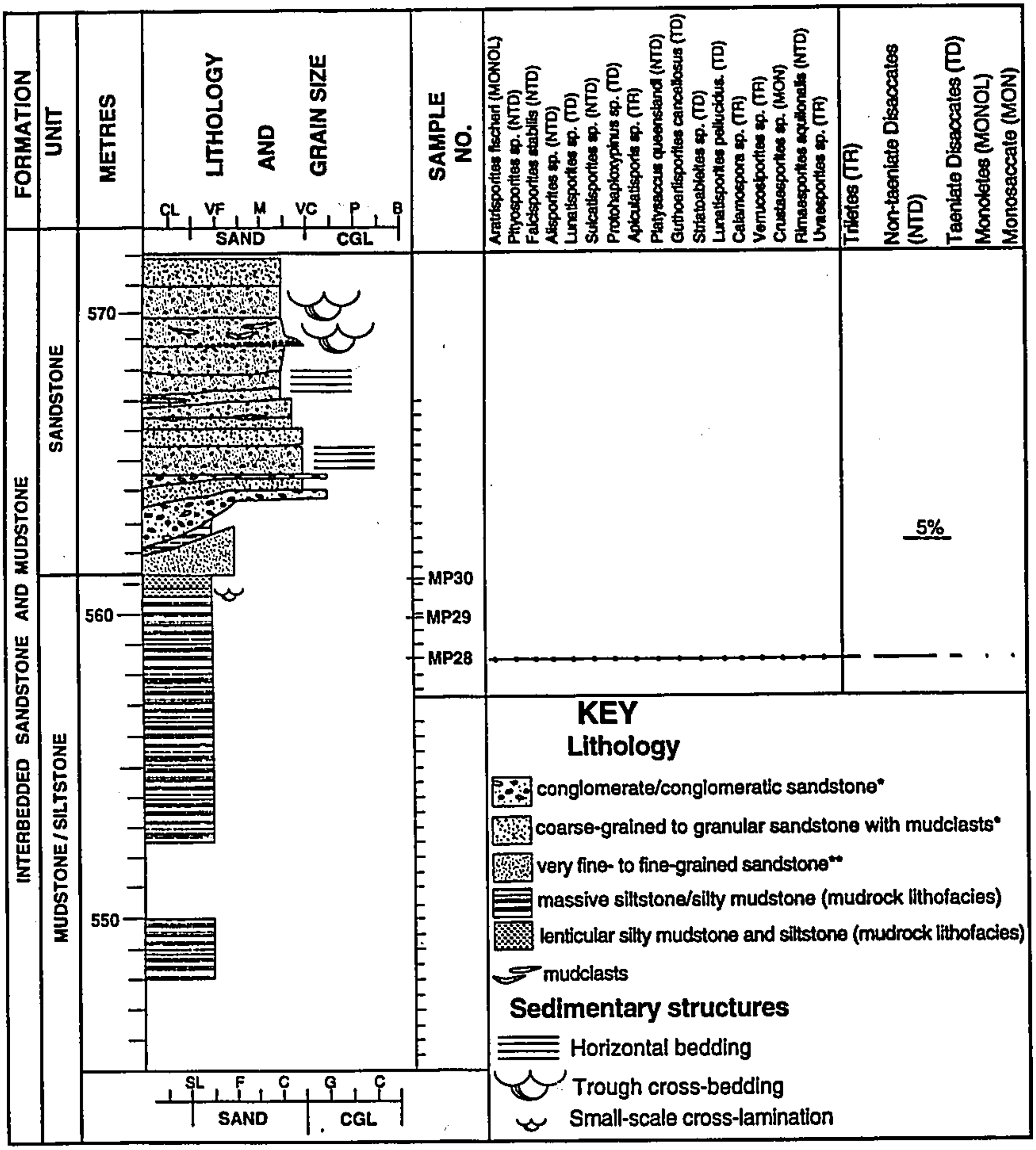


Fig. 4.104 Stratigraphic log of Interbedded Sandstone and Mudstone Formation and recovered palynomorphs, Zhimu River Section 3, Mulungwa map area, mid-Zambezi Valley, Zambia.

*= coarse-grained to pebbly sandstone lithofacies. **= very fine- to medium- grained sandstone lithofacies.

Leiotriletes directus, Cirratriradites africanensis, Apiculatisporis levis and *Acanthotriletes filiformis*), taeniate disaccate pollen (e.g. *Protohaploxypinus limpidus, Striatopodocarpites cancellatus rarus, Protohaploxypinus amplus*), and other taxa such as monolete spores (e.g. *Laevigatosporites minor*), non-taeniate disaccate pollen (e.g. *Pityosporites leschikii*), and monosaccate pollen and polyplicate pollen (e.g. *Vittatina saccata*) (Fig. 4.102). Utting (1978) showed that other forms (not observed in this study) such as colpate pollen (e.g. *Cycadopites cymbatus*) and incertae sedis (e.g. *Pilasporites plurigenus* and *Circulisporites* sp) are present. Preservation of the palynomorphs is fair to poor with corrosion attributed to pyrite crystals growing under anoxic conditions at the sediment/water interface on pollen and spore exines, and to biological degradation. Stratigraphically, the palynomorphs show vertical quantitative changes in relative abundance (especially non-taeniate disaccate pollen and trilete spores). These changes, which were previously noted in the formation (Utting, 1978), were probably in response to environmental changes. The absence of palynomorphs from many samples is attributed to periodic exposure which allowed the organic matter to oxidize. This agrees with sedimentological evidence in that sediments of the Gwembe Coal Formation are commonly mottled, locally bioturbated, and with abundant siderite concretionary beds that have been oxidised to iron oxides (Fig. 4.48). Local rootlet traces are evident. All these features suggest variation in the water table, and periodic exposure.

The productive samples (Gwembe Coal Formation) are assigned to the *Apiculatisporis levis - Vesicaspora potoniei* (LP zone of Utting, 1978) of Ecca age of the Early Permian (within the range of late Asselian to Ufimian). All samples studied were deposited in fluvial or lacustrine environments. A fluvial environment is favoured by sedimentological evidence (see lithofacies interpretation, Gwembe Coal Formation). The samples are dominated by finely dispersed organic debris (10-95%, generally increases upwards), woody and coaly fragments (5-95%, generally decreases upwards) with subordinate exinous material (5-25%, no obvious trend). Resinous material accounts for up to 70% of one sample. The woody and coaly fragments are of terrigenous origin, all transported except for the Main Seam samples, for which an *in situ* origin is favoured.

The thermal alteration index (TAI) of 2 is equivalent to a vitrinite reflectance of approximately 0.5% Ro, indicating a thermal maturity at the 'cool' part of the 'oil window' or 'oil birth line'. The average mean vitrinite reflectance of seven samples (6 from the Main Seam and 1 from the Upper Seam) indicate a value of 1.08% Ro (Price et al., 1992). This value in the oil window defined by the oil birth line (0.5% Ro) and oil death line (1.35% Ro) indicates a strong potential for liquid hydrocarbon from coals of the Gwembe Coal Formation. However, Utting (Report 4-JU-92, 1992) suggests that the relative lack of amorphous kerogen (e.g. *Botryococcus* sp.) indicates a low potential for liquid hydrocarbons, although gas may have been generated.

In the Madumabisa Mudstone Formation, the assemblage recovered (Fig. 4.103) from the three samples represents the first record of palynomorphs from this formation in this part of Zambia. The assemblage is quantitatively characterised by a high percentage of taeniate disaccate pollen (29-56%; e.g. *Guttulapollenites hannonicus*, *Protohaploxypinus limpidus*, *Protohaploxypinus goraiensis* and *Striatopodocarpites*), non-taeniate disaccate pollen (17-24%; e.g. *Sulcatisporites prolatus* and *Vitreisporites pallidus*), monolete spores (8-19%; e.g. *Reticuloidosporites warchianus* and *Polypodiidites mutabilis*), polyplicate pollen remains (9-16%; e.g. *Weylandites lucifer*), algae (2-10%; e.g. *Botryococcus* sp.), a low percentage of trilete spores (1-7%), rare colpate pollen (1%) and sphaeromorphs of unknown affinity (1%).

The age of the assemblage is late Ecca to Early Beaufort (Ufimian? to Kazanian in terms of marine stages of Laurasia - Upper Permian). Because no marine palynomorphs were found, the probable environments are lacustrine and/or fluvial. The predominance of taeniate disaccate pollen and polyplicate pollen suggests that the climate was arid. A lacustrine environment and probably arid conditions is consistent with the sedimentological evidence of very fine-grained mudrock facies, locally abundant fresh water ostracods and bivalves, and pseudomorphs of gypsum, even though the absence of evaporite facies suggests humid or semi-humid conditions.

Most samples of the Madumabisa Mudstone Formation lack palynomorphs and organic material, but productive samples contain substantial amounts of finely dispersed organic debris (40-80%), and woody and coaly fragments (10-60%). Minor amounts of exinous material (0-10%) are present. The thermal alteration index (TAI) of 2, equivalent to vitrinite reflectance of approximately 0.5%Ro, indicates a thermal maturity at the 'oil birth line' or 'cool' part of the 'oil window'. Occurrence of the alga *Botryococcus* sp. and presence of exinous material (5-10%) suggests a potential for liquid hydrocarbon in some restricted intervals of the Madumabisa Mudstone Formation. However, an absence of organic matter in the topmost samples (within 2 m of the contact between the Madumabisa Mudstone and Escarpment Grit formations) supports the sedimentological evidence that the mottling and red coloration prominent in the upper parts of the formation reflect subaerial exposure, during which any organic matter present was oxidized.

One sample from the Interbedded Sandstone and Mudstone Formation of the Upper Karoo Group yielded an assemblage (Fig. 4.104) dominated by non-taeniate disaccate pollen (~70%), with taeniate disaccate pollen (~10%), and trilete spores (~20%). This is the first time that palynomorphs have been recovered from the Upper Karoo in the mid-Zambezi Valley Basin of Zambia. On the basis of *Aratrisporites fischeri*, the assemblage is possibly of Smithian or Spathian or ?Anisian age of the Early to ?Middle Triassic. Most of the samples contained little organic matter, or woody and coaly fragments. In the productive sample, well-preserved pollen and spores are associated with 85% woody and coaly fragments, 10% exinous material and 5% finely dispersed organic debris. A continental environment is suggested by the absence of marine palynomorphs, and the diverse assemblage with common trilete spores, suggests a relatively humid climate in contrast to that of the Madumabisa Mudstone Formation. Sedimentological evidence suggests that these represent braided channel fluvial mudrocks deposited in low-energy environments toward the tops of fining-upward sequences. The abundance of pinkish brown mudrock lithofacies compared to the greyish green mudrock lithofacies suggests aridity rather than humidity. The Thermal Alteration Index (TAI) of 2, equivalent to approximately 0.5%Ro, indicates a thermal maturity at the 'oil birthline' or 'cool' part of the 'oil window'. However, the scarcity of amorphous kerogen and exinous material in most samples suggests a very low potential for liquid hydrocarbons.

In summary, palynomorphs have been recovered for the first time from the Madumabisa Mudstone (Lower Karoo Group) and Interbedded Sandstone and Mudstone (Upper Karoo Group) formations; from the Gwembe Coal Formation (this study; Utting, 1978); and from the Siankondobo Sandstone Formation (Utting, 1978). These identifications enable probable ages to be determined for formations of the Lower and Upper Karoo groups. The arenaceous sediments of the Siankondobo Sandstone Formation are relatively unfossiliferous, although some thin silty mudstone intercalations contain assemblages dominated by monosaccate forms (*Cannanoropollis obscurus* and *Plicatipollenites indicus*) with relatively minor proportions of trilete spores (Utting, 1978). Three concurrent range zones were recognised in the Lower Karoo of the Kazinze area, the *Plicatipollenites indicus-Cannanoropollis obscurus* zone (Zone IO), *Apiculatisporis levis-Vesicaspora potoniei* zone (Zone LP) and *Vittatina africana-Gondispora vrystaatensis* zone (Zone AV). Zone IO occurs in the Siankondobo Sandstone Formation whereas zones LP and AV are exclusive to the Gwembe Coal Formation. Zone LP occurs in the basal parts of formation (includes Maamba Sandstone member, Main Seam and some parts of the carbonaceous mudstone). Even though these zones are present, Utting (1978) indicated that the palynological data do not prove or disprove the existence of an unconformity between the Gwembe Coal and Siankondobo Sandstone formations (cf. Denman et al., 1968). Sedimentological data indicate an abrupt change at the sharp contact between the generally fine-grained non-carbonaceous sandstones of the Siankondobo Sandstone and the coarser-grained richly carbonaceous sandstones of the Gwembe Coal Formation. The only outcrop where an unconformity is suggested is in the Izuma Waterfall Section of the Izuma River where conglomerate (including clasts of Siankondobo Sandstone Formation) of the Gwembe Coal overlies the Siankondobo Sandstone.

The changes in palynological assemblages are attributed partly to increase in temperature that succeeded the Dwyka glaciation. This would have resulted in significant vegetational changes, as reflected in the vertical changes in pollen and spore assemblages from zones IO to AV in the Gwembe Coal Formation, to the assemblages of the Madumabisa Mudstone Formation, to the assemblage of the Interbedded Sandstone and Mudstone Formation. These data suggest that the Siankondobo Sandstone is Late Carboniferous to Early Permian in age (Utting, 1978), the Gwembe Coal Formation is Early Permian, the Madumabisa Mudstone is Late Permian, and the Interbedded Sandstone and Mudstone Formation is Early to ?Middle Triassic.

4.5.3 OTHER PALAEONTOLOGICAL DATA OF THE MID-ZAMBEZI VALLEY

Plant fossils in the Karoo Supergroup were first noted by Livingstone in 1865. Systematic descriptions of fossils were recorded by Molyneux (1903, 1907) from fish, lamellibranchs and plants he discovered in the Lower Karoo of the mid-Zambezi Valley. Fossils recorded by Molyneux (1907) include *Glossopteris* and *Palaeomutela* (from the Gwembe Coal Formation); *Glossopteris indica* and *Gangamopteris* (from coal measures and the Madumabisa Mudstone); pith casts of *Schizoneura*, and *Estheria* (from sandy ironstone); ostracods and silicified wood. Mennell (1929) found silicified wood in the Escarpment Grit Formation. However, the most abundant fossils in the Lower Karoo Group of southern Africa are the fern-like plants of the *Glossopteris* flora which are different from the Carboniferous flora of Europe (Money et al., 1974). A well-preserved specimen of a *Glossopteris* leaf (*Glossopteris damudica* Feistmantel) was obtained at a depth of 23 m from surface in the Gwembe Coal Formation in borehole GS70 of the Siankondobo Coalfield (Utting, 1978), and a well-preserved *Glossopteris indica* below the waterfall on the Izuma River (Money et al., 1974). Fossils obtained from the Madumabisa Mudstone by Gair (1959) and Tavener-Smith (1958, 1960) were identified by Bond and include the lamellibranchs *Palaeomutela neglecta* (Jones), *Palaeomutela rectodonta* Amalitaky, *Palaeonodonta parallela* Amalitaky, *Palaeomutela rhomboidalis* (Sharpe), *Palaeonodonta castor* (Eichwald), *Palaeonodonta* sp., *Kidodia coxi* Bond, *Darwinula* sp., fish scales, *Phyllotheca* sp., and *Glossopteris indica* Schimper.

Gair (1959) suggested that bones from the middle Madumabisa Mudstone Formation are dinocephalian and typical of the *Tapinocephalus* zone, and possibly *Tapinocephalus* itself, whereas the fossil wood (from the Escarpment Grit Formation) includes *Dadoxylon* sp. and *Rhexoxy africanum* (Bancr.). Lacey (1961) summarizes the known plant fossils of the Karoo flora from the mid-Zambezi Valley, including *Glossopteris* sp. and ? *Gangamopteris* sp. Fossil burrows were observed in boreholes GS51 and GS98 in the Siankondobo Sandstone Formation (Money et al., 1968).

In this study abundant ostracods, bivalves, fish remains (scales, bones and teeth), gastropods and fossil burrows (trace fossils; see section 4.3.3.3) have been observed in the Madumabisa Mudstone Formation, and possibly fossil wood in the Escarpment Grit Formation.

CHAPTER V

SEDIMENTOLOGIC AND STRATIGRAPHIC SYNTHESIS: INTERPRETATION OF DEPOSITIONAL SYSTEMS

5.1 GENERAL REMARKS

The concept of the **facies model** has been a most powerful and successful tool for classifying and explaining ancient sediments (Miall, 1985). The concept was first discussed at a conference in 1958 (Potter, 1959) and the first facies models were those of Allen (1963b) and Bernard et al. (1962) for fluvial point bars and of Bouma (1962) for sandy turbidites. A model is a general summary of the characteristics of a particular depositional system, substantiated by many individual examples from recent sediments and ancient rocks (Walker, 1992). It attempts to provide an interpretation of a particular type of facies assemblage in terms of depositional environments (Miall, 1984). Facies models are expressed in several different ways - as idealised sequences of facies (vertical profile logs), as block diagrams, as palaeogeographic sketch maps, or as combinations of all three, and as graphs and equations (Miall, 1984; Walker, 1984). Walker (1984) stated that a facies model should fulfil four functions: (a) it must act as a norm, for purposes of comparison, (b) it must act as a framework and guide for future observations, (c) it must act as a predictor in new geological situations, and (d) it must act as a basis for environmental interpretation.

Descriptions of modern continental environments have led to proposals for at least a dozen models for fluvial deposits alone (Miall, 1980). Fluvial facies models encompass entire depositional environments. Implicit in all fluvial models is the intuitive assumption that each channel pattern (meandering, braided, anastomosing and straight) must yield distinctive lithofacies as a result of distinctive depositional processes (Jackson, 1978). Other models are based largely on surface geomorphological observations (e.g. deltas, alluvial fans); on particularly distinctive suites of sedimentary structures (e.g. turbidite model of Bouma, 1962) or organic processes (e.g. reefs) (Miall, 1985). Many are governed by climatic and tectonic variables, and many are based primarily on the study of modern environments. The facies models characterize the depositional systems (Walker, 1992).

A **depositional system** is a "three dimensional assemblage of lithofacies, genetically linked by active or inferred processes and environments" (Posamentier et al., 1988); it embraces depositional environments and processes acting therein through a particular geological time (Walker, 1992). It consists of environments and their sedimentary products, bounded by unconformities or by facies transitions into adjacent, genetically unrelated systems. The depositional system concept was developed by the Texas Bureau of Economic Geology and is an extension of Walther's Law, which states that in a conformable succession the only facies that can occur together in vertical succession are those which can occur side by side in nature (Middleton, 1973). Use of the concept enables predictions to be made about the stratigraphy of large masses of sediment because it permits interpretations of the rocks in terms of broad environmental and palaeogeographic reconstructions (Miall, 1984).

In the mid-Zambezi Valley, Southern Province, the Sinakumbe Group and the Karoo Supergroup consist of formations (Fig. 4.0) that are packages of sediment, each deposited over a range of depositional environments. These lithostratigraphic units are considered to represent depositional systems. Variations in the primary compositional, textural and structural characteristics of the units (Figs. 4.0, 4.1, 4.19, 4.33, 4.67 and 4.86), indicate differences in depositional environments. In this chapter, the facies assemblages described in the previous chapter are integrated in interpretations of each of the depositional systems as a whole, i.e. of the succession of environments that prevailed in different parts of the depositional basins during Sinakumbe and Karoo deposition. The ultimate aim is to establish a depositional framework for the formations of the Sinakumbe, and Lower and Upper Karoo groups that will aid in future studies. The depositional models should satisfy the above four functions.

5.2 RELEVANT FACIES MODELS

5.2.1 GENERAL REMARKS

No depositional systems in this study show any of the characteristics of the scree-cone, scree-apron, fan-delta and river delta models (McPherson et al., 1987, 1988; Nemec and Steel, 1988; Orton, 1988; Nilsen, 1989) and therefore these will not be considered further in this study. However, other alluvial systems are briefly reviewed below because they are relevant (see Chapter 4) to the elucidation of the Sinakumbe Group and Karoo Supergroup. In addition, the latter contains facies attributable to glacial and lacustrine depositional systems. Careful analysis of the literature, supported by observations made in this study, have served in assigning depositional environments to the subgroups of the Sinakumbe Group and formations of the Karoo Supergroup.

The term alluvial embraces all detrital deposits resulting from the operations of modern rivers, including sediments laid down in river-beds, flood-plains, fans at the foot of mountain slopes, estuaries and to some extent in lakes (Bates and Jackson, 1980). On the basis of facies, geomorphological and geological setting, the alluvial deposits can be subdivided into alluvial fan and fluvial deposit types. The latter can further be divided, on the basis of morphology of the depositing channel system, into braided, meandering, anastomosing and straight river systems (Rust, 1978b).

5.2.2 ALLUVIAL FAN

An alluvial fan is a deposit formed by subaerial flows spreading out and depositing their sediment load downslope of a confined valley or canyon due to a sharp decrease in transport efficiency as the stream emerges from its confined valley onto a plain or major trunk valley (Blatt et al., 1980). This results in a semi-conical landform (segment of a cone) with slopes and transport directions radiating from the mouth of the source valley (Blatt et al., 1980; Fig.6) generally adjacent a steep mountain front or glacier front. These occur mostly above unconformities in humid, semi-arid and arid climates (e.g. southwestern USA), but are also known in modern glacial climates (glacial outwash fans, e.g. Boothroyd and Ashley, 1975) and in humid tropical areas (e.g. Himalayan mountain front). The alluvial fan sizes vary according to the geological setting, with semi-arid fans varying from 1 to 100 sq km (30 km across) and Himalayan fans up to 150 km across.

The main depositional processes on alluvial fans are vertical accretion and lateral accretion. Sediment deposited near the apex of alluvial fans is typically coarse, poorly sorted debris flow deposits or coarse, poorly stratified fluvial gravels that show rapid downslope facies changes. Most fans are dominated by water-laid deposits, predominantly facies Gm (horizontally stratified gravel, commonly imbricate with pebbles dipping upfan) in proximal reaches (Rust and Koster, 1984; Fig. 3, Nilsen, 1968). There is an increase in the abundance of cross-stratal sets, chiefly planar, with transitions from coarse gravel through clast-supported fine-grained gravel, sand matrix-supported gravel to sand (Gm to Gp to Sp). Minor deposits of horizontally laminated or massive mud (Fl, Fm) also increase in abundance downfan (Rust and Koster, 1984; Fig. 3). Stream floods and flows, sandy interbeds with planar stratification, planar and trough cross-stratification (formed by transverse bars, sand waves, and dunes) become more common away from the apex. Alluvial deposits record unidirectional palaeocurrents, which provide an indication of the orientation of ancient coastlines.

Sedimentation is strongly influenced by two factors: the semi-arid climate and the active tectonic setting. For example, red coloration and evaporitic palaeosols (facies P, table 10) in ancient alluvial fan deposits commonly point to a semi-arid palaeoclimate (Williams, 1973). Tectonic influence can be recognized in the form of repetitive cycles of grain size and bed thickness variation within alluvial fan successions.

Ancient fan successions can be thick (5000 m or more), indicating formation in a tectonically-influenced setting where they are frequently preserved because of continuing subsidence of the basin and uplift of adjacent highlands along the boundary faults. The fans contain coarsening-upward sequences about 100 m thick, with coarsening-upward subcycles in the 10 to 25 m range, all attributed to allocyclic (tectonic) causes; internal autocyclic sequences that result from major floods, or from the switching of deposition from one fan lobe to another, are also present.

In summary, most alluvial fans show the following diagnostic features:-

1. Alluvial fans are oxidised deposits that rarely contain well-preserved organic

material.

2. Alluvial fans commonly consist of thick sequences of water-laid sediments deposited by braided distributary streams; of mudflow and coarse-grained, debris-flow deposits; or of both water-laid and debris-flow deposits.
3. The bulk of the deposits consist of sheets that have length/width ratios of roughly 1 to 4. Channel-fill deposits comprise a minor proportion of most fans.
4. Cut-and-fill structures are common near the fan apexes, but are rare near the toes of most fans.
5. Compared to other depositional environments, the hydraulics of transport and deposition are greatly different for the individual beds within a sequence of fan deposits. The result is a sequence of beds that varies greatly in particle size, sorting, and thickness.
6. The relationship between maximum particle size (MPS, mean of 10 largest clasts) and bed thickness (BTh) for both water-laid and debris flow conglomerates show a correlation, and both decrease downslope (Nemec and Steel, 1984). Ancient debris flows commonly show a lack of internal stratification and imbrication, and a sheet-like form, in contrast with the common channel forms of water-laid deposits (Wells, 1984).
7. Alluvial fans commonly show transgressive or intertonguing relations with the deposits of other depositional environments, such as flood plains and lakes.

5.2.3 LOW SINUOSITY BRAIDED RIVER

Braided streams consist of multiple (two or more) broad, shallow, low-sinuosity braid channels with many braid bars and dry islands, and generally carry a coarser sand- to gravel-sized bedload than do meandering and other river types (Miall, 1977). Braiding, caused by sorting as the stream leaves behind load sizes it is unable to carry, is controlled by : (a) geometry and slope of channels (steeper slopes relative to meandering streams), (b) strength and variability of flow discharge, (c) amount and coarseness of bedload, and (d) lack of stabilising vegetation (in post-Silurian sediments this likely indicates an arid climate, (Schumm, 1968).

The five main processes by which the principal depositional facies of braided streams can be interpreted are: (a) bar formation, (b) bedform generation and migration (bars, dunes, megaripples, etc.), (c) growth and deposition in channels (channel scour and fill), (d) low-water accretion and modification processes (falling water stage), and (e) sedimentation in overbank areas during flooding (Miall, 1977; Rust and Koster, 1984).

The most abundant facies is horizontally bedded, imbricate gravel, which may appear massive where bedding is thick and texture uniform. Gravel facies Gp is rare in braided-stream environments; where present it is generated by the migration of linguoid bars during flood stage. Other facies that are uncommon include sand facies that show planar and cross-stratified sand (facies Sp) and horizontally stratified sand (facies Sh). Horizontal bedding or lamination (facies Sh) can occur under two quite different conditions: in shallow water and during flood stage. Mud facies are rarely present, and all increase in abundance very gradually downstream (Miall, 1977). The internal structures are correspondingly complex, and may include planar-tabular cross-bedding of linguoid bar origin, trough cross-bedding of dune or scour origin, ripple marks of various types, coarse-grained lag deposits formed in chutes, and fine-grained drape-and-fill deposits formed in swales.

The record of ancient braided-stream deposits shows that channel deposits rest on scour surfaces and commonly contain a basal gravel lag (Miall, 1970; Smith, N. D., 1970; Cant and Walker, 1976). Stratification and grain size changes are a response to major floods rather than tectonic events.

The facies criteria that are diagnostic for very proximal braided streams are the exceedingly coarse gravel and the low palaeocurrent variance of imbrication of large pebbles and cobbles (Rust, 1975). Other features usually deemed diagnostic of low-sinuosity undivided or braided streams but which may typify many meandering streams include: (a) negligible mud, (b) rapid lateral facies changes over short distances, (c) vertical sequences that do not denote an upward decrease in flow regime, (d) predominance of gravel (sometimes quite coarse), (e) scarcity of cross-stratification (except in some sandy system), (f) absence of natural levees and (g) sheetlike geometry of channel facies. Unfortunately, interpretations cannot provide conclusive identification of a braided-stream deposit in the ancient record, because many of the facies occur in other environments. Another difficulty shown by Coleman and Wright (1975, Table 1) is that, on a world-wide basis, braided rivers are as common as meandering rivers in arctic, temperate, dry tropical and humid tropical regions (Miall, 1977) and therefore cannot be restricted to one climatic region.

The braided environment is locally rather unstable through time due to continuous active bar migration and avulsion, and the resulting deposits are less well organised than in meandering systems (Collinson, 1986).

5.2.4 HIGH SINUOSITY MEANDERING RIVER

Meandering rivers form deposits primarily by the action of lateral accretion on point bars within the concave side of meanders, coupled with a lesser amount of vertical accretion on flood plains, resulting from overbank flooding, (Miall, 1977). The rivers are of high sinuosity (sinuosity being the ratio of channel length to length of meander-belt axis) and their deposits typically form fining-upward cycles (Miall, 1977). The classic fining-upward profile is produced by lateral accretion of the point bar. Flow across the point bar tends to sort the sediment, which becomes finer on the shallower parts of the bar farthest from highest flow energy. The lateral accretion surfaces are preserved within the deposit in the form of large- scale, low angle cross-bedding, termed epsilon cross-stratification (Allen, 1963a). Crevasse splay deposits, which may locally show coarsening-upward trends, develop when flood discharge breaks through the levee and spreads across the dominantly fine-grained floodplain sediments.

The fining-upward point bar model developed more or less simultaneously by Allen (1963b) and by Bernard et al. (1962) and Bernard and Major (1963), later detailed by Allen (Allen, 1964, 1965a, b, and 1970), has been refined by recent workers (Jackson, 1976, 1978, 1981; Collinson and Thompson, 1982; Galloway and Hobday, 1983; Walker and Cant, 1984) as some of the features (e.g. epsilon cross-stratification-ECS) also occur in other river types. In modern meandering rivers, the sediments are deposited in natural levees, backswamp, clay plugs and point bars. The proportion of fine-grained members (largely deposits of natural levees, backswamps, and clay plugs) to coarse-grained members (point-bar deposits) in the meandering phase sediments and their total thickness greatly vary (Jackson, 1978). Based on observations in modern rivers, Jackson (1978) proposed five models: (i) muddy fine-grained rivers, which show a low width/depth ratio, steep bar slopes, often exceeding 20°, and prominent levees, (ii) sandy rivers with thin fine members where scroll bars, chutes, and levees are common, (iii) sandy rivers without mud or gravel with channels having a higher width/depth ratio than the muddy type and lacking levees, (iv) gravelly sand-bed rivers, where gravel is common in the deeper parts of the channel and in the lower part of the point bar deposit; point bar surfaces may be covered by abundant sandy bedforms and dunes (on the lower point bar) and transverse bars (middle point bar), and (v) gravel-dominated rivers on steep slopes in or near mountainous regions that show irregular bed topography with longitudinal bars, and a complex point bar development lacking epsilon cross bedding as the most characteristic feature (Leopold and Wolman, 1957; Jackson, 1978). Variations between the models relate mainly to differences in sediment calibre. Smith, D. G. (1987) proposed three lithofacies models for different meandering river conditions intended for expansion of the facies model concept in meandering channels, which, if applied to the interpretation of a longitudinal trend of ECS in an ancient rock unit, can be used to predict both upchannel and downchannel facies trends.

Planar cross-bedded sand (Facies Sp) generally constitutes only a minor part of the meandering river model (Cant and Walker, 1976 p. 116) but may be tens of metres thick in most braided rivers (Smith N. D., 1970). The facies criteria, which are strongly indicative of meandering include the occurrence of a substantial mud content in the coarse member, a thick fine member, and the presence of asymmetric channel-fills with much mud. Exhumed meander belts with many intersecting sets of highly curved accretionary topography also point to a meandering-stream origin (Jackson, 1978).

Ancient deposits (e.g. Allen, 1970) consist of many alluvial sequences, or cycles, stacked one upon the other. These cycles are mainly related to periodic flooding (see section 5.4.7). The red pigmentation so characteristic of many continental deposits may occur preferentially in the meandering-river deposits, whereas most braided deposits are drab. Associated coal may occur in humid environments (Visher, 1972), and pedogenic carbonate concretions develop by leaching in semi-arid environments.

5.2.5 HIGH SINUOSITY ANASTOMOSING RIVER

The term 'anastomosing' was proposed by Schumm (1968, p. 1580) to be restricted to rivers with relatively permanent and stable systems of high-sinuosity channels with cohesive banks, separated by large, stable, vegetation-covered islands such as those common in southern Australia, and the Saskatchewan River in Canada. Most anastomosing rivers occur in humid and arid environments. In the former, wetlands, peat bogs and flood plain ponds are common (Miall, 1981a). According to Smith and Smith (1980), an anastomosing river forms an interconnected network of low-gradient, relatively deep and narrow, straight to sinuous channels with stable banks composed of fine-grained sediment (silt/clay) and vegetation. Gravelly bedload dominates the channel fill, in contrast to that proposed by Schumm (1968), and the channels are separated by flood plains consisting of vegetated islands, natural levees, and wetlands.

Anastomosing rivers accrete vertically; lateral channel migration and point bar accretion is not characteristic. The most distinctive features of the resulting deposits are the near-vertical facies contacts. Smith and Smith (1980) recognized six sediment facies: (i) peat bog facies - peat layers comprising up to 98% vegetal matter and ranging from a few cm to 1.5 m in thickness, (ii) back swamp facies - silty mud and muddy silt containing various amounts of organic debris, (iii) floodpond facies - laminated clay and silty clay with sparse vegetal matter, (iv) levee facies - sandy silt and silty sand containing 10 to 22% roots by volume; this facies grades laterally into peat bog, backswamp, and floodpond facies; together they compose the bulk of the overbank sediments, (v) crevasse splay facies - thin layers of sand and/or fine gravel, and (vi) channel facies - gravel and coarse sand deposits.

5.2.6 STRAIGHT CHANNEL RIVER

Rivers with straight channels are commonly mixed- or suspension-load streams which occur on relatively gentle slopes (Schumm, 1968, p. 1579). Their sinuosity may be nearly equal to 1.0, but the thalweg, or line of maximum depth, meanders back and forth within the channel, and low mud or silt bars are deposited along the channel edges on the insides of the meanders (Leopold and Wolman, 1957, p. 53). Modern straight rivers are rare, and little is known about their deposits. In straight channels, Allen (1970, p. 313) argued that deposition is by downstream migration of alternate bars within a gently meandering thalweg.

5.2.7 GLACIAL

Physical processes of the glacial environment, as reviewed by Ashley et al. (1985) and Eyles and Eyles (1992) include both ice and water in erosion, transportation, and deposition. The glacioterrestrial depositional environments are grouped into four depositional systems, subglacial, supraglacial, glaciolacustrine and glaciofluvial (Eyles and Eyles, 1992).

Components of the glacial record vary from unsorted boulder-rich till to well-sorted glaciolacustrine silts and clays that occur in an almost infinite variety of lateral and vertical combinations. These sediments are commonly preserved in topographic lows where they are likely to escape erosion. Glacier flow is by two main mechanisms, internal deformation and basal sliding (regelation and enhanced plastic flow). Subglacial erosional processes fall into three main categories: abrasion, plucking, and large-scale block entrainment. Clast-to-clast contacts and clast-to-bed contacts are common, with highly efficient abrasion that results in large quantities of fine-grained "rock flour" (Shaw, 1985). Most glacial debris is carried in the basal zone and is released during seasonal and diurnal subglacial melting, creating large episodic or periodic discharges containing high concentrations of sediment (Ashley, 1985), to be deposited in various environments. For example, tills are diamicton units that accumulate subglacially, commonly in standing water, whereas predominantly coarser debris accumulates in broad alluvial plains (Smith, 1985).

Three mechanisms of **subglacial** deposition are: (i) rain-out of material released from floating ice, (ii) deposition from suspension of sediment brought into the lake by subglacial drainage and (iii) deposition by underflows. Frequent resedimentation by mass flow due to instability of lake beds caused by high sedimentation rates and relatively fine-grained matrix is common. Examples include geomorphological and sedimentological evidence of extensive sheets of meltwater flow beneath Pleistocene ice sheets (Shaw, 1985).

Glaciofluvial sediments are deposited by glacial meltwater rivers on broad outwash plains (sandar) which lie beyond the immediate ice terminus, and are typified by multiple channels (typically braided). Deposition is commonly dominated by large floods, and during early postglacial conditions, swamps may become established in close proximity to water bodies (Eyles and Eyles, 1992), where thick peat accumulations may ultimately generate coals (e.g. Permo-Carboniferous coal-bearing glaciated basins of the southern continents - Martini and Glooschenko, 1985). Subaqueous outwash fans are ice-marginal fan deposits that accumulated underwater, and show a sequence that commonly consists of gravel that passes upward and distally into horizontally bedded (adjacent to gravel facies), planar and trough-cross-bedded sand (occasionally associated with cross-laminated sets) and then a climbing-ripple-dominated upper part (Rust and Romanelli, 1975; Shaw, 1975; Rust, 1977; Cheel and Rust, 1982; Postma et al., 1983). Massive sand with associated ball-and-pillow and dish structures also occurs in the zone of ripples. Channels containing massive or diffusely laminated sand are also present. Identification of glacial environments is complicated because braided river deposits occur in many depositional settings (Eyles and Eyles, 1992).

Glaciolacustrine ponding and basin development result from overdeepening by glacial erosion, glacial disruption of former drainage systems, and the release of large volumes of meltwater (Eyles and Eyles, 1992). Basins range from narrow to large continental lakes (e.g. Lake Agassiz ~ 1,000,000 km^2 - Teller and Clayton, 1983). Modern and ancient glaciolacustrine deposits are highly variable in grain size, mineralogy, bedding thickness and sedimentary structures. Sedimentation is characteristically cyclical, but varies in detail due to temporal variations in sediment influx and dispersal.

The mode of sediment dispersal is controlled by the nature of lake-water density stratification, lake bottom stratigraphy, and the dispersal mechanisms of overflow-interflow, underflow and equal-density mixing (homopycnal mixing), singularly or in combination, and ultimately dictates the nature of the glaciolacustrine deposits. Large currents or unsteady episodic flow events (not more than few minutes) triggered by slumps and debris flows in unstable deltaic or lake margin sediments, create waning flow deposits similar to the "Bouma-model" turbidite (Bouma, 1962). Rhythmic deposition (varves) is the signature of ice-contact and distal glacier-fed glacio-lacustrine environments. Varves (non-ice-contact lakes) are normally considered to be units of sedimentation deposited during a one-year period, strongly driven by seasonal regime between summer supraglacial melting across the ice margin and the rest of the year.

Ice-contact lakes are characterised by variable marginal processes (underflows) and deposits (stacked successions of blanket-like diamicts and variably bedded sands - Eyles and Eyles, 1983), and hence distinguished from distal (non-ice-contact) glacier-fed lakes by rapid lateral and vertical facies changes. Proximal deposits consist of a mixture of water-sorted diamictites (up to boulder size) with syndepositional primary structures and postdepositional collapse structures, interbedded with remobilised till and dropstone-dominated finer-grained sediments (Rust and Romanelli, 1975; Lawson, 1982; Boothroyd, 1984). Diamicts are overlain by channelled units of laminated silty clays that are in turn overlain by a coarsening-upwards succession of ripple-laminated, planar and trough cross-bedded sands which record delta progradation over the sites of diamict accumulation. The most common deltaic facies is a crudely bedded silty sand with abundant liquefaction structures indicating rapid subaqueous deposition. Examples of ice-contact lakes are the extensive Pleistocene glaciolacustrine deposits exposed around the modern Great Lakes of North America (Eyles and Eyles, 1992).

Distal lake deposits are finer (due to distance), consistent and laterally persistent; most are associated with Gilbertian deltas, and fine and thin away from the delta. The deposits are characterised by rhythmites composed of spatially variable coarse layers and more uniform fine layers. Sedimentation is by both overflows-interflows (dispersal of fine silt and clay above the bottom) and underflows (sand, silt and clay moved along the bottom by quasi-continuous or slump-generated flows). Bottom deposits thin and fine from proximal to distal portions of the basin (one source) or more complex deposits (multi-source) with a change in grain size, sedimentary structures and bedding thickness away from the stream mouth.

Overall, a gradational basinward change is observed from a complex unit on the mid-delta foreset (climbing ripple-drift sequences) to lower delta foresets (rippled and multi- laminated beds) to lake bottom (parallel multilaminated beds). A normal deglaciation (ice receding) gives a fining-upward trend in lake sediments that may be reversed with a glacial re-advance.

5.2.8 LACUSTRINE

Lakes are low-energy environments compared to rivers (Fig. 5.0). Hydrological conditions within a lake affect the nature and arrangement of facies; open lakes contain generally fluvially derived sediments, and chemical sediments are restricted to the centre of the lake (Eugster and Kelts, 1983; Allen and Collinson, 1986); closed lakes have a complex mixture of fluvial-derived sediment, reworked intrabasinal sediment, and chemical and biochemical deposits (Eugster and Kelts, 1983). Lakes may be perennially stratified (Fig. 5.0) with permanently stagnant bottom waters (meromictic), overturn infrequently (oligomictic), overturn once yearly (monomictic) or twice yearly (dimictic) (Gore, 1988). The upper water mass (epilimnion) is saturated or supersaturated with oxygen derived from the atmosphere or from photosynthesis, but in the lower water mass (hypolimnion), oxygen may be completely eliminated. The loss of oxygen in the deep water below wave base as the result of respiration and decay, leads to preservation of large quantities of organic matter in the sediments (Allen and Collinson, 1986).

The major factor influencing clastic sedimentation is energy input (i.e. inflowing rivers) (Fig. 5.0) which is largely related to the size of the lake and its state of geomorphic development and climate. Relief within the lake will give rise to turbidity currents, transferring sediments to deep water. Sediment distribution within large rift lakes is controlled locally by variations in tectonism within the basin at a given time, and temporally by regional variations in climate or tectonism (Cohen, 1990). Climate affects sedimentation in rift lakes principally by lake level changes, alteration of influent sediment (basin hydrology) and water discharge, influent and lake water chemistry. Tectonism affects the positioning of pathways and barriers to sediment input and the loci of ultimate sediment storage both along the rift axis and perpendicular to rift structures (Cohen, 1990).

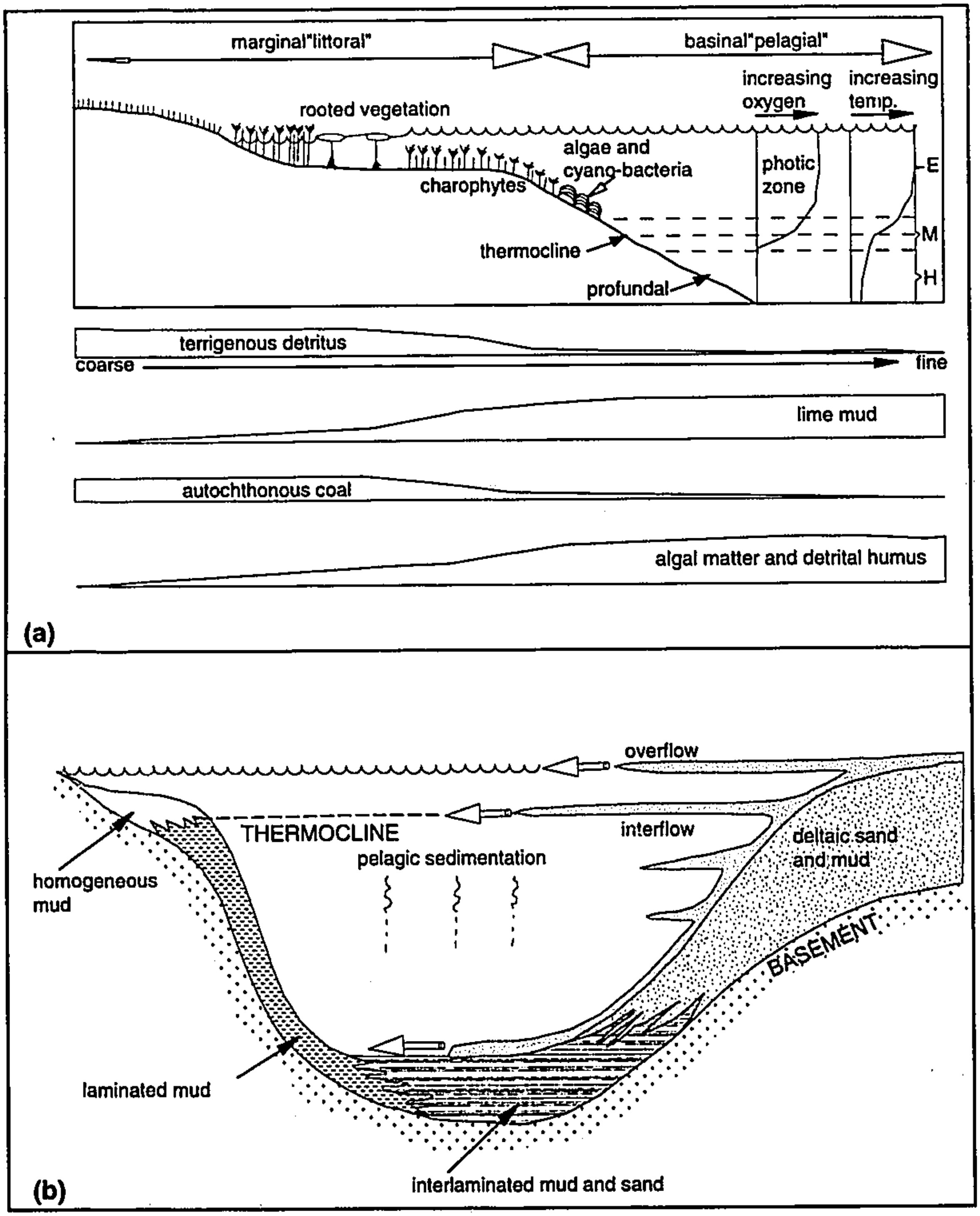


Fig. 5.0 Characteristics of lakes.

(a) Subdivision of lacustrine environments, showing marginal and basinal facies, trends in sediment components and circulation zones in modern lakes (compiled from Selley, 1985, and Platt and Wright, 1991). E= Epilimnion, M = Metalimnion, H = Hypolimnion.

(b) Relationship between water column stratification, clastic processes and clastic deposits in modern lakes (from Sturm and Matter, 1978).

Large lakes give rise to significant wave, current and seiche effects, with correspondingly high energy available for shoreline erosion. The location and nature of the deposit depends on the mode of fluvial transport, and on conditions within the lake. Bedload is deposited first, and suspended load is carried varying distances into the lake (Rust, 1982). Depositional environments and processes in modern East African rift lakes provide useful analogues for the interpretation of ancient rift-lacustrine strata (Robbins, 1983; Bertani and Carozzi, 1984). For example, the total clastic sediment supply in Lake Tanganyika basin is restricted by basin morphology, notably steep relief, backsloping and a limited drainage basin area, whereas in Lake Turkana, sediment supply is partly restricted by ponding in marginal sub-basins due to volcanic barriers (Cohen, 1989). Net sediment accumulation rates for some parts of Lake Tanganyika basin are 6 mm/yr (Barton, 1979) with mean rates of 3-5 mm/yr based upon radiocarbon dates (Johnson et al., 1987).

Biological activity in lakes varies from very low, in oligotrophic high-latitude or mountain lakes (Coakley and Rust, 1968), to dominant in some shallow eutrophic lakes. Biogenic precipitates are dominantly composed of carbonaceous matter, carbonates or silica; chemical precipitates are mainly composed of chlorides and sulphates (Fig. 5.0). Organic material comes from lake plankton, from bottom- and shoreline-dwelling organisms, and from debris carried in by rivers from the drainage basin (Fig. 5.0). Sediments may accumulate organic sulphides, and skeletons of silica (chiefly diatoms, Maurrasse, 1978). In east African lakes, shallow-water gastropodal, ostracodal or chara-bearing muds accumulate in protected embayments in which carbonate deposits become more abundant with increasing distance from influent streams (Cohen, 1990). The combination of underflow current, a narrowly confined zone of clastic sedimentation, and rapid subsidence creates a thick, prograding sandy-delta system in the axial drainage (Cohen, 1990).

A general model for lacustrine deposition must take into account the sensitivity of lakes to climatic influence. The end members are lacustrine evaporites, organic precipitates and clastic accumulations. Lacustrine evaporites are varied, reflecting the geochemistry of the surrounding drainage basin, and indicate arid climates. Organic precipitation suggests tropical and temperate climates, and clastic accumulation reflects deposition in non-arid climates such as in mountains and high latitudes (Rust, 1982). Arid and temperate lakes become increasingly dominated by (respectively) evaporitic and organic accumulation as their drainage basins are worn down and the lake basins fill up, resulting in a decrease in clastic input. Seismic-reflection data collected by Ebainger et al. (1984), Rosendahl et al.(1986), and Scholz and Rosendahl (1987, 1988) demonstrate that rift-lake strata are organised into discrete sequences commonly bounded by unconformities that are linked to major lake-level fluctuations, and abrupt transitions to onlapping deep-water mud (first bioturbated clastic mud and then laminated diatom oozes) reflect rapid fluctuations in water level (Cohen, 1990).

5.3 SINAKUMBE GROUP

5.3.1 GENERAL REMARKS

The ?Ordovician to Devonian Sinakumbe Group occurs widely in the Muzuma-Sikalamba corridor, Nkandabwe map area (Fig. 5.1). To the northeast of this corridor, the group thins (except for a bulge around Nkandabwe River), and eventually wedges out. It is consists of approximately 210 m of sediments with a lower overall coarsening-upward sequence (Lower Sinakumbe Group) (Figs. 4.10 and 4.11) consisting of small-scale coarsening- and fining-upward cycles, and an upper quartz arenite (Upper Sinakumbe Group - Fig. 4.18). The Lower Sinakumbe Group is present throughout the Sinakumbe Group outcrops, but the Upper Sinakumbe Group is absent northeast of the Sikalamba-Muzuma corridor (Fig. 5.1). In the southwestern part of the Nkandabwe area, the Lower Sinakumbe Group is overlain by the Siankondobo Sandstone Formation of the Karoo Supergroup (Fig. 4.10).

The characteristics of the lithofacies and facies assemblages (Chapter 4) suggest that the Lower Sinakumbe Group was deposited in an alluvial fan environment, and that the Upper Sinakumbe Group represents deposition in a braided river system.

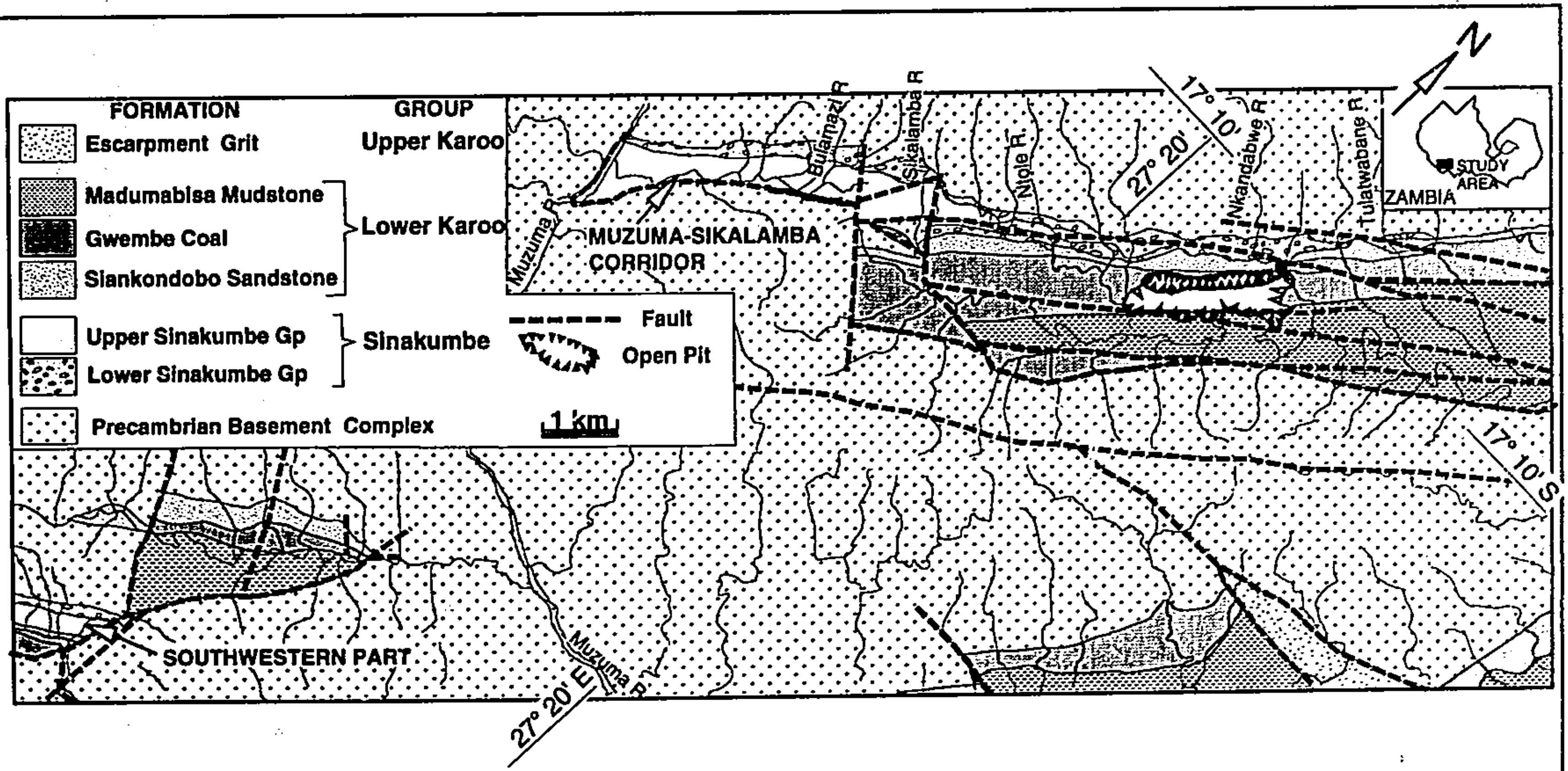


Fig. 5.1 Geological map of the Nkandabwe area showing the distribution of the Sinakumbe Group (?Ordovician to Devonian) and Karoo Supergroup (Permo-Carboniferous to Early Jurassic).

5.3.2 LOWER SINAKUMBE GROUP AS AN ALLUVIAL FAN DEPOSITIONAL SYSTEM

The lower part of the Sinakumbe Group consists of an overall coarsening-upward sequence approximately 55 m thick (Figs. 4.10 and 4.11). The unit starts with coarse-grained to pebbly sandstone lithofacies units (up to 4 m thick) interpreted as sandflat sheetflood deposits that fine upwards into mudflat deposits; locally the unit starts with the latter. The major coarsening-upward cycle contains abundant small-scale coarsening- and fining-upward cycles that are less than 10 m thick. The increase in grain size in the major cycle corresponds to a change from mudflat and sandflat deposits to the braided channel-dominated pebbly sandstone and conglomerate northeast of the corridor (Fig.4.10), and to proximal fan debris flow/sheetflood conglomerates in the corridor (Fig. 4.11). The mud- and sand-flat sequence (mudrocks to medium-grained sandstone) is well developed northeast of the Sikalamba River, particularly on the Hill Slopes (Sections 3a and 3b) in the vicinity of the Nkandabwe River. The alluvial fan conglomerate sequence forms the bulk of the outcrop in the Muzuma-Sikalamba Corridor (Fig. 5.2), and progressively thins northeast of the Sikalamba River. The thick conglomerate assemblage (~55 m) in the Sikalamba-Muzuma corridor indicates that fan progradation was high in this area. The common debris flow deposits of the corridor area are thus replaced by braided stream conglomerate facies to the northeast (Fig. 4.10). The differences in proportions of debris flow (Gms) and stream flow gravels between the Muzuma-Sikalamba Corridor and the main basin to the northeast may be explained by availability in the source area of readily weathered detritus (cf. Hooke, 1967), relief of source area, rainfall, and changes with time (e.g. scarp recession and downward erosion: cf. Miall, 1977). Debris flows and channel-form streamflood processes are diagnostic of proximal fanhead deposition (Beaty, 1963; Bull, 1964; Denny, 1965; Hooke, 1967; Steel and Wilson, 1975), whereas deposition in the midfan below the intersection point is dominated by sheetflood and braided streams that head on the fan surface (McGee, 1897; Davis, 1938; Lustig, 1965; Bull, 1972; Williams, 1973). Distal fan sediments are similar to midfan deposits, except for smaller grain sizes in the former and the addition of aeolian and playa-lake facies (Steel, 1974; Steel and Wilson, 1975).

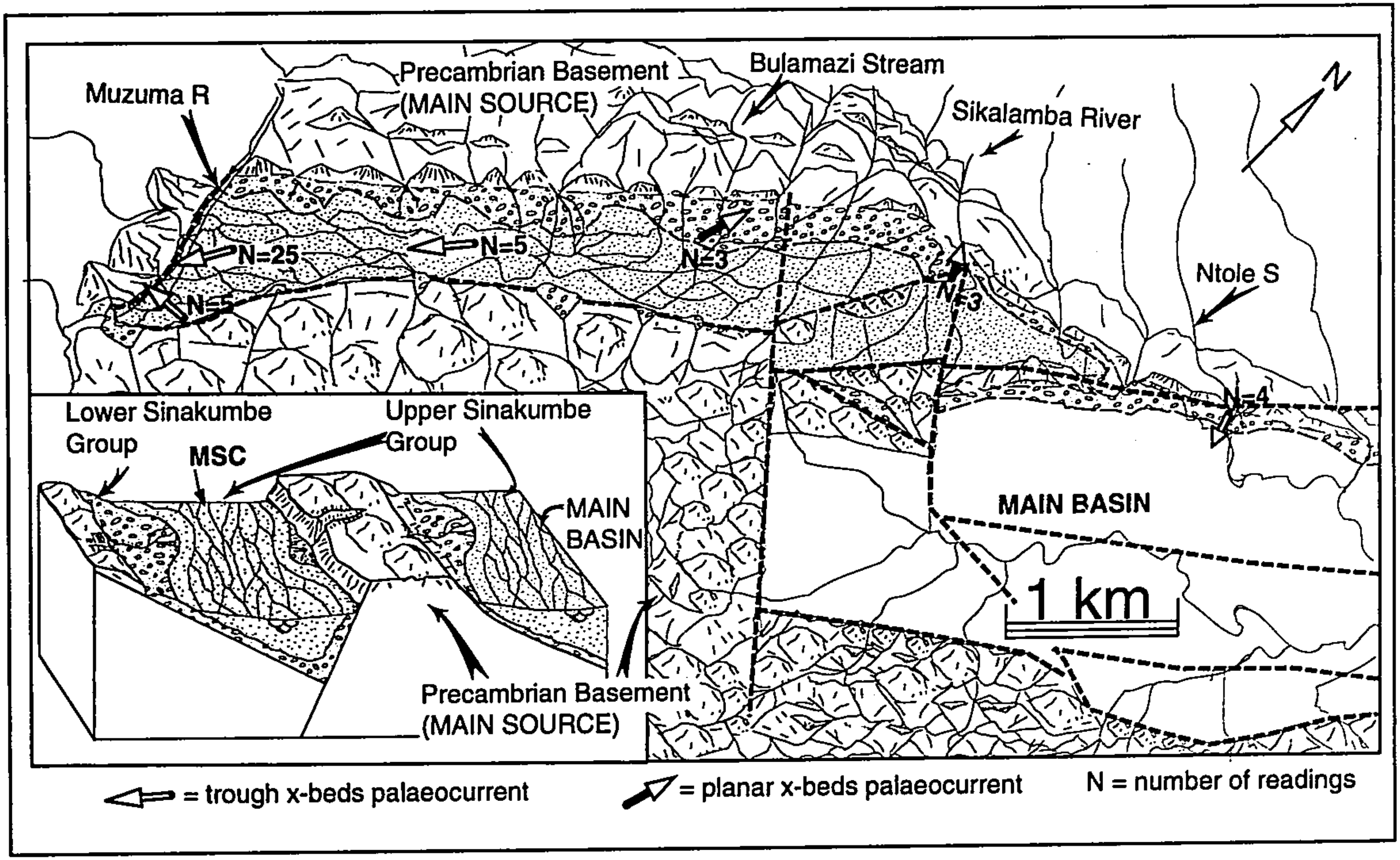


Fig. 5.2 Interpretation of palaeogeography and conceptual block diagram showing probable depositional systems of the Sinakumbe Group in the Muzuma-Sikalamba Corridor (**MSC**). The block diagram represents a view towards the northeast.

Small-scale fining-upward cycles within the major coarsening-upward sequence may record changes from sheetflood, debris flow and braided stream conglomerates to medial and distal sheetflood sandstones and mudrocks of sandflat and mudflat subenvironments. The small-scale coarsening-upward cycles can be explained by lateral migration of braided-streams across the fan (cf. Schumm, 1977; Mack and Rasmussen, 1984), with braided stream deposition only during major floods on the abandoned fan.

The generally coarsening-upward sequence with subordinate fining-upward cycles resembles the unit assemblage of Dunne and Hempton (1984) that is indicative of shelf-type fan-delta models. Walker (1978) and Bose et al. (1992) suggested that coarsening- and thickening-upward trends in a sequence consisting of mudstone/siltstone and pebbly sandstone overlain by increasingly coarser, thicker beds of conglomerate represent coastal fan progradation from the same source area. These variations and abrupt changes are typical of deposition on alluvial fans. The Lower Sinakumbe Group sequence was derived from the basement complex mainly from the north/northwest. Local debris flow deposits, with clasts up to boulder size on the southern faulted side, were derived from the basement to the south. Conditions on this steep valley slope (southern side) gave rise to debris flows that were confined to fanheads, whereas sporadic sheetfloods (thin, relatively unconfined upper regime flows) may have resulted from intense rains on the fan surfaces (cf. Rahn, 1967).

Denman and Money (1970) inferred various depositional environments and processes for rocks of the Sinakumbe Group on the basis of limited data from one drill hole (GS 96). The Lower Conglomerate Formation was interpreted as a succession of turbidites comprising canyon fill and submarine fans overlain by normal, massive turbidites and clean, shallow water, littoral sandstones and quartzites (their Middle Sandstone, Upper Conglomerate and Quartzite formations). Their Lower Conglomerate Formation cycles were considered to represent basal units (a) and (b) of the Bouma (1962) sequence, with upper parts of the sequence absent. The formation was considered to represent 'proximal facies' turbidites near the margin of the basin, probably deposited from density currents, or to be due to slumping within canyon channels. Other sedimentation processes suggested included large gravity slides, grain flow and creep. The high sand and clay content of the formation suggested to them deposition below wave base, and the coarse texture and graded character was taken to indicate a mass flow deposit. The limited areal extent and position were thought to indicate deposition between walls of a canyon or at the very top of a submarine fan at the base of the canyon. The Middle Sandstone Formation (graded, poorly sorted, immature beds) was interpreted as a slope deposit, formed below effective wave action, with modes of deposition similar to the Lower Conglomerate Formation. The Upper Conglomerate Formation was interpreted to represent deposition in a nearshore, shallow water, possibly transgressive environment. Shoreline shelf deposits are characterized by an absence of mud that was removed by winnowing. The Quartzite Formation (clasts collected from the Lower Karoo Group) was interpreted as a shore facies, and similar to the Upper Conglomerate Formation deposited in a high-energy environment. The two formations were considered to be products of rapidly rising sea level with considerable deposition of bay and shelf facies. Denman and Money (1970) claimed that the clean, littoral sand was preserved by a protective cover of mud such as provided during rapid transgression and that the red, muddy siltstones in the Sinazeze area are a remnant of such a protective shelf facies. Eventual regression and the emergence of land were invoked to explain the depletion of the quartzites as a consequence of denudation. The lack of marine and fresh-water fossils suggests that marine and lacustrine influences are absent from these rocks. Although the author has not seen the GS 96 core, all the conglomerates and the quartz arenite (their quartzite) in outcrops are submature, and all of the sedimentary structures indicate fluvial deposition and a lack of wave activity (e.g. effects of reworking by waves). The abundance of mudclast breccia with clasts ranging from sand-size to cobble-size in the Upper Sinakumbe Group is inconsistent with the high-energy shelf facies of marine environments. Even though Denman and Money (1970) recognised that the general fining-upward cyclic sequence in GS 96 has lithological characteristics similar to those of the alluvial fan deposits described by Allen (1965a) and Blissenbach (1954), this interpretation was not favoured because it departed from the interpretation of the well-exposed equivalent sediments of the Sijarira Group of Zimbabwe with which the Sinakumbe Group has been correlated. The alluvial fan/braided river interpretation is favoured by the present study. The Sijarira Group of Zimbabwe has been interpreted as a shallow-water shoreline facies to deeper water slope and canyon head deposits in a continental / basin margin environment (as quoted in Denman and Money, 1970).

The variations in bed thickness and geometry, and rapid facies change (from sheetflood to debris flow/braided stream deposits) support deposition of the Lower Sinakumbe Group in an alluvial fan setting. The lack of marine fossils and the immature to submature sediments support a continental alluvial fan setting for the subgroup. The typically red coloration is probably due to diagenetic alteration of ferromagnesian minerals in near-surface, oxidizing environments, suggesting arid conditions during Lower Sinakumbe Group deposition.

5.3.3 UPPER SINAKUMBE GROUP AS A BRAIDED STREAM DEPOSITIONAL SYSTEM

The quartz arenite facies assemblage (Fig.4.18) of the Upper Sinakumbe Group reflects deposition in a braided stream environment.

The Upper Sinakumbe Group is absent northeast of the Sikalamba River (i.e. at the margins of the main basin in the Nkandabwe area) as well as in the type-log section (GS 96) in the Sinakumbe area. It appears to be confined to sub-basins connected to the main basin such as in areas northwest and southwest of the Nkandabwe area (Figs. 5.1, see also Fig. 2.2a and 2.2b). Its absence outside these sub-basins is due either to poor preservation potential or to non-deposition. The latter is favoured because it would be consistent with initiation of the braided stream systems in relation to tectonics. As discharge increased, the Upper Sinakumbe Group would have accumulated in a braided stream system southeast of the coalescing alluvial fans of the Lower Sinakumbe Group on the northwestern margin of the basin, and abutting local steeply dipping isolated fans on the faulted southeast side of the basin (Fig. 5.2). The restricted nature of the unit attests to origin in a tectonically induced braided stream system rather than on a braidplain (cf. Rust, 1984).

The palaeogeographic extent of the braided-stream depositional system, together with palaeocurrents that are oblique to perpendicular to the palaeoslope of the Lower Sinakumbe Group alluvial fan system, point to deposition within a separate dispersal system (Fig. 5.2). No transitional facies was observed in any of the measured sections exposing the boundary between the lower and upper parts of the group; in every exposure the contact is sharp. The mudclast breccia consisting of red mudrock clasts derived probably from the prevalent mudrock lithofacies of the Lower Sinakumbe Group is not transitional, in that the breccia occurs within the Upper Sinakumbe Group. The braided stream deposits of the Upper Sinakumbe Group are not distal facies of the alluvial fan system of the Lower Sinakumbe Group for the following reasons: (a) palaeocurrent directions in the braided-stream depositional system are nearly perpendicular to the palaeoslope of the alluvial fan system and subparallel to the sub-basin margin, (b) no transitional facies were observed, (c) braided stream facies of the Upper Sinakumbe Group are confined between two opposing Lower Sinakumbe Group alluvial fan facies (the more extensive low-gradient northwestern fans and more local steeply dipping southeastern fans (cf. Hempton et al., 1983), and (d) the Upper Sinakumbe Group is absent northeast of Sikalamba River and was probably not deposited there. The coarse-grained nature of the deposit, presence of mudclast breccia attributed to bank failure, rarity of mudrocks, absence of marine or freshwater fossils, suite of sedimentary structures (poorly defined) and the disorganised nature (no well-defined cycles) of the deposits support braided deposition of the Upper Sinakumbe Group.

In summary, sediment input for the Sinakumbe group was mainly from the north for the Lower Sinakumbe Group and northeast for the Upper Sinakumbe Group (Fig. 5.2), controlled by the half-graben palaeoslope and the fault on the southern side. Heavy minerals, particularly the abundance of garnets, indicate that basement schist and gneiss were the main sources.

5.4 LOWER KAROO GROUP

Characteristics of the lithofacies and facies assemblages of the formations in the Lower Karoo Group suggest various depositional environments ranging from glacio-fluvial and glacio-lacustrine (Siankondobo Sandstone Formation), to fluvial flood plain (Gwembe Coal Formation) to lacustrine (Madumabisa Mudstone Formation).

5.4.1 SIANKONDOBO SANDSTONE FORMATION AS A GLACIO-FLUVIAL / GLACIO-LACUSTRINE DEPOSITIONAL SYSTEM

The Permo-Carboniferous Siankondobo Sandstone Formation consists of diamictite, siltstone and sandstone facies assemblages which are interpreted here as representing glacio-fluvial and glacio-lacustrine deposition (Fig. 5.3). Fig. 5.3 uses a valley glacier to explain the generation of, and relationships between, the lithofacies and the assemblages; glaciation however, was probably of continental ice-sheet proportions, as indicated in Fig. 6.3 (see Chapter 6), comparable to the Ottawa Valley Pleistocene glacial deposits. It is in the topographic lows where some of the sediments were best preserved (e.g. the varve-like sediments). The assemblages occupy the northwestern margin of the study area, directly overlying either the Sinakumbe Group or the basement complex where it is locally faulted against the latter.

In the absence of diagnostic glacial characteristics (tillites, striations, etc.) in the basal facies of the formation, occurrence of the siltstone assemblage (e.g. the sedimentary structure suite) is the only strong evidence for glacial origin for the formation (Rust, pers. comm., 1990). The direct evidence of ice may have been completely destroyed through the reworking of glacial sediments by glacio-fluvial processes (Eyles and Eyles, 1992). Gradation from the diamictite facies assemblage to varve-like sediments overlain by cross-laminated siltstones /sandstones of the siltstone assemblage, overlain in turn by massive sandy sediments, support the glacio-fluvial / glacio-lacustrine interpretation. This association is probably common in subaqueous outwash successions formed during continental deglaciation, because the isostatic effect of a large ice mass tends to cause ponding of fresh water against the glacial margin (Rust, 1977). Seasonal variation in the volume of meltwater and the resultant variations in grain size of the sediment produce graded couplets (varves) in the lake, and associated underflows with subordinate interflow could have produced deposits such as the siltstone assemblage. Density underflows result from high suspended load in inflowing river waters, making them more dense than lake waters (Jopling and Walker, 1968). Ripple-drift units in the siltstone assemblage are attributed to deposition from decelerating traction currents on distal interchannel parts of the fan complex (cf. Rust, 1988).

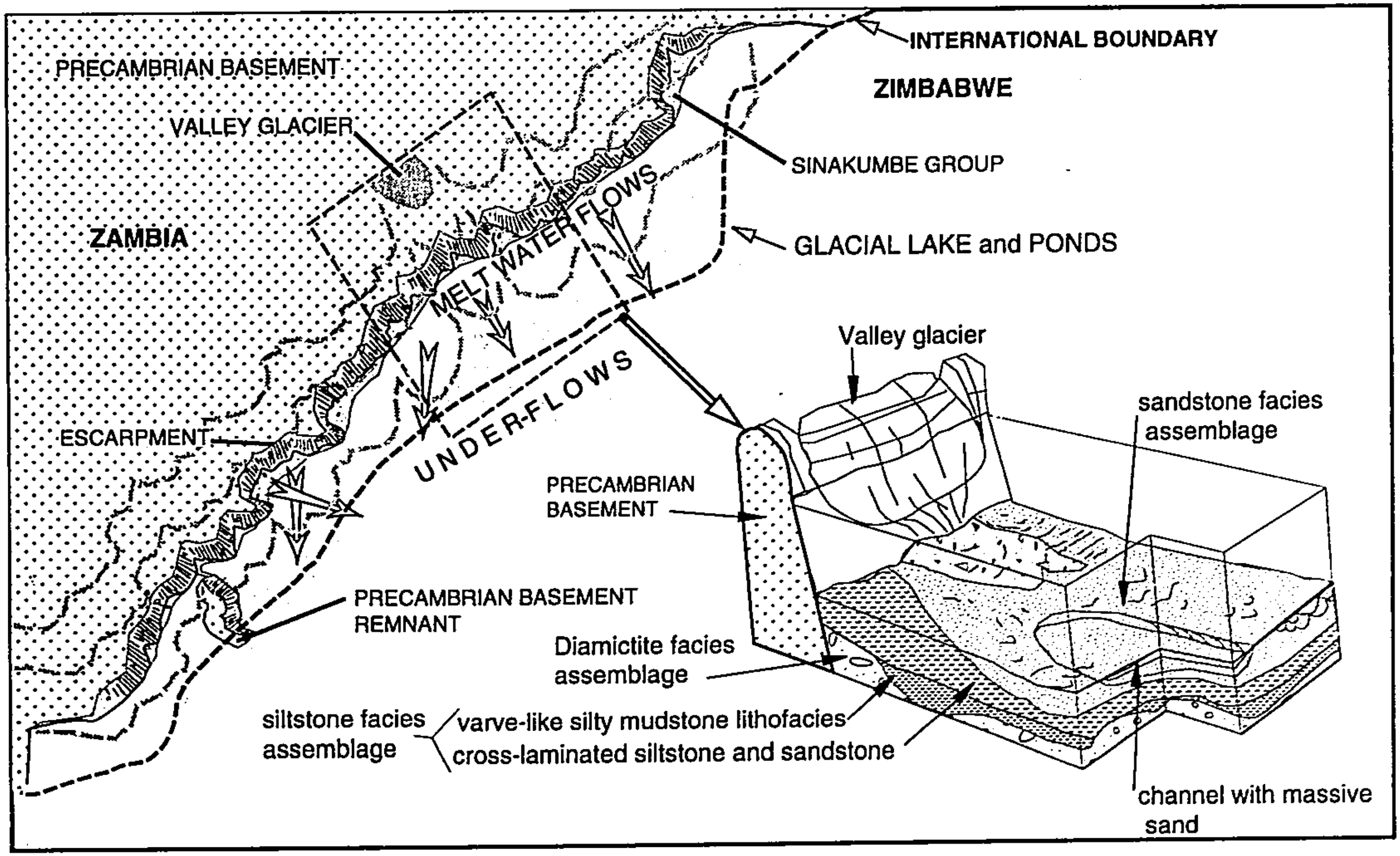


Fig. 5. 3 Interpretation of palaeogeography and simplified conceptual depositional model (block diagram) of the Siankondobo Sandstone Formation, mid-Zambezi Valley Basin, southern Zambia. Glacial lake extent exaggerated.

The coarsening-upward arrangement of the lithofacies (from the base of the varve-like silty mudstone/siltstone to the massive sandstone lithofacies) and a locally fining-upward part (basal diamictite /conglomerate to the top of the varve-like sediments) of the formation is consistent with deposition on a prograding outwash delta, with sediments transported by streams from a retreating glacier into ponds and lakes. Hyperpycnal processes characterize outwash or glaciolacustrine deltas (Bates, 1953) with bottomsets, foresets and topsets (Jopling and Walker, 1968) as the essential components. The bottomset sediments consist of varve-like mudstone/siltstone on the lake floor which grade upward into ripple drift cross-laminated siltstone. A lack of graded beds and scours indicates that subaqueous gravity flow mechanisms (Middleton and Hampton, 1973) dominated by turbidity currents (Gustavson, 1975) were minimal.

The massive sandstone bodies between the varve-like and the cross-laminated sediments and the overlying massive, medium-grained well-sorted sandstones are probably channel-fill deposits resulting from sediment gravity flows. The 35-metre-thick massive sandstone units favour deposition in subaqueous outwash channels rather than subaerial outwash channels, which are much shallower relative to width, and contain well-stratified thinner fill (Williams and Rust, 1969). Rust and Romanelli (1975) considered similar massive deposits to be subaqueous, principally on the grounds that such sediments are unknown from contemporary subaerial glacio-fluvial occurrences. However, their association with downstream accretion bodies and trough cross-bedding at the top strongly suggest that they represent outwash delta foresets that developed through discontinuous avalanching down the prodelta slope. Rust (1988) attributed such large-scale cross-bedding to progradation of a bar on to the submerged fan surface. Smith and Ericksson (1979) considered large-scale cross-beds (Sp) overlying massive channel-fill sandstones to represent outwash delta foresets. The occurrence of cross-bed sets above the massive sandstone as at Nkandabwe suggests that the massive bed aggraded locally in the channel to fill most available space (cf. Wizevich, 1992). The large-scale downstream accretion beds (2.5 m thick) above the massive sandstones are likely to be low flow-regime bedforms formed during waning flow (cf. Wizevich, 1992). Allen (1970) showed that frequent oversteepening of delta foresets results in slumping and this could explain the observed contortion and overturning of the laminated siltstone/sandstone units at the base of and within the massive sandstone assemblage.

The occurrence of undulatory laminated thin beds within the massive sandstone bodies testifies to changes in sediment supply and flow velocity, and could have been developed as the mass flow became diluted and approached more hydraulic conditions (cf. Turner and Munro, 1987; Wizevich, 1992). The mudstone filling the diapirs in the cross-laminated siltstone (Fig. 4. 26b) was probably deposited rapidly as excessive pore water pressure developed in response to increased sediment load, and was locally ejected upwards through more cohesive overlying siltstones and fine-grained sandstone, forming the diapirs. Intervening troughs would have resulted from subsidence of sediment between the diapirs (cf. Cheel and Rust, 1986). Lowe (1975, p.187) recognised diapirs as vertical channels through which fluidized sediment passed during rapid dewatering.

The overall association of lithofacies in this shallowing-upward (coarsening-upward) sequence suggests that it was formed as meltwater influence decreased due to retreat of an ice front, and as uplift raised the substrate toward wave base (cf. Rust, 1988). Consistent with this are the glacio-fluvial deposits at the base (diamictite facies assemblage) followed by glacio-lacustrine deposits of suspended sediment probably moved by density underflows (siltstone facies assemblage). All these features support interpretation of the Siankondobo Sandstone Formation as a glacio-fluvial/ glacio-lacustrine deposit.

5.4.2 GWEMBE COAL FORMATION AS A FLOOD PLAIN DEPOSITIONAL SYSTEM

At the end of deposition of the Siankondobo Sandstone Formation during early postglacial conditions, a broad flood plain was established in the mid-Zambezi Valley on which a high-sinuosity meandering river-system appears to have developed (Fig. 5.4). Deposits of this river system constitute the Maamba Sandstone facies assemblage at the base and the overlying lithofacies are represented by the various subenvironments on the floodplain (Nyambe and Dixon, 1993). The water level in freely meandering river channels is commonly above that of the surrounding floodplain, confined there (except in flood) by its levees (Walker and Cant 1984). A high water table therefore would have

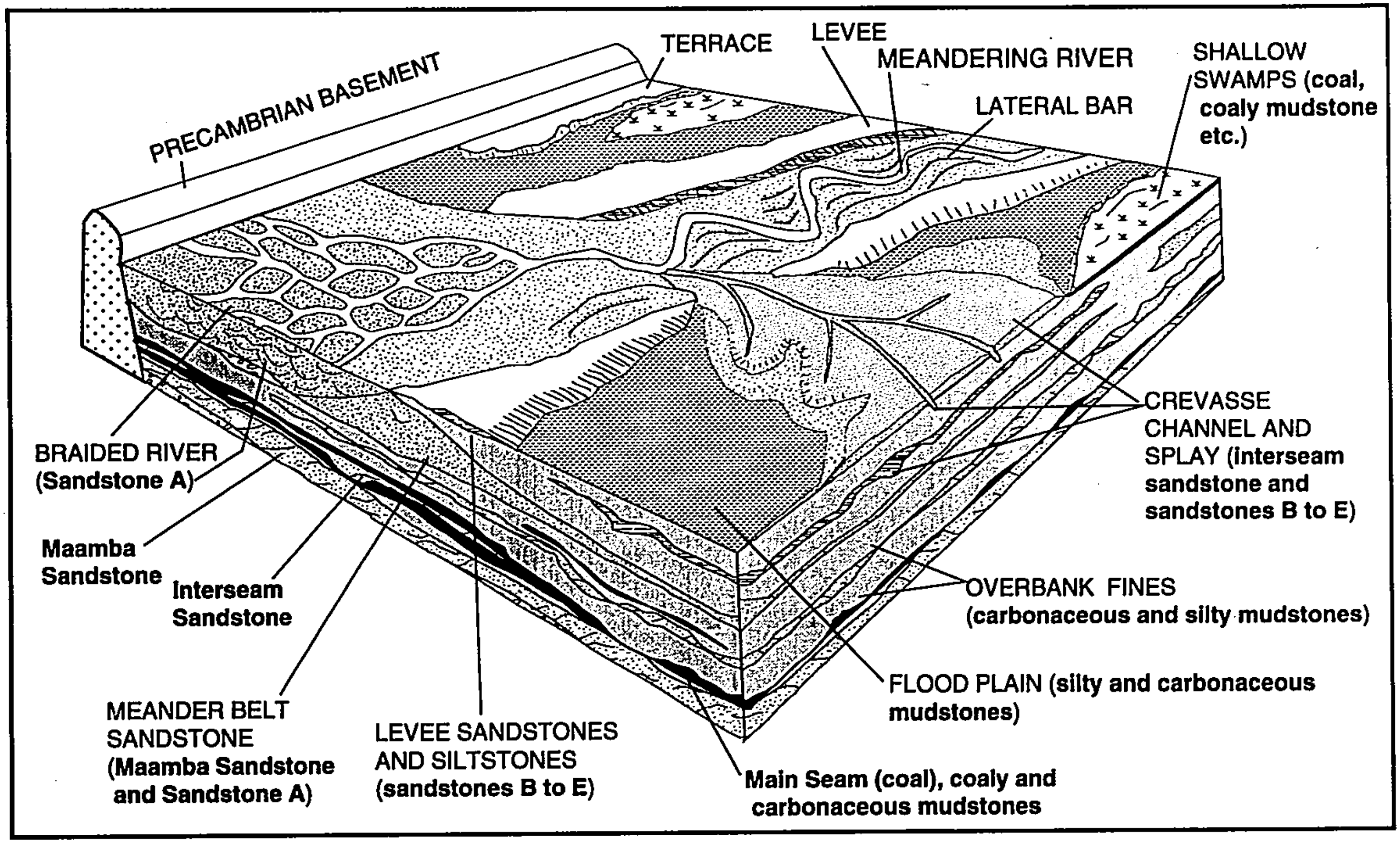


Fig. 5.4 Depositional model of the Gwembe Coal Formation, mid-Zambezi Valley Basin, southern Zambia.

been maintained across the floodplain where swamps became established. Peat accumulated over a broad expanse, provided that subsidence or flooding did not drown the vegetation, allowing accumulation of the coal lithofacies. The swamps received sand incursions as crevasse channels and splays (Interseam Sandstone), which caused lateral splitting of the coal seams and introduced clay into parts of the swamp farther from the channel. The mudrock assemblage was deposited mainly as overbank fines from suspension during floods and as distal crevasse splays and levees. The presence of such a high water table would also explain the formation of siderite (see lithofacies interpretation).

Tectonic uplift of the source area provided the clastic sediment for the braided systems, resulting in deposition of Sandstone A before a change to incised meandering to freely meandering river channels. In braided channels, the water level is below that of adjacent areas, and therefore peat accumulation is unlikely to be thick or widespread, because the vegetated areas are not extensive and the water table is too low most of the time (Rust et al., 1987). Therefore the coal seams above Sandstone A are thin and of poor quality. Lateral movement of the active channel system would have eroded the peat by undermining the clastic sediment beneath it. On proximal braidplains represented by the pebbly components of Sandstone A, the coal seams are remarkably thin, and incorporation of coal and coaly fragments indicates reworking of the coal (e.g. Fig. 4.62a). The change from a braided system to an incised meandering river system meant that active channels became by definition significantly lower than the floodplain. The lower water table would have resulted in effects such as the abundant red/brown coloration of the mudstone and sandstone (e.g Fig. 4.48e) above Sandstone A in the upper part of the Gwembe Coal Formation. The colour changes and mottling (e.g. Fig. 4.46) indicate subaerial exposure coupled with strong bioturbation. Hubert and Reed (1978) observed that red hematitic coloration is imparted to sediments under oxidising conditions by the early post-depositional alteration of iron-bearing minerals, including (i) dehydration reactions in which the limonite stain on detrital particles is altered to hematite, (ii) dissolution of iron silicate and precipitation of the released iron, and (iii) direct oxidation of magnetite and ilmenite grains. This would explain the coloration in the formation.

Kaolinite is the most abundant clay mineral in the Gwembe Coal Formation.

Previous studies have shown that kaolinite is abundant in bituminous coals (O'Gorman and Walker, 1971) and its proposed origin may include: (i) incorporation by normal sedimentary processes such as overbank flooding of the swamp, and reworking of sedimentary material within the swamp (Mackowsky, 1968; Spears, 1987), (ii) diagenetic alteration of pre-existing alumino-silicates within the peat (Davis et al., 1984), possibly by including amorphous, plant-associated inorganic material (Renton and Cecil, 1979), and (iii) alteration of volcanic ash-fall material, usually present in discrete layers known as tonsteins (Price and Duff, 1969; Spears and Kanaris-Sotiriou, 1979; Dewison, 1989). Price and Duff (1969) indicated that diagenetic recrystallisation of alumino-silicate material to form kaolinite is known to occur to a greater extent in coal than in associated mudstones due to more suitable conditions (greater acidity and lower K^+ activity) for kaolinite formation in the coal-forming environment (Garrels and Christ, 1965). In the mid-Zambezi Valley Basin, the kaolinite is more likely to have originated as a result of processes (i) and (ii) because of the lack of tonsteins and the commonly associated mineral anatase. It shows better developed crystallinity, indicated by its uniform XRD peaks in the coals, than in the Interseam Sandstone and mudstone where other clays are present. Patterson and Murray (1984) noted a similar pattern, and concluded that kaolinite formed in the presence of lesser amounts of other clay minerals tends to develop greater crystallinity. Kaolinite is generally the product of intense weathering of feldspathic or argillaceous rocks in hot, humid climates. In such settings, potassium is stripped from the clays to form kaolinite (Scholle, 1979 p.69).

The Gwembe Coal Formation (Fig. 4.33) shows cyclicity mainly as alternating silty mudstone and carbonaceous/sideritic/coaly mudstone or coal. Several mechanisms for control of cyclicity have been proposed (Beerbower, 1964; Miall, 1980). Murchison and Westoll (1968), divided these into three groups:

1. Periodic relative movement of land and sea levels such as: (a) repeated subsidence of the area of sedimentation followed by sedimentary accumulation to or above sea level, either simply or with oscillations, (b) eustatic movements controlled from outside the basin by glaciation (glacio-eustatic change) or as a result of changes in the ocean basins due to increases or decreases in volume of oceanic spreading ridges (tectono-eustatic

change), and (c) repeated uplift and erosion of the continental hinterland;

2. Repeated climatic changes (e.g. glaciation-deglaciation);
3. Cyclic effects from steady change, such as (a) isostatic adjustments, (b) adjustment to tectonic stress, (c) trapping and releasing of sediments from heavily vegetated swamps, (d) effects of compaction of sediments, and (e) effects related to the continuous action of sedimentary processes in rivers and deltas.

The operation of these mechanisms is a subject of current debate and research, but it is generally accepted that sedimentary cycles are related to eustatic changes of sea level, i.e. due to glacio- and tectono-eustatic changes, local tectonics and rates of sedimentation (Plint et al., 1992). Allen (1964) attributed cyclicity in the Lower Old Red Sandstone of the Anglo-Welsh Basin to three mechanisms: (a) autocyclic, in which each river wandered across a portion of the floodplain under conditions of steady subsidence and sediment supply, (b) autocyclic, influenced by allocyclic sea-level changes in which rivers in unison alternately eroded and aggraded the floodplain under steady subsidence and sediment supply conditions, and (c) a combination of allocyclic and autocyclic in which bursts of tectonic activity in the source area led to increased sediment supply through rejuvenated streams that eroded and aggraded the floodplain with no variation in the base level and rate of subsidence of the basin.

Tavener-Smith (1960) suggested that the Gwembe coal-bearing sequence was of lacustrine origin. Money and Drysdall (1975) argued for a floodplain origin for the Gwembe Coal Formation. As an analogue for the mid-Zambezi Valley coal deposits, they used the present-day Niger delta in which peat accumulates in linear back-swamps. The comparable Gwembe coal swamp is envisaged as a southwesterly sloping environment vegetated by probably small plants and shrubs, with few trees, comparable to present-day vegetation of the Upper-Zambezi floodplain between Mongu and Senanga, western Zambia (Money and Drysdall, 1975). Semi-permanent to permanent water in places (e.g. ox-bow lakes) meant that peat accumulated in both reducing (anaerobic) and oxidising (aerobic) environments. Peat accumulation and development was controlled by palaeorelief and size of the floodplain. Distribution of the ash content was controlled by palaeorelief, in particular position of the main river channel, such that away from active streams thicker coal developed. Money and Drysdall (1975) suggested that an abundance of inertinite in mid-Zambezi Valley coal indicates a floodplain origin which allowed strong aerobic decomposition of plant residues at the peat surface due to subaerial exposure; in contrast, the anaerobic conditions prevalent in lakes, would result in the deposition of syngenetic sulphide, resulting in unsystematic distribution of sulphur values in the Main Seam. However, the use of inertinite abundance as an indication of floodplain setting is questionable, because there are currently different schools of thought on inertinite origin; some support an oxidative degradation origin, and others persistent forest fires (Gibling, 1993, written communication).

Differences in the composition and character of the coal seams of northern and southern hemispheres (e.g. absence of tree trunks in Gondwana coals) are attributed to generic conditions by several researchers arguing for *in situ* (autochthonous) origin for the northern coals and drift origin (allochthonous) for the southern coals (Steart, 1919; Lamplugh, 1907; Lightfoot, 1929). Recent studies (Plumstead, 1966; Watson, 1958; Money and Drysdall, 1975) argue for an *in situ* origin of the southern coal based on extent and thickness (up to 15 m in places). The present study has documented rootlets in the sheet-sandstones below the B Seam in the Kazinze Open Pit (Fig. 4.41a, b) which supports *in situ* origin of the Main Seam Coal. The differences can be explained by the type of vegetation which in turn would have been controlled by climate. Plumstead (1966) indicated that northern hemisphere coals were mainly from evergreen vegetation in nearly stagnant waters of extensive coastal swamps under humid tropical conditions, whereas Gondwana coals were from deciduous plants which grew in flood plain and lacustrine swamps in a comparatively cool seasonal climate during and following retreat of the Dwyka ice. This conclusion was echoed by Money and Drysdall (1975) who indicated that the base of the Main Seam is well defined, and the top is interbedded with coaly and carbonaceous mudstone, suggesting that the greater basal part of the Main Seam is of *in situ* origin, but that, redistribution of plant material within the floodplain resulted in an allochthonous origin for the upper part. The sedimentology, palaeogeography, and maceral characteristics of the Main Seam all suggest an *in situ* origin (Money and Drysdall, 1975;

this study).

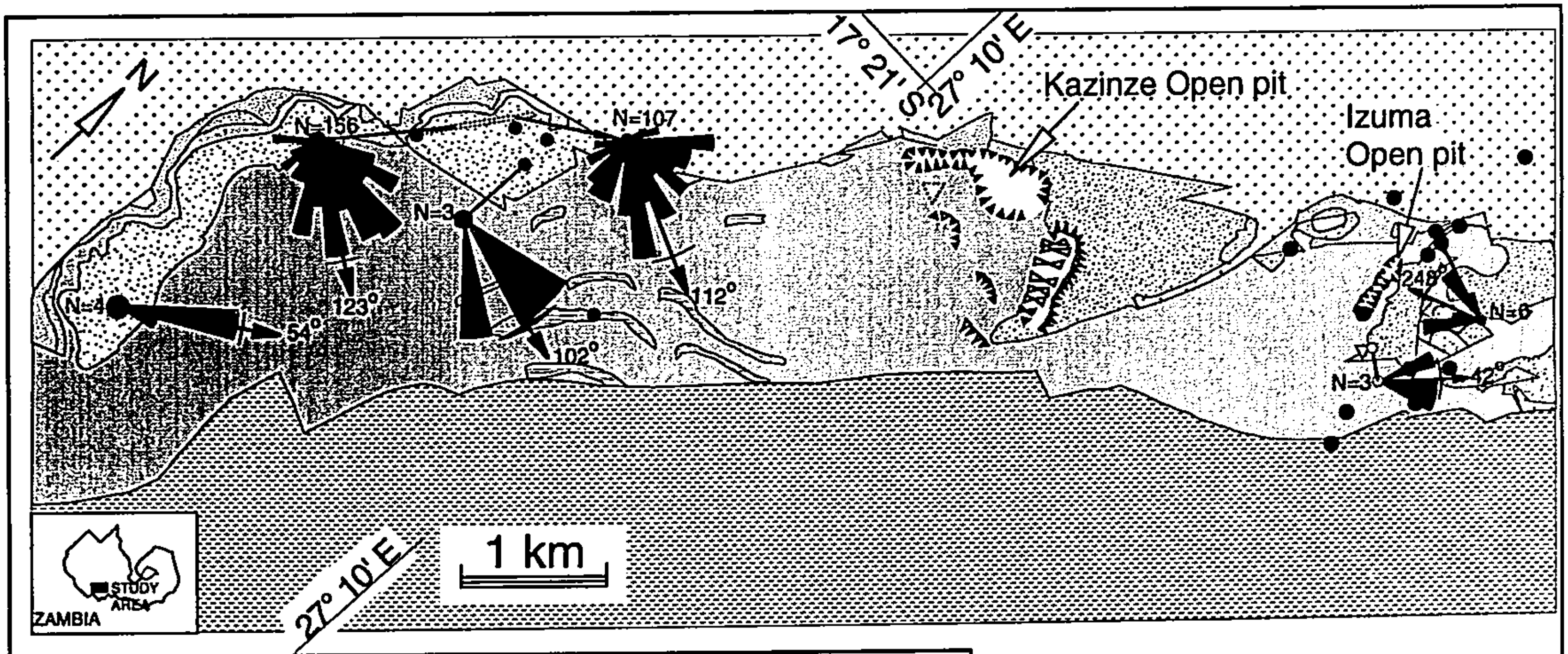
In summary, the lower and upper members in the Gwembe Coal Formation represent two fining-upward cycles. Most probably both allocyclic and autocyclic processes were involved in their formation. Bursts of tectonic activity in the source area would have led to increased sediment supply through rejuvenated streams that eroded and aggraded the floodplain with no variation in the base level and rate of subsidence of the basin. The first cycle, which starts with the Maamba Sandstone facies assemblage, began with a probable tectonic pulse that resulted in increased sediment supply through rejuvenated streams or as a result of isostatic rebound following glacial retreat. The coarser-grained nature of Sandstone A suggests that a tectonic pulse must have started the second cycle that ushered in Sandstone A. For the most part, however, the lower cycle consists of alternating units of silty mudstone and carbonaceous/coaly mudstone that progressively become silty towards the top, and these are best explained by periodic flooding. The second cycle is dominated by thick silty mudstone (slightly carbonaceous) with intercalations of carbonaceous/coaly mudstones and upper coal seams alternating with sandstones A to E. These features can be best explained by (a) high sinuosity fluvial migration and avulsion, and (b) floodplain flooding and vertical accretion. These processes are autocyclic (Allen, P. A., 1982) and not influenced by external forces such as changes in sea level or tectonism (Allen, 1964; Beerbower, 1964). Mineable seams occur in the abandoned Nkandabwe Open pit, Kazinze and Izuma and in a few locales in Sinakumbe-Maze and Mulungwa coalfield areas (exploration in progress). The coal seams generally grade laterally into mudstones (coaly, carbonaceous, silty) indicating localised swampy areas separated by intervening elevated floodplain. The uneven thickness of the Main Seam of up to 12 m, and the scattered mineable deposits in the study area and in the mid-Zambezi Valley in general suggest localised development (Fig. 5.4). Although coal seams of approximately equivalent age occur in many areas across southern Africa, the scattered and isolated coalfields probably represent local rather than regionally continuous (layer-cake) occurrences. The lithofacies association of the meandering stream deposit of Maamba Sandstone at the base, the rootlets in the Interseam Sandstone and mudrock facies assemblage (Figs 4.41a, b and 4.47c), the five sandstone bodies (A to E) all with sedimentary features (structures etc.) characteristic of fluvial deposits and lacking fresh-water fossils (in contrast to the succeeding Madumabisa Mudstone Formation), indicate that the Gwembe Coal Formation is a floodplain deposit. The thick and extensive siderite concretionary beds that suggest lacustrine emplacement, because they are known to occur widely in such deposits, appear instead to reflect deposition in standing water bodies such as ox-bow lakes and submerged portions of the floodplain in an alluvial floodplain setting. The lack of siderite in the overlying Madumabisa lacustrine deposits supports different depositional conditions for the two formations.

Palaeocurrent plots for the Sandstone A facies assemblage in the Siankondobo area indicate sediment transport mainly from the northwest (Fig. 5.5). The one station representing the Maamba Sandstone indicates sediment input from the southwest. One station (6 readings) in the northeastern part of the map for Sandstone A reflects a source area to the northeast, and can be explained as belonging to a separate minor Izuma basin (Izuma Open pit area) that is separated from the Kazinze Open pit area by a major fault. Opposing asymmetry in these basins can explain the opposing sediment source areas.

5.4.3 MADUMABISA MUDSTONE FORMATION AS A LACUSTRINE DEPOSITIONAL SYSTEM

Climatic amelioration followed the late Palaeozoic glaciation and flood plain development, and a high rate of subsidence led to the development of a lake in the mid-Zambezi Valley Basin (Fig. 5.6). The signature of such a lake (Fig. 5.6) is expressed in the lithofacies and assemblages of the Madumabisa Mudstone Formation (Chapter 4).

The sediment influx, as indicated by sparse palaeocurrent indicators, was mainly from the northeast and north, with possibly minor contributions from the northwest and west brought by mainly transverse rivers and streams with probably an axial river. A predominantly terrigenous silt-size sediment accumulated over wide areas of the lake and was reworked by organisms. The vertically alternating sequence of assemblages is interpreted as reflecting the combined effects of variation in climate and clastic supply with time. In modern east African lakes, the muds are typically massive and bioturbated, and commonly contain shelly-sand intercalations at water depths of 20-70 m, below which



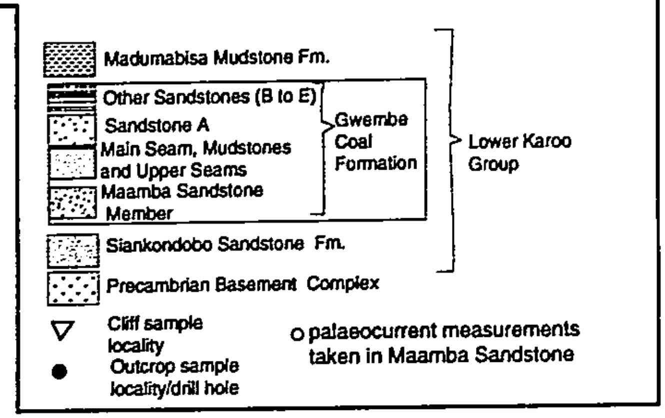


Fig. 5.5 Map showing palaeocurrent directions in Maamba Sandstone (one station, 3 readings near Izuma Open pit) and Sandstone A (rest of the stations) of the Gwembe Coal Formation. Sandstone A shows palaeocurrent d'rections predominantly toward the southeast; and the Maamba Sandstone shows a northeastward palaeocurrent direction, mid-Zambezi Valley Basin, southern Zambia.

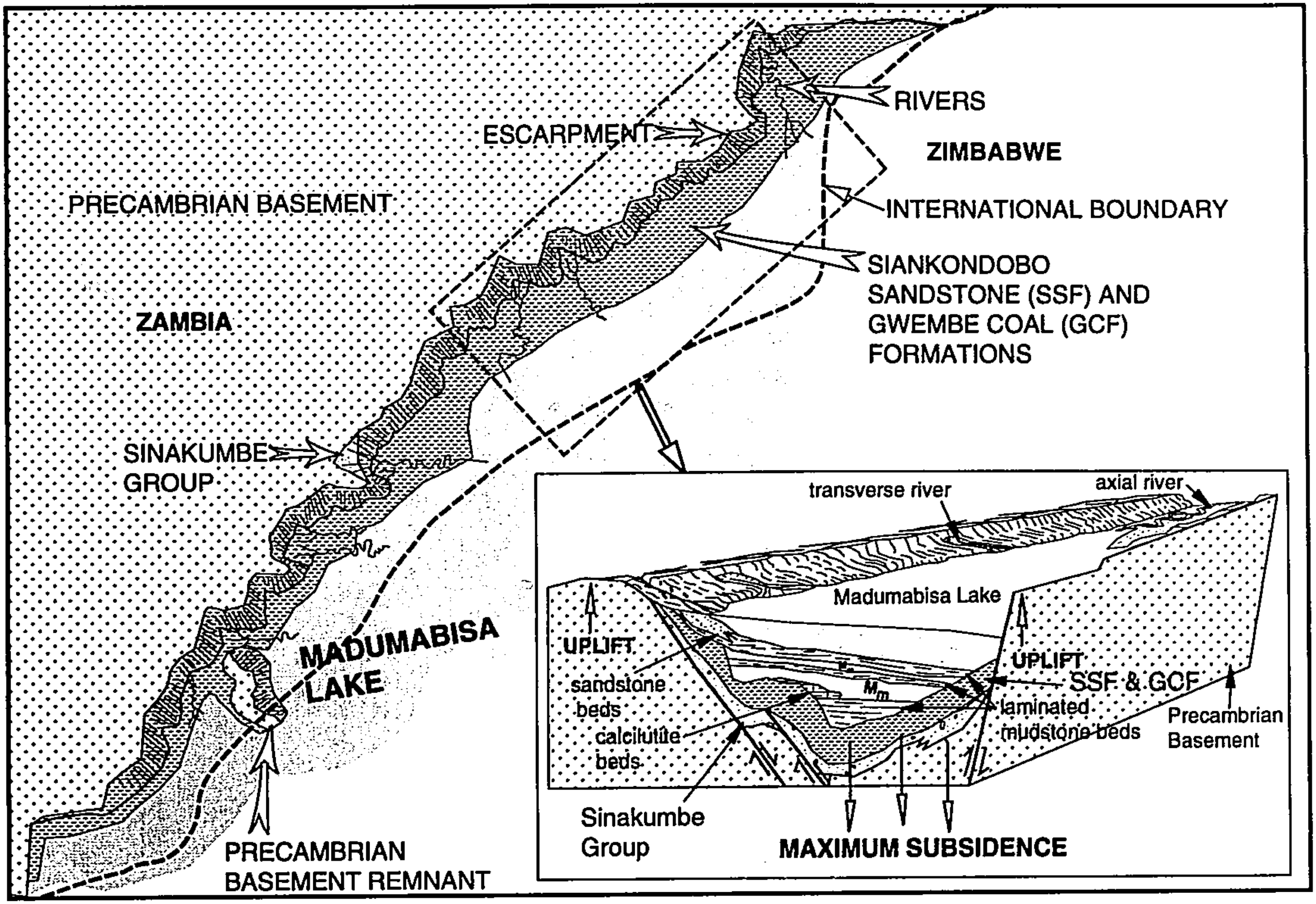


Fig. 5.6 Interpretation of palaeogeography and simplified conceptual depositional model (block diagram) of the Madumabisa Mudstone Formation, mid-Zambezi Valley Basin, southern Zambia. See Fig. 5.0 for the various lacustrine sedimentation processes, environments and water stratification that probable were influential in Madumabisa times. M_m = massive mudstone.

the massive muds are occasionally interbedded with laminated muds (laminae > 2 mm with diffuse contacts) but thinner (with less diffuse contacts) below 100 m deep. Laminated sequences make up an increasing proportion of interbeds in water deeper than 70 m (Cohen, 1990). By analogy the thin laminated silty mudstone beds (< 5 cm) of the Madumabisa Mudstone Formation probably represent deeper water sedimentation. The thickening-upward sequences document gradual shallowing and sediment infilling (regression) following lake expansion and deepening (transgression). The thickening-upward sequences represent progradation of sheetflood. Sharp boundaries between the lithofacies units suggest that the response to climatic factors was rapid (cf. Platt, 1989). Lack of scouring, and few graded beds in the Madumabisa Mudstone Formation, indicate that generation of turbidity currents was minimal. The graded laminae probably were produced by introduction of terrigenous silt to the lake by runoff followed by suspension deposition. The sandstone bodies probably represent confined streams of limited extent that incised the exposed lake margin during lowstand periods. The suite of sedimentary structures further attests to channel fill deposition, and many of the sheet siltstone beds can be interpreted as distal and/or spilled-over deposits of major floods.

Calcareous sedimentation was substantial in the Madumabisa sequence, and the biota of abundant ostracods, bivalves, fish, gastropods and probable calcareous algae, and the evidence of microbial processes, support a lacustrine environment. Kelts and Hsu (1978) indicated that calcite in lacustrine deposits originates through four main processes: (i) inorganic precipitation induced by biological activity (photosynthesis) or physical changes in the environment (temperature, evaporation, or mixing of waters), (ii) accumulation of shells, (iii) introduction of carbonate from extra-basinal sources, or resedimented carbonate derived from fringing playa flats, nearshore or slope deposits, and (iv) diagenetic precipitation. Carbonate precipitation can be generated in the water column either by algal-blooms or by mixing of waters of diverse salinity. In the Madumabisa Mudstone Formation of the studied area, the carbonates occur only as diagenetically precipitated concretionary calcilutite, although Tavener-Smith (1962) has reported some limestone beds in other parts of the basin. This differs from typical lacustrine deposits which commonly contain abundant limestone. Lack of carbonate rocks in the underlying succession of the Sinakumbe Group, Siankondobo Sandstone, Gwembe Coal and basement rocks accounts for the low carbonate input from source terranes, because drainage and weathering control the ionic composition of lake waters (Eugster and Hardie, 1975). Thus the carbonate saturation in the inflow waters was low, whereas the clastic supply was high. This suggests that the Madumabisa Lake was generally open, and that continuous clastic input prevented significant carbonate precipitation (cf. Cohen, 1990).

The thin shells and small size of the ostracods suggest a planktonic habit (cf. Carasco, 1989). Trace fossils are mainly burrows and trails of sediment-ingesting organisms, that are seldom recognizable in the field because of intense reworking and weathering. Bioturbation was prevalent in the mudstone due to lower sedimentation rates with a varying proportion of organic contribution. The low organic content also suggests deposition in oxygen-rich water (cf. Gore, 1988). The development of pedogenic structures and red mottling shows frequent emersions of the sediments. The abundance of bioturbation is evidence of oxic depositional environments even though the green/grey colour indicates at least mildly reducing conditions in surface layers of the sediments not long after sedimentation.

Sulphates are rare, except for barite that locally mimics what were apparently rosettes of gypsum, which suggests that periodic evaporitic conditions were present in the basin. Gypsum pseudomorphs and calcite-filled vugs suggest closed-basin deposition in normal saline to hypersaline waters in response to a semi-arid to arid climate. Encrustations on grey micritic nodules consist of micritic brecciated crusts containing rhizoconcretions, possible vadose geopetal silts, vadose cements and phreatic drusy cements. These features suggest general lacustrine regression, accompanied by soil formation and probably evaporite deposition in the basin. Shallow lakes desiccate or expand very quickly in response to changes in the net water budget (e.g. Lake Chad; Reading, 1982). A lack of desiccation structures in the study area indicates that much of the lake was relatively deep, perhaps greater than 500 m. The overall substrate in the lake varied from oxygenated to mildly reducing as suggested by various colours and mottling. The influence of a reducing microenvironment is further suggested by the occurrence of green coloration filling burrows in light olive grey mudstone. However, the local occurrence of trace fossils identified as *Teichichnus*, *Zoophycos* and *Rhizocorallium* suggests local marine incursions. Furthermore, preliminary examination of fish scales from the Madumabisa Mudstone Formation also suggests possible marine fish (Coultier, 1992 - written communication), and high sulphur contents (~3.2%), such as occur in the Main Seam, have been used elsewhere to indicate marine influence (Williams and Keith, 1963). This combination of characters indicates at least some brackish water influence. Overall, however, the lacustrine interpretation is favoured by the abundance of fresh-water fossils; any marine influence probably was local and brief, perhaps by the way of inland waterways connected intermittently with the sea. Ziegler (1993) mentions brackish water fossils elsewhere in southern Africa, indicating that inland seaways could have been more extensive than formerly supposed.

In summary, the presence of submillimetre-scale lamination, fine grain size, and non-marine fossils collectively suggest deposition in relatively quiet lacustrine waters. The considerable thickness (~ 700 m) of the Madumabisa Mudstone Formation deposits may indicate greater water depth and rapid sedimentation, or greater shoreline stability allowing prolonged sedimentation. The long-lasting lacustrine environments were eventually subaerially exposed, resulting in red and green mottling of the lake sediments as the area was uplifted and became a source of sediment for the Upper Karoo Group. The lake was eventually infilled by southwest- and northeast-prograding fluvial systems of the Escarpment Grit Formation.

5.5 UPPER KAROO GROUP

The coarse-grained siliciclastic sediments of the Escarpment Grit and Interbedded Sandstone and Mudstone formations overlie the Lower Karoo strata, locally spilling over the margins of the basin and resting directly on the basement. The abrupt change at the sharp contact between the lacustrine mudrocks of the Madumabisa Mudstone Formation and the pebbly sandstone of the Escarpment Grit Formation suggests that the latter are of high-energy origin probably in a braided system. This system continued during deposition of the Interbedded Sandstone and Mudstone Formation, but with lesser bedload, as typified by fining-upwards sequences that probably in distal parts of the basin graded into a meandering river system. These are overlain by aeolian red sandstones deposited during arid climatic conditions.

5.5.1 ESCARPMENT GRIT FORMATION AS A BRAIDED RIVER DEPOSITIONAL SYSTEM

The mudrock-very fine-grained to pebbly sandstone facies assemblage is interpreted as a braided channel deposit, in which thickness differences can be related to channels of various sizes that migrated across the floodplain (Fig. 5.7). In comparison to the overlying formation, fining-upward cycles are poorly defined. Coarser components of the cycles are interpreted as deposits of an active braided tract; grain size decreased as the tract aggraded and became inactive (cf. Rust, 1978a). Switching of channels to different parts of the floodplain would have given rise to the erosionally bounded sequences observed in outcrops. The switching would have been accomplished by division around in-channel islands (Coleman, 1969) and by migration across areas of previous floodplain deposition. Rust and Jones (1987) attributed large planar cross-strata to the migration of straight- to sinuous-crested sand waves in the deepest part of the main channel, or as sidebars at the junction of minor channels with the main channel, and the smaller planar sets to the migration of straight- to sinuous-crested bedforms on the backs of sand waves or in shallow water. Planar cross-strata in the Escarpment Grit probably are a result of similar processes. The numerous reactivation surfaces associated with stratified sandstone reflect large oscillations in discharge. The upper thickly stratified sandstone (e.g. Fig. 4.91d) contains water-escape structures that developed as a result of excess pore pressure in the sand due to loading, for example by failure of an adjacent bank (cf. Rust and Jones, 1987). The mudrock lithofacies was formed as an overbank deposit on the elevated floodplain of the river (Williams and Rust, 1969) and less commonly in abandoned channels. Overbank deposition was dominated by flood flow rather than by stagnant-water sedimentation.

Gravel-sized particles in sandy deposits are dispersed or reworked to form lag conglomerates. Rivers with mixed sand/pebble bedload usually result in pebbly sand where simultaneous deposition of both fractions occurs, perhaps with minor current fluctuation; coarser clasts are rarely >1.5 cm. However, where gravel is transported as

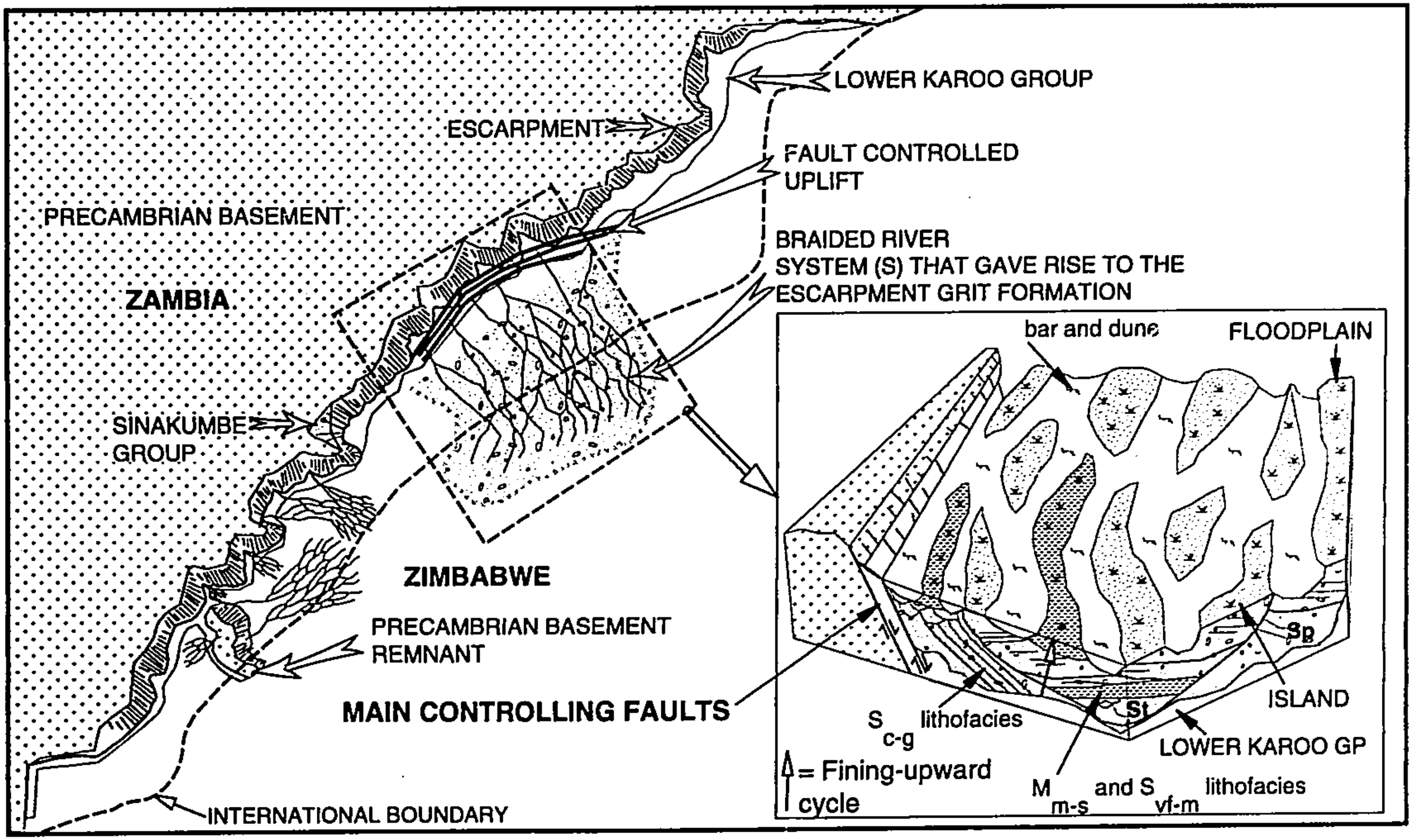


Fig. 5.7 Interpretation of palaeogeography and simplified conceptual depositional model (block diagram) of the Escarpment Grit Formation, mid-Zambezi Valley Basin, southern Zambia.
$M_{m\text{-}s}$ and $S_{vf\text{-}m}$ lithofacies = mudrock, and very fine- to medium-grained sandstone.
$S_{c\text{-}g}$ lithofacies = coarse-grained to pebbly sandstone. Sp = planar cross-stratified sandstone, St = trough cross-stratified sandstone.

bedload and sand in suspension, as in floods, gravel is deposited first during the falling stage, and is infiltrated later by sand (Rust, 1978a). The high and probably fluctuating discharges needed to maintain flow in the Escarpment Grit braided river system were presumably derived from major upland areas to the north/ northeast, and northwest/southwest. Palaeocurrents interpreted for the Escarpment Grit were directed N-NE and S-SW (Figs. 5.8, 5.9). The variation in palaeocurrents is explained by post-Lower Karoo faulting and downwarping that resulted in changes in sediment source areas. The Upper Karoo sandstone consists mostly of subarkosic to arkosic arenite, suggesting derivation from basement rocks of granitic composition, whereas extraformational clasts of Madumabisa Mudstone indicate that the Lower Karoo was a source of sediment for the Upper Karoo.

Proximal sandy braided deposits typically lack mud in primary layers, but mud intraclasts are abundant on erosion surfaces. Horizontally stratified, low-angle (<10°) stratified and trough cross-stratified sandstone beds are also abundant, in vertically and laterally variable successions (Rust, 1978a). These features are common in the Escarpment Grit Formation. Deposition in a meandering river is dismissed because of the paucity of overbank deposits (less than 10%), the absence of epsilon cross-strata and the almost complete lack of repetitive fining-upward sequences (cf. Walker and Cant, 1984). The combination of planar and trough cross-strata in the Escarpment Grit Formation is similar to the South Saskatchewan model of Cant (1978). The occurrence of trough cross-strata in sequences that fine upwards to overbank mudrocks shows that they accumulated in relatively shallow parts of channels (cf. Rust and Jones, 1987). The low mudstone content, the stacking of cross-bedding, the sheet (blanket) geometry of sandstone units and the coarse-grained nature of the predominant lithofacies are consistent with deposition in a broad, low-sinuosity, braided, fluvial system.

5.5.2 INTERBEDDED SANDSTONE AND MUDSTONE FORMATION AS A BRAIDED RIVER DEPOSITIONAL SYSTEM (PROBABLE TRANSITIONAL TO MEANDERING)

The mudrock-sandstone facies assemblage is characterised by fining- and rare

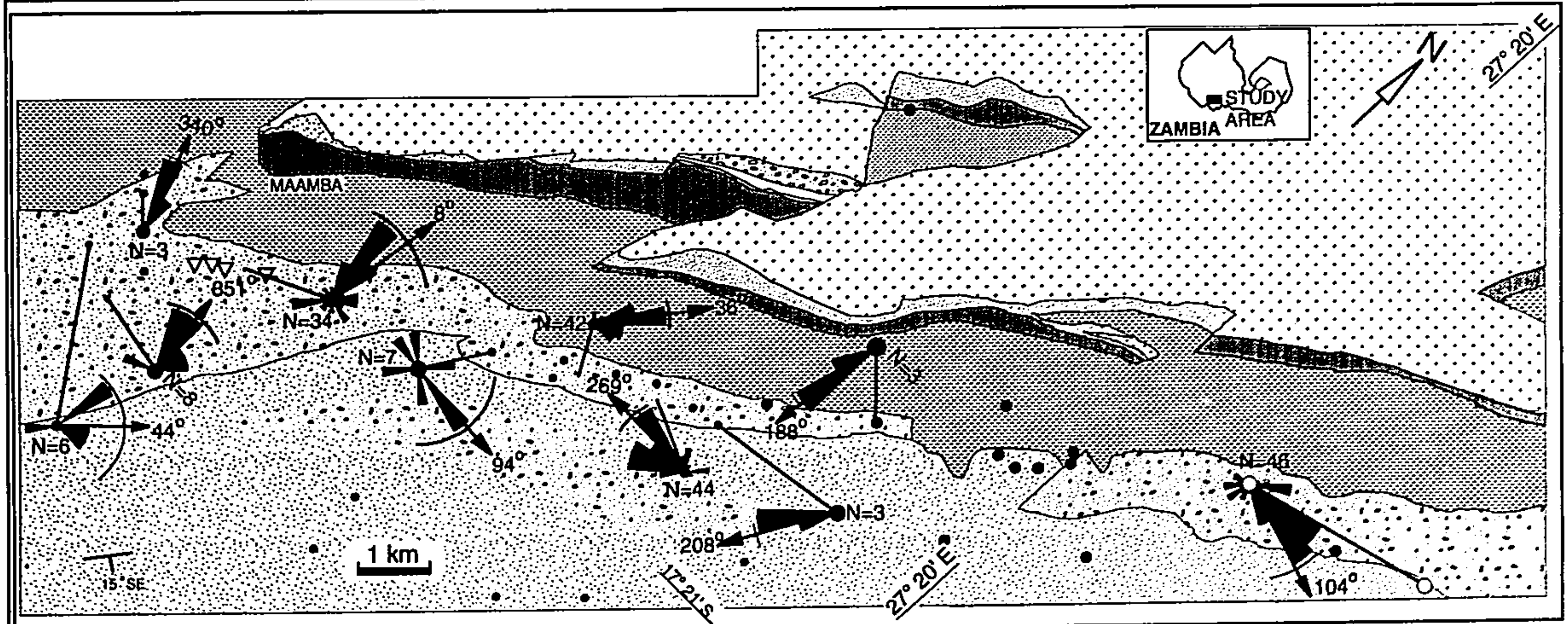


Fig. 5.8 Map showing palaeocurrent directions in the Upper Karoo Group (Escarpment Grit and Interbedded Sandstone and Mudstone formations, mid-Zambezi Valley Basin, southern Zambia. Two palaeocurrent directions are prominent in the Escarpment Grit Formation, to the northeast and southwest, and one to the southeast in the Interbedded Sandstone and Mudstone Formation.

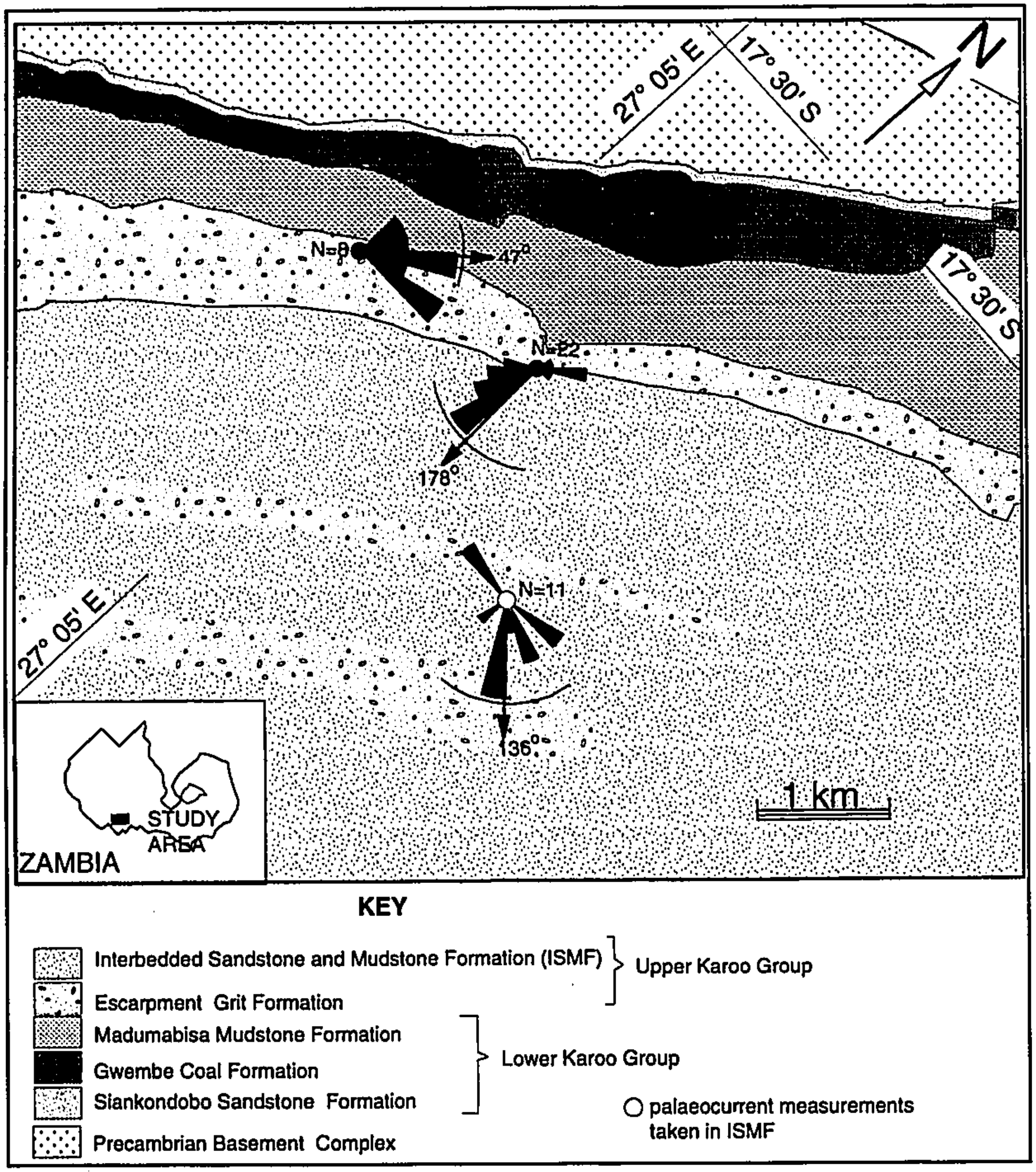


Fig. 5.9 Map showing palaeocurrent directions in the Upper Karoo Group (Escarpment Grit and Interbedded Sandstone and Mudstone formations, mid-Zambezi Valley Basin, southern Zambia. Two palaeocurrent directions are prominent in the Escarpment Grit Formation, to the northeast and south/southeast, and one to the southeast in the Interbedded Sandstone and Mudstone Formation.

coarsening-upward sequences, characteristic of a fluvial environment within which they are interpreted to have been deposited (Fig. 5.10). A fining-upward trend shows the decreasing energy of the current. Channel sequences are 5-15 m thick and typically start with erosion surfaces overlain by lag conglomerate followed by massive sandstone and stratified cosets of sandstone units (planar and trough). The channels become finer upwards by a gradual decrease in the abundance of stratified sandstone relative to cross-laminated and massive mudrocks, and are interpreted to be abandoned channel fills in which some of the upper fill was deposited in stagnant water. Minor changes are attributed to alternating periods of low and high flow in the fluvial systems; high sinuosity configurations correspond to the former, and low sinuosity configurations correspond to the latter.

The fining-upward sequences in the Interbedded Sandstone and Mudstone Formation (ISMF) are repetitive i.e forming cycles (e.g. Fig. 4.101). A modern example of a cyclic braided river deposit is the Donjek (Williams and Rust, 1969, Rust, 1972). Sand-dominated cycles are common in the ancient record (e.g. Devonian Battery Point Sandstone, Cant and Walker, 1976). Repetitive vertical profiles in a braided-river environment can result from: (a) flood cycles, (b) cycles of lateral accretion, (c) cycles of channel aggradation, and (d) cycles of channel re-occupation (Miall, 1977). Distal sandy braided deposits commonly have fining-upward cycles, lateral continuity, and a significant primary mud content, and are transitional to the deposits of meandering systems (Rust, 1978a). The cycles in the ISMF are likely to have resulted from all four mechanisms, although flooding and channel abandonment are likely causes. In gravelly meandering rivers (e.g. Endrick River deposit, Bluck, 1971; Allen, 1965a; Walker, 1976), fining-upward cycles contain pebbly sand deposited at high stage and later reworked at lower stages into isolated localised layers of framework gravel, and the cycles contain one- to two-thirds overbank silt and clay (Rust, 1978a). In the Interbedded Sandstone and Mudstone Formation, the basal conglomeratic beds locally contain mudclasts (e.g. Fig. 4.96d) suggesting unstable bank failure, a feature common in braided channels. However, the high mud content (up to 35 m in bore hole data from Power Nuclear Corporation report, 1987) suggests that a meandering system was periodically established on the

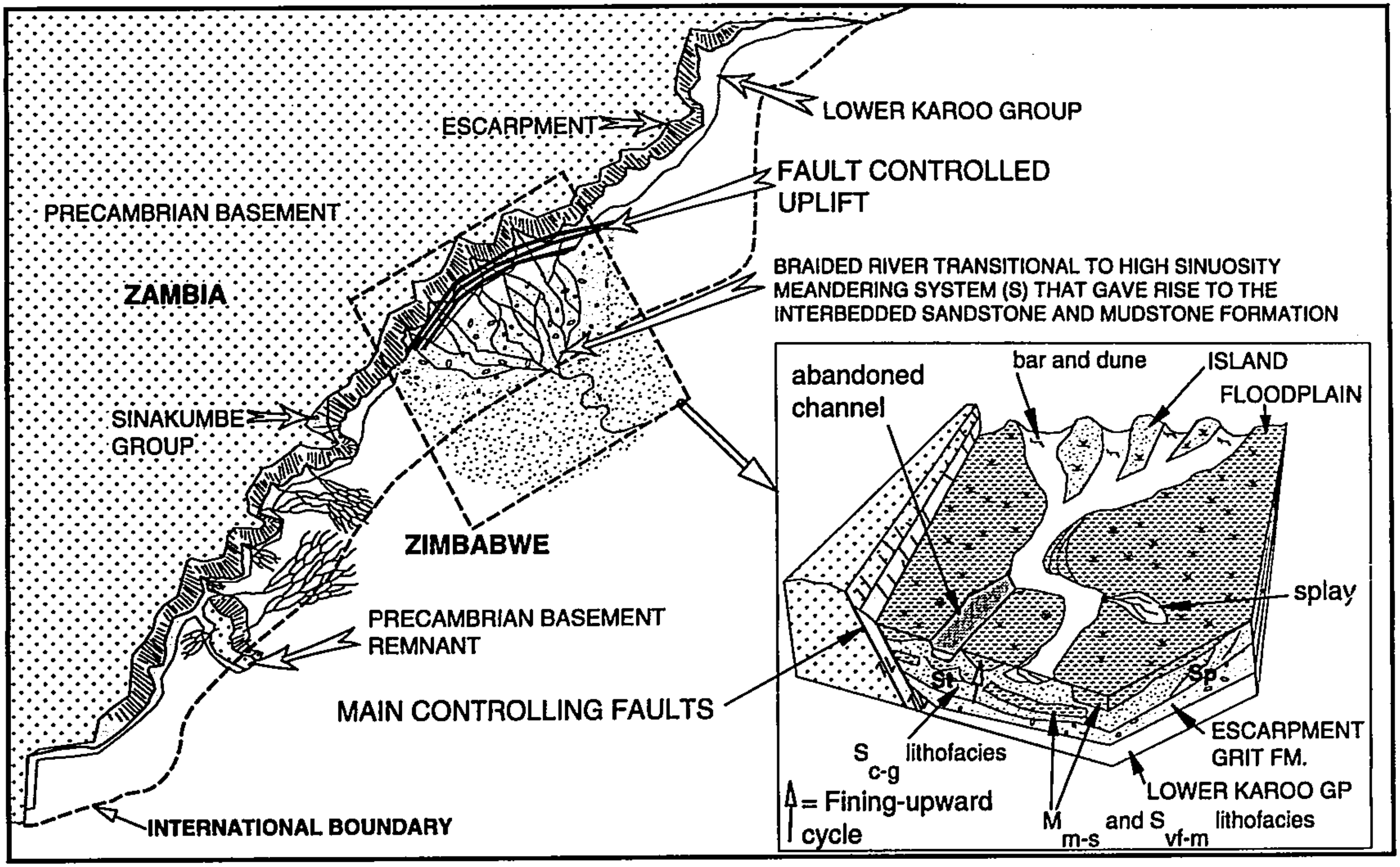


Fig. 5.10 Interpretation of palaeogeography and simplified conceptual depositional model (block diagram) of the Interbedded Sandstone and Mudstone Formation, mid-Zambezi Valley Basin, southern Zambia.
$M_{m\text{-}s}$ and $S_{vf\text{-}m}$ lithofacies = mudrock, and very fine- to medium-grained sandstone.
$S_{c\text{-}g}$ lithofacies = coarse-grained to pebbly sandstone. Sp = planar cross-stratified sandstone, St = trough cross-stratified sandstone.

floodplain even though Miall (1978) indicated that lateral channel restriction on a flood plain, coupled with rapid subsidence, can result in thick overbank deposits in braided rivers. The abundance of trough cross-strata in the assemblage, associated with varying proportions of Sp, Sr, Sh, Se, Sm, Fl and Fm arranged in a thinning- and fining-upward cyclic sequence suggests that the formation represents a sand-dominated braided river (cf. Miall, 1977). Garcia-Gil (1993) discussed the possibility of channels behaving initially as braided channels during periods of high water discharge, but with decreasing stream velocity and water volume, the channels increase their sinuosity so that finer grained sands are deposited, either on previous channel deposits or on floodplain fines. This scenario is the most likely for the Interbedded Sandstone and Mudstone Formation as it explains the absence of desiccation cracks which may have been eroded during floods or not developed because ponding was rare due to the elevated floodplain. No root traces (except for the coaly fragments) were observed in the mudrocks, suggesting that vegetation was not fully established on the flood plain. The absence of cracks and root traces also favours a braided system, because their preservation potential is low in this system, but higher and hence common in floodplains dominated by meandering rivers.

The Interbedded Sandstone and Mudstone Formation is interpreted as the deposits of a sand-dominated braided system that was transitional to a meandering river system (Fig. 5.10). The sediment input was mainly from the northwest as indicated by palaeocurrents directed to the southeast (Figs. 5.8 and 5.9). The abundance of pinkish brown facies compared to greyish green facies suggests deposition in semi-arid conditions. Fluvial sedimentation was succeeded by aeolian sedimentation of the Red Sandstone Formation as conditions became more arid.

CHAPTER VI

THE SINAKUMBE-KAROO TECTONO-SEDIMENTARY BASIN-FILL SUCCESSION AND EVOLUTION

6.1 GENERAL REMARKS

During the Palaeozoic and early Mesozoic eras, Africa was the centre of the Gondwana supercontinent that subsequently broke up during Mesozoic time into the continental masses known today. Before then, the original ancient crustal nuclei which began more than 3000 Ma ago, increased by accretion into larger stable units or cratons up to 550 Ma ago. Regions or zones affected by orogenesis and/or intercratonic instability associated with the nuclei were very active sites of tectonic and sedimentary activity during Palaeozoic and Mesozoic times (Fig. 6.0). These sites included the precursor trough to the mid-Zambezi Valley where the Sinakumbe Group was deposited. During pre-Gondwana split-up (i.e. during Permian, Triassic and Jurassic times), the Karoo sequence and other sediments accumulated in areas of negative relief relative to the cratons. Whateley and Turner (1983) and Whateley and Hopkins (1985, quoted in Falcon, 1989), listed several specific features that exerted a major influence on the nature and form of Karoo sedimentation (Fig. 6.0):

(i) the ancient continental nuclei that provided positive relief or mountainous regions were the sources for the Karoo sedimentation.

(ii) the areas between the ancient cratons became the sites for Karoo and other sediment accumulation, with four basin types being distinguished:

a. large cratonic paralic basins (e.g. Karoo Basin and Angola Basin)

b. intracratonic lineament zones or mobile belts along which the Karoo strata occur in narrow, elongate, fault-bounded grabens or valleys (e.g. mid-Zambezi belts; mid-Zambezi Valley Basin).

c. localized cratonic grabens or fault blocks (e.g. Luangwa Valley Basin)

d. rifted and downwarped continental margins (e.g. part of the Mozambique Belt)

However, because of differences in basin structure, Rust, I. C. (1975) suggested that there

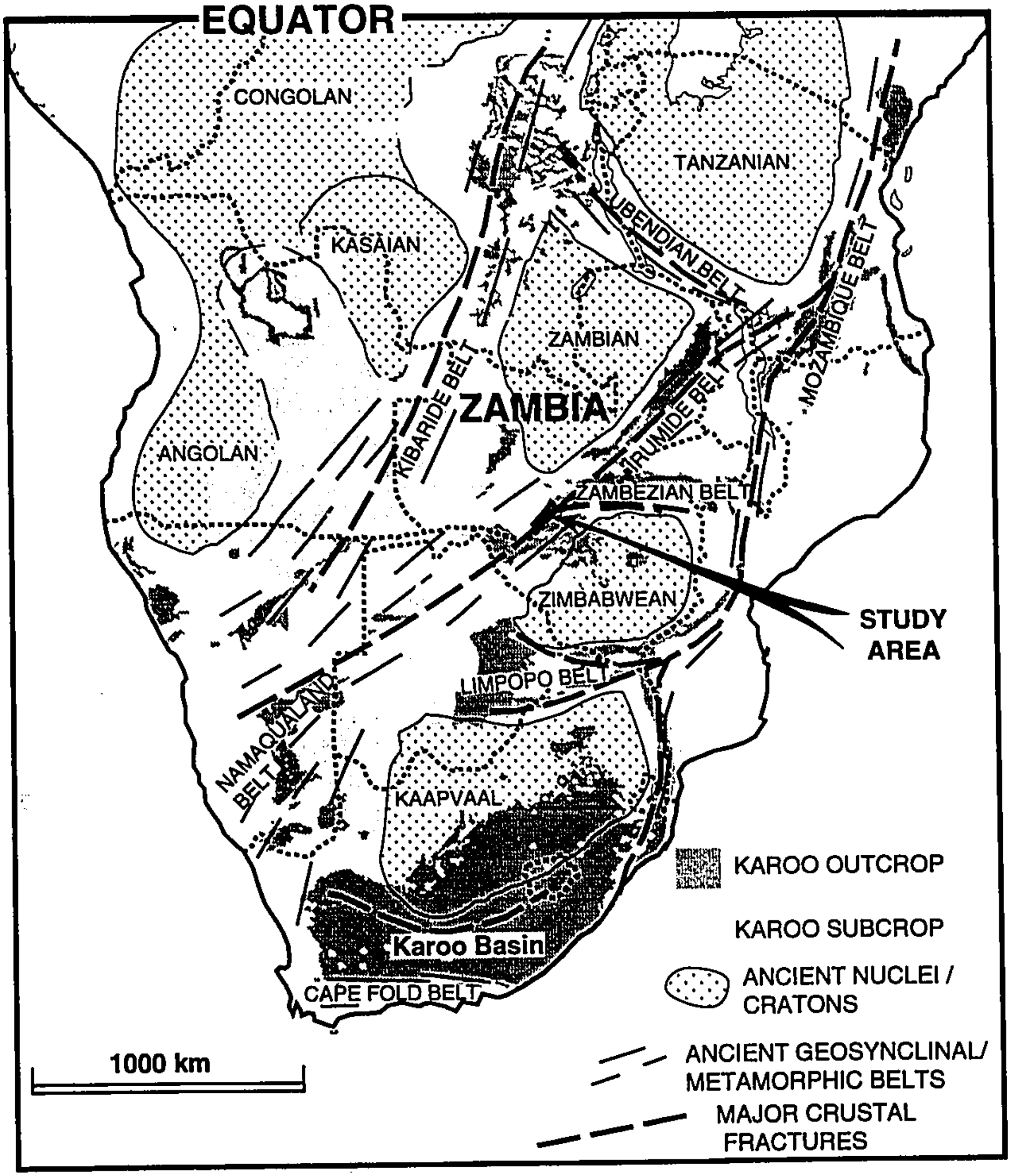


Fig. 6.0 Major structural features affecting deposition of the Sinakumbe Group in Zambia and Karoo Supergroup in southern Africa during Palaeozoic and early Mesozoic times (compiled and modified from Verniers et al.,1989 and Falcon, 1989). Location of the study area in the mid-Zambezi Valley Basin, Zambia is indicated.

were two major tectono-sedimentary terranes, which were separated approximately by the 25° E meridian. The Zambezian Terrain basins (eastern side) were influenced by tensional fault tectonics and include b, c and d of Whateley and Hopkins (1985), whereas the Karoo Terrain basins (western side) are mainly cratonic sags (see (ii)a above).

In the Zambezian Terrain, extensive downwarping took place, resulting in much thicker sequences of Karoo sediment, with extensive cyclic deposition (Falcon, 1980; Whateley and Turner, 1983; this study).

The individual lithofacies described in Chapter 4 represent specific depositional environments which are components of the depositional setting represented by facies assemblages. These depositional settings are in turn components to the major interrelated non-marine Sinakumbe-Karoo depositional systems discussed in Chapter 5, which represent major phases in the evolution and fill of the mid-Zambezi Valley Basin. The arrangement of these systems reveals vertical and lateral changes in environments and limits of basin geometry through time.

Deposition of the Sinakumbe-Karoo strata in the mid-Zambezi Valley Basin was controlled by tectonic movements, with expressions analogous to intracontinental rift systems, and by climatic changes. The movements were mainly on fault-bounded margins in what is interpreted as an extensional basin of the half-graben type. There are three fundamental categories (setting) of rift zones: (a) oceanic (intraoceanic) where the axial graben is bordered by oceanic crust, (b) continental (intracontinental) where both rift floor and shoulders are of continental crust (usually slightly thinned), and (c) intercontinental where the rift has oceanic crust and the shoulders have continental crust (Milanovsky, 1972). The mid-Zambezi Valley Basin has most in common with the intracontinental rift system, and this type of system is reviewed here to provide insights into the development of the basin.

6.2 INTRACONTINENTAL FAULT-BOUNDED EXTENSIONAL BASINS

Rifts correspond to the juvenile state of a sedimentary basin and can evolve in an intracratonic domain, a platform basin, or in the passive margin of a pericratonic domain (Perrodon, 1983). Intracontinental rifts are long, narrow structures where extension of the lithosphere has occurred (Burchfiel, 1980; Burke, 1980). There are two main end-members of fault-bounded basins: distensive linear grabens and transtensive rhombic pull-aparts. Distensive and transtensive basins occur along linear fault zones where an extensional stress field is maintained over a relatively long time (Illies, 1981). Changes in the stress field mav render some structural features inactive, but reactivate others with different senses of motion (Illies, 1981). In a distensive basin, formation and evolution are dominated by vertical subsidence of the basin floor, whereas in the pull-aparts it is by a combination of lengthwise horizontal prolongation and vertical subsidence of the basin floor.

The characteristic processes are crustal extension and vertical movements (observed on surface), lithospheric thinning, and upwelling of mantle material (deep-seated phenomena) (Neugebauer, 1983). Volcanism, faulting, doming and extension are the principal features of rifts. Most fault-bounded basins are elongate parallel to fault trends, with drainage patterns and sedimentation that is transverse and longitudinal to the basin axis (Miall, 1981b). Most rifts are rejuvenated several times during their life history (Sengor et al., 1978). Subsidence in sedimentary basins results from crustal attenuation, thermal subsidence during and following extension, flexural loading due to compression, and sedimentary loading (Ingersoll, 1988).

6.2.1 DISTENSIVE LINEAR (GRABEN) BASINS

Basin characteristics: Grabens are framed by two convergent dip-slip faults which separate downthrow wedge-blocks disintegrated by numerous antithetically listric dip-slip faults (Illies, 1981). Most graben structures follow pre-existing zones of weakness in the basement along which the tensile strength of the lithosphere had diminished relative to the adjoining plate unit. Two methods of formation are favoured: active mantle convection mechanism that generates a crustal hotspot followed by regional doming, crustal thinning, abundant volcanism and rift subsidence (Neugebauer, 1983; Bott and Mothen, 1983)(e.g. East African Rift, Fairhead, 1986; Dunkelman et al., 1988); and active tensional stress at a plate boundary that causes horizontal extension, crustal thinning and stretching, followed by passive mantle upwelling and rift subsidence with little volcanism (Turcotte and

Emerman, 1983; Girdler,1983; Jarvis, 1984) (e.g. West African Rift, Fairhead, 1986; Dunkelman et al., 1988). Crustal thinning (causing subsidence) is the common mechanism that causes broad subsidence followed by narrower rift subsidence whereas crustal heating causes broad doming followed by rift subsidence (Baker, 1986; Watson et al. (1987); Clendennin et al., 1988). The subsidence rate is faster in narrow grabens than wide basins, due to lateral heat flow that encourages rapid and deep subsidence, particularly in the first 10 Ma (Jarvis, 1984). Linear isostatic shoulder uplifts rim the graben due to unloading and rotation of the footwall as the hanging wall subsides (Gawthorpe, 1987), and provide local sediment sources, but also direct most of the runoff away from the graben (Frostick and Reid, 1987). The unloading of the shoulders and loading of the graben floor act as an additional energy input for the evolution of crustal rifting. The resulting distensive basins are typically large (100's km long x 10's km wide x several km deep) and long-lived (10's Ma); they are commonly associated with crustal thinning, mantle upwelling, high heat flow and some volcanism (Neugebauer, 1983).

Nearly all rifts are asymmetric and are broken lengthwise into scoop-shaped segments about 100 km long x 50 km wide (Gibbs, 1984; Rosendahl et al., 1986; Bosworth, 1987; Frostick and Reid, 1987; Leeder and Gawthorpe, 1987; Coletta et al., 1988; Dunkleman et al., 1988). The major listric bounding faults merge at 12-18 km depth along a major mid-crustal decollement surface which separates upper brittle and lower ductile layers (Brun and Choukroune, 1983), and occur on one side only, although there may be smaller antithetic faults on the other side which give a surface form of symmetry to the basin (Gibbs, 1984; Frostick and Reid, 1987; Coletta et al., 1988; Ellis and McClay, 1988). The faults may be planar or listric, so that if one is well developed, then a half graben forms (Bott and Mothen, 1983) or a full graben geometry where basin trough widens (>30-50 km) (Morley, 1988). Each segment (e.g. eight for Lake Tanganyika; Rosendahl, 1988) comprises an asymmetric half-graben/tilt block with the main arcuate listric bounding fault on one side and a hinged hanging wall slope on the other (Rosendahl et al., 1986; Frostick and Reid, 1987) and typically alternate in polarity of asymmetry lengthwise along the rift and are linked end-to-end across basement high accommodation zones or transfer faults which develop early in the history of subsidence (Illies, 1981;

Gibbs, 1984; Rosendahl et al., 1986; Frostick and Reid, 1987; Barrett, 1988; Coletta et al., 1988). Different rates and magnitudes of fault subsidence may therefore be experienced by adjacent segments, although the entire system undergoes a generally similar structural history (Hamblin and Rust, 1989).

Basin-fill characteristics: The basin-fill in distensive basins is large and linear (100's km long x 10's km wide x several km thick) and rests unconformably on basement rocks (Hamblin, 1989). The sediment fill is controlled by environmental conditions and short distance transport from the shoulders towards the basin, with lacustrine and lagoonal facies prevailing (Illies, 1981). Vertical stacking of basinwide stratigraphic units corresponds to major tectonic phases resulting from vertical tectonic motion (McKenzie, 1978). Segmentation of individual sub-basins introduces variation in what would otherwise be a lengthwise-consistent stratigraphic record (Rosendahl et al., 1986; Leeder and Gawthorpe, 1987). The sequence comprises: (i) bimodal volcanics, (ii) coarse subaerial fluvial sediments in a broad sag basin, (iii) a narrow graben (syn-rift) sequence of subaqueous followed by subaerial deposits, and (iv) an overlying (post-rift) sequence of a thermal subsidence phase. The intracontinental bimodal volcanics are commonly extruded in the early history, especially close to bounding faults (Hamblin and Rust, 1989).

Depositional processes and facies arrangements in each segment (sub-basin) display a marked basinwide asymmetry in facies, palaeocurrents and thickness (Leeder and Gawthorpe, 1987) resulting in a wedge-shaped syn-rift sequence, thickening toward the footwall scarp (Frostick and Reid, 1987). The polarity of this asymmetry alternates along the length of the system (Crossley, 1984; Leeder and Gawthorpe, 1987). Sedimentation in distensive basins is controlled by a complex interplay of (i) sediment input, (ii) faulting and block rotation creating tectonic slopes and topography, and (iii) subsidence and climatic changes affecting relative lake level. Modern examples of distensive basins in the east African Rift are Lake Tanganyika (Cohen, 1989; Cohen, 1990; Tiercelin et al., 1992) and Lake Malawi (Crossley, 1984) where alluvial fans occur on the steep fault margins, and floodplains and river deltas characterize the ramp slope margin. Ancient distensive basins (e.g. the Newark Basin) present a tripartite stratigraphy with moderate thicknesses an order of magnitude smaller than the basin size (width). The sequence in the Newark

Basin comprises (i) basal thick alluvial/fluvial conglomerate and sandstone, (ii) middle lacustrine shale, siltstone and sandstone, and (iii) upper reddened fluvial/alluvial smaller-scale sequences that are common and may relate to tectonic motions or climatic phases (Hamblin, 1989).

The structural and stratigraphic record of many distensive basins reflects predominantly vertical tectonic movements. For example, boundary fault throw reached more than 8 km in the Lake Tanganyika Basin, which allowed deposition of 4 km of sediments in the deepest parts of the basin (Rosendahl et al., 1986; Burgess et al., 1988). The basins are characterised by a long subsidence history related to major orogenies, with changes in subsidence rates; uplift and non-deposition may be followed by rapid subsidence (Derito et al., 1983). Subsidence along a fault has an instantaneous deepening effect (Blair, 1987), causing shoreline transgression at both the steep footwall and gentle hanging wall margins, and soft-sediment deformation (Leeder and Gawthorpe, 1987). Lacustrine facies therefore dominate, especially near the steep footwall side of the asymmetric half-graben segment only during periods of maximum subsidence, which results in topographically deep, closed sub-basins (Blair, 1987; Leeder and Gawthorpe, 1987; Watson et al., 1987; Blair and Bilodeau, 1988). The slow rate of erosion and coarse sediment production means that the supply of coarse sediment always lags behind rapid fault-induced subsidence, but as subsidence decreases, scarp erosion and sediment supply catches up, coarse marginal facies prograde from the sides, and a general coarsening-upward sequence develops (Blair, 1987; Watson et al., 1987; Blair and Bilodeau, 1988).

6.2.2 TRANSTENSIVE (PULL-APART) BASINS

Strike-slip faults are classified as transform faults which cut the lithosphere, as plate boundaries, or as transcurrent faults which are confined to the crust. Their primary motion is parallel to the fault trace (Mitchell and Reading, 1986). The fault lengths are hundreds of kilometres for the major faults, and generally less than 100 km (with displacements of a few to tens of kilometres) for the conjugate faults (Sylvester, 1988). The distinctive features of strike-slip belts are the adjacent occurrence of both extensional and compressional features, and the fact that they are contemporaneous. Thus basin sedimentation, folding, thrusting, uplift, and erosion leading to the development of unconformities, commonly with strong angular discordance, should occur together.

Pull-apart basins evolve between overstepping, en echelon, strike-slip faults that bound the basins or form near releasing bends (Crowell, 1974) and are tulip-shaped in profiles normal to strike (Sylvester, 1988). The characteristic features of transtensive basins (Christie-Blick and Biddle, 1985) include: (i) mismatches across basin margins, (ii) longitudinal and lateral basin asymmetry, (iii) episodic rapid subsidence, (iv) abrupt lateral facies changes and local unconformities, and (v) marked contrasts in stratigraphy, facies geometry, and unconformities among different basins in the same region. Pull-apart basins are relatively small (generally <50 km long), relatively short-lived, and asymmetric, with a unique structural history subject to structural alteration as regional movement continues (Mitchell and Reading, 1986). Subcircular depocentres within the basin migrate through time as the pull-apart lengthens (Crowell, 1974).

Basin-fill characteristics include: (i) extreme lateral facies changes, (ii) very thick sedimentary fills of limited lateral extent, (iii) very large and rapid vertical movement along syn-sedimentary faults, (iv) a wrench-fault structural pattern, in particular en echelon folds, and (v) an asymmetric basin fill, both in cross-section due to dominance of one of the marginal faults, and in longitudinal section (e.g. Dead Sea and Ridge basins). The patterns of sedimentation are controlled by strike-slip displacement, structural asymmetry, localised depocentres and uplifts, with most sediment input from one dominant fault margin and the from the uplifted basin end which pulls away (Gloppen and Steel, 1981). Narrow belts of coarse marginal facies and broad belts of sandy central facies are characteristic, whereas fine-grained lacustrine sediments are less common because of the high ratio of sediment input to basin size (Gloppen and Steel, 1981). The dominant strike-slip motion produces basinwide lateral offset that exceeds vertical subsidence in the long term. Most pull-apart basins have low length-to-width ratios in the range of 3:1, owing to their short histories in changing strike-slip regimes (Mann et al., 1983).

Sediment-fill in pull-apart basins is a localised, very thick complex succession resting unconformably on highly faulted basement rocks. The sediment bodies are stacked en echelon lengthwise through time due to episodic migration of the depocentre parallel to major faults (Gloppen and Steel, 1981; Zak and Freund, 1981), leading to lateral diachroneity and rapid accumulation, with apparent stratigraphic thicknesses of the same order of magnitude as the size of the basin, and 2-5 times the actual basin depth, a feature not possible in distensive basins (Speksnijder, 1985). For example, the Devonian Hornelen basin of Norway is 70 km long with >25 km of basin fill; the Permian Cantabrian basin is 55 km long with 15 km of basin fill; and the Quaternary pull-apart of Turkey is up to 15 km long with 5 km of basin fill (Hamblin, 1989). Synsedimentary fault motion is continuous, and soft-sediment deformation is prominent. Petrographic trends reflect the overall migration of depocentres, and lateral offset of the sediment source areas (Ballance, 1980).

6.3 EXTENSIONAL STYLE DURING SINAKUMBE-KAROO DEPOSITION

Evidence for strike-slip faulting is lacking in the mid-Zambezi Valley Basin. The absence of contemporaneous basin sedimentation and folding attests to this. In addition, the absence of dominant bounding faults (strike-faults) at basin margins (the Lower Karoo or Sinakumbe Group commonly overlie the basement unconformably for the most part in the Nkandabwe and Mulungwa map area), the thin basin fill, and large basin size (550 km long x 70-300 km wide - approximate estimates from Fig. 1.1b) are in best accord with the distensive basin model. The Ordovician-Jurassic mid-Zambezi Valley basin is therefore interpreted as a distensive (half-graben type) basin in which the Sinakumbe Group is preserved in small sub-basins along the northwestern margin of the basin, with over 95% of the basin filled by Karoo Supergroup sediments. The localised volcanism (Early Jurassic Batoka Basalt Formation) at the end of Karoo deposition in contrast to abundant volcanism associated with active mantle upwelling rift formation suggest the rift formation resulted from extensional stresses at plate boundaries.

The Sinakumbe Group directly overlies the Precambrian basement, and is overlain by the Karoo Supergroup of Permo-Carboniferous to Early Jurassic age.

6.3.1 THE SINAKUMBE TECTONIC SUCCESSION

The Lower Sinakumbe Group is an alluvial fan complex outcropping at the northern /northwestern margins in some sub-basins (e.g. Muzuma-Sikalamba corridor) of the mid-Zambezi Valley Basin. The lower part forms a coarsening-upward cycle that contains small-scale fining- and coarsening-upward cycles. Observations of modern alluvial fans and experimental fan studies indicate that fan morphology and surface processes are controlled by both allocyclic variables, such as climate and tectonism, and autocyclic variables, such as channel diversion and bar migration, that are inherent to fan depositional systems (Eckis, 1928; Hooke, 1967; Williams, 1973; Steel and Wilson, 1975; Schumm, 1977). On this basis the depositional facies of the Lower Sinakumbe Group can be related to both allocyclic and autocyclic variables, with the overall coarsening-upward cycle of the lower part recording a period of tectonic uplift, and fan progradation (due to slowed subsidence), and the small-scale cycles representing changes inherent to the alluvial-fan system (autocyclic). The major cycle probably resulted from the alluvial fan-lobe prograding downslope in the basin, across the mudflat and sandflat environment, as a result of vertical movements of the basin floor or uplift of the basement area (cf. Ramos et al., 1986) followed by waning subsidence of the basin floor, reworking and progradation of coarse-grained marginal deposits. These were followed abruptly by deposition of the quartz arenite assemblage of Upper Sinakumbe Group.

The sediment distribution of the Sinakumbe Group is consistent with sub-basin geometry of the half-graben type in which the basin slope was towards the southeast, with the alluvial fan system draining in the same direction. The sub-basin geometry was determined by a fault system with east-west and north-south trends. Deposition and drainage in these Sinakumbe Group sub-basins were controlled by these faults. Subsequent tectonic movements, due to renewed faulting, appear to have activated braided-stream systems (probably with the main source in the Sikalamba River area for the Sikalamba-Muzuma corridor, and from the northeast in the southwest part of Nkandabwe area) (Fig.5.1) flowing towards the southwest, giving rise to the Upper Sinakumbe Group. This scenario is suggested by palaeocurrents in the Upper Sinakumbe Group that are oblique/perpendicular to the palaeoslope of the Lower Sinakumbe Group alluvial fan system (Fig. 5.2), and by the absence of transitional facies between the two formations (Figs. 4.11 and 4.14b). This indicates that the low sinuosity braided streams that deposited the quartz arenite resulted from reactivated tectonic movements (cf. Ramos et al., 1986). Later tectonic movements, that occurred before the onset of Karoo sedimentation, seem not to have affected the corridor sub-basin, because sediments of the Karoo are absent and the Upper Sinakumbe Group is preserved. However, both the corridor sub-basin and the surrounding basement areas acted as source areas for the Karoo. The thickness and coarse grain size of the terrigenous detritus indicate that the source terrane had high relief, and locally arkosic composition reflects derivation from uplifts cored by granitic crystalline rocks (cf. Werner, 1974; Mack and Rasmussen, 1984).

According to Bull (1964) and Williams (1973), Quaternary alluvial-fan processes were controlled by climate, with semiarid climate corresponding to fan building and drier-than-normal conditions to dissection and deposition of gravel at the toe. In the Lower Sinakumbe Group cycle, climatic indicators such as palaeosols and evaporites have not been observed. The non-development of palaeosols suggests that wetter-than-normal periods were absent (cf. Williams, 1973) and a lack of playa lakes suggests that sheetfloods were shortlived. It appears, therefore, that climate variation was not a major factor, and probably deposition of the Lower Sinakumbe Group took place in a semiarid environment. Denman and Money (1970) postulated that deposition of the Sinakumbe Group (borehole GS 96) occurred in a linear basin (precursor to the Karoo trough and the present mid-Zambezi Valley) trending north-easterly, approximately parallel to the tectonic strike of the older basement rocks, and that the basin was infilled laterally from both margins along few and widely spaced (on the north-western margin of the trough) submarine canyons, and possibly axially. Whereas there is no evidence for submarine canyons, the filling of these basins was probably mainly transverse to basin margin with relatively minor axial input, except in certain sub-basins such as the corridor where the Upper Sinakumbe Group is preserved.

6.3.2 THE LOWER KAROO TECTONIC SUCCESSION

Initial tectonism, followed by continued subsidence, is reflected in a change from the underlying glacio-fluvial / glacio-lacustrine system of the Siankondobo Sandstone Formation following deglaciation into the probable meandering river system-dominated floodplain on which the Gwembe Coal Formation was deposited. Isostatic rebound following deglaciation probably raised the base level and allowed development of swamps in marginal parts of the basin. The influx of coarse sediments of the Maamba Sandstone (probably in a meander belt) over the Siankondobo Sandstone Formation provided a substrate on which plants flourished in swamps on the flood plain. Money and Drysdall (1975) indicated that after a period of uplift, the quiet-water deposits of the Siankondobo Sandstone Formation were succeeded by floodplain deposits of the Gwembe Coal Formation.

In the mid-Zambezi Valley Basin, Zambian side, coal seams are generally of moderate to poor quality (ash ≤ 22%, sulphur ≤ 2.5%) of highly inertic (semifusinite content > 80%) and of sub-bituminous rank (Money and Drysdall, 1975; this study). In southern Africa, the major coal-bearing strata occur in the Karoo sequence, or equivalent-aged rocks, of basins ranging from Gabon, Angola and Zaire in the north, to South Africa and Namibia in the south. The coals are predominantly bituminous to anthracitic in rank, of Early Permian to Early Triassic age. The *in-situ* seam type ranges from highly vitric (>90% vitrinite) to highly inertic (<10% vitrinite), and most seams contain high proportions of semireactive inertinite. The grade or ash content in the sub-continent varies from 8% to over 50% (Falcon, 1989). These differences are attributed to various structural and sedimentary settings within which the southern African peats were deposited, to the wide range of ages, palaeoclimates, palaeoenvironments and plant communities, and to subsequent geological tectonic events. Falcon (1989) cited climatic conditions, uneven basement topographic features, the history of sedimentation including water-table fluctuations and basin stability, type of environment in which the peat accumulated (including fluctuating pH and Eh), geothermal gradients, and proximity to major features such as contemporaneous river channels as factors that could have affected the rate of plant growth and plant matter degradation. These factors would partly explain the high proportion of inertinite and reactive semifusinite in the older (and climatically colder) Main Seam, in comparison to the younger (warmer) highly vitrinite-rich minor upper seams typical of middle to late Permian times. Dewison (1989) also indicated that durain macerals and dull coals often represent a hiatus in peat accumulation, which could thus produce an apparent increase in the rate of accumulation of extraneous inorganic material. The thickness and geometry of the seams, and the rank of coal, appear to have been influenced by the structural framework of the region, so that high stable cratonic shelf coalfields that are far from palaeogeothermal sources are relatively uncompressed, low rank, few in number and extend over wide areas. In contrast, in the Zambezian Terrain basins, coal seams range from low-rank bituminous on the margins to graphite near sources of higher palaeogeothermal heat and greater depth of burial. The seams are relatively numerous, thin and often discontinuous (Falcon, 1989). During the time of Gwembe Coal Formation, sub-depositional environments were controlled to a large extent by pre-Karoo topography and tectono-sedimentary history. These varied from sub-basin to sub-basin within the mid-Zambezi Valley Basin, resulting in variation in facies within and between map areas (Nkandabwe, Siankondobo, Maze-Sinakumbe and Mulungwa; Figs 2.2 a-d). This is represented by differences in thickness of the various lithostratigraphic units, including coal seams, from one coalfield to another. Within an individual coalfield, variation in lithology and thickness can be significant. For example, in the Siankondobo Coalfield area, the Main Seam has been split in the Kazinze Open pit (Figs. 4.36; 4.58; 4.59 and 4.60), but only a single seam occurs in the Izuma Open pit (Fig. 2.5b), about 2 km away. The two open pits are now separated by post-Gwembe Coal Formation faulting. From the geometry and character of the coal seams and the enclosing strata, the cause of coal seam splits has been variously interpreted to be due to: (i) differences in composition of peat-, clay-, and sand- dominated sequences, (ii) tectonism, and (iii) channel sedimentation contemporaneous with peat accumulation (Broadhurst et al., 1968; Elliot, 1968; Broadhurst and Simpson, 1983; Fielding, 1986). In the Kazinze Open pit, channel sedimentation (Interseam Sandstone) was the cause of coal seam splits (Figs. 4.36a; 4.58; 4.59 and 4.60). The channels and splays provided detrital influx into the peat-forming swamps. An absence of syndepositional deformation structures and fault-planes within the coal seams indicates that faulting and tectonic activity were minimal, and therefore suggests that splitting of the Main Seam was due to periodic flooding that led to avulsion through crevasse channels and splays.

In the modern east African rift valleys (half grabens), Vincens et al. (1986) and

Tiercelin (1986) have shown that tectonism was responsible for partitioning of the peat-forming and sediment-accumulating environments. Coarse clastics are close to the basin margin faults, whereas fine-grained sediments (clays and silts) accumulated outside zones of coarse clastic transport. Because subsidence commonly occurred too quickly for sediments to fill the basin, swamps could develop, for example, in the southern end of Lake Tanganyika (Mondeguer et al., 1987 as quoted in Courel, 1989). In the mid-Zambezi Valley Basin, peat-forming swamps occurred in marginal areas when the rate of plant production was probably equal to the rate of subsidence, and in areas outside high sand and silt accumulation in the most strongly subsiding part of the basin. The physical characteristics and lateral continuity of the Main Seam indicate that the basin was undergoing a relatively constant rate of subsidence (allocyclic control) with a steady supply of sediment that permitted plant growth for long periods over wide areas. Abrupt rejuvenation due to tectonism resulted in an influx of coarse sediments (Sandstone A), representing a braided river system (proximal margins of the basin) that started the second cycle of the Gwembe Coal Formation and terminated thick peat accumulation. Thin Upper seams accumulated instead. Minor sandstone and siltstone bodies such as Sandstones C, D and E are explained mainly by avulsion processes and formation of crevasse channels, splays and levees on the floodplain independent of allocyclic mechanisms.

Block-faulting resulted in the formation of rapidly subsiding half-grabens where the relatively deep Madumabisa Lake was established (Madumabisa Mudstone Formation depositional system). Facies changes in lakes are controlled by climate, catchment area geology, and tectonics, and the geometries of their sediment bodies can be used to infer palaeotectonic features (Platt, 1989). Areal facies and thickness distributions would show strong tectonic control and would reflect the pattern of differential subsidence. However, coarse-grained facies are lacking in the Madumabisa Mudstone except for relatively thin sandstones and siltstones. The absence of differential subsidence in the basin would have resulted in a lack of transitional lacustrine facies, allowing instead the deposition of a uniform sequence that is typified by large volumes of clastics (the mudrock assemblages). The thickening-upward cycles of the laminated mudrock facies assemblage suggest tectonic control. Post-Lower Karoo faulting terminated the lake sedimentation, allowing influx of the overlying Upper Karoo sediments.

6.3.3 THE UPPER KAROO TECTONIC SUCCESSION

Renewed Triassic tectonism, probably related to the Gondwanide orogeny in South Africa (Turner, 1970), initiated the deposition of coarse siliciclastics of the Escarpment Grit Formation (EGF), Upper Karoo Group, creating a broad flood plain in which a braided river system prevailed. Sediments locally spilled over the margins of the basin to accumulate directly on the basement. Changes in palaeocurrents in the Escarpment Grit Formation (in opposite directions) probably indicate local reactivation of faults and downwarping, resulting in different source areas. Precambrian basement remnants forming ridges within the basin could account for different sediment sources and hence opposing palaeocurrents. As the basin stabilised, fining-upward cycles in the Interbedded Sandstone and Mudstone Formation were produced by a combination of flood cycles and channel abandonment, rather than by tectonism. The braided system was eventually replaced by aeolian sedimentation that resulted in the Red Sandstone Formation. These conditions seem to have prevailed until all Karoo sedimentation in the basin was terminated by volcanism (Batoka Basalt Formation) during the Early Jurassic.

6.4 THE OVERALL SINAKUMBE-KAROO TECTONIC SUCCESSION

In the mid-Zambezi Valley Basin, southern Zambia, the overall strato-basin fill is represented in Fig. 6.1. Breaks in sedimentation occur at the bases of the Sinakumbe Group, the Siankondobo Sandstone, the Gwembe Coal and Escarpment Grit formations. The nature of the contact between the Upper Sinakumbe Group and the Lower Karoo Group is not known, whereas the localised nature of the break between the Siankondobo Sandstone and Gwembe Coal suggests a short period of erosion or non-deposition. The rarity of marine strata restricts the mechanism for sedimentary cyclicity in the studied part of the Sinakumbe-Karoo strata to repeated uplift and erosion of the continental hinterland, repeated climatic changes (e.g. glaciation-deglaciation), and cyclic effects from steady change such as: (a) isostatic adjustments, (b) adjustment to tectonic stress, (c) trapping and releasing of sediments from heavily vegetated swamps, (d) effects of compaction of

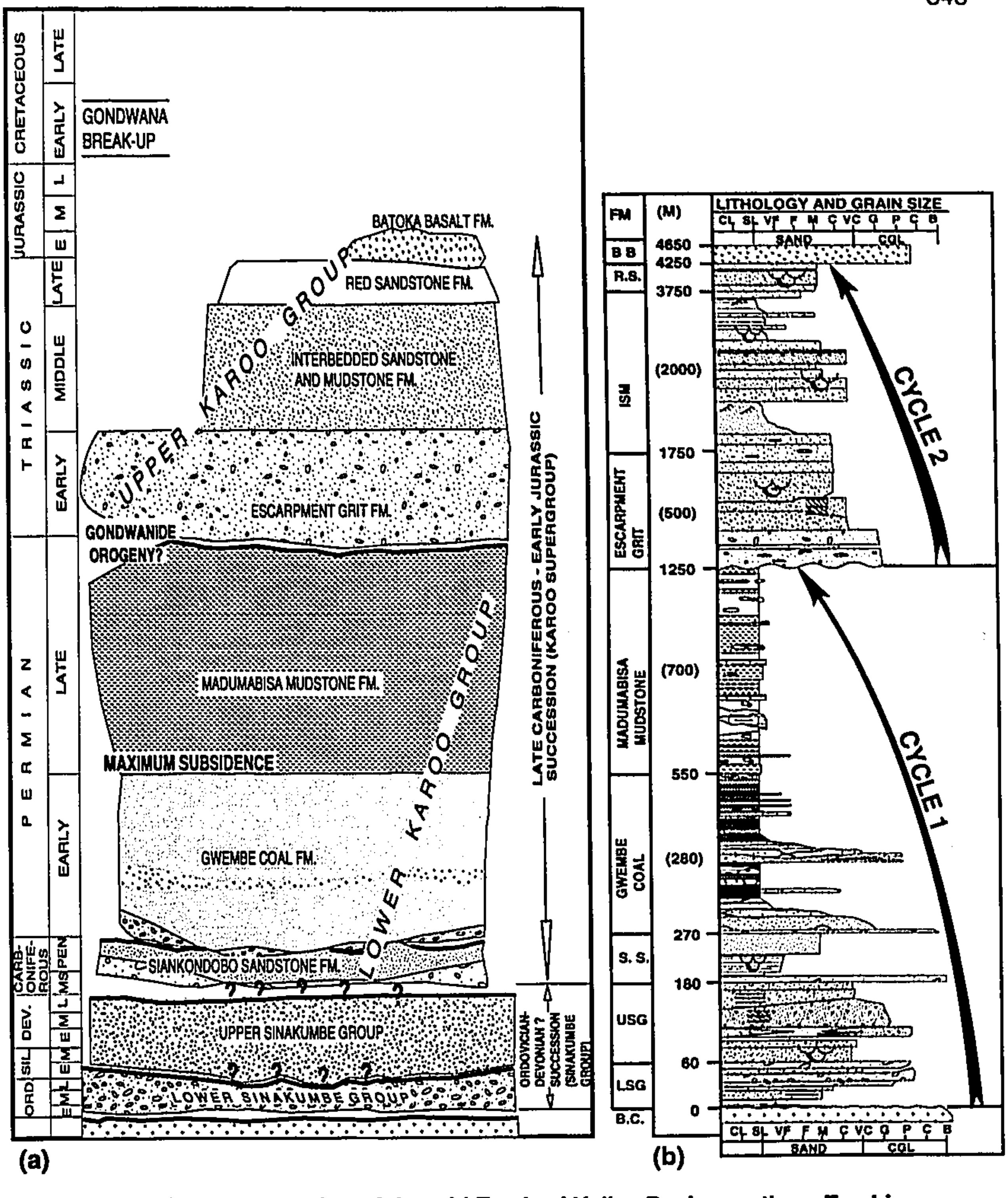


Fig. 6.1 Basin-fill succession of the mid-Zambezi Valley Basin, southern Zambia.
(a) Chronostratigraphic relationships of the two principal stratigraphic successions. Erosional surfaces are shown by bold lines. MS = Mississippian; PEN = Pennsylvanian. Not to scale.
(b) Two major tectonic fining-upward cycles in the mid-Zambezi Valley Basin succession. Not to scale. Legend see Fig. 4.0.

sediments, and (e) effects related to the continuous action of sedimentary processes in rivers and deltas (see Chapter 5 section 5.4.2). However, Falcon (1989) seems to favour Crowell's (1983) hypothesis that glacio-eustatic events may have played a significant role in the origin of the sedimentary cycles in southern Africa in Early Permian time, judging from the synchroneity of the coal-bearing cycles in the Karoo Basin, South Africa (Cairncross, 1989) and other Karoo basins in the subcontinent (Falcon, 1986). Falcon (1989) thought that the cycles may be minor cyclothems similar to the Carboniferous cyclothems in North America, and that, for the most part, they will be masked by delta progradation. The occurrence of coal seams over a long period (Early Permian to late Triassic times) of climatic and vegetational change, means that conditions such as temperature, moisture and parent vegetation must have differed widely in the various peat-accumulating periods (Falcon, 1989). All peat-forming processes ceased in Permo-Triassic times. This was in response to major tectono-sedimentary and climatic conditions, and it briefly resumed locally in the Early Triassic (Falcon, 1989). Correlation of the Early Permian Main Seam (basal), in different basins of southern Africa and many other seams deposited during a period of fast-changing climate and floras lends support to an interpretation involving glacio-eustatic changes. Other variations from area to area could be attributed to tectonism and changes in rates of subsidence. The author is of the opinion that tectonic movements played a major role, and any glacio-eustatic events must have been minor, probably confined to basal parts of the Karoo. This likely tectonic evolution of the mid-Zambezi Valley Basin is shown in Fig. 6.2.

In the mid-Zambezi Valley Basin, the pre-Karoo topography was affected by glaciation producing incised valleys in areas of extensively weathered basement rocks and the highlands over resistant rocks. These topographic constraints provided different source areas for clastic sedimentation, and therefore significantly influenced the accumulation of peat. Two major cycles can be recognised (Fig. 6.1b): (i) the Sinakumbe Group/Lower Karoo Group, and (ii) the Upper Karoo Group. Within the major cycles, minor cycles are present. The first cycle shows an overall decrease in grain-size from the Sinakumbe Group to the top of the Lower Karoo Group. No contact between the Upper Sinakumbe Group and Lower Karoo Group has been observed, suggesting a possible continuous succession to

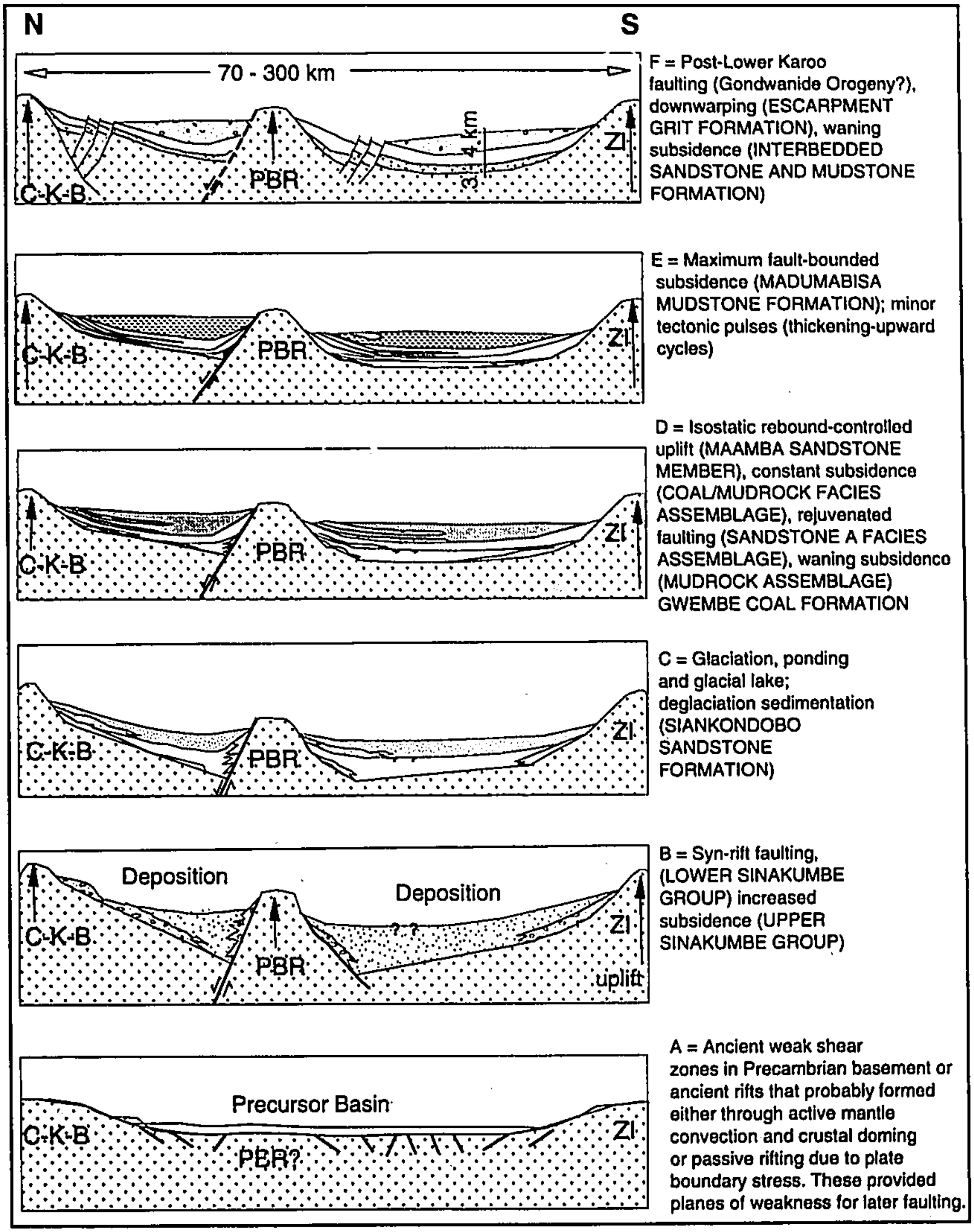


Fig. 6.2 Proposed tectonic evolution of the Sinakumbe and Karoo depositional systems, mid-Zambezi Valley, southern Zambia. C-K-B = Choma-Kalomo Batholith (Zambian craton), ZI = Zimbabwian craton, PBR = Precambrian Basement Remnant (Outlier). arrows = uplift.

the top of the latter. The quartz arenite and quartzite pebbles and cobbles in the Lower Karoo Siankondobo Sandstone were apparently derived from the Upper Sinakumbe Group, and are the only evidence that suggests an unconformity between the two. This overall fining-upward trend from the Sinakumbe Group to the top of Madumabisa Mudstone Formation of the Lower Karoo Group indicates an increase in active fault-related subsidence, and consequent transgression of fine-grained sediments to fill the basin. This evidence and the fact that no contact has been observed, suggest that the two groups form one sedimentary package representing a single tectonic phase. This scenario (Fig. 6.1b) suggests that the Sinakumbe Group could be considered as the basal part of the Siankondobo Sandstone Formation, either confined to the Late Carboniferous or beginning slightly earlier, perhaps in the Middle Carboniferous. This would be more consistent with the thinness (~ 210 m) of the Sinakumbe Group, possibly deposited in the rift basin over a short period, rather than during the 150 million year period suggested by correlation of the group with similar rock types in southern Africa. The thin coarse siliciclastics (diamictite facies assemblage of the Siankondobo Sandstone Formation ~ 9 m thick) at the base of the Lower Karoo is not consistent with a rift basin setting either, unless the Sinakumbe strata are included. The thinness of the diamictite facies assemblage can not adequately be explained by the post Lower Karoo faulting of basin-margin Siankondobo Sandstone deposits against the basement, because the formation commonly overlies the basement unconformably. If Gondwanan glaciation was responsible for eroding large amounts of Sinakumbe strata, then evidence such as striated pavements and pebbles should be widespread, although none have been observed. However, until more data is available on the contact between the Sinakumbe and Lower Karoo groups and palaeontological data can be obtained from the former, the age relationship between the two will continue to be speculative.

The conglomerate and sandstone assemblages of Sinakumbe Group and some in the Lower Karoo Group (notably Sandstone A and probably the Maamba Sandstone) are related to major tectonic movements, but those in the Lower Karoo Group are thinner than their counterparts in the Sinakumbe Group, suggesting only minor tectonic pulses. The mudrocks in the Sinakumbe-Karoo strata record periods of basin stability and maturity.

An increased rate of tectonic subsidence allowed a large standing body of water to accumulate lacustrine mudrocks of the Madumabisa Mudstone Formation. This lacustrine sedimentation terminated the first cycle in the evolution of the basin. The second cycle marks the introduction of thick coarser-grained siliciclastic sediments of the Escarpment Grit Formation of the Upper Karoo Group, initiated by post-Lower Karoo faulting representing the second tectonic phase. The thick mudrocks of the Interbedded Sandstone and Mudstone Formation similarly record a return to basin stability and maturity. The faulting is related to the Gondwanide Orogeny that is believed to be a direct result of collisional processes some distance away at the southern margin of Gondwana (Daly et al., 1991). Tectonism continued through deposition of the aeolian Red Sandstone, and was terminated by outpouring of basalt of the Batoka Basalt Formation in Early Jurassic time.

6.5 CLIMATE AND FLORAS

Colours of the mudrock, sandstone and conglomerate of the Lower Sinakumbe Group can be associated with changes in either climate or sedimentary conditions. There is no evidence for climatic changes in the Sinakumbe Group sequence; however, the predominant red coloration suggests semi-arid conditions with seasonal rainfall. Turner (1980) indicated that under such conditions, early diagenetic reddening of the deposits is possible unless the deposits are buried rapidly by overlying sediments or submerged by water.

The Late Palaeozoic glaciation of Gondwanaland comprised two short episodes, in the Famennian (I) and Visean (II), confined to Brazil and adjacent northwestern Africa, and a long episode that started in the Namurian (IIIA) of eastern Australia and Bolivia/Argentina, expanding to cover much of Gondwanaland in the Stephanian/Asselian (IIIB), and retreating in the early Sakmarian (IIIC) (Veevers and Powell, 1987) (Fig. 6.3). This early Karoo (Dwyka) glaciation, in terms of climate, was the most significant factor influencing Karoo sedimentation in the mid-Zambezi Valley Basin in particular, and southern Africa in general. The Dwyka glaciation was of continental proportions at its greatest extent. A long period of deposition in central southern Africa then followed, recording the extensive continental deposits of Dwyka glaciation (Fig. 6.3e). Falcon (1973,

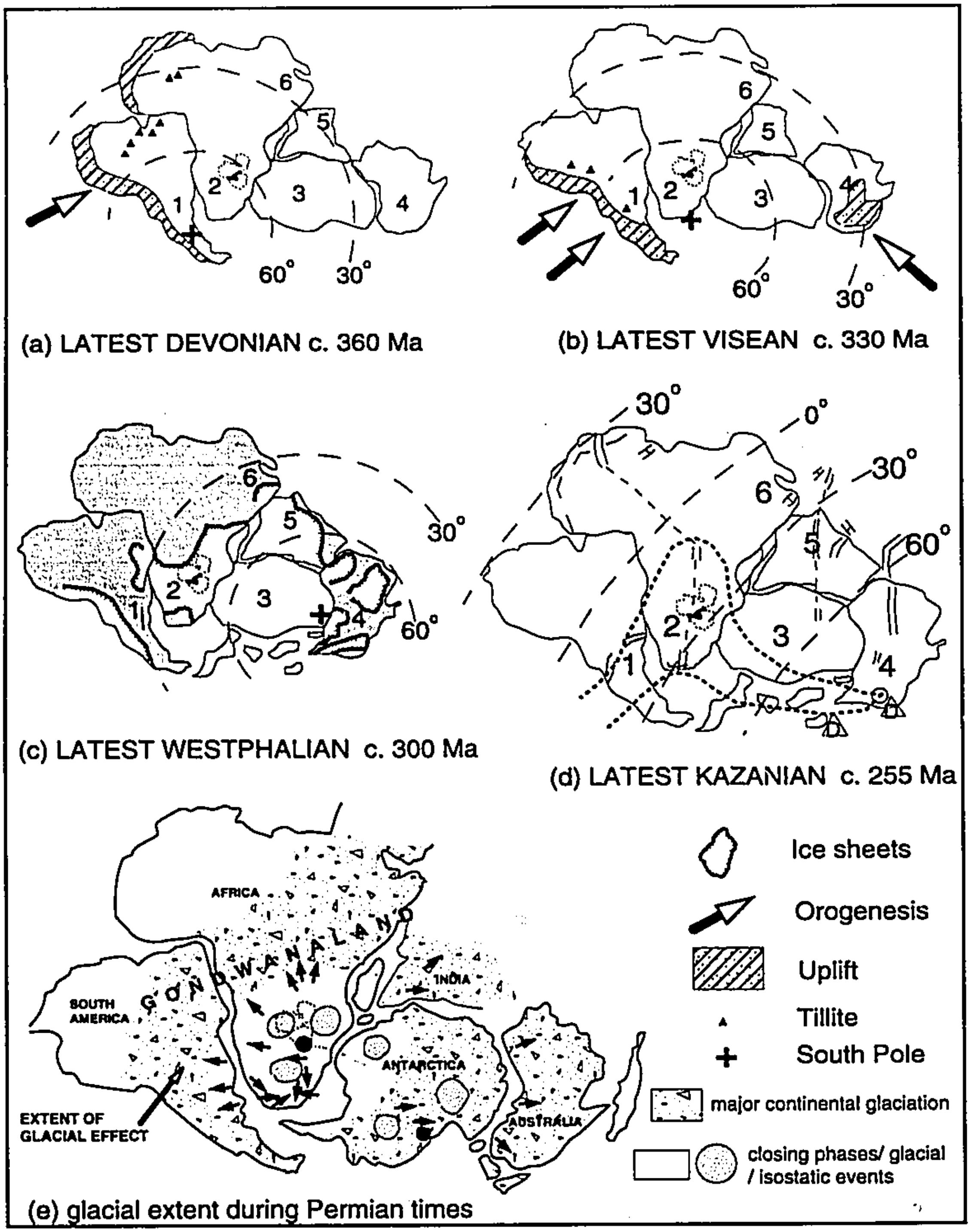


Fig. 6.3 Palaeogeographic maps (a to d) of Gondwana for the latest Devonian, latest Visean, latest Westphalian and latest Kazanian and glacial extent in Permian times (e). Permo-Carboniferous glaciated basins are 1= South American basins, 2 = Southern Africa, 3 = Antarctica, 4 = Australia, 5 = Indian Sub-continent, 6 =Arabian Plate. **Boundaries of Zambia and Zimbabwe (dotted outlines) with mid-Zambezi Valley at their border are plotted.** Compiled and modified from Eyles et al. (1993), Veevers and Powell (1987), and Falcon (1986).

1975) has presented evidence for at least three phases of glacial advance and retreat; Frakes and Crowell (1970) have stated that at least six periods of glaciation took place in South Africa, and that the glaciation may have lasted between 50 and 70 million years. In the Rukwa-Tukuyu region, Tanzania, Dypvik et al. (1990) reported one possible tillite unit. In the mid-Zambezi Valley, Nkandabwe coalfield area, three diamictite (possibly tillites) units are present. The abundance of kaolinite in the formation may suggest that permafrost affected the region. Gradusov and Sokolov (1990) indicated that in soils in the permafrost-characterised western and southeastern areas of Siberia, smectite and kaolinite are the common authigenic clay minerals. A long-lasting glaciation could have led to major depression of a huge landmass which, after ice-melting, could have undergone widespread isostatic rebound. Coupled with rift tectonics in the mid-Zambezi Valley region, this could have had a substantial control on Karoo sedimentation and thickness variations of the Siankondobo Sandstone and Gwembe Coal formations. Some dropstones recognized (e.g. Fig. 4.42d) in the Gwembe Coal Formation are suggestive of seasonal changes in climate, possibly severe winters and warm summers. Veevers and Powell (1987) pointed out that dropstones in eastern Australia indicate that small ice centres lingered to the Kazanian.

The presence of widespread coal deposits in several of the basins suggests a humid climate in the region. Changes in palynomorphs through the investigated sections (Figs 4.97 to 4.99) indicate that the plant communities and palaeoecological environments varied, most likely in response to changes in water level (wet and dry conditions), and by inference, Eh and pH conditions, and amelioration of climate, possibly due to temperature increases following the Dwyka glaciation (cf. Falcon, 1989). Cornet (1977, as quoted in Gore, 1988) pointed out that a high species diversity of spores can be interpreted to indicate a more humid climate; low spore diversity and pollen dominance (primarily conifers) suggests a more arid climate. The high diversity of spores and pollen in the Gwembe Coal, Madumabisa Mudstone and Interbedded Sandstone and Mudstone formations thus suggest humid conditions.

Gypsum pseudomorphs in the Madumabisa Mudstone Formation probably indicate that the basin experienced periodic aridity (cf. Gore, 1988). However, palynomorphs recovered from the formation indicate a predominantly humid climate, suggesting that arid conditions would have been very local and periodic. Cyclical sequences record alternating oxic-anoxic bottom conditions in marginal zones of a meromictic lake, due to cyclical changes in lake water volume that may be linked to climatic changes. Semi-humid conditions (palynological data) of the Interbedded Sandstone and Mudstone Formations were succeeded by arid conditions (aeolian deposits of the Red Sandstone Formation of the Upper Karoo Group).

CHAPTER VII

ECONOMIC RESOURCE POTENTIAL

7.1 GENERAL REMARKS

The foregoing discussion of depositional systems (Chapter V) and tectonic evolution of the basin fill in the mid-Zambezi Valley Basin (Chapter VI) indicates significant economic potential for the sedimentary succession in the basin (Fig 6.0). The basin-fill analysis presented in Chapter VI is essential for assessment of the potential for, and predictability of hydrocarbon and mineral resources. This involves consideration of the interrelationships of tectonic controls, depositional styles and facies distribution. For example, tectonic events create the basin of deposition and potential trap structures, but the sedimentary facies deposited within that basin form the potential source-reservoir-seal rocks for hydrocarbon accumulations. Details of organisation, geometry and predictability of the sedimentary facies thus are important for any evaluation of resource potential.

The mid-Zambezi Valley Basin is fault-bounded, containing sub-basins (half grabens) with a major fault at one side and platform/ramp sedimentary facies (modern East African rift lakes terminology) well developed along the other (e.g. the Nkandabwe map area, where sedimentary successions of the Sinakumbe Group and Karoo Supergroup overlie the basement unconformably). Such distensive basins contain a distinctive suite of natural resources worldwide (Robbins, 1983; Perrodon, 1983). The favourable basin factors include: (a) a localised basin surrounded by crystalline or metamorphic basement, (b) the presence of an igneous heat source at depth and some volcanism, (c) vigourous hydrothermal circulation, (d) rapid tectonic subsidence in multiple phases, (e) a thick sedimentary sequence including porous clastics and carbonates, evaporites and organic-rich deposits which occur in specific geometric arrangements relative to the fault-bounded margins, and (f) little metamorphism and moderate structural complication (Robbins, 1983; Perrodon, 1983; Morgan and Golombek, 1984; Powell, 1986). The resulting suite of natural resources may include: (a) energy resources such as coal, oil shale, oil and natural gas (Illies, 1981), (b) sediment-hosted metallic deposits such as lead/zinc/copper, silver, uranium, gold, molybdenum, (c) industrial minerals such as barite, clays, diatomites, zeolites, phosphates (Tiercelin, 1991), and (d) geothermal energy (Illies, 1981). Both structural and sedimentary style exert major controls on some of these economic deposits. A combination of high thermal gradients, commonly in association with volcanism or hydrothermal activity in reducing environments, often promotes the accumulation of mineral and fossil fuel deposits (Perrodon, 1983).

Any metallic sedimentary mineral deposits present in the terrigenous Sinakumbe-Karoo strata are likely to be related to fluvial sediments associated with redox boundaries between permeable sandstone and reduced impermeable mudstone. Miall (1981a) distinguished three types of economic deposits associated with fluvial sediments: (i) primary placer deposits accumulated by hydraulic sorting and concentration of detrital grains in fluvial channels, including gold, platinum, uranium, diamonds, titanium (rutile, ilmenite), zirconium (zircon), cesium (monazite) and tin (cassiterite), (ii) primary deposits formed as an integral part of the depositional system, such as coal (most important), and sideritic iron ores (no longer mined but important at one time), and (iii) secondary deposits in which the porous sand body acts as a conduit for low-temperature fluid migration and as host for oil, gas, heavy oils, copper and uranium.

The fluvial deposits of primary placer type occur in gravels and sands of proximal to distal braided settings, with most of the best placers occurring in the distal gravelly river (Donjek River type) sequences (Miall, 1981a). Gold and uranium are concentrated in trough cross-bedded channel-fill conglomerates; maps of their distribution reveal intricate braided channel networks. Palaeocurrent data have been used to confirm the sedimentological trends. Good examples are the gold and uranium of the Witwatersrand fields of South Africa (Minter, 1978). In the study area, the most probable occurrence of such deposits is the pebbly to coarse-grained sandstone and conglomerate of the Sinakumbe Group, and braided deposits of the Upper Karoo Group. However, no placer gold or uranium have been reported, and are not further discussed in the thesis. The most significant deposits are the occurrences of sandstone-hosted uranium mineralisation in the Upper Karoo Group. Copper deposits do not occur in the Sinakumbe-Karoo strata, but form the world-renowned Proterozoic stratiform copper deposits of the Zambian

Copperbelt, where the coal mined from the study area is used for copper smelting. No industrial minerals are mined in the mid-Zambezi Valley sedimentary succession, but occurrences of cassiterite (tin ore) and amethyst (locally mined) are present in veins in the basement rocks.

In this chapter the economic potential of the mid-Zambezi Valley Basin is reviewed, with emphasis on the interrelationship between particular minerals or mineral suites and sedimentological data. Because stratiform copper and industrial mineral deposits do not occur in the Sinakumbe-Karoo strata, they are not considered further in this thesis.

7.2 COAL

7.2.1 GENERAL OCCURRENCE

During the Permo-Triassic, the distensive fault-bounded basins of the southern continents saw development of abundant coal resources that are currently exploited. Coal is formed in the landlocked flood plains of river systems (e.g. Permo-Carboniferous of southern Africa) and coastal marshes. An understanding of coal distribution requires some knowledge regarding fluvial and deltaic cyclic depositional processes, particularly the interplay between subsidence rates and the rate of vertical aggradation and lateral channel shifting. Meandering channel and anastomosing channel models, respectively, have been applied to interpret fluvial coal deposits in parts of the Appalachians Basin (Horne et al., 1978) and some Permian coals (e.g. No. 2 coal seam of the central Witbank coalfield) in South Africa (Cairncross, 1980). Some coal seams have been related to the braided river model (e.g. No. 2 Coal seam, east Witbank Coalfield, Cairncross and Cadle, 1988). However, the frequency of crevasse splay development in anastomosing rivers may be a factor inhibiting accumulation of thick coals, and many coal sedimentologists now cite other environments and floodplain processes as more favourable for coal development (e.g. Flores, 1981, 1984). In the Zambian mid-Zambezi valley, Money et al. (1968), Money and Drysdall (1975) and this study attribute coal deposits to meandering systems.

Nearly all countries of southern Africa depend on coal for their energy requirements (Falcon, 1986). The 28 coalfields that occur in the countries south of Zambia and four coalfields in Zambia are confined to the Karoo Supergroup. The largest fields are in the Karoo Basin of South Africa, with total reserves of over 115,000 million *in situ* tons and over 58,700 million run-of-mine tons (Smith and Whittaker, 1986). In the mid-Zambezi Valley Basin of Zambia, the Lower Permian Gwembe Coal Formation is the only current producer, though promising coal seams occur in the Luano and Luangwa valleys (Reeve, 1963) and the other Karoo basins in Zambia. The largest field is in the southeastern part of the basin at Wankie in Zimbabwe, where mining started in 1903 (Duguid, 1986). The Wankie coalfield is 160 km^2 in area, with 2,100 x 10^6 *in situ* tons, 1,400 x 10^6 run-of-mine tons reserves, a thickness up to 12 m (Main Seam), average ash content ~15% (9.77%), volatile matter ~ 23.77%, fixed carbon ~ 65.7%, moisture content ~ 0.76% and calorific value ~ 31.4 MJ/kg. On the Zambian side, four fields are important: the Nkandabwe, Siankondobo, Maze-Sinakumbe and Mulungwa. The Nkandabwe coalfield was the first to be exploited, but the Nkandabwe open-pit is abandoned, and mining is currently carried out only in the Kazinze and Izuma open-pits of the Maamba Mine, Siankondobo coalfield area. The Maze-Sinakumbe and Mulungwa coalfields are still being investigated.

7.2.2 HISTORICAL BACKGROUND

Realising the need for increased energy input in the industrial sector of its economy, Zambia intensified its search for coal resources, particularly after the declaration of independence in Rhodesia (Zimbabwe) in 1965. Most of the coal is used for smelting in Zambian Copperbelt mines, and some is exported to neighbouring countries. The existence of coal in Zambia has been known since David Livingstone's journey towards Sesheke in 1860, when he remarked on the occurrence of coal fragments in alluvium near the confluence of the Zambezi and Chilola rivers (Kotas, 1977). Investigations into the coal potential of Zambia date back to 1907, when A. J. C. Molyneux examined coal deposits of the Lufua and Lusito rivers in the Zambezi valley and Luano valley respectively. Further investigations in this region were carried out in 1918, 1920, and 1928-29 (Kotas, 1977). During 1949-50, a private firm (Mark C. Malamphy and Company Limited) was engaged by the government of Northern Rhodesia (Zambia) to carry out coal investigations. The company drilled seven boreholes, and some underground development was done in 1950-51 in the mid-Zambezi Valley Basin. Coal prospecting has been intensified since 1965, leading to the opening of a coal mine at Nkandabwe (now abandoned), in the Nkandabwe map area (Fig. 2.2a), followed by opening of the Maamba mine (Kazinze area) in the Siankondobo map area in 1967. Except for coking coal, Zambia became self-sufficient in coal during 1972.

The conclusion reached by various workers that thick coal seams are more likely to occur near the margins of the area of sedimentation than out in the open basin (Bond, 1967) aided in exploration for thick coal deposits. The coal subcrop was traced initially by pits sunk on lines at right angles to the strike, down dip from the outcrop of the basal sandstone (Siankondobo Sandstone Formation or Maamba Sandstone member of the Gwembe Coal Formation). The coal project started in 1965-1966, when no detailed topographic maps were available, and thus pits were surveyed by plane table and telescopic alidade (Money et al., 1974). Accurate surveys were made after Fairey's air survey (April, 1966) and 1:250,000 scale maps with contours at 1.5 m and 1:10,000 air photographs became available. In the Mulungwa coalfield area (Fig.2.2d), trenches were used instead of pits because of the high dip of the coal (15-30°). The downdip extension of the Main Seam in each coalfield area was determined by diamond drilling to vertical depths averaging 75 m (Money et al., 1974). Some boreholes penetrated to over 400 m, for example in the Siankondobo area, where the final depth for F149 was 457.6 m. A total of 161 boreholes were drilled between 1965 and 1970, including 38 by Zambia Anglo American Exploration Company in the Nkandabwe coalfield, 42 by Sofremines in the Siankondobo coalfields and 81 by the Geological Survey in the region between Nkandabwe coalfield and the Mulungwa coalfield, with a total length drilled of 12,250 m. Boreholes drilled by Minex Department in the Nkandabwe area in 1976-1977, were over 300 m deep (maximum 654.10 m). Currently there are over 1000 boreholes drilled in the area, including the ones drilled by Maamba Collieries Limited Company.

7.2.3 COAL CHARACTERISTICS AND DISCUSSION

Coal analyses are made to determine the quality of coal, rank and possible commercial use. The most common are proximate and ultimate analyses. Proximate analysis quantitatively determines fixed carbon, ash, volatile matter and moisture contents. The moisture content is the percentage loss in weight, on heating a sample for a specified time at low temperature (~ 110°C). The loss in weight of a heated (at intermediate temperatures) weighed dry coal in an inert atmosphere, expressed as a percentage of the original weight, represents the volatile matter, and the residue is the fixed carbon. The percentage of fixed carbon is defined as 100 minus (% ash + % moisture + % volatile matter) (ASTM, 1979). The ash content is the non-combustible residue left after burning a weighed sample in a stream of oxygen to oxidize all the remaining organic matter (open crucible in muffle furnace) at 700 to 750°C, expressed as a percentage of the original weight of the sample. Ultimate analysis involves quantitative determination of hydrogen, carbon, oxygen (for H, C, O commonly by C-H-N analyser), nitrogen, total sulphur and chlorine. Carbon and hydrogen are determined by burning a weighed coal sample in a combustion furnace, and weighing the carbon dioxide and water collected. Nitrogen is determined by conversion to ammonia, whereas sulphur is determined gravimetrically as barium sulphate after conversion of sulphur to sulphate. Oxygen is determined by the difference through the inclusion of ash content analysis or through direct conversion of oxygen to carbon monoxide, measuring its reaction with iodine pentoxide (I_2O_5). Other analyses include determinations of calorific value, ash softening temperature, types of sulphide mineral and carbon dioxide. Calorific value (calories per gram=Btu/lb) is determined by the weighed sample in a bomb calorimeter, commonly used as a technique for determining coal rank (Bustin et al., 1990). Special tests include determinations of free-swelling index, plastic properties, grindability, screen analysis of crushed coal and washability.

Representative bulk samples, coal sections from core, and portions of the hanging wall (coaly to carbonaceous mudstone) were collected for these analyses, for petrographic description (Alpren, 1968) and for sink and float, and washability tests. The sampling followed the sharp base of the seam (Maamba Sandstone/Main Seam contact) and the gradational top contact was determined by tetrachloride flotation. The results of these tests indicated that the Main Seam has a high ash content (average of ~22%; a range of 13 to 26%), average moisture content from 1.6 to 2.3%, average content of volatile matter of

17.5 to 22.5%, with 25.3% for purified samples, a fixed carbon content of 49.5 to 69.5% (average ~55.7%), average sulphur ranging from 0.25% to 3.2 %, average calorific value of 6000 cal/gm (maximum 6830 cal/gm - Kazinze Open pit), and a mean reflectance for the Kazinze open-pit of 1.1 (1.08, this study).

In the Siankondobo map area, the Izuma coalfield has the most extensive coal outcrop, whereas in the Kazinze coalfield, only two minor outcrops are known. In the other coalfield areas, outcrops of coal are mainly restricted to present streams and rivers. In the Kazinze coalfield the Main Seam becomes thinner downdip to the south-southwest, with an average thickness of 6 m (max = 14.6 m). The Main Seam averages 4.3 m thick (max = 6.7 m) in the Izuma, 3.7 m (max = 7 m) in the Nkandabwe, 3.2 m (max = 5.8 m) in the Maze-Sinakumbe and 7 m (max = 9 m) in the Mulungwa coalfields (Money et al., 1974; this study). Most of the seam consists of massive durain type coal. High ash content is characteristic of the Zambian coal in contrast to European or other Gondwana coals. The Izuma coal has a slightly higher ash content than that in the Kazinze region. The high ash content is largely due to high amounts of inertinite maceral, represented by the lithotype durain-fusain (mainly semifusinite, micrinite and sclerotinite) and higher contents of silica and alumina, indicating a large detrital input (argillaceous laminae) which also lowers the swelling number. The ash contents of coaly and carbonaceous mudstones in and above the Main Seam increase progressively with decrease in the carbon content. Fusinite and micrinite have lower coking ability than vitrinite (International Committee for Coal Petrology, 1963). The ash values vary inversely with the calorific value. The ash has characteristics of a highly refractory material, high melting point (up to 1525°), high sulphur content, high fusion temperatures and high acid oxides (Al_2O_3 and SiO_2) in contrast to basic oxides (CaO, MgO, Fe_2O_3). These characteristics are advantageous for the firing of boilers using Zambian coal. The variation in moisture content of the main seam is related probably to heat flow in the area (cf. Smith 1970). There is no significant variation in volatile matter from Nkandabwe to Mulungwa, but the Zambian values (purified samples corresponding to European coking coal) are significantly lower than those of Zimbabwe and South Africa. The lower volatile content, due to low content of vitrinite, but high content of inertinite (giving poor coking characteristics and dull appearance), classifies the Zambian coal between bituminous hard coal and anthracite (Money and Drysdall, 1975).

The average fixed carbon content (~55.7%) is similar to that in the Witbank coalfield, South Africa (56.2%), but lower than that of Wankie (63.8%), and thus generally increases from Nkandabwe south-southwesterly. On the basis of fixed carbon, the Zambian coal is classified as equivalent to the hard bituminous, moderately coking, compact coals of Europe (Francis, 1961 p.362), though calorific values of the latter (8800 and 9300 cal/gm) are higher than for Zambian coal (only 6000 cal/gm) (Money et al., 1974). However, this study (six samples only) ranked the coal as low volatile bituminous, perhaps reclassifying the Zambian coal in the range of low volatile to anthracite. Washing of the coal increases its calorific value. Sulphur content varies locally and regionally (most sulphur occurring in pyrite), with higher values in the Kazinze coalfield area (Siankondobo map area) than in the Nkandabwe and Mulungwa coalfield areas (Money et al., 1974). Sulphur content decreases upwards stratigraphically, with high concentrations at the base of the Main Seam and only local concentrations at the top. Sulphur in sulphides occurs syngenetically in finely disseminated pyrite, in marcasite flowers on joint and bedding planes, in pyrite nodules, and in thin seams of sulphide. The sulphur was probably derived from vegetable matter, which could give rise to metallic sulphides such as pyrite and siderite under anaerobic (reducing) conditions. This could explain the decrease of iron accompanying the increase of ash content. Teichmuller and Teichmuller (1982) suggested that low sulphur content coals formed under humic conditions and higher content ones under brackish water influence. The grade of the coal (calorific value) varies with thickness of the seam; thick seams have calorific values in the range of 6400 to 6600 cal/gm, whereas thinner ones are up to 68,000 cal/gm (Money et al., 1974).

Reflecting ability of the vitrinite within the Main Seam shows little variation vertically, partly due to relatively thin seams (<15 m). However, reflectance measurements of 1.1 for the Kazinze open-pit and 0.97 +/- 0.11 west of the open-pit suggest decrease in coal rank westwards in the Kazinze area (Money et al., 1974).

Siankondobo Coalfield Area: Coal reserves calculations include mudstone beds underlain and overlain by seam beds of similar thickness. The Kazinze coalfield was divided into eight zones; in zone I, 1.5 tonnes per cubic metre of coal with 18% ash was used for reserve calculations and 1.63 tonnes per cubic metre for the rest of the zones (II-VIII). For the year ending 31st March, 1991, 28,483 tonnes of washed coal with an average ash content of 14.7%* were produced from 502,150 tonnes of raw coal, with an average ash content of 22.36%* from the Kazinze Open-pit (Maamba Collieries Annual Production Report 1977-1990; *=1973 figure). Total usable reserves of coal in the Kazinze area are ~ 40 million tonnes. Annual production of coal is one million tonnes, depleting the reserves by about 0.8 million tonnes of usable coal. Izuma coalfield reserves are ~12.6 million tonnes. The Maamba Township area reserves, with main seam thickness of generally less than 2 m (Denman and Money, 1968), has a reserve estimate of ~2 million tonnes. Kotas (1977) gave the proven reserves for the Siankondobo area at 70.9 million tonnes.

Nkandabwe Coalfield Area: The coal succession dips much more steeply (14-29°) than in the Siankondobo map area. The coalfield is bounded by faults forming a rectangular trough that opens to the mid-Zambezi Valley to the northeast, even though the coal seam does not extend that far but grades into coaly mudstones. Parameters used in the calculation of reserves here were a cut-off calorific value of 4450 cal/gm (5550 cal/gm at Siankondobo) and an assumption that 0.687 cubic metre of *in situ* coal weighs one tonne as at Wankie in Zimbabwe. Mineable reserves of 7.6 million tonnes were almost depleted (unproven remaining reserves estimated at 10 million tonnes). The coal had an average ash content of 24% and calorific value of 5830 cal/gm. Production ceased in March, 1969, when the mine was flooded by heavy rain. Water was up to 15 m deep, and the open-pit is now occupied by a permanent lake (Fig. 2.3a).

Mulungwa Coalfield Area: Tavener-Smith (1960) described a coal seam 4.3 m thick, with two thin mudstone intercalations at the top, and calorific value 4000 cal/gm and over 45% ash content. A reinvestigation (1966-1968) showed a 6.8 m thick seam (dip 40°) with calorific value of 6030 cal/gm, ash content of 23.3% and 0.8% sulphur. The provisional estimate of mineable reserves is 12 million tonnes to a depth of 100 m (Money et al., 1974).

Maze-Sinakumbe Coalfield Area: The coal seam varies in thickness from 0.9 to

5.2 m with an average of 3.5 m. The provisional reserve estimate is 30 million tonnes at a calorific value of 5850 cal/gm and ash content of 26.1% (Money et al., 1974).

Locales of other minor coalfields in the mid-Zambezi Valley Basin are indicated in unpublished bulletin 6 of the Geological Survey of Zambia (Money et al., 1974) and other reports of the survey. These include Katenda, Chongola, Siambobola, Bondo, Masinkilo, Chezya-Bukata, Nsanje and Siamambo.

7.3 HYDROCARBONS

7.3.1 HISTORICAL BACKGROUND

Due to the increased cost of imported crude oil, steps were taken by the Zambian Government to search for hydrocarbons, with preliminary petroleum exploration, beginning in 1970. Money (1981) outlined the hydrocarbon potential of Zambia, suggesting the Barotse Basin (western Zambia) to have the highest hydrocarbon potential, judging from the estimated thickness of sediment fill in the basin. The Luena Hydrocarbon Company was to undertake prospecting there, but failed to do so. The Luangwa Valley Basin (eastern Zambia) showed some potential in preliminary surveys and Placid Oil (Zambia) Ltd. started exploration for hydrocarbons in 1985, but abandoned in 1988 (reason not disclosed).

The study of dispersed organic matter and coal is valuable in assessing the hydrocarbon potential of exploration wells, sedimentary basins and sedimentary provinces, and in exploitation of hydrocarbon and oil shale. Three broad requirements for hydrocarbon accumulation are reservoir rocks, traps and source rocks.

7.3.2 RESERVOIR/TRAPS

In other parts of the world, Gondwana Karoo sediments are producers of hydrocarbons and/or targets for hydrocarbon exploration. For example, the Permo-Carboniferous glacial deposits in Oman (Levell et al., 1988), Argentina and Bolivia are important hydrocarbon producers, and are being actively explored in Brazil, Saudi Arabia and Australia (Eyles et al., 1993). Producing fields have reservoirs in sandy turbidities deposited around basin margins (in Bolivia, Argentina, and Brazil), with rain-out and debris flow diamictites as the stratigraphic seals (Eyles and Eyles, 1992). In Oman, where the largest field contains about 5.6 x 10^8 m^3 of oil, ice-contact deltaic deposits around the basin edge form the reservoir, with glaciolacustrine silts and clays as the stratigraphic seals (Levell et al., 1988). These features (i.e. lithofacies, facies assemblages and changes) are characteristics of the Sinakumbe-Karoo strata deposited in the half-grabens (sub-basins) of the mid-Zambezi Valley. These sub-basins are characterised by different sediment input zones, and vertical and lateral facies distributions that differ from one sub-basin to another (e.g. Sikalamba-Muzuma Corridor and the main basin in Nkandabwe map area). The coarse-grained and reddened Sinakumbe Group strata (mainly pebbly sandstones and conglomerates with abundant secondary porosity related to dissolution of feldspar and rock fragments), form semipermeable oxidised aquifers occupying the northwestern basin margins, notably in the Nkandabwe map area, and are overlain by fine-grained and buff (coarser fractions minor) facies assemblages belonging to the Siankondobo Sandstone Formation glaciofluvial to glaciolacustrine (deltaic) depositional system. These sediments commonly occupy the basin margins where the Sinakumbe Group is absent. The diamictite and siltstone facies assemblages at the base act as an aquiclude, and the stacked massive sandstone assemblage at the top forms a relatively porous and semipermeable aquifer. Basinward (southeastward), the glaciofluvial to glaciolacustrine deposits are succeeded by a coal-bearing flood plain sequence with braided (proximal) to meandering channel (meanderbelt / point bar and distal) and splay system sandstones (notably Sandstone A) that are relatively porous aquifers overlain by largely impermeable mudrocks (carbonaceous/silty mudstone). These grade into grey/green mudrocks (silty mudstone/siltstone also impermeable) with minor moderately porous sandstone bodies of the lacustrine Madumabisa Mudstone. The overlying, largely coarse-grained to pebbly (conglomeratic) sandstones of the Escarpment Grit in the Upper Karoo Group contain abundant secondary porosity and are permeable. The fining-upwards units of the Interbedded Sandstone and Mudstone Formation contain porous sandstone (medium-grained to pebbly, locally conglomeratic) in the lower parts, capped by finer-grained impermeable mudrocks. The permeable sandstone bodies of the Sinakumbe-Karoo strata are capable of acting as reservoirs for hydrocarbon accumulation whereas the finer grained sediments (commonly mudrocks) can form seals in stratigraphic traps (Fig. 7.0), in addition to the commonly known structural traps characteristic in faulted basins (e.g. from post-Karoo faulting; Fig. 7.1). A number of holes drilled in the Gwembe Coal Formation resulted in artesian wells, suggesting that hydrodynamics can be an effective trapping mechanism also in some of the sandstone bodies. In terms of reservoir-source-seal association, Sandstone A encased in carbonaceous and silty mudstones seems to be a favourable reservoir. The updip pinchout of the sandstone towards the northwestern margin of the basin (where deeply buried) and/or mudrock capping offer good stratigraphic traps. The underlying basement rocks are faulted.

In modern tropical rift lakes (e.g. Lake Tanganyika), possible reservoirs are large sandbodies associated with axial deltas (though they lack source and cap rock), and platform deltas that are superior in source-reservoir-seal geometry, whereas the escarpment sands (deltas) are small and unpredictable. Carbonate shoals on platforms are also possibilities (Cohen, 1990). The good reservoir and source rocks have been controlled by both subsidence and uplift. By analogy with these lakes, the Madumabisa Lake likely contained platform and axial-margin sandbodies (clastic mainly, and carbonate in accommodation zones, e.g. limestones reported by Tavener-Smith, 1962), and turbidites or contourites derived from platform or axial sources which can act as significant reservoir facies in contact with source rocks. However, the sandstone bodies in the Madumabisa Mudstone (e.g. Fig. 4.79) are minor and limited in extent, and consist of submature, relatively clean quartzo-feldspathic sandstone with a lot of mica and little porosity, and therefore are not favourable reservoirs. Unless good reservoir sandbodies are deeply buried due to post-Karoo faulting, the only good sandstone reservoirs are the overlying Upper Karoo strata that are capped by thick sequences of mudrocks (estimated thickness in the order 50 m) of the Interbedded Sandstone and Mudstone Formation, and/or are faulted to provide traps.

7.3.3 SOURCE ROCKS

The primary requirements for formation of lacustrine source rocks are: (i) size and

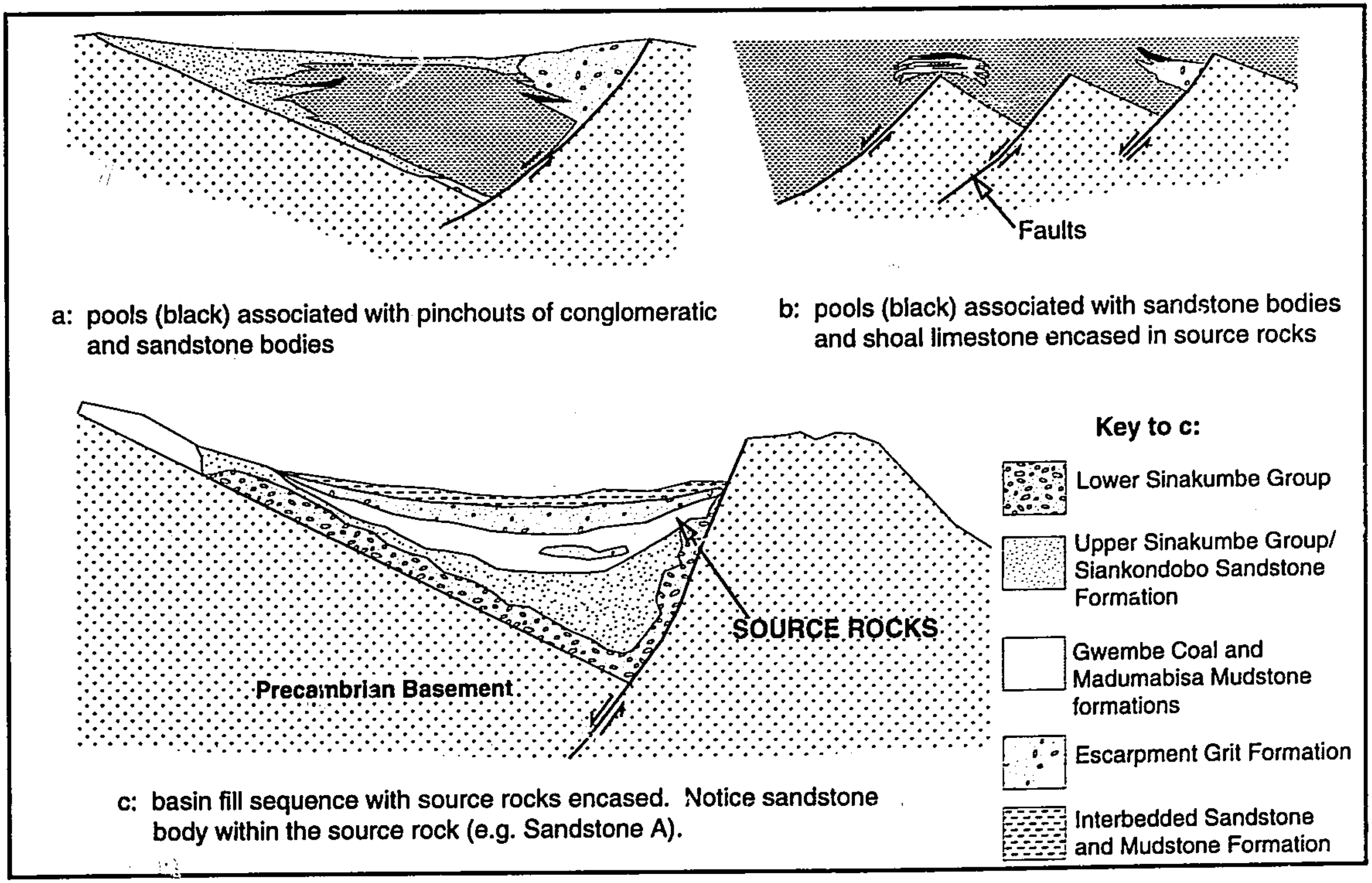


Fig. 7.0 Potential types of stratigraphic traps in the mid-Zambezi Valley sedimentary strata (Sinakumbe and Karoo groups), southern Zambia.

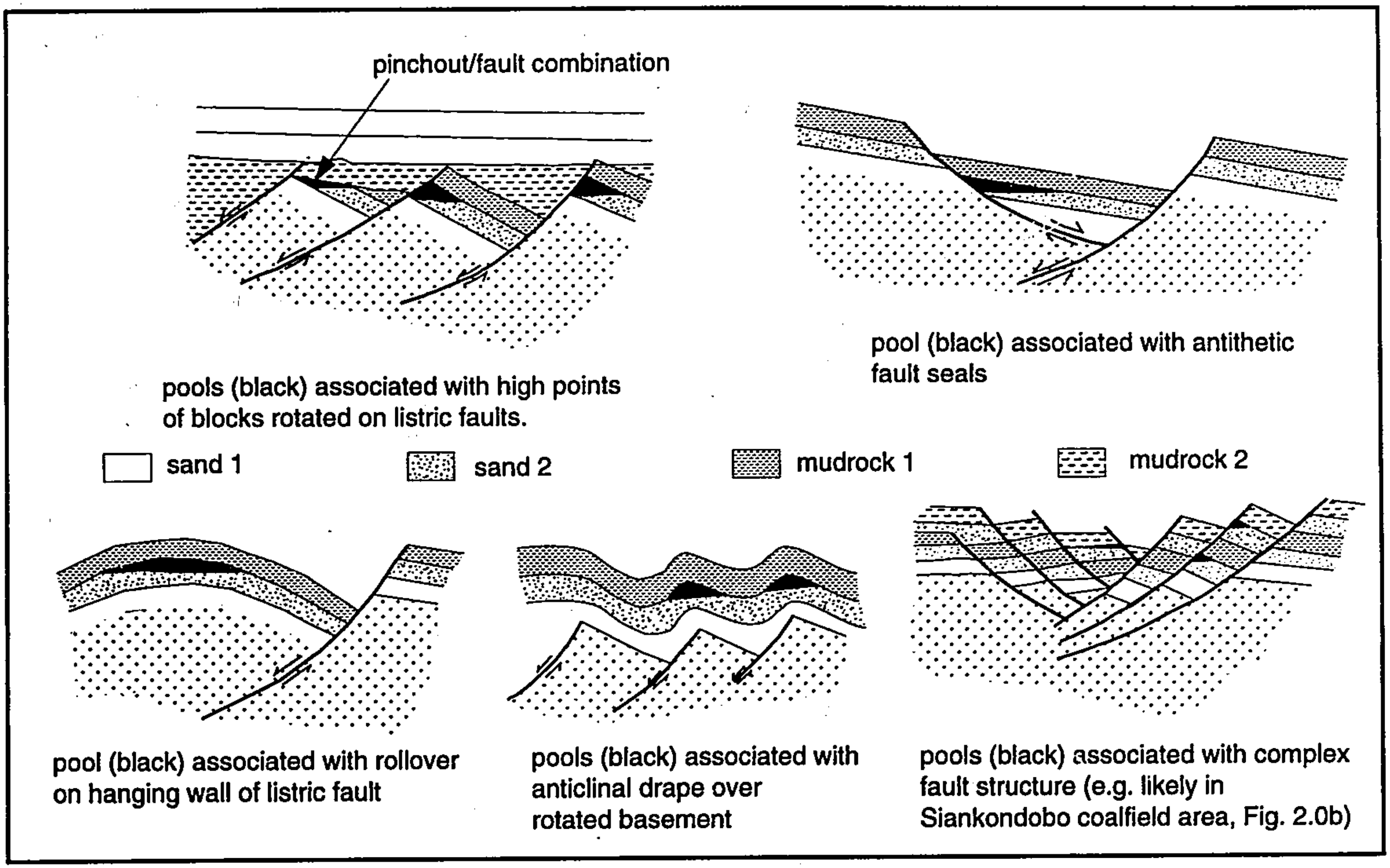


Fig. 7.1 Potential types of fault- and fold-related structural traps in the mid-Zambezi Valley sedimentary strata (Sinakumbe and Karoo groups), southern Zambia.

duration of the lake environment sufficient to allow significant organic matter accumulation, and (ii) burial and maturation sufficient to generate hydrocarbons (controlled by tectonic setting) (Powell, 1986). The three models of lacustrine source rock accumulation widely accepted are: (i) the Green River model (Eugster and Surdam, 1973; Eugster and Hardie, 1975) that suggests source rock (oil shale) deposition in shallow but anoxic waters of stratified, brackish-saline, alkaline lakes developed within major playa systems (modern example is Lake Bogoria, Kenya; Tiercelin and Le Fournier, 1980, as quoted in Tiercelin, 1991); (ii) the deep anoxic lake model (Demaison and Moore 1980; Fan Pu et al., 1980; Ryder, 1980) that suggests accumulation of organic-rich sediments in anoxic waters below a thermocline of deep, permanently stratified, fresh to mildly brackish water lakes in a warm, humid climate, with minimal seasonal contrasts (modern example is Lake Tanganyika), and (iii) the ephemeral lake model (Bauld, 1981; Burne and Ferguson, 1983) that suggests that extensive blue-green algal mats (TOC up to 30%) were the precursors of some laminated oil shales; related environments may contain blooms of the planktonic green alga *Botryococcus* (chlorophyceae). The consensus is that the first and second models apply to continental lacustrine systems, but the third is discounted due to the substantial thickness of packages of organic-rich shale known in producing continental basins (Talbot, 1988). Debris from extensive swamps that line the shores are transported by density inter- or underflows (Fig. 5.0) and resedimentation processes, principally as turbidites generated either at delta fronts or at shallow water sites of accumulation. These would contribute to the abundant plant remains either in discrete laminae, or intimately mixed with clastic material.

In his study of the modern East African rift lakes, Talbot (1988) noted that sediments with the richest oil potential are associated with deep, fresh to mildly alkaline (diluted) waterbodies, meromictic conditions, warm and humid climates that allow stable stratification (reduced wind activity), dense terrestrial vegetation (higher evolutionary plant remains), starved basin conditions (less clastic sediment supply), and chemical weathering that ensures a steady supply of dissolved nutrients to promote high rates of primary productivity within lakes. A stratified water column enhances the relative organic content of the sediment, and accumulation and preservation of oil prone material, and is considered a favourable factor, but not as essential as previously thought (Talbot, 1988). Similar views were reached by Powell (1986) for the ancient Chinese lacustrine basins (e.g. Sonlino Basin) where the most favourable source-rocks are associated with deep lake facies, whereas others did not undergo sufficient burial for hydrocarbon generation. This indicates that the saline lake model is not favourable, and that saline lakes with preserved source rocks (high organic content) might have been deep and experienced humid conditions through time (e.g. Lake Victoria).

In modern East African rift lakes, the preserved organic matter is a mixture of phytoplankton and higher plant remains showing various degrees of bacterial degradation. Organic matter characteristic of axial deep basin sediments (average of 4.3% and maximum of 12-60% TOC) is preserved by anoxic conditions to form highly petroliferous sediments. Their maturation is satisfied by sediment thickness as great as 4 km (Rosendahl et al., 1986) and elevated temperature which is probably partly related to hydrothermal activity (Tiercelin et al., 1989; Tanganydro Group, 1992). Hydrothermal fluids are emitted at temperatures of 55-103°C through basement fractures and open cracks at depths of ~50 m, forming sulphide deposits. Composition of the source rock shows a variation in total organic content (TOC from <1 to >60%, average 1-10%), and kerogen composition (from Type I to Type III), with bacterial, algal and higher plant remains making various contributions. The kerogens are of mixed origin, containing substantial quantities of planktonic and te.restrial plant remains. For example, Type I kerogens of lacustrine origin are composed of organic accumulations dominated by planktonic green algae, particularly *Botryococcus*, or of amorphous material, which may be of blue-green algal (cyano-bacterial) or bacterial origin (Hutton et al., 1980; Cook et al., 1981; Powell, 1986) that form in low gradient basins where distribution of terrestrial components is relatively inefficient (Talbot, 1988). Type II kerogen, common in ancient lacustrine source rocks and East African lake sediments, results from a mixture of phytoplankton (alginite), swamp and terrestrial plant (exinite) material that is reworked by bacteria.

7.3.4 DISCUSSION AND SUMMARY

The likely source rocks in the mid-Zambezi Valley Basin are coal seams, coaly, carbonaceous (locally shaly) and silty mudstone of the Gwembe Coal Formation and mudrock assemblages of the Madumabisa Mudstone Formation. These sediments contain substantial amounts of organic matter (up to 90% in the carbonaceous mudstone) and preliminary reflectance tests carried out on Karoo coals (Price et al., 1992) suggest thermal maturity of the coals in the oil/gas threshhold window, with potential for hydrocarbon generation. Vitrinite and liptinite contents (up to 16%, this study; up to 70%, Utting and Wielens, 1992), and leaf cutinite of the coals are sufficient to have generated hydrocarbons. Utting and Wielens (1992) indicated that organic matter from Karoo basins in Zambia including the mid-Zambezi Valley is within the oil generation zone (thermal alteration index 2- to 2+; 0.5- 0.9 % Ro max; 1.08 % Ro, this study). The organic matter consists of kerogens of types II (generally ~ 25% in carbonaceous shale samples), mainly III, and IV, indicating source rock potential (Utting and Wielens, 1992). In addition, during Madumabisa Lake times, source rock accumulation in a manner similar to that in the present East African lakes was likely. The Madumabisa mudrocks are commonly green/grey, indicating deposition in reducing, possibly anoxic conditions. Swampy areas should have been common. This, together with reworking of the underlying coal sequence, could have supplied the higher plant remains that occur as abundant woody and coaly fragments in certain intervals in the formation. Others beds contain the green alga *Botryococcus* sp. (see Palaeontology section Chapter 4), suggesting that mixing with higher plant remains could have resulted in type II kerogen. Climatic conditions are likely to have been humid to semi-humid, judging from the absence of evaporite minerals (except pseudomorphs after gypsum). The thick sedimentary succession (in excess of 6 km) in the mid-Zambezi Valley Basin, and faulting could have buried some of these strata to considerable depth where appropriate heat conditions (e.g. from deep burial, or geothermal heat associated with intrusions and Batoka Basalt volcanism during the Jurassic) led to maturity levels and generation of liquid hydrocarbon. Partitioned basins (half-grabens) such as those resulting from faulting in distensive basins develop morphological barriers leading to isolation of sub-basins with different histories. In some of these basins appropriate source-reservoir-seal requirements for accumulation of hydrocarbons, coal or other mineral resources could have resulted. The characteristic feature of lacustrine source rocks in tectonic lake basins is their great thickness, which ranges up to 700 m in some Chinese (Li et al., 1984, as quoted in Powell, 1986) and south Atlantic (Brice et al., 1980) rift basins. The mean organic carbon content is up to 3% and occasionally higher in the Chinese examples (Huang et al., 1984, as quoted in Powell, 1986), a maximum of 15% in Lake Kivu for tropical lakes (Stoffers and Hecky, 1978) and up to 60% for deep lakes (Tissot et al., 1978). This is analogous to the Madumabisa Mudstone Formation (MMF), with an estimated thickness of 700 m (560 m measured in Mulungwa map area), but significantly thicker (> 700 m) in the broader and deeper sub-basins, depending on proximity to the main fault axis of the half-grabens in Early Karoo times. Post-Karoo faulting and structural doming common in the basin could form ideal structural traps. Although oxidation and some reworking by soil flora and fauna may be responsible for poor hydrocarbon potential of the Gwembe Coal and Madumabisa Mudstone sediments, Powell (1986) indicated that mild oxidizing conditions are required prior to preservation to promote bacterial and fungal attack on wood and cellulose and concentrate the hydrogen-rich parts from land plants. Further geochemical studies such as RockEval analysis are therefore worth pursuing to determine the potential for generation of hydrocarbon by the coals of the Gwembe Coal Formation and organic-rich intervals of the Madumabisa Mudstone Formation.

7.4 SANDSTONE-HOSTED URANIUM DEPOSITS

7.4.1 GENERAL OCCURRENCE

Uranium mineralisation stems from the leaching and erosion of igneous or metamorphic rocks in upland regions. Uranium occurs in nature, commonly in two valence states. In its oxidized uranyl state (U^{6+}) uranium is soluble, readily transported and will precipitate when reduced to the uranous state (U^{4+}). Sandstone-hosted uranium deposits generally occur in post-Devonian oxidized fluvial sequences deposited in closed basins surrounded by granitic or volcanic highlands (Ruzicka and Bell, 1984). Distribution of the uranium is controlled by sedimentological characteristics of the permeable, oxidized fluvial channel sediments and the impermeable, unoxidized interchannel sediments that contain carbonaceous matter to induce precipitation of the uranium from oxidized groundwaters (Finch, 1967; Seeland, 1978). Organic matter within the sandstone bodies acts as: (i) a reducing agent controlling the oxidation state (Eh) of the subsurface waters and the concentrations of multivalent elements (e.g. uranium ions- U^{4+}, U^{6+}), (ii) a source or sink for hydrogen ions (H^{+}), hence controlling pH, (iii) a complexing agent with metals, and (iv) a decarboxylating agent, thermally or with the aid of bacteria to decompose the organic matter into carbon dioxide and hydrogen gases (Kharaka et al., 1986).

Uranium deposits commonly occur in a classic "roll-front" configuration where the ore is concentrated in irregular zones related to redox fronts (Ruzicka and Bell, 1984). Changes in fluid circulation patterns will arrest the syndiagenetic migration of the redox front and accompanying geochemical cell, forming discordant roll-front deposits (Rackley, 1976).

In these deposits, the reduced facies are typically light grey or drab to nearly white, indicating that necessary anaerobic conditions existed both for coalification and for a microbiological, sulphate-reducing environment in which iron minerals were at least partly pyritized. The oxidized facies are red, light buff or tan, reflecting the creation of iron oxide minerals through early aerobic deposition and preservation under oxidizing conditions, both above and below the local groundwater table (Nash et al., 1981). In Zambia, sandstone-hosted uranium concentrations have been reported in the Upper Karoo Group.

7.4.2 HISTORICAL BACKGROUND

Uranium exploration in Zambia dates back to the 1950s when small concentrations of uranium minerals were discovered in association with copper and cobalt at the Nkana Copper Mine in Kitwe. However, in the Karoo Supergroup, systematic prospecting for uranium started only in 1973, in the Luangwa Valley Basin, Eastern Province of Zambia. In the mid-Zambezi Valley Basin (including the study area), a preliminary uranium investigation, in the form of a car-borne radiometric survey, was undertaken in 1958 (O'Brien, 1960) and led to the discovery of uranium anomalies. As the uranium mineralization was considered to be insignificant in the area, investigations were halted until a countrywide airborne geophysical survey was carried out between 1967 and 1976 (Saviaro, 1977). Significant clusters of uranium anomalies were observed in the Karoo rocks (Escarpment Grit and Interbedded Sandstone and Mudstone formations) in the Kariba Lake area. These uranium surveys (particularly the airborne surveys) culminated in the recent discovery of extensive sandstone-type uranium occurrences in the Karoo rocks of Zambia. Since then, major companies have carried out exploration in the Upper Karoo, notably Agip SPA of Italy and Power Reactor Nuclear Fuel Development Corporation of Japan (PNC). Detailed work has been undertaken by Agip SPA at Bungua Hill, Siavonga area and Lusitu area in the northeastern part of the mid-Zambezi Valley Basin (northeast of the present study) where more promising clusters were located.

7.4.3 URANIUM MINERALISATION

An attempt was made in this study to identify uranium mineralisation in the Upper Karoo Group, using a scintillometer from the Department of Geology, University of Ottawa. The attempt was abandoned because it was difficult to distinguish background noise from anomalous readings. However, the instrument was tried on suspected outcrops where some readings were very high. This section relies heavily on the unpublished exploration work of PNC in the study area, and of Agip SPA northeast of the basin, integrated with the sedimentological data and a few uranium mineralisation observations of this study.

PNC exploration (1980-1986), targeting the Escarpment Grit and Interbedded Sandstone and Mudstone formations of the Upper Karoo Group in the mid-Zambezi Valley Basin, covered an area of 3,300 km^2 and included the present study area. Radioactivity anomalies were also observed in the basement rocks. They carried out geological, geochemical and geophysical surveys in the most promising areas, of which Makonkoto, Ngoma Hill, Sikaneka, Chimoncelo, Sinakoba and Kanchindu west are partly or entirely within the present study area (Figs. 2.2a-d).

In the Sikaneka and Chimoncelo areas, uranium mineralisation including the primary minerals pitchblende and coffinite ($USiO_4$) occurs at 300-500 m depth (max. 0.89% U_3O_8) in 0.3 to 0.7 m thick zones. In the Ngoma Hill and Makonkoto areas, the main secondary uranium mineral is autunite, and radiometric anomalies occur in four lithotypes (Fig.7.2a): ferruginous cemented sandstone, fine- to coarse-grained sandstone, conglomeratic sandstone and mudballs. The last three show similar mineralisation, and occur in the Escarpment Grit Formation, whereas the ferruginous sandstone also occurs in the Interbedded Sandstone and Mudstone Formation. The fine- to coarse-grained sandstone and conglomeratic sandstone types continue laterally up to 200 m. The radioactivity (max. 280 UR/hr) in the ferruginous sandstone is related to high concentrations of limonite and goethite in circular patches less than 50 cm in diameter (Fig. 7.2b). Yellowish coloration observed in the fine- to coarse-grained sandstone (Fig 7.2c) reflects uranium mineralisation judging from the anomalously high reading obtained by the scintillometer. In the Ngoma Hill area, the uraniferous mudballs (max. ~ 460 UR/hr) consist of quartz, feldspar, mica and apatite, with autunite and meta-autunite along cracks in the balls. Radioactivity (max. 180UR/hr) of the conglomeratic sandstone type is related to mudballs and small mudflakes within the matrix, and is differentiated from the mudball type by the presence of basement rock pebbles in the conglomerate. The fine- to coarse-grained sandstone type (max. 280UR/hr) contains phosphate grains.

In the Sikaneka area, uranium mineralisation (autunite and meta-autunite) is confined to sandstone with anomalies hosted in muddy layers and pellets in the Escarpment Grit Formation, and in fine-grained sandstone (max. 1,000UR/hr) of the Interbedded Sandstone and Mudstone Formation. The anomalies are associated with phosphate nodules (A-type anomaly) that occur in thin mineralized layers or along the boundary between sandstone and mudstone, where pitchblende and coffinite are locally present in association with pyrite and carbonaceous matter (B-type anomaly). The B-type (zone thickness of 5-20 m) correlates positively with the content of carbonaceous matter, and occurs mainly at depths below 300 m. In the Chimoncelo area, the A-type anomalies are in medium- to coarse-grained sandstone with grey to brown phosphatic mudballs (phosphate up to 20% of the radioactive rock), and the B-type is associated with laterite (lateritic anomalies of Kogler et al., 1983, as quoted in PNC., 1987). In the Kanchindu west area, the anomalous layers, mainly in the upper part of the Interbedded Sandstone and Mudstone Formation, are of mud-ball type and are interconnected in plan view, suggesting a)

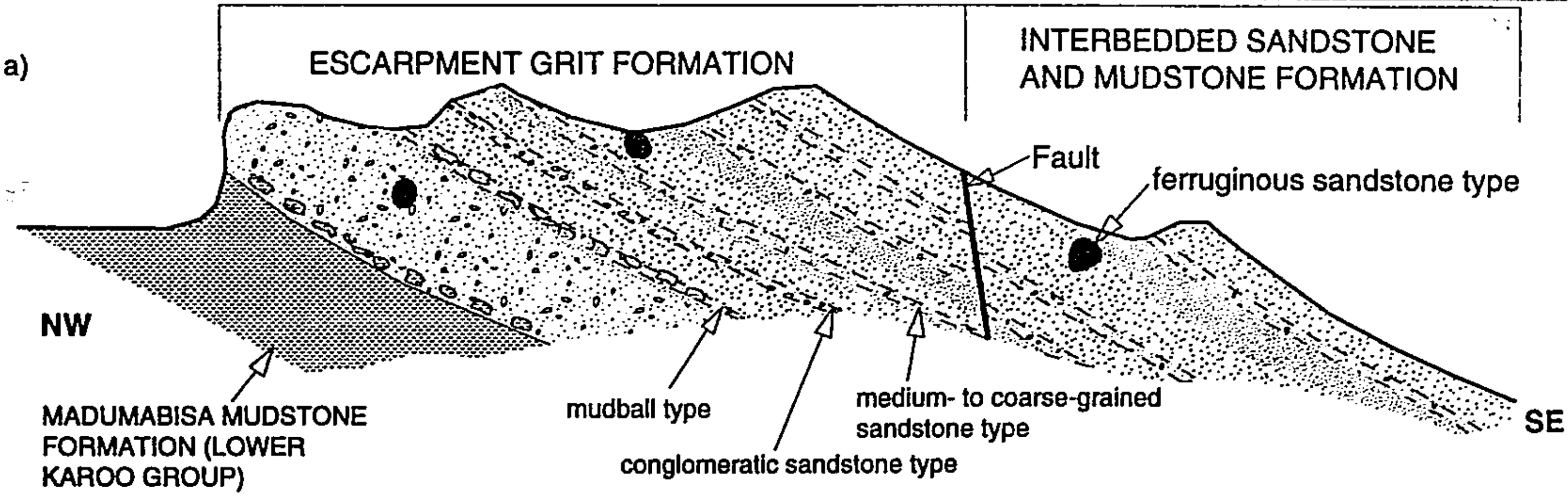
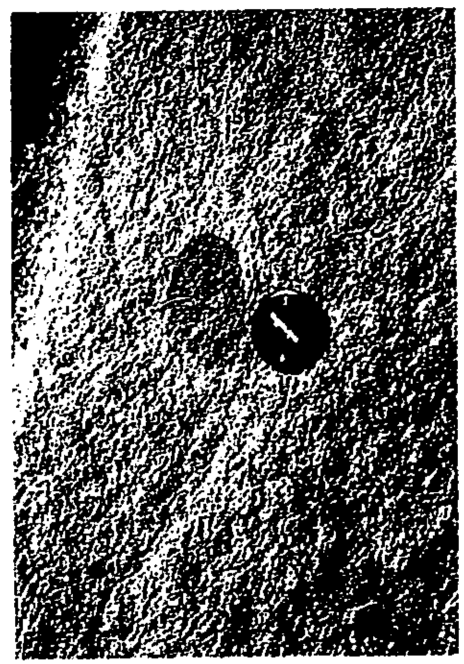


Fig. 7.2: Uranium occurrence in the Escarpment Grit and Interbedded Sandstone and Mudstone formations of the Upper Karoo Group, mid-Zambezi Valley Basin, southern Zambia.

a: Idealized stratigraphic occurrence of uranium (modified from Power Reactor and Nuclear Fuel Development Corporation report).

b: Deep red ferruginous sandstone type anomaly in massive, coarse- to very coarse-grained sandstone; grain size of circular patch similar to host rock but higher matrix content. Road Cut Section, Nkandabwe area. Lens cap is 5.3 cm in diameter.

c: Horizontally bedded coarse-grained sandstone with yellowish coloration probably due to uranium mineration (high scintillometer reading; fine- to coarse-grained type anomaly). Kungwe Hill (Northeast), Siankondobo map area.



b)

c)

that the mineralisation followed a palaeochannel system. Outside this study area (Siansowa and Kanchindu area), uranium content correlates with phosphate content, suggesting that the former was derived from uranium-bearing apatite. In essence, two types of uranium mineralisation are present: one associated with carbonaceous matter, and the other related to uranium-bearing apatite.

In the northeastern part of the mid-Zambezi Valley Basin, airborne and ground gamma radiation surveys led to discovery of uranium-mineralised bodies in the Upper Karoo Group containing up to 95% secondary minerals including autunite, meta-autunite, phosphuranylite, uranophane, abernathyite, boltwoodite and uranocircite with accessory barium, vanadium, molybdenum, phosphorus, manganese and copper. They mainly fill pores, fractures, joints, and bedding planes, and occur as coatings on sand grains and locally along dipping cross beds (Money and Prasad, 1977; Prasad et al., 1977). The characteristics of the deposits are summarised as follows: (i) they occur as fine- to coarse-grained, poorly to moderately sorted, feldspathic to arkosic sandstone blankets (0.1-2.5 m thick beds?; low to medium grade), both concordant and discordant to bedding, with an amoeboid to elongate shape, (ii) they occur in grey to greyish white sandstone with interbedded grey, green and purplish red to brown clayey siltstones (4:1), with finely divided pyrite in unoxidized zones, and brownish yellow bleached rocks and limonitic or hematitic rocks present in oxidized zones, (iii) they have reducing agents that include organic material in finely preserved silts, clays and silicified fossil wood fragments, (iv) they follow formational dips ranging from 5 to 30° conducive to, relatively fast groundwater migration, and (v) they occur in sediments representing braided river plains, laid down in arid conditions (Money and Prasad, 1977). The uranium-bearing zones are generally bleached greyish white, greyish brown, purplish red to reddish brown gritty sandstone. Remobilisation in the deposits was probably brought about by a fluctuating water table, and dipping strata provided the groundwater migration. Two types of mudballs are present: armoured (average diameter ~ 10 cm with up to 20% U_3O_8) and unarmoured (clay balls and pellets). The armoured type consists of greenish/grey clay, surrounded by an armour of arkosic sandstone with mineralisation spread from the clay nucleus to the interface between armour and clay.

7.4.4 DISCUSSION AND SUMMARY

Palaeocurrent data show that the sediments of the Escarpment Grit Formation and overlying Interbedded Sandstone and Mudstone Formation were derived from the basement igneous (mainly granitic) and metamorphic rocks to the northeast, north, and northwest, and from rocks of the Lower Karoo Group. Leaching and erosion of the uplifted basement and Lower Karoo rocks provided the uranyl ion (U^{6+}). Langmuir (1978) suggested that uranium can be transported as uranyl (U^{6+}) carbonates and/or phosphates in solution. The association of uranium with phosphate in the Karoo anomalies supports transportation as uranyl phosphate. Such solutions will precipitate ore minerals when meeting a geochemical barrier, depending on concentration of uranium in solution, and changes in Eh and pH. The uranium minerals pitchblende and coffinite reflect deposition of primary ores, but their current proportions as only 5% of the ores suggest that they are only remnants of the original deposit. Subsequent fluctuations in the water table could have resulted in the remobilisation and redistribution of pre-existing deposits, and reprecipitation in conglomeratic palaeochannels at redox interfaces, and in mudballs and clay minerals. This explains the sporadic and localised nature of deposits. The interbedded aquicludes (namely the mudrock lithofacies (mudstone/siltstone) and fine-grained sandstone) contain considerable amounts of carbonaceous matter (coaly laminae, pyrite, coal fragments) that would have acted as reducing agents to confine solutions and precipitate uranium brought in through the porous coarse-grained to pebbly (conglomeratic) sandstone. The main mineralisation controls were porosity and permeability, which are commonly best in coarse-grained sediments of channels and crossbeds that commonly contain impermeable layers and mudclasts. The Madumabisa Mudstone would have acted as an impermeable barrier to downward movement of mineralised uranium solutions, forcing them to migrate down dip within the Upper Karoo formations.

Roll-front type of mineralisation has not been demonstrated in the Upper Karoo Group of Zambia, and the deposits are generally lensoid, either concordant or discordant (northeastern part of the mid-Zambezi Valley Basin) and associated with palaeochannel mineralisation in the vicinity of the present study area. The implication from PNC (1987) and Money and Prasad (1977) is that both trend deposits (mineralised trends parallel to bounding surfaces of host strata reflecting palaeo-drainage control and/or mineralised trends that cross the palaeo-drainage pattern), and roll-front deposits (biofacies roll-fronts), with both oxidized and reduced facies, occur in the host formations of the Upper Karoo Group in the mid-Zambezi Valley Basin. The latter is more favoured. Although no roll-front deposits have been demonstrated, both alternating sandstone as an oxidised aquifer and mudrock as a reducing aquiclude are evident in the Escarpment Grit and Interbedded Sandstone and Mudstone formations. The deposits occur in braided channel systems of probably humid to semi-humid conditions (from palynological data -Chapter 4) instead of the arid conditions postulated by Money and Prasad (1977).

7.5 SUMMARY

The potential for more coal deposits in the mid-Zambezi Valley is high because such deposits could be hidden by overburden as was the case for most of the Kazinze Open pit area. The subsurface (near-surface) and exposed coal and organic-rich mudstone have been shown to have the potential to generate hydrocarbons. The implication is that similar deep buried sediments had a higher probability of hydrocarbon generation. Viewed in this perspective, hydrocarbon studies are encouraged and should be directed towards inorganic geochemical analysis.

Other deposits that may be of interest in the Sinakumbe-Karoo strata include siderite, which is the major ore of iron (Tiercelin, 1991), and iron-rich sediments (nontronite, vivianite) which are regarded as hydrothermal discharges in the East African rift lakes (Muller and Forstner, 1973; Mondeguer et al., 1989). The source of siderite that formed abundant sideritic bodies in the Gwembe Coal Formation was possibly from derivation of sulphur from vegetable matter to form siderite under anaerobic (reducing) conditions or due to hydrothermal discharge through faults. Biological concentrations of zooplankton faecal pellets and fossil debris (e.g. fish bones and teeth - Fig. 4.74c) are responsible for phosphate (carbonate apatite) accumulation in lacustrine sediments (Porter and Robins, 1981). Apatite and barite are present in the succession but not in economical quantity. Occurrence of sphalerite (zinc) has been reported (Simataa, pers. comm., 1990), but has not been confirmed by the author.

CHAPTER VIII

CONCLUSION

8.1 GENERAL REMARKS

Outcrop, subsurface and laboratory data have been used to re-define the stratigraphy of the Sinakumbe Group, to refine the sedimentology of the Sinakumbe Group and Karoo Supergroup, to analyse depositional systems architecture in relation to tectonic control, and to assess the economic potential of the Sinakumbe-Karoo succession in the mid-Zambezi Valley Basin, southern Zambia.

8.2 STRATIGRAPHY

The ?Ordovician to Devonian Sinakumbe Group unconformably overlies Precambrian Basement rocks and is unconformably overlain by the Karoo Supergroup. In the newly recognized surface exposures in the study area, it can be readily divided into informal lower and upper parts, with thicknesses of 60 and 150 m, respectively.

The succeeding Permo-Carboniferous to Lower Jurassic Karoo Supergroup is divided into two groups, the Lower and Upper Karoo, with total thickness of 4.5 km. In ascending order, the Lower Karoo Group is composed of the Siankondobo Sandstone, Gwembe Coal and Madumabisa Mudstone formations, whereas the Upper Karoo comprises the Escarpment Grit, Interbedded Sandstone and Mudstone, Red Sandstone and Batoka Basalt formations.

8.3 SEDIMENTOLOGY

The Sinakumbe-Karoo succession was deposited in an intracontinental extensional basin confined by fault-bounded basement blocks, which underwent periods of fault motion. The basin-fill strata are similar to those known in fault-bounded distensive basins of half graben type. Facies distribution and palaeocurrents suggest sediment input was mainly from the Precambrian basement to the north, northeast and northwest.

The Sinakumbe Group is regarded as an alluvial fan/braided stream deposit that crops out at the north/northwest margins of the mid-Zambezi Valley Basin. The Lower Sinakumbe Group comprises five lithofacies, grouped into two facies assemblages; mudrock-sandstone and conglomerate. The mudrock-sandstone facies assemblage was deposited largely by sheetfloods on mud- and sandflats. The conglomerate facies assemblage is largely debris flows, sheetfloods and braided stream deposits. The assemblages are arranged in a coarsening-upward sequence that represents an instantaneous deepening due to subsidence and then gradual filling, with erosion and sediment input from the margins. The coarsening-upward sequence is interpreted as an alluvial fan deposit. Strikingly red lithofacies suggest deposition in a semiarid environment. The sharply based succeeding Upper Sinakumbe Group depositional system accumulated in a separate braided stream system, geographically between Lower Sinakumbe Group alluvial fans systems to the northeast and southeast. Sediment dispersal was mainly perpendicular to the southeasterly palaeoslope of the Lower Sinakumbe alluvial fans. The Upper Sinakumbe Group consists of two lithofacies that are grouped into a quartz arenite facies assemblage. Slump deposits (mudclast breccia lithofacies), associated sedimentary structures, and paucity of mudrocks indicate that the facies assemblage is probably a braided stream deposit.

The Lower Karoo Group represents three depositional settings, including glacio-fluvial / glacio-lacustrine (Siankondobo Sandstone Formation), fluvial flood plain (Gwembe Coal Formation), and lacustrine (Madumabisa Mudstone Formation).

The five lithofacies in the Siankondobo Sandstone Formation (diamictite, conglomerate, varve-like silty mudstone and siltstone, cross-laminated siltstone, and massive sandstone) can be grouped into three facies assemblages: diamictite, siltstone and sandstone. The diamictite facies assemblage represents debris flow (diamictite) and braided stream (conglomerate) deposits on an alluvial plain from a retreating glacier. The siltstone facies assemblage (varve-like silty mudstone and siltstone, cross-laminated siltstone/sandstone) represents deposits settled from suspension, probably at lake bottom (varve-like sediments), and underflow subaqueous deposits (cross-laminated siltstone lithofacies). The massive sandstone facies assemblage is interpreted as sediment gravity flows deposited in channels by means of a variety of grain-support mechanism, with sediment supply from meltwater streams. The assemblages are arranged in a fining-upward sequence at the base (diamictite to varve-like sediments) overlain by a coarsening-upward sequence (varve-like sediments to sandstone). The characteristics of lithofacies and assemblages, arrangement and association suggest glacio-fluvial / glacio-lacustrine settings.

Fourteen lithofacies of the Gwembe Coal Formation can be grouped into four facies assemblages: Maamba Sandstone, Coal, Mudrock and Sandstone A. The Maamba Sandstone facies assemblage is interpreted as meandering stream deposits. The coal facies assemblage accumulated in swamps on the flood plain that were interrupted periodically by crevasse channels and splays that deposited the Interseam Sandstone. The mudrock facies assemblage consists of overbank fines whereas the "lithofacies of the other sandstones (B,C,D,E,)" are attributed to crevasse channels and splays, and siderite to diagenetic precipitation. The Sandstone A facies assemblage represents proximal braided stream deposits that grade distally into meandering river system deposits. The characteristics of the lithofacies and facies assemblages support the deposition of the Gwembe Coal Formation on the flood plain.

Five lithofacies of the Madumabisa Mudstone Formation can be grouped into two facies assemblages: massive mudrock and laminated mudrock. The massive mudrock facies assemblage represents deposition out of suspension from sediment-laden river water entering a lake. The presence of concretionary calcilutite beds, rootlets, local reddening and reduction in the assemblage suggest shallowing and possible emergence. The laminated mudrock facies assemblage (siltstone/sandstone) is interpreted as mainly proximal sheetflood and fluvial deposits at lake margins. The thickening-upward cycles in the laminated mudrock facies assemblage suggest shallowing, with thin laminated beds laid down in deeper probably anoxic waters. A biota of ostracods, bivalves, fossil burrows, gastropods and botrycoccal algae indicate a lacustrine deposit.

Six lithofacies of the Escarpment Grit and Interbedded Sandstone and Mudstone formations indicate deposition in braided-fluvial systems. The three lithofacies of the Escarpment Grit Formation form the sandstone/mudrock facies assemblage. The assemblage is arranged in poorly defined fining-upward cycles, with stacked cross-beds (St and Sp mainly), a paucity of mudrock, and coarse-grain size indicating a braided river depositional setting. The overlying Interbedded Sandstone and Mudstone Formation lithofacies are grouped in the mudrock / sandstone facies assemblage. The assemblage occurs in well-defined fining-upward cycles, whose characteristics (association of sedimentary structures, geometry of beds, mudrock abundance) indicate deposition in a sand braided-river environment transitional to a meandering-river environment.

Palaeontological data support the interpretation that the Siankondobo Sandstone, Gwembe Coal, Madumabisa Mudstone, and Interbedded Sandstone and Mudstone formations of the Karoo Supergroup are non-marine deposits. The fossils also indicate that the Siankondobo Sandstone is Late Carboniferous to Early Permian in age, the Gwembe Coal Formation is Early Permian, and Madumabisa Mudstone is Late Permian, and the Interbedded Sandstone and Mudstone Formation is Early to Middle (?) Triassic.

The Sinakumbe-Karoo basin sequence was dominated by vertical subsidence and uplift. Two major fining-upward cycles are recognised, one comprising the Sinakumbe Group and Lower Karoo Group, and the other the Upper Karoo Group. Minor cycles are also present and the cyclicity reflects fault-controlled tectonic movements (except for cycles related to isostatic rebound that followed Dwyka glaciation). Sinakumbe-Karoo basin fill began deposition of the Lower Sinakumbe Group in fault-controlled alluvial fan systems and continued with deposition in the Upper Sinakumbe Group braided stream system.

The Siankondobo Sandstone Formation, deposited in a glacio-fluvial / glacio-lacustrine depositional system, represents isostatic rebound following deglaciation that culminated in a broad flood plain on which the Gwembe Coal Formation was formed. Tectonic pulses resulted in proximal braided stream deposits (Sandstone A) that are transitional into meandering river deposits.

The lacustrine Madumabisa Mudstone depositional system represents maximum fault-bounded subsidence with minor tectonic pulses represented by thickening-upward cycles (abrupt deepening- gradual shallowing). Post-Lower Karoo faulting and downwarping probably due to Gondwanide Orogeny resulted in the lacustrine sequence being terminated by deposition of the Escarpment Grit Formation braided fluvial deposits.

Downwarping, local reactivation of faults and the presence of Precambrian basement remnants (outliers) account for opposing palaeocurrent directions; sediment source areas are inferred to have lain to the northeast and southwest. Waning tectonic instability is reflected in the Interbedded Sandstone and Mudstone Formation by sandy braided river fluvial deposits transitional into meandering river deposits. Palaeocurrents were generally toward the southeast. The succeeding aeolian Red Sandstone Formation was terminated by Batoka volcanism that ended Karoo sedimentation.

8.4 ECONOMIC POTENTIAL

There is significant potential for undiscovered coal deposits in the Gwembe Coal Formation in areas obscured by overburden resulting from post-Lower Karoo faulting. The coals of the formation have a thermal alteration index (TAI) of 2 which is equivalent to a vitrinite reflectance of approximately 0.5%Ro and a mean vitrinite reflectance of 1.08%, indicating a thermal maturity at the cool part of the oil window, and thus have a strong potential for liquid hydrocarbon. The occurrence of the alga *Botryococcus* sp., the presence of exinous material (5-10%), and the TAI of 2 suggest potential for liquid hydrocarbon also in some restricted intervals (commonly thinly laminated dark grey mudstone at base of thickening-upward cycles) in the Madumabisa Mudstone Formation. The Sandstone A facies assemblage of Gwembe Coal Formation, the massive sandstone facies assemblage of Siankondobo Sandstone Formation, and sandstone bodies in the Madumabisa Mudstone Formation and overlying Escarpment Grit Formation have reservoir potential with secondary porosity up to 20% in some units. These strata are locally interbedded with potential source rocks. The overlying thick mudrock units of the Interbedded Sandstone and Mudstone Formation could have acted as a seal, with possibilities for structural fault traps and stratigraphic pinchout traps.

There is a strong potential for both trend and roll-front type uranium deposits in the down dip direction (southeast) in the Upper Karoo Group. The mineralisation is uneconomical at present market conditions, but may be of significance in the future.

8.5 RECOMMENDATIONS

This study focussed on the sedimentology, tectonic control and economic potential of the Sinakumbe-Karoo succession in a regional context. It is the hope of the author that future studies will focus on these topics at a smaller scale, perhaps at formation level, utilising both surface and subsurface data. The potential for discovery of more coal deposits in the mid-Zambezi Valley Basin is quite high, and the search for them will depend largely on drilling. To test the potential for hydrocarbons, future studies should concentrate on geochemical studies such as RockEval analysis, concentrating on the coal sequence and certain intervals (beds) of the Madumabisa Mudstone Formation. The preliminary palynology results of this study are encouraging, and more results are needed from the Madumabisa Mudstone Formation and the Upper Karoo Group to substantiate this study's results. Uranium subsurface data in unpublished reports and drill logs left behind by the Power Nuclear Reactor Corporation of Japan and all other data, should be built into data banks that can be used in future exploration studies. Some could be used to construct isopach maps that portray uranium concentrations.

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