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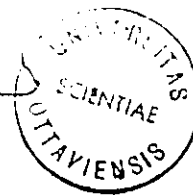
UNIVERSITÉ D'OTTAWA
UNIVERSITY OF OTTAWA

ARCHEAN MAGMATISM AND METALLOGENY:
GEOLOGICAL SEQUENCES IN SOME ARCHEAN OREFIELDS

by

W. WALKER

A thesis submitted to the School of Graduate Studies
in partial fulfillment of the requirements for the
degree of Ph.D. in Geology



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CONTENTS

	<u>PAGE</u>
ABSTRACT	12
INTRODUCTION	14
Purpose of the Study	14
Definitions: Some Terms of Reference	14
Nature of the Study	15
Previous Work	18
Acknowledgements	18
VOLCANIC CYCLES AND VOLCANIC UNITS	20
Volcanic Cycles	20
Volcanic Units	22
GENERAL GEOLOGY	34
Canada	39
Yellowknife	41
Hanson Lake-Flin Flon-Snow Lake-Sherridon	58
. Hanson Lake	60
. Flin Flon	67
. Snow and File Lakes	75
Rice Lake	87
Abitibi Belt	99
. Timmins	101
. Kirkland Lake	116
. Noranda	132
. Chibougamau	148

	<u>PAGE</u>
Brazil	161
Rio das Velhas	162
Southern Africa	173
Barberton Mountain Land	175
Limpopo	192
Vumba and Tati	203
Midlands	216
Goa	238
Western Australia	247
Pilbara	248
Eastern Goldfields	264
AGE	283
Evaluation	284
CONCLUSIONS	297
General Geology	297
. Vulcanism	297
. Sedimentation	303
. Plutonism	304
. Deformation	305
. Metamorphism	306
Metallogeny	307
. Metal Associations	307
. Geological Associations	314
. Time Associations	317
. Regional Associations	317
. The Dollar Factor	318
. Perspectives for Exploration	319

	<u>PAGE</u>
Age	320
Summary of Conclusions	322
Appendix 1 - Mine Output Ratings	324
Appendix 2 - Radiometric Data	326
Bibliography	363

FIGURES

	<u>PAGE</u>
1. Comparison of Archean volcanic stratigraphy, Canada, South Africa, Western Australia (Wilson model).	26
2. Hypothetical Archaean stratigraphic column (Anhaeusser model).	28
3. Symbols for charts.	36
4. Location map, Canadian areas.	40
5. Location map, Yellowknife area.	42
6. Chart, time relations of geological features, Yellowknife area.	43
7. Geology, Yellowknife area.	45
8. Geology, plutonics of Cameron and Beaulieu rivers.	49
9. Geology, plutonics of Blachford Lake.	49
10. Structure, Ross and Gordon lakes.	52
11. Geology, Hanson Lake-Flin Flon-Snow Lake.	59
12. Chart, time relations of geological features, Hanson Lake.	61
13. Chart, time relations of geological features, Flin Flon.	68

14. Stratigraphy and structure, Flin Flon.	71
15. Chart, time relations of geological features, Snow and File lakes.	76
16. Geology, Snow Lake.	78
17. Structure, Snow Lake.	78
18. Geology, File Lake.	81
19. Geology, Rice Lake.	88
20. Chart, time relations of geological features, Rice Lake.	89
21. Metallogenic relations, Abitibi Belt.	100
22. Chart, time relations of geological features, Timmins.	102
23. Stratigraphy, Timmins.	105
24. Stratigraphic columns, Timmins.	106
25. Chart, time relations of geological features, Kirkland Lake.	117
26. Stratigraphic synthesis, Kirkland Lake.	120
27. Geological sketch map, Kirkland Lake.	120
28. Stratigraphy, south margin Abitibi Basin.	121

	<u>PAGE</u>
29. Round Lake batholith.	124
30. Chart, time relations of geological features, Noranda.	133
31. Geology, Rouyn-Noranda.	136
32. Stratigraphy, Rouyn-Val d'Or.	137
33. Metamorphic zones, Rouyn-Noranda.	142
34. Stratigraphic sections, Waite-Amulet.	145
35. East Waite ore deposit.	145
36. Time relations of geological features, Chibougamau.	149
37. Geology, Chibougamau.	151
38. Ore and structure, Chibougamau.	159
39. Geology and copper-gold mines, Chibougamau.	159
40. Location map, Rio das Velhas.	163
41. Chart, time relations of geological features, Rio das Velhas.	164
42. Geology, Rio das Velhas.	165
43. Archaean granite-greenstone terrain, Rhodesian and Kaapvaal cratons.	174

44. Chart, time relations of geological features, Barberton Mountain Land.	176
45. Stratigraphic sections, Swaziland sequence.	179
46. Granitic rocks, Swaziland and eastern Transvaal.	182
47. Contact phenomena, Theespruit tonalite pluton.	183
48. Tectonic style, tonalitic plutons.	183
49. Ultramafic complexes and asbestos mines.	187
50. Stolzburg ultramafic body showing asbestos mineralization.	187
51. Gold mines, southern Barberton Mountain Land.	190
52. Chart, time relations of geological features, Limpopo.	193
53. Structural section, Pikwe-Selebi.	195
54. Eastern Geotraverse, Botswana.	204
55. Schist relics, Eastern Geotraverse.	204
56. Chart, time relations of geological features, Vumba and Tati.	205
57. Correlation, Vumba and Tati.	207
58. Geological setting of gold and nickel-copper, Tati.	213

59. Geology and mineral occurrences, eastern Botswana.	214
60. Chart, time relations of geological features, Midlands, Rhodesia.	217
61. Geology, Midlands.	220
62. Correlation, Midlands and Barberton.	220
63. Geology sections, Selukwe.	221
64. Field relations of granitic rocks.	227
65. Chromite producing areas.	232
66. Veins and stress field, Selukwe.	234
67. Fissure system, Selukwe.	234
68. Gold deposits in iron formation, Rhodesia.	235
69. Geological and tectonic map of the Dharwar protocontinent.	239
70. Chart, time relations of geological features, Goa.	240
71. Geology, Pilbara.	249
72. Chart, time relations of geological features, Pilbara.	250
73. Geology, part of West Pilbara goldfield.	252

74. Facies changes in the Roeburne Group.	253
75. Correlations in the Roeburne Group.	253
76. Geology, Munni Munni Complex.	255
77. Tin granite occurrences, Pilbara goldfield.	257
78. Geology, Moolyella tinfield.	257
79. Iron ore deposits, Port Hedland district.	262
80. Geology, Mount Goldsworthy area.	262
81. Geology, Nos. 1, 2, and 3 iron ore deposits, Mount Goldsworthy.	262
82. Geology, Kalgoorlie-Norseman.	265
83. Chart, time relations of geological features, Eastern Goldfields.	266
84. Geology, Coolgardie-Kurrawang.	268
85. Columnar section, Coolgardie-Kurrawang.	268
86. Stratigraphy, Coolgardie-Kurrawang.	269
87. Correlation, Coolgardie-Kurrawang and Barberton.	271
88. Geological plans and sections, Kalgoorlie.	280
89. Structure, Golden Mile Dolerite.	281

90. Distribution of gold lodes, Kalgoorlie.	281
91. Tectonic development of the Rhodesian craton.	290
92. Chart, Archean areas.	299
93. A geological model for the Southern hemisphere and India, 3.4 to 3.3 b.y.	300
94. A geological model for the Canadian Shield, 2.8 to 2.7 by.y.	301
95. Ores and associations.	308
96. Histogram of radiometric dates, Canada	350
97. Histogram of radiometric dates, Barberton.	351
98. Histogram of radiometric dates, Rhodesia.	352
99. Histogram of radiometric dates, India.	353
100. Histogram of radiometric dates, Pilbara.	354
101. Histogram of radiometric dates, Yilgarn.	355
102. Histogram of radiometric dates, Canada, Africa + India, and Australia.	356

103.	Histogram of radiometric dates, Canada, Africa, India, — and Australia.	357
104.	$^{87}\text{Sr}/^{86}\text{Sr}$ ratios and Rb-Sr dates, Canada.	358
105.	$^{87}\text{Sr}/^{86}\text{Sr}$ ratios and Rb-Sr dates, Southern Africa.	359
106.	$^{87}\text{Sr}/^{86}\text{Sr}$ ratios and Rb-Sr dates, India.	360
107.	$^{87}\text{Sr}/^{86}\text{Sr}$ ratios and Rb-Sr dates, Australia.	361
108.	Development times of $^{87}\text{Sr}/^{86}\text{Sr}$, all areas.	362

ABSTRACT

The deposition and emplacement of sedimentary, volcanic, and plutonic rocks are related to the history of deformation and metamorphism. Integrated into the sequence is the genesis and subsequent history of those metals which, in the Archean, commonly form ore. Geological and radiometric data have been tabulated and studied from Archean ore-fields in Canada, Brazil, southern Africa, India, and Western Australia.

Contrasts between magmatic products in Canada and those of southern Africa and Australia lead to consideration of metallogenic epoch and province, time and space.

Radiometric data, when studied as suites rather than as individual analyses, indicate that Canadian greenstone belts took less than 100 m.y. to form, starting in the period 2.8 to 2.7 b.y., and that the greenstone belts of the southern areas also took less than 100 m.y. to form, probably starting in the period 3.4 to 3.3 by., but at least pre-dating the Canadian examples. The 100 m.y. durations of development compare to those of the Phanerozoic.

The geological contrasts are in magmatism and metallogeny. In the southern regions the volcanism was consistently cyclical whereas in the Canadian Shield in some places it is cyclical, in others it is not. Volumes of volcanic product vary so as to be characteristic, a komatiite in the southern region, felsic products in the Canadian Shield. The dominant plutonic sequence in all regions is early tonalite-quartz monzonite diapirs followed by granites accompanied by migmatites and lastly discordant stocks of tonalite, granite, and syenite. Additions to this simple three-part sequence are rare in the southern regions, common in the Canadian Shield.

The differences in geology are considered to be related to the difference in evolutionary stages of earth history, but because they are also divided in space, and neither period is well represented in the other region, the difference may be related to place rather than to time. The oldest known Archean period, about 3.8 b.y. old, includes the iron formation at Isua, Greenland, but as no orefield has yet been developed, the period is not represented in the study.

Gold appears to originate in all types of rock. Upgrading to ore is generally related to metamorphism and to structural channelways and traps common to all Archean areas.

/ Iron, too, appears at various levels of the volcano-sedimentary system. In the areas considered, ore is developed in the younger cycles where the sedimentary component prevails.

Nickel and chrome are related to ultramafic rocks. While thick ultramafic developments are favoured, the restriction of major deposits of nickel to Western Australia and the Val d'Or area of Quebec, and of chrome to Rhodesia is not understood.

Copper-zinc deposits are related primarily to an upper felsic suite noted only in Canada.

The principal direct economic products of Archean plutonism are the pegmatite ores: tin, lithium, beryllium, and cesium. No preference of time or place is observed.

The lack of definition of metallogenic contrast indicates the need for a better understanding of the variations in Canadian successions from place to place. Data from India and Brazil are also needed before the simplicity of southern areas can be affirmed.

INTRODUCTION

PURPOSE OF THE STUDY

The purpose of the study is to establish geological relationships which may lead to a better understanding of the genesis of metal, so that prospecting may be better directed. The ultimate source of all metal is magmatic. Subsequent processes of erosion and sedimentation, deformation, metamorphism, and renewed magmatism can lead to the further dispersal of metal, or to its concentration to ore grades, or to modification of its form. The present work considers some of the Archean ore-fields where the geology is better known, documents their features in a standard format, and draws comparisons to see what the Archean patterns of geology, including metallogenesis, appear to be.

DEFINITIONS: SOME TERMS OF REFERENCE

Metallogeny is the study of the genesis of mineral deposits, with emphasis on their relationship in space and time to regional petrographic and tectonic features of the earth's crust. It contrasts with economic geology, the analysis and exploitation of geologic bodies and materials that can be utilized profitably by man. (AGI Glossary of Geology).

Magma is the naturally occurring mobile rock material, generated within the Earth and capable of being intruded and extruded; and magmatism is the development, movement, and solidification to igneous rock, of magma (AGI Glossary of Geology).

For purposes of the present study, Archean relates to the period of formation of rock from the earliest known (at present about 4 b.y.) to about 2.5 b.y. In the ore-fields studied, only a minor amount of basement, not studied, is older than about 3.5 b.y.

NATURE OF THE STUDY

There are two concepts of the position of metallogeny in the broad field of geology: one accords with the definition from the AGI Glossary, cited above, whereas in the other it is an aspect of economic geology. Ramović (1968) adheres to the former concept: "By the end of the 19th and at the beginning of the 20th century, Louis de Launay founded metallogeny which was gradually developed into a separate branch quite distinct from the science of economic geology. Up to that time it was considered to be a part of the latter". Routhier (1963) considers two elements, "Caractères appartenant en propre aux gisements", which might under the foregoing considerations be considered to be economic geology, and "caractères de l'enveloppe des gisements", which, to compare with the AGI Glossary definition, is the aspect of metallogeny which emphasizes relationships of mineral deposits in space and time to regional petrographic and tectonic features of the earth's crust.

The aspect of metallogeny which in recent years has gone unemphasized is that which integrates ore deposit geology and regional geology. When this aspect is given due emphasis, metallogeny appears more as an aspect of economic geology. In this context, Gross (pers. comm. 1976) points out that metallogeny is the relationship and sequences of geological processes which create concentrations of elements or minerals in the earth's crust that are useful, and that it implies an understanding of both regional geological processes and those processes that were directly instrumental in forming the mineral concentrations or deposits themselves.

At the outset of the study, it was hoped that enough data would be forthcoming for the two facets, geological setting and mineral deposit geology, to be integrated. Though, as Gross (pers. comm. 1976) points out, a great deal of structural mapping, for example, was carried out in Canadian mines more than 25 years ago, all of it predates modern structural analysis as developed largely by Ramsay in the 1950's. Only

two published studies of Archean orefields are known in which the relationship of ore type to deformational and metamorphic histories has been considered, that of Pekwe-Selebi, Botswana, by Wakefield (1976) and that of the Selukwe goldfield, Rhodesia, by Stowe (1968-3). In some places, reasonable interpretations of the literature are possible, and the work of Boyle (1961) at Yellowknife, McRitchie and Weber (1971) at Rice Lake, and Ramsay (1963) at Barberton are particularly useful in providing guides to the integration of mine and regional geology in the study of gold metallogeny. Though these works are guides, they are too few to be the basis of models and any use as models must be with the proviso of significant anticipated change.

In general, therefore, the theme followed is the geological settings of Archean ore deposits. The theme of the history of metals is a topic for the future, after later periods have been considered in the same way as the Archean, and after attention has been given to metallogenic provinces. Hopefully, by that time, other workers will have considered ore deposits in terms compatible with the regional studies and the split, perhaps related to working scale, will be healed.

Routhier (1963) has four rubriques for the "caractère de l'enveloppe" which are particularly appropriate to the present study:

1. Nature lithologique et stratigraphique des roches encaissantes.
2. Forme des gisements en liaison avec les structures des roches encaissantes.
3. Roches plutoniques ou (et) volcaniques (proches).
4. Age du gisement et recapitulation rapide de l'histoire géologique de la region.

I have considered Archean settings of ore deposits under sedimentation, vulcanism, plutonism, metamorphism, and deformation. In order to facilitate comparisons, the data are reduced to tabular format and accompanied by yet simpler pictorial charts, so forming the chapter on General Geology.

The time element of time and space noted in the definition of metallogeny is also dwelt upon at length (for the Archean) under Age. Space will be considered as metallogenic provinces when the Proterozoic and Phanerozoic have also been reviewed.

In a study such as this, broad comparisons and contrasts tend to become predominant at the expense of the unique. Watson (oral comm. 1976) notes the dominant control of the Golden Mile Dolerite in hosting gold at Kalgoorlie, and one may add to this the unique alkaline hosts to 85% of the gold ore at Kirkland Lake. The Proterozoic Rand and Sudbury are often spoken of as unique: the same may be true of smaller hosts to Archean ore deposits.

The AGI Glossary definition of metallogeny includes the relationship of mineral deposits to regional petrographic and tectonic features of the earth's crust. In the title to this work the magmatic (i.e., petrographic) features are noted and tectonic features are omitted. Tectonic features may guide or transect petrographic zones: just as the relationship of ore to host rock is now appreciated (Bilibin 1968, Stanton 1972, King 1973), so too is the significance of major structure (Billingsley and Locke 1941, O'Driscoll 1971, Kutina 1971, Scheiber and Stevens 1974). Here the major concern is the host rock, wherein the magmatic products are regarded as the primary control of mineralization, and such features as sedimentation, deformation, and metamorphism as the secondary features by which mineralization may be enhanced to ore grade, or modified, or dispersed.

PREVIOUS WORK

A review of the history of metallogeny has been given by Ramović (1968) and the evolution of my own thinking on the topic is perhaps best expressed in two works (Walker 1975, 1976). My concern here, therefore, is solely with those works which provide direct guides to the present study. Goodwin (1962 et seq.) developed the concept of volcanic cycles, perhaps better termed sequences; Anhaeusser, Roering, Viljoen, and Viljoen (1968 et seq.) developed a model of the elements and evolution of an Archaean fold belt which is extensively utilized in the present work; and Wilson (1974) and his co-workers, having complemented this model, are also extensively followed here. The format of part of the charts showing time relations of geological features is largely due to Fyson (1971, 1975, pers. comm.): his concern with deformation has provided me with a control for the utilization of old data gathered at a time of less understanding of the inter-relationship of plutonism, deformation, and metamorphism.

An important aspect of the study is the change with time. Veizer (in press.) has shown a semi-quantitative summary of changes in proportion of sedimentary facies and ores of sedimentary affiliation throughout geologic history. Pereira and Dixon (1965), Watson (1973), and Hutchinson (1976) have discussed changing patterns of ore deposition with time; and Douglas and Price (1972), in the final chapter of their jointly edited "Variations in tectonic styles in Canada", review changes from Archean to Proterozoic and from Proterozoic to Phanerozoic. These works give one an awareness of the significance of evolutionary changes as they affect ore deposition.

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Geological Societies tour of the British Caledonides, I would have had no knowledge of the Scottish Highlands, which provided a well dated guide to geological successions: I thank him and B. R. Rust for allowing me to work out the history of Scotland. When the radiometric dates were tabulated, J. Veizer recognized that the plots of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios might add weight to my argument that the emplacement of Canadian and southern areas was at two discrete periods, each lasting about 100 m.y. That this argument is supported on geochronologic terms is largely due to him. W. K. Fyson and A. J. Baer have prodded and, invariably it seems, laid fingers on the problems throughout the course of the present study. I particularly thank Dr. Baer for providing the opportunity for the theme to develop at Ottawa University.

As a metallogenist, G. A. Gross has been most concerned with ore paragenesis. His concern is appreciated, and the works of Wakefield at Pikwe and Stowe at Selukwe indicate the benefits that devolve from the integration of ore paragenesis and the histories of deformation and metamorphism.

It had been my intention to compare ~~more~~ rigorously the relationship of ore paragenesis to deformation and metamorphism. The present review reflects the availability of data. I would thank the mine managers and mine geologists who provided data and hope that in the years to come we appreciate better both "les caractères appartenant en propre aux gisements" and "les caractères de l'enveloppe".

Barbara MacDonald typed this thesis.

VOLCANIC CYCLES AND VOLCANIC UNITS

VOLCANIC CYCLES

Anhaeusser (1971-1) has done much to clarify concepts of Archean cyclicity: "No general agreement has yet been reached on the terminology necessary to describe rhythmic or cyclic periodicity of geological sequences. Restrictive definitions appear unwarranted as flexibility is necessary to absorb the many and varied cyclic combinations possible. For this reason the writer has suggested a number of general terms, the use of which will be clear from their context in the discussion which follows.

Cyclicity in the Archaean volcanic belts can be classified into a number of types. Firstly, there are mini-cycles, which would probably be measured in centimetres, or parts thereof, where repetition of units takes place on a very small scale, being particularly evident in sedimentary members of the stratigraphy. This type of cyclical repetition is frequently found in greywacke-argillite successions that show evidence of having been deposited by turbidity current action.

The second type of cycle, referred to here as a minor-cycle, is developed on a very much larger scale. Minor-cycles constitute thicknesses that would be measured in terms of metres, tens of metres, or even hundreds of metres, and are particularly prominent in the volcanic sequences in the Archaean. Evidence of cyclicity of this type in sedimentary successions has, however, been described.

The third type of cycle, here referred to as a major-cycle, has been recognized in a number of volcanic belts, particularly in Canada, but also in South Africa and Western Australia. The major-cycle is of an order of magnitude larger in its dimensions than the minor-cycle, usually embraces a number of the latter cycles, and generally ranges in thickness from a few hundred metres upwards to many thousands of metres. The major-cycles commonly contain generalized mafic-to-felsic volcanic sequences but major sedimentary cycles are also known.

The remaining type of cycle recognized in the Archaean, and referred to as a super-cycle, embraces the total volcanic and sedimentary pile and may show the changes from calcic, through calc-alkaline, to alkaline vulcanism, and a sedimentary terminal phase. The total thickness of the pile is generally of the order of tens of thousands of metres and usually constitutes the complete stratigraphic column of any individual greenstone belt. Examples of the super-cycle are available from all the shield areas and generally conform to the suggested breakdown of Archaean greenstone belts into an initial Ultramafic Group, a Greenstone Group, and a Sedimentary Group. Thus, the Onverwacht, Fig Tree, and Moodies Groups of the Swaziland Sequence constitute the super-cycle which is the Barberton Mountain Land. Similarly the Sebakwian, Bulawayan, and Shamvaian Groups together constitute super-cycles in many of the greenstone belts on the Rhodesian craton.

Cycles of varying dimensions may occur throughout the entire stratigraphic pile but there is a tendency for the earliest cycles to be larger and more complex than the later cycles. This trend appears to be controlled by the type of magma being erupted at any particular stage in the evolution of the volcanic pile. The earliest volcanics are generally mafic or ultramafic in composition and have lower viscosities than the later more felsic varieties. The changes, with time, of the viscosities of the magma-types greatly influence the degree of flowage from depth. As the lavas become more felsic, and hence more viscous, their passage to surface is gradually retarded, or even totally blocked. When this occurs, explosive activity commences and clears the way for the start of a new cycle.

The initial volcanic phases as well as the volcanogenic sedimentary phases of greenstone belts generally demonstrated the "cycle within cycle"

relationship - a feature not commonly encountered in the more arenaceous, terminal phase sedimentary successions. In the case of the latter, the cyclicity, if developed at all, appears to be more characteristic of the major-cycle variety. The decrease in cyclic activity with time also corresponds to a general decline in volcanic activity during the terminal sedimentary phases of the greenstone belt evolution".

The nature of the gradation from vulcanism with minor sedimentation to the major sedimentation and minor vulcanism of the argillaceous groups such as the Fig Tree, is worth reiterating. Bliss and Stidolph (1969) see no essential difference between Shamvaian sedimentation and that accompanying the earlier vulcanism: the consideration is furthered by the presence of volcanics in the Shamvaian. The Temiskaming is not only similar to the Shamvaian but is followed by volcanic cycles (Ridler 1976-2). Glikson (1971-2) has spoken of the changing character and proportions of vulcanism and sedimentation in the Yilgarn and Ryan (1965) has described the laterally equivalent volcanic and sedimentary sites in the Pilbara. So it may be reasonable to consider together the changing members of the volcano-sedimentary pile.

Volcanic Units

Recognition of volcanic units is critical to the exploration geologist in knowing what type of ore deposits are likely to be present. Their characteristics, as noted by the Winnipeg and Johannesburg schools, merit reiteration.

The Winnipeg group, headed by Wilson (1974), has described measured sections in northwestern Ontario and the Flin Flon belt of Manitoba (Fig. 2).

The Johannesburg group has extended the Barberton model (Fig. 3) to Australia (Anhaeusser 1971-2) and the Midlands Belt of Rhodesia (Viljoen and Viljoen, 1969-7). Wilson (Fig. 2) suggests that his model also applied to southern Africa and Australia, but major points of difference can be recognized: the ultramafics of his Lower Ultramafic Unit have no equivalent in his Canadian areas and his Upper Diverse Unit has no equivalent in southern Africa and Australia. The highly repetitive Greenstone Group of southern Africa and Australia contrasts with Wilson's Middle Mafic and Middle Felsic equivalent, which comprises a single mafic to felsic sequence.

The Anhaeusser model appears to be valid for the volcano-sedimentary successions reviewed from southern Africa and the Yilgarn (and he considers it so for the Pilbara). The Wilson model is less easy to apply, for example, to the various sequences of different parts of the Abitibi Belt, but interpretations are advanced.

N.W. Ontario and the Flin Flon Belt (Fig. 1)

Upper Diverse Unit

Complicated volcanic stratigraphy with interlayered sediments and intrusives. Lavas with various compositions from basalt to rhyolite erupted simultaneously. Some cyclical eruption, komatiite or basalt, andesite, dacite, and rhyolite, followed by sedimentation. Some thick, uniform, basalt edifices. (Morrice 1974-1).

Structures: subaqueous pillows and ash flows, subaerial concretionary lapilli and ignimbrites. Flows and fragmentals common, variolitic pillows almost everywhere. (Morrice 1974-1).

Geochemistry: meagre data. Magnesian, calc-alkaline. (Wilson and Morrice 1974).

Sub-volcanic intrusions: anorthositic gabbro complexes, small, irregular, green-hornblende gabbro bodies, diorite-gabbro sills, granitic porphyries. (Wilson 1974-2).

Ore deposits: copper-zinc are associated with rhyolite breccias, gabbros, and rarely other rock types. Small copper-nickel orebodies (up to 1 m tons av. 1.5% Ni, Ni-Cu 2 to 5:1, sulphides seldom contain more than 8% Ni). (Wilson 1974-3).

Middle Felsic Unit

Monotonous fragmental volcanics, lower part andesite, grading rapidly to dacite. (Morrice 1974-1).

Structure: entirely breccia, angular fragments in matrix of composition similar to that of fragments. Fragments 1 to 20 cm diam., in few places 1m. Bedding inconspicuous although tuffaceous and smaller fragments become more common in upper part. Origin not known but general characteristics of lahars.

Geochemistry: abrupt change from Middle Mafic Unit: iron oxides, lime and titania decrease abruptly, silica and potash increase rapidly, soda increases more rapidly, magnesia drops more rapidly. Calc-alkaline.

Sub-volcanic intrusions: differentiated layered sills, gabbro through pyroxenite to peridotite, some more than 1 km thick, of fresh non-hydrated minerals. (Wilson and Morrice 1974).

Ores: none known, even scattered mineralization sparse.

Middle Mafic Unit

Structure: vesicular flows, first occurrences of brecciated flow tops and flow breccia increasing upward though not prominent until near top of unit. Pillows exhibit internal structure as radial fractures or vesicular trains or concentric features, vesicle distribution or mineralogical variation. Selvages thicker (5 - 10 mm) than in the Lower Mafic Unit. (Morrice 1974-1).

Geochemistry: continues low K, iron and titanium increase. Tends to be tholeiitic. (Wilson and Morrice 1974).

Sub-volcanic intrusions: large gabbro sills, up to 2 km thick, little differentiated other than moderate flow differentiation. Ultramafic sills rare, small (up to 100 m thick). (Wilson 1974-2).

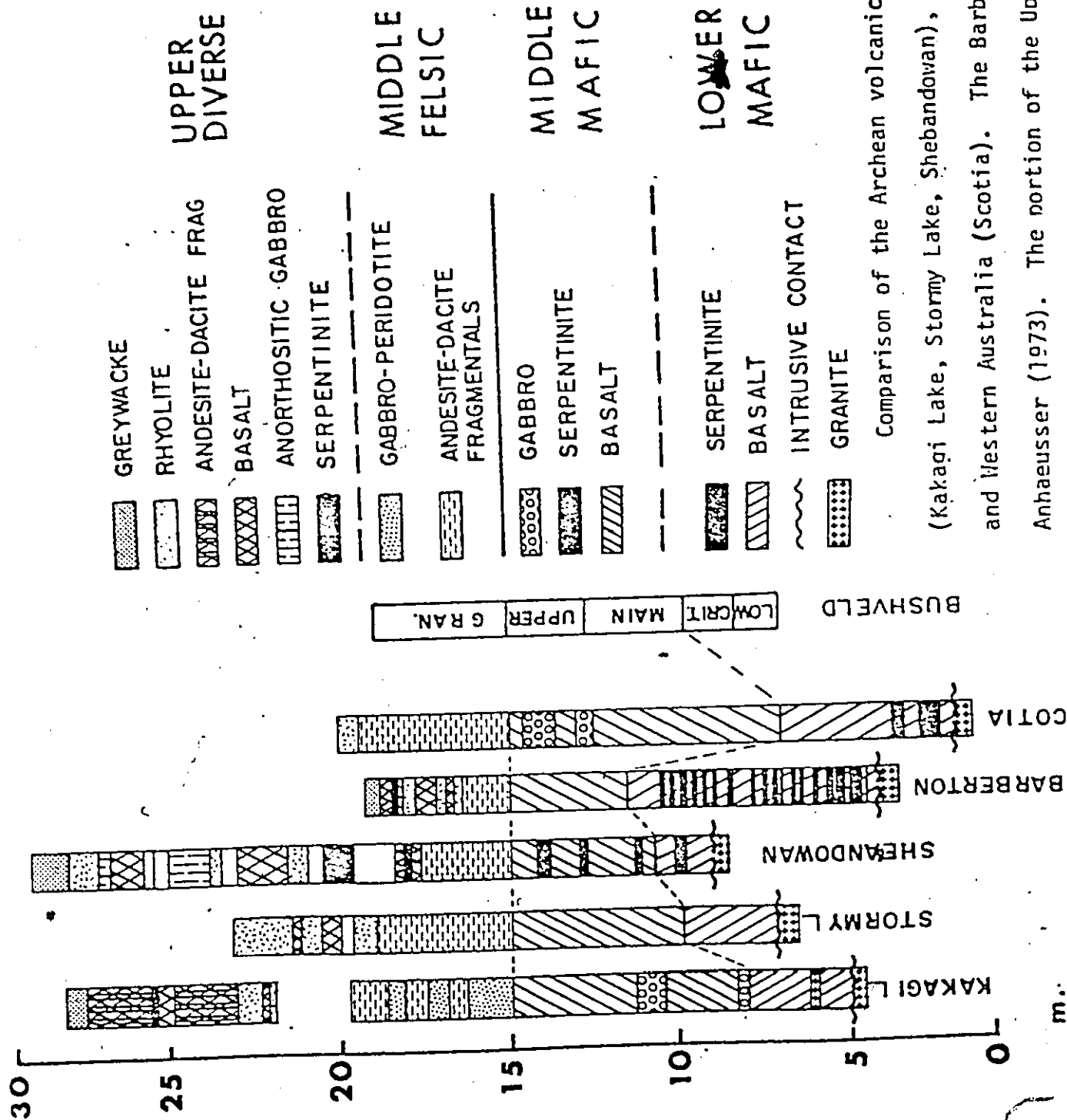
Ore deposits: none known. (Wilson 1974-3).

Lower Mafic Unit

Highly interlayered sequence of pillowed and massive basalt flows, 10 to 15 m thick. (Morrice 1974-1).

Structure: pillows massive, devoid of internal structure, thin selvages, flattened bottoms, non-vesicular. Contacts with adjacent flows sharp. No brecciated tops, little breccia of any kind. Few thin tuffaceous horizons. (Morrice 1974-1).

Fig. 1 after Wilson (1974)



Comparison of the Archean volcanic stratigraphy in Canada (Kakagi Lake, Stormy Lake, Shebandowan), South Africa (Barberton) and Western Australia (Scotia). The Barberton section is after Anhaeusser (1973). The portion of the Upper Diverse section lying above the Kakagi Lake section is termed the Kenora section and is separated structurally from the Kakagi Lake section

Geochemistry: pillows uniform composition, low-K, constant silica, iron increases rapidly, titanium similar to iron but peak concentration somewhat higher. Tends to be komatiitic. (Wilson and Morrice 1974).

Sub-volcanic intrusions: ultramafic sills several hundred m thick, now serpentized dunite and carbonated tremolite-chlorite schist. Difficult to distinguish from flows. Non-differentiated gabbro sills not more than few hundred m thick. (Wilson 1974-2).

Ore deposits: no Canadian deposits noted. (Wilson 1974-3).

Barberton (Anhaeusser 1971-1) (Fig. 2)

Greenstone Group

3. Swartkoppie Formation 900 m

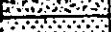
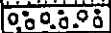
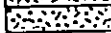
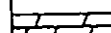
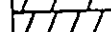
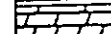
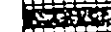
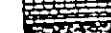
Alternating felsic volcanic and pyroclastic rocks, substantial chert horizons. Conformable ultramafic bands.

2. Kromberg Formation 1920 m

Same rock-types as Hoeggenoeg, mafic to felsic cyclic trend not so strikingly apparent. Cycles terminated by chert horizons with associated carbonate and carbonaceous shale interlayers.

1. Hoeggenoeg Formation 4800 m

Five or more cycles, each with large accumulation of basalt, pass upward into thinner zones of dacite to rhyodacite lavas. Cycles

	JASPILITES, BANDED IRON FORMATIONS	Arenaceous Assemblage	<u>SEDIMENTARY GROUP</u> Cyclic sedimentation. -alternating coarse-to- fine sedimentary assemblages. -minor volcanic development
	MINOR VOLCANICS AND PYROCLASTS		
	SHALES		
	SILTSTONES		
	QUARTZITES		
	CONGLOMERATES	Argillaceous Assemblage	
	BANDED IRON FORMATIONS		
	MINOR VOLCANICS AND PYROCLASTS		
	CHERTS		
	SHALES		
	GREYWACKES		
	GREYWACKE GRITS		
	CONGLOMERATES		
	CHERTS		
	RHYOLITES		
	RHYODACITES	<u>GREENSTONE GROUP</u> Cyclic mafic-to-felsic volcanics and pyroclastic assemblages. -minor sedimentary development.	
	DACITES		
	ANDESITES		
	MINOR PERIDOTITES AND THOLEIITIC BASALTS		
	RHYOLITES AND CHERTS		
	RHYODACITES		
	DACITES		
	ANDESITES		
	MINOR PERIDOTITE AND THOLEIITIC BASALTS		
	MINOR RHYODACITES, RHYOLITES, AND CHERTS		
	DACITES		
	ANDESITES		
	THOLEIITIC BASALTS		
	PERIDOTITES		
	DACITES		
	ANDESITES		
	THOLEIITIC BASALTS		
	PERIDOTITE		
	ULLAK-TYPE BASALTIC KOMATIITES		
	PERIDOTITIC KOMATIITES		
	SODA-RICH PORPHYRIES	<u>ULTRAMAFIC GROUP</u> Cyclic ultramafic-to- mafic volcanics and pyroclasts. -minor sedimentary development	
	BARBERTON-AND BADPLAAS- TYPE BASALTIC KOMATIITES AND SILICEOUS ALUMINOUS TUFFS		
	PERIDOTITIC KOMATIITE		
	BASALT		
	PERIDOTITE		
	MAINLY BASALTIC AND PERIDOTITIC KOMATIITES		

Hypothetical Archaean stratigraphic column.

Fig. 2 after Anhaeusser 1974-1

terminated by chert horizons. Basalt decreases upward, from 1350 m to 180 m. chert and acidity increase upward. Some cycles begin with sill-like ultramafics, differentiated commonly into lower peridotite and upper pyroxenite. Uppermost felsic zone displays at least four cycles, each coarse rhyodacite agglomerate grading into coarse rhyodacite agglomerate grading into coarse tuff and terminated by fine, well-bedded tuffs.

The Middle Marker is a chert sequence varying from a parting to 9 m at the base of the Hoeggenoeg.

Geochemistry: tholeiitic basalts or high Mg basalts similar to oceanic basalts.

Ore deposits: the Swartkoppie hosts the two largest asbestos deposits and the Sheba and Fairview gold mines, two of the major producers, and in Rhodesia several of the major producers including the Cam and Motor are in the Bulawayan.

Ultramafic Group

3. Komati Formation 3450 m

The Komati Formation is 70% mafic volcanics and 30% ultramafic rocks. Siliceous members are lacking but there are intrusive quartz and feldspar porphyries (Anhaeusser 1971-2). The ultramafics are extrusive or near-surface sills, typically resistant lenses of green serpentinite and metamorphosed green to dark blue-black peridotites. In strongly deformed areas the serpentinites give way to zones of tremolite, talc, or talc-carbonate-chlorite rocks. The interlayered Mg-rich schists (meta-basalts) include tremolite-actinolite, chlorite-talc, and tremolite-chlorite-talc schists plus dolomitic and carbonate rocks, often in strongly disturbed zones.

Ultramafics predominate in the lower half of the formation where individual ultramafic and pillow basalt horizons thin sympathetically, the ultramafics varying in thickness from 9 to 500 m. The thickest horizons are banded.

The mafic rocks, almost exclusively basalts, are generally green to gray-green amphibolites, of four chemical types: one is comparable to tholeiites, the other three form the primitive group, basaltic komatiite.

The Barberton type of basaltic komatiite is in pillowed flows associated with massive phases or near-contemporaneous sills in the lower part of the formation. The pillows vary in size, are usually well-formed, and often darker and finer crackled-looking selvages. Variolitic and spherulitic textures are diagnostic, as light-coloured orbicular patches which weather as craters or domes. Amygdules are rare. The composition

of the Barberton type is mainly tremolite-actinolite amphibole, stubby laths in the massive varieties, slender needles in the pillowed varieties, altered from diopsidic pyroxene. The plagioclase is usually oligoclase. The spherules are a quartzo-feldspathic mosaic.

The Badplaas type of basaltic komatiite is a coarse, equi-granular, massive pyroxenite in the lower part of the formation. Pillows are rare and most appear to be near contemporaneous sills. They are composed of tremolite-actinolite derived from a diopsidic pyroxene.

The Geluk type of basaltic komatiite is confined to the upper part of the formation which lacks the abundant ultramafic materials. Pillows are well developed in places but lack the spherules and gas cavities of the other two varieties. The main minerals are chlorite, Mg and Ca amphiboles, talc, epidote, and carbonate with minor plagioclase. This assemblage is an incompetent rock, readily sheared, beds of carbonate interbedded with chlorite and finally the chert and carbonate Middle Marker (Viljoen and Viljoen 1969-2).

2. Theespruit Formation 1850 m

The formation is composed of mafic and ultramafic volcanic rocks, water worked felsic tuffs, talc-chlorite-carbonate schists and other minor ultramafic horizons (Anhaeusser 1971-2). The siliceous and often aluminous schists make it easily recognizable. Quartz-fuchsite also appears to be characteristic (Viljoen and Viljoen 1969-2 and 7). In places the more siliceous varieties have been recrystallized and resemble quartzites with large muscovite crystals. The felsic horizons are often overlain by impersistent, black, carbonaceous, cherty sediments.

Most cherts appear to be formed by silica precipitation though some are cross-bedded. The mafic rocks are lavas and tuffs, the lavas usually massive but with some pillows, spherulites, and variolites. They are of all four types represented in the Komati Formation. The ultramafic rocks are less common than in the Sandspruit and Komati formations. They are usually fine-grained, dense, dark blue-green, and resemble those of the Komati Formation (Viljoen and Viljoen 1969-2).

1. Sandspruit Formation 2100 m

Comprising 60 - 70% ultramafic rocks with the remainder mafic rocks and minor primitive sediments (Anhaeusser 1971-2). Tonalitic granites have eliminated possible lower formations at Barberton. Most of the rocks are xenoliths. They are mainly bands, lenses, and pods of ultramafics with minor mafic bands and lenses. The ultramafics generally have a micaceous and dark green to khaki green appearance and range from serpentinites through antigorite-chlorite-tremolite varieties to tremolite-chlorite rocks. Ubiquitous chlorite gives the micaceous appearance and is probably a contact metamorphic product of magnetite and antigorite. The sediments are composed of quartz and diopside. Pillows and other volcanic structures are rare. Both the amphibolites and ultramafics are usually massive: the ultramafics may be lavas or sills. The basalts include tholeiites and all three types of komatiite. (Viljoen and Viljoen 1969-2).

A number of early intrusive sill-like or pod-like ultramafic bodies have been emplaced in the Lower Ultramafic Group, principally in the Komati Formation, and some differentiated sills also occur in the Middle Mafic to Felsic Group. All give rise to ore deposits.

Stolzberg-type: an alternating succession of serpentized dunite and generally altered orthopyroxenite. The type body is 1 km wide, 16 km long, and has six dunite-bronzitite cycles (80% dunite).

Noordkaap-type: generalized sequence, serpentized olivine peridotite, pyroxene peridotite, amphibolitized pyroxenite, and meta-gabbro with anorthositic phases.

Kaapmuiden-type: layered sequence, narrow chill-zone peridotite, extensive zones of olivine peridotite and dunite, narrowing zones of bronzitite, websterite, and anorthositic gabbro or norite succeeded by an extensive upper zone of dunite peridotites and dunites (Viljoen and Viljoen, 1969-6).

Ore deposits: the nickel and gold of the Yilgarn is in the equivalent of the Ultramafic Group (Viljoen and Viljoen 1969-1, Anhaeusser 1971-2). Viljoen and Viljoen (1969-6) note the varied asbestos content of the layered intrusives in the Komati (and Hoeggenoeg) formations. Fripp (1976-2) notes the preponderance of gold mines in the Sebakwian (=Lr. Onverwacht (Viljoen and Viljoen 1969-7)) of Rhodesia.

GENERAL GEOLOGY

In this section the aim is to put data from orefields in Canada, Brazil, southern Africa, India, and Australia in such a form that comparisons can readily be drawn. This has been done in two ways, by tabulated data for vulcanism, plutonism, metamorphism, deformation, ore deposition, and ore production, and by charts in which these are depicted pictorially. Every section reads upwards, from older to younger, and most are followed by a commentary.

There are two criteria for area selection, that the area has ore-fields and that there are enough data. In practice the amount and suitability of data vary. The relative ages of plutonism are commonly most readily recognized by both crosscutting relationships and relationship to deformation (Rice Lake, Manitoba, and Vumba and Tati, Botswana, provide the best examples). Wherever possible, therefore, areas where structural studies have been undertaken are incorporated. For example at Yellowknife, all the gold mines are west of Yellowknife Bay, but the studies on sedimentation, structure, and plutonism have all been east of the Bay, so the area reviewed incorporates both parts. Again, in the Flin Flon belt, intensive studies have been localized and except for ore deposition have been treated separately in the present study. The patterns of vulcanism at Kirkland Lake are incomplete, and as they are unusual the study of vulcanism and related sedimentation is extended to Matachewan. One must restrict such expansion, nevertheless, and at times, in doing so, ore-fields important to a full knowledge of Archean metallogeny have been omitted: the chromite and pegmatite ores of Cat River, Manitoba, the copper-zinc of Mattagami, Quebec, the pegmatites of Bikita and the world's major corundum supplies, both in Rhodesia, and the Kolar gold field of India. Goa, in India, is included because data in adaptable form were supplied by a mine geologist, Mr. P. Sen; Rio das Velhas, Brazil, is included because it is the only area in South

America where the available data approach requirements, even though all volcanic products appear to be distal and not diagnostic as to volcanic sequence. Stratigraphic charts with legend as Fig. 3. precede each regional description. The 100 m.y. bar forms a guide to duration, which is based on cycling time discussed under "Age".

Sedimentation: turbidites and fluvial deposits are noted where they are interpreted as such in the literature: where not, descriptive terms such as graywacke must suffice as a guide to sedimentation.

Vulcanism: the attempt is to have each "volcano" symbol depict a volcanic cycle. The various scales of volcanic cycles are considered in the previous chapter.

Plutonism: Rice Lake and Vumba and Tati are well-controlled examples which illustrate clearly that not all plutonism is associated with the main period of deformation (D_1 to D_3), and the episodes of plutonism and deformation rarely coincide. Nevertheless, deformation commonly has to be used to mark episodes of plutonism because of the lack of data. The duration of plutonic and deformational episodes is a related problem considered further in the present study. In places where the relationship of plutonism to deformation is not given in the literature, the prevalent Archean pattern, D_2 tonalite diapiir, gneiss and migmatite, and D_3 discordant pluton, forms a guide, provided the sequence is noted in the literature. Question marks are used in such instances. In the older plutons, concordancy and discordancy may be a matter of the structural level exposed by erosion. Whether the same is true of late-stage granites is more questionable: Watson (1964) has suggested that concordant late intrusives were emplaced into hot country rock whereas discordant late intrusives were emplaced into cold country rock.

SYMBOLS FOR CHARTS

SEDIMENTATION



TURBIDITE



FLUVIAL



GRAYWACKE



SANDSTONE



SHALE



LIMESTONE



CONGLOMERATE

IF

IRON FORMATION

Ch

CHERT

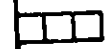
METAMORPHISM



GREENSCHIST

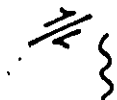


AMPHIBOLITE



GRANULITE

DEFORMATION



THRUST



FAULT WITH ATTITUDE

FOLD PROFILE WITH

ATTITUDE AND FOLIATION

RADIOMETRIC DATE

2720 Rb-Sr

IGNEOUS ACTIVITY

PLUTON



DISCORDANT

CONCORDANT



DYKE - SILL



VOLCANIC CYCLE



FELSIC



INTERMEDIATE



MAFIC



ULTRAMAFIC

gr

t.

GRANITE

TONALITE

trond p

TRONDHEMITE

PORPHYRY

q

rn

QUARTZ

MONZONITE

sy

di

SYENITE

DIORITE

gb

db

GABBRO

DIABASE



ANORTHOSITE

(ko) KOMATIITIC

(th) THOLEIITIC

(c-a) CALC-ALKALINE

(a) ALKALINE

ORE DEPOSITION

Symbol at host rock
and concentrating event

CROSS REFERENCES TO TEXT

Deformation: the conventional letters, D, F, S, and L are used for periods of deformation, folding, foliation, and lineation. F, S, and L are accorded the same number as D, so an available F, S, and L number may not be utilized if there are no data. Where the original references have required interpretation, questions marks are added. This is particularly the case for Timmins, Chibougamau, Rio das Velhas, the Pilbara, and the Eastern Goldfields, where no structural studies have been found in the literature.

Metamorphism: metamorphism is commonly mapped as accompanying deformation, but with Rice Lake and Vumba and Tati as well-controlled examples, much other tabulation is oversimplification. I find it particularly difficult to allocate M_1 to a post- D_2 event, even though there is no record in the literature of earlier metamorphism. The spatial relationship of metamorphic zones to plutons demands a map rather than a table.

Ore deposition: representation of source rock, mobilizer, and eventual site of the ore is made simply by symbol. As the main metal mobilized in the Archean is gold and the pattern appears in many cases to match that demonstrated by Boyle (1961) at Yellowknife, the problem of representation of complexities comparable to those of younger periods does not arise, as yet, though the work of Wakefield (1976) on the nickel-copper ore varietal changes with deformation and metamorphism at Pikwe indicates that modification of the symbology will be needed in future works.

Ore production: production figures are perhaps the best means available for making comparisons of the ore potential of a metallogenic environment though development has not taken place in all areas of potential interest. The need is for relative figures rather than accurate statistics. The Mining Magazine



has found that tonnage of ore mined provides a way of comparing size. Tonnage figures have the benefit of being objective, whereas any system of weighting for grade and value is a matter of personal choice, never universally acceptable. The Mining Magazine tonnage figures for 1974 are reproduced because they provide universal coverage and are the latest available. The full tabulation and system of rating is given in Appendix 1. Cumulative tonnage figures are reproduced from various sources, wherever available: in many cases statistics for individual mines on orefields are not available, and the generally available production figures by country are inappropriate to a study of orefields.

CANADA

1. Yellowknife
2. Hanson Lake-Flin Flon-
Snow Lake-Sherridon
3. Rice Lake
4. Abitibi Belt

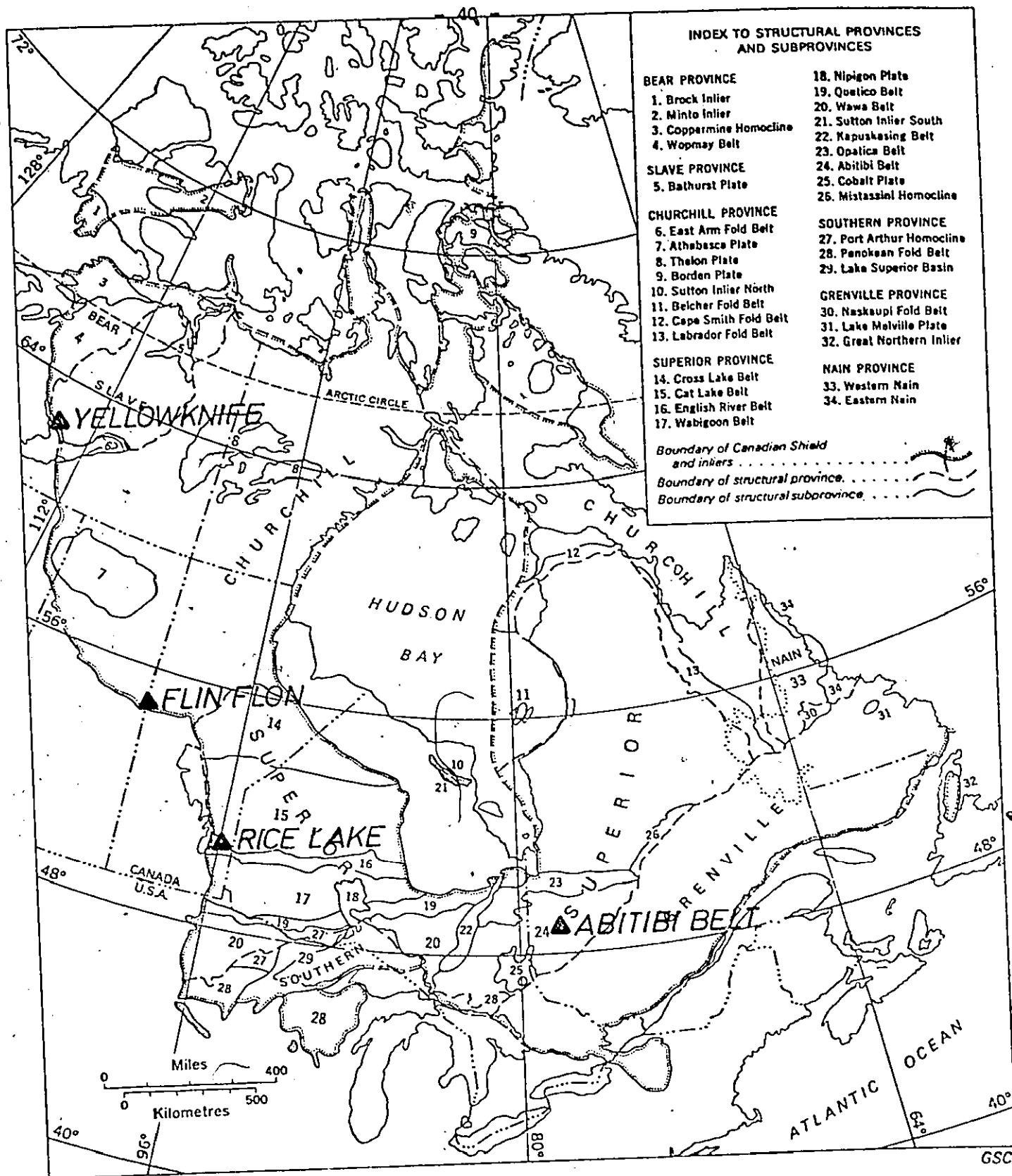
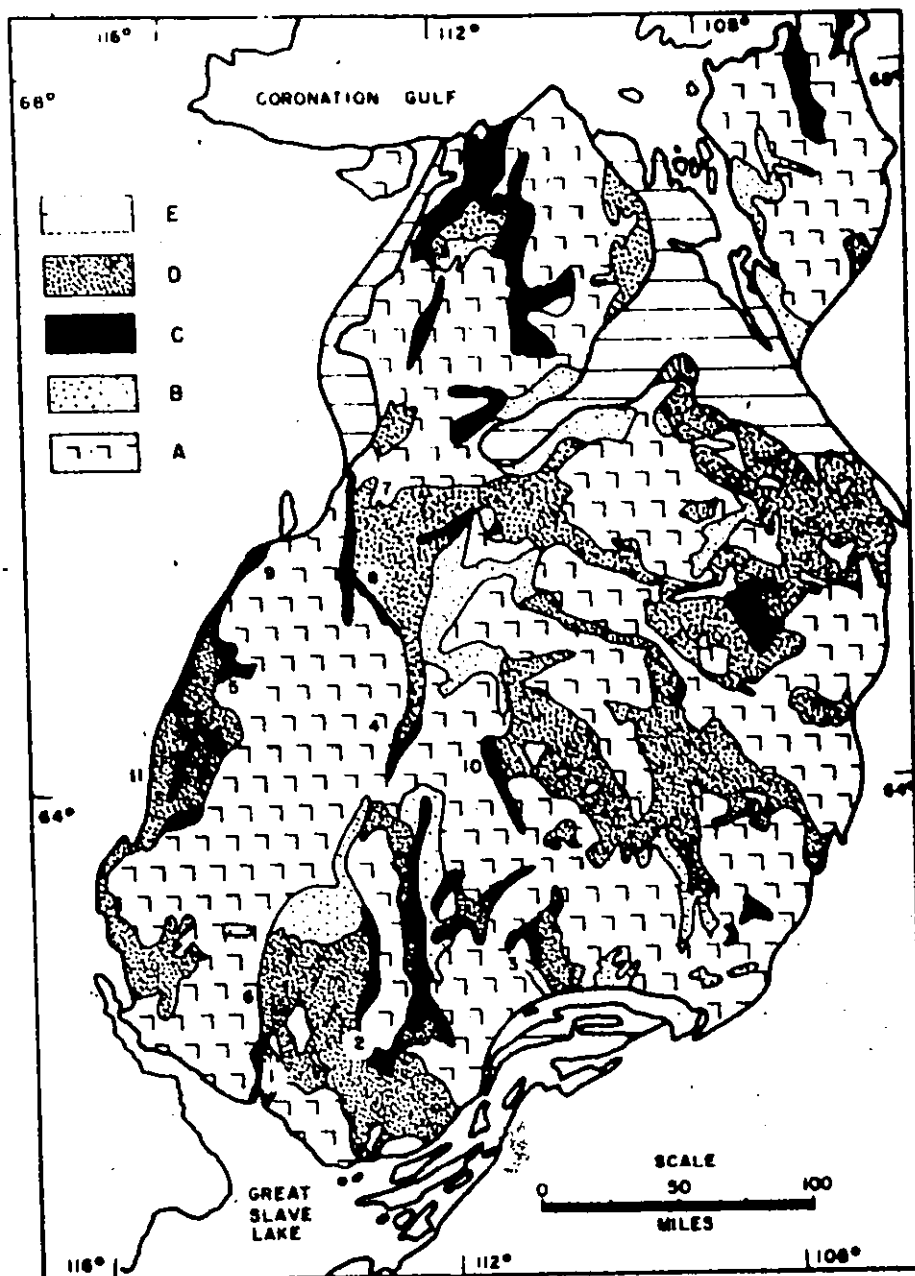


Fig. 4. from Douglas 1970
LOCATION OF AREAS SELECTED FROM CANADA

- 41 -

YELLOWKNIFE, NWT.



- A - Predominantly granitic rocks.
 B - Mixed granitic and metasedimentary and metavolcanic rocks.
 C - Volcanic rocks of the Yellowknife Supergroup.
 D - Sedimentary rocks of the Yellowknife Supergroup.
 E - Aphebian cover on the Slave Province.
- | | |
|---|------------------------------------|
| 1. Yellowknife area. | 6. Glaouque Lake area. |
| 2. Ross Lake, Cameron Lake, Beaulieu River areas. | 7. Itchen Lake area. |
| 3. Benjamin Lake area. | 8. Point Lake area. |
| 4. Winter Lake area. | 9. Mesa Lake area. |
| 5. Arseno Lake area. | 10. Courageous Lake-Matthews Lake. |
| | 11. Ingray Lake area. |

Fig. 5 Generalized geological map of the Slave structural province. From McGlynn and Henderson 1970

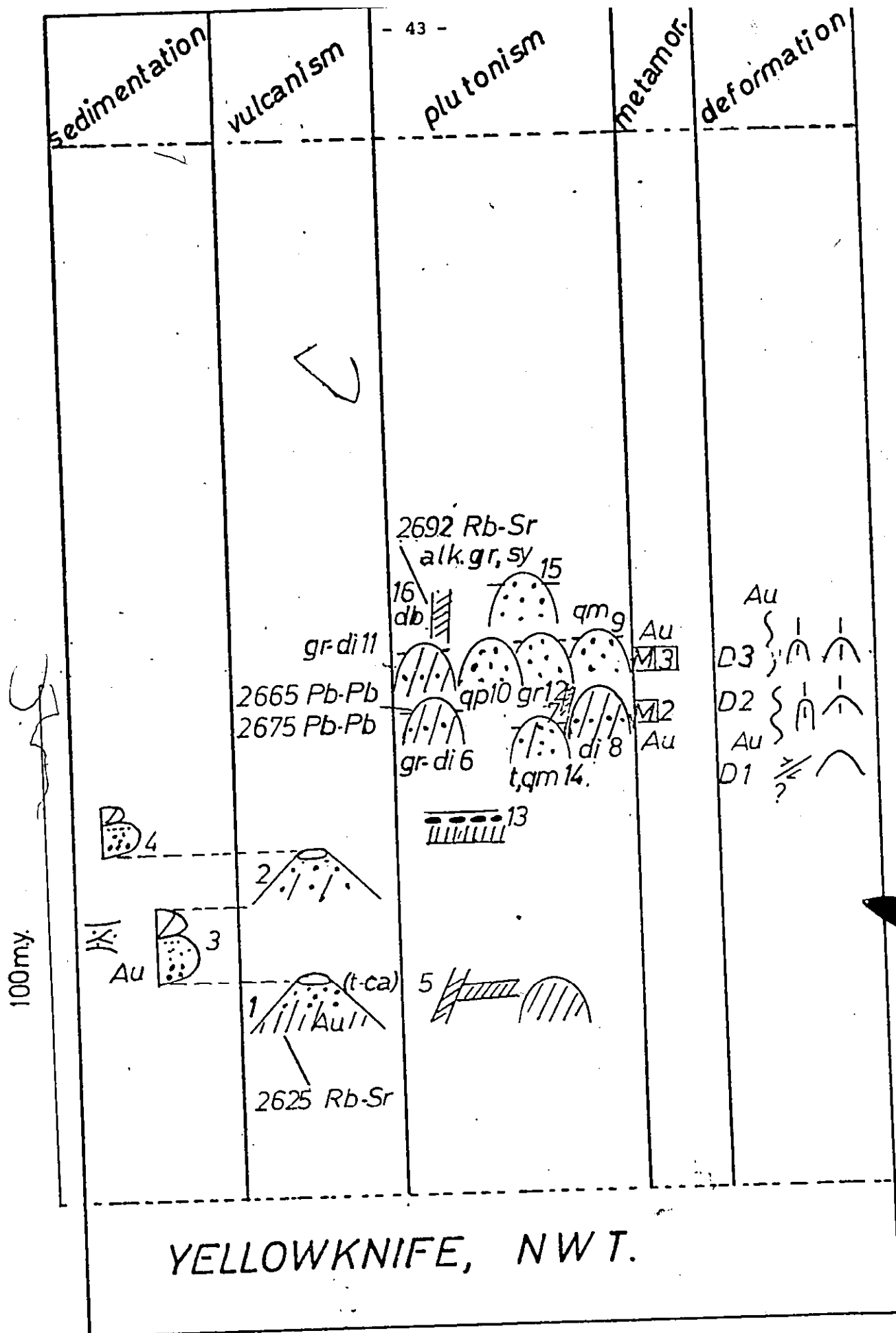


Fig. 6 Time Relations of Geological Features

Vulcanism (Figs. 5 and 7)

Middle Mafic and Middle Felsic Units?

Banting Formation (2)*

Dacites, trachytes, agglomerate and tuffs interbedded with conglomerate and graywacke. Separated from underlying formations by faults on west side of Yellowknife Bay, conformable on east (Hoffman and Henderson 1972).

Kam Formation (1)

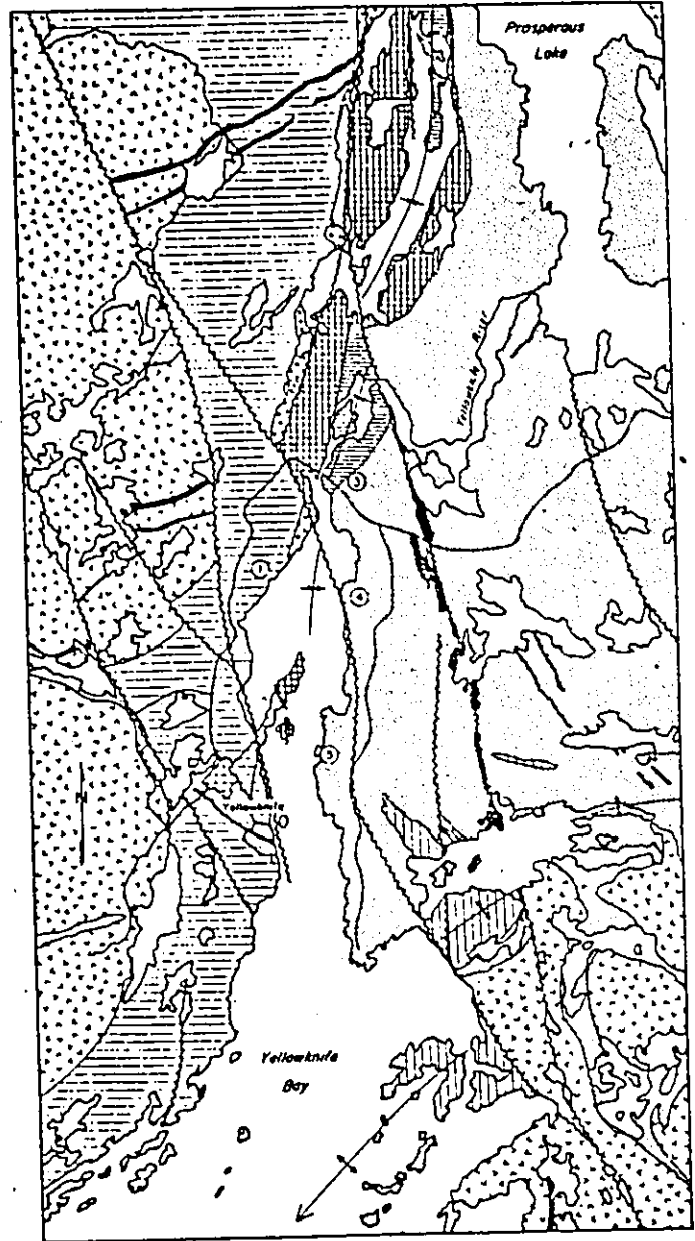
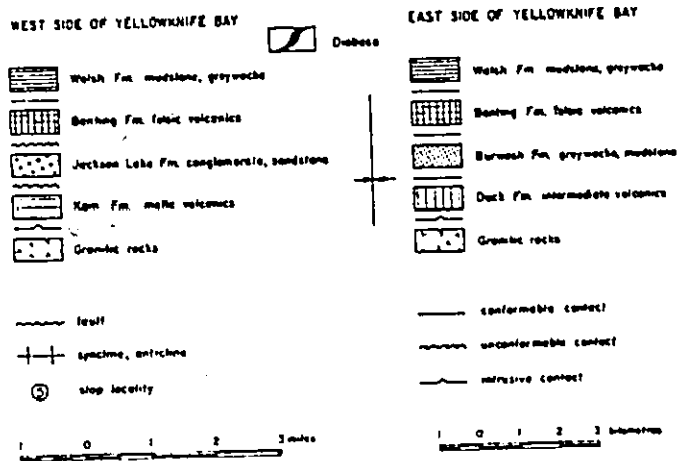
9000 m

Basaltic and andesitic flows, bottom cut off by granodiorite (Henderson and Brown 1966). Pillows and massive flows about equally abundant. About halfway up the pile is a 350 m thick dacitic unit. The more felsic flows are coarsely fragmental, characterized by breccia and agglomerate. Tuff, agglomerate, and breccia become more abundant upwards, and some tuffs have much sulphur and carbon. The trend is mixed, tholeiitic and calc-alkaline (Hoffman and Henderson 1972). East of Yellowknife Bay, the intermediate volcanics of the equivalent Duck Formation occupy the core of an anticline.

The flows are extensively intruded by dykes, sills, and irregular bodies (5) of composition similar to the flows, but there is no evidence that the dykes are feeders (Boyle 1961).

The Kam Formation (1) thus forms one complete major cycle, in the terms of Anhaeusser (1971-1). The Banting Formation (2), in contrast, shows no regular pattern of change and is either incomplete or perhaps of the nature of Wilson's (1974) Upper Diverse with the Kam Formation representing his Middle Mafic and Middle Felsic Units.

* - Numbers in parentheses refer to chart (Fig. 6).



Generalized Geology of the Yellowknife area.

Fig. 7 from Hoffman and Henderson 1972

Sedimentation (Figs. 5 and 7)

Walsh Formation (4)*

Similar to the Burwash from which it would not be separable but for the intervening Banting felsic volcanics. Conformably overlies the Banting north of Yellowknife Bay (Henderson 1972)

Burwash Formation (3)

4500 m

A thick homogeneous sequence of graywacke-mudstone turbidites. Lithic fragments of both sedimentary and volcanic origin indicate a source probably to the east. Occupies the main part of the basin east of Yellowknife (Hoffman and Henderson 1972, Henderson 1972)

Jackson Lake Formation (3)

Several hundred m

(b) Silicic volcanic wackes, minor mudstones, scattered conglomerate horizons. Derived from a now eroded volcanic cap to the main sequence or from a volcanic terrain now completely removed. Cross-bedding is common. Small scale channels and scours are locally prevalent and indicate turbulence. High flow velocities are also indicated by parallel lamination in the sands. These sediments probably represent a complex of braided rivers. The high energy conditions were probably a result of periodic floods (Hoffman and Henderson 1972).

(a) Basal conglomerate fills erosional depression on the surface of the unconformity between it and the Kam Formation. The depressions are typically shallow but locally up to 250 m deep. The conglomerate has angular blocks of mainly mafic volcanics of local provenance and lesser amounts of felsic porphyry, quartz porphyry, rounded granite, vein quartz, and rare chert.

Up to 250 m

The three sedimentary formations are typical of the turbidity-fluvial sequences which normally accompany the pre-tectonic vulcanism.

* - Numbers in parentheses refer to chart (Fig. 6).

Plutonism (after Davidson 1972)

Numbers on left are from Davidson and accord with his maps (Figs. 8 and 9). Only No. 15 has been related to deformational episodes (Fyson 1975).

<u>No. on Map</u>	<u>Cameron and Beaulieu Rivers Area (Fig. 8)</u>
15. Late D ₃ ?	Redout Lake muscovite-biotite granite (12)* cuts across foliation of Ross Lake granodiorite and locally contains inclusions of granodiorite and amphibolite. Pink, fine-to medium-grained, variable. Small pegmatite patches; pegmatite dykes.
14. D ₃ ?	Three large and three small plutons, sharply defined and in detail cross-cutting. Generally homogeneous, massive, biotite granodiorite (11).
13.	Small irregular bodies of biotite granodiorite (11) cutting Yellowknife strata and older than pegmatites presumed related to No. 15. Possible related pegmatites and granite dykes.
12.	Gray granodiorite (11) in separate plutons and in dykes which cut No. 10 and sediments.
11.	Large mass of medium-grained, foliated, biotite-muscovite granite (11).
10.	Fine-grained gray quartz porphyry (10). Intrudes sediments and contains innumerable dykes of No. 12.
9. D ₃ ?	Core of plutonic area. Two mica adamellite, K-spar megacrysts (9). Cuts Nos. 1, 2, and migmatites; is in contact with Nos. 5 and 8. No. 9 lacks megacrysts.
8. D ₂ and basement?	Dark dioritic gneisses, trend NE with steep dips (on strike with Nos. 1, 3, and 5; position here, from Davidson, may indicate migmatization).
7. D ₃ ?	Small plutons and dykes of fine-grained diorite, No. 7 (8) and microgranitoid, No. 7a. Cuts Nos. 3, 6 and amphibolite dykes. (The semi-concordant nature and position, on strike with No. 1 may be interpreted to indicate this is re-mobilized basement and so related to No. 8 which it adjoins - W.W.).
Post D ₂ Pre D ₃ Unnumbered	Massive amphibolite dykes (7) with foliated biotitic margins. NNW trend. Cut Nos. 3 and 6.
6. D ₂ ?	Metamorphosed and foliated granodiorite pluton (6). Cuts No. 3.

* - Numbers in parentheses refer to chart (Fig. 6).

5. Migmatic granitoid gneisses. Change, by virtue of being less recrystallized, to No. 3.

Deformation: -----

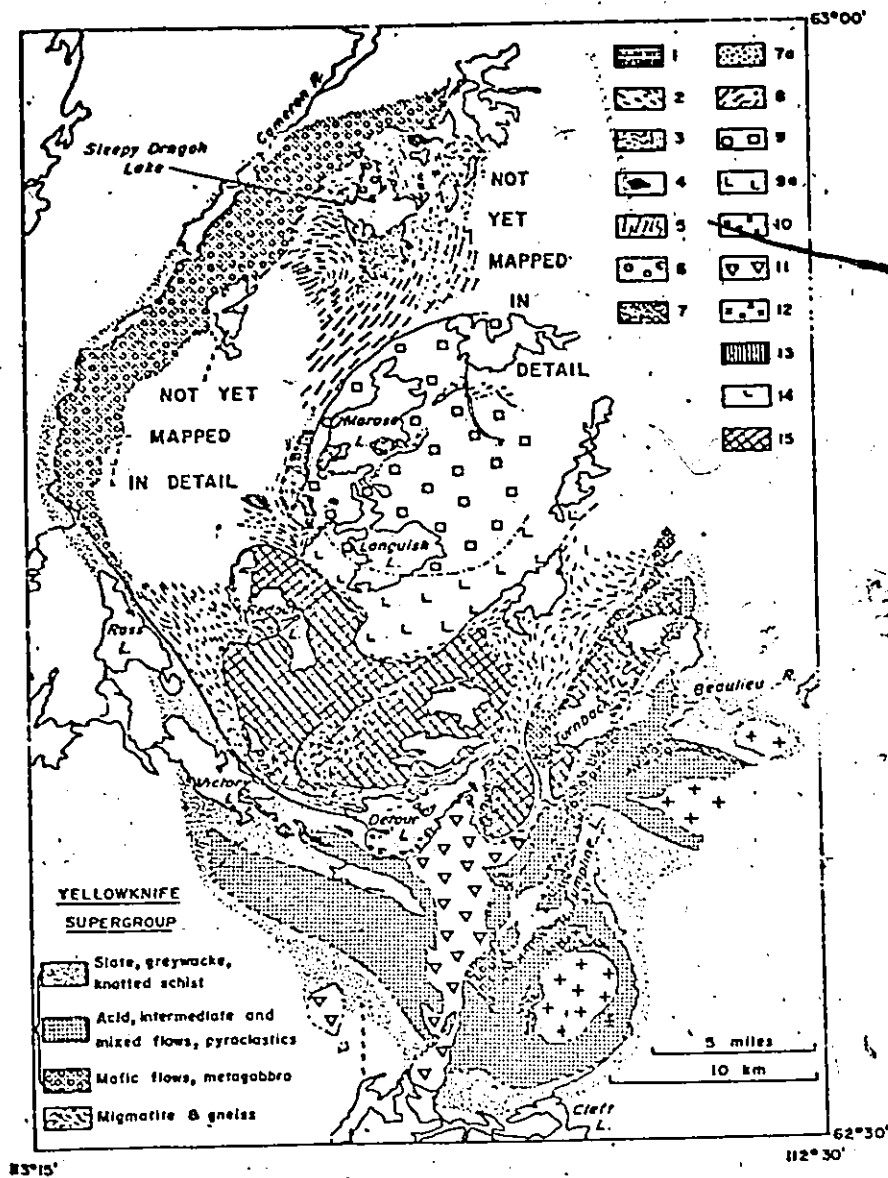
Unnumbered Closely spaced, NW trending mafic dykes, now amphibolite (5).
Cut No. 2 and flows of No. 4.

4. Pre-tectonic Mafic flows of the Yellowknife Supergroup. Gabbro (5).

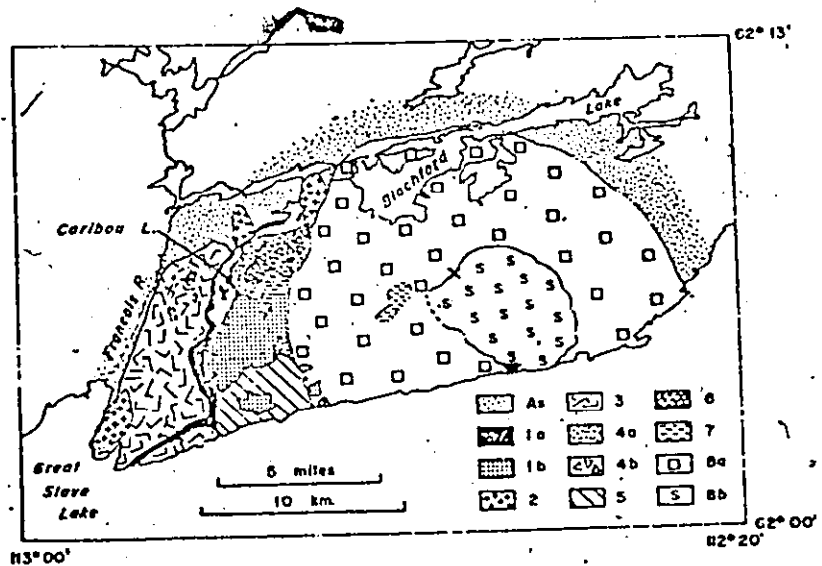
3. Basement? Cataclastic gneiss. Includes augen-granite gneiss, mylonitic granite and pegmatite, and thin amphibolite schist lenses.

2. Ross Lake Granodiorite.

1. Metamorphosed diorite.



Figs. 8 and 9
from Davidson 1972



No. on Map

Blachford Lake Area (Fig. 9)

8. D₃ or later? Coarse-grained hornblende alkali granite (No. 8a) (15) forming a cylindrical pluton 19 Km. diam. Outer contact dips steeply and cuts cleanly across older plutonic rocks to west. Contains rafts of syenitized anorthosite and red quartz syenite. Surrounds a core of massive hornblende syenite (No. 8b).
7. Mass of relatively fine-grained hornblende diorite or monzonite (Giant inclusion?).
6. D₃? Small plutons of fine-grained, pink, hornblende-biotite granite. Subhedral K-spar phenocrysts in peppery textured ground mass. Dykes common in leuco-gabbro and anorthosite. Cuts syenites (Nos. 4a, 5) and anorthosite (No. 16).
5. D₃ or later? Pluton of pink, red-weathering, hornblende quartz syenite (15) Xenocrysts of dark gray plagioclase with K-spar overgrowths. Intrudes basic complex and dykes of adamellite, No. 3.
4. Green, brown-weathering, hornblende syenite, No. 4a, forms incomplete ring around a central melange, No. 4b, huge blocks of metasediment, AS, gabbro, and anorthosite, Nos. 1a, 1b, and tonalite, No. 2, separated and cut by syenite dykes.
3. D₂? Pluton of cream to pink, biotite leuco-adamellite (14) with K-spar megacrysts. Uncertain age relationship to No. 2; intrudes gabbro.
2. D₂? Pluton of gray, even-grained biotite tonalite (14) and granodiorite. Uncertain age relationship to No. 3; intrudes gabbro.
1. Pre-tectonic Basic complex (13). Western rim and southwest dyke-like extension of gabbro, No. 1a, commonly rich in magnetite. Grades eastwards with increasing grain size to coarse leucogabbro and anorthosite, No. 16. Intrudes metasediments of Yellowknife Supergroup (AS).

The basic pattern common to Archean plutonism can be discerned: early tonalite and quartz monzonite (adamellite) (14) followed by metamorphosed and foliated granodiorite (6) and discordant syenite, granite, and quartz monzonite plutons (9, 12, 15). Other varieties are common here.

The deformational correlation suggested both for the plutonism of the Cameron and Beaulieu rivers area, and for the Blachford Lake area, built on the basic three part Archean plutonism, is highly interpretive. To relate metamorphism to plutonism would be even more speculative (there is not necessarily a direct relationship), therefore no attempt is made to bridge the gap from plutonism to metamorphism and hence to gold deposition.

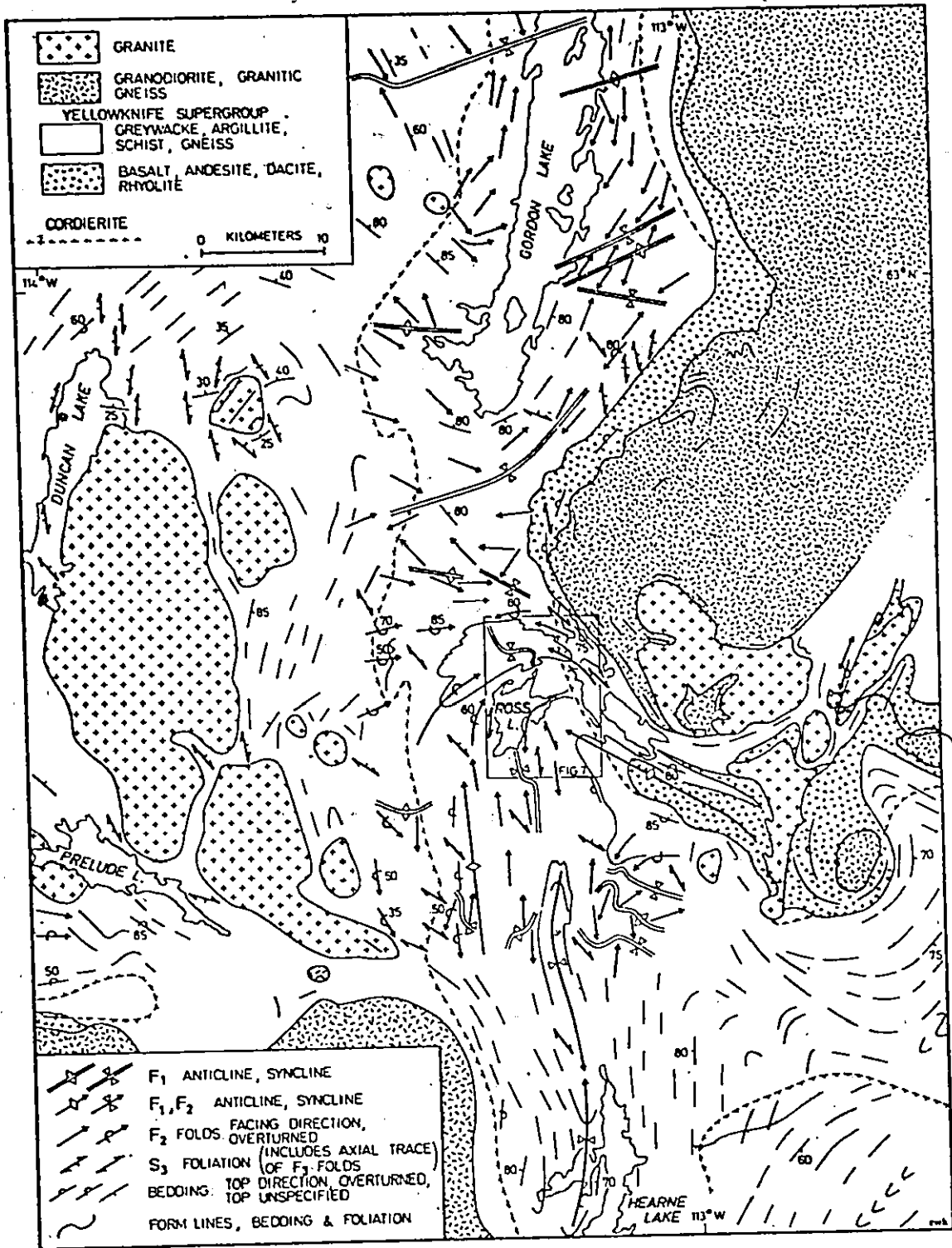
Deformation (after Fyson 1975) (Fig. 10)

- D_3F_3 Open to tight, subvertical, small-scale folds, not present in most outcrops.
- S_3 Steep axial plane schistosity with consistent trend over large area.
- D_2F_2 Open to isoclinal folds, usually near upright. Some overturned, varying trend.
- S_2 Quartz inclusion trails in biotite porphyroblasts oblique to S_3 muscovite and biotite laths; quartz-rich and mica-rich zones alternating.
- D_1F_1 Large linear depressions and anticlinal culminations, partly concordant with the part-basement granite complex.
- S_1 Not noted.

Boyle (1961) notes that the major ore-bearing Giant-Campbell shear zone system probably formed along a major thrust zone at an early stage, considered here as D_1 .

Major early thrusting, S_1 , not noted, the change to vertical tectonics accompanied by schistosity, and isoclinal to more open folding with time, are features common to deformational histories of Archean and younger periods.

The deformational and metamorphic history of the Ross Lake-Gordon Lake area east of Yellowknife is well established by Fyson (1975) but has not been integrated with the full pluton sequence mapped in the same area by Davidson 1972 (see Plutonism) nor with the gold producing area to the west of Yellowknife Bay.



Structural map, Ross Lake - Gordon Lake area.

Fig. 10, from Fyson 1975

Metamorphism (after Fyson 1975 for the Ross Lake-Gordon Lake Sector)

- M₃ Crenulate muscovite laths and coarsely crystalline alignment of muscovite and biotite. Muscovite augen. Middle greenschist facies. Cordierite developed late- or post-D₃. Amphibolite facies. Andalusite developed pre-end D₃.
- M₂ Defines S₂ by aligned quartz and muscovite (+ chlorite). In much of the area obscured by S₃. Lower greenschist facies. (Presumably amphibolite facies associated with plutons).
- M₁ No fabric. (Amphibolite grade metamorphism accompanied major thrusting postulated by Boyle (1961)).

Fyson (oral comm. June 1976) specifically makes the point that his surveys to date are in the greenstone belts and not the gneisses. Thus in considering the above metamorphic phenomena, no attention has been paid to the relative position, for example, of the migmatization and possible migmatization of Nos. 5, 7, and 8 in the Cameron and Beaulieu rivers tabulated under Plutonism. Boyle (1961) notes that the metamorphic facies at Yellowknife show a distinct relationship to the granodiorite-greenstone contact and grade outwards from this contact. The zoning includes a marked amphibolite facies adjacent to the granodiorite and grades outward from this contact into the greenstone as a broad, central, epidote-amphibolite facies, and an irregular and ill-defined greenschist facies farthest from the granite.

The metamorphic data integrated by Fyson with the deformational history in the Ross-Lake-Gordon Lake area, has yet to be firmly tied to the igneous activity in the area or to the sequence of ore forming events indicated by Boyle (1961) west of Yellowknife Bay.

Ore Deposition

Syn-tectonic

Gold

A relationship to deformation can be interpreted from Boyle's (1961) work:

D₄ and later Cooling and structural adjustments. Au, Ag, Sb₂S₃, SiO₂, CO₂, etc. exsolved from early sulphides. Successive generations of native gold, sulphosalts, pyrite, quartz, carbonates.

D₂, D₃ Migration of liberated compounds and elements to "2nd degree" low pressure dilatant zones. Precipitation of quartz, carbonates, and Au and Ag-bearing pyrite and arsenopyrite.

Marked temperature gradients: H₂O, CO₂, S and chalcophile elements migrated, funnelled along "1st degree" dilatant zones. Chloritization, carbonatization, pyritization of enormous tonnages of volcanic rock. Liberation of Si, K, Ca, Fe, Au, Ag, etc. in altered rock.

D₁ Development of shears as major channelways.

Boyle (1961) summarizes the controls of gold deposition: Two ages of shear zones occur in the greenstone belt: (1) early shear zones which parallel the lava flows in strike and dip and contain a few small, high-grade, gold-quartz lenses, and (2) shear zones which transect the lava flows and contain the large economic gold-quartz veins and lenses of the district. The Giant-Campbell shear-zone system is the major ore-bearing system and probably formed along a major thrust fault zone. The smaller Con and Negus-Rycon systems are subsidiaries of this large system.

In the shear-zone systems, the principal ore controls are shear-zone junctions and flexures, and folded parts of large schist zones.

In the sedimentary rocks of the Yellowknife Group, concentrating processes were similar to those in the volcanics. Gold-quartz lenses developed in faults, folds, saddle reefs, ruptured and sheared axes of isoclinal folds, and other structures (Boyle 1961). Fyson (1975) adds that the gold at the Thompson-Lundmark mine was mined on F₁ culminations.

These descriptions by Boyle of mobilizing processes leading to gold concentration are probably the most quoted in the literature. Yellowknife has become the type example. The need now is for complementary structural

studies in the mines area, to ascertain the suggested relationships to deformation and to formulate the description of shears and folds which control gold deposition.

Beryl and Tantalite

Beryl and tantalite have been recovered from pegmatites of the Yellowknife-Beaulieu area (Lang et al. in Douglas 1970). The D₃ granites (Fyson 1975) are pegmatite bearing.

Ore Production

	<u>Prod. Period</u>	<u>Production Tons Ore</u>	<u>Ozs. Au Recovered</u>	<u>Ref.</u>
Giant Yellowknife	1948 - 74	8,463,233	\$6,062,433	1
Con	)			
Con Rycon	)			
Negus	)			
Cons. Discovery	)	Not Available		
Thompson Lundmark	)			
Ptarmigan	)			

Reference

1. Financial Post Survey of Mines 1976.

Mining Magazine ratings for 1974 production:

Giant Yellowknife	D	Au
Con Rycon	E	Au

HANSON LAKE-FLIN FLON-SNOW LAKE-SHERRIDON

1. Hanson Lake
2. Flin Flon
3. Snow and File Lakes

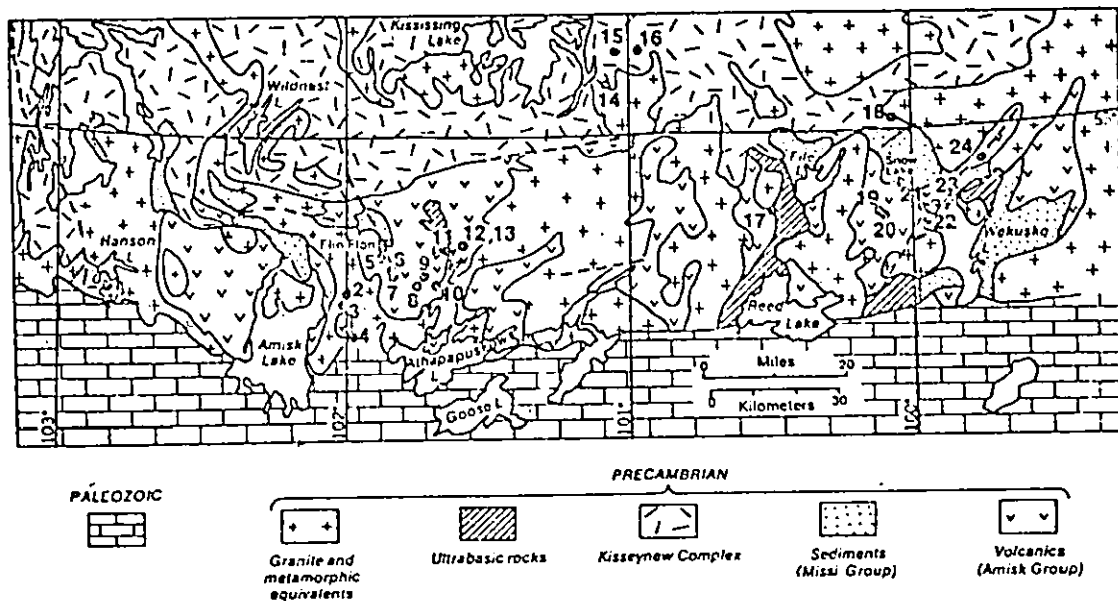
Hanson Lake-Flin Flon-Snow Lake-Sherridon

This area is regarded here as an entity because it forms one greenstone belt but is treated in three parts because structural and metamorphic data are available only for the Hanson Lake, Flin Flon, and Snow Lake sectors. The reviews of age, radiometric dates, ore deposition, and ore production are combined for the belt as a whole.

The volcanics and volcanoclastic sediments of the Flin Flon-Snow Lake area comprise the Amisk Group. They are unconformably overlain by sediments forming the Missi Group (Bailes 1971). Together they form an east-west trending unit which is paralleled to the north by metasedimentary gneisses, named the Kiseynew gneisses, in which is Sherridon. Bailes (1971) favours the hypothesis that the Kiseynew gneisses are a complex of different ages including strata equivalent to both the Amisk and Missi Groups, the Nokomis being the stratigraphic equivalent of the Amisk Group sediments and the Sherridon gneisses the equivalent of the Missi Group.

In part because of dating problems discussed elsewhere, and in part because of a gap of 3 to 7 km, occupied by intrusive rocks, between volcanics and sediments contiguous with the type area for the Amisk and those of the same nature at Hanson Lake, Coleman and Gaskarth (1970) preferred the term Amisk-type for the Hanson Lake area. Their parallel usage of Kiseynew-type is for gneisses which are the metamorphosed lower part of the volcano-sedimentary complex in the Hanson Lake area.

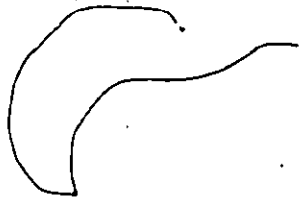
Ore deposition and production for the belt as a whole is considered at the end of the section (i.e., after Snow Lake).



General geology of Hanson Lake - Flin Flon - Snow Lake mineral belt and locations of massive sulfide deposits. Geology slightly simplified from Geol. Surv. Can. Map 1164A (Carrot River). Base metal sulfide deposits numbered as follows: 1. Western Nuclear 2. Flexar 3. Birch Lake 4. Coronation 5. Flin Flon 6. Mandy 7. Schist Lake 8. White Lake 9. Cuprus 10. Centennial 11. Pine Bay 12. Don Juan 13. North Star 14. Sherridon 15. Bob Lake 16. Jungle 17. Dickstone 18. Wim Lake 19. Chisel Lake 20. Ghost Lake 21. Anderson Lake 22. Stall Lake 23. Little Stall Lake (Rod) 24. Osborne Lake.

Fig. 11 from Sangster 1972

- 60 -



HANSON LAKE, SASKATCHEWAN



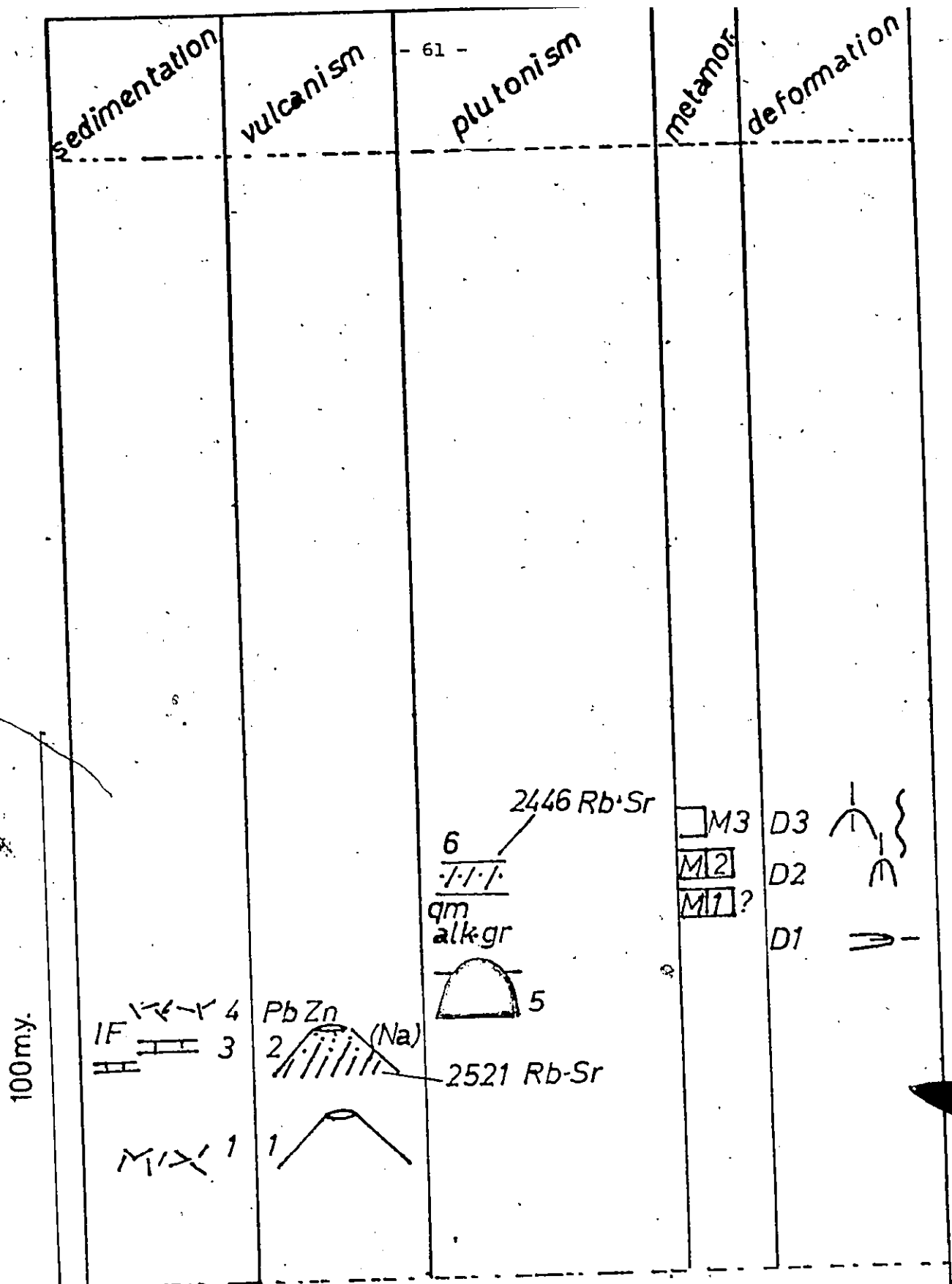


Fig. 12 Time Relations of Geological Features

HANSON LAKE, SASK.

Vulcanism (after Coleman and Gaskarth 1970) (Fig. 11)

Upper Diverse Unit?

Amisk type volcanics and sediments (2)*

Felsic volcanics: predominantly fragmented lavas, agglomerates, and tuffs, large units of soda-rhyolite porphyry interlayered in the upper part of the section: mostly flows, larger bodies ignimbritic, some may be near-surface intrusions.

Complex folding and faulting, lack of marker horizons, and discontinuous units make thickness estimates impossible

Intermediate volcanics: continuous, uniform unit. Pyroclastic flow (?) possibly from glowing avalanche type eruption. Lenses of basaltic or andesitic lapilli tuff or welded scoria.

Mafic volcanics: characterize lowest part. Hornblende gneisses on flanks of complexes interpreted as mafic tuffs. Comparable to tholeiitic basalts. Amphibolites with indistinct pillows interpreted as massive mafic lavas.

Kisseynew-type gneisses (1)

Formed from a sequence of sediments and volcanics. Smith (1970) considers they were deformed, metamorphosed, and denuded prior to Amisk-type extrusion. Coleman and Gaskarth (1970) consider them part of the succession.

Bailes (1971) considered that domes in the Kisseynew gneisses north of Snow Lake are basement and it may be that deformed and metamorphosed basement is separable from a younger part of the Kisseynew gneisses. The Amisk sequence forms one complete major cycle in the terms of Anhaeusser (1971-1), and by comparison with Morrice (1974-2) for Flin Flon must be classified as Upper Diverse Unit, though the relationship of the two sections is not clear.

* - Numbers in parentheses refer to Chart (Fig. 12).

Sedimentation (after Coleman and Gaskarth 1970) (Fig. 11)

Amisk-type

Graywacke (4)*: fine-grained and thinly bedded, in places with agglomeratic horizons. Two small outcrops of iron formation. Exposed only in east of area in synclinal uppermost section.

Calc-silicate rocks (3): in layers and lenses throughout Amisk-type volcanics and sediments, and one small body in Kiseynew-type gneisses.

Kiseynew-type gneisses (1)

Geosynclinal sediments (and volcanics) lying below Amisk-type sequence.

The brief description "geosynclinal sediments" would be considered inadequate by present standards. Calc-silicate rocks, though not common in the Canadian areas reviewed, are not unusual in the Canadian Shield and are described from the Limpopo and Vumba and Tati areas.

* - Numbers in parentheses refer to chart (Fig. 12).

Plutonism (after Coleman and Gaskarth 1970) (Fig. 11)

- | | |
|-----------------------------|--|
| Late or post-D ₃ | Beryliferous granite pegmatite dykes transecting all foliations, folds, and other pegmatites. Sharp boundaries, lack of internal deformation, and trends suggest emplacement in tension fractures after relief of D ₃ compression. Mainly in Kisseynew-type rocks in core of Jackpine Lake Complex. |
| Late or post-D ₃ | Non-beryliferous granite pegmatite dykes and lenses, Either discordant and subparallel to the axial plane of the Jackpine Lake fold (F ₃) or concordant and parallel to the layering which delineates it. Sharp contacts. Lack of penetrative foliation suggests that they were emplaced after folding of the country rocks. |
| M ₂ | Non-beryliferous granite pegmatite as small, irregular veins and lenses and as discontinuous layers within Kisseynew-type quartz-dioritic rocks and migmatites. Gradational contacts. Associated with migmatization of Kisseynew-type rocks. |
| D ₂ ? | Four granitic sills (6)*, essentially alike. Alkali granite or quartz monzonite, massive, granitoid, and with some xenoliths and thin pegmatoid lenses. Coleman and Gaskarth (1970) note some foliations are probably S ₂ . If so, the tabulation with D ₃ by Gaskarth (1971) would appear to be erroneous. |
| Post-volcanic | A plug-like body of pyroxenite (5) which appears to truncate a contact between mafic and felsic volcanics. |

The relatively small Hanson Lake area has a curtailed sequence, and the lack of integration of the granitization of the Kisseynew gneisses in the above scheme is unfortunate. No other plug-like body of pyroxenite is noted in other areas covered in the present study.

The integration of deformation and plutonism is by Coleman and Gaskarth (1970).

* - Numbers in parentheses refer to chart (Fig. 12).

Deformation (after Coleman and Gaskarth 1970, Gaskarth 1971)

- $D_3 F_3$ Micro to large folds, subvertical axial surfaces, gentle open to kink (chevron). Small open F_3 common in quartz diorite, chevron common in quartz diorite and migmatite.
- S_3 Zones of intense shearing parallel to axial planes.
- L_3 Elongate streaks of metamorphic biotite and hornblende; lenses in quartz diorite.
- Faulting.
- $D_2 F_2$ Tight to isoclinal folds, commonly with shorter limbs than F_1 . Most minor folds are F_2 and plunge steeply.
- S_2 Axial planar foliation.
- L_2 Flattened or elongated grains or groups of grains, e.g., quartz lenticles in quartz diorite, pebbles in graywacke; lenticular biotite in quartz diorite of the gneissic suite.
- $D_1 F_1$ Isoclinal folds with long limbs, recumbent prior to F_2 and best seen in basalt.
- S_1 Axial planar schistosity.
- L_1 May be some of the features described under L_2 .

Minor folds are more readily recognizable in the Kisseynew-type gneisses than in the Amisk-type volcanics. There is a complete gradation in fold styles. F_2 and F_3 axes are close to parallel though axial planes are oblique. Many F_1 hinges are rotated nearly parallel to F_2 axial planes.

The sequence from recumbent isoclinal folds to open upright folds is common to many deformational sequences elsewhere and at other times. S_1 schistosity noted here, is also present at Snow Lake, absent at Flin Flon, so comparing with the sporadic nature of S_1 in southern Africa, for example.

Metamorphism (after Coleman and Gaskarth 1970)

M₃

Retrograde metamorphism. Chlorite replaces biotite and garnet, white mica replaces plagioclase, and serpentine replaces pyroxene (in pyroxenite). Mylonitization, development of muscovite and of veinlets of epidote, feldspar sericitization, and silicification are common in sheared zones and near faults.

M₂

Migmatization; amphibolite facies; culmination of regional metamorphism. The unfoliated quartz-dioritic component of the Kisseynew-type gneisses truncates D₂ foliation in the foliated quartz-dioritic component and must have been mobile after the foliation formed. Quartz diorite intrudes pulled apart amphibolitic blocks which retain F₂ folds in an overall F₃ fold. Coleman and Gaskarth (1970) consider that this implies quartz dioritic material was present during D₃.

M₁?

Migmatization, amphibolite facies. Metamorphic foliation in quartz diorites and migmatites of Jackpine Lake and Tulabi Lake complexes.

The early (M₁?) designation for amphibolite facies metamorphism and migmatization is atypical and must be compared with the note by Smith (1970) in which pre-Amisk metamorphism is considered. One suspects that parts of the Kisseynew gneisses are remobilized basement.

FLIN FLON, MANITOBA

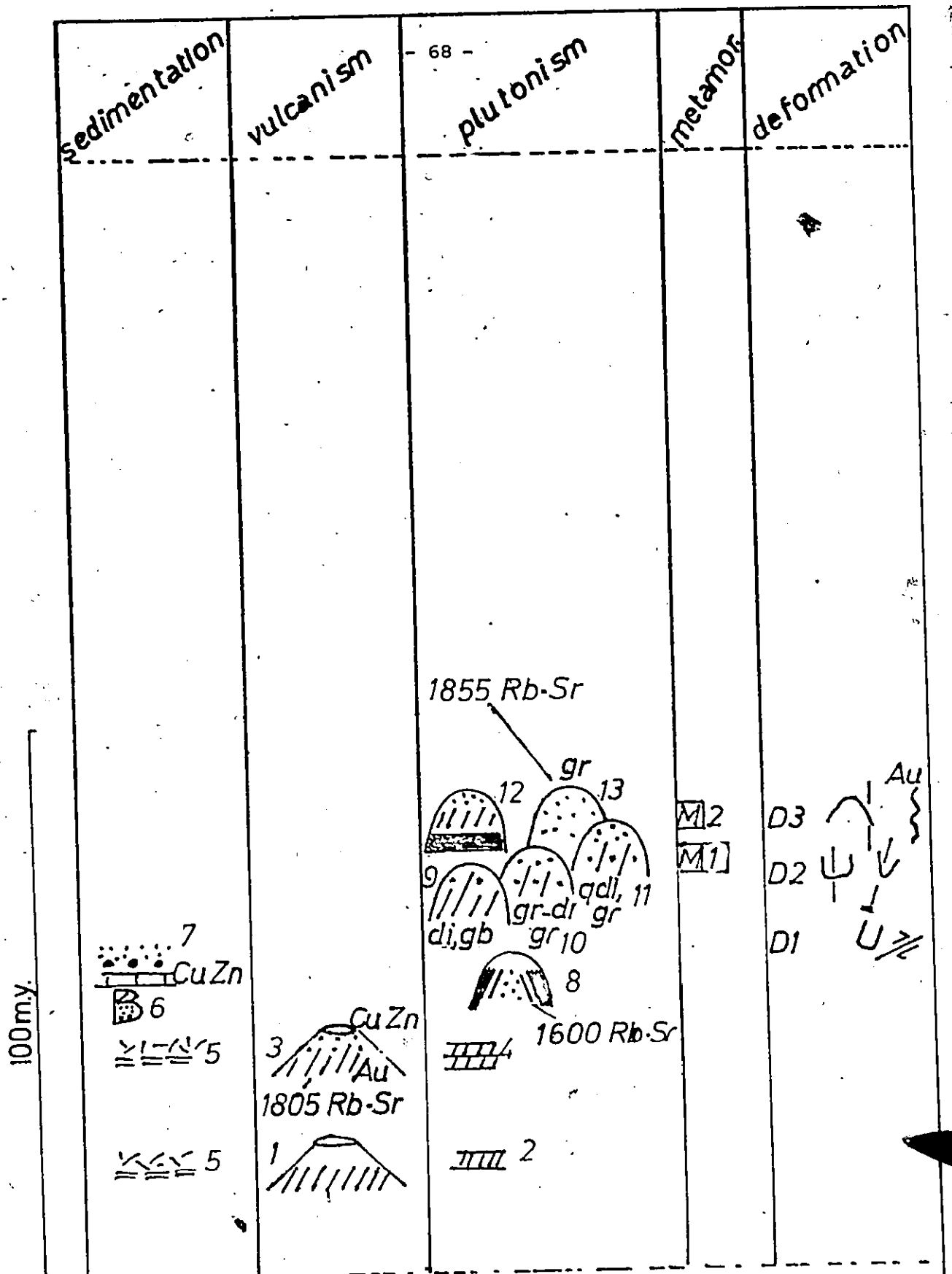


Fig. 13 Time Relations of Geological Features

FLIN FLON, MAN.

Vulcanism (Morrice 1974-2) (Fig. 11)

Amisk Group

Upper Diverse Unit (2)*

Mafic, intermediate, intermediate-felsic flows
and breccia. 700 m.

Fine and coarse, intermediate-felsic,
pyroclastic-epiclastic 2500 m.

Numerous fine-medium-coarse-pegmatitic
grain sized layered gabbro-diorite
sills (4)

Middle Mafic Unit (1)

Non-pillowed mafic flows with 25 percent
of epidotized clots. Subordinate mafic
and intermediate tuff, tuffaceous
sandstone, and lahars. 1600 m.

Fine-medium grained homogeneous gabbro-
diorite sills. (3)

Vesicular pillowed and massive mafic
flows, flow breccia, and lahar. 1950 m.

Fine-medium grained massive gabbro-
diorite sills. Felsic sills, may be
in part flows, commonly auto-brecciated.

Morrice measured this section on Provincial Trunk Highway 10, southeast of Flin Flon, between Hook and Whitefish Lakes, in a corridor 6.9 km long.

The relationship of this section to the sequence at Hanson Lake is not clear. In that the lower part is mafic and the upper includes intermediate and felsic volcanics, repeated, one must consider the possibility of equivalents of the major and minor cycles of Anhaeusser (1971-1). This sequence is the best example of the work of the Winnipeg group in the areas of the present study.

* - Numbers in parentheses refer to chart (Fig. 13).

Sedimentation (after Bailes 1971) (Figs. 11 and 14)

Missi and Sherridon Groups (7)

Missi Group sediments overlie the Amisk Group and Post-Amisk Intrusive Group in the greenstone belt. They are a relatively clean, detailed sequence of arkose, graywacke, and quartzite. Pebble and boulder conglomerate beds with clasts of the two older groups are located near the base.

The Sherridon Group, (the upper part of the Kiseynew gneisses) is finely laminated quartzitic and arkosic sediments of a shallow water or fluvial environment. Limestones and orthoquartzites at the base imply a stable, shallow water environment with a limited supply of detrital material.

Amisk and Nokomis Groups

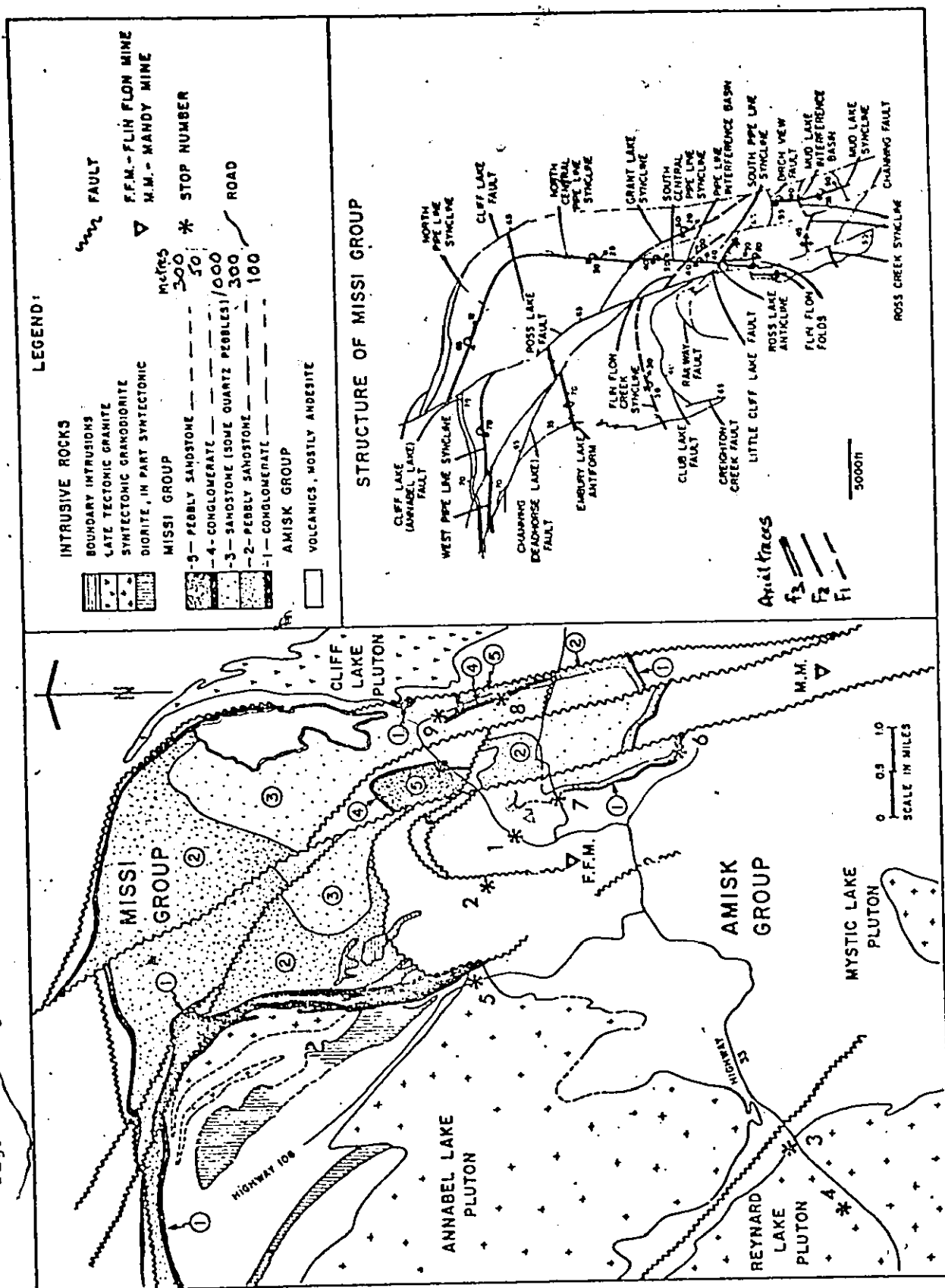
Amisk Group sediments are at various levels throughout the volcanic sequence, more commonly with the later, acidic phases. They are (a) volcanoclastic thin beds of tuffaceous siltstones and graywackes (5), and (b) thicker and more widespread turbidite graywacke and siltstone (6).

The Nokomis Group (the lower part of the Kiseynew gneisses) has turbidites (6) implying a relatively deep water environment with an adjacent elevated land mass.

The Kiseynew gneisses have gone through various correlations. That of Bailes (1971) is followed here.

Thicknesses on Figure 5 are averages from Stauffer and Mukherjee (1971).

The stratigraphic position of the Missi Group sediments is unusual for the Archean in that it follows the earliest plutonism, the Post-Amisk Intrusive Group. The nature of the sedimentation, turbidity products followed by shallow water or fluvial sediments, is typical of that associated with Archean vulcanism.



Plutonism (after Mukherjee, Stauffer, and Baadsgaard 1971) (Fig. 14)

Late- to post-D ₃	Granite (13). Phantom Lake.
Late- to post-D ₃	Peridotite to granite (12). Boundary intrusions.
Post-D ₂ , pre-D ₃	Quartz diorite to granite (11). Cliff Lake pluton.
Late- to post-D ₂ pre-D ₃	Granodiorite to granite (10). Annabel Lake, Reynard Lake, and Mystic Lake plutons.
Pre- to syn-D ₂	Diorite and gabbro (9) some of which may be pre-Missi.
Post-Amisk, pre-Missi	Quartzeyite granite and mafic intrusive rocks (8) in close spatial relationship and possibly co-magmatic (Bailes 1971). The Iskwasum Lake pluton is zoned: serpentine, gabbro, and diorite on the outside, then amphibolite, tonalite, granodiorite, adamellite, and granite core. (Hunt 1970). Scoates (oral comm.) is of the opinion that the serpentine at Iskwasum Lake is country rock but Bailes notes that many of these intrusions contain ultramafic phases, some, for example the Chisel Lake intrusion, noticeably so.

The pattern of plutonism in the greenstone belt, though integrated by Mukherjee et al. with deformation, has yet to be integrated with that in the gneiss belt and with the gneissic portions of the greenstone belt and thus granitization does not appear (in the usual D₂ position) above. The zoned Iskwasum Lake pluton includes tonalite and quartz monzonite (adamellite (8)), but the relationship of such early zoned plutons to early unzoned plutons of these compositions is not understood. The late granitic plutons are usual in Archean plutonic sequences, but the diorites, gabbro, and peridotites are additions to the simple sequence, early tonalite-quartz monzonite (8,9), followed by products of granitization (10?) and discordant plutons of syenite, granite (13), and tonalite.

Deformation (after Stauffer and Mukherjee 1971) (Fig. 14)

D₃ F₃

Large scale open folds; minor small scale monoclinial folding along fault zones.

S₃

Crenulate foliation; local shear foliation. All faults. (Coats et al. 1972 believe curved faults are early, due to thrusting from the south).

D₂ F₂

Tight, asymmetric to box folds; moderately dipping axial planes.

S₂

Well-developed: schistosity parallel to axial planes.

L₂

Well-developed: stretched pebbles and sand grains.

D₁ F₁

Tight to isoclinal, V to box folds. Moderate to steep axial planes. Thrusts (Coats et al. 1972)

The pattern of deformation shows little unusual: early thrusting (with no schistosity noted) and tight to isoclinal folding, later well developed schistosity and open, upright folding, are typical of the areas studied. Box folding, however, is not recorded from other areas.

Metamorphism (after Stauffer and Mukherjee 1971)

M₂

Chlorite along fault zones.

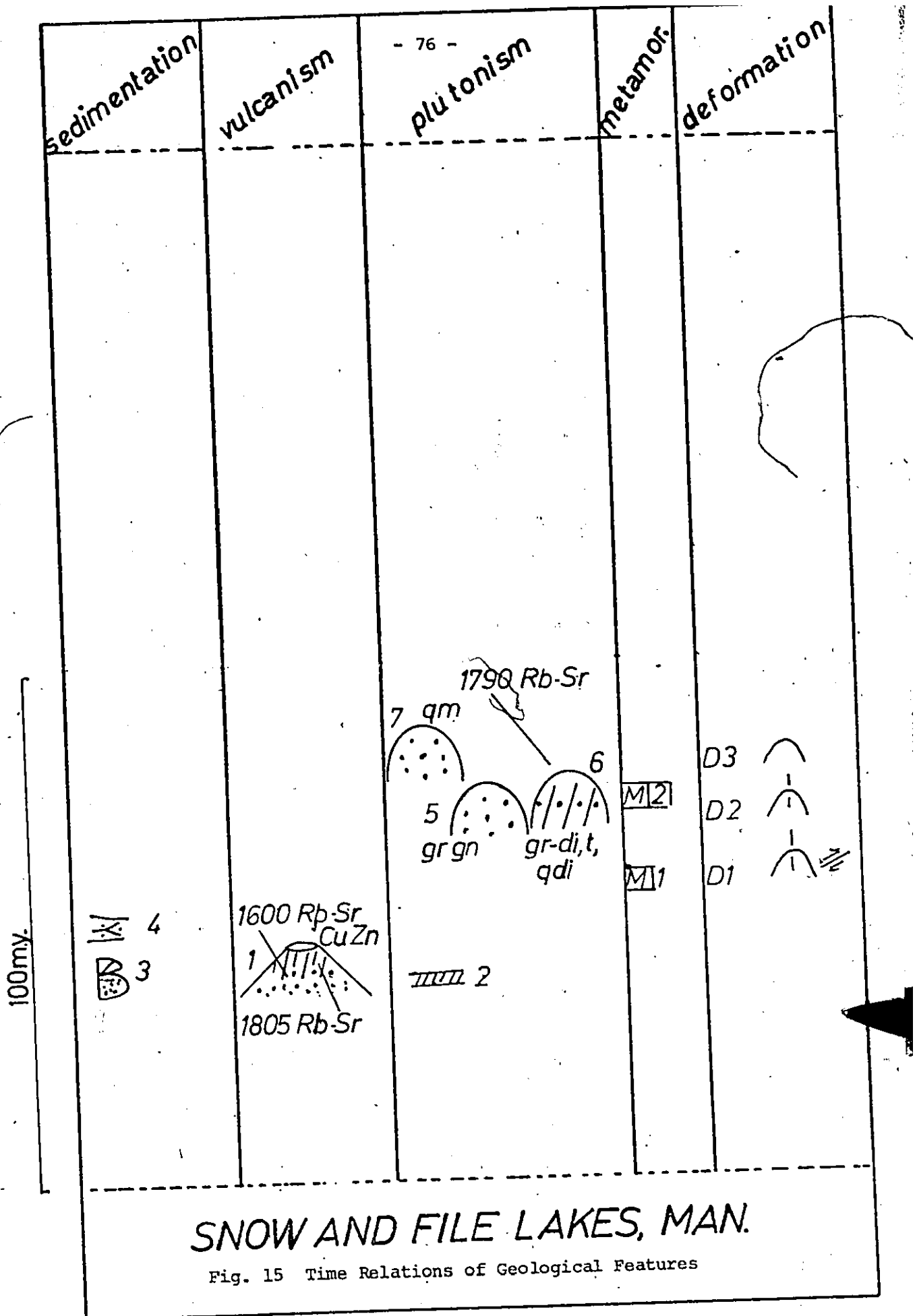
M₁

In the volcanic belt: garnet (greenschist) in the north, chlorite (greenschist) in the south.

In the Kiseynew gneisses: amphibolite grade.

In the chart (Fig. 13) M₁ is represented as penecontemporaneous with D₂. The lack of mention of metamorphism accompanying D₁ and principal metamorphism about the time of D₂ accords with the usual pattern.

SNOW AND FILE LAKES, MANITOBA



Vulcanism (after Morrice 1974-3) (Figs. 11 and 16)

Amisk Group

Upper Diverse Unit (1)

Column 2	Interlayered, pillowed, and massive mafic flows, often vesicular. Minor tuff and amphibolite.	2500 m
----------	---	--------

Numerous thin gabbroic sills (2).

Column 1	(b) Mafic: Mafic lahar and tuffaceous sandstone. Vesicular, intermediate flows.	200 m
----------	---	-------

	Tuff and tuffaceous sandstone	1000 m
--	-------------------------------	--------

	(a) Felsic: Felsic and intermediate-felsic lahar, tuff, and tuffaceous sandstone.	650 m
--	---	-------

	Felsic ash flow ("quartzeye granite or gneiss")	220 m
--	---	-------

Numerous gabbro sills with abundant feldspar phenocrysts (2).

The felsic to mafic sequence noted here after Morrice would not appear to represent the full section at Snow Lake: Bailes (1971) plots several interspersed mafic and felsic zones, each pair thick enough to be considered a major cycle in the terms of Anhaeusser (1971-1).

Fig. 16 Geology,
Snow Lake area from
Moore and Froese
1973

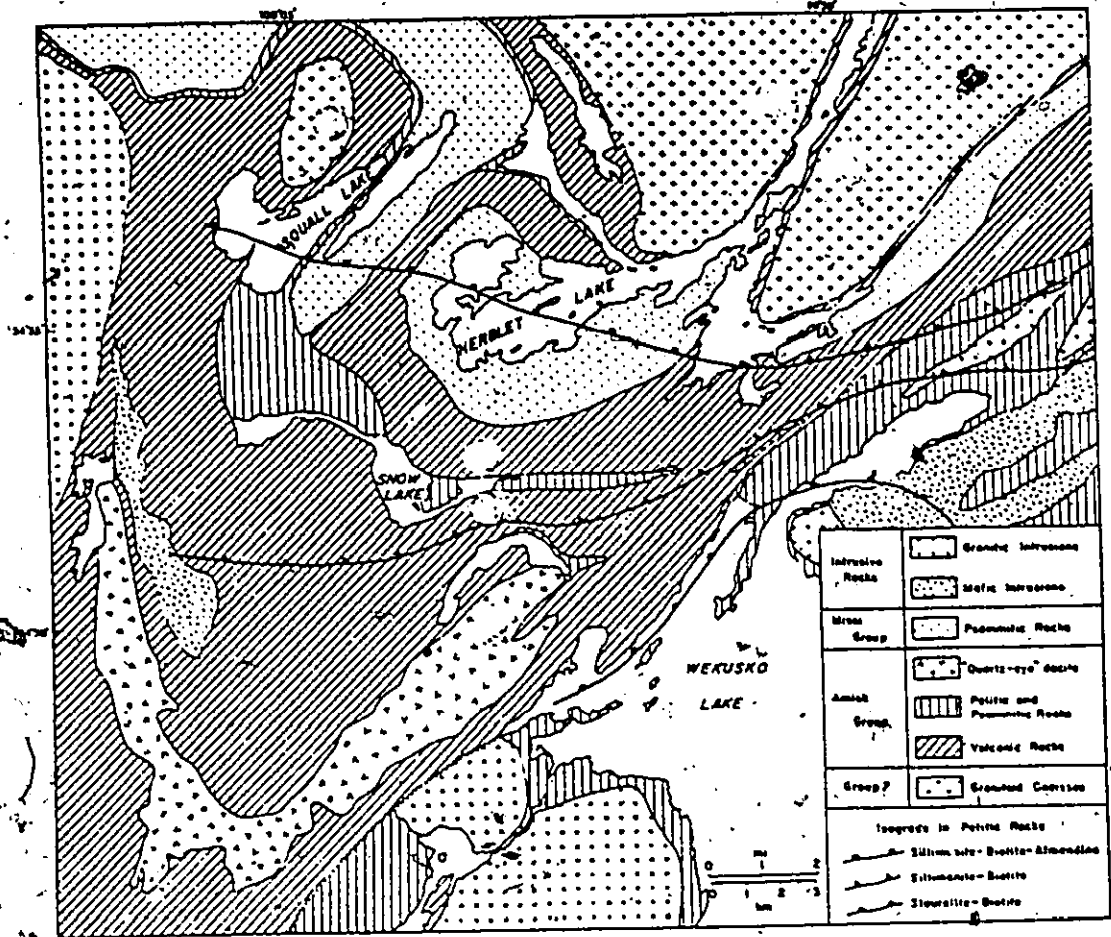
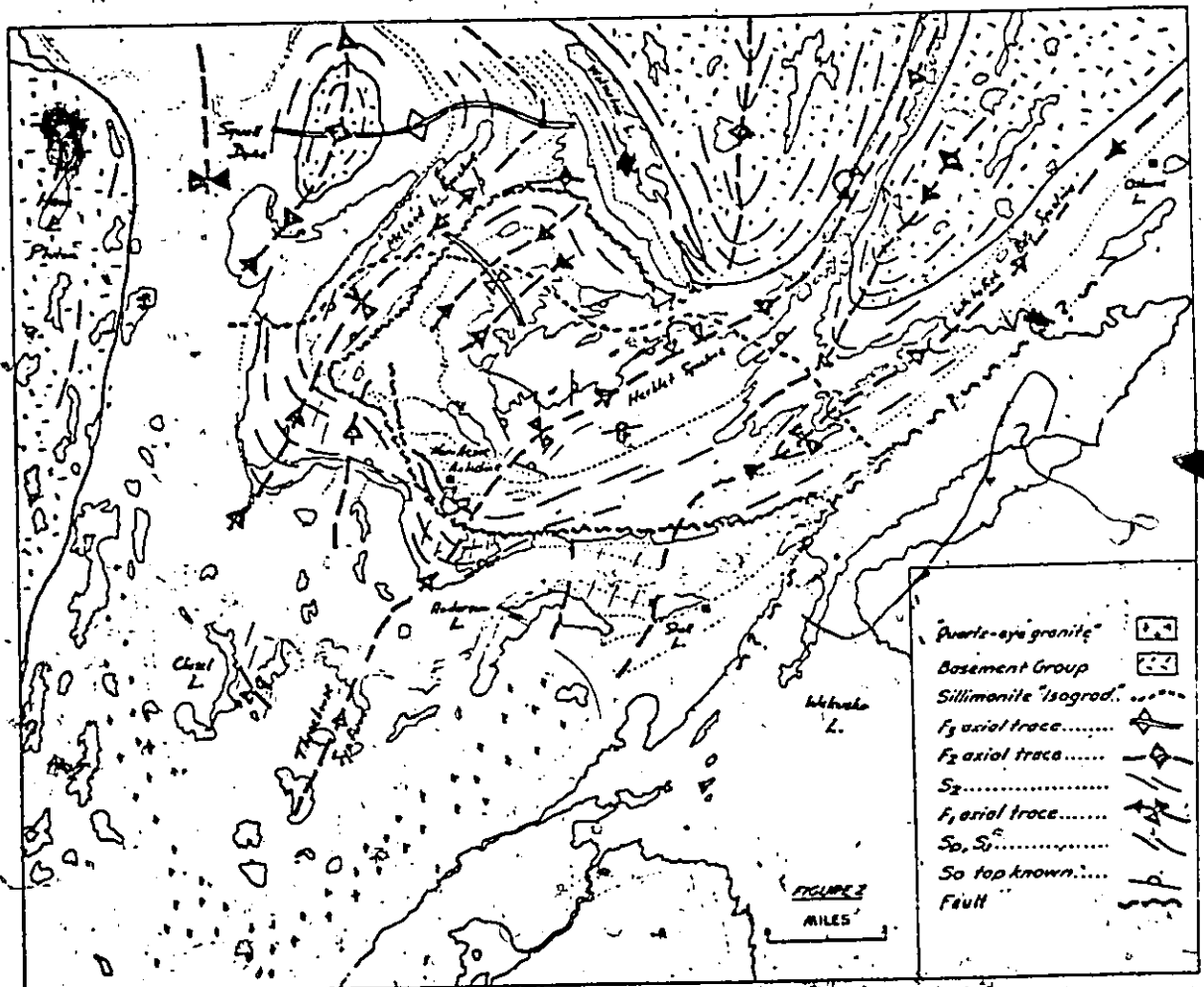


Fig. 17, Structure
and Metamorphism
Snow Lake area
from Moore and
Froese 1973



Sedimentation (after Moore and Froese 1973) (Figs. 11 and 16)

Missi Group (4)

Homogeneous sequence of commonly cross-bedded arkoses and graywackes, reflecting a shallow-water deltaic environment.

Amisk Group (3)

Beds of argillite and graywacke, displaying primary structures such as graded bedding, flame structures, convolute laminations, and scour channels, interlayered with volcanic rocks.

The sedimentary succession is typical of that found in the Archean areas reviewed.

Plutonism (after Josse et al. 1974) (Fig. 18)

- | | |
|----------------|--|
| D_3 or later | Pegmatite dykes |
| $D_3?$ | Porphyritic microcline quartz monzonite (7). |
| $D_2?$ | Granodiorite, tonalite, quartz diorite (6); Ham
pluton, anatectic complex. Granitoid gneiss
derived from Missi Group: File dome (5). |

The File Lake area adjoins the Snow Lake area on the west (Fig. 11) and has been utilized here because plutonic sequences are described by Josse et al.

Josse et al. (Fig. 18) show a variety of intrusives as pre-to early-kinematic. One suspects that both this grouping and that opposite $D_2?$ (above) is amenable to separation. Tonalite, for example, is commonly early D_2 and granitoid gneisses and anatectic complexes late D_2 . With better definition, the plutonic sequence may well be found to conform to the usual Archean pattern.

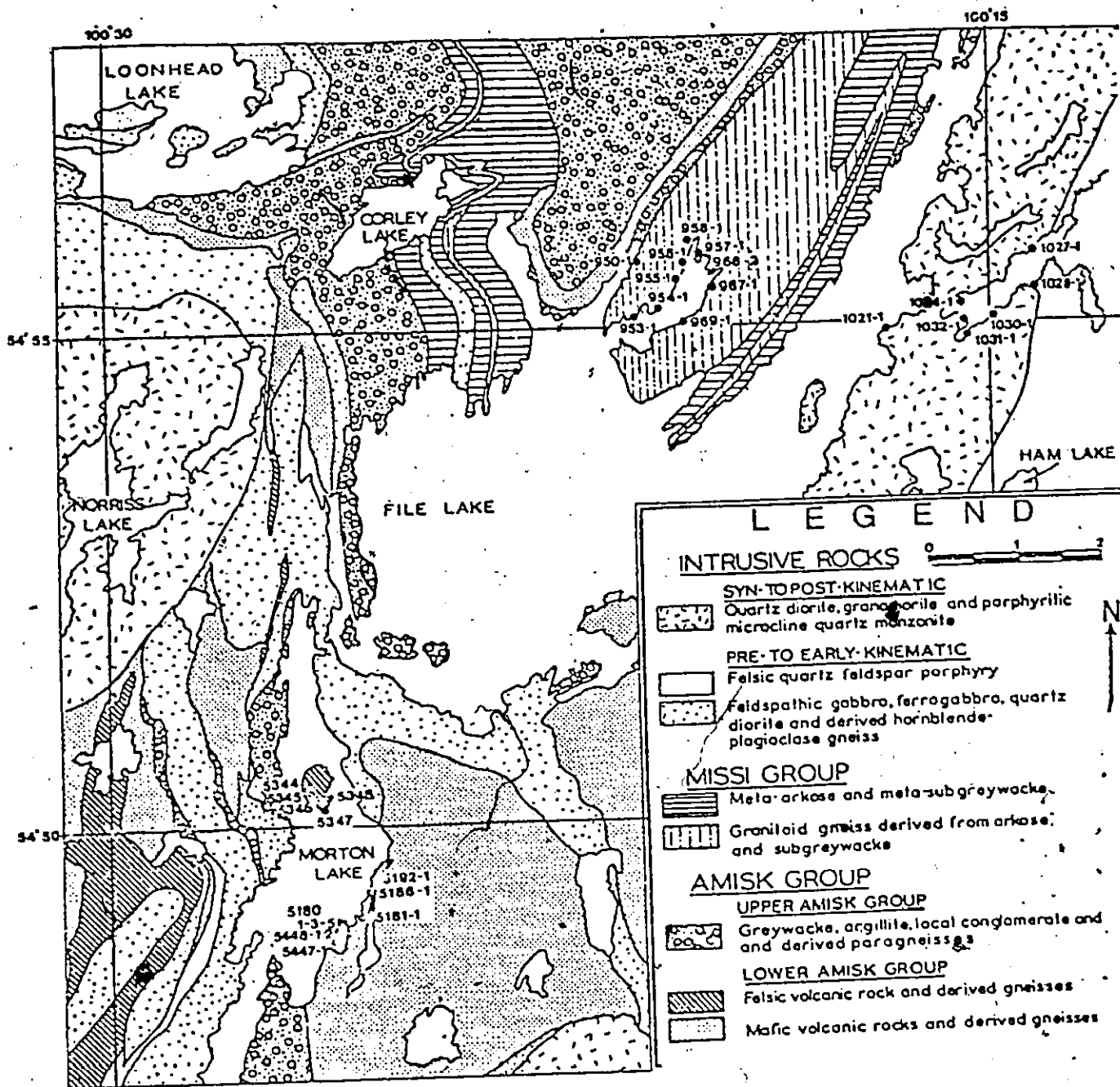


Fig. 18, Geology, File Lake area from Jesse et al. 1974

Deformation (after Moore and Froese 1973) (Fig. 17)

- $D_3 F_3$ Open folds deforming F_2 antiforms into domes.
- $D_2 F_2$ Folds producing dominant NE trend and crenulations from deformation of S_1 .
- S_2 Axial plane foliation in biotite bearing rocks.
- $D_1 F_1$ Open folds near Chisel Lake.
Thrusting.
- S_1 Prominent planar fabric: mineral lenticles and flattened fragments in Amisk rocks.

The sequence is similar to that in the Hanson Lake sector of the belt.

Metamorphism (after Moore and Froese 1973) (Fig. 17)

M₂?

Staurolite in pelites in south, sillimanite in north - amphibolite facies.

M₁?

Biotite fabric developed - greenschist facies.

The S₁ prominent planar fabric is related here to M₁, so placing the amphibolite facies metamorphism as penecontemporaneous with D₂.

Ore Deposition (Fig. 11)

Pre-tectonic

Copper-zinc-lead

Ore deposits in the Flin Flon area are considered by Howkins and Martin (1970) to have a definite stratigraphic control because they occur in acid members of the Amisk Group between basic lava flows and pyroclastics (Coats et al. 1972). Koo and Mossman (1975) note the presence in massive ore at Flin Flon of banding and zoning reminiscent of the conformable sedimentary sulphide bands and zoning in Kuroko ore deposits. Mineralogical zoning in Kuroko ore shows distribution upward as Cu, Zn-Pb, and Pb-Sb-Ag, Au. At Flin Flon the comparable zoning is chalcopyrite, sphalerite, galena, and tetrahedrite. They also note that the Flin Flon deposit is comparable in many ways to deposits at Noranda and at Jerome, Arizona. Coats et al. (1972) note that shearing and folding segment the ore into many lenses which parallel the plunge of the prominent lineation, L_2 .

At Snow Lake, Amisk Group sediments and volcanics and Kisseynew-type gneisses host copper-zinc sulphides. Either pyrrhotite or pyrite can be dominant. Elongation along plunge results in plunge-strike length ratios as much as 10:1 (Coats et al. 1972, Howkins and Martin 1970).

The Par deposit at Hanson Lake was a massive sphalerite, galena, pyrrhotite deposit with lesser amounts of chalcopyrite, silver bearing minerals, and gold. The wall rocks are generally felsic volcanics with interlayers of metasomatized volcanics on the west, rhyolite porphyry on the east. North of the mined section the zone is sheared (Coleman and Gaskarth 1970).

At Sherridon, the ore was preferentially localized in hornblende-plagioclase gneiss horizons at the contact between the Nokomis and Sherridon sequences (Bailes 1971). The ore was relatively coarse grained and ranged from massive to disseminated. Metallic sulphides in order of abundance were pyrite and pyrrhotite (2:1), chalcopyrite, sphalerite, minor chalmersite, and subordinate gold and silver (Davies et al. 1962).

All the deposits associated with the volcanics are regarded as volcanic exhalative. Bailes (1971) describes the deposits associated with the Kisseynew gneisses as syngenetic sedimentary: this broad categorization is probably valid but further study is necessary to establish possible relationships, for example with vulcanism in the greenstone belt, with eH/pH changes in disconnected shallow basins, and with the possible biogenic carbon prevalent at this horizon.

Syn-tectonic

Gold

Gold recovery has been principally from the base metal deposits, but it has also been mined from veins in shear zones and basalt in the mafic part of the sequence (Davies et al. 1962).

The paucity of gold ore at Flin Flon must be considered in relationship to the paucity of iron formation (no economic deposits) and ultramafics (no economic nickel deposits), but in making such considerations, the similar paucities at Yellowknife, which is a productive gold area, must be borne in mind.

The comparison with Noranda, Japan, and Jerome merits more detailed evaluation by work comparable to that of Spence and de Rosen Spence (1975) at Noranda.

Ore Production (Fig. 11)

<u>Base Metal</u>	<u>Prod. Period</u>	<u>Prod. (tons)</u>	<u>Ref.</u>
Stall Lake (HBMS)	1963 - 74	2,094,092	1
Osborne Lake	1968 - 74	1,447,300	1
Cyprus	1948 - 54	509,050	1
Centennial	1974 - 74	2,000	1
Mandy	1917 - 44	137,000	1
Schist Lake	1951 - 74	1,955,373	1
White Lake	1972 - 74	319,000	1
Don Jon	1954 - 57	87,440	1
Flin Flon	1930 - 74	61,096,364	1
North Star	1953 - 58	264,420	1
Anderson Lake	1970 - 74	1,133,500	1
Birch Lake	1957 - 60	307,265	1
Chisel Lake	1960 - 74	3,647,515	1
Ghost Lake	1972 - 74	204,200	1
Dickstone	1970 - 74	736,549	1
Flexar	1969 - 72	337,300	1
Sherridon	1931 - 51	8,531,500	1
Coronation	1960 - 65	1,412,860	1
Hanson Lake	1967 - 69	162,400	1

Gold

		<u>Prod (ozs.)</u>	
Gurney	1937 - 39	25,164	2

References

1. Geol. Surv. Canada, R. Thorpe, pers. comm., June 1976.
2. Davies et al. 1962

The Mining Magazine ratings for 1974 are:

Stall Lake	E	Cu
Anderson Lake	D	Cu, Ag, Au
Chisel Lake	E	Cu, Zn, Pb
Dickstone	E	Cu, Zn
Flin Flon	D	Cu, Zn, Pb

Based on the Flin Flon ore-bodies, the area has been a major producer.

- 87 -

RICE LAKE, MANITOBA

GEOLOGY OF THE RICE LAKE GREENSTONE BELT

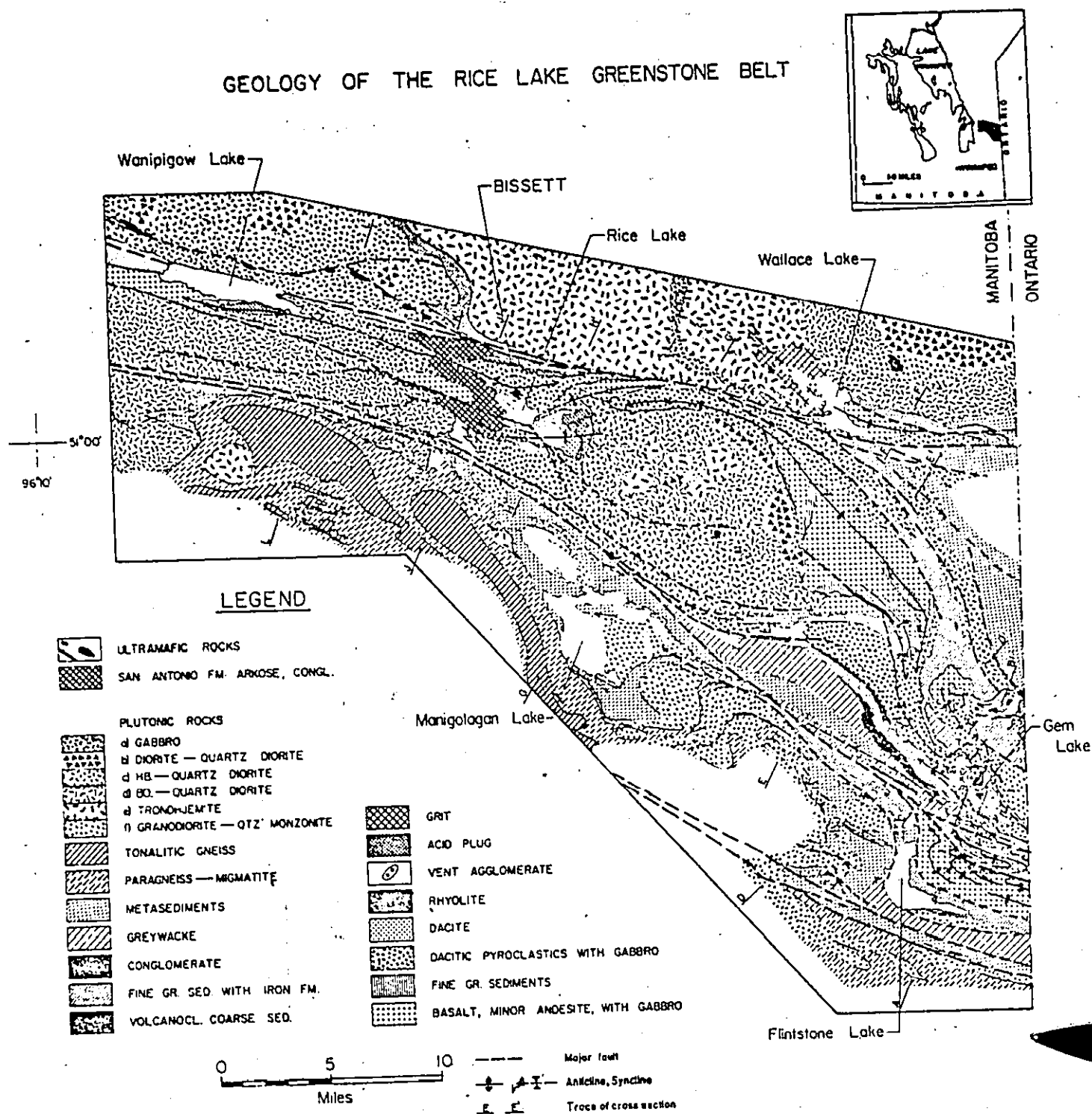
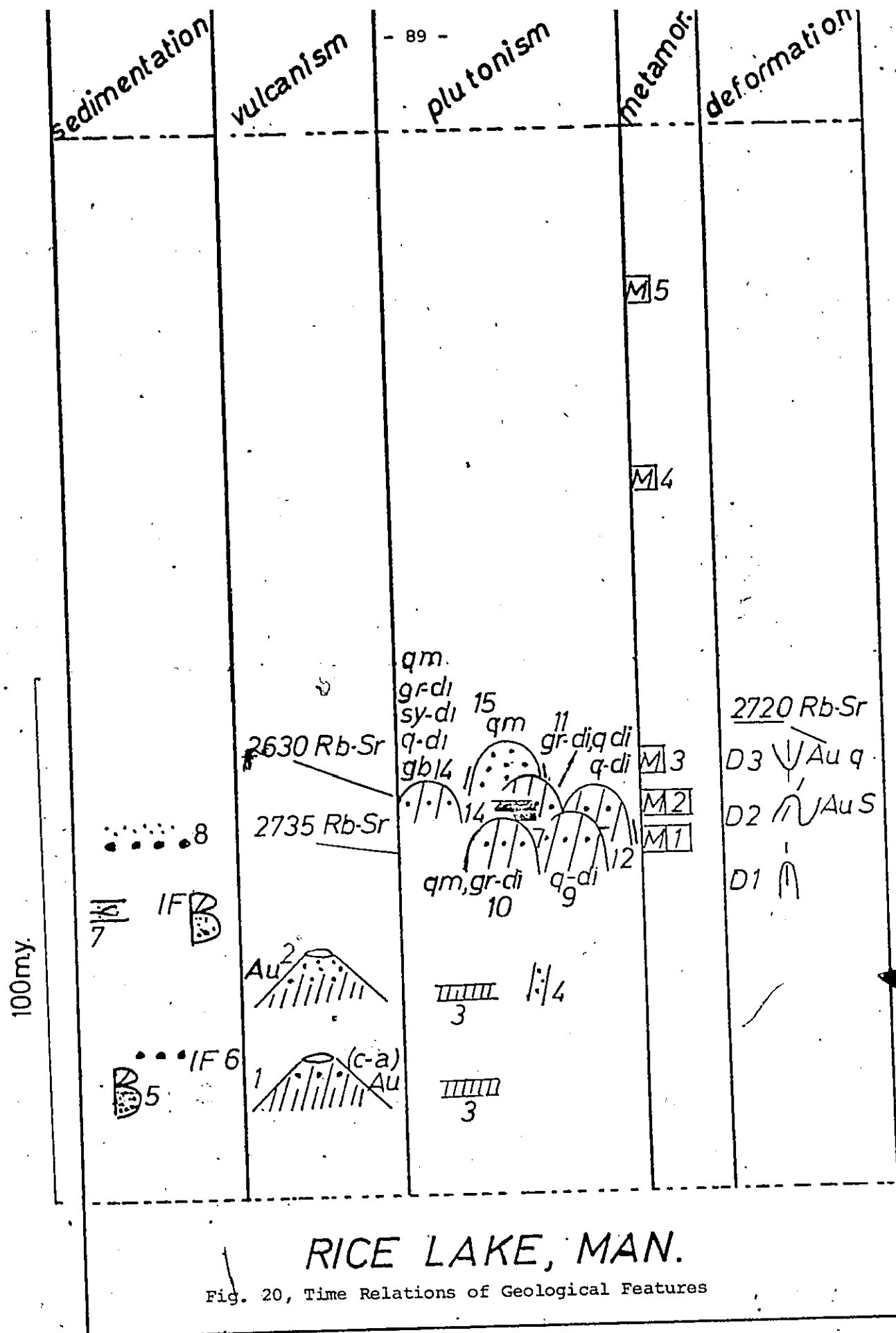


Fig. 19 from Weber 1971-2



Vulcanism (after Weber 1971-2) (Fig. 19)

Upper Diverse Group?

Cycle 2. (2) Gem Lake Subgroup

3000 m

Rathall Lake Formation

(300 m)

Volcaniclastic, fine and coarse sediments.
Felsite.

Banksian Lake Formation

Vent agglomerate.

Rhyolitic rocks: rhyolite tuff and
breccia, flow rhyolite.

Dacite to rhyodacite, mainly pyroclastic rocks.

Andesite.

Basalt.

Cycle 1 (1) Bidou Lake Subgroup

6000 - 8000 m

The Narrows Formation.

Dacite pyroclastics, tuff breccia, and crystal
tuff.

(3000 m)

Stormy Lake Formation

Fine and medium-grained sediments, iron
formation, conglomerate, basalt

(300 m)

Gunnar Formation

Basalt

(1250 m)

Dove Lake Formation

Fine volcaniclastics, conglomerate

(300 m)

Tinney Lake Formation

Basalt

(1250 m)

Stovel Lake Formation

Fine volcaniclastics, conglomerate

(300 m)

Unnamed basalt

(1250 m)

The basic volcanics of the Bidou Lake Subgroup cluster near the end point of the Icelandic olivine basalt trend, and the acid volcanics are in the acid line of the Cascade calc-alkaline lavas (Church and Wilson 1971).

Fine-grained, thin, gabbro bodies (3) occur mainly within the basalts and are probably related to them. Coarser-grained, larger, gabbro bodies, including one emplaced in the Bidou Lake subgroup, with an anorthositic core (5), are commonly crudely layered: they may belong to the same intrusive period or to a later one (Weber 71-1). Acid plugs and quartz-feldspar porphyry (4) are also considered to be volcanic products.

As Weber describes the cycles, Cycle 1 is incomplete (lacking a felsic component), and Cycle 2 is complete. Both fulfill the concept of major cycles (Anhaeusser 1971-1). They appear to compare best with the Upper Diverse Group (Wilson 1974).

Sedimentation (Fig. 19)

Post-D₁ ~~Pre-D₂~~

San Antonio Formation: molasse (8) (Weber 1971-2)

Pebbly arkose with minor interlayered conglomerate or pebble bands. Granitic detritus derived from quartz diorite to south and from granitic rocks, probably to the north. Southern basal section of coarse landslide material and boulder conglomerate. Cross-bedding, channel filling, and lack of graded bedding characterize it as a continental delta deposit; shallow water indicated by limestone matrix in conglomerate. Preserved in graben. Deformed by D₂ (McRitchie and Weber 1971).

Rice Lake Group

Pre-D₁

Edmunds Lake Formation: ancient turbidite (7)
(Weber 1971-2)

2300 m

- (c) Interbedded feldspathic graywacke and shale with isolated lenses of chert and iron formation.
- (b) Quartzose graywacke with isolated beds of shale and sandstone.
- (a) Massive arkosic sandstone and pebble conglomerate (Campbell 1971).

Conley Formation: shelf facies (7)
(Weber 1971-2)

Grit and sandstone with minor tonalite-boulder conglomerate, siltstone, euxinic shale, iron formation, and limestone. (Possible time equivalent of Edmunds Lake).

Gem Lake
Subgroup

Rathall Lake Formation (6): Quartz-
volcaniclastics (Weber 1971- 1 and 2)

300 m

Subgraywacke, arkose, minor shale (fragments like pebbles in conglomerate). Feldspathic graywacke. Volcanic boulder conglomerate (largely felsic, minor mafic volcanic pebbles).

Bidou Lake
Subgroup (5)

Proximal, transitional, and distal
turbidites.

The Narrows Formation

Minor sandstone accompanies volcanics.

Stormy Lake Formation

Feldspathic graywacke, chert, arkose,
and iron formation.

300 m

Gunmar Formation

Thin horizons of chert locally inter-
layered in basalt.

Dove Lake Formation

Lower graywackes, chert, and siltstone:
upper agglomerate and conglomerate.

300 m

Tinney Lake Formation

Thin beds of chert and siltstone in
basalts

Stovel Lake Formation

Feldspathic graywacke, thin chert, and
siltstone.

300 m

These Bidou Lake, synvolcanic sediments were deposited in a rapidly
subsiding basin (Campbell 1971).

The sequence from turbidites to deltaic deposits accords with typical
Archean sequence noted in the preponderance of areas covered in the present
study.

Plutonism (Fig. 19)

The relationship of plutonism to deformation is:-

- D₃ or later Quartz monzonite (15), Lac du Bonnet. Accompanied by dykes and pegmatites. (McRitchie, Weber, and Scoates 1971).
- D₃ Rice Lake-Lake Winnipeg, serpentine belt (tectonically re-emplaced?) (McRitchie, Weber, and Scoates 1971).
- Late-syn-D₂ Turtle-Tooth Lakes phacolithic and dome-shaped stocks (14). Mezozonal quartz monzonites and granodiorites, epizonal quartz monzonites, granodiorites, syenodiorite, gabbro, and quartz diorite. Pink pegmatite. White pegmatite intrudes and is folded by D₂ and is related to Tooth Lake quartz monzonite. Contact metasomatism at Caribou Lake stock encloses paragneiss rafts, containing S₂ foliation (McRitchie 1971-1, p. 28).
- D₂ Beresford Lake, Wallace Lake, and Garner Lake ultramafic bodies. Garner Lake layered body (13) appears to cut structure of Wanipigow River Suite (Weber 1971-1 p. 93) though Scoates (1971 p. 192) disagrees. Certainly post D₁: layering discordant to Edmunds Lake beds.
- D₂ Wanipigow River quartz diorite (12) emplaced synchronously with intense folding of greenstones (McRitchie 1971-1 p. 121).
- D₂ Leucogranodiorite-quartz diorite stock-like bodies (12) on flanks of Manigotagan gneiss belt. Mega-boudins formed during D₂ (McRitchie 1971-1 p. 24 - 25).
- Post-D₁,
-pre-D₂ Black River metasomatic and anatectic suite (10). Includes Black Lake inequigranular biotite quartz monzonite, equigranular biotite quartz monzonite, quartz monzonite sills, and layered and relatively unfoliated hornblende and biotite granodiorite (McRitchie 1971-1 p. 22, McRitchie, Weber, and Scoates 1971).
- Post-D₁,
-pre-D₂ Ross River and Great Falls quartz diorites (9) (McRitchie, Weber, and Scoates 1971). Ross River pluton is oval, has vertical edges; contact metamorphic garnet porphyroblasts. Great Falls series of large oval, homogeneous batholiths; sharp transgressive contacts: xenoliths incorporated without assimilation: conformable dyke-like offshoots: contact metamorphic garnet and biotite (Paulus and Turnock 1971).

D₁ . . . Quartz dioritic + granodioritic gneissic suite; generation of trondhjemitic magma at depth (McRitchie, Weber, and Scoates 1971).

The evidence for the positions allocated by McRitchie, Weber, and Scoates is not known for the gneisses accompanying D₁, and Nos. 9, 10, and 15. Complexity is imposed on the basic system: diapir (9), anatectic suite (10), discordant suite (14, 15).

Deformation and Metamorphism (McRitchie and Weber 1971)

<u>Def.</u>	<u>Met.</u>	<u>Fabric</u>
D ₆	S ₆	Late stage fracturing and linear formation of zones of micro-brecciated mylonite and ultramylonite, with associated oxidation. No recrystallization of silicates.
	M ₅	Late growth of chlorite, carbonate, and epidote sub-parallel to D ₅ axial planes.
D ₅	S ₅	Regional Z-warping with Z and S kinks developed in association with N-S and NE-SW fractures.
	M ₄	Largely retrogressive muscovite and chlorite recrystallization restricted to shear zones.
D ₄ D _{3A}	S ₄	Development of sinusoidal, schistose, sheared zones, parallel to a combination of the earlier axial planes and short fold limbs; formation of mylonites.
	M ₃	S ₃ Overprinting of S ₂ foliation by muscovite porphyroblasts parallel to D ₃ axial planes.
D ₃		Local large scale concentric S-folding and development of incipient strain-slip cleavage.
	M ₂	S ₂ Matrix coarsening phase. Development of main penetrative axial planar schistosity consisting of epitaxial biotite and muscovite, parallel to D ₂ axial planes. Weak secondary regional zonation, imposed upon M ₁ with slight extension of chlorite and biotite zones to north. In gneissic belt, local staurolite development and in higher grade regeneration of sillimanite as fibrolite.
D ₂		Regional asymmetric Z-folding and rotation of M ₁ porphyroblasts. Mainly associated with emplacement of quartz monzonite plutons.
	M _{1A}	Main regional metamorphic zonation-growth of chlorite, biotite, hornblende, almandine, andalusite, cordierite, orthoclase, and sillimanite porphyroblasts.
	M ₁	S ₁ Recrystallization and development of planar oriented fabric, now preserved as inclusion trails in M _{1A} porphyroblasts.
D ₁		Largely confined to southern region of Manigotagan gneissic belt. Major isoclinal folds, axial traces parallel to margins of gneissic belt. Minor folds only locally developed. Identified in thin section as the development of a planar S ₁ fabric.
	S ₀	Original sedimentary fabric.

Ore Deposition

Syn-tectonic

Gold

D₃ et seq?

Gold quartz veins. Gold separated from pyrite host and deposited as free gold, in places with tellurides. Several phases. (Stephenson 1971, Amukun and Turnock 1971, McRitchie, Weber, and Scoates 1971).

D₂?

Gold pyrite (Stephenson 1971).

Stephenson considers that the gold originated in the various volcanic hosts of volcanic cycles 1 and 2.

Ore Production

- 98 -

Gold

	<u>Prod. Period</u>	<u>Ozs. Produced (approx.)</u>	<u>Ref.</u>
San Antonio-Forty Four	1963 - 68	1,200,000	1
Central Manitoba	1927 - 37	160,000	1
Gunnar	1936 - 42	100,000	1
Ogama-Rockland	1942 - 43, 48 - 51	50,000	1
Jeep	1948 - 50	11,000	1
Diana	1931 - 35	6,000	1
Oro Grande - Solo	1938 - 39	200	1

Reference

1. Stephenson 1971

ABITIBI BELT

1. Timmins
2. Kirkland Lake
3. Noranda
4. Chibougamau



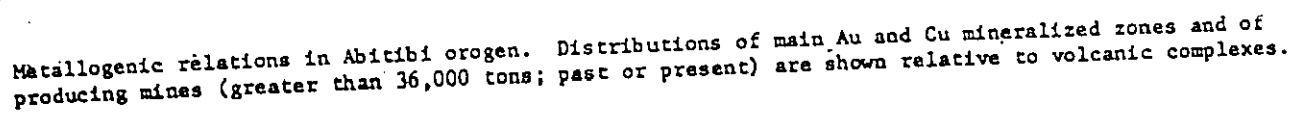


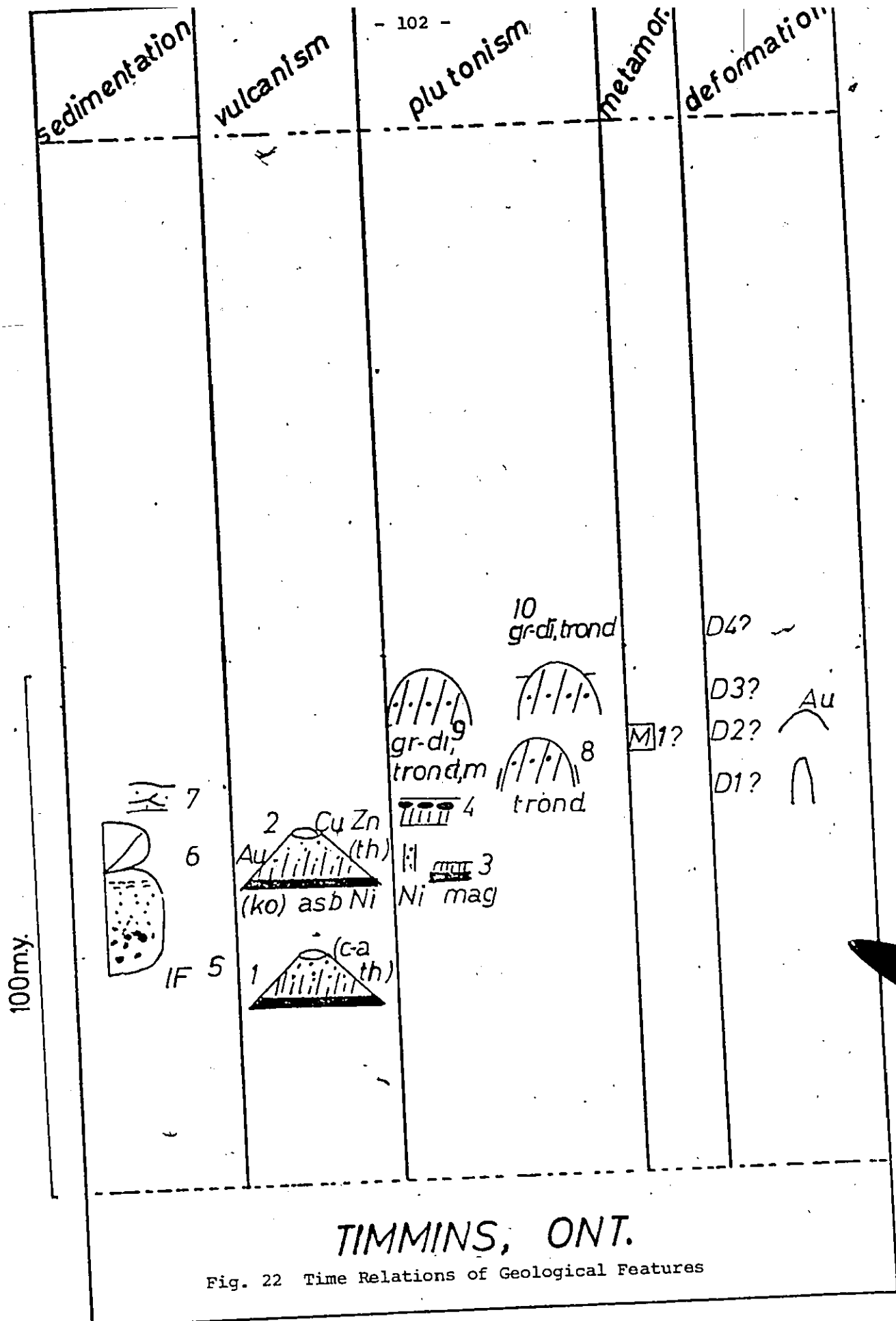
Fig. 21 from Goodwin and Ridler 1970

- 101 -



TIMMINS, ONTARIO





Vulcanism (after Pyke 1975) (Figs. 22, 23, 24)

Upper Diverse Unit?

Cycle 2 (2) Tisdale Group

Krist Formation

Felsic volcanics, largely breccia and tuff breccia.

Schumacher Formation

High Fe tholeiitic basalts, commonly pillowed, locally variolitic. Local interlayered ultramafic volcanics.

Goose Lake Formation

Ultramafic volcanics and high Mg basalts.

Middle Mafic and Middle Felsic Units?

Cycle 1 (1) Deloro Group

Boomerang Formation

Intermediate to felsic volcanics, largely tuff, less tuff-breccia. Interlayered sulphide and oxide iron formation.

Redstone Formation

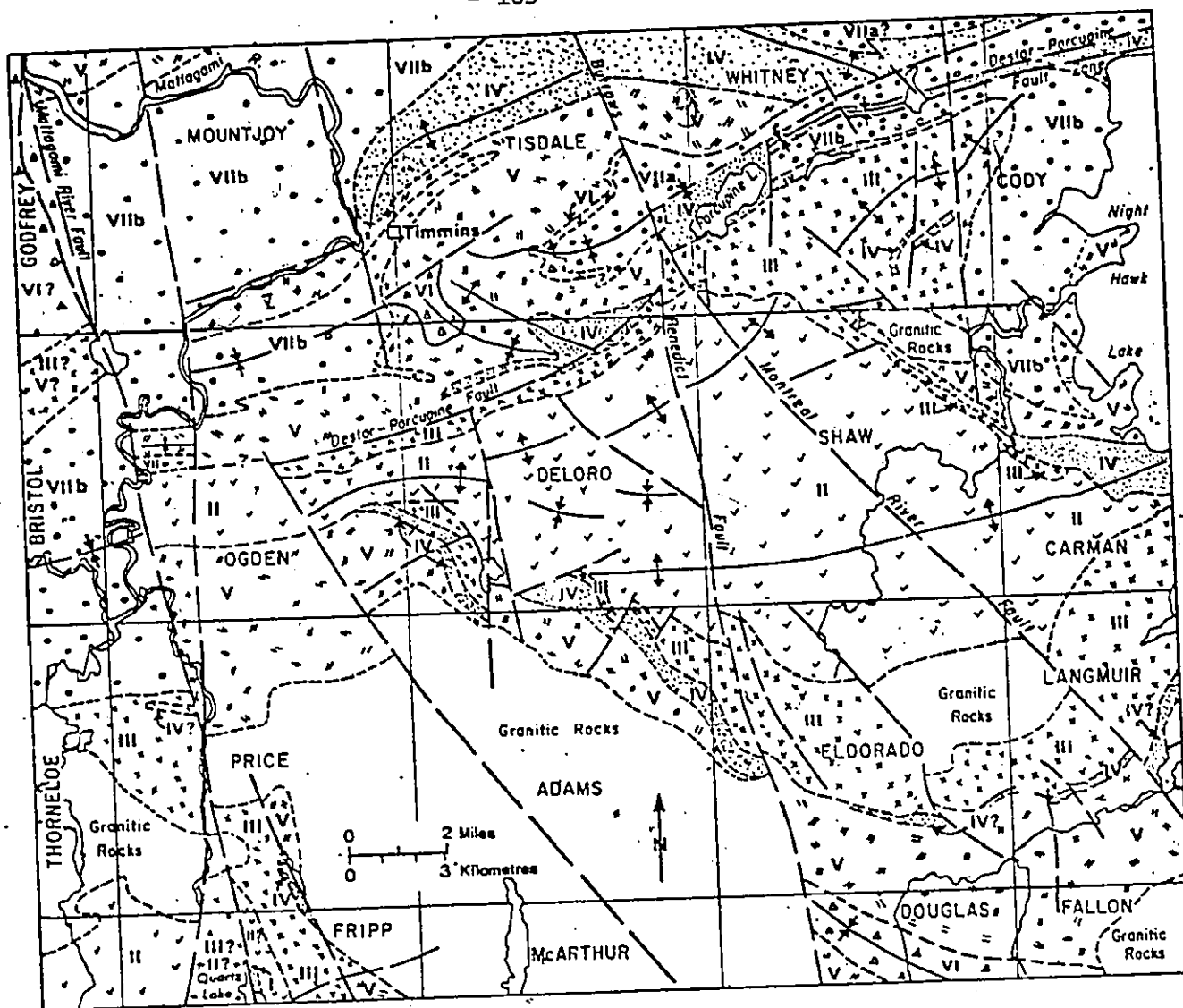
Mafic volcanics, mainly calc-alkaline andesite and basalt, less tholeiitic basalt. Pillow breccia and intercalated tuff and lapilli-tuff.

Donut Lake Formation

Ultramafic volcanics

Large sills of medium-to coarse-grained dunite and peridotite (3) were emplaced in the upper part of Cycle 1 (Deloro Group) and are probably the equivalent of basal Cycle 2 ultramafic volcanics. Differentiation produced a narrow zone of pyroxenite and gabbro along the roof of some sills. The Kamiskotia Complex (4) is a layered norite-gabbro and anorthositic gabbro and may be compared to the Dore Lake complex at Chibougamau. It, too, may be late- or post-volcanic. Many small quartz-feldspar porphyry intrusions are probably sub-volcanic. Both cycles are major, in the terminology of Anhaeusser (1971-1).

The correlation with Wilson's (1974) model is based on his identification of the hosts to nickel ore as Upper Diverse, and the model relationships of layered (anorthositic) sills and copper-zinc ore to Upper Diverse.



LEGEND

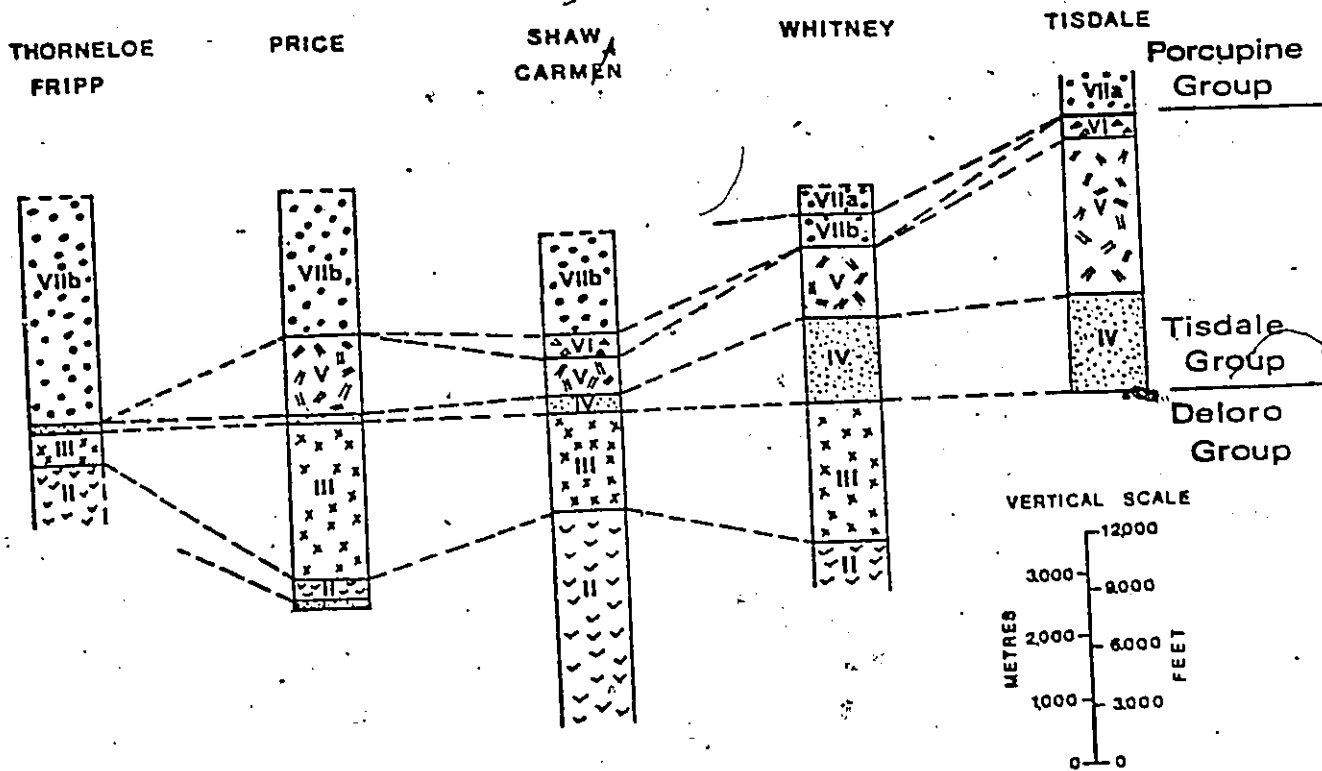
- VII Porcupine Group
 - a Upper Formations
 - b Lower Formations
- VI Tisdale Group
- Krist Formation
- V Schumacher Formation

- IV Goose Lake Formation
- Deloro Group
- III Boomerang Formation
- II Redstone Formation
- I Donut Lake Formation

SYMBOLS

- Geological boundary
- Fault
- Anticlinal axis
- Synclinal axis

Tentative distribution of stratigraphic units in the Timmins area



Stratigraphic columns for the Timmins area illustrating generalized correlations for the various stratigraphic units (numerals refer to same formations as in Figure 23) from Pyke, 1975

Sedimentation (Figs. 22, 23, 24)

Timiskaming Group (Bright in Pye et al. 1972)

450 m

Conglomerate, graywackes, quartzites,
and argillites (7) (fluviatile sediments -
Pyke 1975 after Lorsong 1975).

Hoyle Group (Bright in Pye et al. 1972)

900 m

Graywacke, siltstone, and lesser conglomerate (6)
turbidite sequence; lower part, time equivalent
to the Tisdale and upper Deloro volcanics (Pyke
1975 after Lorsong 1975).

Deloro Group (Pyke 1975)

Boomerang Formation

Largely tuff, intermediate to felsic, inter-
layered sulphide and oxide iron formation (5).

Redstone Formation

Tuff and lapilli tuff intercalated in volcanics.

The sedimentary sequence, turbidity to fluviatile, entirely pre-
tectonic, is the common one in Archean ore-fields studied.

Plutonism

- D₃? Unmetamorphosed Late Felsic Intrusive Rocks:
Granodiorite-trondhjemite (10) with migmatite and
agmatite (Middleton 1973).
- D₃? Ovoid stocks of biotite-hornblende trondhjemite (Eldorado
Twp.), porphyritic granodiorite (Adams and Price Twps.),
and monzonite (9) (Fallon Twp.) (Pyke 1975).
- D₂? Early Felsic Intrusive Rocks:
Foliated trondhjemite (8) (mainly along contact between
Kamiskotia Complex and volcanics) (Middleton 1973)
- Basement? Complex batholith extending far to N and S in west
part of Timmins area. At base of Cycle 1 in Peterlong
area. (Pyke, Ayres, and Innes 1972).

The notation of migmatite and agmatite as Late Felsic Intrusive is unlike that of such suites in the better studied Archean areas, where D₂ is the usual position. If the ovoid stocks do in fact precede the migmatite, they are probably early D₂, if later than the migmatite, probably D₃ or later. On the chart (Fig. 22) the sequence is according to Middleton.

Deformation

No studies of the succession of deformation have been undertaken in the Timmins area and in their absence it is hazardous to attempt the integration into the present study of the abundant data on faults and folds exemplified in the C.I.M. volume "Structural Geology of Canadian ore deposits" 1948. From Pyke (1975 Figs. 4 and 5) one may conjecture:

D_2 or D_3 ? Subvertical open folding

D_1 or D_2 ? Isoclinal folding

Metamorphism

No systematic study of metamorphism of the Timmins area is known. Middleton (1973) records greenschist facies in the Robb-Jamieson area, as do Walker, Matulich, et al. (1975) at the Kidd Creek mine. This is probably related to the D_2 ? plutons.

Ore Deposition (Fig. 21)

Pre-tectonic

Magnesite and Asbestos

Magnesite production is from an ultramafic sill which intrudes the felsic, upper part of Cycle 1 volcanics of the Shaw dome. Most asbestos has been produced from the komatiitic ultramafic volcanics east of the Timmins area at Matheson.

Nickel

Komatiitic flows of basal Cycle 2 host syngenetic ore at the Texmont deposit south of Timmins and probably have the same setting at the Alexo east of Timmins. On the Shaw dome, the equivalent sills host the INCO-Noranda deposit. Wilson (1974-3) interprets the host as the Upper Diverse Unit.

Copper-Zinc

Almost all, if not all the copper-zinc deposits of Superior Province belong to the class characterized as stratiform, massive, base-metal sulphides, and Wilson (1974-3) notes the preferential ore deposition in the Upper Diverse Group rather than the Middle Felsic Group (i.e., Cycle 2 ore-bearing, Cycle 1 barren). The Cycle 2 position appears to be valid for the deposits on the east flank of the Kamiskotia Complex, but the structural complexity and little outcrop of the Kidd Creek area have inhibited correlation of this dominant ore zone (Walker, Matulich, et al. 1975). These authors synthesize the data from the Kidd Creek mine, saying the deposit lies concordantly within a steeply-dipping, overturned,

rhyolitic, volcanoclastic pile overlain by younger, mafic, barren, volcanic rocks, and the rocks of the area are complexly folded and faulted and metamorphosed to greenschist grade.

Syn-tectonic

Gold

In the west part of the camp, most of the gold deposits are within Cycle 2 (Tisdale) volcanics, related to porphyry stocks which Bright (in Pye et al. 1972) says may be the equivalent of the Krist volcanic tuff. In this description he appears to include the Pearl Lake porphyry which also carries copper, described by Bright and others as porphyry-type. Pyke (1975) also notes the spatial relationship of ultramafics and gold. Ridler (1976-2) agrees with Pyke that the ultramafic volcanics could provide a source bed. Pyke, however, sees a need for the ultramafics to be particularly rich in gold, which does not appear to be necessary (Ridler 1976-2).

In the eastern part of the camp, ultramafics are present but porphyries are not, and closely spaced en echelon quartz veins indicate that here structure rather than lithology provided a host for gold deposition. Also in the eastern part of the camp, as Allerston (oral comm. 1974) notes, carbonaceous horizons are closely associated with gold and may have provided a secondary source which in origin compares to the Carbon Leader on the Rand. For the Carbon Leader, Plumstead (1969) invokes biogenic activity to capture gold released from older volcanics. In both parts of the Timmins camp one may invoke a primary exhalite source of gold, associated with the related extrusion of ultramafics and exhalite iron (Ridler 1976-2).

Copper

The Pearl Lake porphyry was noted under gold, for which it has been mined since 1912. Copper has been produced since 1963, 8 million tons remaining with a cut-off grade of 0.7 percent at the time of Bright's report (in Pye et al. 1972).

Ore Production

Base Metal

	<u>Prod. Period to 1974</u>	<u>Prod. Tons Ore</u>	<u>Ref.</u>
Kidd Creek	1966 - 74	28,604,836	1
Can. Jamieson	1966 - 71	639,000	1
Jameland	1969 - 72	509,356	1
Kam-Kotia	1943 - 72	6,606,140	1
Noranda-INCO	1975 - 74	288,450	2

	<u>Prod. Period to 1968</u>	<u>Prod. Tons Ore</u>	<u>Ref.</u>
Genex	1966 - 68		3
McIntyre Porcupine	1963 - 68	6,449,618	3
Munro Copper	1966 - 68		3
Alexo	1912 - 44	538,046	3

Asbestos

	<u>Prod. Period to 1965</u>	<u>Prod. Tons Ore</u>	<u>Ref.</u>
Munro	1950 - 64	57,304,074	3
Reeves			

Gold

	<u>Prod. Period to 1965</u>	<u>Prod. Tons Ore</u>	<u>Ref.</u>
Aunor	1940	62,173,234	3
Dome	1910	264,264,345	3
Hallnor	1938	48,225,189	3
Hollinger	1910	553,910,754	3
McIntyre Porcupine	1912	305,902,365	3
Pamour Porcupine	1936	60,905,568	3
Preston	1938	54,427,248	3
Ross	1936	20,519,169	3
Banner Porcupine	1927 - 35	14,840	3
Broulan Reef	1938 - 65	31,285,877	3
Buffalo Ankerite	1926 - 56	35,483,898	3
Cons. Gillies Lake	1929 - 37	462,482	3
Davidson Tisdale	1918 - 20	53,914	3
Delnite	1937 - 64	33,052,567	3
Gold City Porcupine	1937 - 44	50,100	3
Highmont	1947 - 47	1,862	3
Hollinger	1911 - 41	12,721,178	3
Hoyle	1941 - 49	2,689,438	3
Hugh-Pam	1948 - 65	4,129,947	3
Kenilworth	1932 - 64	1,933,336	3
McLaren Porcupine	1933 - 37	6,819	3
Moneta Porcupine	1938 - 43	5,589,356	3
Munro Croesus	1915 - 48	326,894	3
Nakhodas	1940 - 44	1,106,084	3
New Hope	1926 - 42	1,366,707	3
Porcupine Paymaster	1922 - 66	41,607,895	3
Westfield Minerals	1913 - 61	37,396,410	3
Miscellaneous		637,715	3

References

1. Geol. Surv. Canada, R. Thorpe, pers. comm. June 1976.
2. Canadian Mines Handbook 1975 - 76.
3. Pye et al. 1972.

The Timmins area was second only to the Witwatersrand as a gold producer. From first production in 1910 until the end of 1969 over 52 million ounces were produced (Lovell p. 5 in Pye et al. 1972) compared to over 1 billion ounces up to the end of 1973 from Witwatersrand (Pretorius 1976).

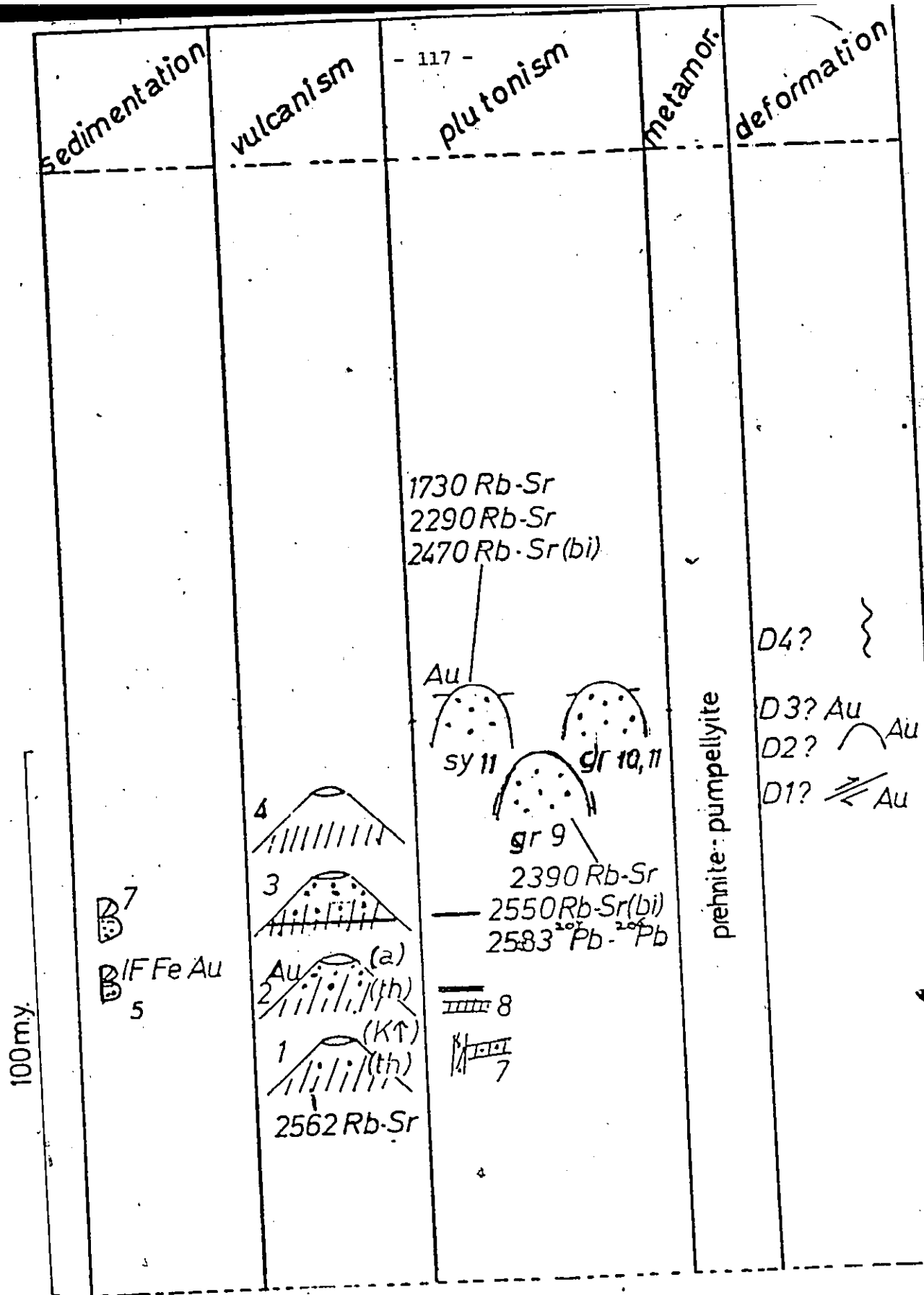
Kidd Creek is the largest volcanogenic base metal deposit known.

The Mining Magazine classification of ore produced in 1974 is:

Aunor	E	Au
Dome	C	Au
Pamour	C	Au
Ross	E	Au
Schumacher	C	Cu, Au
Kidd Creek	A	Zn, Ag, Cu, Pb
Langmuir	E	Ni, Cu
Reeves	B	Asbestos

- 116 -

KIRKLAND LAKE, ONTARIO



KIRKLAND LAKE, ONT.

Fig. 25 Time Relations of Geological Features

Vulcanism (after Ridler 1970, 1971, 1976-1) (Figs. 21, 26, 27)

Middle Mafic and Middle Felsic Units?

Cycle 4: (4) Un-named unit E

Pillowed and massive lavas

Cycle 3 (3) Un-named Unit D

3000 m +

Intermediate to felsic, micro-porphyritic, unbedded breccia and massive crystal tuff. Proximal assemblage grades E to felsic fragmentals, carbonate rich chloritic tuffs, and immature sediments, then to distal turbidites.

Highway 11 basalts

0 - 1500 m +

Andesite

Basalts with macro-variolitic member

Tholeiitic basalts and ultramafic flows and intrusives.

Cycle 2 (2) Timiskaming

300 - 3000 m

Dominantly sedimentary. Commonly the volcanics are pyroclastics but flows are known. Igneous rocks locally constitute more than half the section as in the Kirkland Lake trachyte-syenite complex.

McVittie basalts

0 - 10000 m

Compositionally heterogeneous (andesites, tholeiites-alkali basalts, feldspathoidal basalts) pillow lavas, flow breccias, and associated gabbroic phases. Gabbroic and ultramafic sills at all levels.

Cycle 1 (1) Skead (McElroy) pyroclastics

0 - 7000 m

Andesite and dacite breccias, tuffs, and hypabyssal equivalents, minor trachyte. K-enrichment.

Catherine (Boston) basalts

2000 - 9000 m

Pillow lavas and banded tuffs, quartz gabbro phases. Tholeiitic, K-deficient.

Pacaud tuffs

300 - 1500 m

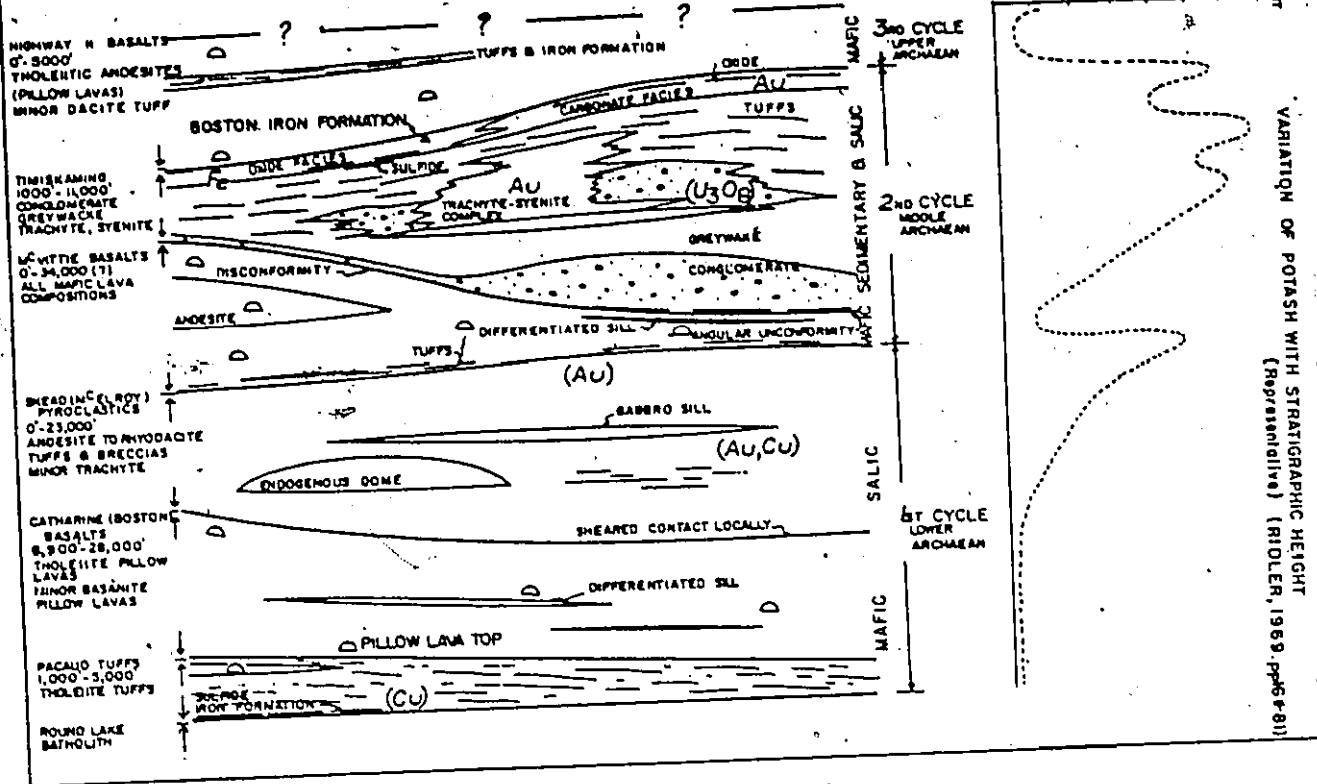
Tholeiitic, similar composition to Catherine basalts.

This correlation as Middle Mafic and Middle Felsic is not in accord with Ridler (1971) (Fig. 28), if the Cu-Zn bearing Noranda complex is Upper Diverse.

The number of cycles compares with that of the Greenstone Group (Anhaeusser 1971-2) contrasting with Wilson's (1974) model Middle Mafic and Middle Felsic.

IDEALIZED STRATIGRAPHIC SYNTHESIS OF THE KIRKLAND LAKE AREA WITH FOLDING REMOVED

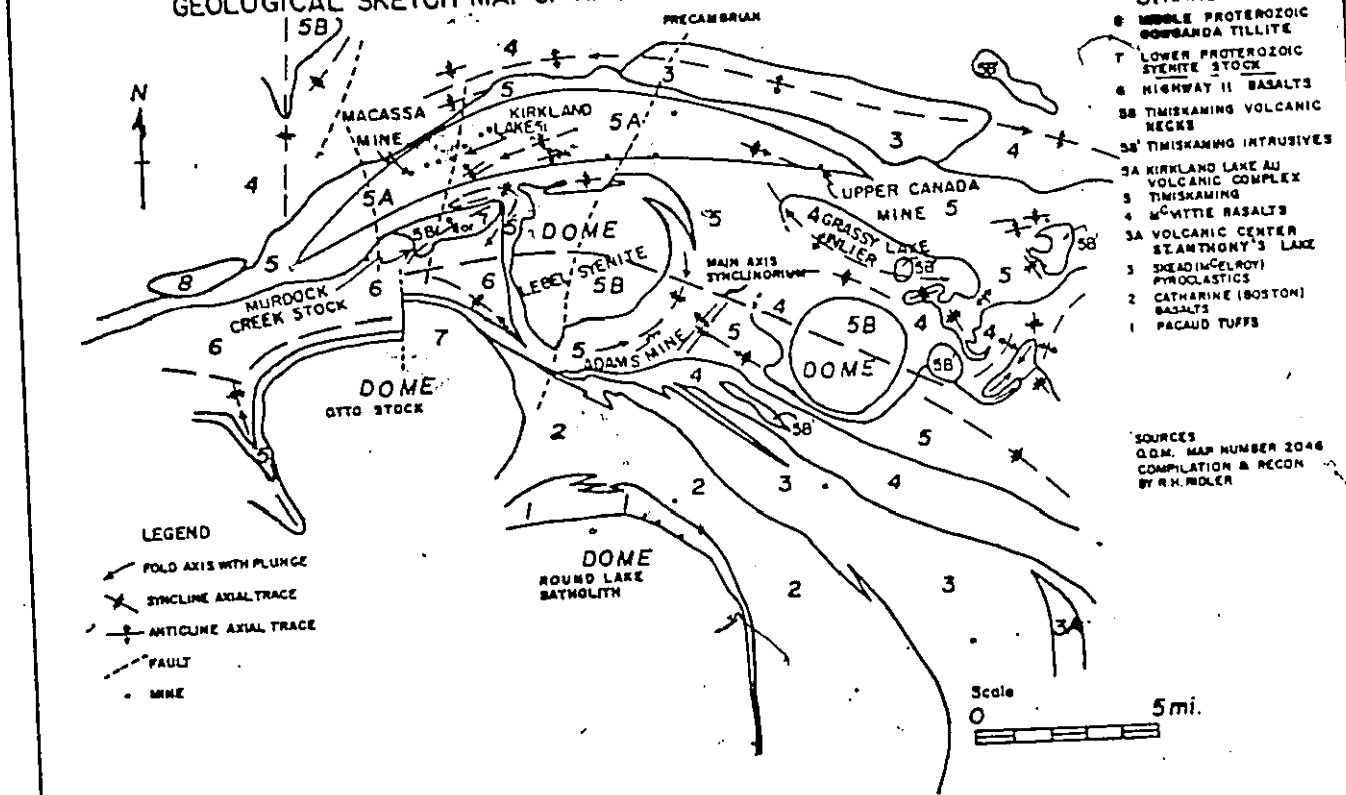
FIG. 26



Figures 26 and 27 from Ridler 1970

GEOLOGICAL SKETCH MAP OF KIRKLAND LAKE AREA

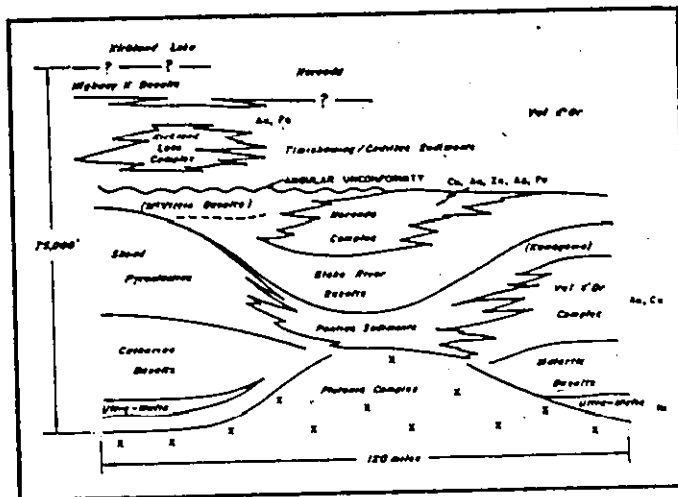
FIG. 27



- STRATIGRAPHY**
- 8 MIDDLE PROTEROZOIC GORDANA TILLITE
 - 7 LOWER PROTEROZOIC STENITE STOCK
 - 6 HIGHWAY II BASALTS
 - 5B TIMISKAMING VOLCANIC NECKS
 - 5A TIMISKAMING INTRUSIVES
 - 4 KIRKLAND LAKE VOLCANIC COMPLEX
 - 3 TIMISKAMING
 - 2 MCVITTIE BASALTS
 - 1 VOLCANIC CENTER STANTHONY'S LAKE
 - 0 SHEAR (MC ELROY) PYROCLASTICS
 - 2 CATHARINE (BOSTON) BASALTS
 - 1 PACAUD TUFFS

SOURCES
 G.D.M. MAP NUMBER 2048
 COMPILATION & RECON
 BY R.H. RIDLER

Fig. 28
From Ridler 1971



Generalized stratigraphy at the south margin
of the Abitibi Basin

Sedimentation (after Ridler 1970, 1971, 1976-1) (Figs. 26, 27, 28)

Cycle 3 (upper) (6) Unit D

Heterogeneous zone of felsic fragmentals, carbonate-rich chloritic tuffs and immature sediments, the gradational group between proximal volcanics and distal turbidites.

Cycle 2 (5) Timiskaming

Iron formation.

Quiescent volcanogenic sedimentation.

Volcanogenic sedimentation accompanying the alkaline vulcanism.

Coarse sedimentation.

Cycle 1 (1) Skead pyroclastics

Skead pyroclastics - tuffs.

Catherine basalts - banded tuffs.

Pacaud tuffs.

The pattern of sedimentation brings in the factor of proximal and distal turbidites, not commonly recorded in the areas studied.

Plutonism (Figs. 27, 29)

Late D₃ or D₄?

Otto and Lebel syenite stocks (12) (Goodwin et al. 1972). The Otto stock is a diapiric alkaline intrusive complex exhibiting zoning including nepheline syenite and radioactive border phases. It has a pronounced contact aureole. The Lebel stock occupies the centre of a trachytic volcanic domical complex for which it may have been the feeder, consolidating later. It has a gneissic margin, mylonitic girdle, thin metamorphic aureole, and is locally slightly discordant.

D₃?

Post-tectonic Crooked Creek granite stock (11) cuts Round Lake batholith (Ridler 1976-1) (Offshoot of RLB core?).

Round Lake batholith (Ridler 1976-1):

D₃?

3 Cannibalistic core of massive granite (10) intruded post-strain.

D₂?

2 Marginal zone of compositionally layered, mylonitized, and isoclinally folded gray gneiss (9).

Basement?

1 Interior annulus of homogeneous granodiorite gneiss, faint gneissosity trends E-W.

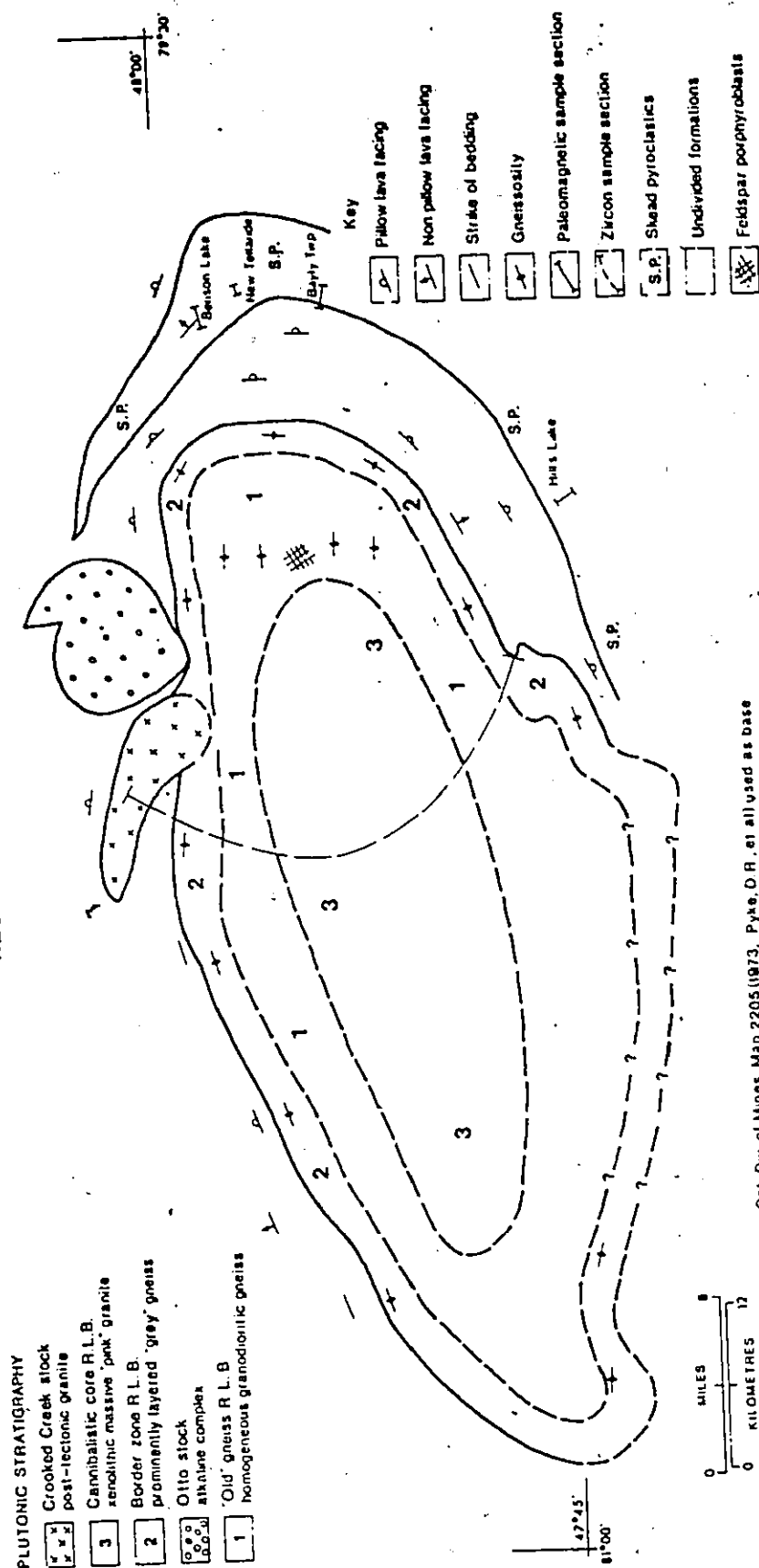
The reworking of basement gneisses, a little-demonstrated phenomenon in the areas studied, is a matter of increasing interest at Kirkland Lake and elsewhere. Comparison with Stowe's model from Rhodesia is merited (Fig. 64). The Round Lake batholith and Chibougamau pluton, both in the Abitibi Belt, particularly merit comparison with the Rhodesdale batholith of the Midlands Belt, Rhodesia, which bears many similarities to the Ancient Tonalites of Barberton.

The early (9) and late (10, 11, 12) members of the characteristic Archean suite are therefore present, but the syn-tectonic migmatite member is not noted.

Fig. 29 from Ridler 1976-1

ROUND LAKE BATHOLITH

RECONNAISSANCE MODEL



Deformation

No structural mapping has been undertaken in the Ontario sector of the Abitibi Belt. The following suggestions are advanced here:

- D₄? Faulting.
- D₃ ?
- D₂? Axial plunges and bedding planes became vertical to subvertical. Rising stocks acted as buttresses (Ridler in Goodwin et al. 1972-1). Development of synclinorium.
- D₁? Development of mylonite bordering Round Lake batholith. (Ridler 1976-1). Pre-ore displacement on the Kirkland Lake fault system... a vertical thrust of about 1,500 feet on the main Kirkland Lake fault. Approximately the same amount of displacement occurs in the structure on the western part of the No. 2 vein at the Lake Shore mine (Thomson in Thomson et al. 1948).

Metamorphism

The metamorphism at Kirkland Lake is the lowest grade described in the present synthesis. The first metamorphism, on burial, caused development of prehnite-pumpellyite assemblages, regional in scope. Later, several intrusive episodes produced localized aureoles of albite-epidote-actinolite hornfels and hornblende hornfels facies. The greenschist facies of regional metamorphism is absent. (Jolly 1974).

The absence of higher grades of regional metamorphism is presumably related to the absence of the syn-tectonic migmatitic plutonic member.

Ore Deposition (Fig. 21)

Pre-tectonic

Iron

The only economically significant iron formation at Kirkland Lake is the Boston iron formation, which Ridler (1970) considers to be the closing quiescent phase of Timiskaming volcanogenic sedimentation.

Magnetite and chert predominate at the oxide facies, and locally jasper, specular hematite, chlorite, and pyrite are abundant. Trachytic tuffs and trachybasalts are contemporaneous.

The carbonate facies is argillaceous or siliceous ferrodolomite, associated with carbonate-rich shale, graywacke, tuff, and black chert.

Syn-tectonic

Gold

A detailed description of faults, by Thomson, and of ore paragenesis, by Hawley (both in Thomson et al 1948) may be related to the unmapped deformational history:

8. Post-ore faults. Transverse or cross faults, generally clean cut, gouge-filled, single or multiple slips; they frequently contain fault breccia and occasionally show stringers of late quartz and calcite.
7. Post-ore strike faults, more or less parallel to the productive veins. They generally have a flatter dip than the veins or vein faults. They exhibit shearing, wall-rock alteration, and even traces of mineralization, barren quartz and calcite and occasionally barite and gypsum.

6. Main deposition of sulphides, later tellurides, and gold.
5. Minor and local introduction of calcite.
4. Main introduction of quartz.
3. Pyritization of wall-rocks.
2. More extensive alteration of wall-rocks.
1. Pre-ore thrusting on Kirkland Lake fault system.

The gold is invariably seen along fractures in the quartz, although it also occurs in the secondary minerals, in pyrite and in tellurides. The alteration of the country rock adjacent to veins and breaks is a prominent feature of the Kirkland Lake camp. The zone of alteration, unless accompanied by vein quartz, never carries sufficient gold to be classified as ore (Thomson in Thomson et al. 1948).

Ridler (1970) groups the gold deposits into three types:

3. Laterally extensive gold-quartz veins associated with syenite complexes (the Main break of Kirkland Lake).
2. Gold-quartz vein stockwork in carbonate bodies (Kerr-Addison).
1. Gold associated with pyrite and arsenopyrite in what may be altered volcanics (Omega Mine).

At Kirkland Lake there is gold in all types of rock but 85% of the ore is in syenitic stocks, trachytic tuffs, and flows (Cycle 2). Lake Shore and Wright-Hargreaves are 2493 m deep, but the ore does not appear to bottom out within several hundred m below: much high grade cannot be mined because the great depth of gold-bearing material was not envisaged during early planning (Lovell in Pye et al. 1972).

The ore in the syenite may well compare closely with gold ore associated with well preserved Tertiary volcanic centres, as Stanton (1972 p. 598) suggests, and it may be unnecessary to invoke subsequent remobilization. Nevertheless, heat was available on the intrusion, at a late stage, of the Lebel stock, and I suggest some remobilization is probable.

The carbonate host: Ridler proposes that the carbonate ore bodies of Larder Lake are auriferous carbonate facies iron formation, probably correlative with the Boston iron formation. The siliceous pyritic carbonate horizon is folded conformably with the sediments and volcanics in which it lies and locally displays sedimentary banding. He suggests that the carbonate zone formed first as an exhalative volcanic sediment, similar to those of the Helen Range of the Michipicoten area (Goodwin 1962, 1964) but low in iron, rich in gold. During metamorphism, deformation, and relaxation, carbonate recrystallized and silica and gold segregated into dilational networks. Some unveined cherty auriferous carbonate survives.

The volcanic (?) host: Ridler proposes that flow or dacite ore of Larder Lake may be lean, sulphide facies, tuffaceous, iron formation. The deposits have sedimentary geometry but compared to the carbonate ores have significant plagioclase and much more pyrite and arsenopyrite. Locally it is coarse volcanic breccia with pods of pyrite, pyrrhotite, and chalcopyrite, so comparable to the Noranda sulphide deposits.

Ridler leads in the field of exhalite studies, and because his work has widespread acceptance (e.g., Sawkins and Rye 1974, for gold deposition at Homestake), his most recent work (Ridler 1976-2) merits amplification. He notes the long-standing controversy over what he terms gold-rich carbonate exhalites earlier workers calling the rock dolomite,

believing it to be sedimentary, later workers suggesting that the rock represented epigenetic replacement within a major fault zone, the Larder Lake Break. He does not, however, say where he stands on the controversy. I suggest that in considering the carbonate an exhalite (capable of replacing practically any rock, intrusive or flow, rhyolite to basalt to ultramafic, fragmental to pillowed, as he has observed) in so doing he documents evidence of a fault source, (a thrust, as it is described at Noranda (Dimroth, Côté, et al. 1975)).

Ore Production

Kirkland-Larder Lakes

<u>Gold</u>	<u>Prod. to 1967?</u>	<u>Million oz. Au</u>	<u>Ref.</u>
Kerr Addison		9.0	1
Upper Canada		1.5	1
Sylvanite		1.5	1
Toburn		1.0	1
Wright Hargreaves		5.0	1
Kirkland Minerals		1.5	1
Lake Shore		7.5	1
Macassa		2.0	1
Teck-Hughes		3.0	1

Reference

1. D. R. E. Whitmore in Douglas 1970

<u>Iron</u>	<u>Prod.</u>	<u>Total Crude Tonnage = Concentrate</u>	<u>Ref.</u>
Adams	1964 - 1976	100,000,000 = 30,000,000	1,2

Reference

1. Gross 1965.
2. Lovell in Pye et al. 1972.

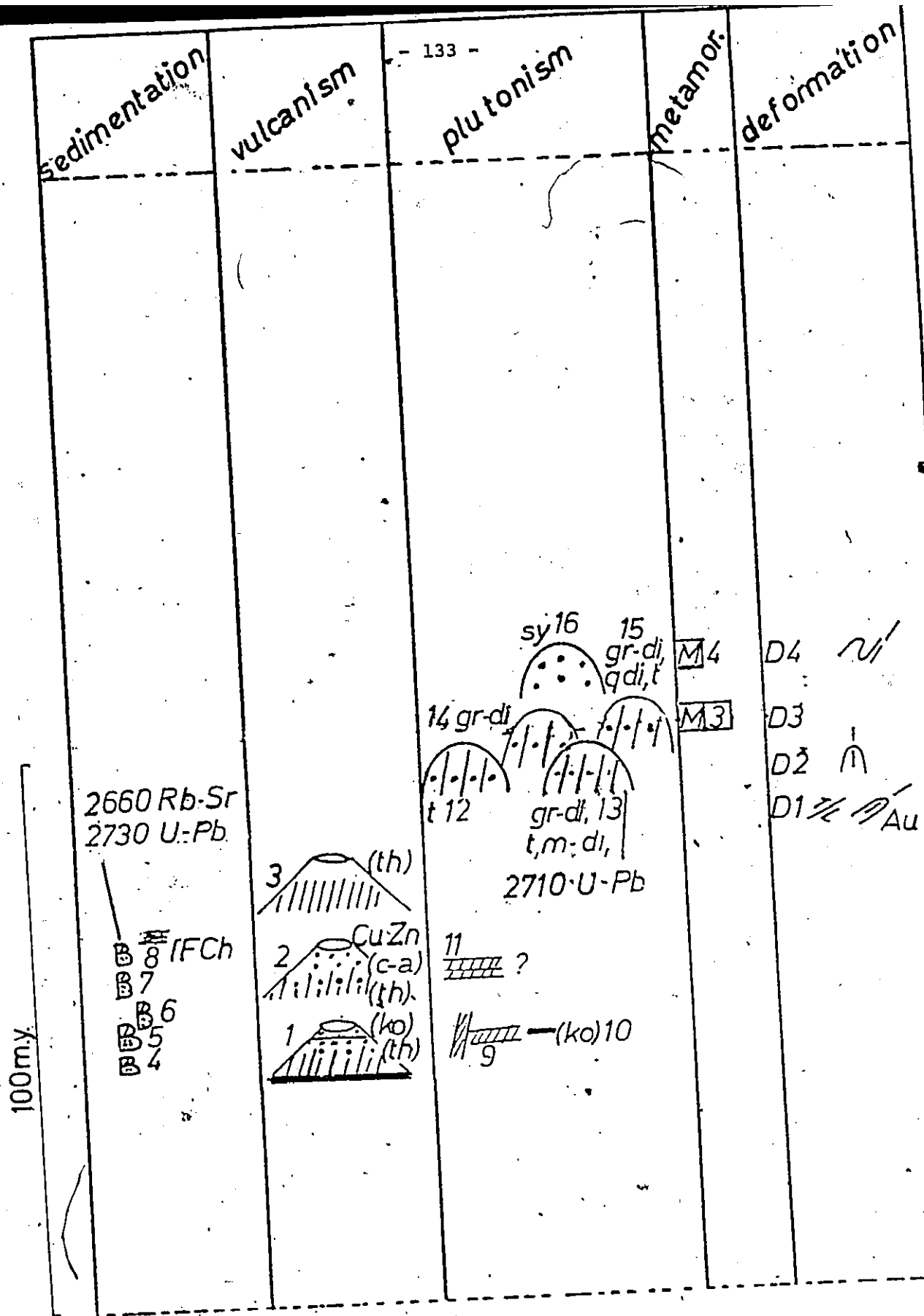
The Kirkland-Larder Lakes area has a history as one of the major gold mining camps of the world with a production until 1969 of over 33 million ounces. It was only exceeded to that date by Timmins, over 55 million ounces (Lovell in Pye et al. 1972) and the Witwatersrand, over 1 billion ounces to the end of 1973 (Pretorius 1976).

The Mining Magazine classification of ore production for 1974 is:

Kerr-Addison	C	Au
Macassa	E	Au
Adams	A	Fe

- 132 -

NORANDA, QUEBEC



NORANDA, QUE.

Fig. 30 Time Relations of Geological Features

Vulcanism (after Dimroth, Gelinas et al. 1975, cycles after Ridler, 1970, 1971, thicknesses from Goodwin et al. 1972) (Figs. 21, 31, 32)

Upper Diverse Unit?

Cycle 3 Upper part of Blake River Group (3)

Tholeiitic basalt sheets.

Cycle 2 Lower part of Blake River Group (2)

- (b) Calc-alkaline or differentiated shield volcanoes including the Noranda volcano. Basalt, andesite, dacite, and rhyolite flows and fragmentals (five main andesite-rhyolite successions (Spence and de Rosen Spence 1975) 900 - 1500 m
- (a) Tholeiitic basalt sheets with prominent variolitic marker 15000 m

Middle Felsic Unit?

Cycle 1 Kinojevis and Malartic Groups (1)

- (d) Small rhyolite domes and flows of komatiite (10) along the regional Duparquet-Destor-Manneville fault and Cadillac break (Imreh 1976).
- (c) Tholeiitic basalt-andesite-rhyolite shield volcano (the Destor volcano, shallow water basalt, subaerial rhyolite, stockwork of gabbro dykes and sills (9)).

Middle Mafic Unit?

- (b) Extensive and thick sheet of tholeiitic basalt erupted in deep water. Mg-Fe fractionation in at least two cycles.
- (a) Mafic and ultramafic units.

Notes: Cycles 1 and 2 are the equivalent of sedimentary cycles 1 and 2.

The division here of the Blake River Group into two cycles implies that the Timiskaming sediments were laid down between the two divisions and that the Upper Blake River basalts are the equivalents of the Highway 11 basalts at Kirkland Lake. The implication requires substantiation.

A layered gabbro complex east of Duparquet Lake may define a mixed centre (11).

Major and minor cycles (Anhaeusser 1971-1) are evident in the above description. The suggested correlation with the volcanic units of Wilson (1974) is highly tentative. The correlation with the Upper Diverse Unit is based on the Noranda copper-zinc ores, below which Cycle 1 can be divided into Mafic and Felsic.

LEGEND

PROTEROZOIC

16 Cobalt Group

ARCHEAN

Intrusive rocks

Pyroxenite 1)

Uncorrelated "granitic" rocks 1)

Heterogeneous granodiorite

Pyroxene monzonite

Grey tonalite-granite

Layered gabbro complex of Duparquet lake 1)

"Granitic" intrusions related to volcanic rocks

15

14

13

12

11

10

9

8

7

6

5

4

3

2

1

136

1

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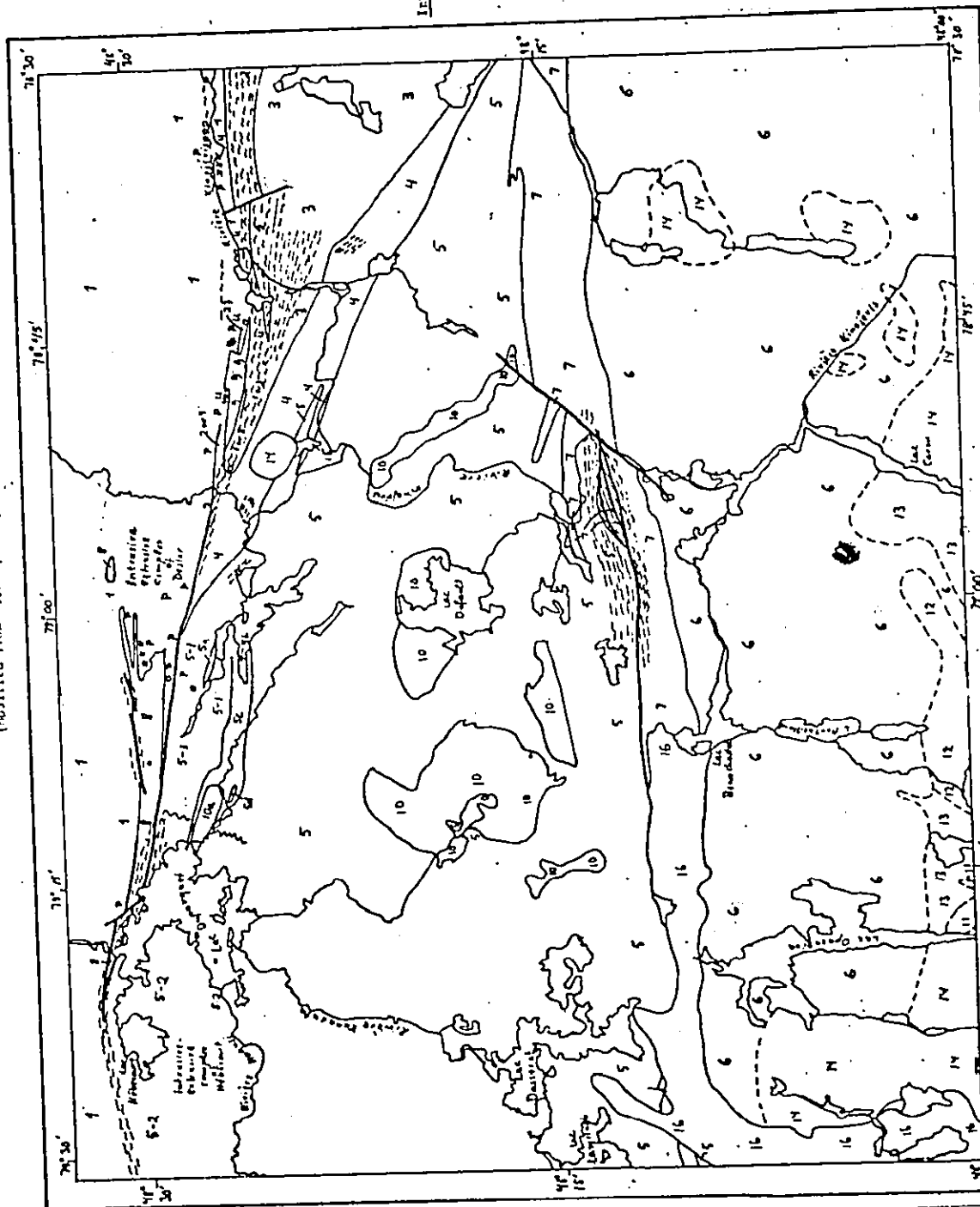
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1

1



Notes: 1) age relative to other units unknown
2) age relative to units 2-7 unknown
3) may be equivalent to unit 9
4) may be equivalent to unit 5

Top
Zone of strong schistosity.
Intense folding known or suspected
Zone of extremely strong schistosity.
Probably intense folding and faulting.
Faults, if present, poorly defined.
Carbonatization widespread.
Fault zones, probably well defined

Compilation: E. Dimroth 1973
Map scale: 1:50,000
Scale bar: 0 to 5 miles
North arrow

PUBLIC

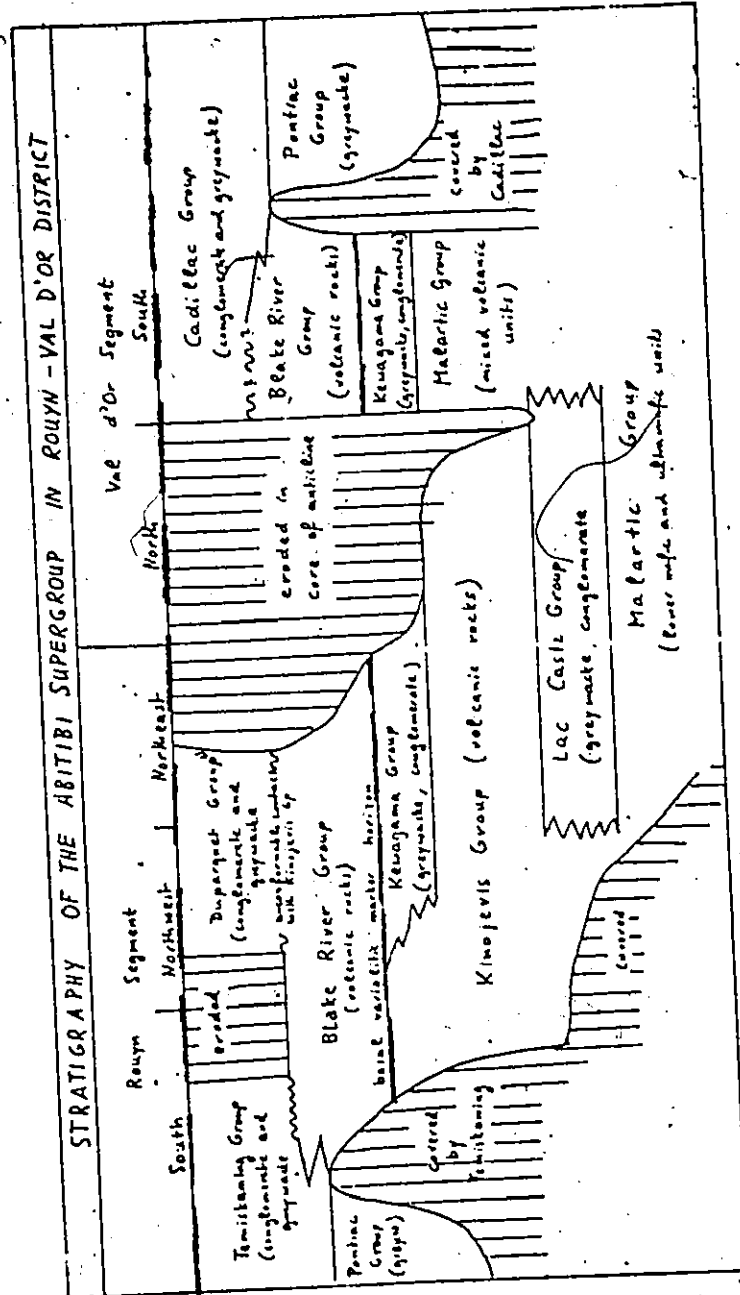


Fig 32 from Dimroth, Coté et al. 1975

Sedimentation (after Dimroth, Gelinas, et al. 1975, cycles after Ridler 1970, 1971) Figs. 31, 32]

Cycle 3 Timiskaming, Cadillac, and Duparquet groups.

(c) (8) Turbidites from a volcanic source, interdigitated, fluviatile deposits, and (Duparquet Group) piedmont fans grading into turbidites with marine pelites distal from one fan.

(b) (7) Turbidites derived from mixed volcanic and granitic terrain.

(a) Interdigitating fans derived from Blake River Group volcanic islands.

(a) and (b) may correlate with youngest Pontiac turbidites.

Cycle 2 Upper part of Pontiac Group (6)

Turbidite fan and basin fill.

Cycle 1 Lac Caste (4), Kewagama (5), and lower part of Pontiac (6) groups.

Turbidite fans include detritus from the Destor volcano.

Note: Cycles are the equivalent of volcanic cycles.

Chert and iron formation in Cycle 3 (Timiskaming) may be a continuation of the Boston iron formation of Kirkland Lake (Ridler 1970). Goodwin et al. (1972) give some thicknesses:

Cadillac (Timiskaming) Group basal conglomerate: 300 to 1650 m

Pontiac sediments: 2100 to 2400 m

The sequence, turbidites to fluviatile deposits, is typical of the Archean ore-fields studied.

Plutonism (Fig. 31)

- $D_3?$ or later Small stocks of syenite porphyry (16) intrude volcanics (van der Walle in Allard et al. 1972).
- $D_3?$ Granodiorite intrusions (15), the Flavrian Lake, Lake Dufault, and Powell stocks. There are numerous transitional facies between granophyre, granodiorite, and quartz diorite. The Lake Dufault stock is cross-cutting. The Flavrian Lake body (mainly a sodic quartz leucotonalite) is less clearly intrusive. The Powell stock, faulted on all sides, is probably an offshoot of the Flavrian stock (van der Walle in Allard et al. 1972). Hornfels around the Lake Dufault granite is described as a post-kinematic thermal metamorphic effect by Dimroth et al. (1974).
- $D_2?$ Heterogeneous granodiorite (14) fills a complex system of dykes and sills. Inclusions of Pontiac Group are generally present deep within the massifs: narrow synclinal zones with steep schistosity separate domical anticlinoria underlain by granite (Dimroth et al. 1973). Synkinematic metamorphism is related to the massifs (Dimroth et al. 1974).
- $D_2?$ Hornblende granodiorite, tonalite, and monzodiorite (13). Three homogeneous varieties; with and without feldspar phenocrysts and monzodiorite. In places in contact with Pontiac and with numerous inclusions of schist and amphibolite. Invaded by Heterogeneous Granodiorite (13) (Dimroth et al. 1974).
- $D_2?$ Gray leucocratic tonalite gneiss (12) includes dome NE of Angliers. Homogeneous cores, schistose screens parallel to S_1 (Dimroth et al. 1974 and 1973).

The sequence is relatively simple: the tonalites (12) compare with the typical early D_2 tonalite diapirs, the heterogeneous granodiorite (13) with typical late D_2 plutonism, and the late granodiorite (15) and syenite (16) stocks with typical late discordant stocks. The added plutonism is the granodiorite, tonalite, and monzodiorite (13), though these may be grouped with the early diapirs.

Deformation (after Dimroth, Coté, et al. 1975)

- D_4S_4 Axial plane schistosity trends ENE, dips subvertically NW. Generally subordinate to S_1 , in a few areas more pronounced. In thin section seen to be widely spaced shear planes of asymmetrical crenulation folding on S_1 . Kinking progressing into tight folding.
- D_3S_3 Axial planar schistosity, barely detectable, trend SE, dip steep to NE.
- D_2S_2 Axial planar schistosity, poorly developed in volcanics, well developed in sediments. Strike coincides with S_1 but has shallow dip, $20 - 30^\circ$ N.
- L_2 Sub-horizontal lineation (S_1/S_2) weak and not widespread.
- D_1F_1 Large scale isoclinal folding with steeply dipping axial planes (recumbent in Dimroth et al. 1973 text and Fig 3. In the developing model, updoming batholiths and marginal synclines are inter-related, so producing the steeply dipping axial planes now seen). Hinge zones are narrow and in them bedding cannot be recognized because of schistosity: hinges are determined mainly by opposing younging directions.
- S_1 Axial plane schistosity, rarely deviates more than 15° from bedding direction. Maximum stretching of varioles reflect flattening.
- Cadillac-Larder fault thrusts older volcanics over younger sediments and is considered here to be D_1 .

Other faults are of several generations.

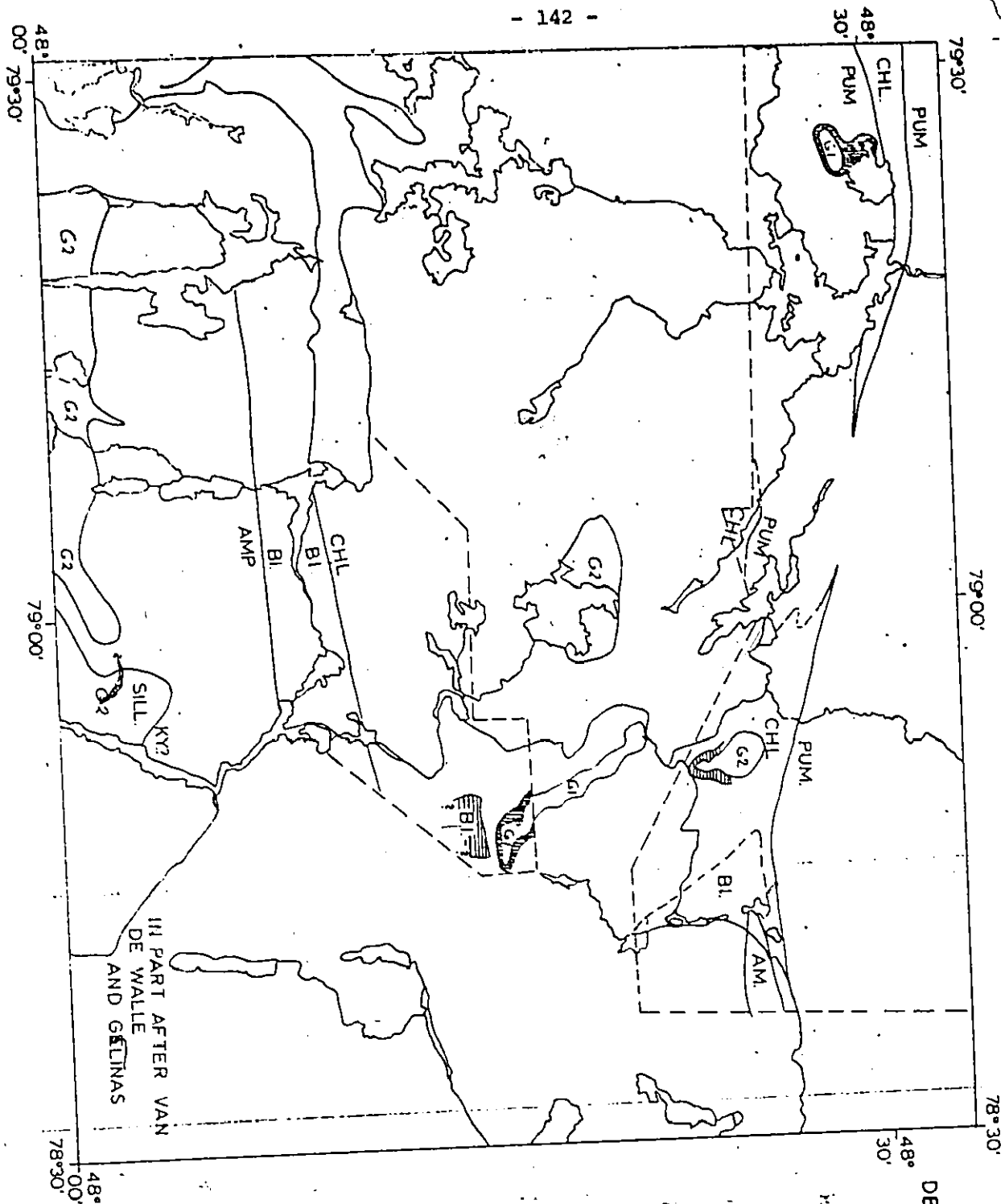
The deformational history is normal to the Archean areas studied and to that of younger areas. The presence of S_1 is noted: it will be interesting to see how extensive it is in the Abitibi Belt and how it relates (or otherwise) to thrusting.

Metamorphism (after Dimroth et al, 1974) (Fig. 16)

The five phases described by Dimroth et al. are not directly related by them to deformational phases, but the relationships here are based on Dimroth's description.

- Late D_3 ? Post-kinematic thermal metamorphism: retrograde muscovite and sericite in the Pontiac Group, hornfels around the Lake Dufault granite.
- Earlier D_3 ? Syn-kinematic metamorphism. The pumpellyite-prehnite facies of the north borders a zone of greenschist and amphibolite facies along the Duparquet-Bestor break, and the grade increases southward, attaining amphibolite facies, related to the late tectonic intrusion of granodiorite and trondhjemite-tonalite massifs, in the Pontiac Group.
- D_2 ? Pre-kinematic metamorphism, amphibolite facies, around the granite massif north of Lac Montsabras and the Clericy granodiorite.
- pre- D_1 Pre-kinematic load metamorphism: pumpellyite-prehnite facies.
- pre- D_1 Propylitization: chlorite and sericite haloes below sulphide ore bodies.

Fig. 33 after Dimroth et al. 1974



DEPARTMENT OF NATURAL RESOURCES

Fig. 2 METAMORPHIC ZONES IN THE KATANGA AREA

1 = orthozone metamorphic
vertical faulting around 1000 ft. of the zone
contact between 1000 ft. and 1000 ft. zone
2 = neo-orthone (a north side orthozone metamorphic
horizontal faulting around 1000 ft. of the zone
orthozone metamorphic

Partial metamorphic

- PUM = orthozone metamorphic (across section of zone)
- CHL = orthozone metamorphic (across section of zone)
- BI = orthozone metamorphic (across section of zone)
- AMP = amphibolite (across section of zone)
- KY2 = pseudomorph after quartzite
- SILL = sillimanite

Note: boundary between CHL and BI zone refers to
appearance of coarse grained texture.



GEOLOGICAL EXPLORATION SERVICE

DP-246

Ore Deposition

Pre-tectonic

Copper-zinc (Figs. 34, 35)

Descriptions of the last twenty years are of volcanogenic, stratiform, polymetallic, sulphide deposits. Spence and de Rosen-Spence (1975) write that they overlie chloritic pipes of alteration, occur at or near the top of rhyolitic formations, and many are associated with primary volcanic features such as lava domes and explosive breccias. They show a zoning of copper-zinc ratios and evidence of fragmentation of some massive sulphides prior to being covered by later flows of andesite or rhyolite. They attribute them to submarine volcanogenic processes forming sulphide sinters over hot springs. They recognize two main types of deposit, copper-zinc-rich in the third rhyolitic zone and zinc-rich in the fourth rhyolitic zone, while only a massive pyrite body is known in the fifth zone.

Dimroth, Coté, et al. (1975) suggest that the rhyolite domes so commonly underlying ore deposits may not be the source of the ore metals but of heat. Ore metals may then have been extracted from a much larger volume of volcanic rock, by means of brine circulation that was initiated by a heat source. This hypothesis may be considered as complementary to that of Spence and de Rosen-Spence.

Hopwood (1976) is concerned with the relationship of quartz-eye porphyroidal acid rocks to the ore and postulates that these rocks may be the source of the metal, and pyrite (of volcano-sedimentary origin) the source of sulphur. He notes the porphyroblastic growth of quartz-eyes during the development

of S_2 and the common elongation of orebodies in L_2 . He cites the Horne mine as an example, the No. 5 ore zone (pyrite) stratigraphically controlled and the Lower H elongate in L_2 . His evidence appears to be equally amenable to the interpretation that deposits and host rocks with origins as described by Spence and de Rosen Spence (1975) and Dimroth, Côté, et al. (1975) have been subsequently metamorphosed and deformed.

Syn-tectonic

Gold (after van der Walle in Allard et al. 1972)

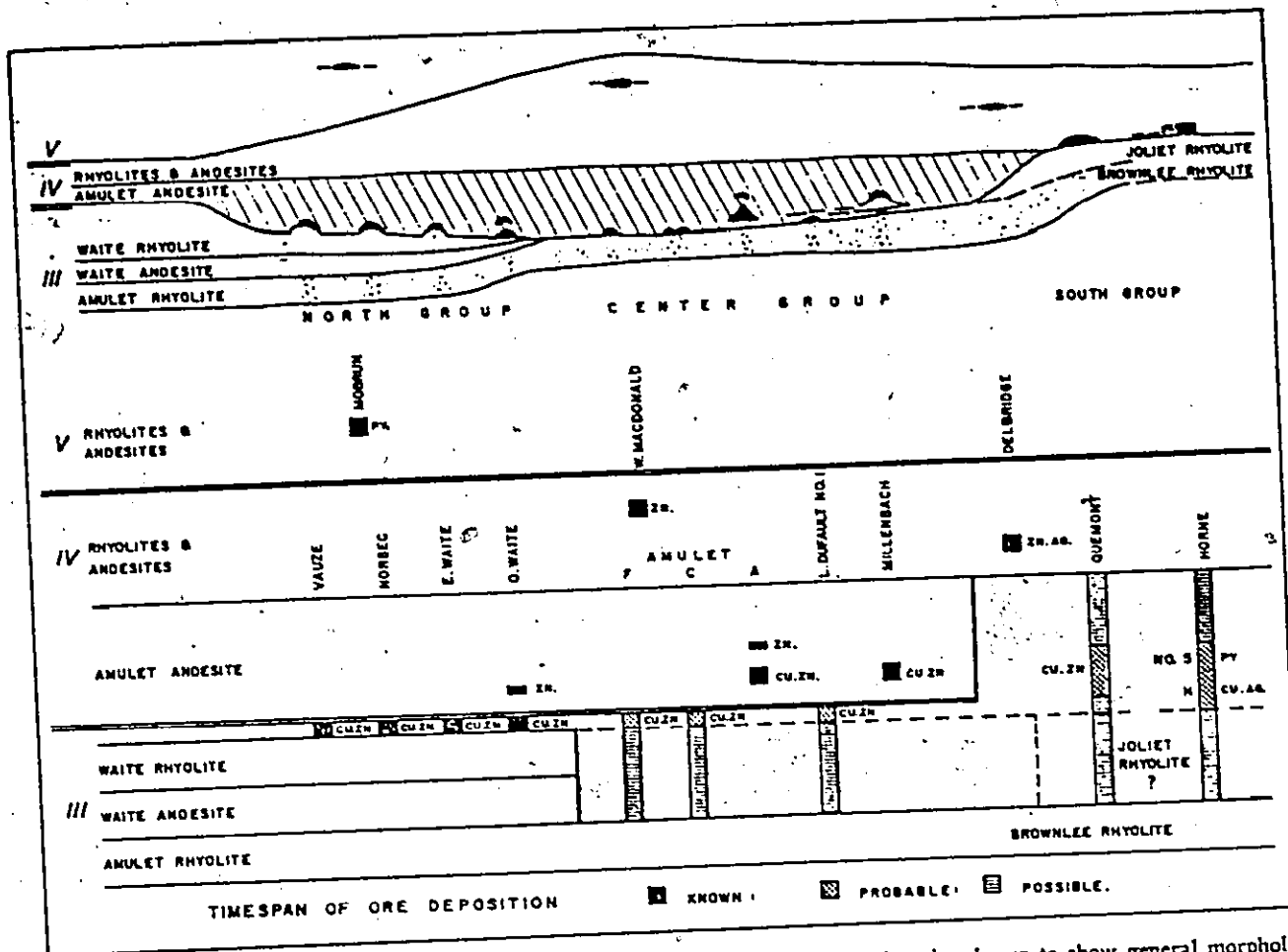
Most gold deposits at Noranda are associated with cross-cutting veins in three groups:

Quartz veins in a small syenite porphyry.

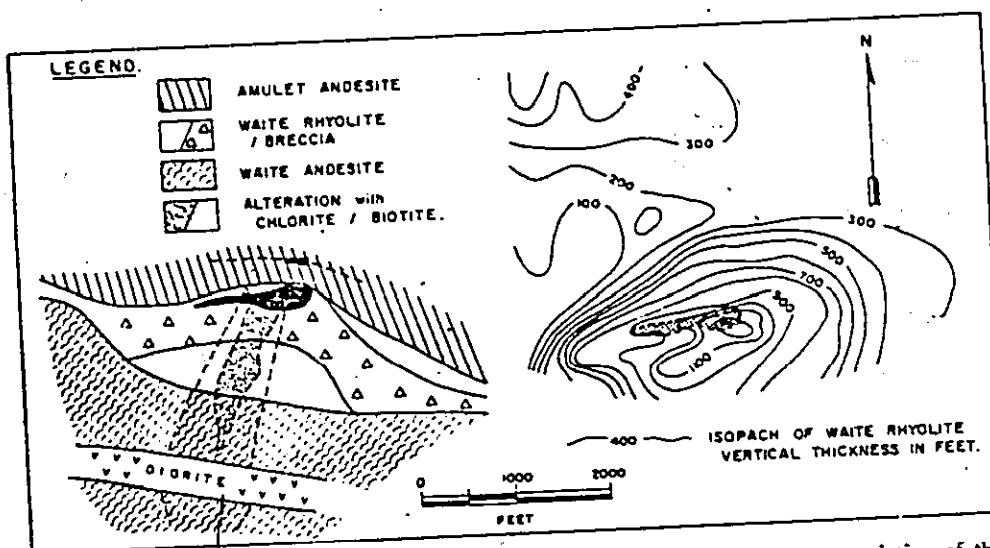
Associated with quartz veins, various strike cutting any rock type. They are generally in minor tension fractures. Accessory minerals are ankerite, pyrite, chalcopyrite, specularite, and galena.

Associated with major E-W shear zones branching off the Cadillac-Larder Lake break in volcanics or sediments. Quartz carbonate lenses or veins, locally heavily and finely pyritized. Accessories are chlorite, fuchsite, talc, albite, tourmaline, arsenopyrite, scheelite and molybenite.

SULFIDE MINERALIZATION IN NORANDA



Top: Diagrammatic N-S section showing stratigraphic position of ore deposits, drawn to show general morphology at the time of deposition of the copper-zinc ores. Bottom: Representation of the known, probable, and possible time spans in which sulfides were deposited.



The East Waite ore deposit showing in schematic E-W section the association of the sulfide body to a rhyolite dome and breccia (W. L. Bancroft, pers. commun.) and the domal feature defined by isopachs as determined by R. C. J. Edwards.

Base metals mines (+ precious metals)

Property	Years	Ore (Tons)	Copper (Tons)	Zinc (Tons)	Gold (Ozs.)	Silver (Ozs.)	Remarks
Aldermac	1931-43	2,057,101	30,845	—	10,750	389,100	—
D'Eldona	1950-52	90,000	14	4,542	10,990	68,645	—
Delbridge	1969-70	254,994	1,884	26,660	19,547	878,106	—Flux ore
Don Rouyn	1956-70	3,353,483	4,447	—	—	—	—
Horne (M. Noranda)	1927-70	56,264,651	1,226,018	—	8,549,029	—	—Flux ore
Joliet	1949-70	1,372,974	13,540	—	—	—	—
Lake Dufault	1964-70	2,800,237	93,242	134,034	58,318	3,524,269	—
Quemont	1949-70	15,013,548	183,801	283,991	1,895,771	8,241,356	—
Vauze	1961-65	385,000	11,150	3,600	7,435	266,600	—
Waite-Amulet	1930-62	9,658,000	404,009	352,921	261,448	7,692,690	—
(Amulet A)		5,872,000					—
(Amulet B, C, D, E, Bluff) ..		596,000					—
(Amulet F)		290,000					—
(Old Waite)		1,245,000					—
(East Waite)		1,655,000					—
West MacDonald	1955-59	1,030,000	125	30,000	2,000	5,300+	pyrite
TOTAL		92,279,988	1,969,075	835,748	10,815,288	21,066,066	

Gold

Anglo-Rouyn	1948-51	145,708			34,192		
Arntfield	1935-42	529,989			55,662		
Donalda	1948-56	694,752			113,669		
Elder Peel	1947-66	2,375,485			384,338		Flux ore
Eldrich	1955-62	717,655			99,890		Flux ore
Francoeur	1938-47	572,152			92,589		
Granada	1930-35	181,744			51,447		
Halliwel	1938-38	2,719			1,165		
Lake Wasa	1951-51	10,230			1,029		
McWatters	1934-44	356,609			108,317		
New Marlon	1947-49	108,188			19,170		
New Rouyn Merger	1948-48	32,198			3,895		
New Senator Rouyn	1940-55	1,739,798			235,969		
Powell Rouyn	1938-56	3,084,647			351,790		
Quesabe	1949-52	98,182			30,000		Estimated
Stadacona	1936-58	3,023,400			465,951		
Wasamac No. 1	1965-70	2,015,943			245,407		
Wasamac No. 2	1968-70	402,206			66,686		
TOTAL		16,081,605			2,325,166		
GRAND TOTAL		108,365,286	1,969,075	835,748	13,140,454	21,066,066	

From Allard et al. 1972

References

The Mining Magazine classification of ore production for 1974 is:

Camflo	D	Au
East Malartic	C	Au
Lamaque	C	Al
Louven	E	Cu
Horne	B	Cu, Au
Lake Dufault	C	Cu, Zn
Manitou Barvue	E	Zn, Pb, Ag

- 148 -

CHIBOUGAMAU, QUEBEC

Sedimentation

vulcanism

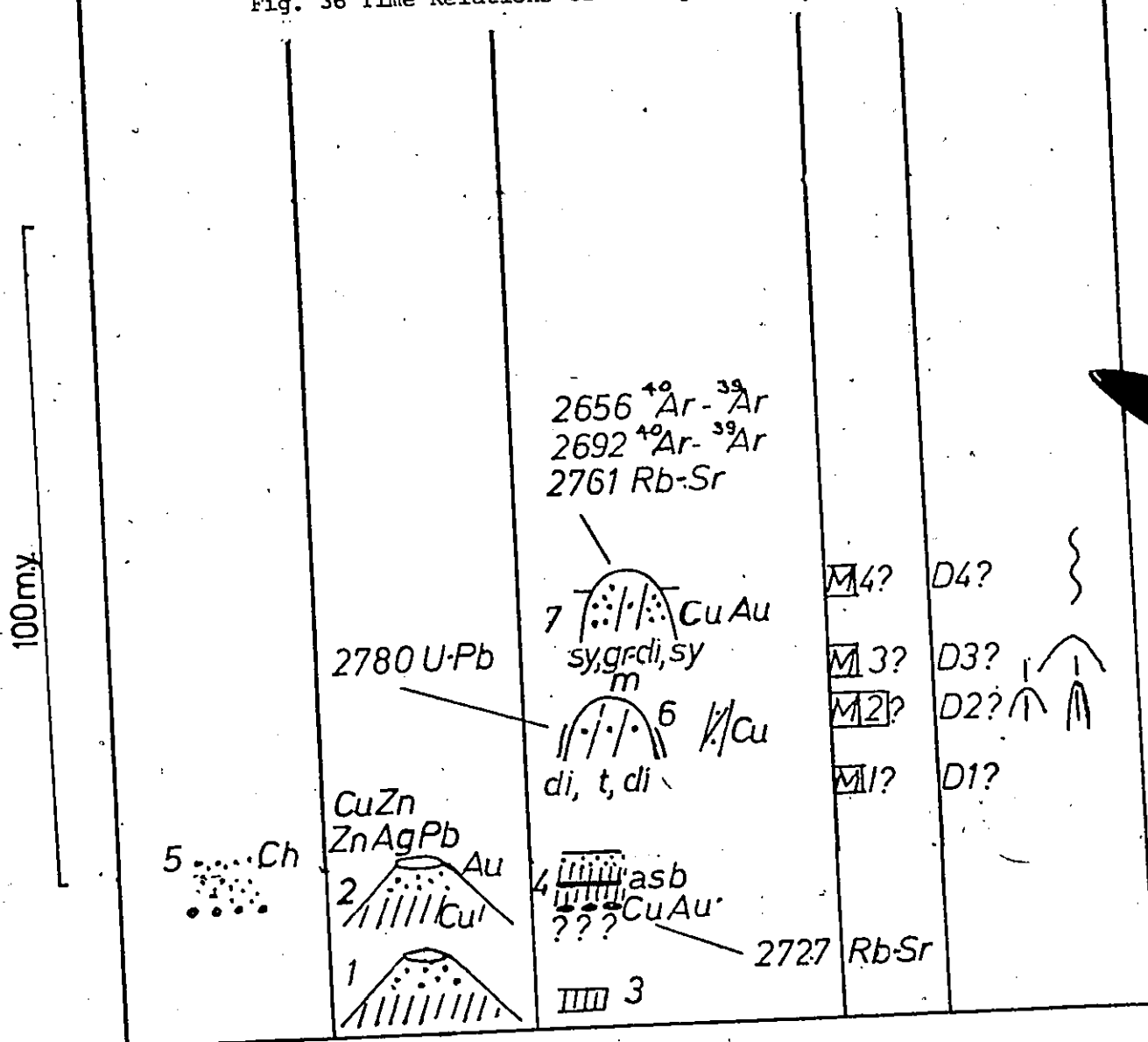
49 -
plu tonism

metamor

deformation

CHIBOUGAMAU, QUE.

Fig. 36 Time Relations of Geological Features



Vulcanism (Fig. 37)

A comparison with other parts of the Abitibi Belt can best be made by considering the vulcanism of the Roy Group, as mafic to felsic cycles. Based on the data of Jones, Walker, and Allard (1974), Cycle 1 appears to be the equivalent of Wilson's (1974) Middle Mafic and Felsic Units, and Cycle 2 his Upper Diverse Unit. Alternatively, both may be Upper Diverse.

Roy Group

Cycle 2 (2) Blondeau Formation

1000 m

Upper Diverse Unit

Well bedded felsic pyroclastic and volcanoclastics. Cherty-tuffs and chert beds interlayered with crystal tuffs, graphitic argillite, pyrite beds, and agglomerates.

Gilman Formation

3500 m

Pillow basalts with minor intercalations of tuffs and agglomerates.

Cycle 1 (1) Waconichi Formation

12000 m

Middle Felsic Unit

Lac Sauvage Iron Formation

Felsic lavas (Na-rhyolites) and volcanoclastics

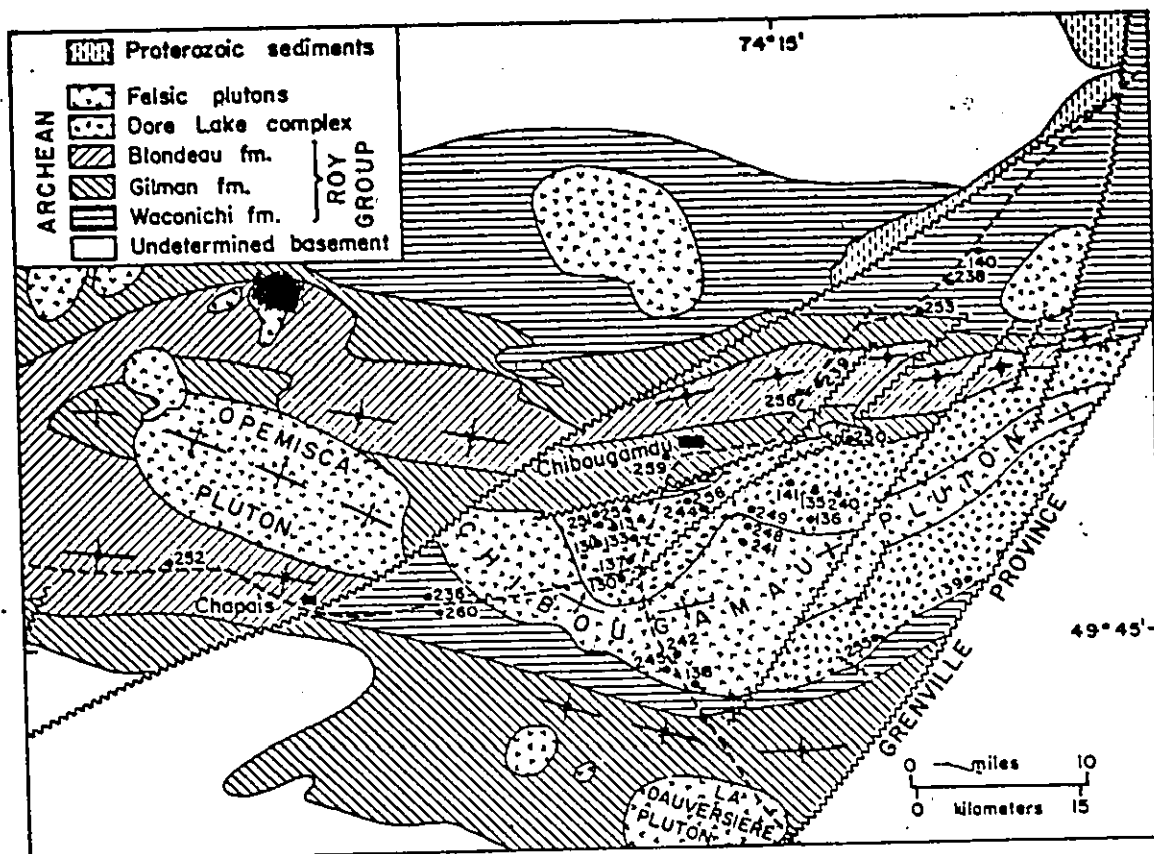
(9000 m)

Middle Mafic Unit?

Mafic Pillow basalts

(3000 m)

The assemblage carries several conformable mafic (3) intrusive bodies which Duquette (in Allard et al. 1972) suggests may be regarded as hypabyssal equivalents of the mafic lavas. In the present paper they are treated as such. The thicker layered sills (4) include the Dore Lake Complex which Allard (in Allard et al. 1972) believes is transgressive across most of the Roy Group and (Durocher pers. comm. June 1976) regards as post-volcanic, though pre-deformation.



Simplified geologic map of the Chibougamau greenstone belt in the vicinity of the towns of Chibougamau and Chapais, Quebec. The numbers indicate the approximate location of the samples.

Fig. 37 from Jones et al. 1974

There are four thicker differentiated sills, the Dore Lake Complex and the Roberge, Ventures, and Bourbeau sills.

Allard (in Allard et al. 1972) provides a section of the Dore Lake Complex:

Upper Border Zone

400 m ⁺₋

Gabbro

Sodagranophyre Zone

800 m ⁺₋

Sodagranophyre

P₃ Member - Pyroxenite - thin layers of gabbro
150 - 450 m

A₂ Member - Gabbroic Anorthosite - Anorthositic gabbro

300 - 4200 m

Layered Zone

500 - 1000 m

P₂ Member - Pyroxenite - Gabbro - layers massive oxides

10 - 25 m

A₁ Member - Gabbroic Anorthosite - Anorthositic gabbro

7 - 50 m

P₁ Member - Pyroxenite - gabbro - layers massive oxides

30 - 50 m

Gabbro - Disseminated oxides

Gabbro

Anorthositic Gabbro

Gabbroic Anorthosite

Anorthosite

Anorthosite Zone

2500 - 4000 m

Intrusive Contact

Intruded by Chibougamau Lake Tonalitic Complex

The Roberge sill, less than 600 m thick, caps the Gilman Formation and consists essentially of serpentinized dunite and peridotite.

The Ventures Sill (a little above the Roberge Sill):

Coarse gabbro	500 m
Green to black clinopyroxenite interlayered with serpentinized peridotite	600 m

Bourbeau Sill (125 m. above the Ventures Sill)

Dark-green, quartz ferrodiorite	350 m
Leucogabbro	300 m
Peridotite	25 m

(Allard in Allard et al. 1972).

Wilson (1974) says the most characteristic intrusions of the Upper Diverse Group consist of anorthositic gabbro complexes; that small, irregularly shaped, green hornblende-bearing gabbro bodies are common and also appear to be diagnostic; and that diorite-gabbro sills are abundant in places.

A further argument that the sills pre-date the end of Cycle 2 is based on a proposal by Allard (in Allard et al. 1972): The contrast between the ore deposits of the Chibougamau-Opemisca area and those of Noranda is striking. The Chibougamau deposits are shear zone replacements in the anorthosite zone of the Dore Lake Complex. The volcanic channelways which led to the surface during the formation of the upper Blondeau could have been the fractures we now see as shear zones on the Dore Lake Complex: the porphyry dykes in the shear system are like the Blondeau volcanics. The sulphides which would normally come out at the surface in volcanogenic deposits were trapped and deposited in the dilatant zones of the main channelways, and the surface mineralization is uneconomic. At Opemisca the Ventures Sill played a similar role.

If the theme is valid, the sills cannot be post-volcanic.

Sedimentation (Fig. 37)

The turbidites so prevalent in the southern part of the Abitibi Belt are not noted at Chibougamau. They may be represented by the high proportion of volcanoclastics noted under Vulcanism.

Cimon and Gobeil (1976) describe the Stella Formation (5) on the southern limb of the Chibougamau anticline as conglomerates, arkose, sandstones, argillites, black shales, and minor volcanics, with the basal conglomerate overlying and containing a large number of clasts from the Dore Lake and Chibougamau complexes. They describe the volcanics of the formation as hosting the Lemoine deposit, but their co-worker Allard (1976) describes the host as "the top of Waconichi Formation (end of the first cycle)". Earlier authors have also differed on this sequence. Dugas, Latulippe, and Duquette (1967) on Map 1600 Sheet 4 called this suite sedimentary rocks. Duquette (1970) on Map 1686, omitting a critical section south of the Dore Lake Complex in Lemoine Twp., called the rest Blondeau Formation, i.e., Cycle 2.

With such diverse opinions I prefer to consider that south of the Chibougamau anticline the newly named Stella Formation is in part the proximal sediment equivalent of the Blondeau Formation, basing this choice on the model of Wilson (1974-3) in which copper-zinc ores are absent in the Middle Felsic Unit and present in the Upper Diverse Unit.

North of the Opemisca pluton, on the north limb of the Chibougamau anticline, sediments also called the Stella Formation do appear to be post-Blondeau (M.E. Durocher, oral comm. May 1976).

Plutonism (Fig. 37)

D₃?

Post-kinematic granodiorite (7). Irregular, cross the trend of the local country rocks, carry little evidence of mechanical deformation. The Opemisca pluton shows slight concentric zoning from inner leucocratic hornblende granodiorite to an outer narrow zone of hornblende syenite. It has a well-defined metamorphic contact aureole. The La Ronde pluton is concentrically zoned from porphyritic hornblende quartz monzonite core to hornblende monzonite margin but lacks an aureole. (Duquette in Allard et al. 1972). The dated Dauversiere stock is also round to ovoid.

D₂?

Tonalite-diorite suite (6). The Chibougamau pluton is strongly zoned from hornblende diorite on the outside to hornblende tonalite leucotonalite, and minor biotite trondhjemite in the core. It is intrusive into the Dore Lake Complex. Most of the rocks of the pluton show the effects of folding and regional metamorphism (Jones et al. 1974). It is therefore assigned a position no later than early D₃, but from its position at the base of the stratigraphic section may be basement re-intruded during the Kenoran orogeny, so bearing comparison with the Round Lake batholith, similarly on an axial zone, at Kirkland Lake, the Rhodesdale batholith of the Midlands Belt, Rhodesia, and probably the Ancient Tonalites of Barberton.

Two of the three plutonic suites which characterize the Archean are therefore present. The absent migmatic suite may be at least part of the gneisses to the north, though these are currently regarded as basement (Goodwin and Ridler 1970).

Deformation

No study of deformation is known. Data from Duquette (in Allard et al. 1972).

- $D_3?$ $F_3?$ Steeply plunging folds, canoe shaped structures formed at end or after Kenoran orogeny. Faulting.
- $S_3?$ Down dip crenulations.
- $D_2?$ $F_2?$ Regional synclinatorium. Isoclinal and symmetrical folds plunge few degrees east and west.
- $S_2?$ Alignment of mafic minerals (biotite, hornblende, and chlorite) and cataclastic structures produced by granulation and elongation of quartz grains in gneisses, parallel to those in adjacent country rock.

The absence of reported D_1 is not unusual. The change from tight to open folds with time is typical of deformational histories of all periods.

Metamorphism

Duquette (in Allard et al. 1972) notes greenschist or, less commonly, amphibolite facies metamorphism, but no study of the metamorphism of the area appears to have been undertaken. The paucity of higher grades of metamorphism is presumably related to the absence of reported syn-tectonic migmatitic granites.

Ore Deposition (after Duquette in Allard et al. 1972)

Pre-tectonic

Copper-Gold

Thirteen deposits associated with pre-ore dykes in quartz shear zones in the anorthosite zone of the Dore Lake Complex. Massive sulphide lenses with chalcopyrite, pyrite, pyrrhotite and occasional sphalerite in sericite-chlorite (chloritoid)-carbonate (siderite)-quartz. The Chibougamau Lake copper ore-bodies have a different strike and no dykes. All major ore zones and dykes are vertical when the host anorthosite roof to the Chibougamau pluton is considered in its pre-folding position. Duquette suggests a volcanogenic origin.

Copper-Zinc-Lead

Lemoine copper-zinc deposit in volcanic horizons within Stella (Cimon and Gobeil 1976) or Waconichi (Allard 1976) or Blondeau formations, and so typically volcanogenic exhalative.

Asbestos

Asbestos deposits have been outlined in the Roberge sill (Duquette in Allard et al. 1972).

Syn-tectonic

Copper-Gold (Figs. 38, 39)

Related to Opemisca pluton? Ore bodies structurally controlled in upper gabbroic part of Ventures sill. Chalcopyrite, pyrite, pyrrhotite, and magnetite with minor molybdenite, scheelite, bornite, valleriite, sphalerite, hematite, arsenopyrite and native gold. Carbonate, quartz, and chlorite gangue.

Gold in association with pyrite, arsenopyrite, and (at Key Anacon) chalcopyrite in quartz veins of greenstone assemblage. Both Norbeau and Key Anacon (or Chibex) appear to be associated with tonalite plutons.

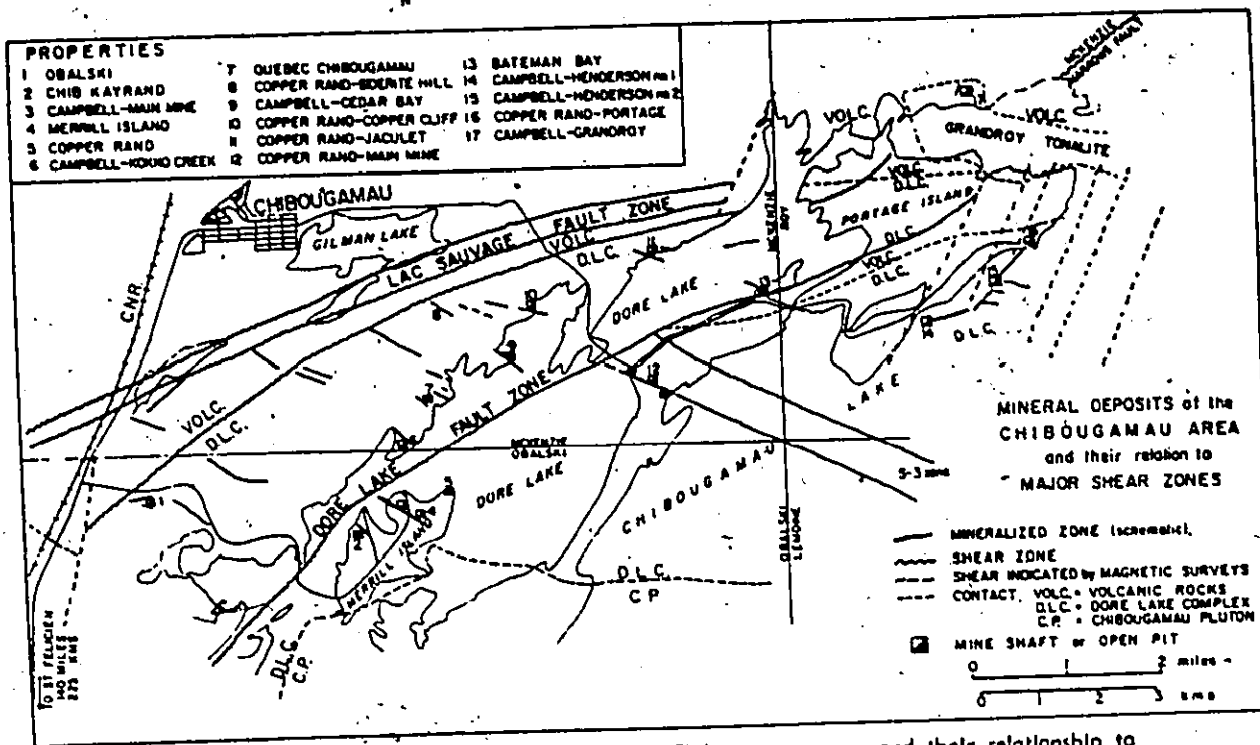
Bruneau: stockwork of chalcopyrite-pyrite-magnetite-carbonate-epidote veinlets in Gilman basalts and pyroclastics.

Grandroy: stockwork of chalcopyrite-pyrite magnetite-hematite veinlets oriented E-W along major N-S fault in satellite? of tonalitic Chibougamau pluton.

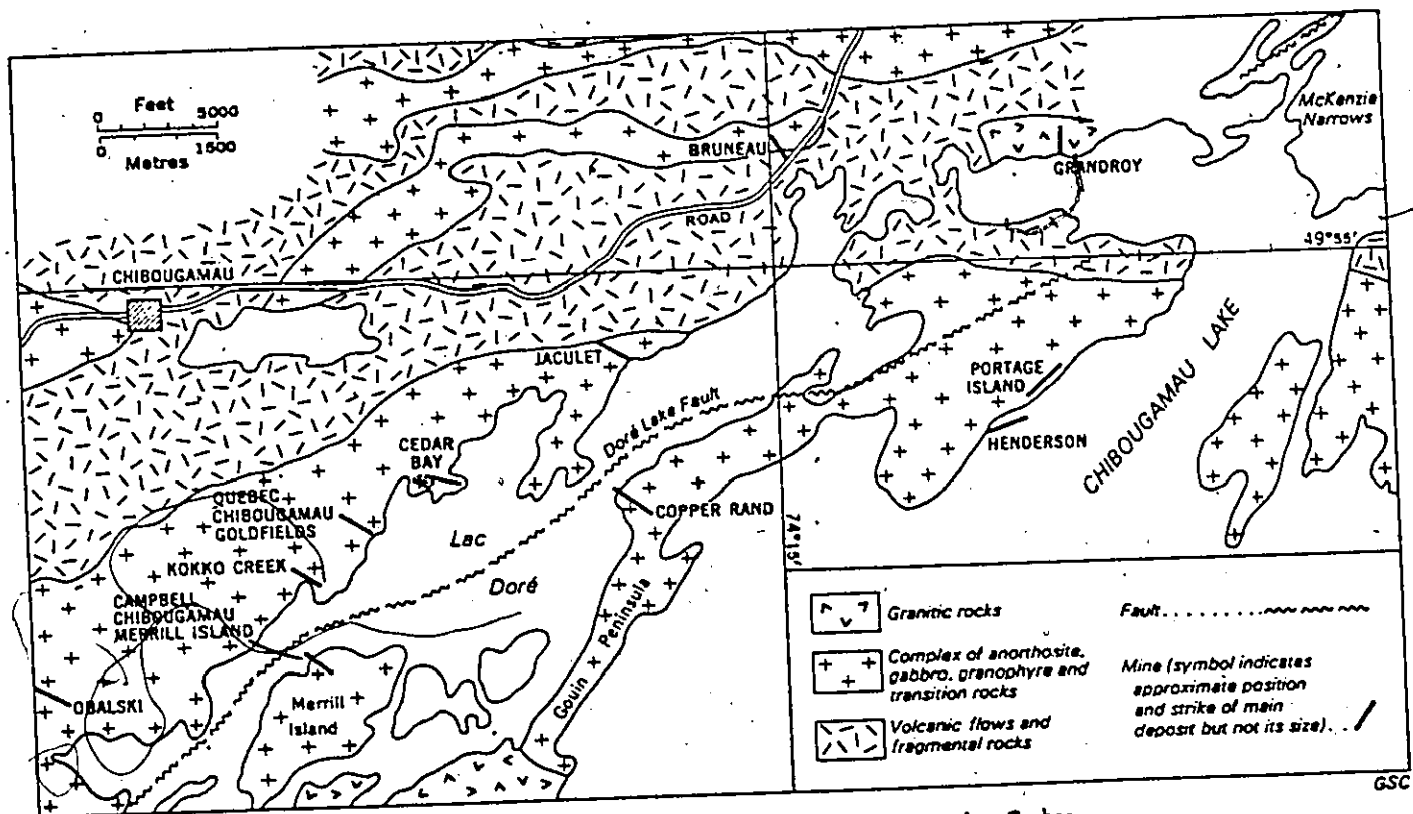
D₃?

D₂?

Fig. 38 from Allard et al. 1972



Distribution of ore deposits in the Chibougamau area and their relationship to structural features.



Generalized geology and copper-gold mines of Chibougamau region, Quebec

Fig. 39 from Douglas 1970

Ore Production

	<u>Prod. Period</u>	<u>Prod. Tons Ore</u>	<u>Ref.</u>
Falconbridge-Opemiska	1954 - 74	13,795,000	1
Campbell Chibougamau	1956 - 75	17,815,000	1
(Campbell Chib, Kokko Cr.			
Cedar Bay, Main-Merrill			
Henderson Chib-Kayrand			
Patino N.V.			
(Main Copper Rand			
Copper Cliff			
Chibougamau Jaculet			
Portage Island			
Bouzan			
Lemoine)			
Norbeau	1964 - 69	250,000	2
Chib. Ex. (Key Anacon)	1956 - 64	682,287	2
Camp Total	1954 - 72	25,000,000	2

References

1. Financial Post Survey of Mines 1976.
2. Duquette in Allard et al. 1972

In 1970 the camp produced one-third of the total copper produced in Quebec and one-tenth of the Canadian total. Three million tons of ore were extracted from twelve mines by four companies (Duquette in Allard et al. 1972).

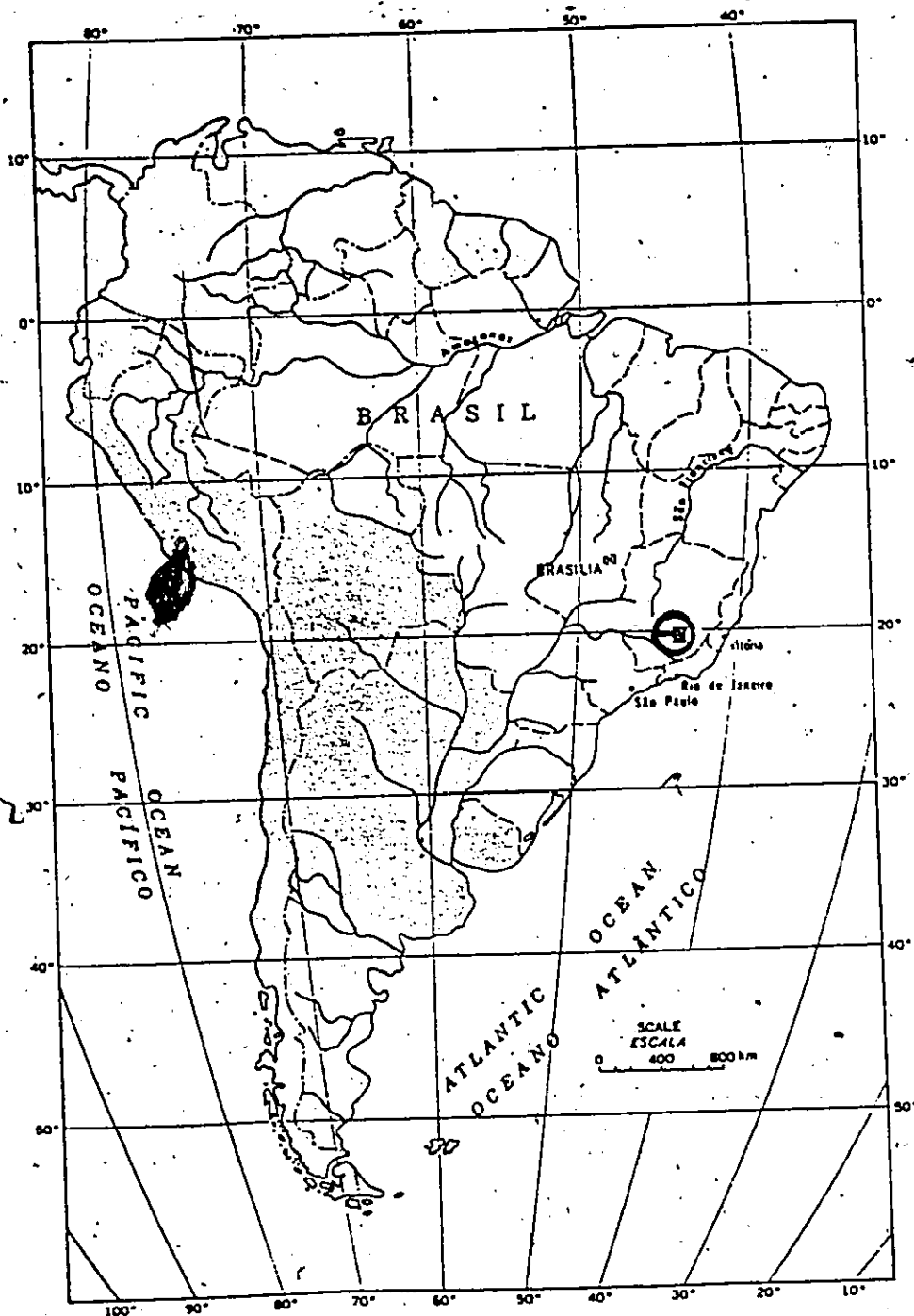
The Mining Magazine classification of ore production for 1974 is:

Chibex	E Au
Springer (Opemiska)	C Cu

- 161 -

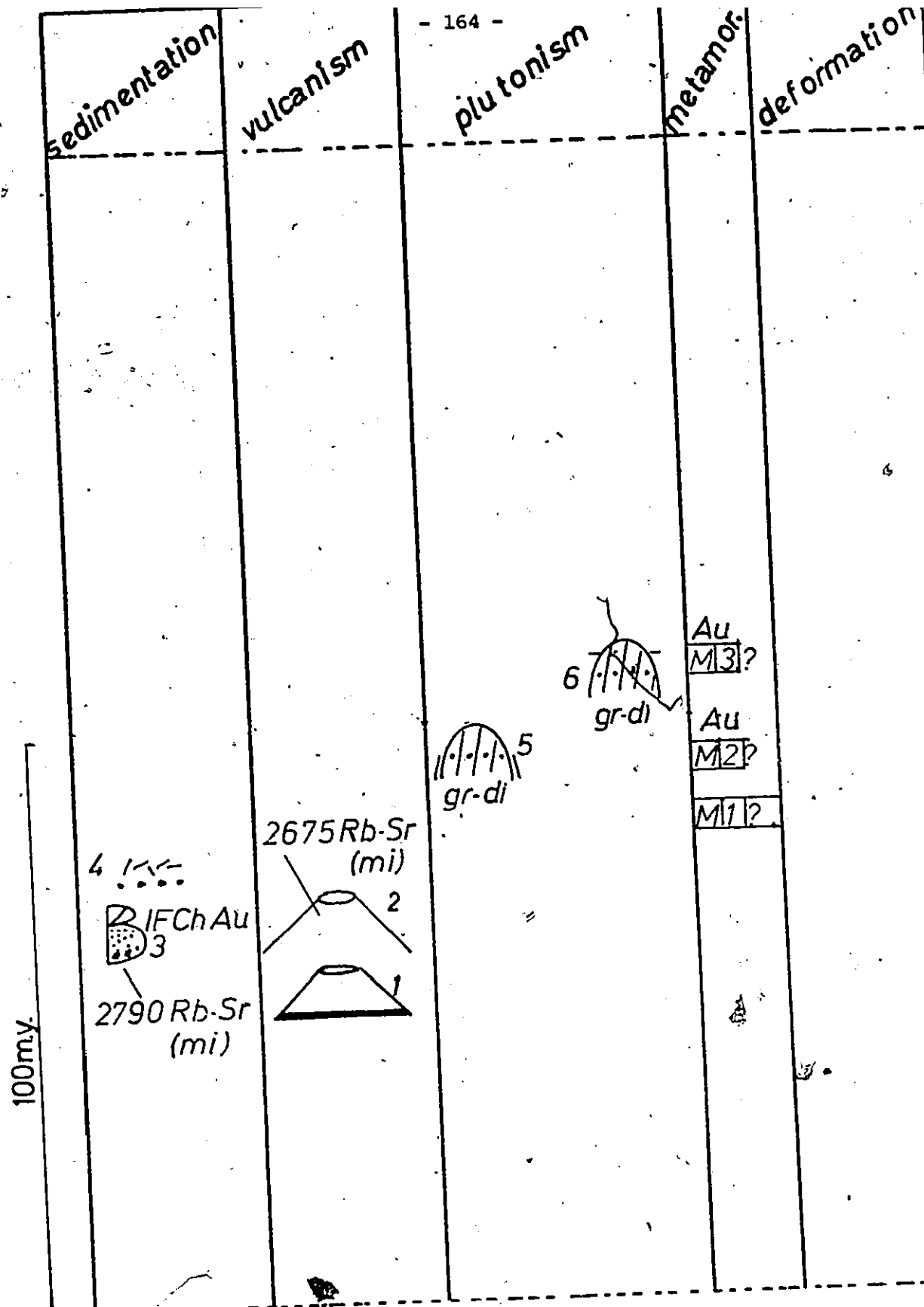
BRAZIL

RIO DAS VELHAS, QUADRILATERO FERRIFERO
BRAZIL



Location Map, Rio das Velhas

Fig. 40 from Dorr 1969



RIO DAS VELHAS, BRAZIL.

Fig. 41 Time Relations of Geological Features

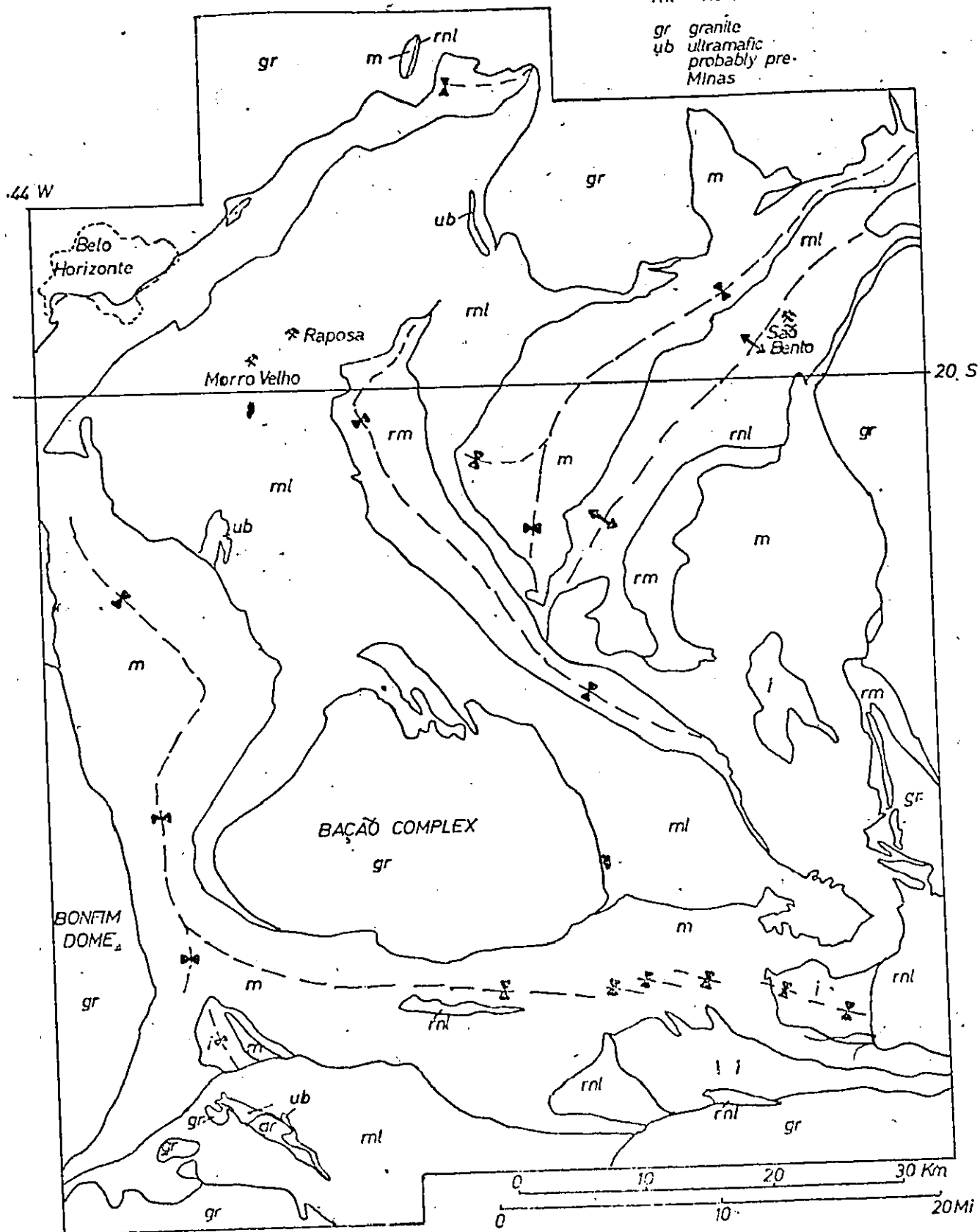
Fig. 42 from Dorr 1969

GEOLOGY, RIO DAS VELHAS, BRAZIL

PRECAMBRIAN

i Itacolomi
m Minas
r Rio das Velhas
rm Maquine
rnl Nova Lima

gr granite
ub ultramafic
probably pre-
Minas



Vulcanism (after Dorr 1969) Fig. 42)

Greenstone Group?

Nova Lima Group (largely sedimentary)

Volcanic ash (2) as part of fine grained clastics. Minor volcanics, probably ash and some flows, source perhaps to west. Carbonate facies iron formation and chert.

Ultramafic Group?

In the Congonhas and Nova Lima districts are large sills and stocks of altered peridotite, dunite, and other ultramafics (1) (Herz 1970).

The distal products of vulcanism are not amenable to any interpretation of cyclicity, but the large volume of ultramafics may be correlative with the Ultramafic Group of southern Africa and Australia. If so, the volcanic ash and iron formation may be equated with the Greenstone Group, as a distal part, rather than the lowest unit of the Sedimentary Group.

Sedimentation (after Dorr 1969). (Fig. 42)

Rio das Velhas Series

Maquine Group (4)

400 + m

Casa Forte Formation

Protoquartzite, grit, conglomerate, minor phyllite, and subgraywacke: molasse

1400 m

Palmital Formation

Phyllite, quartzose phyllites, Protoquartzite, graywacke, subgraywacke: molasse
Minor basal conglomerate.

Local erosional and possibly angular unconformity.

Nova Lima Group (3)

4000 + m

Phyllite, largely chloritic, graywacke, carbonate facies iron formation, volcanics, minor quartzite, tilloid, conglomerate, and dolomite: flysch.

Dorr interprets an abrupt change from the argillaceous and volcanic source of the Nova Lima to a more quartzose and nearshore environment for the Maquiné. The change from flysch to molasse is typical of the Archean areas studied. Tilloid is not noted in the other areas, however, and if truly glaciogenic is perhaps the oldest recorded.

Plutonism (after Herz 1970) (Fig. 42)

D₃? Anatectic part of the granodiorite (6) of the Bação complex and Congonhas district. Style of mantled gneiss dome.

D₂? Granodiorite of the Bação complex (5) and Congonhas district. Gneiss grades into migmatites and granodiorite. Foliation in surrounding rocks not everywhere parallel to that of the gneiss. Metamorphic aureole as high as garnet-amphibolite facies. At Congonhas the suite includes tonalite and K-leucogranodiorite, contrasting with the Na-rich Engenheiro Correa leucogranodiorite of the Bação complex.

Better definition of the succession is desirable. The Bação complex bears comparison with the Round Lake batholith at Kirkland Lake. If the comparison is valid, and extended to the Rhodesdale batholith of Rhodesia and the Ancient Tonalites of Barberton, the style of mantled gneiss dome accords with the consideration of Viljoen and Viljoen (1969-4) for the Ancient Tonalites, and the anatectic part with the cannibalistic core of the Round Lake batholith (Ridler 1976-1). The migmatites must be considered as the third, late D₂ member of the normal three-part Archean plutonism.

Deformation

Dorr (1969) contrasts epeirogenic uplift and resulting unconformities with the multiple deformation of orogeny, and notes that the multiple deformation of orogeny preceded the deposition of the Minas Series. The pattern of deformation has yet to be unravelled and may prove difficult to determine, except in the mines, in this area of deep weathering.

Metamorphism

The metamorphism of the Nova Lima Group varies from very low rank, far from granitic bodies, to granitic gneiss (Dorr 1969), presumably from Burial metamorphism to amphibolite facies. The Maquiné rocks have generally been metamorphosed to greenschist facies. If the suggested deformational match to plutonism is valid, metamorphism may be:

M₃? greenschist

M₂? amphibolite and granulite (Herz 1970 p. 48)

Ore Deposition

Syn-tectonic

Gold

Gold-bearing quartz veins (Dorr 1969). Many localities, generally neither rich and persistent nor very productive.

Iron

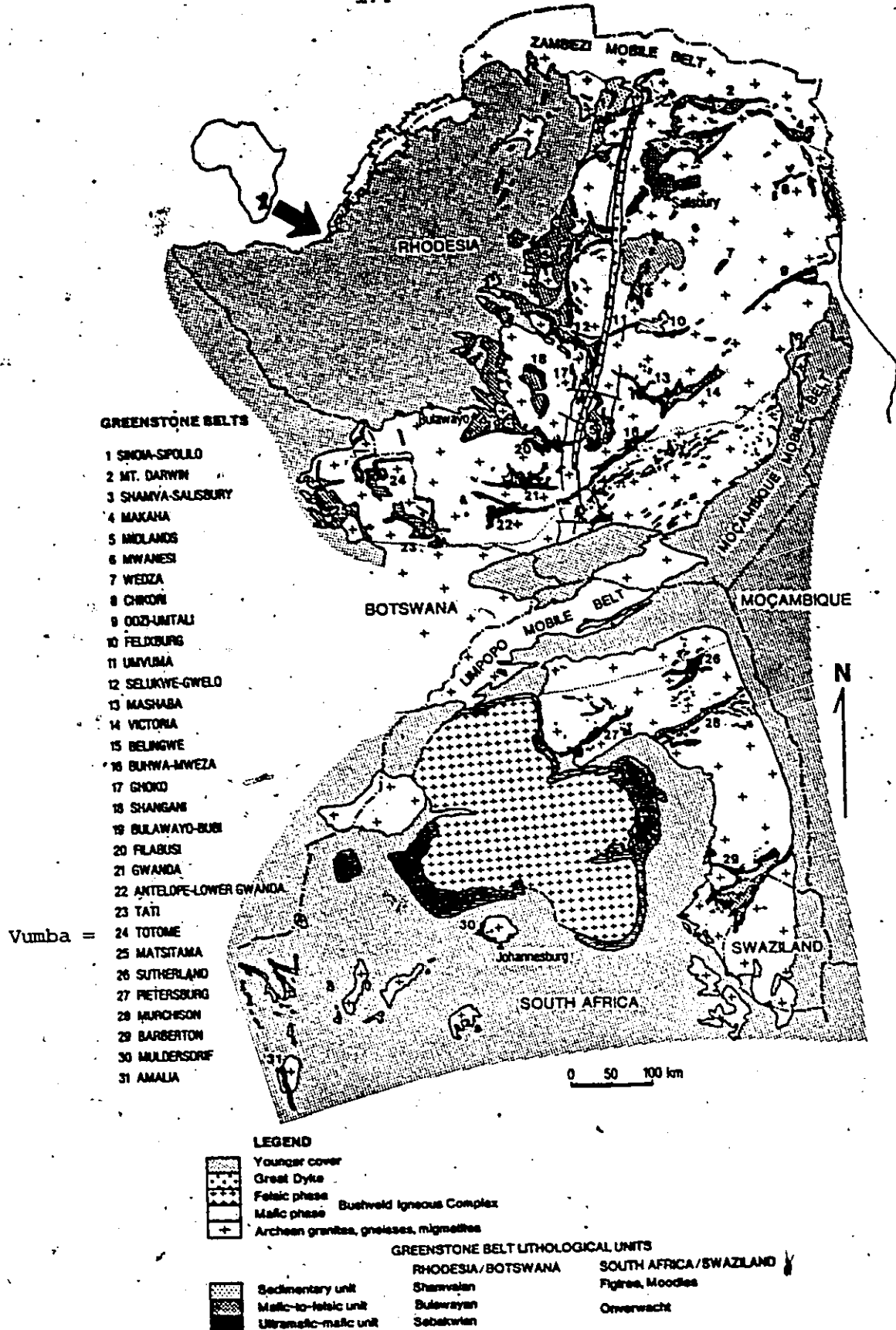
"Lapa Seca" a gray, massive quartz-carbonate rock that resembles dolomite is host for gold ore in the Morro Velho, Bela Fama, Raposas, São Bento and Bicalho mines and probably many others now collapsed (Dorr 1969). The ore is predominantly quartz containing massive sulphides, pyrrhotite most abundant, then arsenopyrite, pyrite, and chalcopyrite. Accessory wolframite, scheelite, tetrahedrite, bornite, sphalerite, galena, and stibnite. At Morro Velho, 2454 m deep, 5 kms long, no perceptible changes in ore though grade is variable, av. 0.25 to 0.30 oz/ton. Lapa Seca is quartz dolomite or quartz-ankerite. At Espirito Santo and Raposas mine, 1500 m stratigraphically higher and 5 kms ENE of Morro Velho, host rock is sideritic iron formation instead of sideritic quartzite. At both Morro Velho and Raposas, ore bodies are rod-like replacements of Lapa Seca, plunges parallel to fold axes". (Park and MacDiarmid 1975, Matheson 1956).

Ore Production

"The Quadrilatero Ferrifero played an essential role in the development of both the Portuguese Empire of the 18th and early 19th centuries and in the evolution of the Brazilian nation. During the Colonial period, several hundred tons of gold produced from the rich placer deposits of the region formed a large part of the financial foundation for the rapid expansion of the Portuguese Empire and the influence of that nation in world affairs. Early in the 18th century the placer deposits were exhausted and lode mining commenced. Quadrilatero Ferrifero has produced in the order of 2,000 tons of gold since mining activity began in the early 18th century. Much of this was won from placers, more of it from hypothermal replacement deposits in the Nova Lima Group rocks, and much from supergene enriched deposits in the Caue Itabirite and the hematite ores associated therewith" (Dorr 1969). Dorr suggests that much of the rich placer gold was derived from the short, non-persistent, low grade quartz are replacement deposits.

SOUTHERN AFRICA

1. Barberton Mountain Land
2. Limpopo
3. Vumba and Tati
4. Midlands



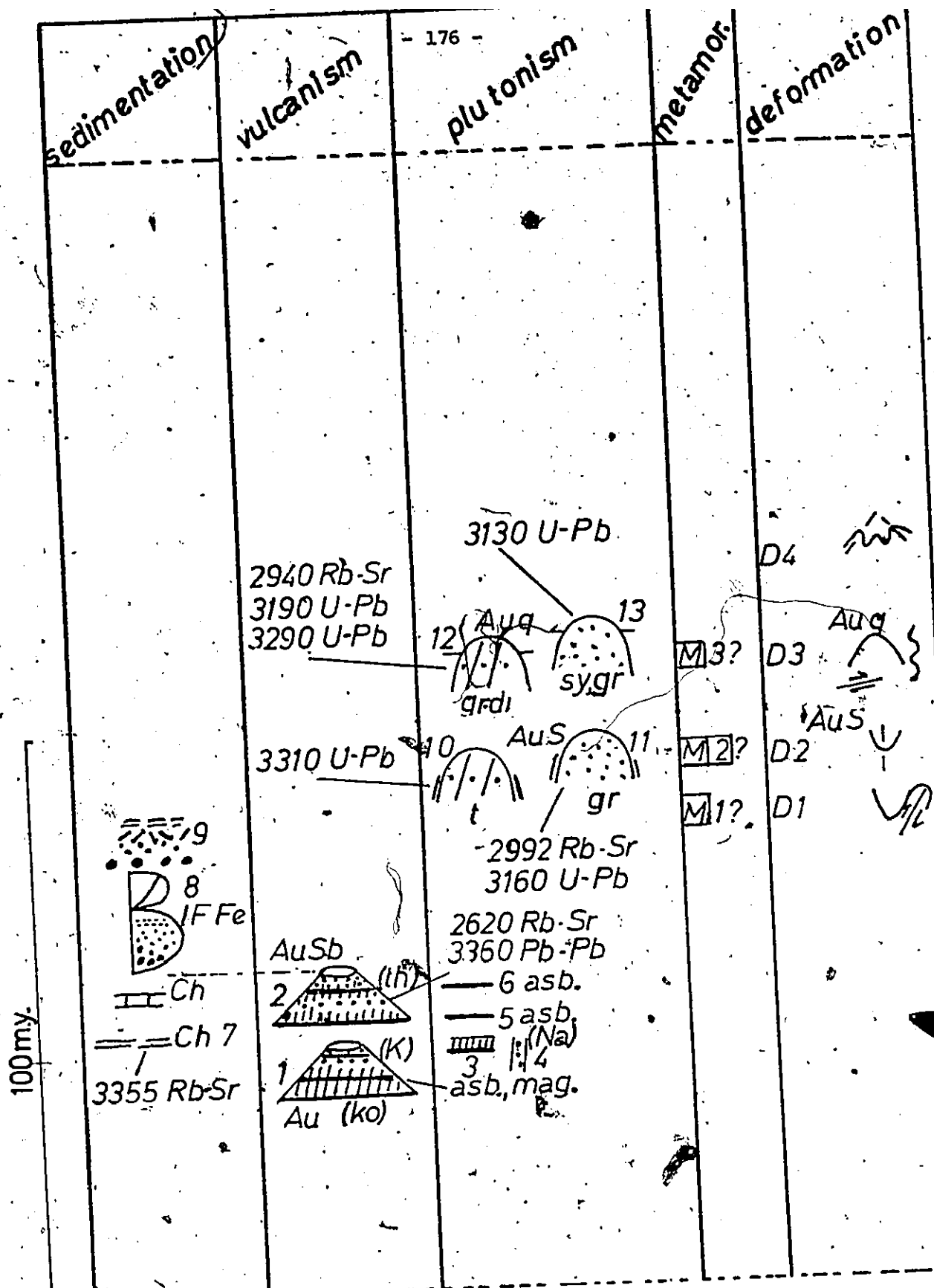
Archean granite-greenstone terrane of the Rhodesian and Kaapvaal cratons.

Fig. 43 from Anhaeusser 1976-1



BARBERTON MOUNTAIN LAND
SOUTH AFRICA AND SWAZILAND





BARBERTON MOUNTAIN LAND

Fig. 44 Time Relations of Geological Features

Vulcanism (Figs. 43, 45, 49)

Anhaeusser (1971-1 and 1971-2) has synthesized the volcanic stratigraphy. In the more detailed description, given elsewhere, penecontemporaneous sills are also considered.

Sedimentary Group

(Fig Tree Group)

Minor alkaline volcanics and pyroclastics.

(Onverwacht Group)

Greenstone Group (2)

Zwartkoppie Formation

900 m

Intermediate to felsic volcanics. Interlayered chert. Normal tholeiitic lavas, minor primitive peridotitic and basaltic volcanics.

Kromberg Formation

1920 m

Mafic lava, felsic lava, chert, pyroclastic volcanics, and calc-silicate and carbonate rocks. Normal tholeiitic lavas, minor primitive peridotitic and basaltic volcanics. Like Hoeggenoe but less striking sequences.

Hoeggenoe Formation

4800 m

Five or more sequences with large accumulations of basalt passing upward to thinner zones of dacitic to rhyodacitic lavas capped by substantial chert horizons. Basalt component lessens and chert component increases upwards. Some sequences start with ultramafics. In the upper pyroclastics gradation is from agglomerates to coarse tuffs to fine tuffs. Normal tholeiitic lavas, minor primitive peridotitic and basaltic volcanics.

Ultramafic Group (1)

Komati Formation

3450 m

Mafic rocks (70%) and ultramafic rocks (30%). Intrusive quartz and feldspar porphyries.

1850 m

Theespruit Formation

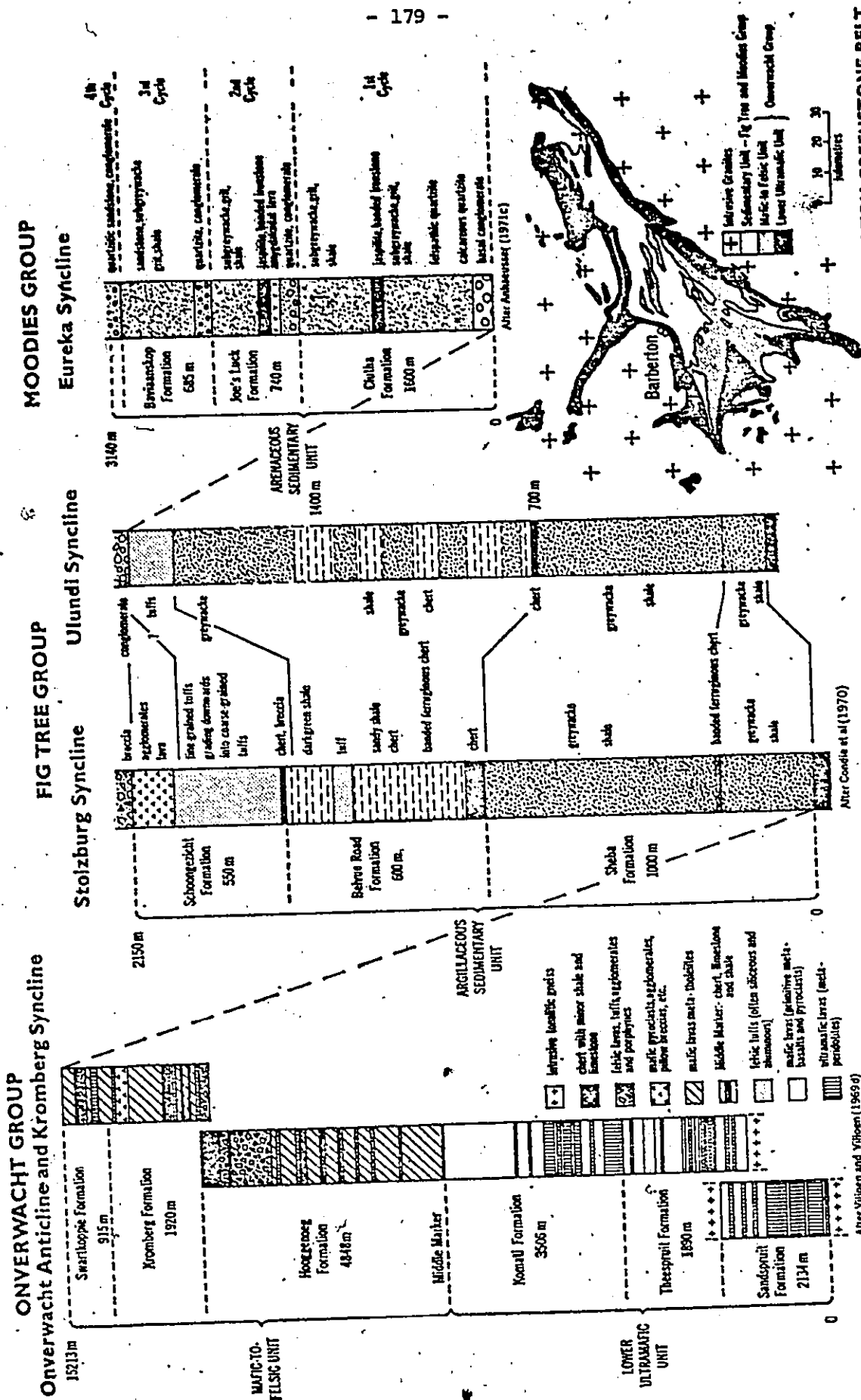
Mafic and ultramafic volcanic rocks, water-worked felsic tuffs. Talc-chlorite-carbonate schists and other minor ultramafic horizons. Sequences of peridotitic and basaltic komatiite, tholeiitic basalt, and felsic tuffs.

2100 m

Sandspruit Formation

Ultramafic rocks (60 - 70%), mafic rocks and minor primitive sediments. Sequences of peridotitic komatiite, basaltic komatiite, and tholeiitic basalt.

Fig. 45 from Anhaeusser 1973



Stratigraphic sections depicting the various volcanic and sedimentary successions of the Swaziland Sequence in the Barberton Mountain Land, South Africa. The distribution of the lower ultramafic unit, the mafic-to-felsic unit, and the combined sedimentary units are shown in the inset general geological map of the early Precambrian (≥ 3400 Ma old) Barberton greenstone belt.

Sedimentation (after Anhaeusser 1971-1, 1971-2) (Figs. 43, 45)

Moodies Group (9)

3500 m in
the Saddleback
syncline

- Cycle 4: Small-pebble conglomerate grit.
- Cycle 3: Alternating sub-graywacke, grit, sandstone, and shale. Minor localized conglomerate and quartzite.
- Cycle 2: Shales, sub-graywackes, and grits.
Banded magnetic jaspilite.
Minor amygdaloidal lava.
Conglomeratic quartzite.
- Cycle 1: Shales, sub-graywackes, and grits.
Banded magnetic jaspilite.
Lava?
Shales, sub-graywackes, and grits.
Feldspathic quartzites.
Calcareous quartzites.
Conglomerates.
- conformable to unconformable -

Fig Tree Group (8)

2000 m in
the Stolzburg
Syncline

Rhythmic sedimentation, graywacke to shale, reflecting instability. Chemical precipitates, chert, banded iron, and jaspilite reflect periods of quiescence. Turbidite flows originated as a result of instability and were responsible for local development of shale-pebble conglomerates. Black, carbonaceous shales with pyrite and greenish-black shales indicate deep water sedimentation in a reducing environment.

Onverwacht Group

Volcanogenic sediments noted under vulcanism. The Middle Marker (7) is a persistent sedimentary horizon at the top of the Lower Ultramafic Unit.

As with the vulcanism at Barberton, the sedimentary sequence is part of the Anhaeusser (1971-1) model.

Plutonism (after Viljoen and Viljoen 1969-4 and Ramsay 1963) (Figs. 46, 47, 48, 49)

D₃?

The Young Granite plutons. Truncate earlier structures. Narrow contact metamorphic aureoles and lack of dynamic metamorphism (flattening and stretching) indicate emplacement at high structural levels. Cauldron subsidence suggested by Viljoen and Viljoen affirmed by roof pendants. Older group, Dalmain and Salisbury Kop, are similar granites (12). Younger group includes Sinceni and M'Pageni granites and Bosmankop syenite (13).

D₂

Homogeneous Hood Granite (11) and Nelspruit Granites and migmatites. Different levels of same phenomena. Viljoen and Viljoen visualize dykes of K-rich magma metasomatizing the older, larger tonalitic gneiss and greenstone terrain, merging and mixing to form high level hood granite. In many instances it passes down through a complex migmatite zone into the Ancient Gneiss Complex. Pegmatite stockwork. Viljoen and Viljoen compare it with the late-kinematic granites of Eskola.

D₂

Ancient Tonalitic Gneisses (10). Diapiric plutons or domes. Include Nelshoogte, Stolzburg, Kaapvaal, Theespruit, and Doornhoek granites. Tonalite, minor granodiorite, and diorite; many should be termed leuco-biotite-quartz tonalite or biotite trondhjemite. Foliation varies in intensity. Generally conformable with Swaziland Sequence, commonly lit-par-lit. Responsible for most metamorphism of Onverwacht rocks. Viljoen and Viljoen compare them with the synkinematic granites and mantled gneiss domes of Fennoscandia, though in discussion an Eden rebuts.

The three-part sequence, tonalite diapiric plutons, granite-migmatite complex, and truncating plutons, is the basic form of Archean plutonism. Viljoen and Viljoen are followed here in their consideration that remnants of Sandspruit, Theespruit, and Komati formations are recognizable in what Hunter (1974-1) considers to be basement gneisses. Their comparison of Ancient Tonalitic Gneisses with mantled gneiss domes implies remobilized basement, which allows both views of the suite (pre- and post-volcanic) to be correct.

THE GRANITIC ROCKS OF SWAZILAND AND THE EASTERN TRANSVAAL

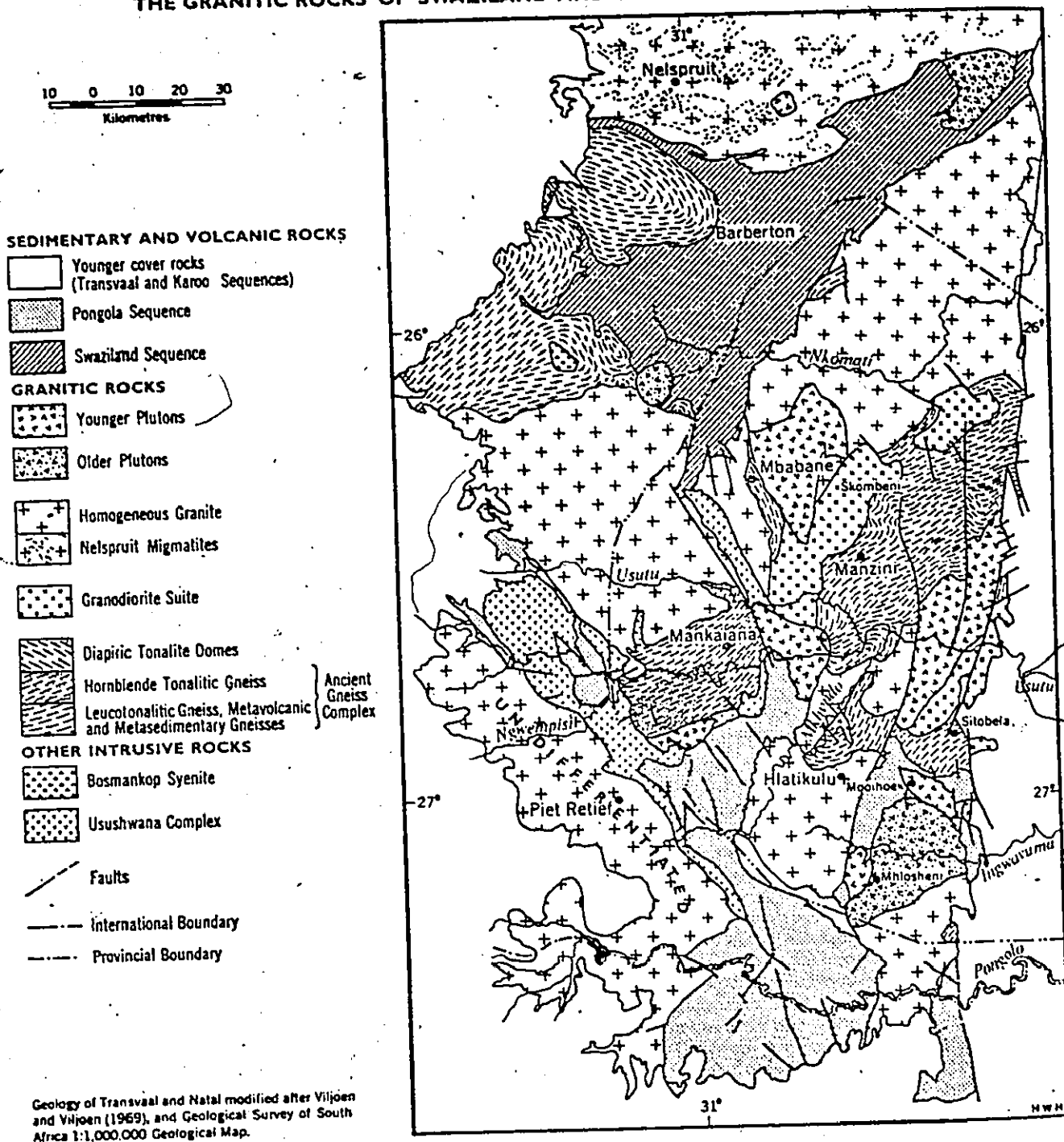
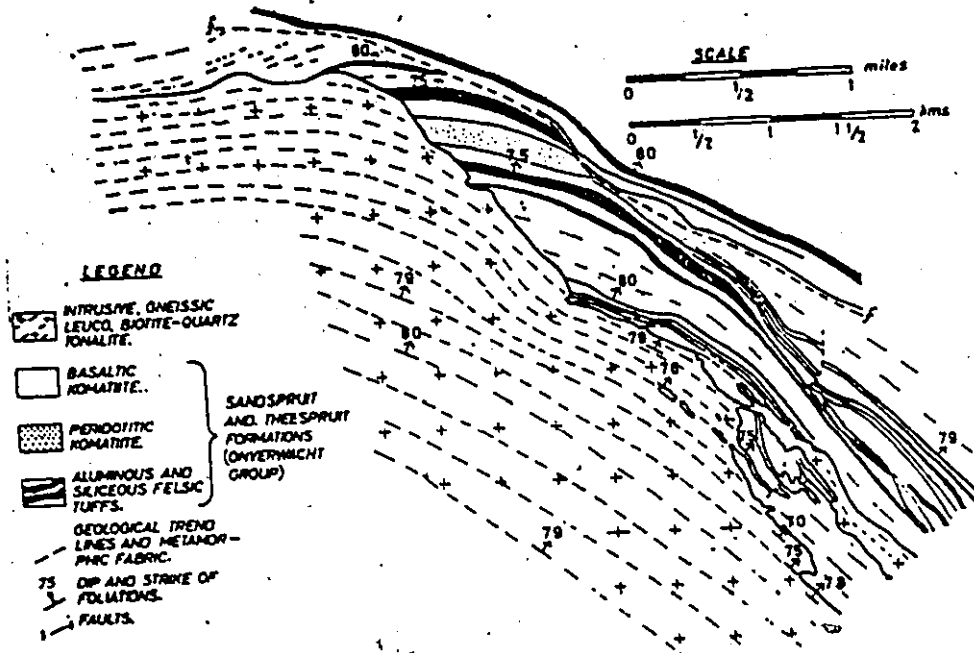
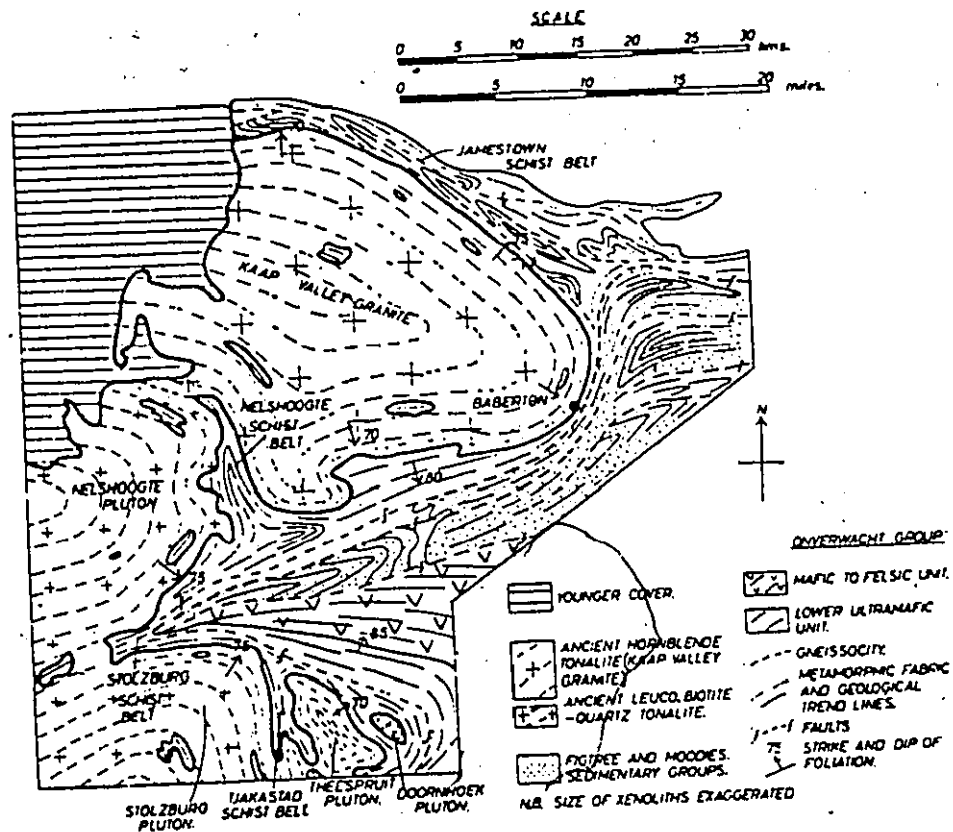


Fig. 46 from Hunter 1973



Typical contact phenomena of an ancient diapiric tonalitic pluton as demonstrated by the northern margin of the Theespruit pluton.

Figs. 47 and 48 from Viljoen and Viljoen 1969-4



General tectonic style and mode of emplacement of the ancient diapiric tonalitic plutons or domes.

Deformation (after Ramsay 1963)

- D₄ F₄ Small, flat-lying, crenulation folds (kink band folds). Monoclinal folds which, when fully developed, are in conjugate pairs.
- L₄ Horizontal to sub-horizontal. Associated with crenulation folds.
- D₃ F₃ Large open upright folds. No significant minor folds. Thrusting along Sheba anticlinorium? Faults, fractures, and shear zones related to inflection of Eureka syncline.
- D₂ F₂ Very few major folds: S folds plunge steeply on F₁ limbs. Minor folds may be related to cleavage. Complex interference structures, small basins and domes.
- S₂ Slaty cleavage, well developed in the hard brittle shales, not readily detectable in massive quartzitic units. Cuts obliquely across bedding of Eureka syncline and is most evident in the area of inflection of the major fold, where intersection of bedding and cleavage is a maximum.
- L₂ Stretch lineations, probably related to emplacement of Kaap Valley and Nelspruit granites. Cleavage bedding intersections (?) in Bariaanskop quartzite.
- D₁ F₁ Large folds: synclines and isoclinally folded anticlinoria, steeply dipping axial surfaces. Thinning by shearing and boudinage, locally by thrusting, decollement on talc carbonate. Minor folds 1 cm to > 1 m.
- S₁ Not noted.

The steep dip of D₁ thrusts is not noted in other areas studied, though it may be implicit in the interpretation of Coats et al. (1972) for Flin Flon. In all other respects, the deformational history follows the pattern common to Archean and later periods.

Metamorphism

Anhaeusser (1971-2) notes that the structural history can be followed step by step petrologically by examining thin sections of the metamorphic rocks of the area. The metamorphism produced by the granites caused mineral reorientation and several periods of mineral development and deformation. Some retrograde metamorphism occurred in the waning phases. Unfortunately, the details have yet to be published.

Viljoen and Viljoen (1969-1) note that as with most greenstone belts, the entire Barberton Mountain Land suffered only low-grade regional greenschist facies metamorphism, and within the sedimentary core there are virtually no signs of even the lowest grade of metamorphism. Along the immediate granite contact zone, the Onverwacht volcanics are upgraded to upper greenschist facies and locally to amphibolite and granulite facies.

Ore Deposition

Pre-tectonic

Asbestos and Magnesite (Viljoen and Viljoen 1969-6) (Figs. 49, 50)

The two mines in the Swartkoppie (uppermost Onverwacht) Formation produce more asbestos (chrysotile) than all others together in the Barberton Mountain Land. Very strong shearing is typical and the only rocks positively identified are resistant chert bands. All the serpentine pods hosting the asbestos are in the same stratigraphic position and probably constituted a differentiated sill (6). Relict olivines indicate the original rock was peridotite or dunite.

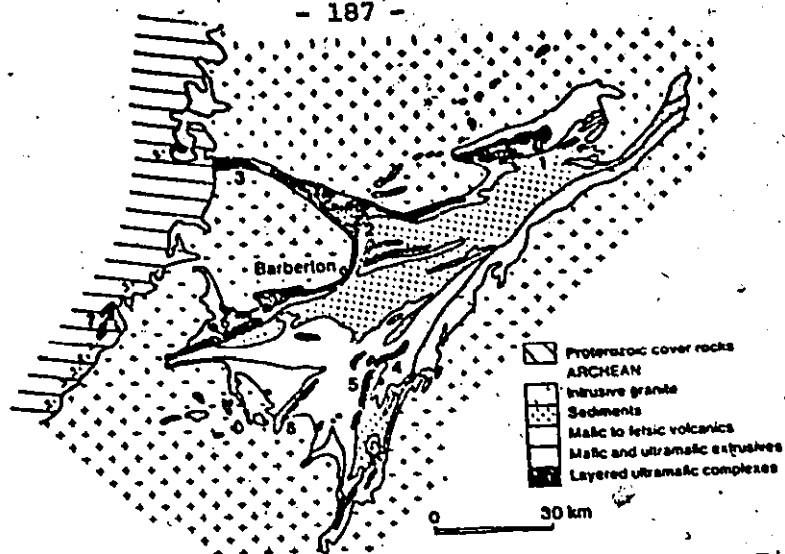
Up to fifteen small mines have operated in the serpentinized differentiated ultramafic bodies of the lower Onverwacht, primarily in the Komati Formation.

Stolzberg-type ultramafic bodies include some of the more important producers. The Stolzberg body itself is almost entirely an alternating succession of dunite and orthopyroxenite.

Noordkaap-type ultramafic bodies are sequences of olivine peridotites, pyroxene peridotites, pyroxenite, and gabbro. This is less differentiated than the Stolzberg type and ore, which is in olivine peridotite rather than dunite, is low grade.

Kaapmuiden-type ultramafic bodies have a narrow chill-zone of peridotites at the base followed by olivine peridotites-dunite zones, orthopyroxenite, anorthositic gabbro or norite, and an upper zone of dunite-peridotite. The asbestos, of minor importance, is in the dunite-peridotite zones, and also in these zones are extensive magnesite deposits.

In the Upper Onverwacht, in addition to the rich Swartkoppie bodies discussed earlier, the Hoeggenoe Formation carries asbestos, again in basal dunite and peridotite layers of ultramafic sills (5).

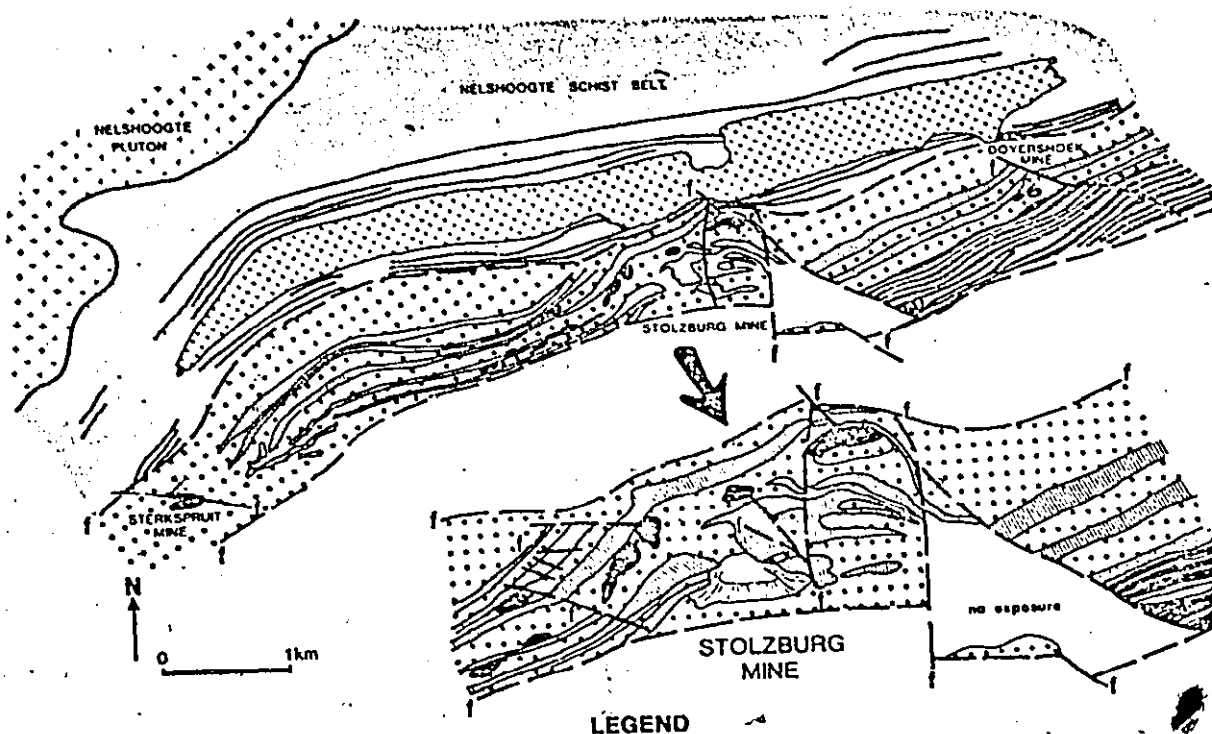


Figs. 50 and 51 from
Anhaeusser 1976-2

LAYERED ULTRAMAFIC COMPLEXES

- 1 Koedoe Ultramafic Body
- 2 Handsup-Mundi's Concession Ultramafic Body
- 3 Kaapsehoop Ultramafic Body
- 4 Havelock Asbestos Mine, Swaziland
- 5 Msauli Asbestos Mine
- 6 Stolzberg Ultramafic Body
- 7 Kalkkloof Ultramafic Body
- 8 Rosenblum Ultramafic Body

✕ Chrysotile Asbestos Deposits in Dolomites
of the Transvaal Supergroup



- | COUNTRY ROCKS | | STOLZBURG DIFFERENTIATED BODY |
|--|------------------------|--|
| ONVERWACHT GROUP | INTRUSIVE ROCKS | |
| Basaltic lavas and tuffs-
Peridotitic lavas | Diabase sheet | Rodingite-altered gabbro |
| Quarry | Leuco-tonalite gneiss | Metagabbros and noritic rocks |
| Dump | Fault | Serpentinized peridotites, harzburgites |
| | Breccia | Orthopyroxenites |
| | | Serpentinized dunite ("ore zone" serpentinite) |

Geologic map of portion of the Stolzberg layered ultramafic body showing the distribution of asbestos mineralization at dunite-orthopyroxenite contacts and associated with cross faults. Folding accompanies the faulting in the Stolzberg mine area.

Iron

Fig Tree iron formations are mined at Ngwenya (Bomvu Ridge) (Bursill et al. 1964]. At the mine, the base of the Fig Tree Group consists of banded ferruginous chert which is overlain by a thick zone of banded iron formation (Beukes 1973, Anhaeusser 1976-1).

Syn-tectonic

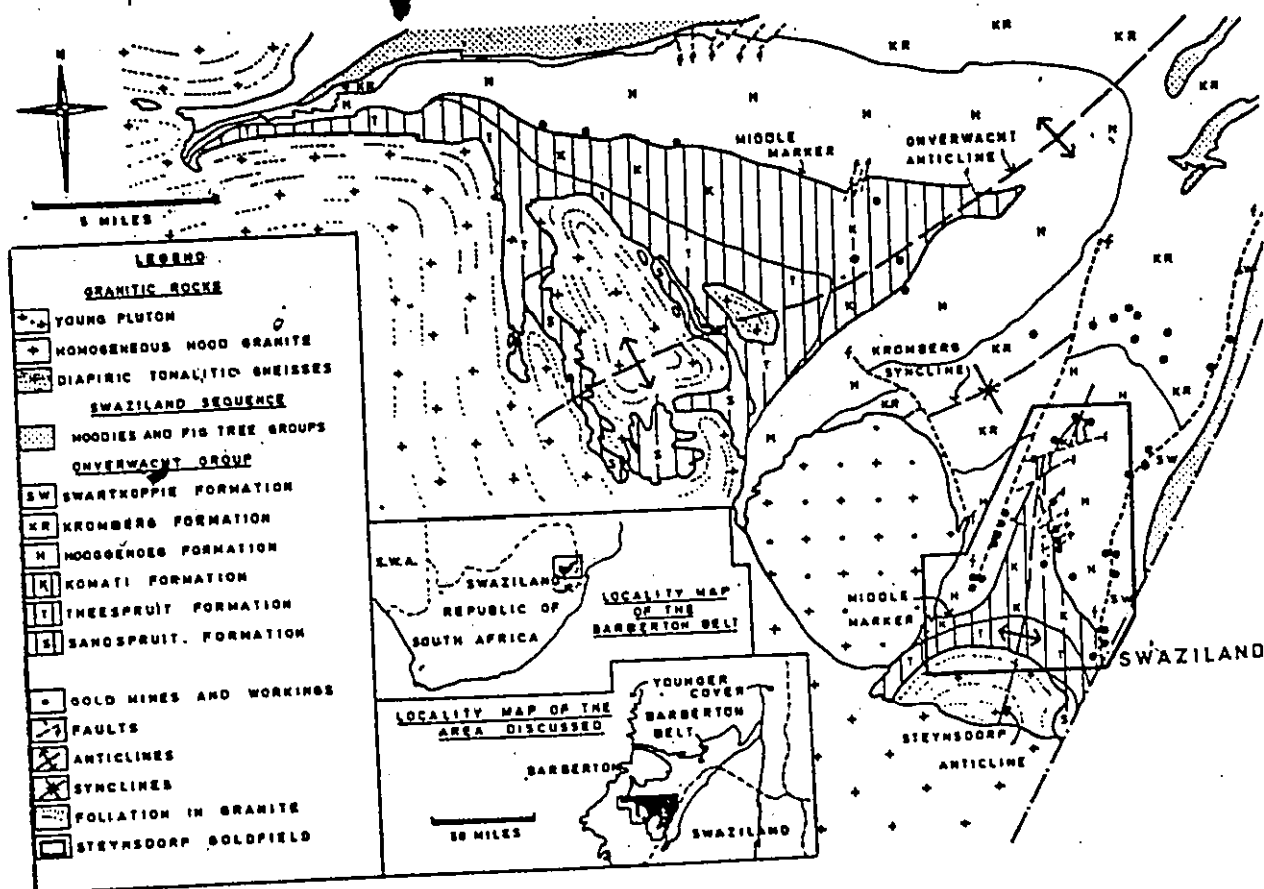
Gold (Fig. 51)

D₃ Gold-quartz with subordinate sulphides in fractures.

D₂ Gold-sulphide mineralization.

(Ramsay 1963 and subsequent discussion)

Anhaeusser (1976-11) in one paragraph covers the essentials of gold genesis: "Gold mineralization occurs throughout the Archean stratigraphic column but is preferentially developed in the volcanic-rich units and in banded iron-formation, cherts, and, to a lesser extent, in argillites and quartzites. Some gold also occurs in the granitic rocks, particularly where these occur adjacent to greenstone belts or their xenolithic remnants. The ultimate source of the gold appears to be genetically related to volcanogenic activity... Although no quantitative supporting data are available... (the opinion of Anhaeusser, the Viljoens, and Saager is)... that the basaltic and peridotitic rocks of the Lower Ultramafic Unit were the primary hosts of much of the gold mineralization... Gold and associated sulphides are, however, widespread in volcanogenic rocks of the Mafic to Felsic Unit. These rocks are generally further removed from intrusive granite bodies than the stratigraphically lower basaltic and peridotitic assemblages and have, therefore, been less affected by metamorphism than the latter successions. The concentration of the mineralization in the areas rimming the granite bodies... may therefore be linked with the heat effects consequent on granite intrusion rather than reflect initially higher gold content of these rocks". These considerations, applied by Anhaeusser to all the Archean of southern Africa and not just Barberton are similar to those of Boyle (1961) for Yellowknife, and both have found wide acceptance elsewhere. In addition, as he says, some of the migratory gold may have eventually ended up in the Witwatersrand sedimentary basin.



DISTRIBUTION OF GOLD MINES AND PROSPECTS IN THE SOUTHERN PORTION OF THE BARBERTON MOUNTAIN LAND.

Fig. 51 from Viljoen, Saager, and Viljoen 1969

Ore Production

Anhaeusser (1976-1) notes that up to the end of 1963, a total of 5.65M. oz. Au had been produced from 274 recorded producers. Of this total, 62% came from three mines (Sheba, Consort, Fairview) whereas 99.3% of the total came from 45 mines. The balance of 0.7% came from the remaining 229 deposits.

The Mining Magazine classification of ore production for 1974 is:

Ngwenya	B	Fe
Havelock	B	Asbestos

- 192 -

LIMPOPO BELT
RHODESIA, BOTSWANA, AND SOUTH AFRICA

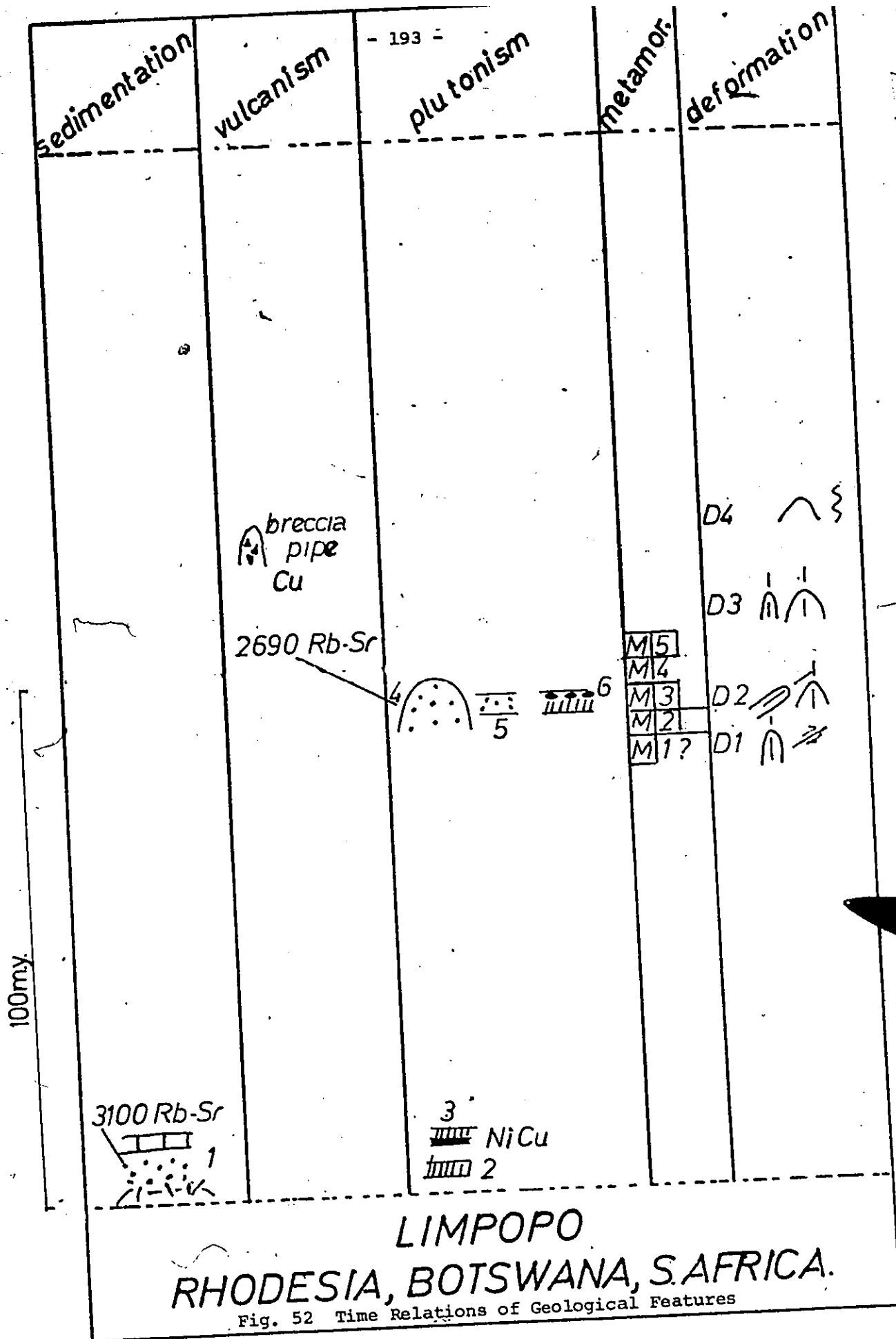


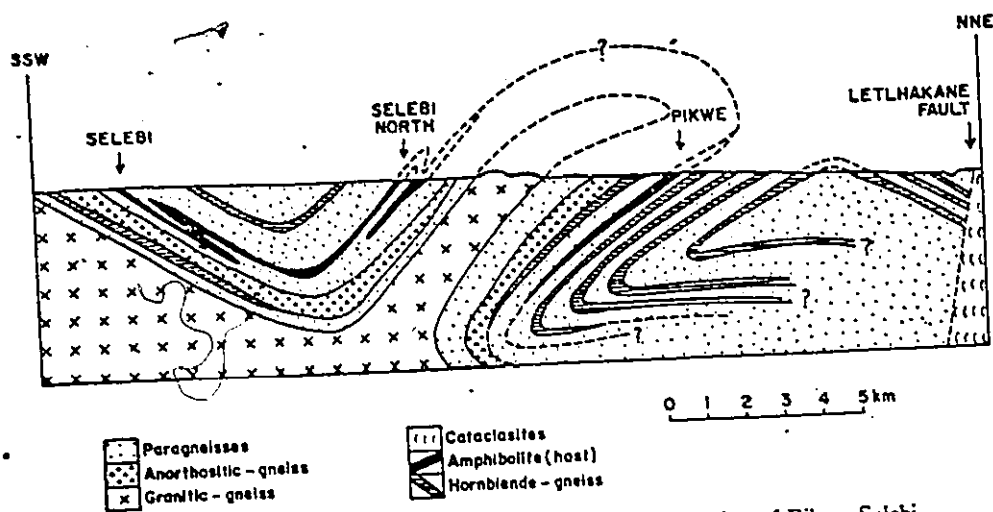
Fig. 52 Time Relations of Geological Features

Stratigraphic Succession (Figs. 43, 53)

This heading is used rather than Vulcanism and Sedimentation as the Limpopo succession is largely gneisses, and origins are not all known. At Pikwe, Hickman and Wakefield (1975) give the succession (1) as:

<u>Unit</u>	<u>Name</u>	<u>Description</u>
10.	Upper Sedimentary Group	Calcite-dolomite marble and impure quartzite with minor pelite, ironstone, and amphibolite horizons.
9.	Pelitic Schist	Cordierite-sillimanite-garnet-bearing biotite schist with local gneissic intercalations.
8.	Diopside Amphibolite	Banded diopside - hornblende amphibolite with hornblende gneiss and garnetiferous amphibolite.
7.	Biotite and Hornblende Gneiss	Variously migmatized gray gneiss with local sillimanite-bearing horizons.
6.	Ore Horizons (3)	Host amphibolite with pyrrhotite, chalcopyrite, pentlandite, and magnetite.
5.	Banded pink gneiss	Migmatitic granitoid gneiss with subordinate gray gneiss and thin horizons of cordierite-sillimanite-biotite gneiss.
4.	Hornblende Gneiss and Amphibolite (2)	Gradational contact with unit 5 as hornblende content increases.
3.	Anorthositic Gneiss	
2.	Quartzofeldspathic Gneiss	Quartz-rich, pink, banded gneiss.
1.	"Basement" Granite Gneiss	Homogeneous, pink, locally porphyroblastic, granite gneiss.

The lithology of the Messina Formation, 200 km to the east, is comparable. Mason (1973) notes quartzofeldspathic gneisses, amphibolites, quartzites, and calc-silicate rocks: most of the amphibolites and some of the inter-layered serpentinitized ultrabasic horizons represent sill-like basic and ultrabasic intrusions within the Messina Formation, which may or may not be related to major anorthosite complexes. Key et al. (1976) correlate the Messina with the Tutume of Vumba.



Simplified section showing probable structural setting of Pikwe-Selebi nickel-copper deposits

Fig. 53 after Gordon 1973

Plutonism

$M_3 - D_2$ Anorthosite (6) (Key et al. 1976)

Pre- D_2 Intrusion of large sheets of granite often porphyritic.
Migmatite units. Segregation of quartzo-feldspathic
material, emplacement of granite and pegmatite veins (4)
(Coward et al. 1976).

Pre- D_2 migmatite is not recorded (other than as basement) from other areas studied, but a relationship may prove to be demonstrable with remobilized basement, for example in the Rhodesdale batholith of the Midlands Belt in Rhodesia and the Round Lake and Chibougamau plutons at Kirkland Lake and Chibougamau in the Abitibi Belt.

Late anorthosite has not been noted in other Archean areas studied.

Deformation (after Gordon 1975, Key et al. 1976 and Coward et al. 1976)

- $D_4 F_4$ Slight folding of F_3 fold axes.
- $D_3 F_3$ Tight isoclinal and more gentle open folding.
- S_3 Axial planar schistosity.
- $D_2 F_2$ Plastic and cataclastic deformation. Over most of the period, rocks were plastic. Phases of cataclastic deformation evident from shears and mylonite. Open folds in south, more intense and recumbent folds in north.
- S_2 Penetrative fabric, locally weak, intensified in shear zones.
- L_2 Rodding parallel to fold axes.
- $D_1 F_1$ Tight to isoclinal folding. Major folds best seen on aerial photographs.
- S_1 Foliation of varying intensity, absent over most of area.

Key and Hutton (1976) note F_3 overturning to the east on the north side and to the west on the south side of the Tuli-Sabi Straightening Zone, relating this to buckling of upright F_2 folds during dextral movement of the shear zone.

Recumbent folding during D_2 has not been noted in other areas of the study, and tight isoclinal folding during D_3 is similarly atypical.

Metamorphism

Key et al. (1976) have the following match with Tati-Vumba:

M ₅ et seq.	Retrogressive.
M ₅ (post-D ₂ , pre-D ₃)	Ultrametamorphism producing anatectites, i.e., amphibolite grade.
M ₄ (=D ₂)	Lower greenschist facies.
M ₃ (=D ₂)	Amphibolite facies (probably granulite locally, vide Coward et al. 1976).
M ₂ (pre-D ₂)	Hornblende and pyroxene hornfels facies (low to medium pressure, high temperature).
M ₁ (=D ₁ ?)	Obliterated by later metamorphism.

This compares with the more simple version established by Wakefield in an early stage of investigations (Gordon 1973):

M ₃	Accompanied F ₃ . Almandine amphibolite facies.
M ₂	Accompanied F ₂ . Retrogression to low epidote - amphibolite facies.
M ₁	Accompanied F ₁ . Granulite facies.

The unusual feature of Limpopo metamorphism is the pre-D₂ granulite facies.

Ore Deposition

Pre-tectonic

Nickel-Copper (Fig. 53)

The work of Wakefield (1976) on the Pikwe orebody is of the type desirable for all pre-orogenic orebodies. For this particular body, he notes, for example, that the practical value of structural geology lies mainly in the prediction of local areas of structural complexity in which the dip, strike, and thickness of the orebody may vary substantially over distances of 20 m or less in the predominantly regular stratabound horizon. Structural and metamorphic history is also related to sulphide textural type:-

Structure of the Pikwe Orebody (Wakefield 1976)

- D_3F_3 Minor structures are sporadically developed, upright, symmetrical folds, generally plunging at low angles to SW. Major structure interpreted as very open antiform.
- D_2F_2 Axes of minor folds show considerable variations in orientation, majority plunge NW. Open to tight, asymmetric, with gentle to moderately dipping axial planes. S shaped major antiform (overturned recumbent host to Pikwe orebody). Cataclastic rocks concordant with S_1 (D_2b) in zone up to 10 m thick on sheared (D_2b) E edge of orebody.
- D_1F_1 Minor folds are rare.
- S_1 Gently dipping foliation
- L_1 Rodding lineation well developed in wall rock gneisses, plunge 22° SW.

Sulphide Deformation of the Pikwe Orebody (Wakefield 1976)

The final product of intense sulphide-silicate deformation is breccia sulphide containing numerous subangular silicate fragments.

- Late D_3 Large undeformed angular inclusions probably incorporated into sulphide sill.
- Post D_2 Plastic deformation of sulphide. Sulphide sill locally cuts across F_2 minor folds.
- D_2 Contorted inclusion sulphide associated with areas of D_2 deformation and therefore considered to be mainly of D_2 age. Sulphide sill, though broadly concordant, commonly cuts across S_1 foliation and contains numerous S_1 foliated gneissic inclusions.

Sulphide Textural Types Related to Deformation and Metamorphism of the Pikwe Orebody (Wakefield 1976)

- Post M_3
Cooling Shear zones entirely within massive sulphide. Average thickness 3 cm, lateral 15 m parallel to sulphide sill. Steeply aspect due to fine intergrowth of extensively twinned pyrrhotite and elongate chalcopyrite. Annealing recrystallization of pyrrhotite. Kink bands in pyrrhotite crystals.
- D_3M_3 Recrystallization of sulphides deformed in D_2b . Pyrite crystallized. Coarse, pre-existing pyrrhotite textures deformed by ductile deformation, probably by twin gliding on (0001). Plastic deformation of main sulphide sill.
- D_2b Shear zones with 10% pyrite forming small (0.01 mm) euhedral crystals generally surrounded by chalcopyrite. Pyrrhotite occurs as fine polygonal grains (0.01 to 0.03 mm) or as larger irregular crystals (0.3 mm). Chalcopyrite appears to replace both pyrrhotite varieties. Pentlandite forms flames in the coarse pyrrhotite or equant grains interstitial to the polygonal pyrrhotite crystals. Textures are interpreted as product of M_3 recrystallization of sulphides deformed in D_2b (Wakefield groups D_3 and M_3 but under D_2b does not say which textures are interpreted as M_3).

- D_2S_2 Banded ore, composed of sub-parallel lenses and discontinuous bands of chalcopyrite in pyrrhotite. Bands up to 1 cm thick along contacts between massive sulphide and gneiss in limbs of F_2 folds.
- Late M_1 Pegmatoid sulphides. Pyrrhotite up to 5 cm. Well-developed rims of interstitial pentlandite. Pyrrhotite irregular in shape, no preferred orientation. Chalcopyrite interstitial or associated with gangue minerals. Pegmatitic fabric suggests crystallization under essential hydrostatic stresses, supporting late M_1 interpretation of age.
- D_1S_1 Disseminated or semimassive sulphide in amphibolite occurs in thin discontinuous bands parallel to S_1 . Pyrrhotite with preferred orientation (0001) subparallel to S_1 . Flame pentlandite well developed, interstitial pentlandite forms continuous rims around pyrrhotite crystals. Preferred orientation of pyrrhotite interpreted as due to recrystallization during D_1 .
- Emplacement Blobs of one or two pyrrhotite crystals, containing flame pentlandite and bordered by discontinuous runs or isolated crystals of interstitial pentlandite. Chalcopyrite and ilmenite-free magnetite also occur peripherally, seldom as more than one crystal or crystal aggregate in each blob.

Wakefield (1976) also discusses the morphology of the Pikwe deposit. Though the trend of the thick amphibolite is subparallel to both L_1 and F_3 he considers a relationship with D_3 appears unlikely in view of the open style of the F_3 antiform and the limited intensity of the D_3 deformation in the area around the deposit. On the regional scale the Pikwe, Selebi North, and Selebi orebodies fall on a line which appears to be subparallel to L_1 and so a product of D_1 deformation. The shape of the host amphibolite may be at least in part an original igneous feature which subsequently localized D_1 and D_2 at originally thin places in the troctolite intrusion.

Ore Production

Ore
Produced

Pikwe

Not Available

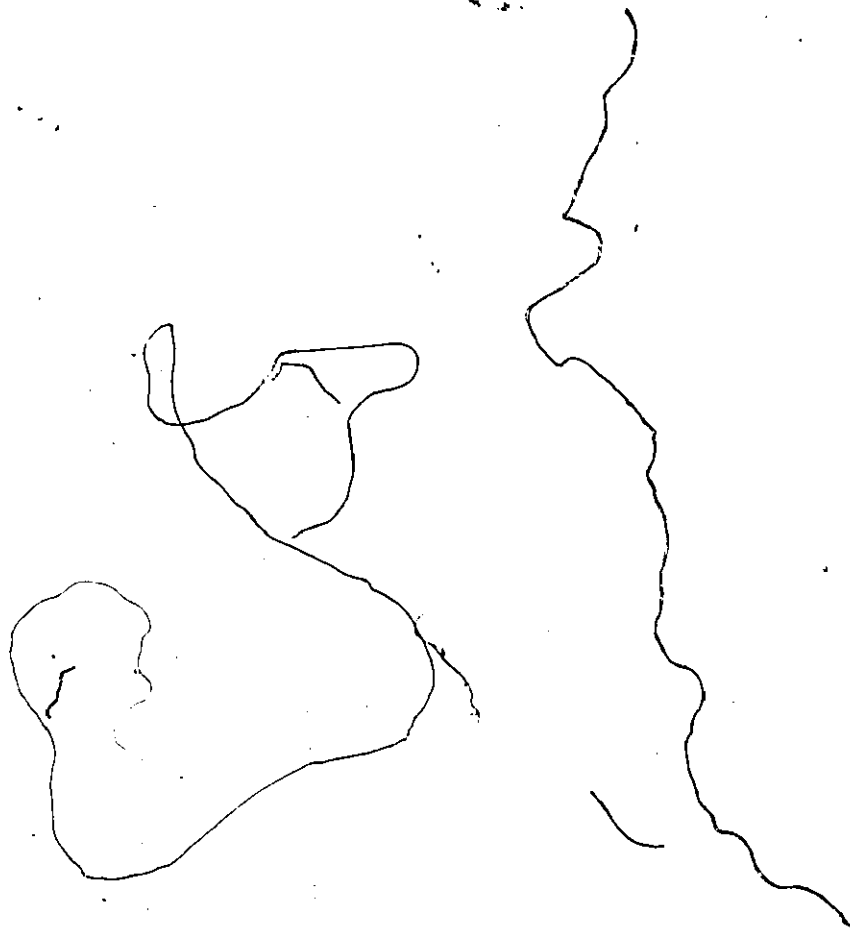
The Mining Magazine classification of ore production for 1974 is:

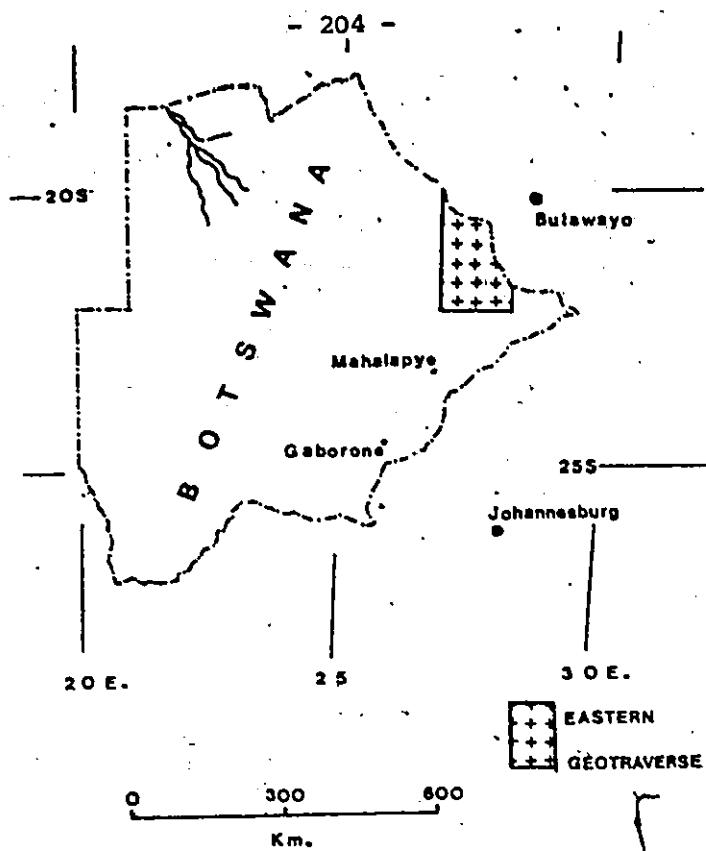
Pikwe

B

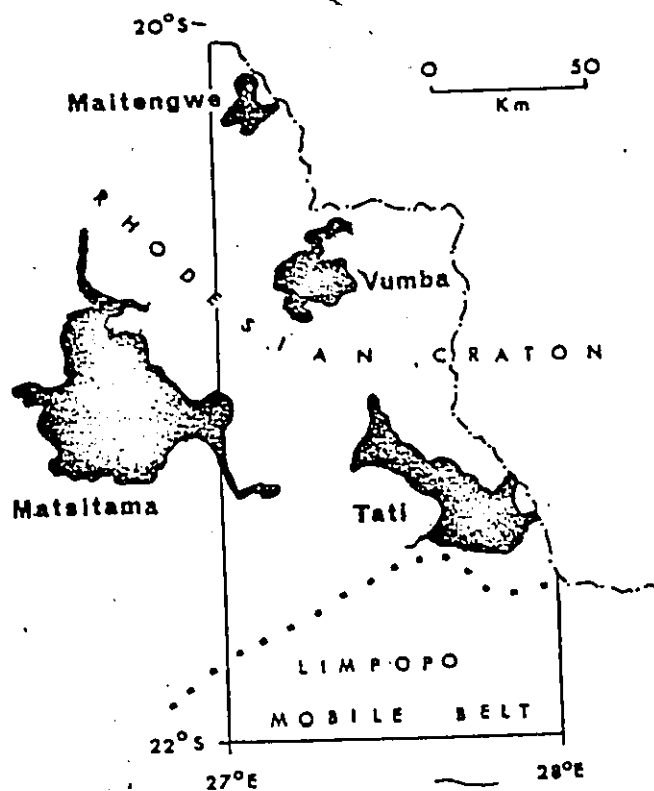
Cu, Ni

VUMBA AND TATI, BOTSWANA

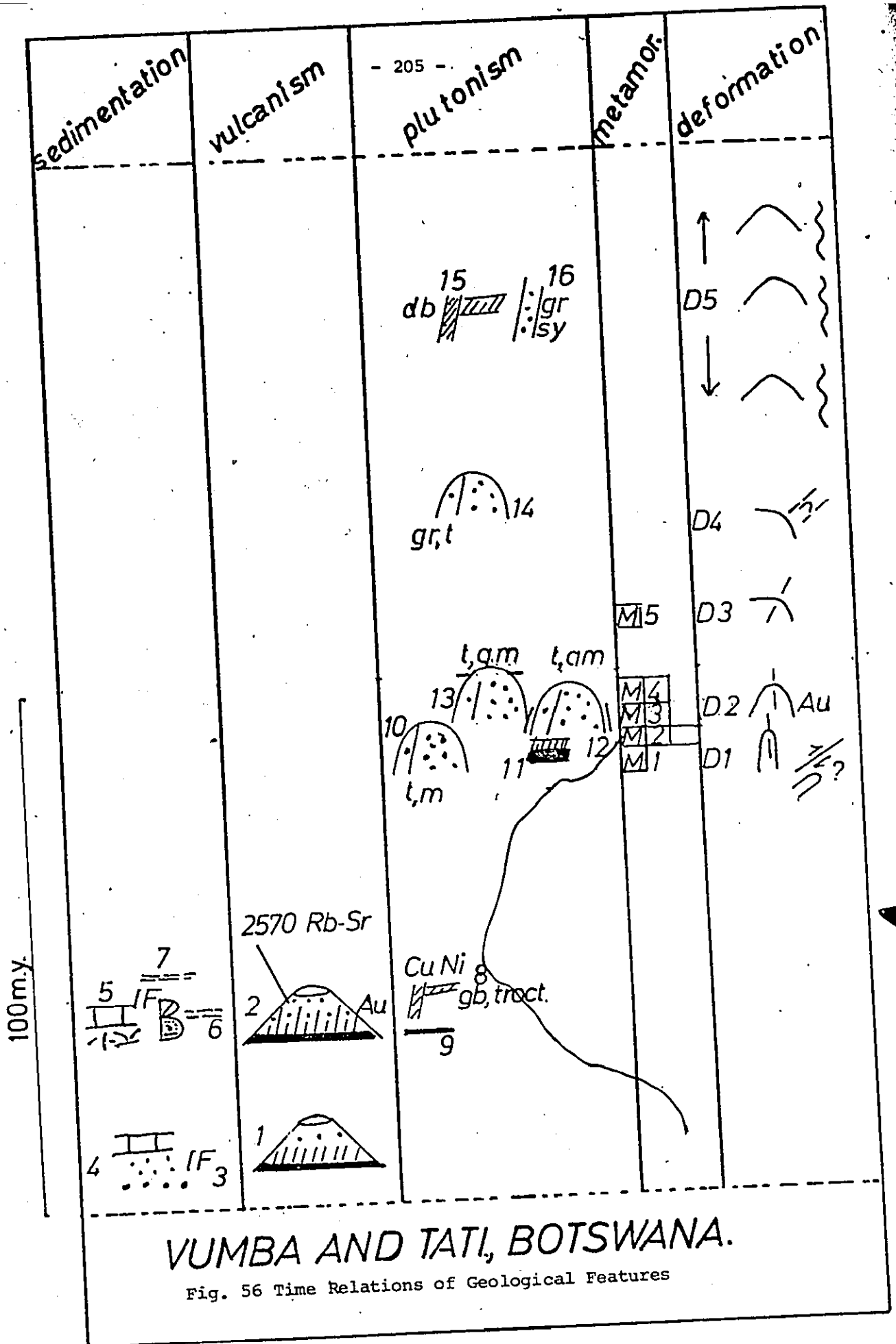




Figs. 54 and 55
from Key et al. 1976



Location of the four schist relics of northeast Botswana in relation to the Eastern Geotraverse which is outlined on the diagram.



Vulcanism and Sedimentation (after Key et al. 1976) (Figs. 43, 55, 57, 58)

Tati

Greenstone Group?

? Thickness

4. Selkirk Volcanic Formation

Wedge-shaped body of acid volcanics. Quartz-, feldspar-, and quartz-feldspar dacite porphyries with minor felsic agglomerates, tuffs, basalts, and rare semi-pelites. (7) Gabbro intrusives. (8).

3. Penhalonga Formation

3500 to
> 9000 m

(c) Andesite lavas, agglomerates, and tuffs with minor sediments (7).

(b) Thin aluminous schist (6).

(a) Basin

Flanks of basin (2)

Pelagic graywackes (turbidites) and graphitic phyllites (5) with andesites, basalts, felsic volcanics (2), and minor clastic ironstones and conglomerate.

Andesites, rhyolites, limestones, sub-graywackes, and calc-phyllites.

Ultramafic Group? (1)

1750 m

2. Lady Mary Formation

Amphibolites with extensive basalts and dolerites and discrete horizons of ultramafic schists, serpentinites, jaspilites, limestones, and semi-pelites to pelites. The amphibolites locally contain vesicles, amygdalae, and pillows.

1. Old Tati Arkose Formation
Kgarimacheng Ultramafic Formation

The Shashe Gneiss

The Old Tati arkose has interlayered quartz-pebble conglomerates (3), pelites (4), amphibolites, ultramafics (1), and jaspilite. The Kgarimacheng ultramafics (1) also include Fe-quartzites, fuchsite quartzites, arkoses, and felsic tuffs (4).

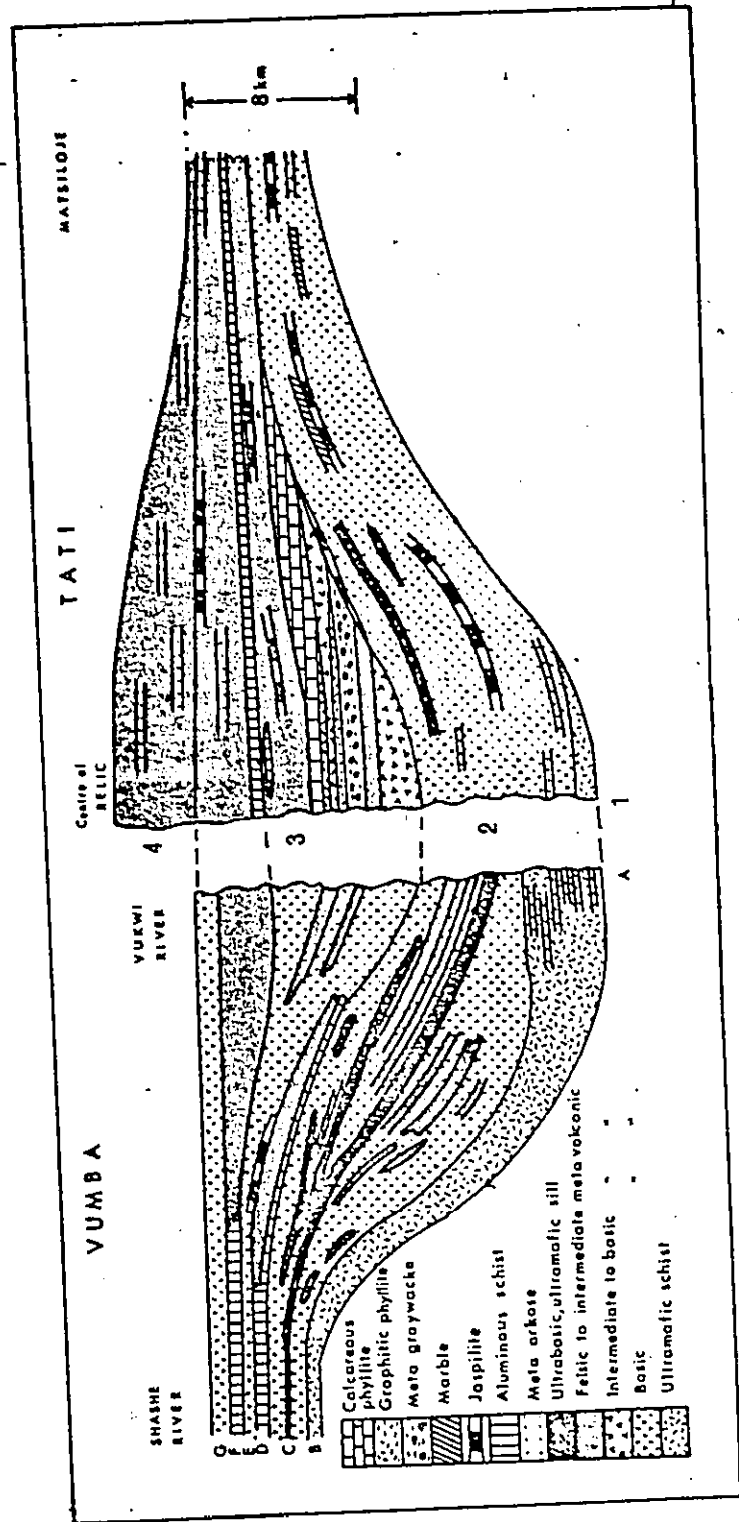
The Shashe Gneiss is dominantly marble and quartzite with minor pelites, calc-silicates, Fe-quartzites (4), amphibolites, and ultramafics (1), interlayered with arkoses.

Correlation of formations in the Tati and Vumba schist relics			
Tati schist relic	Vumba schist relic		
Selkirk Formation	4		
Penhalonga Mixed Formation	{ Upper Vumba Mafic Formation		
	{ Upper Vumba Felsic Formation		
	{ Lower Vumba Mafic Formation		
{ Lower Vumba Felsic Formation			3
Lady Mary Formation	{ Vumba Mixed Volcanic Formation		
	{ Sebina Ultramafic Formation		
{ The Extended Schist Relic Succession continues beneath these formations			1
			2

= Bulawayan

= Sebakwian

Fig. 57 from Key et al. 1976



Diagrammatic correlation of the stratigraphic successions at Vumba and Tati.

N.B. the beds are steeply dipping.

One has the impression that Units 1 and 2 are the equivalent of the Sebakwian (= Lower Ultramafic) and Units 3 and 4 are the equivalent of Bulawayan (= Greenstone Group). A more precise correlation is suggested here on the basis of fuchsite quartzites in the Kgarimacheng Ultramafics (Unit 1) and those in a zone of the Rhodesdale batholith of Rhodesia, where "xenoliths consisting largely of quartz-fuchsite and sericite schists as well as ultramafic material... are closely comparable with the diagnostic rock types of the Theespruit formation" (Viljoen and Viljoen 1969-71). The arkosic fraction provides evidence of contemporaneous erosion from a continental environment.

The Penhalonga Formation exhibits the cyclicity which characterizes the Greenstone Group of Anhaeusser (1971-1). Key et al. (1976) suggest the aluminous schists may have been bauxites: if so, whatever these were weathered from, the bauxitic product would be one of the oldest known.

The amount of carbonate noted in these areas and the adjoining Limpopo is unusual in the areas studied.

Plutonism (after Key et al. 1976)

The relationship of the plutonism and granitization to deformation is:

D₅ Dolerite (15) dykes and sills, granite and syenite (16) dykes.
Granite stocks (14) (G₅).
Tonalite stocks (14) (G₄)

D₄

D₃ Granite veining and local anatexis (12) (G₃)

D₂ Regional granitization (G₂)

Tonalite-monzonite plutons (10), minor basic and ultrabasic intrusions (11) (G₁).

D₁

G₁ The monzonites (10) are hybrid with xenoliths of stope blocks. Marginal zones of the tonalites (10) often contain blocks of country rock. Contacts are sharp. There are a few marginal pegmatites.

G₂ Granitization produced lit-par-lit gneisses, adamellite (12) from the clastics of the Tutume Group and tonalite (12) from the volcanics.

G₃ Tonalite and adamellite anatectites (13).

G₄ Small tonalite (14) stocks lacking fabric, with sharp contacts and numerous pegmatites.

G₅ The Timbale granite (14) differs from other G₅ granites in having a metamorphic aureole with granite pegmatite sheets.

Other than the D₅ hypabyssals (15 and 16) (which may or may not be related to the sequence) the sequence is identical to the Barberton model: early D₂ tonalite-monzonite diapirs (10), granitization (12 and 13), and discordant stocks (14).

Deformation (after Key et al. 1976, Coward et al. 1976)

- | | | |
|-------------------------------|---|---------------------|
| D ₅ F ₅ | Open warps | } several episodes. |
| S ₅ | Brittle shearing | |
| D ₄ F ₄ | Monoclinial flexures. Crenulations. | |
| S ₄ | Shear cleavage on steeper limbs of crenulations. | |
| D ₃ F ₃ | Folding and local intensification of F ₂ on similar trend.
Large monoclinial flexures. Upright. | |
| S ₃ | Generally steeply dipping crenulation cleavage. | |
| L ₃ | Locally penetrative. | |
| D ₂ F ₂ | Rare folds related to compression between laterally moving plutons. Axes parallel to subvertical lineation. | |
| S ₂ | Penetrative regionally but varying in intensity. Preferred orientation of chlorite, hornblende, and mica; pressure solution stripes; deformed pillows, spherulites, ocellae, pebbles and grit clasts in conglomerate; preferred orientation of minerals and shape of deformed grains and inclusions in granite and gneiss. Usually subvertical; (unusual shallow dips may be due to shape of intrusive, Key et al. 1976). | |
| S _{2a} | Cuts across S ₂ , nucleates from G ₁ plutons. | |
| L ₂ | Steeply plunging. | |
| D ₁ F ₁ | Subvertical folds steeply plunging minor folds. | |
| S ₁ | Slight flattening of volcanics. Fabric defined by chlorite-mica wisps parallel to bedding. | |

The deformational history is standard but details are so well known and integrated with metamorphic and plutonic histories as a result of the work of Key et al. (1976) that the area provides a model for comparison.

Metamorphism (after Key et al, 1976)

M₅ et. seq. Retrogression related to shearing and other minor tectonism.

M₄ Localized ultrametamorphism producing G₃ anatectites; K metasomatism.

M₃ Synchronous with D₂.

In the amphibolitic gneisses:

Pyroxene overprinted by amphibole.

At Vumba:

Kyanite, staurolite, sillimanite, and garnet, i.e., Barrovian-type, amphibolite facies.

At Tati:

Three steeply-dipping isograds:

Pyrophyllite/kyanite; chlorite/biotite; tremolite/hornblende. Centre of belt, low grade greenschist facies with chlorite, white mica, primary plagioclase and hornblende in the volcanics. Margin of belt, upper greenschist facies.

Mineral growth of M₃ continued after D₂, producing rosettes of chloritoid and amphibole overprinting D₂ structures.

M₂

Progressive, culminating in widespread migmatite.

Outside the greenstone belts:

Clinopyroxene in the amphibolites;
Grunerite-cummingtonite in the ironstones;
Andalusite, sillimanite, white mica, biotite and feldspar in the gneisses, i.e., high-temperature, Abukumu-type metamorphism. Local replacement of mica by sillimanite and feldspar indicates local pyroxene hornfels facies.

Within the greenstone belts:

Lower metamorphic grade, centres almost unmetamorphosed.

M₁

Synchronous with D₁. Chlorite, talc, and sericite wisps indicating greenschist facies metamorphism

The work of Key et al. (1976) results in the area being a model for comparison. The relationship to deformation indicates no direct equivalent when details are discerned.

Ore Deposition

Pre-tectonic

Nickel-Copper (Baldock et al. 1976) (Figs. 58, 59)

Three deposits in the Selkirk felsic volcanic succession of the Tati belt are of commercial interest. One is vein-like in shears. High Ni-Cu ratios suggest derivation from ultramafics. Of the other two, one is associated with troctolite, the other with gabbro.

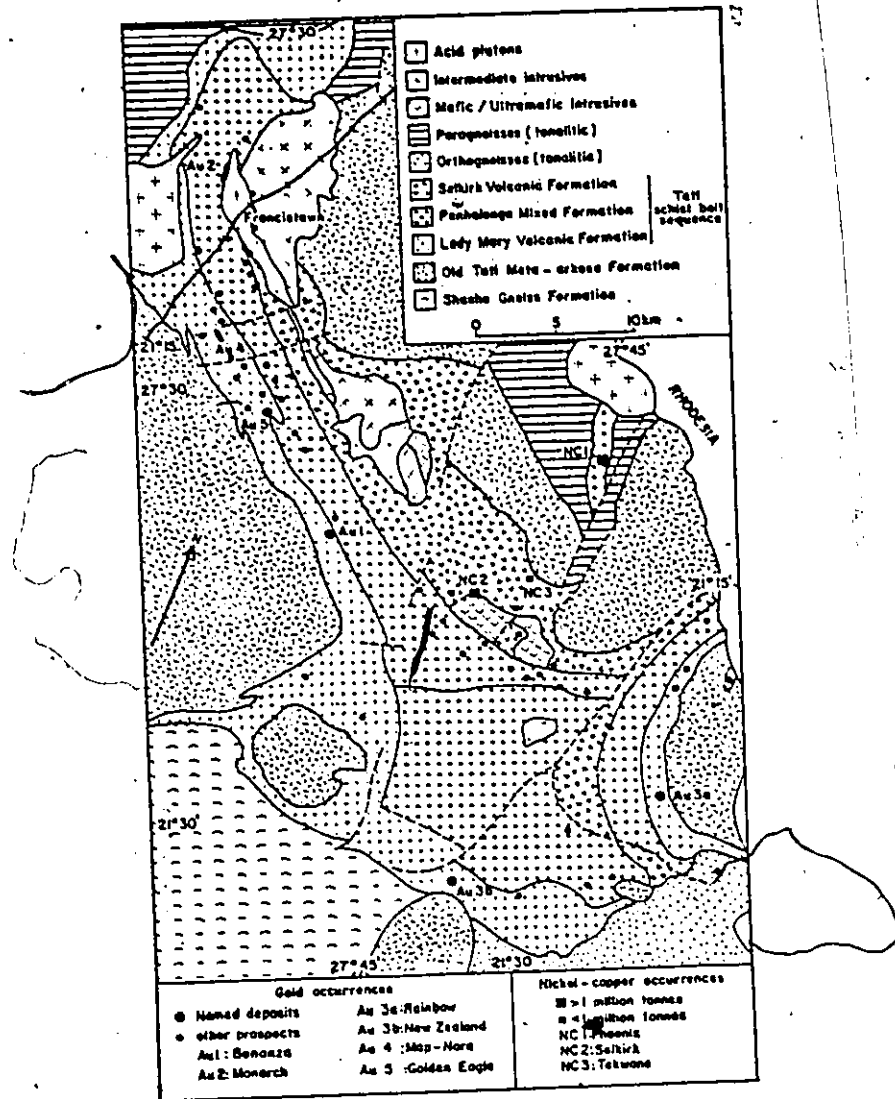
Syn-tectonic

Gold (Fig. 58)

D₃

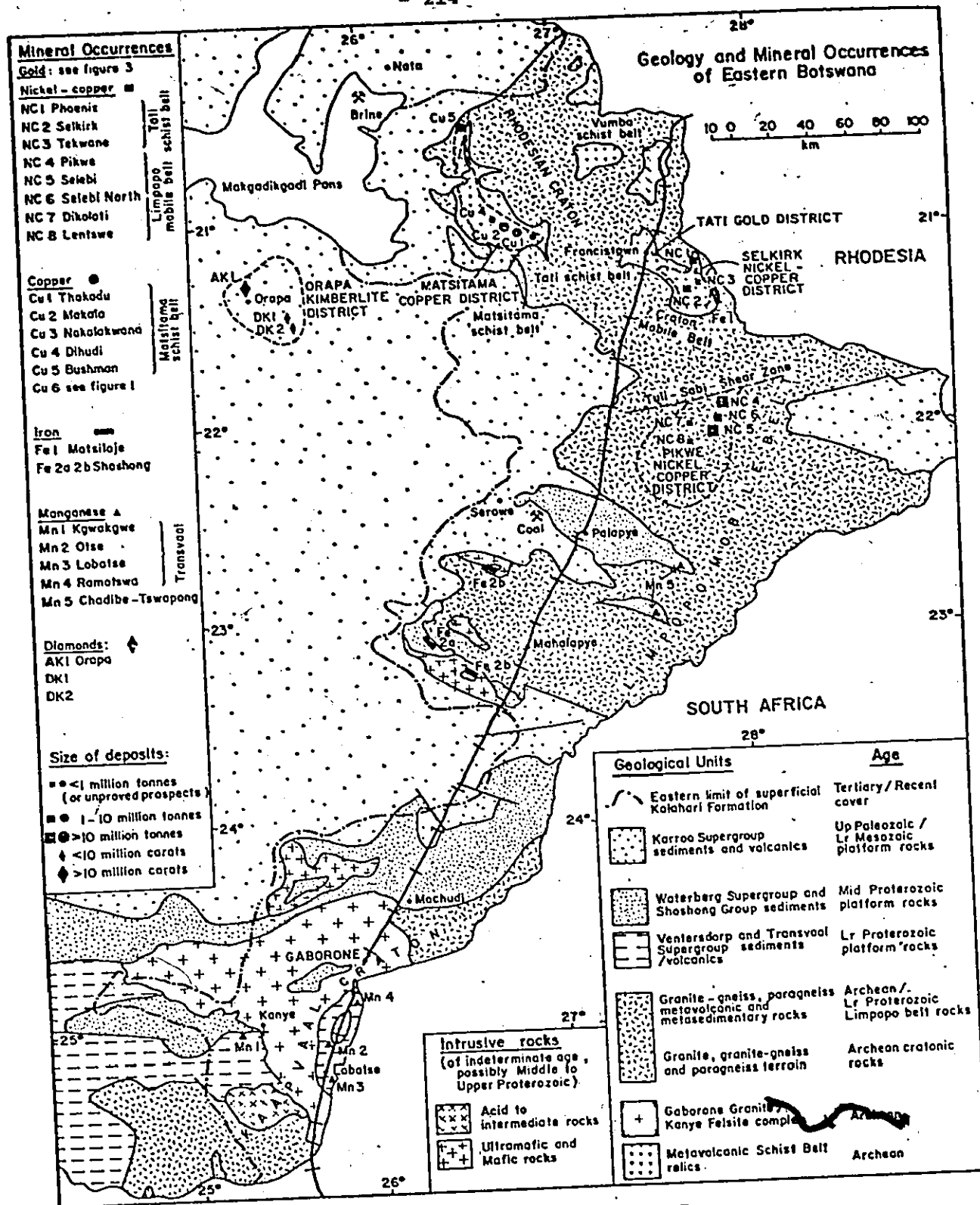
Five classifications are proposed by Boocock (1965): one is dissemination in a structurally disturbed area, the other four are quartz reefs:

- (a) en echelon in volcanics.
- (b) in shears at granite schist contacts.
- (c) near banded iron formation.
- (d) near the top of the Lady Mary volcanic formation.



Geological setting of gold and nickel-copper occurrences in the Tati schist belt.

Fig. 58 from Baldock et al. 1976



Geology and mineral occurrences of eastern Botswana.

Fig. 59 from Baldock et al. 1976

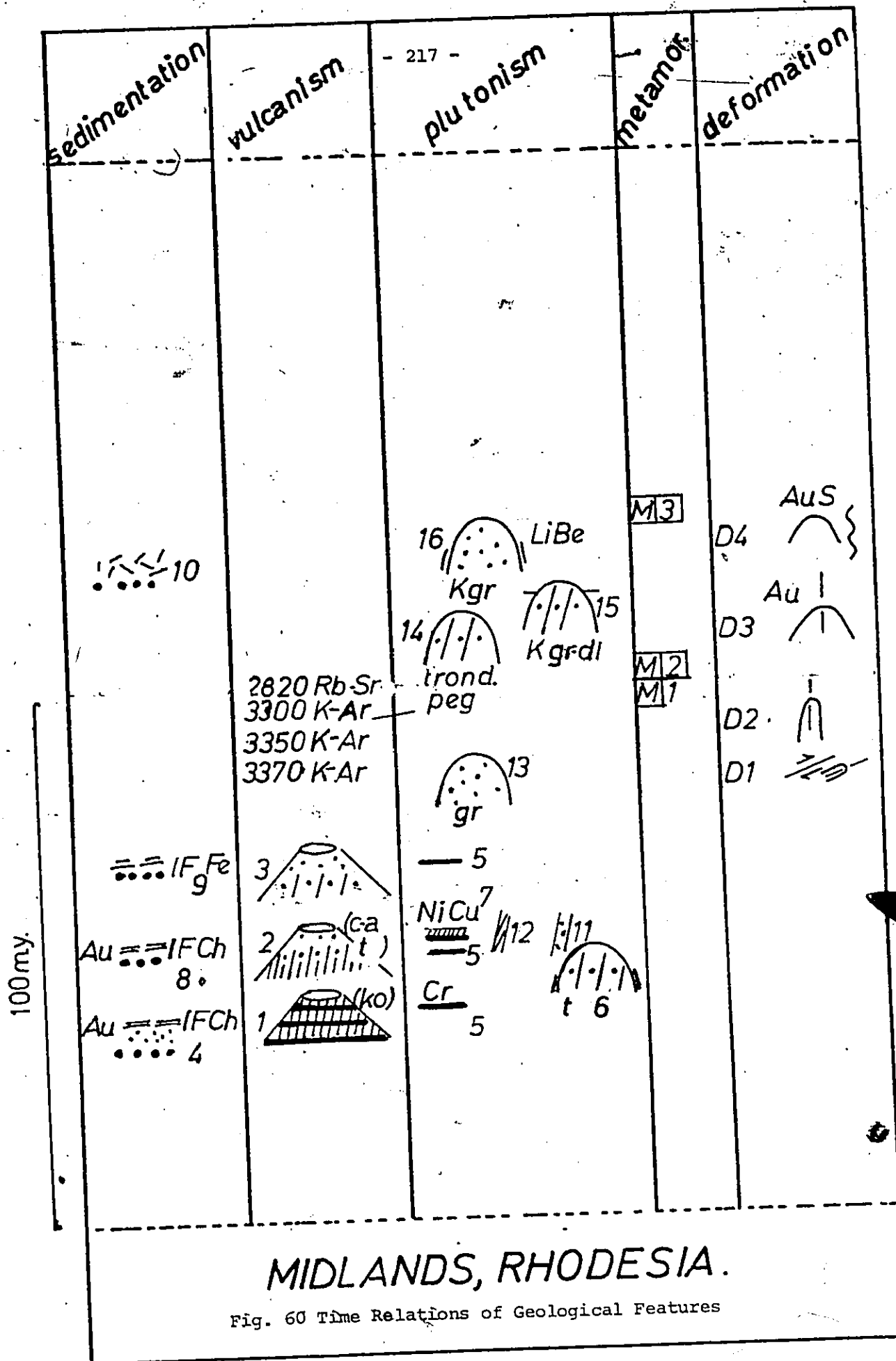
Ore Production (Baldock et al. 1976)

Gold

There are over 60 abandoned gold mines in the Tati area. Peak production was in 1938, when almost 600,000 g were extracted. Silver was a minor by-product. Output ceased in 1964.

- 216 -

MIDLANDS GREENSTONE BELT, RHODESIA



Vulcanism (Figs. 43, 61, 62, 63)

Sedimentary Group (Que Que area) (Harrison 1970)

(Shamvaian Group) (Sediments) (3)

(In other areas includes andesites to felsic types, often rhyolitic: Wilson 1973). Bliss and Stidolph (1969) see no clear distinction between Shamvaian sediments and those intercalated with underlying volcanics).

Greenstone Group

(Bulawayan Group) (2) (Que Que area) (Harrison 1970, Condie and Harrison, 1976)
Felsic Formation

Breccias, tuffs, and flows of andesites and dacites. Intrusive (11) and extrusive felsite, porphyry, and rhyolite. Calc-alkaline. Main type is purple or dark gray, often porphyritic lava. Agglomerate with dacite fragments. Bedded tuffs rare. Intruded by quartz porphyry (11), dolerite, and gabbro (12).

Maliyama Formation

Tholeiitic and andesitic breccias, tuffs, and flows. Agglomerates most conspicuous. Amygdaloidal lavas with rounded amygdules filled with white quartz or carbonate. Porphyritic lavas with white feldspar or dark green phenocrysts. Infrequent, large, white, irregular vesicles. Poor pillows. Intruded by dolerite and gabbro (12).

Mafic Formation

Highly carbonated, pillowed, low-alkali tholeiites with minor but widespread chert and jaspilite (8) clastic sediments (8). Intruded by felsites and small ultra-mafic bodies.

Ultramafic Group (Selukwe area) (Stowe 1968-3)

Lower Greenstone Series (1)

Magnesian pyroclastic schist
Jaspilitic quartzite
Actinolite schist
Chlorite schist

0 - 100 m
0 - 15 m
0 - 150 m
0 - 150 m

Mont d'Or Series (Sediments) (4)

Ultramafic sills intruded in the Lower Greenstone Series.

150 - 1000 m

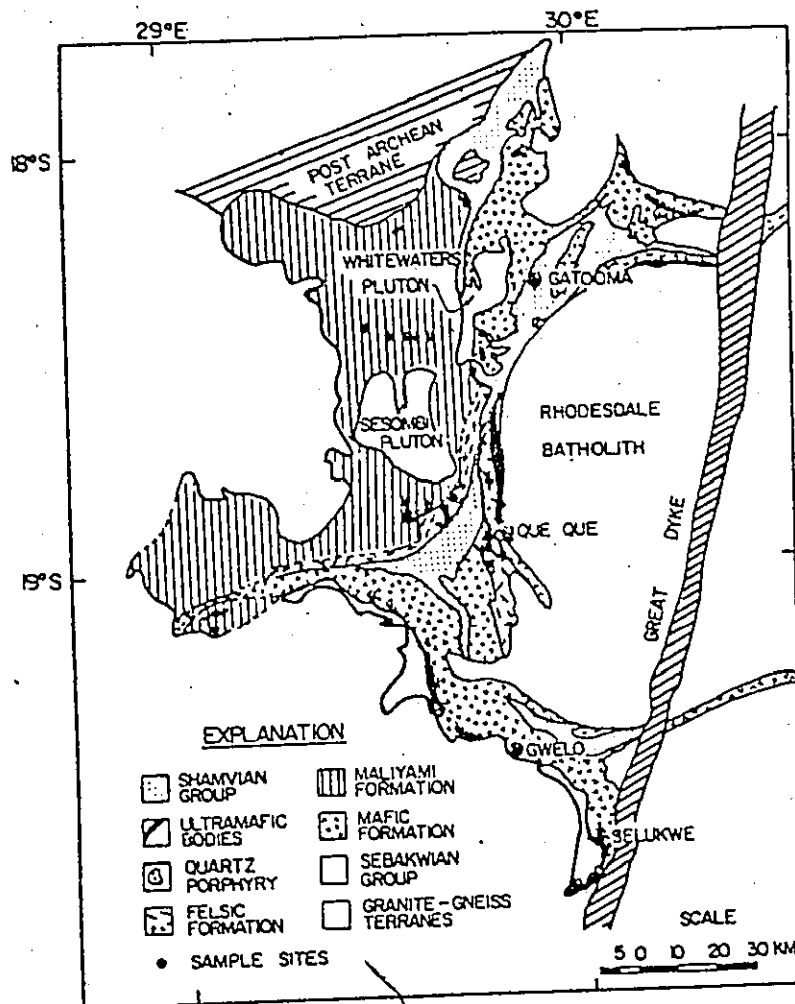
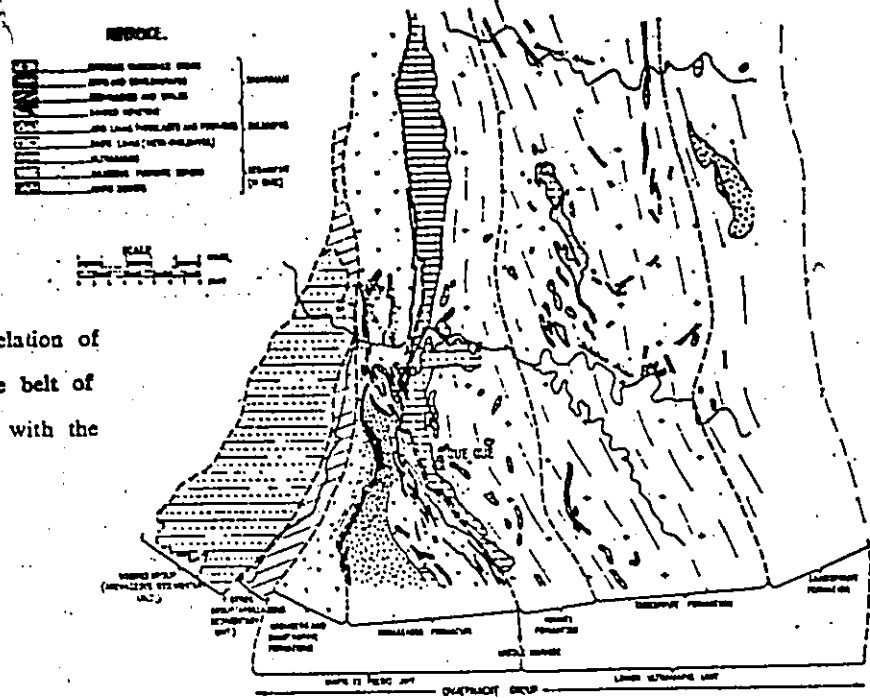
At Que Que, the lower ultramafic unit, as described by Harrison (1970) and Viljoen and Viljoen (1969-7) (Fig. 26), has been extensively intruded by granite of the Rhodesdale batholith and is now largely incorporated as xenoliths.

Their full comparison can be tabulated:

<u>Que Que</u>	<u>Barberton</u>
Shamvaian	
Arenaceous assemblage (9)	Moodies
Narrow argillaceous unit (3)	Fig Tree
 Bulawayan (2)	
Sedimentary interlayers	(Swartkoppie
	(Kromberg
	(
Cyclic mafic to felsic units terminated by iron formation	Hoeggengoeg
 Contact	Middle Marker
 Sebakwian (1)	
Mafic and ultramafic xenoliths	Komati
Xenoliths consisting largely of quartz-fuchsite, sericite schists, mafic and ultramafic material	Theespruit
Mafic and ultramafic xenoliths	Sandspruit

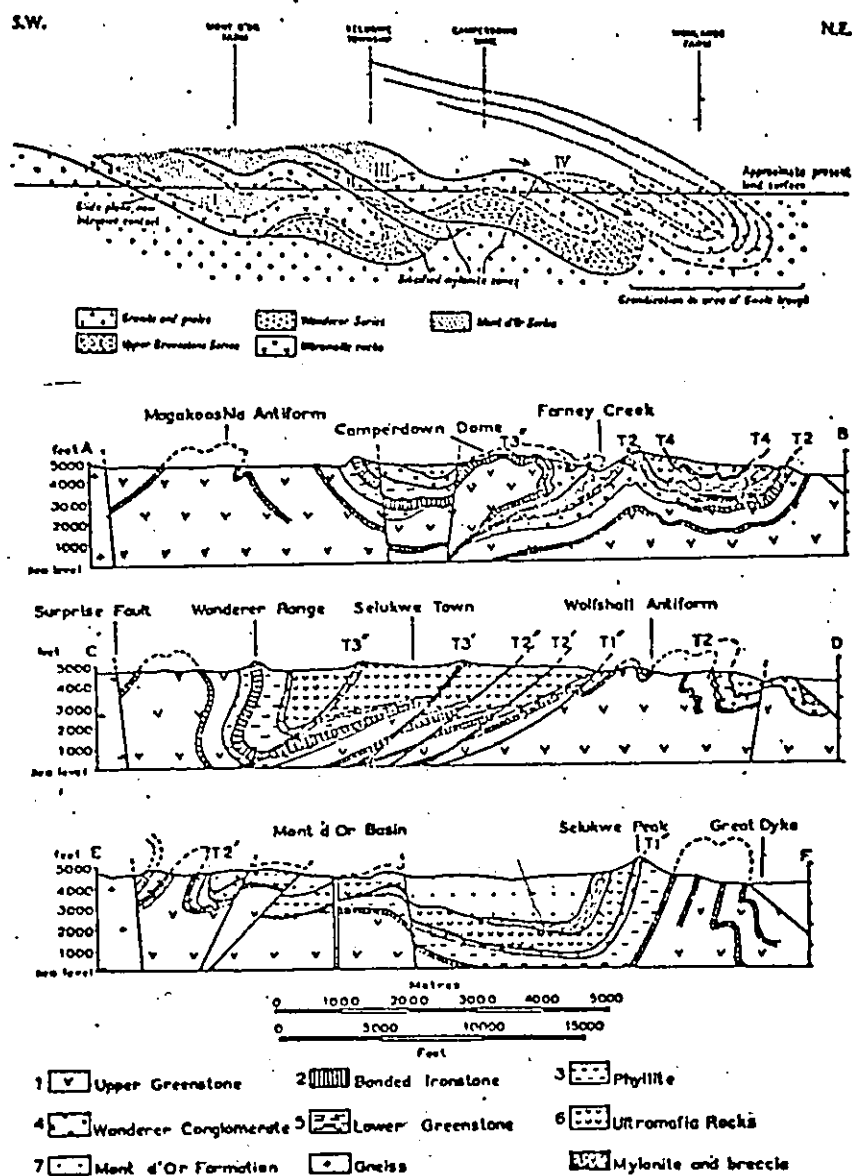
Fig. 62 from Viljoen
and Viljoen 1969-7

Suggested lithostratigraphic correlation of
part of the Midlands greenstone belt of
Rhodesia in the Que Que area with the
Barberton stratigraphic model.



Generalized geologic map of the Midlands greenstone belt, central Rhodesia.
Fig. 61 from Condle & Harrison 1976

GENERALISED DIAGRAM TO SHOW IMBRICATION OF LOWER LIMB OF SELUKWE NAPPE



Sedimentation (Figs. 61, 62, 63)

Shamvaian Group (Que Que areal. (Harrison 1970)

- Upper Graywacke Formation (10)
- Lower Graywacke Formation (10)
- Unconformity and folding

Greenstone Group

- Hematite Slate Formation (9)
- Basal Grit Formation (9)

Under Plutonism, reason is given for considering the two lower formations as pre-tectonic, the two upper ones as post-tectonic.

Bulawayan Group

Felsic Formation

Minor bedded tuffs, some felsites may be fine-grained ash beds.

Maliyami Formation

Tuffs

Mafic Formation

Chert, jaspilite, and minor clastic sediment interbedded in volcanics (9).

Sebakwe River Conglomerate

- (b) Large granitic boulders derived from Rhodesdale pluton.
- (a) Green chloritic matrix derived from volcanics.

The Sebakwe River Conglomerate is interpreted by Harrison as having a torrential flood origin in a drainage channel of a large river which crossed the Rhodesdale Batholith.

Lower Ultramafic Unit (Selukwe) (Stowe 1968-3)

Lower Greenstone Series

Jaspilitic quartzite

0 - 15 m

Mont d'Or Series (4)

0 - 300 m

Arkosic grits

Arkosic-wackes and graywackes with thin beds of chloritic argillite

1000 m

The arkosic members of the Mont d'Or series provide evidence of contemporaneous erosion from a continental environment.

The Sebakwe River Conglomerate holds special interest in that it may provide evidence of igneous activity between the volcanic periods of the Lower Ultramafic and Greenstone sequences. What is not yet clear is the relationship of the uncovering of the Rhodesdale batholith, the source of the early Bulawayan granitic boulders, to the metamorphism of the Sandspruit, Theespruit, and Komati formation equivalents which were laid down on what may have been the basement equivalent of the batholith. There is, as yet, no unequivocal evidence of igneous activity between the vulcanism of the Ultramafic Group and that of the Greenstone Group, but merely of erosion. The matter is of some concern in deciphering Archean evolution (Glikson and Lambert 1976).

6)

Plutonism (Fig. 64)

One may merge Stowe's (1968-3) Table of Geological Formation and Events, his table of structural correlations (1968-1) and his numbering of structures (1974) for the Selukwe district:

Archaean (Basement Complex)

Potassium metasomatism

Nalatale granite and pegmatites: lepidolite, beryl (coeval with Shamvaian) (16)

Intrusive contact

Quartz-veins with gold, molybdenite, pyrites, galena, sphalerite

Intrusive contact

Metadolerite dykes

D₃ Folding on N. 55 E axes
 Unconformity. Erosion and gradual up-doming.
 Intrusive contacts (mainly syntectonic)

Somabula granodiorite. Granite plutons and dykes.

Metasomatism of the gneissic granite. Pegmatites. Quartz veins with scheelite.

Low-grade metamorphism. Carbonatization of ultramafics.

D₂ Folding on NW axes.

D₁ Folding on NW nappe folds from south to Selukwe.

Thrust faults. Cataclastic granite (13), mylonite, etc.

Post-Sebakwian-pre-Bulawayan: Rhodesdale granodiorite batholith (6)
(Harrison 1970).

The Rhodesdale batholith (6) at Que Que intrudes the Lower Ultramafic Unit (Harrison 1970 and Viljoen and Viljoen 1969-7) but also provide detritus for the Sebakwe River conglomerate in the Mafic Formation of the Bulawayan

(Harrison 1970). The interpretation preferred here is that the batholith is remobilized basement which provided detritus before remobilization, probably during D_2 , when its present form analagous to the Ancient Tonalites of Barberton was attained.

The Somabula granodiorite (14) (trondhjemite) is a deep-level, even-textured, concordant dome with foliated margins. Segregation bands, pegmatite veins, and inclusions are absent. The intermediate level gneissic roof has been folded into dome structures. Cupolas of granodioritic magma appear molded concordantly into the domes, and near the fold belts, in more intense folds, upper level, late tectonic, K-rich cupolas (15) transgress the greenstone margins.

Barren pegmatites are plentiful as swarms in the gneiss and migmatite but are not found in the massive granodiorites.

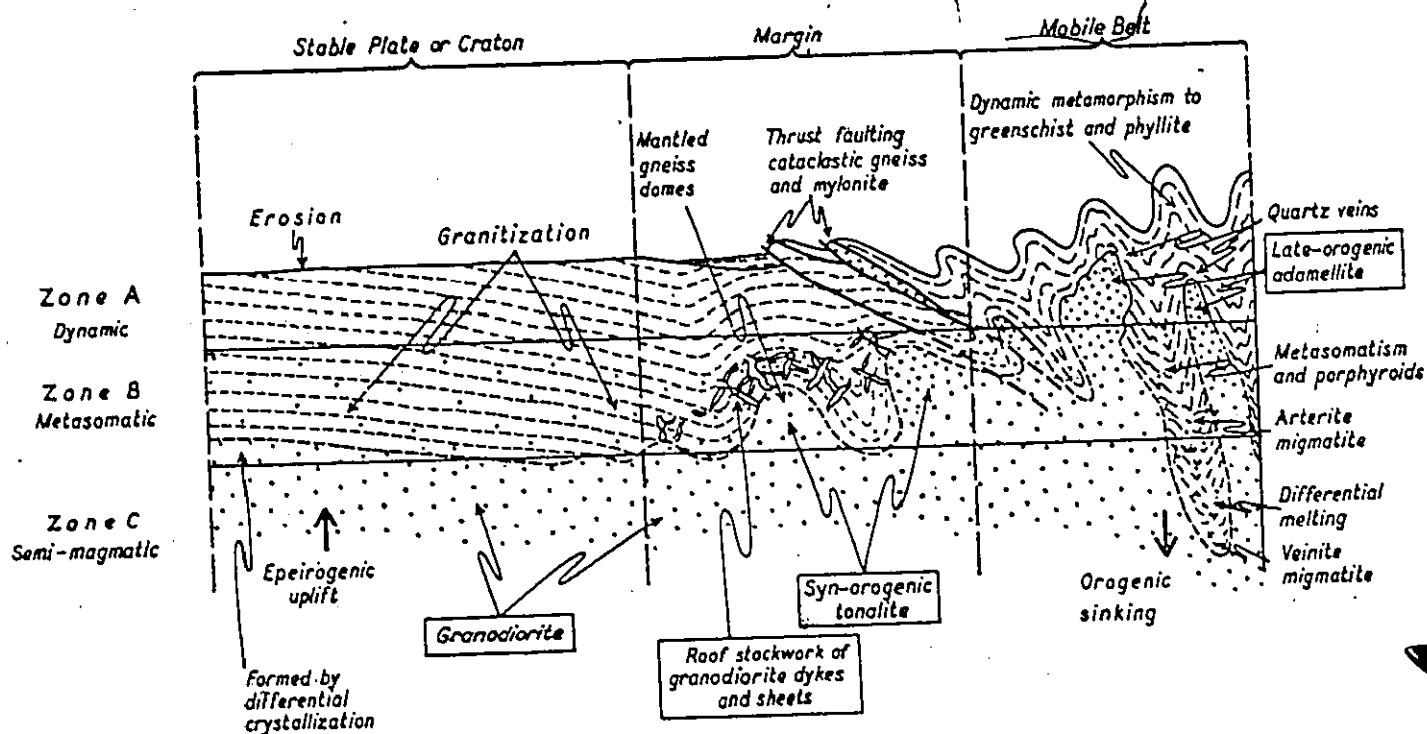
The Nalatale granite (16) is an elongate stock, concordant with folded gneisses and migmatites. It is surrounded by a halo of potassium metasomatism, about half a mile wide, readily discernible by the development of pink microcline porphyroblasts in the older gray gneiss and migmatites. Stowe (1968-3) believes it to be of Shamvaian age. If the gneisses are basement, it could be an early concordant diapir, but whereas concordancy is unusual in late stocks, pegmatites are unusual with early diapirs.

In his Table on Geological Formations and Events for Que Que, Harrison (1970) shows many post-Shamvaian intrusives. All but the Sesombi tonalite (and quartz veins and dolerite dykes) are part of the Rhodesdale batholith. The batholith is a basement feature which became a gneiss dome with multiple injection phases. All can be equated with those noted for the Somabula dome near Selukwe. Even the Sesombi tonalite is

described as post-Shamvaian because "deformation of the syncline into a synclinorium in the area around Sebakwe Port is thought to be due to the emplacement of the Sesombi tonalite to the north". No structural mapping has been done at Que Que. On Harrison's map of Que Que, in the legend he shows "unconformity and folding" following the two lower formations. Perhaps, as Viljoen and Viljoen suggest, the older formations are pre-orogenic, the equivalent of the Moodies, and, it is suggested here, the upper formations are post-orogenic. In such event, the structural position of the Sesombi tonalite is not defined.

The Somabula granodiorite, with its gneissic roof is typical of the syn-tectonic intrusives, and likewise the transgressive cupolas of late-tectonic intrusives. Early diapirs are not recorded, but the Nalatale granite may be a representative of the older gray gneiss and migmatites which it intrudes are basement, and the Rhodesdale batholith is so regarded here, by analogy with the Ancient Tonalites of Barberton (Viljoen and Viljoen (1969-4)).

DIAGRAM TO ILLUSTRATE THE FIELD RELATIONS OF GRANITIC ROCKS



PROCESS ZONE ↓	TECTONIC ENVIRONMENT	Tectonic Environment		
		Craton	Margin	Mobile belt
		Epeirogenic uplift		Folding and plastic flow
A. Dynamic zone	Erosion ↑ Sedimentation ↓ Intrusion ↑	Basement gneiss	Dynamic metamorphism to form greenschist and phyllite. Cataclastic gneiss and mylonite	Greenschist and phyllite Late-orogenic adamellite
B. Metasomatic zone	Metasomatism ↓ Recrystallization ↓ Intrusion ↑ Differential crystallization ↑	Recrystallized basement gneiss	Recrystallized basement Granodiorite stockwork Syn-orogenic tonalite	Porphyroid Syn-orogenic tonalite Arterite migmatite
C. Semi-magmatic zone	Differential melting ↓ Magmatic differentiation ↑	Granodiorite	Granodiorite	Veinite migmatite Granodiorite

Fig. 64 after Stowe 1968-1

Deformation (after Stowe 1968-1 and 1974) (Figs. 63, 64, 65, 66)

- D₄ F₄ Domes and rim synclines.
- D₃ F₃ Upright to steeply dipping antiforms, ~~synforms~~ and domes. Minor folds larger than F₂ in banded iron formation. Plunge more constant than F₁ and F₂.
- S₃ Axial planar cleavage; strain-slip cleavage.
- D₂ F₂ Tight symmetrical folds, wavelength 30 m, vertical axial planes. Larger F₂ obscured by F₃ but may be recognized by lines of culmination of domes. These minor features are dominant in argillaceous sediments and phyllonite; in banded iron formation there is plastic flow and attenuation; in phyllonite, symmetrical flex-slip corrugation or chevron kink folds; in Lower Greenstone, tight folds.
- S₂ Axial planes marked by closely spaced jointing in more competent sediments and by strain-slip cleavage in chloritic phyllonite.
- D₁ F₁ Folds not common owing to intense shearing. Minor folds in jaspilite, banded iron formation, and quartzite. Thrusting with inversion and imbrication produced recumbent nappes.
- S₁ Widespread penetrative schistosity or slaty cleavage. Parallel mica, chlorite, and talc. In carbonate, phyllonite coincides with compositional banding; in conglomerates, with plane of pebble flattening.
- L₁ Long axes of pebbles; elongation of chromite bodies; mineral streaks; rods in phyllonite.

Note: Though S₁ is widespread at Selukwe, this is probably because of the relationship to thrusting. It is not so evident elsewhere in Rhodesia (Coward et al. 1976).

Harrison (1970) notes several episodes of folding in the Shamvaian at Que-Que, further discussed under plutonism.

Of the Archean areas studied, Selukwe provides the best examples of thrusts and with them of S₁ and L₁. The D₄ domes and rim synclines are not reported from other areas studied.

Metamorphism

Stowe (1968-3) lists metamorphism and deformation in his Table of Geological Formations and Events for the Selukwe area and one may add the numbering from his 1974 paper:

- M₃ (post Nalatale granite): potassium metasomatism
- M₂ (post-D₂, pre-D₃): metasomatism of the gneissic granite
- M₁ (post-D₂, pre-D₃): low-grade metamorphism, carbonatization of ultramafic rocks.

In the Que Que district, Harrison (1970) also notes retrograde metamorphism (amphibole replaced by chlorite).

Saggerson and Turner (1976) review the distribution of metamorphism in the Rhodesian craton. They distinguish zones of metamorphism in Bulawayan rocks from those in Shamvaian and Limpopo belt rocks. They write: "Bliss and Stidolph (1969) commenting on the occurrence of Shamvaian-type sediments across the Rhodesian craton have indicated that these are younger than a post-Bulawayan period of metamorphism and folding, but are themselves involved in subsequent metamorphism and folding along a distinctive NNE trend as well as a major period of post-Shamvaian granite intrusion". Yet Bliss and Stidolph, in the quoted paper, write: "The Shamvaian Group was established as the Shamvaian System by Macgregor (1947) who correlated seven unconnected sedimentary successions which overlay the Bulawayan Group, with the Shamva Grits at Shamva as the type Shamvaian. There is no clear distinction between the sediments of the Bulawayan and the overlying Shamvaian Group except at Shamva. Some of the successions designated as Shamvaian may be integral parts of the Bulawayan Group, whilst others, which post-date Bulawayan Group, should be described as of Shamvaian type rather than as Shamvaian Group". Saggerson is attempting to make correlations in preparing his segment of the Metamorphic Map of the World, but in many parts of Rhodesia it appears that the geological correlations on which he must base his data are not yet reliable. Nevertheless, a broad relationship of metamorphic zoning and granitic intrusion is evident on

the sketches (Saggerson and Turner 1976). In the Midlands belt, more specifically, Stowe (1968-3) notes that regional metamorphism reached the lower greenschist sub-facies at Selukwe and the greenschist amphibolite sub-facies in the Ghoko Range which may be of an earlier age, according to Stowe (1968-1 and 3). At Que Que the regional metamorphism was lower greenschist sub-facies, ranging to upper greenschist towards the contact of the Sesombi batholith and amphibolite grade in the Rhodesdale batholith (Harrison 1970).

Ore Deposition

Pre-tectonic

Chromium (Fig. 65)

The most important chromite occurrences in the Archean of southern Africa are those at Selukwe (5), where deposits are high grade. The host is the ultramafic sill which intruded between the Mont d'Or sediments and Lower Greenstones of the Sebakwian. The chromite deposits formed by magmatic segregation as cumulate layers at intervals in the differentiating ultrabasic intrusion. The thickest layers accumulated in down warps on the chamber floor (Cotterill 1969). Stowe (1968-3) adds that the host serpentine was derived from dunite and harzburgite and that some chrome ore bodies formed as late intrusive sheets a short time after the segregations. Usually, if the ore horizons were not eroded away in pre-Bulawayan times, the high grade zone is within 250 m of the basal unconformity. Folding produced discontinuously scattered groups of chromite lenses.

Nickel-copper

The Empress nickel-copper deposit is pyrrhotite, pentlandite, and chalcopyrite in a differentiated gabbroic sill (7) with picrite, pyroxenite, norite, and diorite. The sill intrudes the Umniati Group (=Maliyami) which is Bulawayan (Viljoen et al. 1976).

Iron

Anhaeusser (1966-1) notes that enriched high-grade hematite orebodies are being mined near Que Que. Presumably this is from the Hematite Slate.

Copper-Zinc

A few small mines, such as the Cactus, south of Que Que are minor representatives of the volcanogenic massive base metal sulphide deposits. The Cactus has Cu-Pb-Zn ore with appreciable Sb, Au, and Ag, in structurally disturbed quartz-feldspar porphyries and felsic tuffs (Anhaeusser 1976-1).

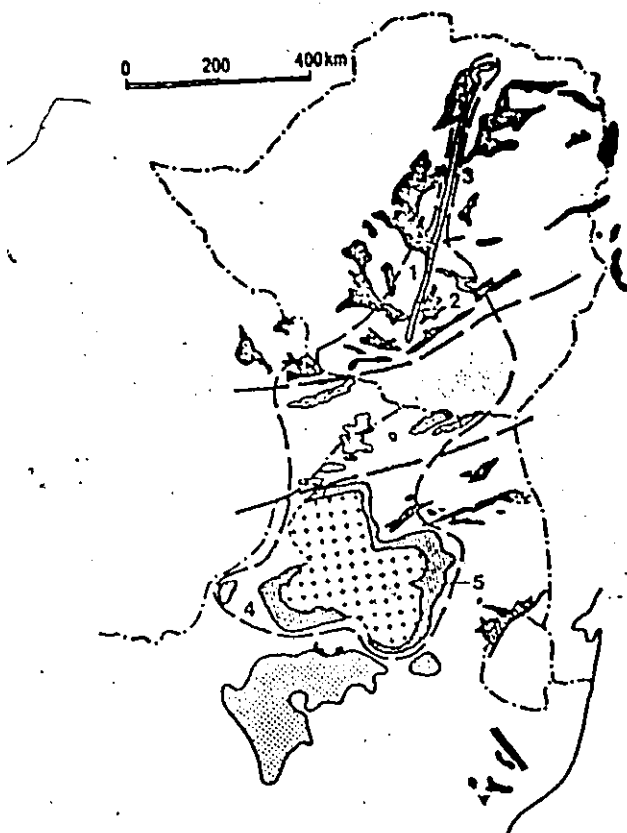


Fig. 65 from Anhaeusser 1976-1

- MAIN CHROMITE PRODUCING AREAS**
- 1 SELUKWE GREENSTONE BELT (SEBAKWIAN)
 - 2 MASHABA IGNEOUS COMPLEX (POST SHAMVAIAN)
 - 3 GREAT DYKE
 - 4 WESTERN BUSHVELD
 - 5 EASTERN BUSHVELD

— LIMPOPO MOBILE BELT —

[] REGION OF
OPTIMUM
CHROMITE
DEVELOPMENT

**IGNEOUS COMPLEXES AND FORMATIONS
IN WHICH CHROMITE OCCURS**

- | | |
|--|---|
| | <p>Tugela Randt Complex, Natal</p> <p>Detrital Chromite in Witwatersrand (~2.5-2.75 b.y.)</p> <p>Sedimentary Basin</p> <p>Bushveld Igneous Complex (~2.0 b.y.)</p> <p>Great Dyke (~2.5 b.y.)</p> <p>Messina Formation (~3.0 b.y.)</p> <p>Mashaba Igneous Complex (~3.0 b.y.)</p> <p>Archaean Greenstone Belts (~3.0-3.5 b.y.)</p> |
|--|---|

Syn-tectonic

Gold

Anhaeusser (1976-1) writes that most of the gold of the Archean greenstone belts of Southern Africa is now considered to be genetically related to rocks of volcanic origin. The superimposed effects of granite intrusion, metamorphism, and deformation are largely responsible for the migration of much gold. Some is associated with oxide and sulphide facies iron-formation, of volcanic-exhalative origin.

In the Selukwe district the Mont d'Or Formation, arkoses and graywacke, hosted about 170 mines (Figs. 66, 67) and Stowe (1968-2) recognized four structurally controlled sets associated with D_3 , a fifth set associated with a post D_3 fault zone, and saddle veins following the plunge of D_3 . Parageneses varied with the directions by which sets are categorized. Size and width of veins are often related to a lineation such as rodding. Stowe (1968-3) writes that all the gold occurrences in the Selukwe area are grouped in or near the Basement Schist rocks in the northeast of the area mapped, that is they all belong to one geochemical province, that it is worth noting that the metamorphosed Bulawayan basaltic and andesitic igneous rocks occur only in the gold-bearing province, and that A. M. Macgregor (1951) has suggested that they may be a possible primary source for the gold in the veins in Rhodesia.

Frapp (1976-1) (Fig. 68) studied stratabound gold deposits in the banded iron formations of Rhodesia, including the Camperdown at Selukwe, Beehive, and Sherwood Starr at Que Que, and Pickstone at Hartley. These ores are predominantly in the Sebakwian Group. The ore is stratiform gold-bearing sulphide and mixed sulphide-carbonate facies banded iron formation which Frapp proposed were precipitated out of geothermal brines during fumarolic activity.

IDEALISED BLOCK DIAGRAM TO SHOW
THE RELATIONSHIP OF THE VEINS TO THE STRESS FIELD

- 234 -

Fig. 66
from Stowe
1968-3

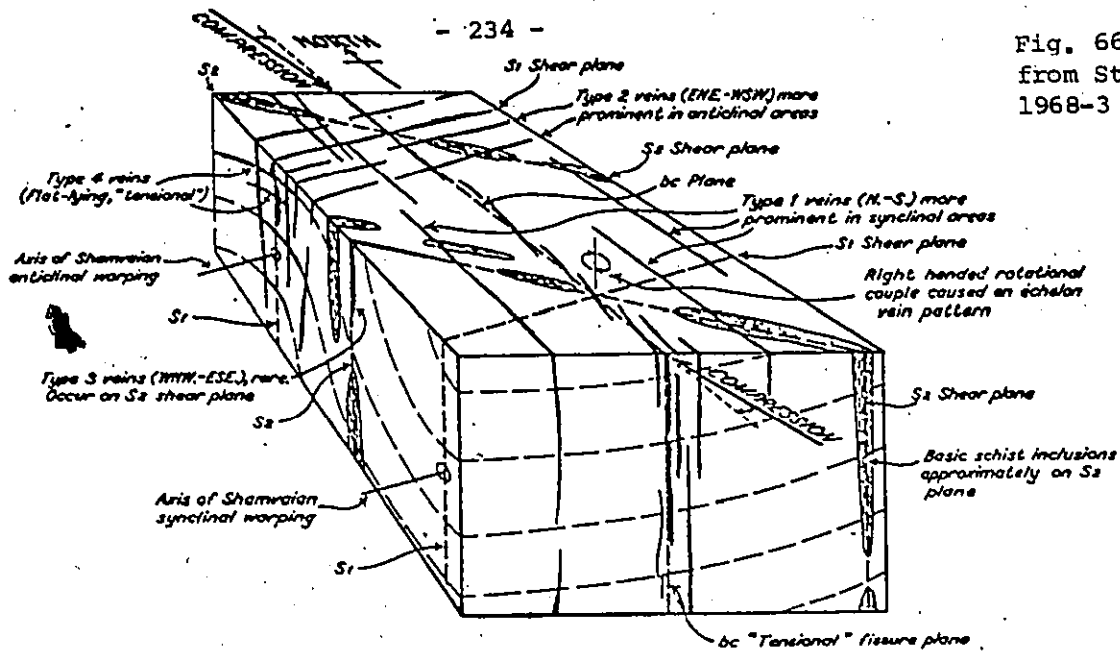
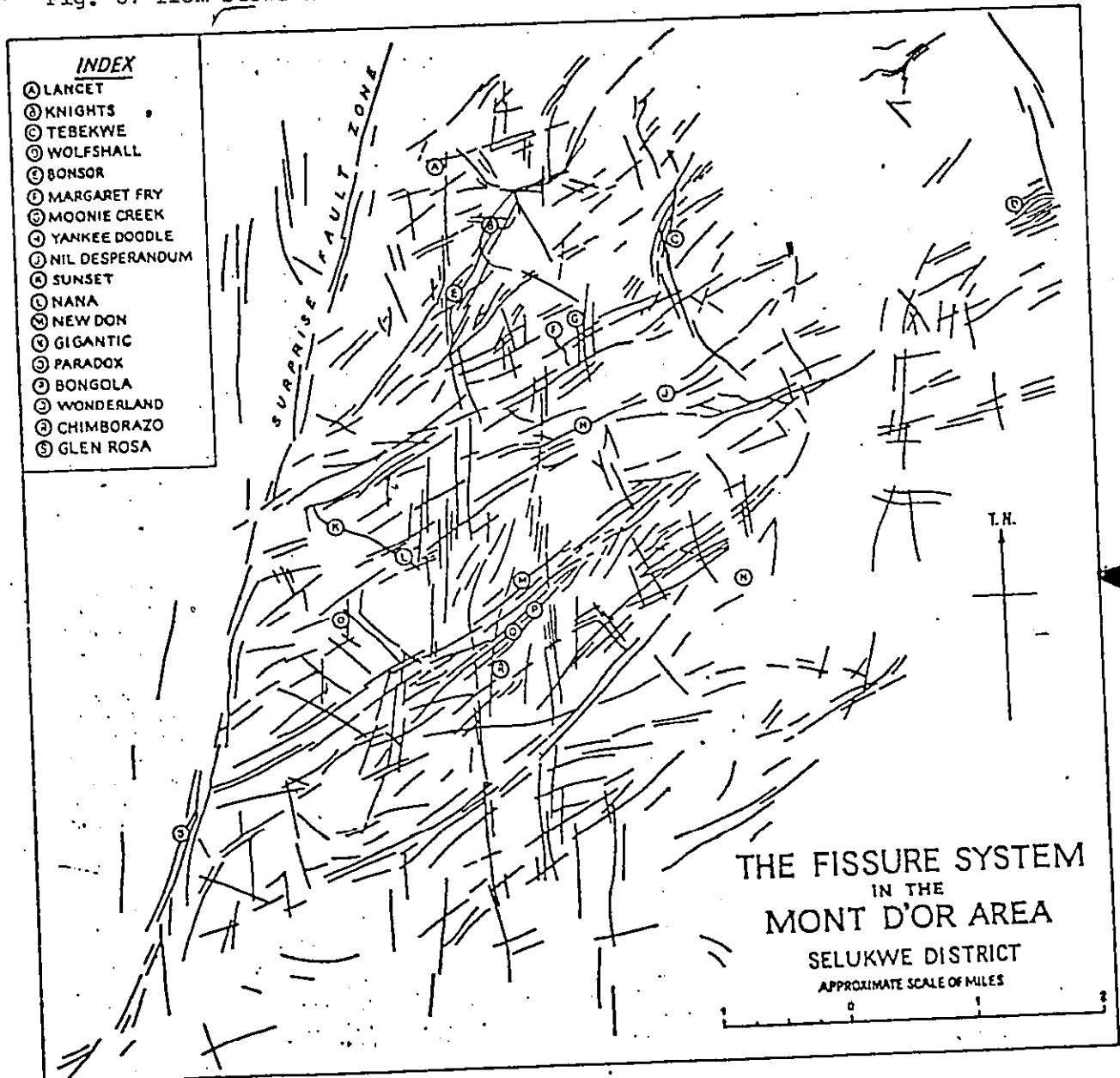
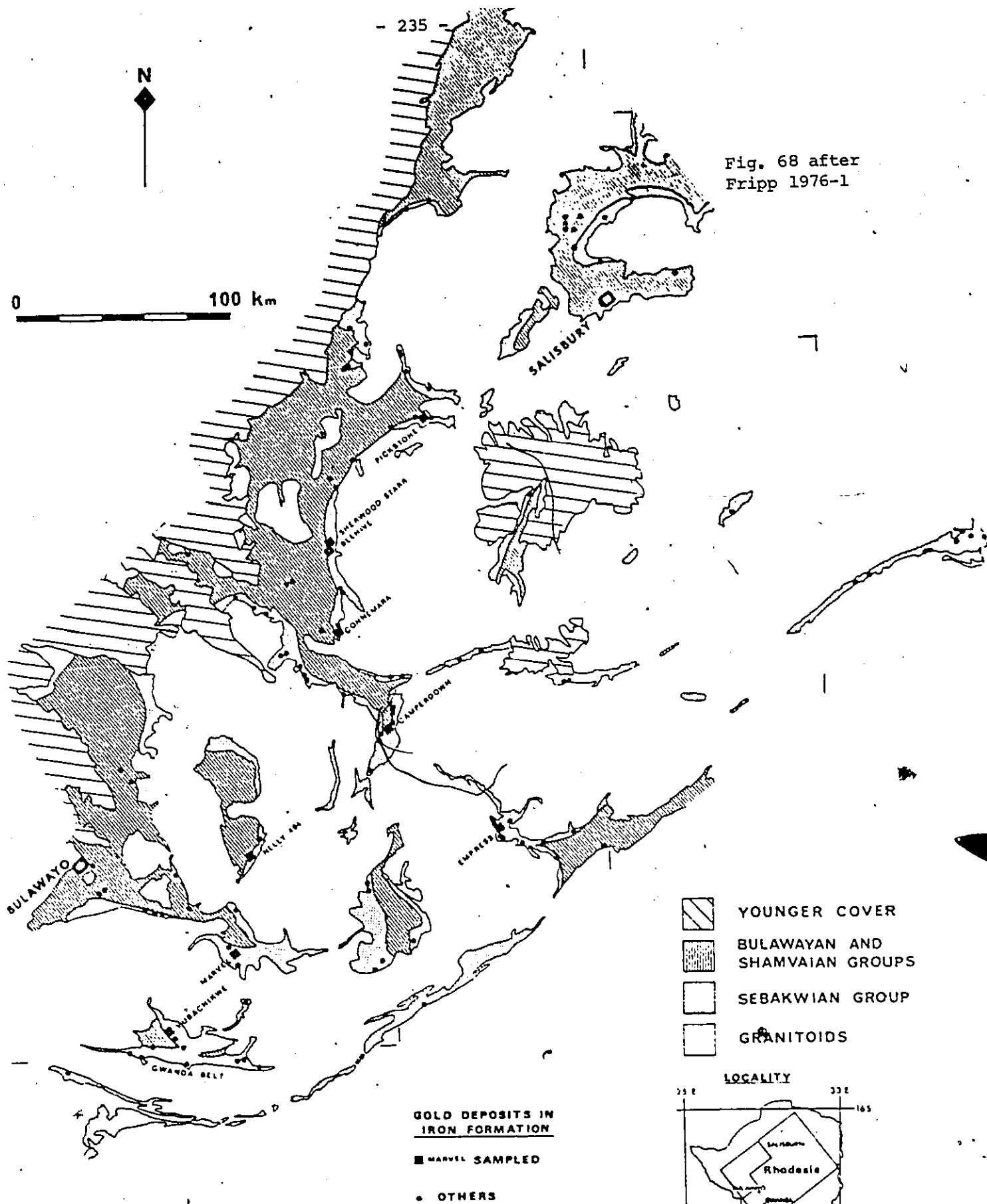


Fig. 67 from Stowe 1968-2





Antimony and Mercury

Several small deposits of antimony and mercury are noted by Anhaeusser (1976-1). Antimony is recovered as a by product of gold mining. The close association of the mineralization with intermediate to felsic volcanics suggests an exhalative sedimentary environment.

Magnesite

The Barton Farm deposit near Gatooma is the only one in southern Africa not formed by alteration of ultramafic rocks. It is in Shamvaian dolomitic argillites and arkoses. (Anhaeusser 1976-1).

Ore Production

Phaup (1964) showed that around Gatooma, in the northern part of the Midlands belt, 359 mines had been worked prior to 1961 - of the total production of over 4.5 m. oz. Au, 64% came from the Cam and Motor, 8.6% from the Giant, 4.4 from the Thistle Etna, and 23% from the remainder. Less than 1% came from 165 mines or prospects.

The Mining Magazine classification of ore production for 1974 is:

Pickstone	E	Au
Empress	D	Ni, Cu
Que Que Iron Ore	D	Fe
Rhodesia Chrome	D	Cr

- 238 -



GOA, INDIA

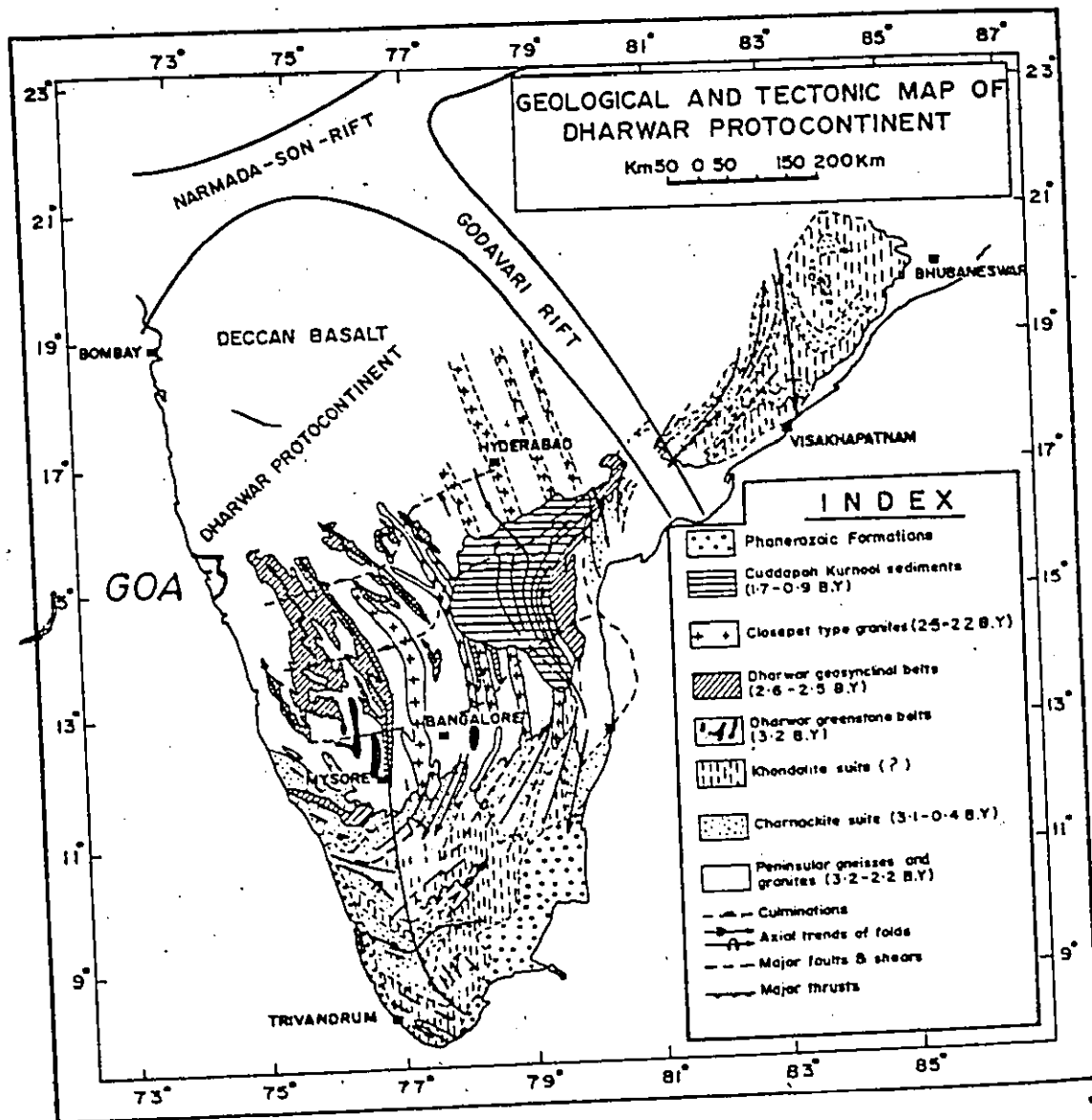
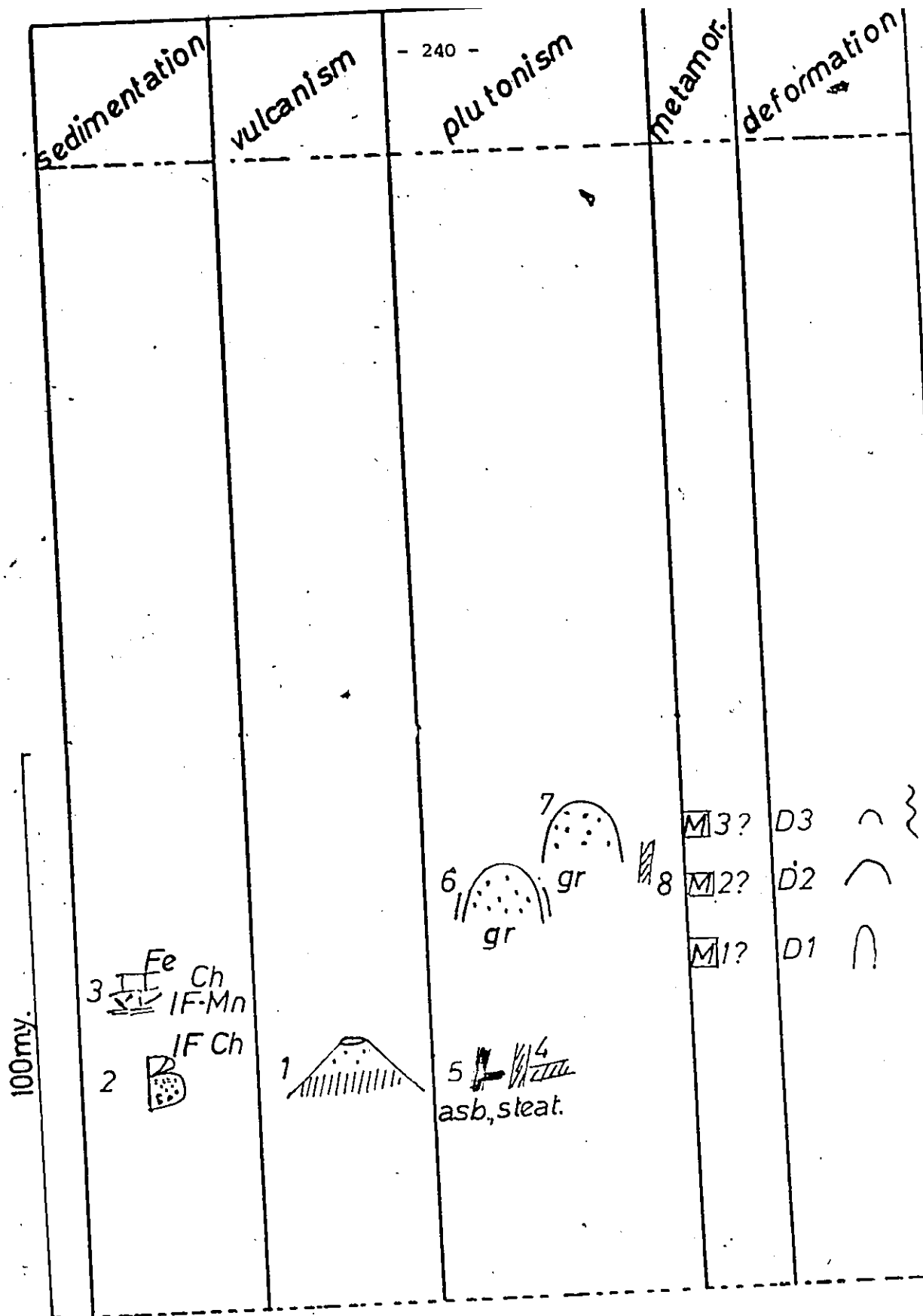


Fig. 69 from Naqvi 1976



GOA, INDIA.

Fig. 70 Time Relations of Geological Features

Vulcanism

Sen (pers. comm. 1976) says the Dharwarian rocks of Goa predominantly represent eugeosynclinal (2) to shallow shelf (3) epicontinental facies. The intercalated volcanics (1) are basaltic flows with some acid flows and tuffs. Banded chert and ironstone are presumably volcanogenic chemical deposits.

Mafic (4) and ultramafic dykes (5), normally components of the volcanic pile, are represented here.

While the term epicontinental might carry connotations of Proterozoic style sedimentation, for example, Archean deposits, less frequently perhaps, can also be of this type. Ryan shows a variety of sedimentary environments in the Pilbara (Fig. 74).

Sedimentation

The facies which accompanies vulcanism includes typical, flysch-type graywacke, shale, conglomerate assemblages. Chemical deposits are banded chert and ironstone.

The shallow-shelf, epicontinental facies include limestone and, within an extensive pink phyllitic horizon, manganiferous chert, quartzite, and banded hematite-quartzite as lenticular bodies.

Plutonism

- 243 -

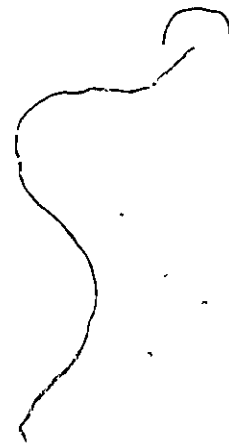
- $D_3?$ Pink porphyritic granite (7)
- Post D_2 ,
pre- $D_3?$ Diabase and gabbro (8)
- $D_2?$ Batholithic gneissose granite (6)

(Sen, pers. comm. 1976).

This is in general accord with the three main categories of granitoids in the Peninsular shield (of which Goa is a part) (Sreenivas and Srinivasan 1974):

3. A series of coarse grained and porphyritic granites:
The Closepet granite.
2. Island-like granitoid intrusives in greenstone belts:
The Champion gneisses.
1. A migmatite complex with more homogeneous granite phases:
Peninsular gneisses.

The equivalents of the Ancient tonalite diapirs of southern Africa are not noted. Further mapping may identify them, as has recent work in Australia.



Deformation

$D_3 F_3$ Minor upright folds. Faults?

$D_2 F_2$ Upright open folds.

$D_1 F_1$ Upright isoclinal folds.

(Sen pers. comm. 1976)

The pattern of deformation appears to be a standard one, but detailed studies are needed.

Metamorphism

Metamorphic grade is low, rarely exceeding greenschist facies. The relationship to deformation is unknown.

Ore Deposition

Pre-tectonic

Iron and Manganese

The banded ironstone of the epicontinental deposits is productive. Deformation has resulted in concentration in hinge folds. Most ore is above the water table, indicating secondary enrichment. Sen's use here of epicontinental may not imply radical difference from the sediments of volcano-sedimentary piles such as those described at Noranda, and Ryan has depicted a variety of sedimentary environments in the Pilbara (Fig. 74).

Manganese ores are all lateritic.

Asbestos and Steatite

Some asbestos and steatite are associated with the Ultramafics.

Ore Production

The Mining Magazine classification of ore production for 1974 is:

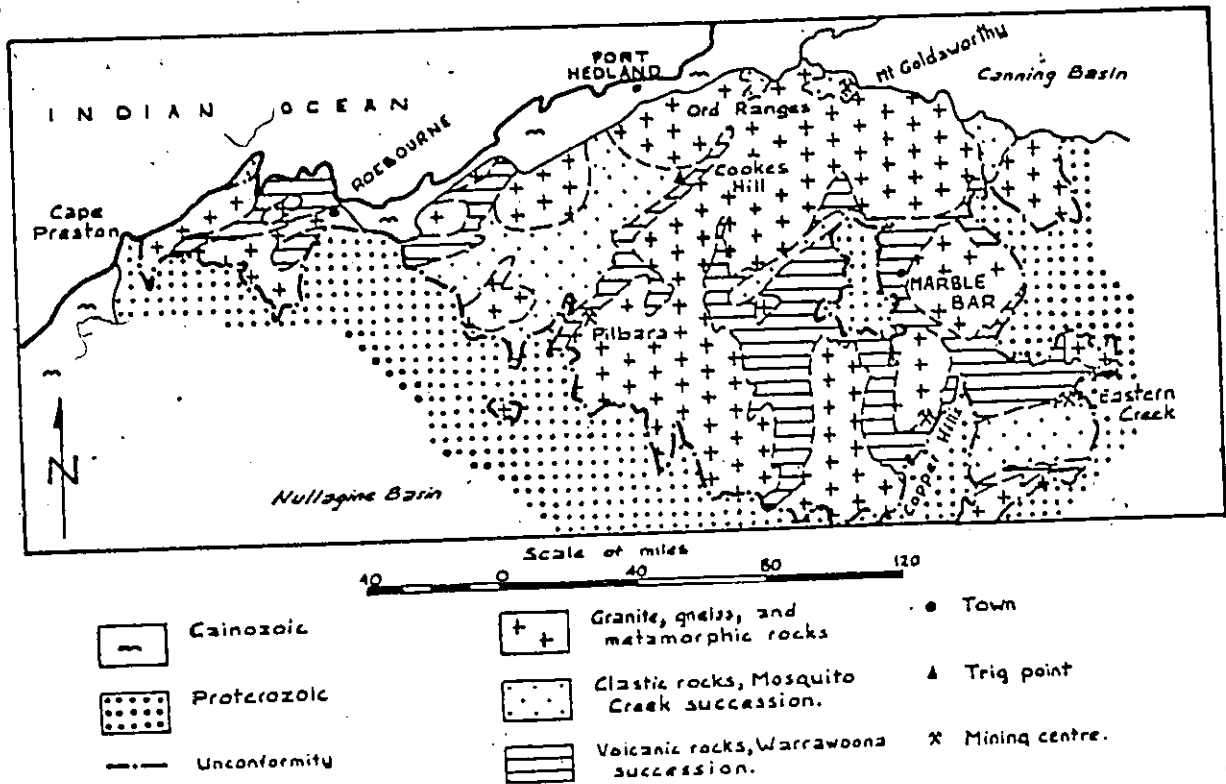
Chowgule	B	Fe
Kudnem	D	Fe
Pailigao	D	Fe
Sanquelim	C	Fe
Sirigao	D	Fe

WESTERN AUSTRALIA

1. Pilbara
2. Eastern Goldfields
(Yilgarn)

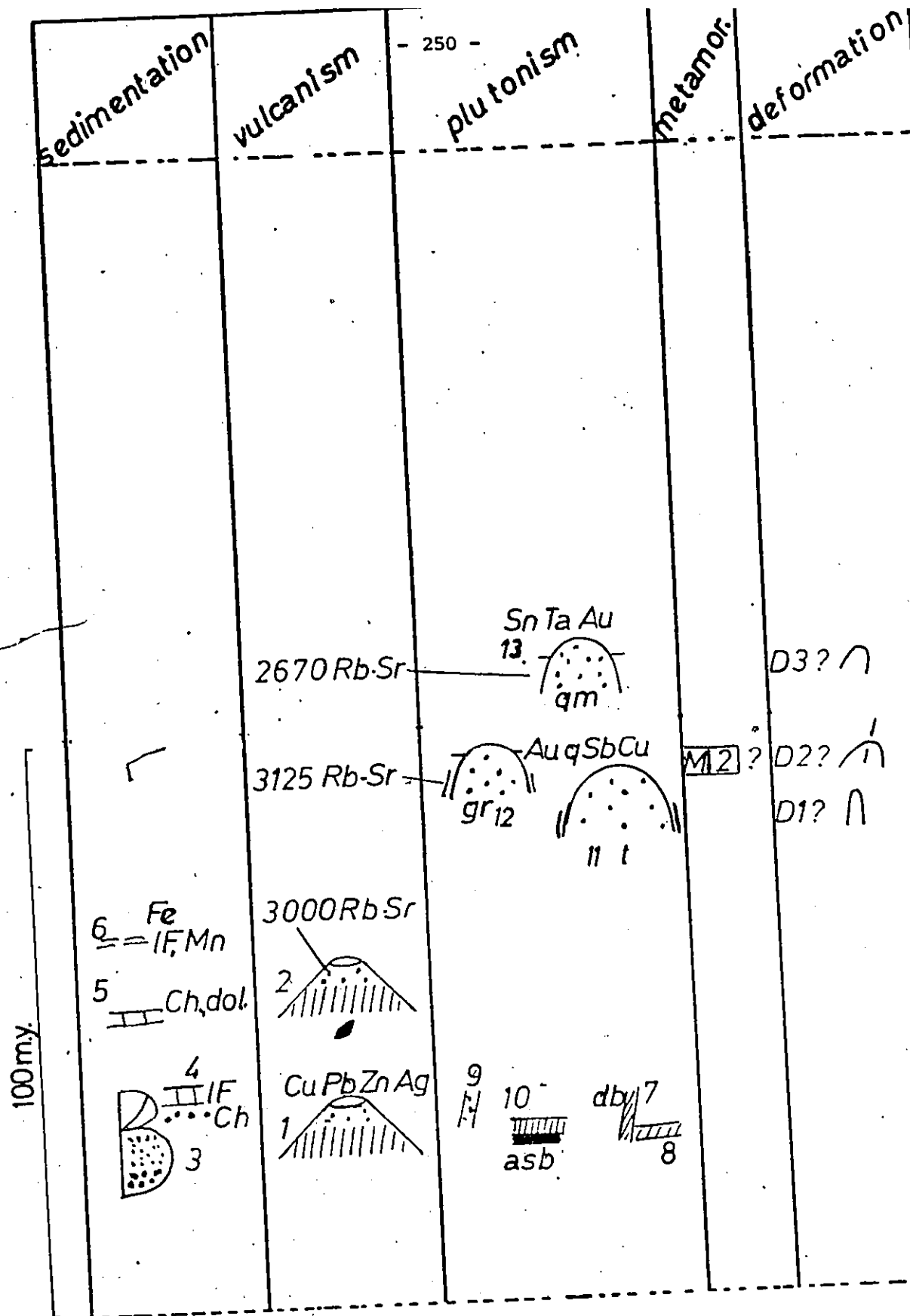
- 248 -

PILBARA, WESTERN AUSTRALIA



Geology, Pilbara

Fig. 71 from Ryan 1965



PILBARA, W. AUSTRALIA.
 Fig. 72 Time Relations of Geological Features

Vulcanism and Sedimentation

Ryan (1965) integrated the work of Noldart and Wyatt (1962) (Fig. 71) in the eastern Pilbara with his own in the west (Fig. 73). He designated all the sedimentary and volcanic rocks of the Pilbara System as the Roeburne Group. He writes: "Despite the difference between the successions of the volcanic and sedimentary facies (Figs. 74, 75), the Roeburne Group can be divided roughly into three stratigraphic units. The psammitic rocks which lie disposed around the Croydon granite comprise the lower-most unit (3), which has not been recognized so far in the volcanic succession. The middle unit is characterized by volcanic rocks (1) and (2) and chemical sediments in the sedimentary facies. Acid rocks are most common along the boundary between the two facies. Sulphides and magnetite are present in the banded chert formation (4). The upper unit reflects a change to more tranquil conditions (6) in which the vulcanicity was subdued or absent. Banded iron formation with associated pelitic rocks and probably tuff is present in the volcanic succession whereas shale, siltstone, and graywacke predominate in the clastic succession..."

Preconsolidation movement is described by Ryan, indicated by tabular or lenticular bodies of breccia of fragmented sediment in a disoriented granular matrix, pull-apart structures, apophyses of laminae in banded iron formation, a siltstone dyke, beds intricately folded between undisturbed strata, quickstone, mixed sedimentary and igneous rocks, and turbidites with graded bedding, small-scale cross-bedding, bottom-erosion features, and clay pellets.

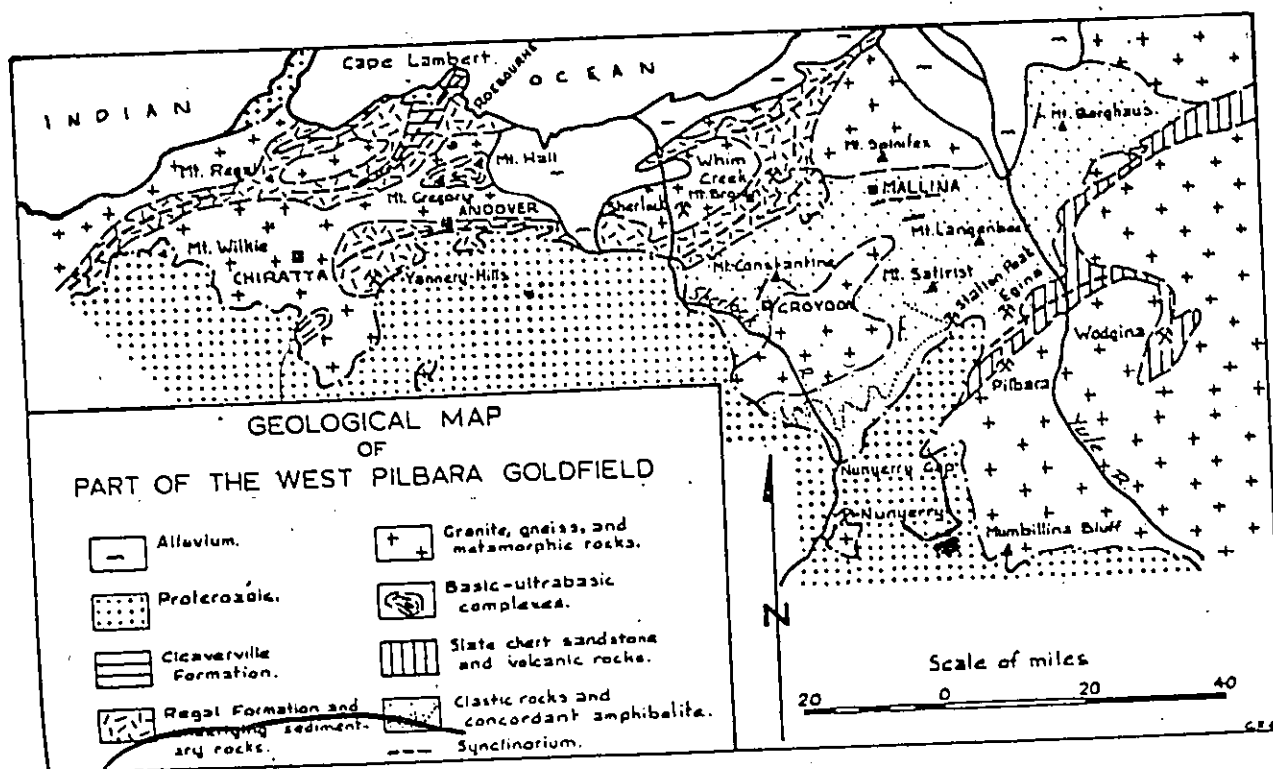
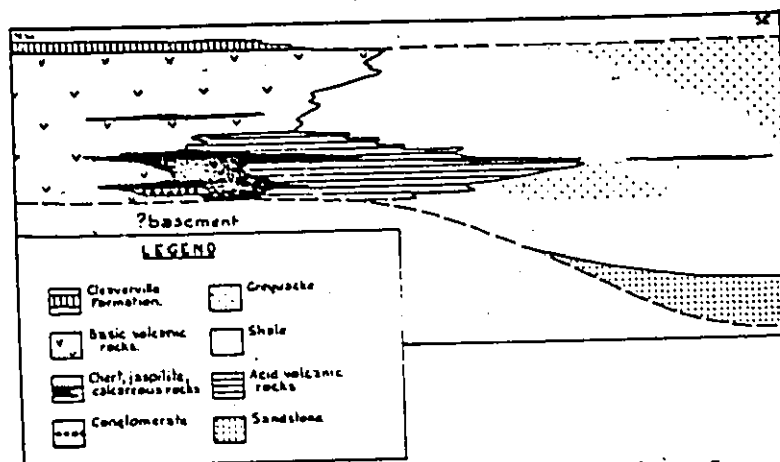


Fig. 73 from Ryan 1965

Fig. 74 from Ryan 1965



Diagrammatic representation of facies changes in the Roebourne Group.

Postulated correlations in the Roebourne Group

	Roebourne-Whim Creek	Mt. Satirist-Mt. Berghaus	Pilbara	Gorge Creek	Warrawoona-Mosquito Creek	Yarria	
ROEBOURNE GROUP	Jaspilite, shale (<i>Cleaverville Fm.</i>)			Jaspilite, sandstone, conglomerate (<i>Gorge Creek Fm.</i>)	Shale, siltstone, greywacke, conglomerate	Jaspilite	Mosquito Creek Succession
	-----	Greywacke	Sandstone, chert, phyllite, schist	-----	===== (disconformity) =====		
	Basic volcanics, acid volcanics, thin metasediments (<i>Regal Fm.</i>)	Shale, siltstone, slate	Basic volcanics, banded chert	Basic volcanics, acid volcanics	Basic volcanics, acid volcanics	Basic volcanics, etc.	Warrawoona Succession
	Banded cherts, slate, calc. schist, acid volcanics, basic volcanics (Local conglomerate over disconformity)	Calc. shale, banded chert, metadolomite, greywacke, shale	Banded chert, acid volcanics, calc. schist, slate, shale	Metasediments, (banded chert, schist, etc.)	Metasediments, (banded chert, schist, etc.)		
	Amphibolite		Hornblende schist				
	Gneiss	Shale, greywacke, sandstone ?	Gneiss	Gneiss	Gneiss	?	

Fig. 75 from Ryan 1965

Igneous rocks associated with vulcanism include dolerite (7) intruding basic lavas and truncated by a pre-Regal unconformity; concordant amphibolite bodies (8) in the clastics; feldspar porphyry (9), and two large complexes of intrusive mafic and ultramafic rocks (10) (Fig. 76). Both complexes are crudely stratified and in both cases the stratification is parallel to foliation and banding in the adjacent gneiss and to the inferred regional structure of the Roeburne Group. The complexes may represent a mixture of basic intrusive rocks and serpentized basic volcanics. If so, the mid-position of the Mt. Hall body, between synclines, indicates a relatively low stratigraphic position.

One must add to these descriptions by Ryan the note by Anhaeusser (1971-2) that the assemblages appear to be mainly representative of the Greenstone Group. The Warrawoona succession appears to conform to the concept of two major cycles of Anhaeusser (1971-1).

Plutonism (after Noldart and Wyatt 1962, de Laeter and Blockley 1972)

D₃? Tin-bearing biotite adamellite stocks (13) (Figs. 6, 7) with sharp irregular contacts cutting the banding of the older granite and intruded after folding. The Moolyella granite has marginal xenoliths and roof pendants. Swarms of albite pegmatites, the primary source of alluvial cassiterite.

D₂? Syn-tectonic granite (12) (Fig. 77) formed by partial melting of gneissic granite during folding. Dome-like, on a broad scale concordant with the supracrustals but with clearly intrusive contacts. Greater part of dome a mixture of migmatite, gneissic granite, and nebulitic folded granite. Migmatite best developed near margins: lit-par-lit zones of injection of amphibolite by granite up to 1 km wide. Migmatite grades inwards to well-banded gneissic granite and this in turn to foliated granite.

D₂? Older gneissic granite derived by granitization of a supposed basement.

D₂? Oval shaped diapirs of the tonalite, trondhjemite, granodiorite suite (11) (Glikson 1976).

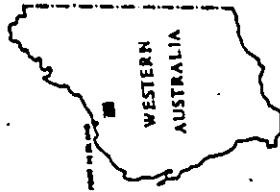
Anhaeusser (1971-2) compares the behaviour of the granites to that of the large gregarious batholiths of Rhodesia "and may be held responsible for the assimilation of the early Ultramafic Group assemblages".

The granitization given as the origin of the Older gneissic granite could well accompany that forming the syn-tectonic granite.

The other three units are typical of the basic Archean plutonic sequence.

Fig. 77 from Blockley 1970

Geological map of portion of the Pilbara Goldfield showing known tin granite occurrences.



Geological map of the Moolyella tinfield showing localities of samples used in Rb-Sr age determinations.

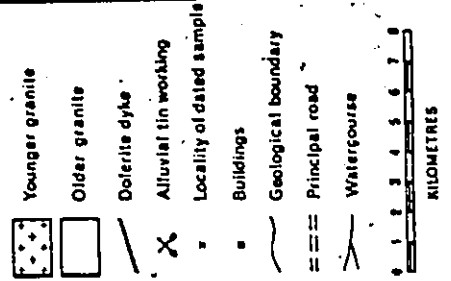
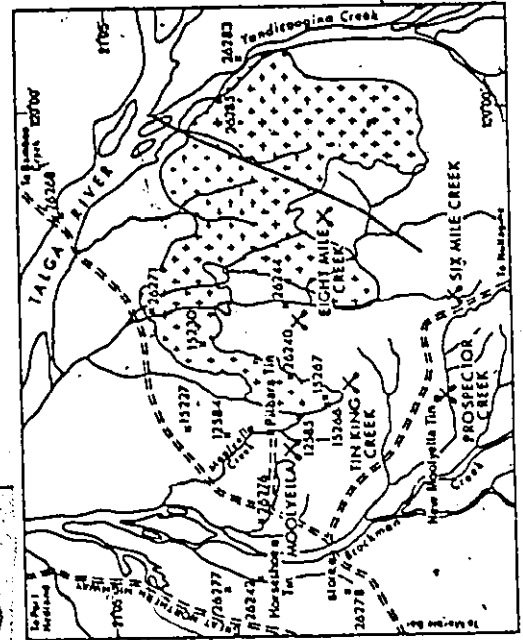
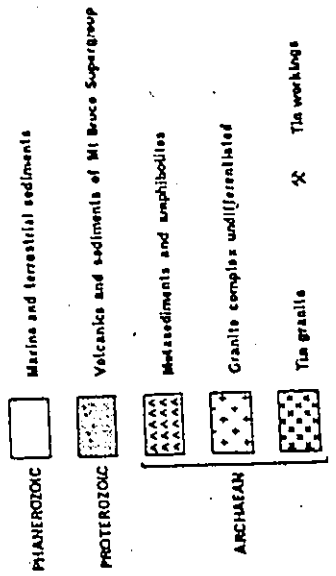
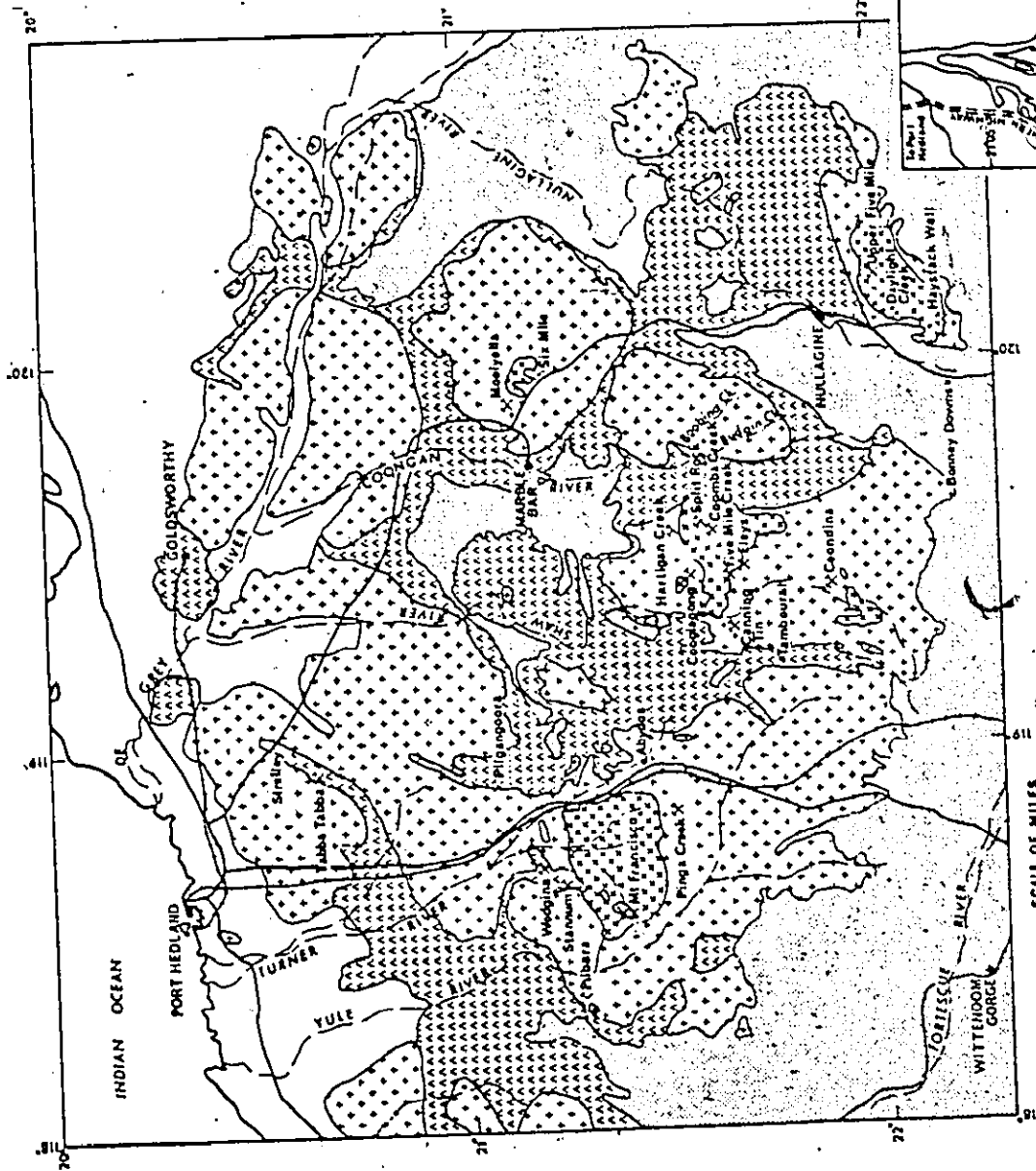


Fig. 78 from De Laeter and Blockley 1972



Deformation (after Noldart and Wyatt 1962)

- D₃? F₃? Intensification of folding (by granitic emplacement - Noldart and Wyatt). Normal faults, generally en echelon.
- D₂? F₂? Asymmetrical upright to overturned. Fold patterns following marginally on the granitic plutons in Warrawoona succession (volcanics). Cross flexures away from plutons in Mosquito Creek (sedimentary) succession, strike WNW.
- S₂? Schistosity.
- D₁? F₁? Upright sub-isoclinal folds with individual axes difficult to determine because of lithological similarity. ENE in W. part of Mosquito Creek succession of Marble Bar area, gently arcuate to E-W in central and eastern sections.

No structural mapping in the Pilbara has been noted and is needed.

If the suggested relationships are valid, the only non-standard feature is the intensification of folding by granitic emplacement at a late stage. Relationships of this aspect normally appear earlier, late granites being discordant.

Metamorphism (Ryan 1965)

M₂? (=D₂?)

Low grade (greenschist facies?) to amphibolite and granulite facies on flanks of domes: wide zones of cataclastic gneiss, migmatite, and metasomatized country rock.

No mapping of the metamorphic sequences of the Pilbara has been noted.
It is needed.

Ore Deposition

Pre-tectonic

Iron

The deposits of the Port Hedland district (Figs. 79, 80, 81) (Ord Range, Mt. Goldsworthy, Yarrrie) are in small areas of metamorphosed, folded, and faulted volcanics and sediments intruded by granitic rocks. The banded iron formations range from fairly pure white cherts to red and black types consisting of alternating bands of siliceous hematite and ferruginous chert (Matheson et al. 1965). Ryan (1965) correlates them with the Cleaverville and Gorge Creek formations at the top of the Roeburne Group.

Copper-lead-zinc-silver

The main interest in recent years has been in the sizeable low-grade copper-lead-zinc-silver deposits at Mons Cupri and Whim Creek. The environment is the felsics of the middle unit of the Roeburne (Ryan 1965, Warren 1972).

Syn-tectonic

Gold

Gold occurs in quartz veins and with antimony primarily in carbonatized basic rocks. The low temperature gold-quartz veins have been attributed to concealed intrusions of granite, but the close association of deposits and basic volcanics suggests mobilization of gold from the volcanics during deformation and deposition in suitable structures nearby (Warren 1972). Noldart (in Noldart and Wyatt 1962) notes that most of the deposits contain copper and are generally within a mile or so of the granitic or granitized contacts.

Tin-Tantalum-Lithium-Beryllium (Figs. 77, 78)

D₃? Pegmatites fall into three categories:

1. Ta-bearing, in volcanic terrains (+ Sn, Li, Be, Ce, REE), productive at Wodgina.
2. Sn-bearing in granite, producing from eluvial detritus.
3. Be-bearing, (and Cb and lepidolite) in granite from which beryl is hand picked.

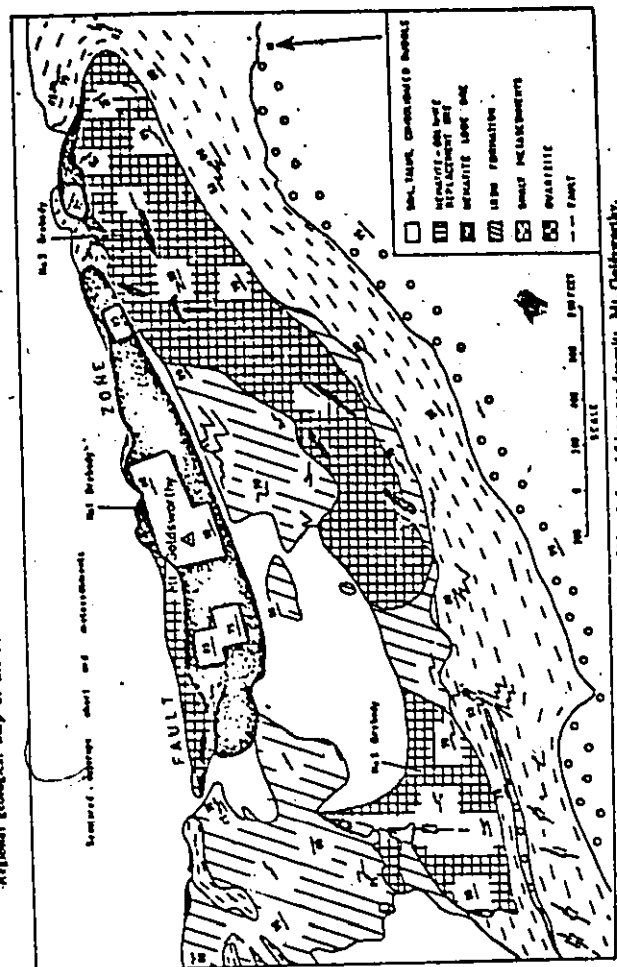
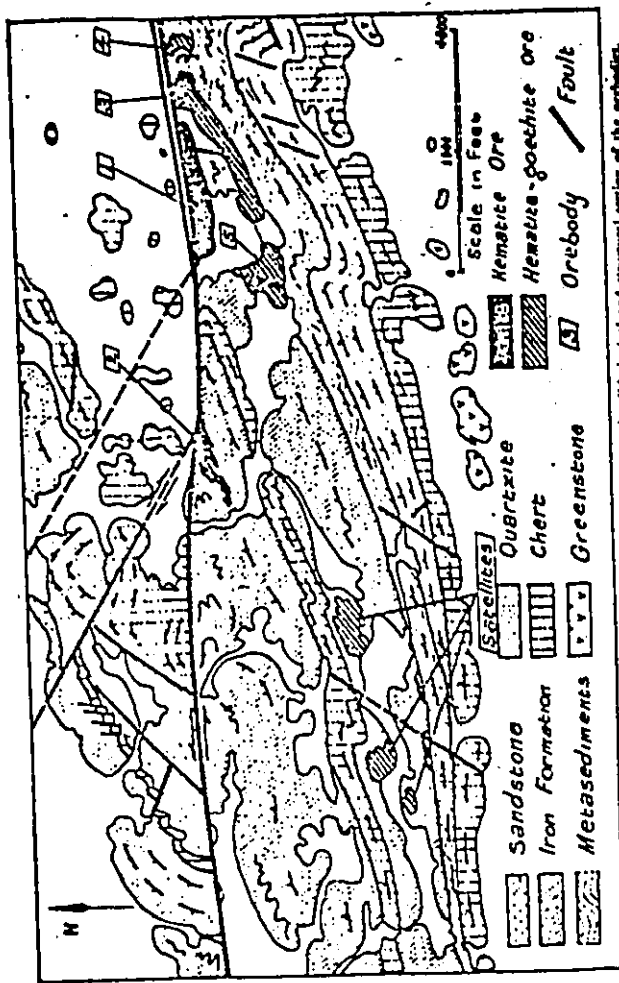
Tungsten has been produced from wolframite and scheelite in quartz-veins in metavolcanics at the margin of a granite pluton. (Warren 1972).

Antimony

D₃? Antimony in mineable concentrations occurs only in two areas. East of Nullagine, in an area mapped as Warrawoona Succession, basic and acid volcanics and chert, schist, etc. (Figs. 1, 4, 6), a line of quartz lodes containing gold and stibnite crosses the axial trend of folding at a low angle and therefore must transgress the bedding. East and north of Whim Creek, in an area mapped as basic and acid volcanics and thin metasediments of the Regal Formation and underlying sedimentary rocks, all of the Warrawoona succession, gold antimony deposits were mined chiefly for their gold content in the late 19th century (Warren 1972).

Asbestos

Chrysotile has been produced in the west Pilbara from serpentinites enclosed within granite and gneiss and from the Mt. Hall locality (Ryan 1965).



Figs. 79-81 from Matheson et al. 1965

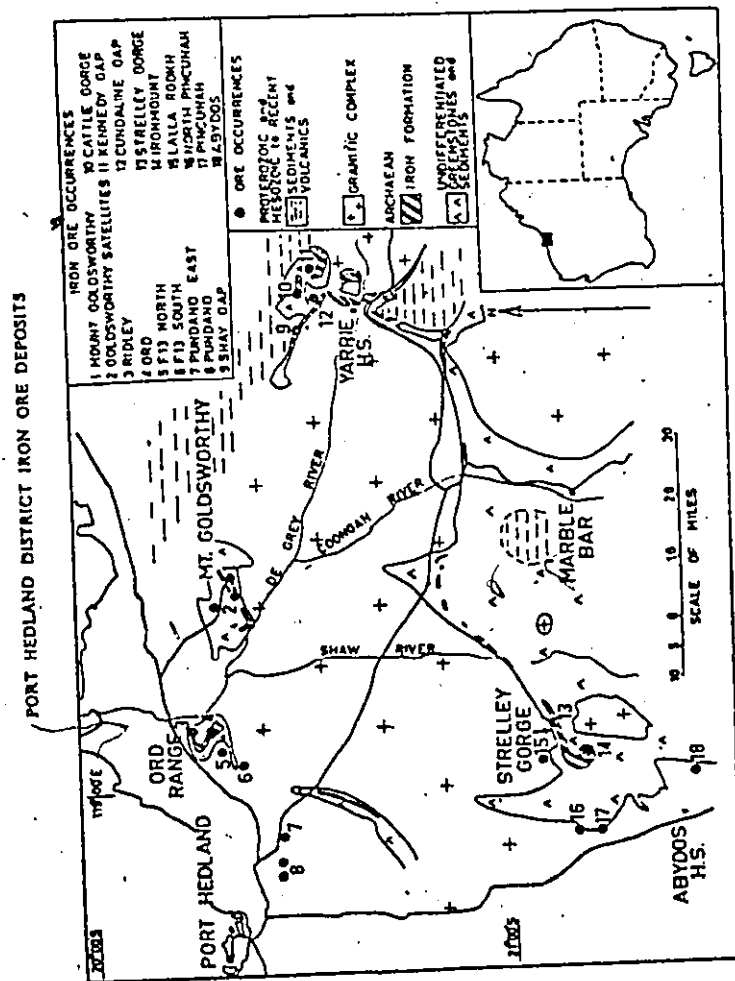
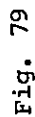


Fig. 81

Ore Production

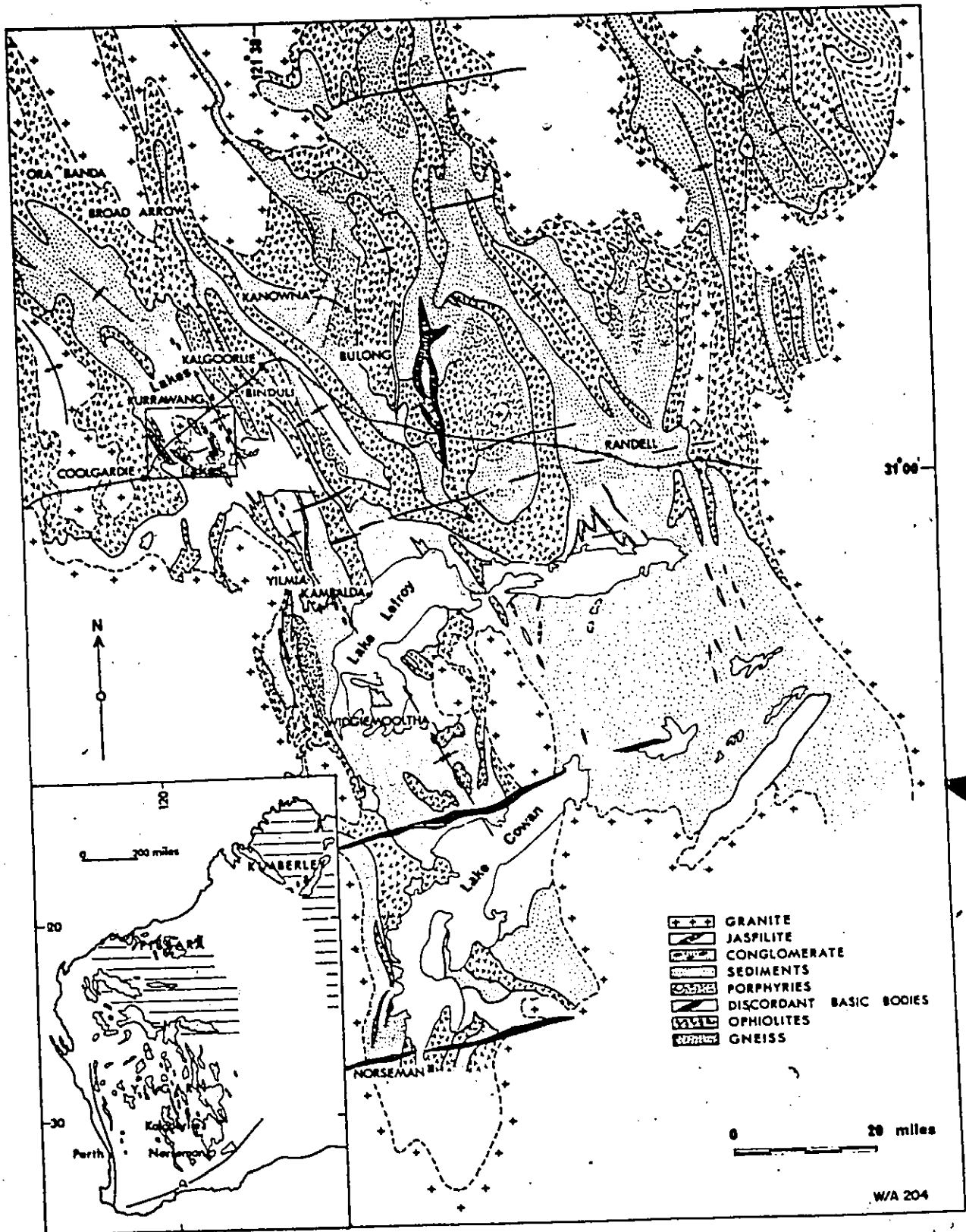
The Mining Magazine classification of ore production for 1974 is:

Mt. Goldsworthy	A	Fe
Shay Gap	A	Fe

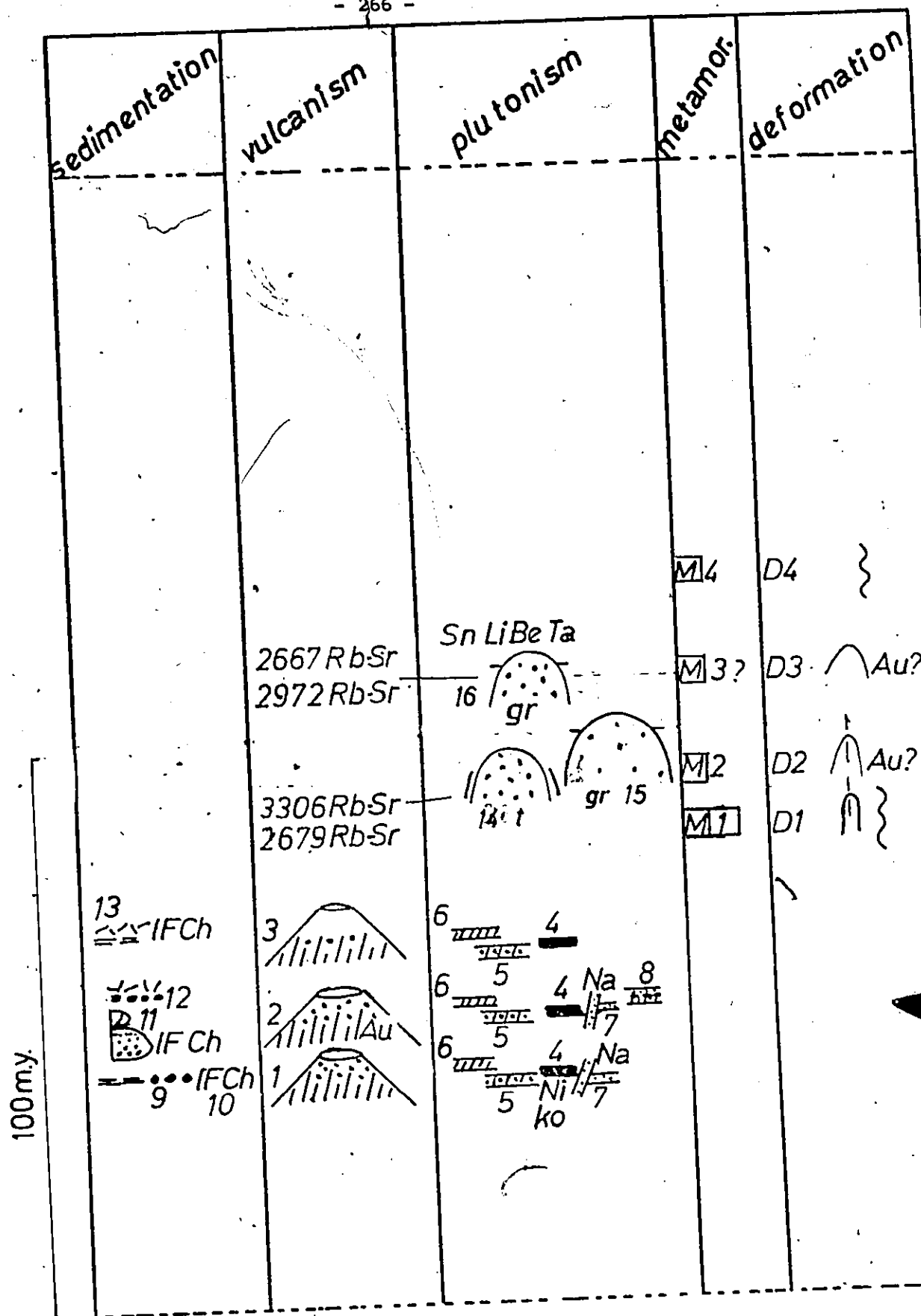
- 264 -

EASTERN GOLDFIELDS, AUSTRALIA

Fig. 82 from Glikson 1971-2



Geological sketch map of the Kalgoorlie-Norseman area. The framed area represents the Coolgardie-Kurrang sequence. After sketch maps by the Geological Survey of Western Australia.



E. GOLDFIELDS, W. AUSTRALIA.

Fig. 83 Time Relations of Geological Features

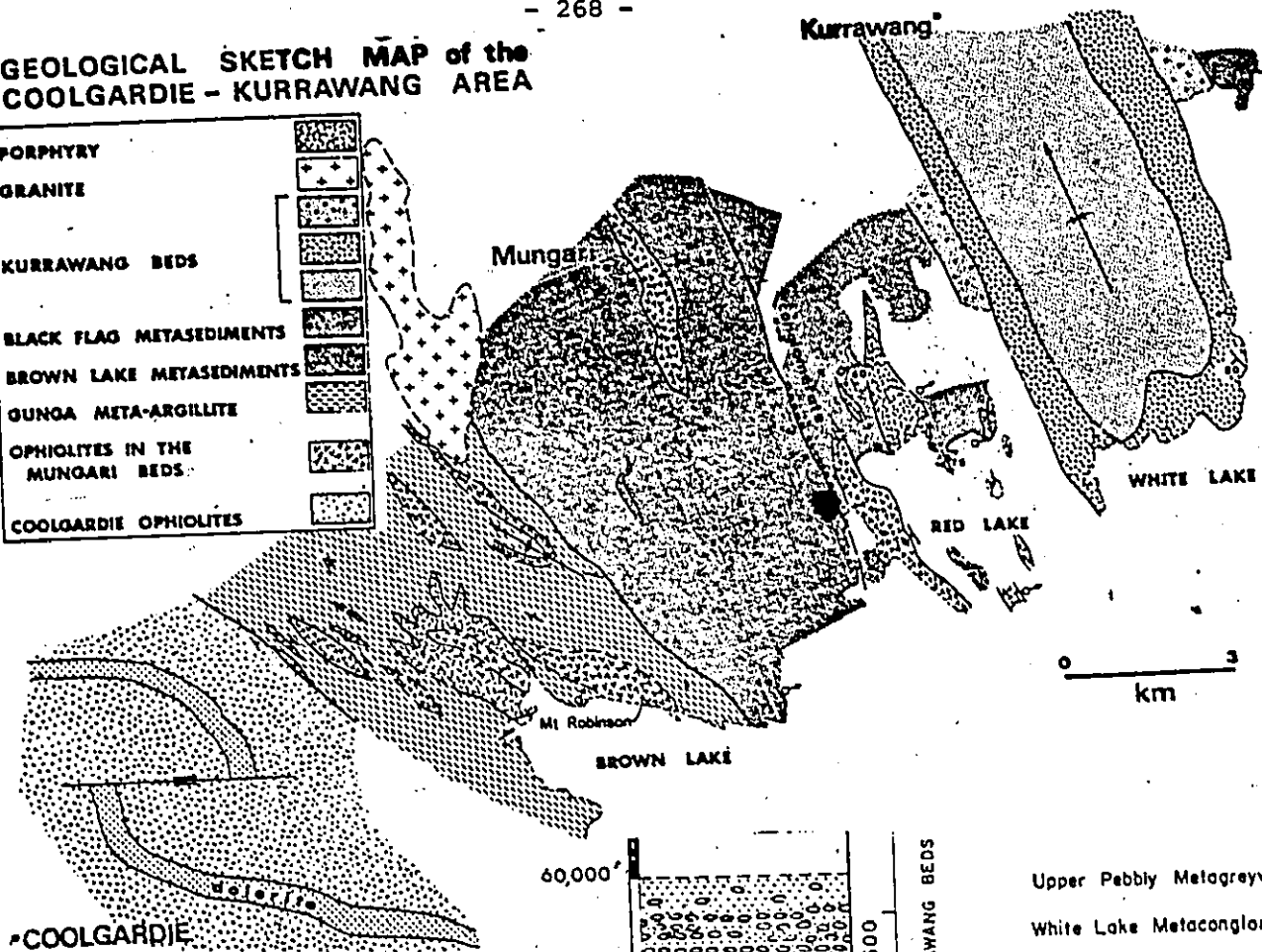
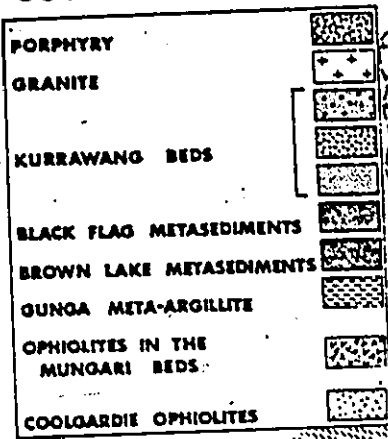
Vulcanism

The stratigraphic correlations in the Eastern Goldfields have been approached by Glikson (1971-2) in a paper entitled "Archean geosynclinal sedimentation, Kalgoorlie, W.A." and the theme that such correlation may properly fall under the purview of sedimentation is followed here. International correlations are largely based on volcanic stratigraphy, however, and so are pursued in the present section. Figs. 82 to 85 show the disposal of the sequence, Fig. 86 tabulates it, and Fig. 87 shows correlation with Barberton.

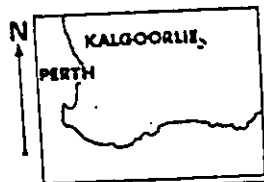
Glikson (1971-2) notes that the variations in type and abundance of igneous rocks are cyclic: (1) the Coolgardie ultrabasic to basic assemblage represents a major magmatic event, the waning of which is represented by the Mount Robinson belt which includes acid porphyries. The second cycle (2) is represented by the Red Lake igneous belt which comprises basic, ultrabasic, intermediate, and acid igneous rocks, and was evidently a comparatively minor episode. Though, as Glikson says, the Kurrawang Beds include no igneous rocks, he does correlate them with Association IV in the Kurnalpi Sheet area (Williams 1969) which includes chert, jaspilite, acid to intermediate extrusive rocks, acid intrusive rocks, and acid pyroclastics (3) in a predominantly sedimentary succession.

Viljoen and Viljoen (1969-7) (Fig. 87) compare the Coolgardie-Kurrawang sequence with that at Barberton. Anhaeusser (1971-2) writes that these unsighted attempts at lithostratigraphic correlation are of interest but open to criticism. However, he does not proceed to criticize his colleagues and from his text the only recognizable change in his visit to the area brought about was the consideration that the Kapai Slate rather than the Gunga Argillite is the equivalent of the Middle Marker: one is left with the impression that the Slate and Argillite are also equivalents. Cycle 1, the Coolgardie ultrabasic to basic assemblage is therefore regarded as the Ultramafic Group and is followed by the Greenstone Group composed of two major cycles.

GEOLOGICAL SKETCH MAP of the COOLGARDIE - KURRAWANG AREA



SYNCLINE
 GEOLOGICAL BOUNDARY
 FAULT
 STRIKE & DIP
 FOLIATION
 YOUNGING DIRECTION



Figs. 84 and 85 from
 Glikson 1971-2

Composite columnar section
 Thickness figures are approximate.

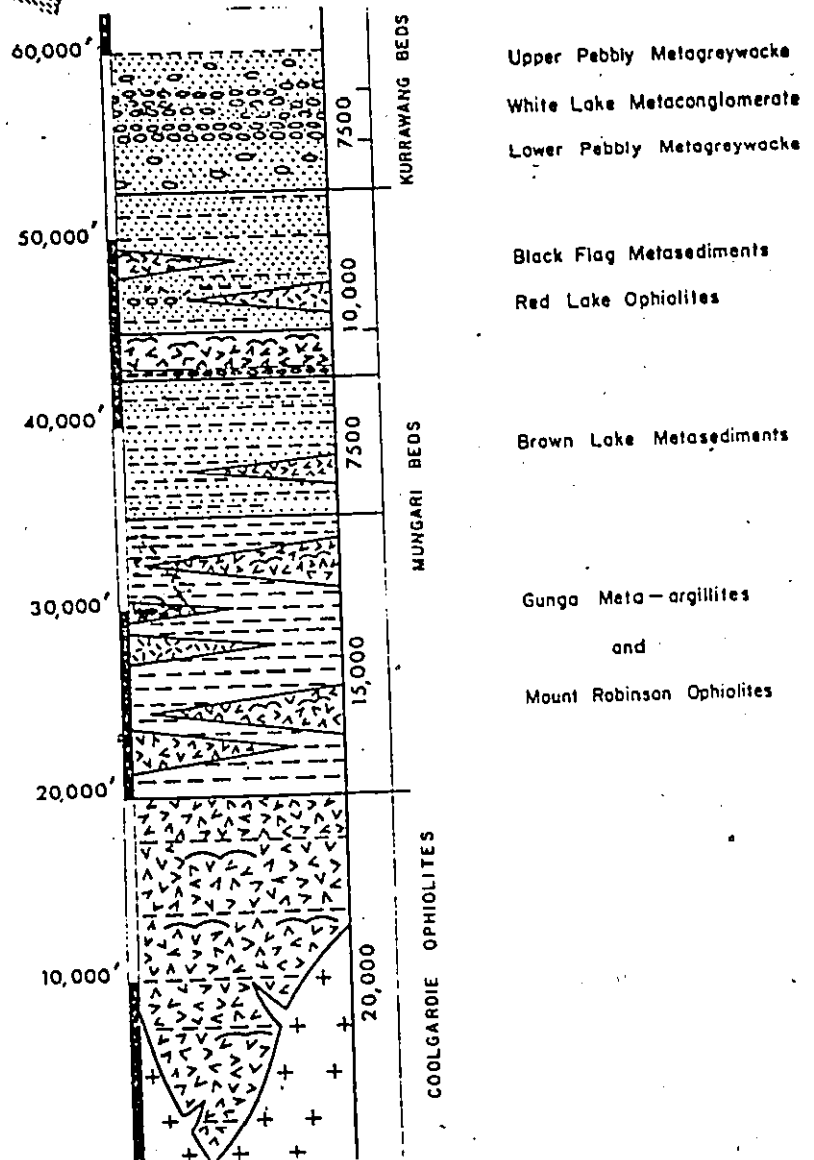


Fig. 86 from Glikson 1971-2

Stratigraphy of the Coolgardie-Kurrawang sequence

Major stratigraphic unit*	Minor stratigraphic unit*	Estimated thickness (metres)	Lithology	Notes
KURRAWANG BEDS	Upper pebbly metagreywacke	1200	Lithic metagreywacke and quartzose metagreywacke, with isolated pebbles of quartzite and sodic porphyry. Cross-bedding and crude sedimentary lamination are common.	No meta-igneous rocks and no pelitic sediments are known from the Kurrawang Beds.
	White Lake metaconglomerate	700	Pebbles and boulders of sodic porphyry, jaspillite, quartzite, metabasalt, metadolerite, sodic granite, gneiss and granophyre (in decreasing order of abundance), embedded in lithic metagreywacke matrix. Interbedded with cross-bedded metagreywacke. The granite pebbles were dated at 3000-3100 m.y. (Compton & Arriens, 1968)	
	Lower pebbly metagreywacke	800	Lithic, quartzose and feldspathic metagreywackes, with intercalations of pebbly metagreywacke. Thin silty beds occur at the base.	
MUNGARI BEDS	Black Flag metasediments	2300	Interbedded metagreywackes, soda-rich feldspathic and tuffaceous metagreywackes, feldspathic metasilstones, slates, minor pebbly and conglomeratic metasandstones. Minor acid and basic meta-igneous sheets.	Correlates with the Black Flag Beds. The sediments are probably mainly derived from the associated porphyries.
	Red Lake ophiolites	600	Metabasalts, meta-andesites, pillowed meta-andesites, metadolerites, metapyroxenites and sodic metaporphyries. The basic and intermediate meta-igneous rocks are stratiform, whereas the porphyries form lenticular bodies. The ultrabasics occur mainly at the base, whereas the intermediate and acid rocks occur at the top. A thin basal conglomerate is present.	This unit correlates with the Yilma greenstones and possibly the greenstones of the Golden Mile of Kalgoorlie.
	Unconformity? Brown Lake metasediments	2500	Interbedded and laminated phyllites, metasilstones, quartzose metagreywackes and metagritstones (in decreasing order of abundance). Fine-scale grading and cross-lamination, and small-scale slumps are common. Andalusite-garnet-cordierite schists occur near granites. Metabasites and porphyries are minor occurrences.	This unit represents a transitional facies between the pelitic Gunga meta-argillite and the arenaceous Black Flag metasediments.
	Mount Robinson ophiolites	3200	Metabasalts, pillowed metabasalts, metadolerites, metapyroxenites, albite-amphibole metaporphyries and albite metaporphyries, with slate intercalations.	
	Gunga meta-argillites	1700	Siliceous meta-argillites, slates, graphitic slates. No metasandstones were observed. Minor intercalations of banded iron formation are present. The metasediments are intercalated with basic meta-igneous rocks, which form up to 50 per cent of the sequence.	No basal pelitic unit is recorded from the Lake Lefroy sequence (McCall <i>et al.</i> , 1967).
COOLGARDIE OPHIOLITES		170	Metabasalts with intercalated meta-argillites.	The Coolgardie ophiolites possibly correlate with the Spargoville belt west of Lake Lefroy (McCall, 1969), with the Norseman greenstones, and the Ora Banda greenstones.
	Bonnie Vale belt	2000	Chlorite-tremolite metapyroxenites.	
		320	Metabasalts with slate intercalations.	
		600	Metadolerite sill, with an ultramafic base.	
		160	Metabasalts with intercalated meta-argillites.	
	Hampton belt	1850	Serpentinities, associated with slate intercalations.	
		10	Sodic metaporphyry.	
		800	Pillowed metabasalts and slate intercalations.	
	Tindals belt	330	Chlorite-tremolite metapyroxenite.	
		230	Metabasalts underlain by a horizon of porphyritic metagabbro ("Cat rock").	
	Lord Robe belt	170	Serpentinities.	

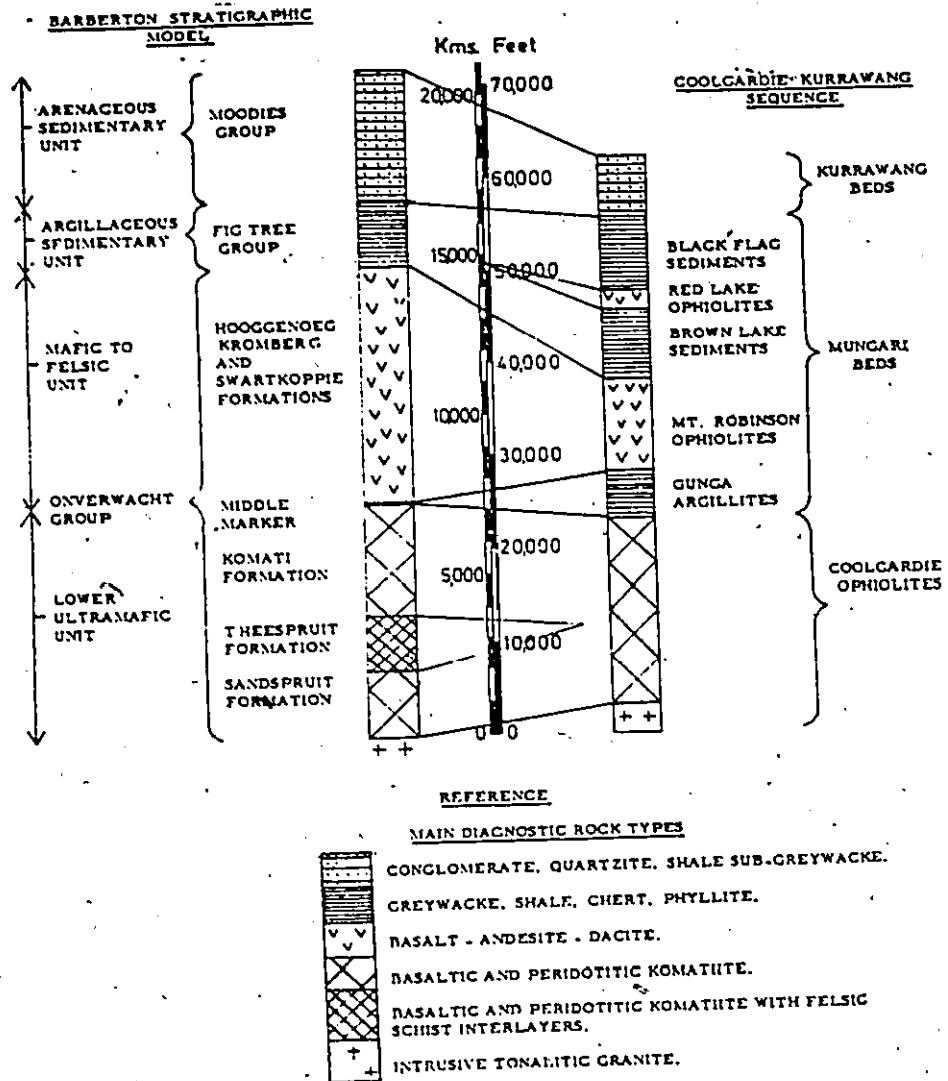
Particular points of correlation that Anhaeusser is able to add are the occurrence of intrusive soda-rich porphyries (7) in the Ultramafic Group (Glikson 1968) and he was shown quartz-fuchsite schists interlayered with ultramafic and mafic rocks south of Coolgardie. He does not go on to correlate these with the Theespruit, where they are characteristic (Viljoen and Viljoen 1969-2 and 71, perhaps wisely, for Williams (1969) notes minor occurrences in his Association III, the partial equivalent of the Fig Tree. Perhaps more diagnostic are the komatiitic varieties (4) interlayered with tholeiites in the Lower Ultramafic units and cyclical, largely tholeiitic, mafic and felsic units of Cycle 2.

As in Canada, recent studies on the volcanics of Western Australia emphasize geochemistry: Hallberg (1972), working in the area south of Kalgoorlie, notes the monotonous sequences of tholeiitic pillow basalts showing little vertical or lateral variation. Analyses for mafic rocks from the Coolgardie area quoted by Anhaeusser (1971-2) show a range from Komatiites (1) to oceanic tholeiites and even some continental tholeiites. The Mungari basalts (2) are similar to average tholeiitic andesites.

The geochemical studies extend to the related intrusives: differentiated sills (8) in the Eastern Goldfields are tholeiitic, serpentinites and pyroxenites at the base passing upwards into gabbro and granophyre, whereas those of South Africa are ultramafic (Anhaeusser 1971-2).

Some dolerite sills (6) are basaltic, others andesitic (5) (Glikson 1970). The best known is the Golden Mile Dolerite with which the gold ores of Kalgoorlie are associated. It is differentiated:

Intermediate zone (narrow)
Basic zone
Ultrabasic zone



Suggested lithostratigraphic correlation of the Coolgardie-Kurrawang Sequence on the western limb of the Kurrawang syncline between Coolgardie and Kalgoorlie, Eastern Goldfields of Western Australia, with the Barberton stratigraphic model.

Fig. 87 from Viljoen and Viljoen 1969-7

Na-rich intrusive porphyries (7) are found in the ultramafics of both Barberton and the Eastern Goldfields (Anhaeusser 1971-2) and to a less extent K-rich porphyries are also associated with the volcanics (Glikson 1970).

I.R. Williams (1969) points out that in the Kurnalpi area, whereas the basic parts of Cycles 1 and 2 contain sills and dykes of acid porphyry rocks (7), they are missing from Cycle 3. Apparently there never was a felsic part to Cycle 3.

In the Mt. Monger area, southeast of Kalgoorlie, D.A.C. Williams (1972) has recognized the upper, felsic part of Cycle 1 and the complete Cycle 2 equivalent of the Kurnalpi sequence. Sixteen small layered sills (8) intrude the high-Mg basalts and sediments of Cycle 2. Despite their small size (the largest is only 14 km²) a full, Stillwater-type differentiation is developed: harzburgite, orthopyroxenite, norite, norite-gabbro, gabbro, anorthosite, and granophyre, with all the features typical of layered intrusions - phase, cryptic, and rhythmic layering and cumulate textures.

Sedimentation (after Glikson 1971-2, Williams 1969) (Figs. 82 - 87)

Fig. 82 is the geological map of the Kalgoorlie-Norseman area. In the Kurnalpi area from which the NE part of Fig. 82 was compiled Williams (1969) described three mafic to felsic volcanic cycles. The upper, felsic part of Cycle 2 is accompanied by a great deal of sediment and all the sediment shown in the equivalent portion of Fig. 82 relates to this. To the west and south, however, sediments shown on Fig. 82 also include those of the Mungari Beds (Fig. 86) as reference to the framed Kurrawang and Coolgardie area of Fig. 82 and to Fig. 84 indicates. Glikson (1971-2) compares the sequences:

Upper sedimentary zone	Kurrawang Beds	(Association V?)	Cycle 3? (3)
	Black Flag Sediments	Association IV	
Upper Volcanic Zone	Red Lake Volcanics		
	(+Yilmiã Volcanics	Association III	Cycle 2 (2)
	and Kambalda-Kalgoorlie)		
	Belt)		
Lower Sedimentary Zone	Brown Lake Sediments		
	Mt. Robinson Volcanics	Association II	
	Gunga Argillite		Cycle 1 (1)
Lower Volcanic	Coolgardie Volcanics		
	(+Bulong, Spargoville,	Association I	
	and Norseman?)		

Glikson also notes that the ratio of sedimentary to igneous rocks decreases with age. Low stratigraphic levels are characterized by a predominance of pelitic sediments (9) (Gunga argillite), which are replaced gradually by a turbiditic graywacke-slate association (1) (Brown Lake sediments and Black Flag sediments), which subsequently grade into a graywacke-conglomerate facies.

For Kurnalpi, Williams (1969) data can be tabulated:

Cycle Assoc.

3	V	Basic to intermediate lavas and fine-grained pelites, chert, jaspilite, banded iron formation, and minor coarse grained fragmentals (13). Concurrent intrusion of mafic-ultramafic sills and dykes (4, 6).	1500 - 4500 m
	IV	Felsic to intermediate lavas, breccias, agglomerates, and large quantities of pyroclastics, thick but restricted. Flanked by oligomictic conglomerate (felsic volcanic clasts) derived from complex by contemporary erosion. Thick clastic deposits of graywacke, shale, siltstone, sandstone, and lenses of polymictic conglomerate (12).	Max. 10,000 m
2	III	Basic to intermediate lavas and fine-grained pelites, chert, jaspilite, banded iron formation (11) and minor coarse grained fragmentals and fuchsitic schists. Concurrent intrusion of mafic-ultramafic sills and dykes (4, 6). Minor felsic intrusions (7).	1500 - 4500 m
	II	Felsic to intermediate lavas, breccias, agglomerates, and large quantities of pyroclastics, thick but restricted. Flanked by oligomictic conglomerate (felsic volcanic clasts) derived from complex by contemporary erosion. Thick clastic deposits of graywacke, shale, siltstone, sandstone, and lenses of polymictic conglomerate.	Max. 10,000 m
1	I	Basic to intermediate lavas and fine-grained pelites. Concurrent intrusion of mafic-ultramafic sills and dykes (4 - 6). Minor felsic intrusions (7).	1500 - 4500 m

Plutonism

D₃?

Post-kinematic batholiths (16) slightly elongated and conforming to the regional strike but locally discordant. Dykes, pegmatites, aplites, and quartz veins are common (Prider 1965).

D₂?

Older (syn-kinematic) Granite (15): a thick succession of granitic gneisses resulting in part from granitization of the Kalgoorlie-Yilgarn succession and in part from concordant intrusions into it. The structures in the gneisses are concordant with the folded and metamorphosed country rock and in many places contain relict lenses in various stages of granitization. (Prider 1965).

D₂?

Tonalitic gneissic diapir responsible for structural complexity near Norseman (Anhaeusser 1971-2). Oval-shaped diapiric bodies of the tonalite, trondhjemite, granodiorite suite (Glikson 1976) (14).

These are the three basic units of the standard Archean plutonic sequence.

Deformation

The detailed geology of the area is obscured by laterite, alluvium, and aeolian cover. The delineation of the structural pattern in the poorly exposed zones of the Kalgoorlie System depends largely on the interpretation of aeromagnetic maps and the recording of small-scale details from isolated outcrops on the banks of dry salt lakes. Subject to these restrictions, Glikson (1971-1) found the evidence indicates the following sequence of deformation, metamorphism, and intrusion:

5. ENE basic dykes on joints.
4. Granitic intrusion with hornblende hornfels contact metamorphism; steep axis flexures.
3. Metamorphism; fracture cleavage (strain-slip, pitching 20 - 50°S, micro-crenulation of flow cleavage); cross-folding. Growth of small porphyroblasts of biotite.
2. Regional metamorphism to greenschist-amphibolite transition; axial plane flow cleavage parallel or sub-parallel to bedding; shear zones.
1. Folding in NNW axes.

To this one may add the vertical isoclinal folds at Kalgoorlie illustrated by Woodall (1965) and with specific attention to deformation, rephrase:

- | | |
|-------------------------------|--|
| D ₄ | Faults. |
| D ₃ F ₃ | Upright flexures. |
| D ₂ F ₂ | Cross folding E-W upright (vide Glikson 1971 Fig. 1). |
| S ₂ | Fracture cleavage. |
| D ₁ F ₁ | Isoclinal, upright-folds. |
| S ₁ | Flow cleavage and shear zones. Longitudinal faults replace anticlines. |

The sequence holds no unusual features.

Metamorphism

The metamorphic history may be extracted from the sequence of deformation, metamorphism, and intrusion, reiterated from Glikson (1971-1) under Deformation:

- M₄ Retrogression.
- M₃ Hornblende hornfels metamorphism by granitic intrusions.
- M₂ Greenschist facies: growth of small biotite porphyroblasts.
- M₁ Regional metamorphism to greenschist-amphibolite transition: actinolite to hornblende in the amphibolite, scarcity of garnet and epidote.

This history is for the Coolgardie-Kurrawang area. The Kalgoorlie System consists of meridional belts of metamorphic rocks engulfed by the extensive granites of the Yilgarn Shield (inset, Fig. 82). The metamorphic grade recognized within these belts increases from east to west (Glikson 1970, Binns et al. 1976).



Ore Deposition

Pre-tectonic

Nickel

Known mineral occurrences are closely associated with komatiites and, except for Mt. Windarra, are limited to a mobile median through the Kalgoorlie region in which chert but not banded iron formation is present. The deposits around the Kambalda dome are at or near the base of an ultramafic sheet, with which they appear to be co-magmatic, though the shoots lie in steeply plunging folds (Warren 1972 after Williams 1971 and Woodall and Travis 1969). For Kambalda, Ross and Hopkins (in press) note that the ultramafic sequence is in basalts, showing many of the monotonous features (noted under Vulcanism) described by Hallberg (1970) and a probable correlative of the Coolgardie assemblage.

Syn-tectonic

Gold

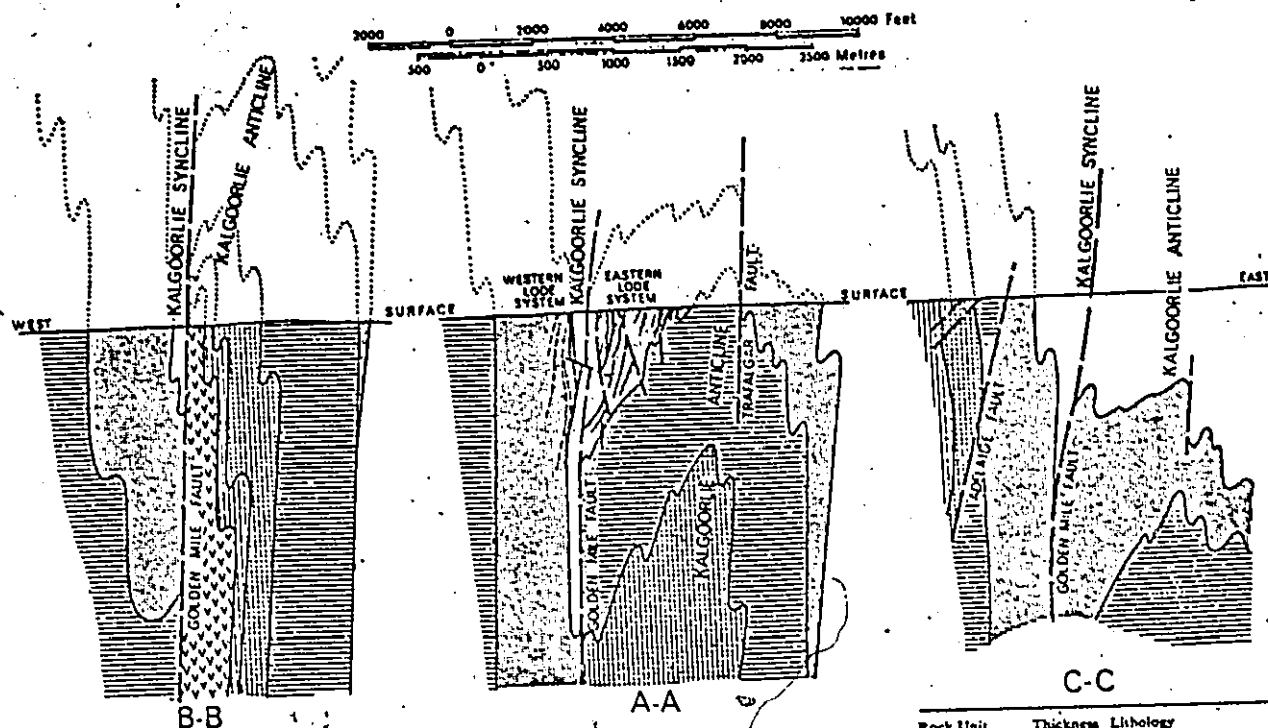
Warren (1972) quotes Williams (1970, unpublished notes on the Kurnalpi sheet). The granites of the Kalgoorlie area do not bear gold; elsewhere, though gold may be found in all types of rock, igneous bodies were favoured. There is a spatial link between acid dykes and sills and gold mineralization not previously noted, he points out, and so presumes a genetic link. Nevertheless, most of the productive lodes occur in quartz dolerite but many profitable shoots have been mined in calc-schist (Finucane 1965) (Figs. 88 - 90). The Kalgoorlie lodes have been formed by auriferous solutions which have penetrated along shears, fractures, and faults,

and have replaced and impregnated the quartz dolerite and the calc-schist in the immediate vicinity with quartz, pyrite, gold, and gold tellurides (Finucane 1965). Further study would be required to see if the ultramafics (Viljoen, Saager, and Viljoen 1970) or basalts (Keays and Scott 1976) are the source of the gold.

Tin

Tin has been produced from lithium-bearing pegmatites at Norseman, emplaced with granites during D₃.

Regional cross sections of Kalgoorlie area.



- HANNANS LAKE SERPENTINITE
- BLACK FLAG BEDS
- GOLDEN MILE DOLERITE
- PARINGA BASALT
- WILLIAMSTOWN DOLERITE
- DEVON CONSOLS BASALT
- PORPHYRY

- LODES
- FAULTS

Rock Unit	Thickness	Lithology
Black Flag Beds	3000m	Tuff, acid to intermediate lavas and agglomerate, sandstone, shale, slate and quartzite.
Golden Mile Dolerite	100-750m	Sill of meta-quartz-dolerite and gabbro with minor more basic sections.
Paringa Basalt	300-900m	Meta-basaltic lavas, in part pillow lavas, with minor interbedded slates.
Williamstown Dolerite	150-300m	Sill of meta-dolerite and meta-gabbro transitional to meta-quartz-dolerite near top and hornblende near base.
Kapal Stare	3m	Graphitic slate.
Devon Consols Basalt	60-150m	Meta-basaltic lavas, typically pillow lavas.
Hannans Lake Serpentinite	300-900m	Massive, fine-grained serpentinite.

Geological plan of Kalgoorlie productive area.

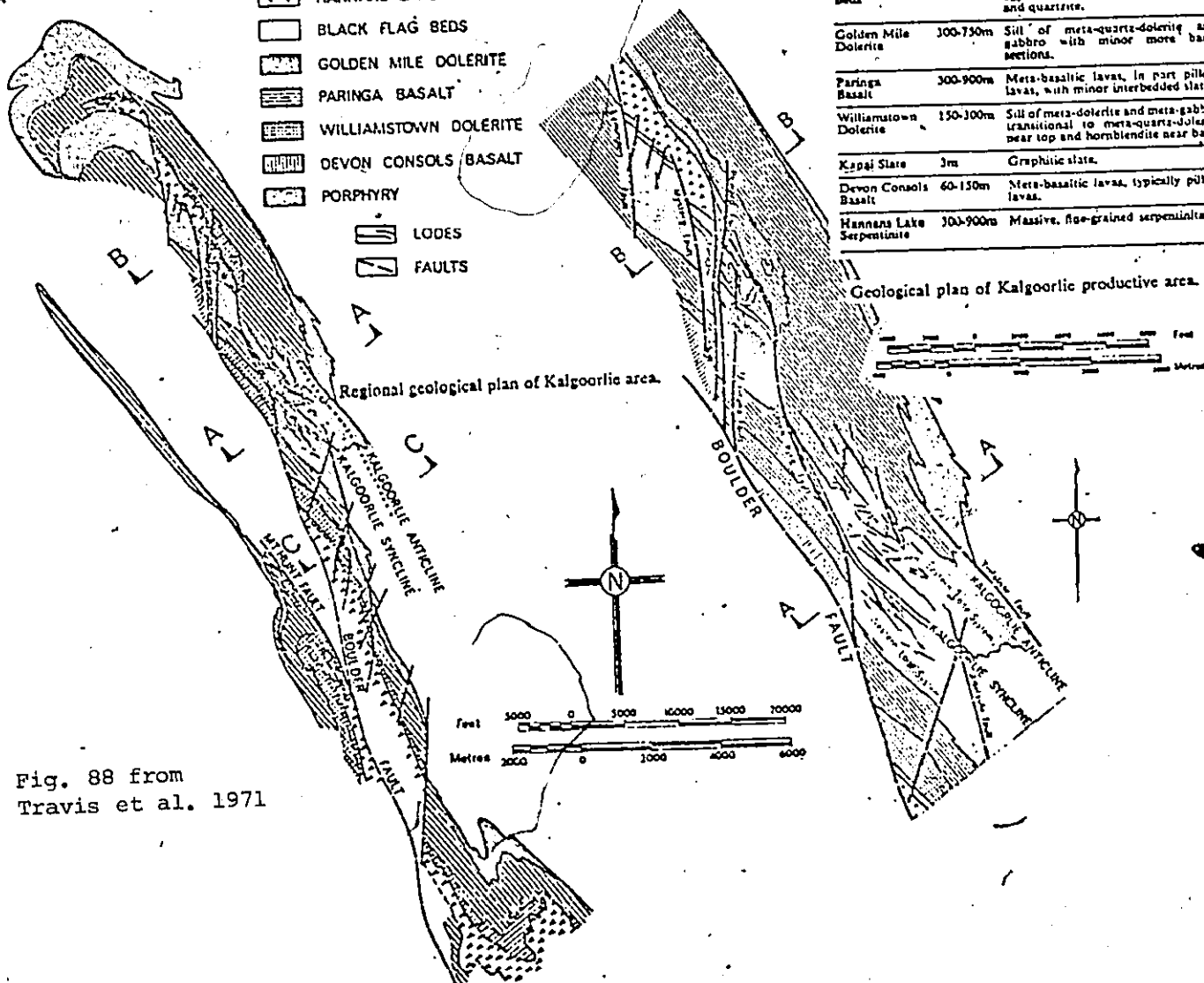
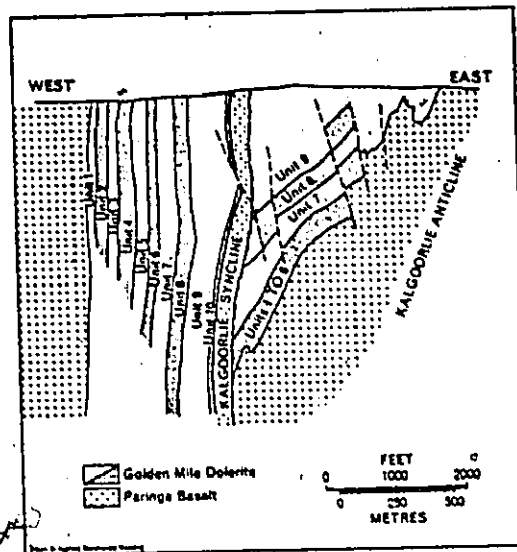
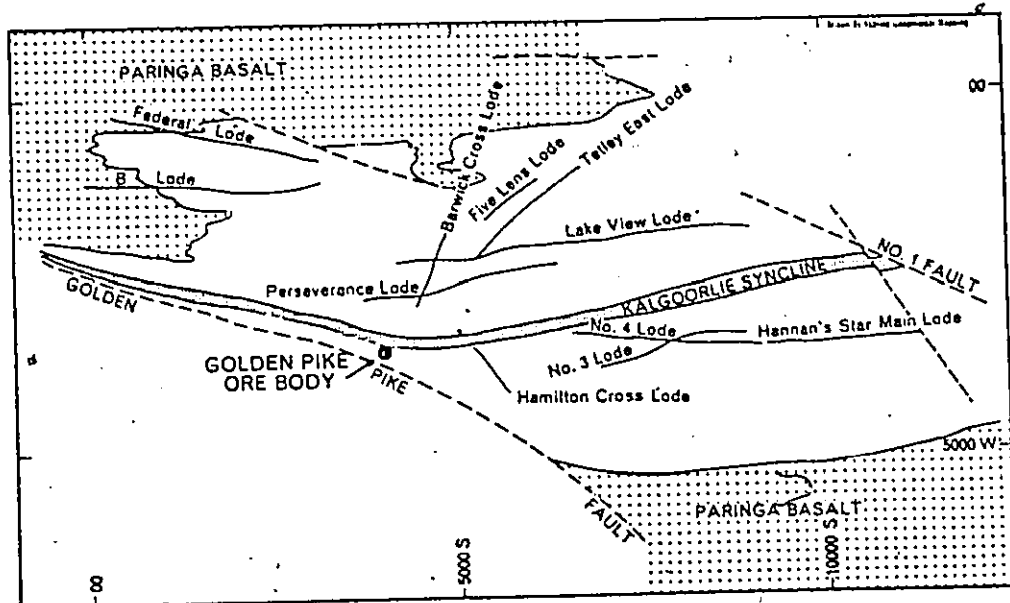


Fig. 88 from
Travis et al. 1971

Fig. 89 from Bartram and McCall 1971



Generalised diagram showing the structure of the Golden Mile Dolerite on either side of the Kalgoorlie Syncline, and its relationship to the Paringa Basalt



The distribution of the more important lodes studied

Fig. 90 from Bartram and McCall 1971

Ore Production

The Mining Magazine classification of ore production for 1974 is:

Central Norseman	E	Au
Lake View	D	Au
Mt. Charlotte	C	Au
N. Kalbarli	E	Au
Kambalda	B	Ni
Nepean	E	Ni
Redcross	D	Ni
Scotia	E	Ni
Spargoville	E	Ni
Windarra	C	Ni

AGE

"Most of the published ages are K-Ar analyses... this method is notorious for yielding low age values as the result of argon loss..." (Gates and Hurley 1973).

"If the laboratory procedures are properly controlled, some geologic errors can be isolated, as for example, aberrant samples in a Rb-Sr suite that give rise to an "errochron". Most difficult to detect are errors resulting from pervasive geologic processes, such as low-grade metamorphism, that may affect a rock system so that Rb-Sr data points may fit an isochron within analytical error, giving a "fallacious" isochron". (Goldich 1976).

These are the conclusions of geochronologists. Radiometric data considered in the present study lead to similar conclusions. The concern here is not why dates are "wrong" but how to recognize dates which may be significant to the work. In order to validate metallogenic periods one needs valid dates.

Four ways of evaluating radiometric dates are used in the present work: (1) Self-elimination where there are several dates on one rock unit or suite, (2) Relationship of dates to geological superposition, (3) Consideration of evolution of ($^{87}\text{Sr}/^{86}\text{Sr}$) ratios, and (4) Comparison of histograms of radiometric dates.

Some notes by geochronologists on the uses of various techniques are appended as are dates from the areas studied here.

EVALUATION OF DATES

Self-eliminating Dates

A table of U-Pb and Rb-Sr dates on intrusives from Barberton is illuminating:

<u>Date</u>	<u>Technique</u>	<u>Ancient Tonalites</u>	<u>Hood and Nelspruit Granites</u>	<u>Young Plutons</u>
2810 $\pm$ 80	U - Pb			Mpageni
2830	Rb - Sr			"Younger granite"
2880 $\pm$ 340	Rb - Sr			Ngampisi
2940	Rb - Sr			Dalmein
2992 $\pm$ 70	Rb - Sr		Nelspruit	
3030 $\pm$ 40	Rb - Sr		Consort pegmatite	
3060 $\pm$ 30	U - Pb			Salisbury Kop
3070 $\pm$ 60	Rb - Sr		Hood	
3130 $\pm$ 30	U - Pb			Bosmankop
3160 $\pm$ 50	U - Pb		Nelspruit	
3190 $\pm$ 70	U - Pb			Dalmein
3220 $\pm$ 40	U - Pb	Nelshoogte		
3250 $\pm$ 40	U - Pb	Theespruit		
3290 $\pm$ 80	U - Pb			Dalmein
3310 $\pm$ 40	U - Pb	Kaap Vaal		

If the members of the three intrusive suites were emplaced as the geological evidence indicates, Ancient tonalites during early D₂, Hood and Nelspruit granites during later D₂ and Young Plutons during D₃ or later, only the two oldest dates would appear to be primary. The other dates are excluded because they are older dates on the same suites. The older dates in this case are supported by the similar but slightly older dates of the Onverwacht Volcanics and Middle Marker.

Except for the youngest of the suite of dates, U-Pb gives consistently older dates than Rb-Sr, (about 250 m.y. difference) both as groups and for individual plutons. The U-Pb dates of plutonism are about 50 m.y. younger than the dates on the Middle Marker and quartz porphyry and so comparable with relative times of vulcanism and plutonism reported from Rainy Lake, Ontario (Hart and Davis 1969) and from Scotland (discussed elsewhere in this paper).

Dates and Geological Superposition

Yellowknife

The Prosperous Lake granite (12), usually considered to be the latest of the granitic intrusives at Yellowknife, is cut by diabase dykes (16) of Mackenzie Set 1, dated by Gates and Hurley (1973) at 2692 ± 80 m.y. (Rb-Sr). The date compares well with Pb-Pb dates, 2675 ± 15 m.y. from the western granodiorite (6) and 2665 ± 40 m.y. from the southeast granodiorite (6) (Cumming and Tsong 1975).

Hanson Lake-Flin Flon-Snow Lake

The reasons for non-acceptance of Archean Rb-Sr and model lead dates are discussed elsewhere. However, even the two Archean Rb-Sr dates are young compared to the prevailing 2.7 to 2.8 b.y. oldest dates now available from several Archean belts of the Canadian Shield.

Rice Lake

The two oldest Rb-Sr dates are considered as primary because they are in common with oldest dates from several other Archean belts in the

Canadian Shield, in the 2.7 to 2.8 b.y. range and because they are geologically reasonable:

Black Lake quartz monzonite. (12) 2735 ± 55 m.y.

Gold quartz veins 2720 ± 185 m.y.

These were statistically pooled as 2730 ± 50 m.y. (Turek 1971). McRitchie (pers. comm. in Turek 1971) suggested this was M_1 , post-dating D_1 and D_2 (p. 318 op cit.) and on p. 239 of the same volume McRitchie and Weber (1971) tabulate M_1 as post- D_1 , pre- D_2 . In the present work M_1 , at 2735 ± 55 m.y. is regarded as post- D_1 , pre- D_2 . Boyle (1961) (see under Ore Deposition, Yellowknife) gave reason for considering gold-pyrite mineralization to be followed by separation, resulting in gold-quartz mineralization related to late metamorphic and deformational episodes. The earliest this is likely to be is late D_2 and probably D_3 is more typical. 2720 ± 185 m.y. is therefore taken as D_3 . The 2530 m.y. date on one sample of biotite separate from paragneiss is certainly not primary, because the paragneiss is intruded by the Black Lake quartz monzonite (2735 ± 55). Similarly the 2630 m.y. date on the Tooth Lake pegmatite would appear to be secondary as the pegmatite is considered to be M_2 by McRitchie and Weber (in Turek 1971 p. 318) and so older than the gold quartz veins. The analytical errors on the dates from the veins and those from the veins pooled with the quartz monzonite (185 and 50 m.y.) must also be considered. With no other geological control, the significance of the younger dates is difficult to determine and is not hazarded here.

Abitibi Belt

Several dates in the range 2.7 to 2.8 b.y. appear to establish the age of vulcanism and plutonism: granodiorites at Noranda (2710 m.y.),

volcanics at Noranda (2710 $\pm$ few m.y.) and the Chibougamau pluton (2735 m.y.) (Krogh and Davis 1971); Pontiac granitoid (2665 m.y.); the Dauversiere Stock et al. (2761 $\pm$ 170 m.y.) (Wanless et al. 1970) or the Dauversiere Stock alone (2817 $\pm$ 180 m.y.). (Dallmeyer et al. 1975 from the data of Wanless et al. 1970); and the Preissac-Lacorne batholith (2650 $\pm$ 26 - 65 m.y.) (Steiger and Wasserburg 1969).

Rio das Velhas, Brazil

The 2790 m.y. date (Aldrich et al. 1964) is the oldest in the area but, as an Rb-Sr mineral age, must be considered a minimum. More dates are desirable.

Barberton

Dates from Barberton are reviewed above. Those considered to be primary are:

Dalmeir Pluton: 3290 $\pm$ 80 m.y. (U-Pb apatite).

Kaap Vaal Tonalite: 3310 $\pm$ 40 m.y. (U-Pb).

Quartz Porphyry, Hoeggenoeg Formation: 3360 $\pm$ 100 m.y. (U-Pb).

Middle Marker: 3355 $\pm$ 70 m.y. (Rb-Sr).

Rhodesia

There are essentially three schools of thought regarding the age of Rhodesian greenstone belts:

1. Hawkesworth et al. (1975) from a new programme of Rb-Sr dating consider that most of the volcanic rocks from the main greenstone

belts were extruded approximately 2.6 to 2.7 b.y. ago. Older dates, particularly that of 3520 ± 130 m.y. on the Mushandike granite (Hickman 1974) are considered to be on basement, though the distribution of basement and younger sequences is not discussed.

3. Bliss and Stidolph (1969) consider the importance of old K-Ar dates, the reliability of which must be questioned, because they are early analyses.

Piper Moss Pegmatite: 3300 ± 99 and 3440 ± 103 averaging 3370 m.y. (Ahrens 1955).

Pope's Mine Lepidolite: 3350 ± 300 m.y. (Nicolaysen 1954).

Bikita Lepidolite: 3340 ± 300 m.y. (Nicolaysen 1954).

The Piper Moss pegmatite cuts Sebakwian inclusions in the Rhodesdale gneiss. The Pope's Mine and Bikita pegmatites are post-Bulawayan. Thus the probability is that, if the three dates are true indications of geologic age, the Bulawayan Group is older than about 3.3 b.y. with the Sebakwian still older, and both have been affected by an igneous event at 3.3 b.y.

Hickman (1974) has an Rb-Sr date of 3520 ± 130 m.y. from the Mushandike granite which Wilson (1973-2) considers to post-date a sedimentary formation which is part of the Bulawayan Fort Victoria greenstone Belt, geologically comparable and apparently of the same age as the many other belts from which there are numerous dates, by Rb-Sr and other techniques, ranging from 3100 m.y. to the 2550 ± 30 m.y. date on the Great Dyke and younger (Saggerson and Turner 1976).

The possibility of two periods of vulcanism must be considered, or of minor basement remnants and major younger activity. Remnants of ultramafics in a central nucleus (Fig. 91) are commonly cited as evidence (e.g., Stowe 1971). The Rhodesdale batholith is a major part of this "central ancient nucleus", but Harrison (1970) has discussed this as a post-Sebakwian intrusive in which Sebakwian remnants are recognizable. Viljoen and Viljoen (1969-7) extend the theme: they recognize remnant lithologies directly comparable to the Sandspruit, Theespruit, and Komati sequences of Barberton, with the overlying Bulawayan matching the Hoeggenoe and Fig Tree, and the Shamvaian matching the Moodies.

Viljoen and Viljoen (1969-4) and Anhaeusser (1973) consider that all granitic rocks intrude the volcano-sedimentary pile in Rhodesia and at Barberton, thus refuting Hunter (1968). There are two problems, nevertheless: Stowe (1968-1) has depicted structures affecting "basement" southwest of Selukwe which are pre D_1 of the volcano-sedimentary pile (Stowe 1974) and Viljoen and Viljoen say they have evidence of Lower Onverwacht remnants in the Ancient Gneisses of Swaziland, but have yet to publish this evidence.

On balance, the vulcanism, plutonism, and deformation of the Rhodesian and Kaap Vaal cratons appears to have been coeval at about 3.4 to 3.3 b.y.

Goa, India

Crawford (1969-2) says he has made nearly 400 Rb-Sr analyses on the Precambrian of India, Ceylon, and Pakistan, but none of these nor of other workers appear to be from Goa. They are considered because many of them are on the Dharwar craton.



Fig. 91 from Stowe 1971

Goa is at the northwest corner of the Archean of southern India, the Dharwar craton (Pichamuthu 1974). In 1951 Pichamuthu found a well marked band of ironstone, manganese formations, and limestone could be traced almost without interruption right across the main outcrops of the Dharwars from west to east. This emphasized the fact that what were described hitherto as separate schist belts could be considered as stratigraphically and structurally united. The abundance of inclusions, frequently some kilometres long, which are dispersed throughout the Peninsular Gneiss in southern Karnataka also bears witness to the former continuity, Pichamuthu (1974) considers. With this background, though controversy over ages and sequences persist, one may follow Venkatasurbramanian et al. (1971) and add deformational probabilities from similarities in other parts of the world:

D ₃	Closepet granite.
D ₂ ?	Peninsular granite: intrudes Dharwars, coarse grained gneissic granite to migmatite, inclusions of Dharwars, banded gneiss, augen gneiss, gneissic granite, granodiorite.
D ₂ ?	Champion gneiss: tectonized gneiss.
Dharwars	Hornblende schist and amphibolite.

Western Australia

Arriens (1971) follows Prider (1943, 1944, 1945) in using for the gneisses of Toodyay, Armadale, and Canning Dam in the western Yilgarn the informal term "Older Granite" to distinguish these gneisses from younger granites which can be seen to intrude discordantly. He continues to use this classification for the rest of the Yilgarn. Noldart and Wyatt (1962) and De Laeter and Blockley (1972) follow the same usage for the Pilbara. No other characterization has been noted in the literature.

Other classification is by radiometric date alone. Arians (1971) writes that total-rock Rb-Sr isochrons for granites and gneisses in the Yilgarn Block give ages of emplacement between 3.1 - 2.9, 2.7 - 2.55, and 2.3 - 2.2 b.y. This would appear, therefore, to conflict with the geological evidence by which Prider's (1943, 1944, 1945) Older granite and Younger granites are similar to D_2 and D_3 granites of a single period, as at Barberton (Viljoen and Viljoen 1969-4). An alternative is that some if not all of these dates are secondary. An analogy may be drawn with the great majority of the dates from southern Africa.

Evolution of $(^{87}\text{Sr}/^{86}\text{Sr})_0$ Ratios

Moorbath (1976) has discussed the theory of evolution of $(^{87}\text{Sr}/^{86}\text{Sr})_0$ ratios, commonly referred to as Initial Ratios (I.R.). In essence, limits of ^{87}Sr decay in the mantle are known and may be drawn as an envelope from an $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.699 at about 4.6 b.y. to present day ratios of 0.702 and 0.706 (Jahn and Nyquist 1976). Magma fractionating from the mantle at a given time produces ratios similarly limited by the Rb/Sr ratios of the fractionation products.

Rb/Sr dates and their I.R.s, listed in Appendix 2 have been plotted for each of the continents, using only data from the areas reviewed (Figs. 103 to 106). Some conclusions may be drawn from these figures. From Fig. 103 (Canada), the data tend to cluster within the mantle limits between 2.4 and 2.8 b.y. This is particularly the case for samples from the Abitibi Belt, which is a broad unit so having a major proportion distant from flanking cratons. Samples with high I.R.s are from Rice Lake and Yellowknife.

Several alternatives are available:

- (a) Contamination of the granitic melts by older crustal material.
- (b) Remelting of the volcano-sedimentary pile some considerable time after its formation (fractionation from the mantle).
- (c) Internal mineral re-equilibration.

The first alternative is consistent with geological arguments indicating the presence of basement at Yellowknife and Rice Lake. The second alternative is less appealing, because the ages are similar to the low I.R. group. Even if valid, the indicated pre-granitic history is less than 250 m.y. (Figs. 103 and 107), suggesting that the fractionation from the mantle did not occur prior to about 2.8 b.y. in both regions.

The data from southern Africa (Fig. 104), India (Fig. 105) and Western Australia (Fig. 106) show a pattern contrasting with that from Canada. Though the analytical limits of the Australian data are particularly broad, both for dates and I.R.s, nevertheless the centres of gravity of the plots from the southern areas are similar. I.R.s for the 2.8 to 2.4 b.y. dates are notably higher than those for Canada, most being outside the mantle limits. The same arguments may be introduced as for the high I.R. samples from Canada. The first alternative is feasible, and though smaller areas are available for consideration as basement than in Canada, the common occurrence of basal arkoses, noted earlier, for example, indicates continental crust. The second alternative allows for up to about 500 m.y., consistent with a 3.5 to 2.5 b.y. formation of the volcano-sedimentary pile. The third alternative allows about

250 m.y. pre-equilibration history, still falling within a range of 3.5 to 2.5 b.y. At this stage, with the quality of data available, it is not advisable to advocate any preference. All possibilities can be involved in addition to factors as yet unknown.

Two groups of data are problematical. From Canada, some of the 1800 m.y. dates from Flin Flon have mantle I.R.s which would seem to preclude the possibility of longer pre-crustal history (Bell, Blenkinsop, and Moore 1975). Some data from Rhodesia are also tightly constrained (Hawkesworth et al. 1975) and plot in the mantle limits at about 2.6 b.y.: it is difficult to see how they could have separated from the mantle about 700 m.y. earlier as suggested by geological correlation.

Histograms of Radiometric Dates

Histograms on which dates by each technique are plotted against time for each region (Figs. 95 to 102) add to the utility of the listings of dates.

Rb-Sr mineral dates are generally younger than Rb-Sr whole-rock dates, at Yellowknife and in the Abitibi Belt for example.

Pb-Pb dates show a similar pattern to Rb-Sr dates. Model leads from ores of the Abitibi Belt and Barberton are considerably older; 600 m.y. in the Abitibi Belt, (may be remobilized lead), 200 m.y. at Barberton.

U-Pb dates are generally older than Rb-Sr dates in the Abitibi and at Barberton.

^{40}Ar - ^{39}Ar dates in the Abitibi Belt are about the same as Rb-Sr.

In Canada, other than the model lead suite on Abitibi ores only one date is older than 2800 m.y., the 2801 m.y. ^{40}Ar - ^{39}Ar date from north of Chibougamau on pre-Kenoran gneisses.

In Rhodesia, the Barberton Mountain Land, India, the Pilbara, and the Yilgarn, in contrast, there are numerous dates older than 2800 m.y., most from intrusives mapped as post-volcanic. One may add Brazil, if the 2790 m.y. Rb-Sr mineral age is accepted as too young, which would accord with the evidence from Canadian Rb-Sr dates noted above. Thus the plutonism accompanying the major development of greenstone belts is interpreted as post 2.8 b.y. in Canada, pre 2.8 b.y. in the southern areas.

Histograms on radiometric dates from the volcanics and post-volcanic plutons in Canada (Fig. 95) indicate that the principal activity was younger than 2.8 b.y. A review of the dates and successions indicated that much of the plutonism accompanied deformation between 2.8 and 2.7 b.y.

In southern Africa, Rb-Sr dates on sediments and volcanics and U-Pb dates on plutons indicate that the comparable vulcanism and plutonism was between 3.5 b.y. and the Canadian dates.

The histogram of all dates gathered in the study (Fig. 102) shows rapid build up and subsequent decline to peaks at 2.7 and 3.0 b.y., the 2.7 b.y. peak having more than twice the number of dates than the 3.0 peak. The 2.7 b.y. peak is interpreted as related to the 2.8 to 2.7 b.y. vulcanism and plutonism. No similar vulcanism and plutonism is known in the southern areas in the period 3.1 to 3.0 b.y. Examination of the histograms shows that the plots from individual regions do not peak as clearly at 3.0 b.y. as do those for 2.7 b.y. All are Rb-Sr (all but one W.R.). Most are from Barberton and India, four each.

At Barberton, there are no Rb-Sr dates between 3.3 b.y. and 3.1 b.y. and there is only one from India. From the table in the first part of this chapter on age, it will be recalled that the Rb-Sr dates on intrusives from the Barberton Mountain Land are consistently younger than U-Pb dates, as suites averaging over 200 m.y. difference. A similar date difference is noticeable for the two techniques in the Canadian Shield (Loveridge, pers. comm. July 1976). One is tempted to relate the 3.1 b.y. dates to a worldwide thermal episode (Walker 1975) but the data compiled here do not support accompanying vulcanism, plutonism, and deformation in the southern hemisphere, so making it desirable that the evidence from the Ukraine (Semenenko et al. 1968), for example, be re-evaluated. In contrast, the 2.7 b.y. thermal event does appear to be worldwide: it is strongly marked in the Yilgarn and 100 m.y. younger in southern Africa and India. The suggestion here is that major widespread thermal activity in the mantle accompanied more localized mobile belt formation.

No dates listed for India and Australia are U-Pb; of the very few on volcanics the Huttu hornblende schist from India gives an old K-Ar date, 3295 ± 200 m.y. Little work has been done, therefore, by which dates in the range 3.3 to 3.4 b.y. comparable to those on the Onverwacht volcanics and sediments might have been obtained. The work which has been done gives a comparable pattern for Africa plus India and Australia, from 3.2 b.y. on.

CONCLUSIONS

The geological data from the sixteen ore-fields studied can be synthesized, and this is the theme of the first part of these conclusions. The metallogenic relationships are then considered in various ways, first the geological setting of each of the ore types; then the ores associated with vulcanism, sedimentation, deformation, metamorphism, and plutonism; followed by restrictions on ore which appear to be imposed by time and space. A rating of metal as ore depends on costs, which vary with a multiplicity of factors, some of which are indicated: this consideration leads readily to that of ore potential. The review indicates major gaps in our knowledge, which may be regarded as research potential. The radiometric dates are the final subject of review: the knowledge of metallogenic epochs depends on their proper interpretation.

A brief summary completes the conclusions.

GENERAL GEOLOGY

Vulcanism

In the Introduction, two of the more detailed models of Archean volcano-sedimentary sequences are reproduced as frames of reference which might prove to be convenient. That of Wilson (1974) and his co-workers at Winnipeg, though originating in concept form from Western Australia, was given substance in northwestern Ontario and the Flin Flon area of Manitoba. That of Anhaeusser (1974-2) and his co-workers at Johannesburg originated in the substance of Barberton and was expanded by him to the comparable substance of Western Australia and by Viljoen and Viljoen (1969-7) to that of the Midlands Belt of Rhodesia.

Thus the utilisation of these models for the present study has a varied background. The Barberton model was firmly based before being extended to areas considered in the present study. The Canadian model, constructed in the southwest part of the Canadian Shield, has yet to be extended by the original workers to areas considered in the present study, though some suggestions have been made by them.

The Barberton model is considered first. The formations of the Ultramafic Group were recognised by Viljoen and Viljoen (1969-7) as xenoliths in the Rhodesdale batholith of the Midlands Belt in Rhodesia. The Kgarimacheng ultramafics described under Vumba and Tati have comparable lithology and stratigraphic position. Probably most of the Sebakwian of Rhodesia, whether as xenoliths incorporated in batholiths or as the unintruded lowest part of the volcano-sedimentary pile can be equated with the Ultramafic Group of the Barberton model. From Brazil, one must consider the large sills and stocks of altered peridotite, dunite, and other ultramafics of the Congonhas and Nova Lima districts as candidates for membership of the Ultramafic Group. No equivalent is apparent in Goa or in the Pilbara, though Goa is but a small part of the Archean of peninsular India, and the serpentized basic volcanics of the Pilbara merit further attention. In Western Australia, the Coolgardie ultrabasic to basic assemblage is equated with the Ultrabasic Group of the Barberton Model.

The Greenstone Group of the Barberton Model is equated with the Bulawayan of the Midlands Belt by Viljoen and Viljoen (1969-7). Only interpretations of radiometric data are serious problems in equating the Bulawayan of other parts of Rhodesia with the Greenstone Group, and reason is given under "Age" for supposing that the ages of the Barberton and Rhodesian belts are similar. The Penhalonga and Selkirk formations of Tati

Fig. 92

SEDIMENTATION	YELLOW KNIFE	FLINTFON	RICE LAKE	ABITIBI	BARGERION	RHODESIA	GOA	PILBARA	YILGARN
DEFORMATION									
METAMORPHISM									
PLUTONISM									
VULCANISM									
D4			Auq			sy gr			
D3	sy gr qtz qm di	gr ub Au	LiCsta qm Auq	sy Au gr	sy Auq gr	gr Au trond	gr	qm Sn Ta Au	Au gr
D2	AuS	gr di	qm AuS gr	Au gr	AuS gr	gr tm	gr	gr	Au gr
D1		di gb	qm q-di			gr			
		gb gr		Au Ni asb Cu Zn Au	asb Au	Fe Au Ni Cu			
	Au Au	Au Cu Zn	Au						

Chart: of Archean Areas

A GEOLOGICAL MODEL FOR THE SOUTHERN HEMISPHERE AND INDIA, 3.4 to 3.3 b.y.

(LARGELY AFTER ANHAEUSSER 1971 AND KEY et al. 1976)

SEDIMENTATION	VULCANISM	PLUTONISM	METAMORPHISM	D
104		Granite and syenite stocks Tonalite stocks	M ₆ local, retrogressive Au qv	D ₄ Po Normal
		Granite veining	M ₅ Local, retrogressive Au qv	D ₃ up Polyp deform and c
			M ₄ Local anatexis, ultrametamorphism. Au qv	
			M ₃ Regional zonation, amphibolite facies Au S	D ₂ up to op Domin
		(Granitization), Sn, Be, Ta, Li	M ₂ Regional graniti- zation and migmatiz- ation. Au S	
		Tonalite diapirs	M ₁ Regional, green- schist facies	D ₁ Re tal t isocl thrus Schis to th
<u>Sedimentary Group</u> Fluvial deposits Chemical deposits Fe Turbidites				
Siliceous aluminous schists Pelites	<u>Greenstone Group</u> Mafic to felsic cycles Calc-alk. Minor ultramafic and trachytic vulc. Tholeiitic basalt Au	Differentiated mafic sills Au, asb.		
	<u>Ultramafic Group</u> Peridotitic komatiites alternate with basaltic komatiites: Geluk type Badplaas type Barberton type Au	Peridotitic komatite sills: Stolzburg/ Noordkaap, Kaapmuiden- type: Ni, Cr, asb. Basaltic komatiite sills: Geluk type Badplaas type Barberton type Au		

A GEOLOGICAL MODEL FOR THE SOUTHERN HEMISPHERE AND INDIA, 3.4 to 3.3 b.y.

(LARGELY AFTER ANHAEUSSER 1971 AND KEY et al. 1976)

REGION	VULCANISM	PLUTONISM	METAMORPHISM	DEFORMATION
		Granite and syenite stocks Tonalite stocks	M ₆ local, retrogressive Au qv	D ₄ Polyphase, brittle. Normal faulting Au qv
		Granite veining	M ₅ Local, retrogressive Au qv	D ₃ upright folding. Polyphase brittle deformation: kinks and crenulations. Au qv.
			M ₄ Local anatexis, ultrametamorphism. Au qv	
			M ₃ Regional zonation, amphibolite facies Au S	D ₂ upright isoclinal to open folding Dominant schistosity. Au S
		(Granitization), Sn, Be, Ta, Li Tonalite diapirs	M ₂ Regional granitization and migmatization. Au S	
			M ₁ Regional, green-schist facies	D ₁ Regional horizontal tectonics: isoclinal folding, thrusts. Schistosity related to thrusts locally
Group posits eposits Fe				
aluminous	<u>Greenstone Group</u> Mafic to felsic cycles Calc-alk. Minor ultramafic and trachytic vulc. Tholeiitic basalt Au	Differentiated mafic sills Au, asb.		
	<u>Ultramafic Group</u> Peridotitic komatiites alternate with basaltic komatiites: Geluk type Badplaas type Barberton type Au	Peridotitic komatiite sills: Stolzberg/Noordkaap, Kaapmuiden-type: Ni, Cr, asb. Basaltic komatiite sills: Geluk type Badplaas type Barberton type Au		

29/2

A GEOLOGICAL MODEL FOR THE CANADIAN SHIELD, 2.8 to 2.7 b.y

(LARGELY AFTER WILSON 1974, MORRICE 1974, AND MCRITCHIE, WEBER AND SCOATES 1971)

SEDIMENTATION	VULCANISM	PLUTONISM	METAMORPHISM	
10f		Granite and syenite stocks Tonalite stocks	M ₄ local, retrogressive Aug. Au q	D ₄ p Norm
		Granodiorite to granite Quartz monzonite + dykes and pegmatites Sn, Be, Ta Cs, Li	M ₃ local retrogressive Au q	D ₃ u brit kink
		Quartz monzonite - granodiorite. Layered ultramafics.	M ₂ regional zonation, amphibolite facies Au S	D ₂ u to c Dom
		Granodiorite, quartz diorite, gabbro		
			M ₁ regional zonation, greenschist facies	D ₁ x tect fold Sch to t
Fluvial deposits Chemical deposits Fe Turbidites	<u>Upper Diverse Unit</u> Complex. Basalt to rhyolite. Some cyclical. Calc-alk. Cu-Zn, Au, small Ni	Anorthosite-gabbro sills. Layered gabbro sills Granite porphyries		Gra
Chemical deposits Turbidites	<u>Middle Mafic and Middle Felsic Units</u> Mafic to felsic sequence - minor cycles Calc-alk. Minor ultramafic and trachytic volc. Au Tholeiitic basalt Au	Gabbro sills		

A GEOLOGICAL MODEL FOR THE CANADIAN SHIELD, 2.8 to 2.7 b.y
 (LARGELY AFTER WILSON 1974, MORRICE 1974, AND MCRITCHIE, WEBER AND SCOATES 1971)

REGION	VULCANISM	PLUTONISM	METAMORPHISM	DEFORMATION
		Granite and syenite stocks Tonalite stocks	M ₄ local, retrogressive Au q	D ₄ polyphase, brittle Normal faulting Au q
		Granodiorite to granite Quartz monzonite + dykes and pegmatites Sn, Be, Ta Cs, Li	M ₃ local retrogressive Au q	D ₃ upright folding brittle deformation, kinks and crenulations Au q
		Quartz monzonite - granodiorite. Layered ultramafics.	M ₂ regional zonation, amphibolite facies Au S	D ₂ upright isoclinal to open folding Dominant schistosity Au S
		Granodiorite, quartz diorite, gabbro		
			M ₁ regional zonation, greenschist facies	D ₁ regional horizontal tectonics; isoclinal folding, thrusts. Schistosity related to thrusts locally
deposits	<u>Upper Diverse Unit</u>	Anorthosite-gabbro sills. Layered gabbro sills Granite porphyries		Graben faulting
deposits s	<u>Middle Mafic and Middle Felsic Units</u> Mafic to felsic sequence - minor cycles Calc-alk. Minor ultramafic and trachytic volc. Au Tholeiitic basalt Au	Gabbro sills		

1272

and equivalents at Vumba are equated here with the Bulawayan and the Greenstone Group. The distal products of vulcanism described from the Nova Lima Group of Brazil must be considered as candidates for membership of the Greenstone Group. Anhaeusser (1971-2) has suggested that the volcanic assemblages of the Pilbara are equated with the Greenstone Group, and more firmly equated with the post-Coolgardie sequences of Australia. Whether or not the sedimentary Kurrawang Beds and their volcano-sedimentary equivalent at Kurnalpi are considered as part of the Greenstone Group or the Sedimentary Group is not clear. Volcanic equivalents of the Shamvaian of Rhodesia might have posed a similar problem, were not the Fig Tree, Moodies, and bulk of the Shamvaian sedimentary.

The only area included in the present study which has been investigated in detail by the Winnipeg group is the Flin Flon belt. Morrice (1974-2) classifies the Amisk Group into Middle Mafic and Upper Diverse Units. The Amisk Group of the Hanson Lake area appears only to be composed of the Upper Diverse Unit. Morrice (1974-3) does not appear to have measured the full sequence at Snow Lake, where he worked in the Upper Diverse Group. At Snow Lake, Rice Lake, and in parts of the Abitibi Belt, the repetitions of mafic (and in places ultramafic) to felsic sequences is a barrier to equating sequences firmly with the non-repetitious Middle Mafic, Middle Felsic, and Upper Diverse model. Correlations are therefore made primarily on the nature of the related intrusives and mineralization. For example, the anorthositic core of a sill in the Rice Lake belt weights the correlation towards Upper Diverse, and the copper-zinc ores play a similar role in the Abitibi Belt. The analysis is not satisfactory. The volcanic stratigraphy of measured sections in the Abitibi belt needs to be determined so that comparisons can be made with a reasonable degree of accuracy, at present not available.

Comparisons have been drawn between the Canadian, South African, and Australian areas (Wilson 1974-1 and Viljoen and Viljoen 1969-7). Contrasts must also be considered: there is no known equivalent of the Ultramafic Group in Canada or of the Upper Diverse Group in the southern areas. The Middle Mafic and Middle Felsic sequence is linear, whereas some parts of the Canadian Shield and all the Greenstone Group and equivalents in the southern areas are repetitive.

Sedimentation

The earliest recorded sediments include basal conglomerate with rounded granite, other felsic products, and chert, at Yellowknife; feldspathic graywacke at Rice Lake; quartzo-feldspathic gneiss in the Limpopo Belt; arkoses of the Old Tati Arkose Formation and Shashe Gneiss at Vumba and Tati, and the Mont d'Or Series at Selukwe in the Midlands Belt; psammitic rocks around the Croydon granite in the Pilbara. These materials provide evidence that the volcano-sedimentary basins of these areas were emplaced on continental crust.

In the individual sections, little comment has been made on the intra-volcanic sediments. Intra-volcanic sediments have been studied in most detail at Rice Lake, by Campbell (1971). In almost every area, turbidity sedimentation is followed by fluvial sedimentation, in some places as at Rice Lake in the volcanic depository, in other places as in the Pilbara in a flanking basin. These paleogeographic aspects of geology are a concern to the metallogeny not pursued in the present study, where temporal sequences are the prime interest. Thus while Anhaeusser (1971-2) makes a three-part model comprising Ultramafic, Greenstone, and Sedimentary Groups; the temporal implication of this as a stratigraphic

model requires modification. Figure 74, the diagrammatic representation of facies changes in the Roeburne Group of the Pilbara, illustrates the point. Ridler (1976) is describing similar facies changes from vulcanism to sedimentation in the Kirkland Lake area, as are Dimroth and his co-workers at Noranda. As paleogeography becomes better appreciated the need for suitable nomenclature becomes more pressing.

Two distinctive phenomena merit note as amongst the oldest known, the tilloids of the Nova Lima Group of Brazil, if they prove to be tillites, and the aluminous schists of the Rhodesian craton, if they prove to be bauxites.

Although the mountain building which accompanied deformation, metamorphism, and plutonism must have been accompanied in every area by erosion and sedimentation, the only post-tectonic sediments recorded in the areas studied are the Shamvaian of the Midlands Belt. Probably both pre- and post-tectonic sediments comprise the Shamvaian in this area. The only other sediments known to have followed plutonic activity are the Missi of the Flin Flon area, which followed the earliest plutonism. The Sebakwe River conglomerate of the Midlands Belt of Rhodesia incorporates granite derived from the Rhodesdale batholith, but it is not yet clear whether at the critical time the batholith was exposed basement or re-exposed (remobilized) intrusive. The Pongola, though not studied, appears to be the post-tectonic part of the Swaziland sequence.

Plutonism

The volume of names in igneous petrology tends to mask common characteristics. Three suites are present in most areas, early (D_2) diapiric tonalites and quartz monzonites; granite, commonly referred to as

syntectonic, appearing later in D_2 , dome-like, on a broad scale concordant with the supracrustals, but with clearly intrusive contacts and a mixture of migmatite, gneissic granite, and nebulitic folded granite; and late- or post-tectonic (D_3 or later) discordant stocks of syenite, granite, and quartz monzonite, commonly with pegmatites.

Additions to these basic petrographic suites are common at Yellowknife, Flin Flon, and Rice Lake. The simplicity of the mapped plutonism in the Abitibi Belt may therefore be an argument for detailed study. In the southern hemisphere and India, additions to the three basic suites are uncommon, even in such well-mapped areas as Barberton and Vumba and Tati. The simplicity of the southern areas and additions to the basic theme, concordant D_2 , discordant D_3 , in the Canadian Shield are considered to be characteristic. The additions in the Canadian Shield include pre- D_2 granodiorite, quartz diorite, and gabbro, a questionably syn- D_2 layered ultramafic body at Rice Lake, and post- M_3 granodiorite to granite. Late ultramafics are also present at Flin Flon and Rice Lake.

Deformation

D_1 thrusts are interpreted at Yellowknife (Boyle 1961), Flin Flon (Coats et al. 1972), the Abitibi Belt, and Rhodesia, and D_1 high angle reverse faults at Barberton. F_1 folds are usually isoclinal: In most areas they are upright, but in some they are recumbent (e.g., Selukwe). It is possible that later deformation may account for some of the steeply inclined folds, as Dimroth, Côté, et al. (1975) interpret at Noranda. S_1 schistosity is associated with the thrusts at Selukwe but is absent in the south of Rhodesia, though in the Limpopo Belt, where imbrication is noted, metamorphism and deformation may have obliterated the evidence (Coward et al. 1976). F_2 folds are usually upright and vary from isoclinal

to open. S_2 schistosity is ubiquitous and commonly the strongest. F_3 folds are usually upright and open. S_3 schistosity is usually widespread but discontinuous. Vertical faulting is common at late stages and though not so commonly recognized at earlier stages probably originates early, as graben faults control the form of volcano-tectonic basis (Goodwin and Shklanka 1967).

No differences are noted in deformational histories between Canada and the southern areas.

Metamorphism

In many areas, metamorphism appears to be related to plutonism; Yellowknife, Barberton, and the Midlands providing the best examples. The precise relationships of metamorphism and deformation have only been studied at Yellowknife (Fyson 1975), Rice Lake (McRitchie and Weber 1971) and Vumba and Tati (Key et al. 1976). At Rice Lake, McRitchie and Weber (1971) consider that deformational periods are followed closely by metamorphism, in paired cycles. At Vumba and Tati, Key et al. (1976) regard some deformation and metamorphism as occurring together, other metamorphic episodes are unaccompanied by deformation. Usually M_2 , the period of principal igneous activity (granitization and migmatization), is the peak of metamorphism, the sites of granitization being marked by amphibolite or even granulite facies metamorphism, grading off to greenschist or even prehnite-pumpellyite facies in the synclinal cores. At Vumba and Tati, Key et al. (1976) describe an early pyroxene hornfels metamorphism outside the supracrustal relics: the relationship to granulite metamorphism in the adjoining Limpopo straight belt (Hepworth 1967) is not clear. The problem of metamorphic succession in straight belts is comparable to that in the belts not accompanied by such intense linear deformation and metamorphism.

As with deformational histories, no differences are noted in metamorphic histories between Canada and the southern areas.

METALLOGENY

Metal Associations

Iron

The treatment of the topic of geological settings of Archean ore deposits is stratigraphic (in its broadest sense, encompassing facets of geologic history such as deformation and metamorphism) rather than paleogeographic. This is perhaps most evident in the case of iron. Gross (1965) has reviewed the varieties of iron ore and notes that relatively limited information is available about the geological setting, the nature and kind of associated sediments, and the general tectonic framework of the areas in which many iron formations occur. He himself did much in review of the nature and kind of associated sediments. A feature added in the present study is the appreciation that although iron formation is common in various parts of the pre-tectonic volcano-sedimentary sequence, the principal ores come high in the pre-tectonic sequence, and though fumarolic, in the parts where there are more sediments than volcanics. Though sedimentary basin contemporaries of early vulcanism are known, as in the Pilbara (Fig. 74) these appear not to be the loci of iron ores (Fig. 75).

Asbestos

All the production is from ultramafics of volcanic association where the principal metamorphism is greenschist facies. Though the potential might appear to lie in the best developed ultramafics, that is the Ultramafic Group of the southern areas, and there are many deposits in the differentiated sills of the Group, all are small and better, though fewer, deposits are found higher in the sequence.

YK - Yellowknife
 FF - Flin Flon
 RL - Rice Lake
 Tim - Timmins
 KL - Kirkland Lake
 Nor - Noranda
 Chib - Chibougamau

RV - Rio das Velhas
 Barb - Barberton
 Limp - Limpopo
 V-T - Vumba & Tati
 Mid - Midlands
 Goa - Goa
 Pilb - Pilbara
 E.G. - Eastern Foldfields

- 308 -

Fig. 95

ORES AND ASSOCIATIONS

Association	Fe	Asbestos	Cr	Ni	Cu-Ni	Cu-Zn	Cu-Au		Sulphide Veins, Stringer Lenses
							Disseminated	Vein	
<u>Plutonic</u>									
Felsic							<u>Tim</u>	<u>Chib</u>	<u>Chib</u>
Mafic									
Ultramafic									
<u>Metamorphic</u>									
Amphibolite					Limp	<u>Nor, Pilb</u>			<u>YK, RL, B</u>
Greenschist		<u>Tim, Chib,</u> <u>Barb, Goa</u>			VT, Mid	<u>FF, Tim, Nor</u> <u>Chib, Pilb</u>	<u>Tim</u>	<u>Chib</u>	<u>YK, RL, Nor</u> <u>Chib, Barb</u> <u>Mid, E.G.</u>
Prehnite- Pumpellyite									<u>KL</u>
<u>Deformational</u>								<u>Chib</u>	
Late									
D ₄									<u>Chib</u>
D ₃									<u>YK, RL, KL</u>
Early									<u>Chib, Barb</u>
D ₂					Limp	<u>FF, Nor</u>			
D ₁									
<u>Sedimentary</u>									
Flysch	<u>KL, Barb</u> <u>Mid, Goa,</u> <u>Pilb</u>					<u>FF</u>			<u>Nor, RV, B</u> <u>Mid</u>
Chemical									<u>KL, RV, B</u> <u>Mid, E.G.</u>
<u>Volcanic</u>									
Felsic						<u>FF, Tim, Nor</u> <u>Chib, Pilb</u>			Barb
Mafic					V-T				<u>YK, Nor, B</u> <u>Mid, E.G.</u>
Ultramafic		<u>Tim, Chib</u> <u>Barb, Goa</u>	Mid	<u>Tim, E.G.</u>	Limp, Mid, V-T				Barb, Mid

10f

elhas
on
Tati

Fig. 95

ORES AND ASSOCIATIONS

Foldfields

	Cu-Ni	Cu-Zn	Cu-Au		Au			SnLiTa
			Disseminated	Vein	Sulphide Veins, Stringers Lenses	Quartz Veins	Minor in Base Metal Ore	
			<u>Tim</u>	<u>Chib</u>	<u>Chib</u>	<u>Chib</u> , V-T Barb		Pilb, E.G.
	Limp VT, Mid	<u>Nor</u> , Pilb <u>FF</u> , <u>Tim</u> , <u>Nor</u> <u>Chib</u> , Pilb	<u>Tim</u>	<u>Chib</u>	<u>YK</u> , <u>RL</u> , Barb <u>YK</u> , <u>RL</u> , <u>Nor</u> , <u>Chib</u> , Barb Mid, E.G. <u>KL</u>	<u>YK</u> , <u>R.V.</u> , Barb, <u>YK</u> , <u>RL</u> , <u>Tim</u> , <u>Chib</u> , <u>R.V.</u> Barb, V-T Mid, Pilb <u>KL</u>	Pilb	
	Limp	<u>FF</u> , <u>Nor</u>		<u>Chib</u>	<u>Chib</u> <u>YK</u> , <u>RL</u> , <u>KL</u> <u>Chib</u> , Barb	<u>YK</u> , <u>RL</u> , <u>Tim</u> , <u>KL</u> , Pilb <u>Chib</u> , Barb, Mid <u>Chib</u> <u>YK</u>		<u>YK</u> , <u>Chib</u> , Yilg
		<u>FF</u>			<u>Nor</u> , <u>RV</u> , Barb Mid <u>KL</u> , <u>RV</u> , Barb, Mid, E.G.	<u>YK</u> , <u>RV</u> , Barb, Mid <u>KL</u> , <u>RV</u> , Barb, V-T		
	V-T Limp, Mid, V-T	<u>FF</u> , <u>Tim</u> , <u>Nor</u> <u>Chib</u> , Pilb			Barb <u>YK</u> , <u>Nor</u> , Barb Mid, E.G. Barb, Mid	<u>KL</u> <u>RL</u> , Barb, V-T <u>Tim</u> , V-T	<u>FF</u> , <u>Nor</u>	

n, E.G.

272

Chromium

Though mined from younger Archean volcanic units, as from the Cat River differentiated ultramafic sill in Manitoba, the world's principal deposits of high grade chromite are at Selukwe, Rhodesia, in the Ultramafic Group. Cotterill (1969) relates the thickest development of chromite to downwarps in the chamber floor. As with nickel, it appears that most chromite is developed in thick ultramafics, but also as with nickel, the process by which chromite is concentrated to ore grade is little understood. Current work on the extensive chromite beds of the Bushveld complex may help resolve the problem. Perhaps the most important factor after metallogenic period is metallogenic province: the chrome province of southern Africa is shown in Fig. 65.

Nickel

Nickel occurs with komatiitic ultramafics, most commonly sills, as in the Yilgarn and the Shaw Dome, near Timmins, Ontario, but also flows, as at Texmont, south of Timmins. Wilson (1974-3) notes the difference in size of the small Canadian deposits and large ones of the Yilgarn, and relates this to stratigraphic position, those of the Yilgarn being in the lowest volcanic unit, the Ultramafic Group, and those of the Abitibi Belt in the highest volcanic unit which he equates with the Upper Diverse Unit of north-western Ontario. Although stratigraphic position may be a significant factor, whether this is related to volume of komatiite and volume of komatiite to volume of nickel is unresolved. Large ultramafic bodies in the Barberton area have a large volume of low grade nickel silicate (de Waal 1970). Factors necessary for concentration of nickel from silicates are topics of current studies at the University of Toronto.

Copper-nickel

Copper-nickel ore is hosted by the Umniati Group at the Empress deposit in the Midlands belt, and perhaps by the same Greenstone Group equivalent in the Pikwe-Selebi deposits of the Limpopo belt, though in other parts of the Rhodesian craton the host is the ultramafic Group (Anhaeusser 1976-1 and Hickman and Wakefield 1975). The Empress is a metamorphosed, differentiated sill of gabbro with picrite, pyroxenites, norite, and diorite (Anhaeusser 1976-1) and the Pikwe-Selebi bodies are also in a sill, now amphibolite. The best ore at Pikwe is associated with D₂ (Wakefield 1976).

Copper-zinc

The Archean copper-zinc deposits associated with felsic volcanism are dominantly in North America. The Cactus mine in the Midlands belt of Rhodesia and Mons Cupri and Whim Creek at the Pilbara are representatives of the lesser ore tonnage of the southern areas.

All the Canadian deposits are considered by Wilson (1974-3) to be associated with the Upper Diverse unit, though this requires substantiation. Even those of the Sherridon area which are distal, being in the Kiseeynew gneisses, may be related to this unit. Most are proximal and submarine, though the Coronation deposit near Flin Flon, in being associated with sub-volcanic intrusives, indicates that the magmatic host is the primary consideration, the ultimate depositional environment secondary.

Noranda deposits have become the model for Archean copper-zinc deposits. Spence and de Rosen Spence (1975) describe them in current terms: "The ore deposits, which overlie chloritic pipes of alteration, occur at or near the top of rhyolitic formations and many are associated with

primary volcanic features such as lava domes and explosive breccias.

They show a zoning of copper-zinc ratios and evidence of fragmentation of some massive sulfides prior to their having been covered by later flows of andesite or rhyolite. They are attributed to submarine volcanogenic processes forming sulfide sinters over hot springs".

Ridler (1976-2) emphasizes the close time constraints to the deposition of the similar Miocene Kuroko ores of Japan, and the theme also follows the work of Spence and de Rosen Spence (1975). They note five successive periods of rhyolitic activity at Noranda: copper-zinc rich deposits occur in the third zone, zinc rich deposits in the fourth zone, and only a massive pyrite body is known in the fifth zone. The upward change from copper to zinc is common in volcanogenic base metal ores.

As a counterpoint to the zonal constraints of Noranda and Japan, which merit further attention elsewhere, Wilson (1974-3) notes that there is little to be gained by prospecting further for copper-zinc in the Middle Mafic and Middle Felsic units, where the lack of copper-zinc ore and even lack of mineralization is characteristic.

L₂ lineation at Flin Flon and the Lower "H" orebody at Noranda modified the form of the orebodies.

Copper-gold

Copper and gold ores are perhaps most commonly associated in porphyry deposits, and the association persists in the Canadian Archean. Several have been mined in the Abitibi Belt, the best known example being the Pearl Lake porphyry at Timmins. The shear zone deposits at Chibougamau have been described by Allard (in Allard et al. 1972) as sub-volcanic, related to the volcanogenic copper-zinc deposits. Most volcanogenic copper-zinc deposits are zoned, but while the lack of zinc at Chibougamau may be related to zoning, the relationship has yet to be demonstrated. Ore bodies structurally controlled in the upper part of the Ventures sill in the Opemisca part of the Chibougamau area may be related to the Opemisca pluton.

Gold

The origins of gold are varied. Sawkins and Rye (1974), Ridler (1970 et seq.), and Fripp (1976-1 and 2) have demonstrated the relationships of gold to chemical iron deposits such as normally accompany the last, quiescent siliceous phase of volcanic cycles. Viljoen, Saager, and Viljoen (1969) have indicated a relationship to ultramafics, and Keays and Scott (1976) have demonstrated a relationship to basalt. The unique localization of gold in the Kirkland Lake trachytic complex adds another lithology. As Ridler (1976-2) says, the primary source of gold appears to be less important than mobilisers, all that is required of the primary source is the presence of gold, a high average content is unnecessary. These conditions are fulfilled in all volcanic units, a variety of plutons provides heat, and low pressure fractures abound.

R

The porphyry golds may be considered as hosted by a pluton which may have assimilated the gold from the volcanics but in which the combination of H_2O , CO_2 and S and heat flow was not conducive to expulsion but rather deposition within the host.

Barberton and Selukwe (Midlands) provide the examples of known relationships of deformation to ore types, D_2 sulphide association and D_3 et seq. quartz (vein) association. Other areas, particularly Yellowknife, Kirkland Lake, and the Eastern Goldfields bear ready comparison. One may extend the deformational theme to Yellowknife, adding it to the work of Boyle (1961): major D_1 faults provide primary channelways for the migration of gold H_2O , CO_2 , S, and chalcophile elements during heating related to plutonism during early D_2 . Where the relationship to plutonism is questioned in the Eastern Goldfields, two factors must be considered, the lack of knowledge of plutonism, and the disruptive effect of major channelways on concentric metamorphic zoning. This primary migration resulted in gold sulphide deposits. Secondary migration related to subsequent heatings result in separation of the gold and pyrite and deposition of a succession of gold quartz deposits.

Tin-tungsten-lithium-beryllium

The pegmatite ores of these metals are related to plutons intruded during D_2 and D_3 . Many Archean plutons are pegmatite-bearing but enhancement to significant sized ore deposits is so rare that metallogenic requirements are not known.

Geological Associations

Volcanic

Ultramafic

Nickel and chromium are only associated with ultramafic volcanics, copper-nickel largely so. An origin of gold in the ultramafic volcanics appears probable.

Mafic

Copper-nickel at Vumba and Tati has ore potential. Gold is associated with and believed to have an origin in mafic volcanics in areas in Canada, southern Africa and Australia: they are probably important sources in all Archean orefields, but better discrimination of mafic and ultramafic sources is needed.

Felsic

Copper-zinc, the most important Archean ore, is restricted to the felsic volcanic association of Canada, of the Pilbara, and minor ores in Rhodesia. In that the alkaline vulcanism of Kirkland Lake may be considered felsic, it is also host to a major gold province. Until intensive studies on the origins and subsequent history of gold are considered, the adage "gold is where you find it" will continue to be true.

Sedimentary

Chemical (iron, chert)

All Archean banded iron ore has this association. With iron formations are the gold ores of this association: there is a lack of data on the inter-relationship of sulphide and quartz.

Flysch

The chemical banded iron ore association is restricted to the upper part of the volcano-sedimentary piles where flysch is predominant. Nevertheless, the ore is now considered to be fumarolic. Gold of iron ore affiliation falls in this association. The Sherridon copper-zinc deposit is at the upper contact of flysch deposits; the ore is contemporary with felsic vulcanism in the greenstone belt to the south of the flysch.

Deformational

D₁

The effect of D₁ on ore is largely unknown. At Pikwe, discontinuous bands of pyrrhotite are parallel to S₁. Thrusting at Yellowknife is considered by Boyle to have provided channelways for gold bearing fluids. Comparable phenomena are probably common.

D₂

The alignment of orebodies at Flin Flon and of the Lower H orebody at Noranda is L₂. Ore lensing at Pikwe is primarily S₂. Gold-pyrite,

the first stage ore at Barberton, is associated with D_2 and comparable relationships are evident at Yellowknife, Rice Lake, and Kirkland Lake. They are probably common.

D_3

Several types of D_3 structures host gold veins at Selukwe. At Barberton the gold quartz veins are D_3 and the relationship at Yellowknife, Rice Lake, and Kirkland Lake is comparable. Elsewhere the relationship is probably similar. D_3 at Pikwe resulted in deformation of the sulphide ore. This, too, may prove to be common, though not studied elsewhere.

Metamorphic

Little study has been done on the relationship of metamorphic history to ore. The lowest, highest, or average metamorphic grade of an area may or may not be related to ore. Thus at Kirkland Lake, the prehnite-pumpellyite grade was enough for the full phenomena of gold emplacement and the higher levels noted elsewhere may bear no relationship to gold-bearing fluid circulation. On the other hand, no gold is noted in areas with granulite grade metamorphism. That most gold is associated with areas of greenschist grade probably merely reflects the fact that most areas have greenschist grade. The M_3 metamorphism at Pikwe resulted in coarsening of the sulphide ore, and the phenomenon must be considered as common.

Plutonics

No ores in the Archean areas are associated with the ultramafic and mafic plutons - which are few. Felsic plutonism has associated

gold and copper, both veins and disseminated, and a relationship is possible. Both metals may originate in source beds. Felsic plutons are also associated with the pegmatites.

Time Associations

The ultramafic-associated magmatic ores are predominantly old: the nickel of Australia and chrome of Selukwe (Midlands). The nickel of the Timmins area is minor. Copper-nickel is entirely related to the older period.

Copper-zinc is largely restricted to the younger period of the development of Canadian greenstone belts. The few deposits in the older period are restricted to the Pilbara and Rhodesia.

All the copper-gold ore, disseminated and vein, is in the younger area of the Canadian Shield.

Gold, iron, and the tin, tungsten, tantalum suite of pegmatites are unrestricted by time divisions within the Archean.

Regional Associations

Iron has no regional restriction in the Archean.

Asbestos is widespread, but probably the most important ore deposit is at Havelock, in the Barberton Mountainland, associated with the major sequence of ultramafic development in the regional but not the local sense.

Chrome ore in the areas considered is restricted to southern Africa (it is minor in unreviewed parts of Canada).

Nickel is dominant in Australia; as sulphide ore it is surprisingly poorly represented in the ultramafic rich areas of southern Africa, and is a minor commodity in Canada.

Copper-nickel is entirely a product of southern Africa.

Copper-zinc is almost entirely restricted to Canada. The exceptions are in the Pilbara and minor ores of Rhodesia.

Copper-gold ores, disseminated and vein, are restricted to the Abitibi Belt.

Gold, in any of its associations, has no regional restriction in the Archean.

The tin, lithium, tantalum pegmatite association is unrestricted by Archean time divisions, on the evidence of both the minor deposits in the areas reviewed and the major deposits at Bernic Lake and Bikita, in areas not reviewed.

The Dollar Factor

As mining turns from small tonnage, high grade deposits to large tonnage, low grade deposits, changes from ore mined to ore potential become apparent.

No change is to be anticipated in the cases of iron, asbestos, chromium, copper-nickel, copper-zinc, and the pegmatite ores. The changes will be from

nickel sulphide to nickel silicate and from gold veins to disseminated gold, probably to an increasing extent as by product, unless the demand for gold causes a dramatic increase in price. Vein gold, as with any commodity, can only be produced when the return is greater than the outlay and this is unlikely in the foreseeable future.

Perspectives for Exploration

Ore Potential

Prior to 1950 most discoveries were at surface, by prospecting. Geophysics extended the depth of perception by 50 m in the following 25 years, and airborne techniques are increasing this depth towards 300 m. The trend must now be turned towards geological discovery. Better discrimination of metallogenic provinces will be possible as more is known of geochemical constraints, a topic not touched upon in this study. The iron deposits are in adequate supply and there is no demand for study. Copper-zinc deposits, only regarded as volcanogenic for 20 years, need better understanding for improved returns on prospecting. There are disseminated (porphyry) gold and copper-gold deposits in the Canadian Shield, but not enough is known of tonnage at grades now submarginal.

The main ore potential of the Archean, other than iron, is therefore likely to be base metal (nickel and copper-zinc) volcanogenic.

Research Potential

The principal gaps in knowledge of the geological control of the main ores with potential are the sedimentary aspects of volcano-sedimentary environment and the deformational history, the latter particularly as, where it has been

worked out, D_2 deformation normally exerts a major control on ore disposition. Metamorphic history is probably less significant, though as study can normally be integrated with that of deformational history, cost is minimal. The relationship of ore-associated felsic plutonics to deformation may aid in the discrimination of pre-, syn-, and post-tectonic affiliations.

AGE

Radiometric dates have been assessed in four ways, by self-elimination where there are several dates on one rock suite, by relationship of dates to geological superposition, by consideration of evolution of initial ratios, and by comparison of histograms of radiometric dates.

The conclusions reached from this study have two concerns, firstly, the relationship of dates to geology, and secondly, the reliability of dating techniques.

First, the relationship of dates to geology. The lack of dates older than 2.8 b.y. and the grouping of initial ratios within or close to mantle limits is strong evidence that the Canadian greenstone belts studied formed after 2.8 b.y. The histogram of the duration of their crustal pre-history (Fig. 107) suggests that for most samples the duration between fractionation from the mantle and the latest recorded episode (granitization?) did not exceed 100 m.y. Contamination by older crust is indicated by the initial ratios for Yellowknife and Rice Lake, and the prevailing I.R. decrease with age may indicate later remelting and contamination in younger plutons. Some of the dates from Flin Flon are Archean, some are Proterozoic: the integration of the dated rocks into the deformational history of the Flin Flon Belt leads to the interpretation that all were emplaced during the Archean. High I.R.s. for dates younger than 3 b.y. at Barberton and younger than 2.2 b.y. in Australia indicate re-equilibration.

Radiometric dates from greenstone belts from each of the southern areas (except Brazil, where there are few dates) include several to many dates older than 2.8 b.y. and there is thus prima facie evidence that the belts are older than those of Canada. The consideration of the evolution of initial ratios indicates separation from the mantle in these areas between 3.5 and 2.5 b.y., so overlapping the 2.8 to 2.4 b.y. population from Canada. Self-elimination of Barberton dates indicates that emplacement was between 3.5 and 3.3 b.y. The Barberton dates have comparable cohesion to those of Canada, and this together with the histogram of crustal pre-history for all areas (Fig. 107) indicates that the period of development was usually no more than 200 m.y. On this evidence, and by examination of the groups of dates in the histograms, it is considered probable that all the greenstone belts of the southern areas could have formed between 3.5 and 3.3 b.y., or at least that their formation pre-dated Canadian examples, formed between 2.8 and 2.7 b.y.

The period of development, usually no more than 200 m.y., accords with that of the Paleozoic and Alpine (Mesozoic-Tertiary) periods: the volcano-sedimentary and orogenic periods of the Scottish Paleozoic lasted from about 600 m.y. to 450 m.y. with post-orogenic plutonism continuing to about 380 m.y. (Pankhurst 1974, et al.); the four Paleozoic tectono-magmatic cycles of New South Wales (Scheibner 1973) lasted about 50 m.y. each; the Alpine system of the Hellenides developed between 200 m.y. and the present (Aubouin 1965); and the four structural-magmatic systems of the west Pacific (Zonenishain et al. 1974) each took about 50 m.y. to develop.

SUMMARY OF CONCLUSIONS

- (a) There are two geological successions in the Archean areas studied. One is in Canada, the other is in Brazil, southern Africa, India, and Australia. These contain almost all Archean orefields (Figs. 92, 93 and 94).
- (b) There are two periods of formation of the areas, one starting in the period 2.8 to 2.7 b.y., the other starting in the period 3.5 to 3.3 b.y.
- (c) The maximum duration of vulcanism and sedimentation matches that of the Phanerozoic, of the order of 100 m.y., and the main period of deformation, D_1 to D_3 , and accompanying plutonism lasts a maximum of about 50 m.y.
- (d) Whereas all sequences of sedimentation and vulcanism in the younger period started between 2.8 and 2.7 b.y., the same restriction is not necessarily true for the older sequences, and though it began between 3.5 and 3.3 b.y. some members of the system may overlap in age those of the younger system.
- (e) The older succession is confined to the southern areas, the younger to North America (Eurasia not being studied).
- (f) The dichotomy of regions and periods is reflected in some ore formation, nickel and chrome being largely in the older southern areas, copper-zinc and copper-gold in the younger Canadian areas. Where geological features are common to both regions and both periods, related metals, gold, iron and the pegmatite ores are equally unrestricted by region or time.

- (g) If the differences between Canada and the southern areas are controlled by time rather than solely related to place, the change reflected in the increasing complexity of the younger rocks is related to the evolution of the earth.
- (h) The main ore potential of the Archean, other than iron, is likely to be the volcanogenic base metal ores, nickel and copper-zinc.
- (i) The principal gaps in knowledge of ore control of nickel and copper-zinc are the sedimentary aspect of volcano-sedimentary environment and the localising effects of deformation, particularly D_2 .

APPENDIX 1

(Mining Magazine, September 1975)

In 1974, 1072 mines accounted for 90% of all output other than coal. The mines are divided into five size classifications:

A = plus 3 million tonne/year

B = 1 million to 3 million tonne/year

C = 500,000 to 1 million tonne/year

D = 300,000 to 500,000 tonne/year

E = 150,000 to 300,000 tonne/year

Included are:

Canada

Aunor	E	Au
Camflo	D	Au
Chibex	E	Au
Con Rycon	E	Au
Dome	C	Au
East Malartic	C	Au
Giant Yellowknife	D	Au
Kerr Addison	C	Au
Lamaque	C	Au
Macassa	E	Au
Pamour	C	Au
Ross	E	Au
Sigma	C	Au
Louvem	E	Cu
Springer	C	Cu
Stall Lake	E	Cu
Anderson Lake	D	Cu, Ag, Au
Chisel Lake	E	Cu, Zn, Pb
Dickstone	E	Cu, Zn
Flin Flon	D	Cu, Zn, Pb
Horne	B	Cu, Au
Lake Dufault	C	Cu, Zn
Schumacher	C	Cu, Au
Osborne Lake	E	Cu, Zn
Kidd Creek	A	Zn, Ag, W, Pb
Manitou Barvue	E	Zn, Pb, Ag
Dumbarton	D	Ni, Cu
Langmuir	E	Ni, Co
Adams	A	Fe
Tantalum Mining Corp	E	Ta, Cs
Reeves	B	Asbestos

Brazil

Morro Velho

Cu Au

Australia

Central Norseman

E Au

Lake View

D Au

Mt. Charlotte

C Au

N. Kalgurli

E Au

Mt. Goldsworthy

A Fe

Shay Gap

A Fe

Kambalda

B Ni

Nepean

E Ni

Redcross

D Ni

Scotia

E Ni

Spargoville

E Ni

Windarra

C Ni

Botswana

Pikwe

B Cu, Ni

Rhodesia

Pickstone

E Au

Empress

D Ni, Co

Que Que Iron Ore

D Fe

Rhodesia Chrome

D Cr

Swaziland

Ngwenya

B Fe

Havelock

B Asbestos

India

Chowgule

B Fe

Kudnem

D Fe

Paligao

D Fe

Palii

D Fe

Sanquelim

C Fe

Sirigao

D Fe

APPENDIX 2
RADIOMETRIC DATA

Review of Techniques

K-Ar

Green and Baadsgaard (1971) have compared zircon U-Pb, whole rock Rb-Sr isochron, and K-Ar mineral dates from several Archean rock units at Yellowknife. They have several findings: In general, the observed K-Ar age pattern is hornblende > muscovite > biotite. Where mineral pairs are available, K-Ar dates on biotite and co-existing muscovite or hornblende often lie outside the error limits of the analytical procedures. Such discordance requires a geological explanation in terms of gradual cooling or "updating" by a later event. It is obvious, they say, that the oldest apparent K-Ar ages from a given rock unit will most nearly approach the time of crystallization of that unit. They question the suggestion that the mean of a number of K-Ar mica dates is correlated with the peak of an orogenic episode: rather, such a peak may represent the termination of a ^{40}Ar diffusion episode. Differences in the relative argon retentivities of different minerals result in a spectrum of apparent ages that lie between the limits of the mineral-forming orogenic event and subsequent thermal closure. It is recognized that a similar spectrum of apparent ages may be produced by ^{40}Ar loss during a metamorphic episode that occurs shortly after the mineral-forming event. I would question only the use of "shortly" in the last sentence. Some K-Ar dates from Rhodesia are old, discrete, and match well other evidence considered here. Nevertheless, Wilson and Harrison (1973) reluctantly rejected as an anomalous result, due to excess argon, a K-Ar date of 3282 m.y. on a micropegmatite dyke from the Gwenoro dam, following a $^{40}\text{Ar} - ^{39}\text{Ar}$ spectrum study in which a date of 2635 ± 15 m.y. was obtained. In light of subsequent studies

(Hickman 1974) I would reinstate the older date and recheck other dates discarded because of suspected Ar excess. These findings by Green and Baadsgaard give reason for restricting the use of K-Ar dates to the oldest in a sequence, as is done here, and then only provided there are supporting data. Nevertheless, Rhodesian K-Ar and Rb-Sr (WR) dates are remarkably alike.

Rb-Sr

Rb-Sr dates have commonly been regarded (by geologists if not by geochronologists) as more reliable than K-Ar because ⁴⁰Ar is susceptible to loss. The evidence presented here is that while Rb-Sr dates are commonly older than K-Ar, under some circumstances they are little more reliable, perhaps being susceptible to even low-grade thermal events. Rb-Sr whole rock isochrons are acknowledged to be more reliable than mineral dates. Variations in reliability of isochrons are discussed.

Three areas provide examples of a preponderance of non-primary dates from Rb-Sr Scotland, Canada, and South Africa.

From Scotland, Pankhurst and Pidgeon (1976) note that U-Pb isotopic ratios on zircon size and magnetic fractions from the Ben Vuirich granite precisely define a chord which intersects concordia at $514 \pm 6 - 7$ m.y. and $1316 \pm 26 - 25$ m.y. Geological evidence suggests that the lower intersection is structurally constrained. The upper intersection on the concordia is considered by Pankhurst and Pidgeon to reflect the presence of old zircon xenocrysts incorporated into the granite magma

without complete isotopic resetting. Rb-Sr whole-rock systems of the Ben Vuirich granite are also strongly discordant, they note, although 8 out of 13 data points scatter about an "erroschron" of 564 ± 24 m.y., I.R. about 0.716. They interpret this as a spurious result due to incomplete homogenization of Sr isotopes in the source region during partial fusion. Initial ratios at the time of emplacement indicated by the zircon data ranged from 0.7173 to 0.7191. Whole-rock samples from the Dunfallandy Hill granite have Rb/Sr ratios 2 - 3 times higher than those from Ben Vuirich and define a reasonably good isochron age of 491 ± 15 m.y., I.R. 0.7185 ± 0.0008 .

From Canada, Bell, Blenkinsop, and Moore (1975) write that "The Flin Flon-Snow Lake volcanic-sedimentary belt... has traditionally been regarded as Archean on the basis of its approximate east-west trend and its similarity to Archean greenstone belts in the nearby Superior Province to the east... Deformation, metamorphism and plutonism have been ascribed, in large part, to the Hudsonian orogeny. Age determinations have indicated some evidence for an Archean history for the Hanson Lake area, near the western part of the belt, but of an Aphebian age (1700 - 1800 Myr) of magmatism for the Flin Flon-Snow Lake area". Coleman (1970) reported Aphebian as well as Archean dates from Hanson Lake. To resolve the problem, Coleman and Gaskarth (1970) considered vulcanism as Archean, folding, plutonism, and metamorphism as Aphebian. Although Sangster (1972) considered the possibility that the vulcanism at Hanson Lake is of a different age to that at Flin Flon (only 3 miles separates the areas) Coleman and Gaskarth (1970) and Byers et al. (1965) regarded them as of the same age. In summary, either the geological relationships are out of

character or the Aphebian ages are not primary. Cumming and Gudjurgis (1973) questioned Sangster's single-stage interpretation for model Pb age because of possible homogenization of lead isotope ratios during regional metamorphism. The case for the Rb-Sr ages is pursued by Bell et al. (1975): "Of the six (new) isochron ages none is Archaean, none is older than 1.750 Myr and all reflect a Proterozoic event which we believe corresponds to the age of magmatic activity... It is possible to interpret the analytical data in two different ways, one of which we have mentioned. The other interpretation assumes that the rocks are considerably older and that the Proterozoic ages are the result of a resetting and updating of the Rb-Sr systems by the Hudsonian Orogeny. This we feel unlikely on the following grounds: First there is very little scatter of the data other than what can be attributed to analytical uncertainty. The low MSWDs (between 2 and 5) suggest that there is little "geological noise" of the type to be expected from a disturbance of the Rb-Sr systems. Second, all of the rocks have relatively low, uniform initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios which suggest that these rocks have not had an extensive earlier history. Third, single-stage model-lead ages for the stratabound sulphide deposits, which on geological grounds are coeval with their host rocks, predominantly volcanics of the Amisk Group, fall between 1900 and 1780 Myr. Although these ages are strongly model-dependent the isotopic data can be interpreted as consistent with our Rb-Sr results (but see above W.W.). Finally, if the Hudsonian Orogeny were responsible for the complete resetting of the Rb-Sr systems then a process would have to be invoked which behaved independently of chemical composition, grain size and metamorphic grade".

Two of the same authors (Bell and Blenkinsop 1976) subsequently undertook Rb-Sr whole-rock studies of the Otto Stock at Kirkland Lake, Ontario, on which Purdy and York (1968) had reported a whole-rock Rb-Sr isochron age of 1730 ± 56 m.y. (All Rb-Sr ages noted by Bell et al. are based on the 50 b.y. half-life of Rb^{87}). Ages previously reported for the Otto stock include single K-Ar and Rb-Sr determinations of 2500 and 2470 m.y. (Aldrich and Wetherill 1960). From their new study, Bell et al. report

an age of 2160 ± 80 m.y. I.R. 0.7015 ± 0.0006 . They discuss the data: "The discordancy between our 2160 m.y. age and Purdy and York's (1968) value of about 1700 m.y. is puzzling. We have found petrographic evidence... that could be used to argue that a younger thermal event has affected the Otto stock, a feature that is consistent with the K-Ar ages of about 1700 m.y. found further to the south. But even accepting a later metamorphism at this time, it is still extremely difficult to explain how such an event could reset some parts of the Rb-Sr whole-rock systems and leave others in the same intrusion untouched".

Whatever the explanation may be, it could equally explain the Aphebian ages at Flin Flon-Snow Lake. One must also consider the likelihood of the 2500 K-Ar and 2470 Rb-Sr dates (Aldrich and Wetherill 1960) being a closer approximation to the time of intrusion. They and the 2160 m.y. date are consistent with the geology.

From Barberton, South Africa, Hurley et al. (1972) report a 3355 ± 70 m.y. Rb-Sr date on the Middle Marker. They were careful to select a sample free of calcite and so not likely to have been enriched in strontium, which would give an erroneously old date. In contrast, weathered flakes of the same rock give a date of 3200 m.y. They consider 3355 m.y. to be a minimum age. Van Niekerk and Burger (1969) report a Pb-Pb date on zircon from quartz porphyry of the Hoeggenoeg Formation as 3360 ± 100 m.y.

Pb-Pb and U-Pb

From the Onverwacht lava at Barberton, Van Niekerk and Burger (1969) drew comparisons between ^{207}Pb - ^{206}Pb and U-Pb data. The ^{207}Pb - ^{206}Pb date on zircon from quartz porphyry of the Hoeggenoeg Formation, noted as 3360 ± 100 m.y. in the previous section, compares with 2060 ± 100 m.y. by ^{206}Pb -

²³⁸U. The authors note that small losses of lead, while seriously affecting the U-Pb determinations, would have no significant influence on the Pb-Pb ratios because the loss of lead would not be selective.

²⁰⁷Pb-²⁰⁶Pb dates on sulphides from the Onverwacht are 3470 ± 100 m.y., 3450 ± 100 m.y., 3450 ± 100 m.y., and 3390 ± 100 m.y. corresponding to a calculated age of 3.4 b.y. (Van Niekerk and Burger 1969).

Yellowknife

	Date (m.y.)	Ref.
Stock Lake intrusive, acidic phase	1870 ± 80 Pb-Pb	1
-	1880 ± 90 Pb-Pb	1
Western granodiorite, pegmatite	2470 ± 45 Pb-Pb	1
-	2520 ± 35 Pb-Pb	1
-	2525 ± 50 Pb-Pb	1
-	2525 ± 100 Pb-Pb	1
-, diorite	2550 Rb-Sr (biotite)	2
Prosperous Lake granite	2575 ± 25 Rb-Sr mineral isoch. IR 0.712	2
-	2575 ± 40 Pb-Pb	1
Western granodiorite	2610 ± 40 Rb-Sr mineral isochr.	3
Southeast granodiorite	2610 ± 58 Rb-Sr W.R. IR 0.7035	2
Western granodiorite	2625 ± 160 Rb-Sr W.R. IR 0.7022	2
Yellowknife greenstones	2635 ± 20 Pb-Pb	1
Western granodiorite	2640 ± 5 Pb-Pb	1
-, pegmatite	2665 ± 40	1
Southeast granodiorite		
Stock Lake intrusive, mafic phase	2670 ± 60	1
Western granodiorite	2675 ± 15 Pb-Pb WR	1
-	2675 ± 15 Pb-Pb concordia	1
Mackenzie Set 1 diabase dykes	2692 ± 80 Rb-Sr IR 0.7028 $\pm$ 0.0005	4

References

1. Cumming and Tsong 1975.
2. Green et al. 1968.
3. Van Breemen 1965.
4. Gates and Hurley 1973.

Hanson Lake-Flin Flon-Snow Lake

	<u>Date (m.y.)</u>	<u>Ref.</u>
Flin Flon	1880 Model Pb	1
Amisk-type rocks and granite combined	2425 $\pm$ 30 I.R. 0.7013 $\pm$ 0.0006 Rb-Sr	2
Amisk-type metavolcanics	2521 $\pm$ 60 I.R. 0.7012 $\pm$ 0.0005 Rb-Sr	2
Granite	2446 $\pm$ 16 I.R. 0.7008 $\pm$ 0.0005 Rb-Sr	2
All pegmatites	1799 $\pm$ 2 I.R. 0.6980 $\pm$ 0.0015 Rb-Sr	2
Beryliferous pegmatite	1799	2
Pegmatites emplaced during late folding	1647 $\pm$ 7 I.R. 0.7055 $\pm$ 0.0003 Rb-Sr	2
Annabel Lake pluton	1805 $\pm$ 14 I.R. 0.7023 $\pm$ 0.0007 Rb-Sr	3
Amisk volcanics	1775 $\pm$ 89 I.R. 0.7039 $\pm$ 0.00126 Rb-Sr	3
Osborne Lake	1900 $\pm$ 44 Model Pb	4
Flin Flon	1850 $\pm$ 44 Model Pb	4
Schist Lake	1800 $\pm$ 44 Model Pb	4
Western Nuclear	1780 $\pm$ 44 Model Pb	4
S of Snow Lake Amisk Group basic meta. volc.	1805 $\pm$ 45 Rb-Sr I.R. 0.7020 $\pm$ 0.0005	5
N of Snow Lake Amisk Group -	1805 $\pm$ 40 Rb-Sr I.R. 0.7017 $\pm$ 0.0007	5
Triangle Dome bi-hb granite	1855 $\pm$ 70 Rb-Sr I.R. 0.7017 $\pm$ 0.0010	5
East Dome -	1805 $\pm$ 110 Rb-Sr I.R. 0.7024 $\pm$ 0.0018	5
Squall Dome leucogranite	1790 $\pm$ 60 Rb-Sr I.R. 0.7014 $\pm$ 0.0009	5
S of Snow Lake Quartz-eye dacite	1600 $\pm$ 110 Rb-Sr I.R. 0.7019 $\pm$ 0.0006	5
Av. of 8 separates, granitic, Iskwasum L.	1760 Rb-Sr	6
5 feldspar and 1 WR granitic Iskwasum L.	1904 $\pm$ 37 Rb-Sr I.R. 0.702	6
Burntwood Lake graywacke (Kisseynew gneiss)	1850 $\pm$ 80 I.R. 0.7033 $\pm$ 0.0011	7
Ferrohypersthene intrusive, Burntwood Lake	1825 $\pm$ 80 I.R. 0.7030 $\pm$ 0.007	7
Elmes Island Formation	1737 $\pm$ 257 I.R. 0.7020 $\pm$ 0.0002	8
Morton porphyry	1715 $\pm$ 83 I.R. 0.7027 $\pm$ 0.0001	8
Ham pluton	1860 $\pm$ 112 I.R. 0.7019 $\pm$ 0.0005	8
File gneiss dome	1760 $\pm$ 43 I.R. 0.7038 $\pm$ 0.008	8
Late pegmatite dykes	1741 $\pm$ 55 I.R. 0.710 assumed	8
	1763 $\pm$ 55 I.R. 0.710 assumed	8

References

1. Stacey et al. 1969
 2. Coleman 1970
 3. Mukherjee et al. 1971
 4. Sangster 1972
 5. Bell et al. 1975
 6. Hunt and Denison 1971
 7. Clark, Anderson, and McRitchie 1974
 8. Josse et al. 1974
- C

Rice Lake

Northern granite	2500 $\pm$ 80 I.R. 0.7031 $\pm$ 0.0021 Rb-Sr	1
Gold quartz veins	2720 $\pm$ 185 I.R. 0.6997 $\pm$ 0.0028 Rb-Sr	1
Shear in San Antonio Formation	2530 assumed I.R. 0.70 Rb-Sr	1
Rice Lake Group Phyllites	2490 $\pm$ 90 I.R. 0.7022 $\pm$ 0.0009 Rb-Sr	1
Pegmatite in Manigotagan Gneiss Belt	2630 Rb-Sr W. R.	1
Northern-granite	2750 $\pm$ 150 Pb-Pb	2
	2630 $\pm$ 20 and 2240 $\pm$ 200 U-Pb	2
Lac du Bonnet Quartz Monzonite	2495 $\pm$ 130 I.R. 0.7088 $\pm$ 0.0068 Rb-Sr	3
Maskwa Lake Quartz Diorite	2640 $\pm$ 135 I.R. 0.7014 $\pm$ 0.0021 Rb-Sr	3
Bird River Volcanics	2650 $\pm$ 35 I.R. 0.7015 $\pm$ 0.0015 Rb-Sr	3
Black Lake Quartz Monzonite	2735 $\pm$ 55 I.R. 0.7019 $\pm$ 0.0008 Rb-Sr	4
Ross River Quartz Diorite	2555 $\pm$ 70 I.R. 0.7016 $\pm$ 0.0012 Rb-Sr	4
Mylonites	2345 $\pm$ 100 I.R. 0.7044 $\pm$ 0.0024 Rb-Sr	4

References

1. Turek and Peterman 1968.
2. Ozard and Russell 1971.
3. Penner and Clark 1971.
4. Turek 1971.

Abitibi Belt

		<u>Ref.</u>
Granodiorite, Noranda	2710 U-Pb zircon	1
Granodiorite, Noranda	2710 U-Pb zircon	1
Volcanic, Noranda	2710 + few m.y. U-Pb zircon	1
Granitic, Chibougamau Pluton	2735 U-Pb zircon	1
Timiskaming Conglomerate	2730 U-Pb zircon	2
Pontiac Granitoid	2665 U-Pb sphene	2
Timiskaming	2660 Rb-Sr isochron	2
Keewatin	2660 Rb-Sr isochron	2
Preisac-Lacorne Batholith	2630 $\pm$ 38 I.R. 0.7002 $\pm$ 0.0008 Rb-Sr W.R.	3
-	2650 $\pm$ 25-65 U-Pb zircon	4
Dauversiere Stock et al.	2761 $\pm$ 170 I.R. 0.7011 $\pm$ 0.0015 Rb-Sr	5
Dore Lake Complex	2727 $\pm$ 173 I.R. 0.7009 $\pm$ 0.0005 Rb-Sr	6
Pre-Kenoran Gneisses 5Km N of Chibougamau	2599 $\pm$ 40 ⁴⁰ Ar ³⁹ Ar	7
-	2801 $\pm$ 40 ⁴⁰ Ar ³⁹ Ar	7
Opemisca Pluton	2692 $\pm$ 30 ⁴⁰ Ar ³⁹ Ar	8
-	2656 $\pm$ 30 ⁴⁰ Ar ³⁹ Ar	8
La Ronge Lake Pluton	2650 $\pm$ 30 ⁴⁰ Ar ³⁹ Ar	8
-	2623 $\pm$ 30 ⁴⁰ Ar ³⁹ Ar	8
Chibougamau Pluton	2563 $\pm$ 79 I.R. 0.7005 $\pm$ 0.0002 Rb-Sr	6
Otto Stock	2290 $\pm$ 80 I.R. 0.7015 $\pm$ 0.0006 Rb-Sr	9
-	1730 $\pm$ 50 I.R. 0.7046 $\pm$ 0.0010 Rb-Sr	11
Otto Stock	2470 (biotite) Rb-Sr	10
Round Lake Batholith	2390 $\pm$ 80 I.R. 0.7009 $\pm$ 0.0009 Rb-Sr	11
-	2550 (biotite) Rb-Sr	10
Round Lake Batholith, Old Gneiss Phase	2583 Pb ^{207/206} (discordant)	13
Granite, Keefer Twp.	2510 (biotite) Rb-Sr	10
Lead Sulphides, Val d'Or, Barvue, Renabie, Kirkland Lake, Kerr Addison	3250 $\pm$ 150 and 2300 $\pm$ 150 Pb-Pb	12
Skead Group Pyroclastics	2652 $\pm$ 55 I.R. 0.7011 $\pm$ 0.0005 Rb-Sr	15
Matachewan Diabase	2690 $\pm$ 93 I.R. 0.7000 $\pm$ 0.001	14

References

1. Krogh and Davis, 1971.
2. Wanless memo 1968.
3. Wanless and Loveridge 1972.
4. Steiger and Wasserburg 1969.
5. Wanless et al, 1970.
6. Jones Walker and Allard 1974.
7. Dallmeyer 1974.
8. Dallmeyer et al, 1975
9. Bell and Blenkinsop 1976.
10. Aldrich and Wetherill 1960.
11. Purdy and York 1968.
12. Kanasewich and Farquhar 1965.
13. Ridler 1976-2.
14. Gates and Hurley 1973.
15. W. D. Loveridge pers. comm. 1976.

Rio das Velhas, Brazil

	<u>Date (m.y.)</u>	<u>Ref.</u>
Rio das Velhas Mica Schist	2790 Rb-Sr Mica	1
Pre-Minas Amphibolite	2675 Rb-Sr Mica	1
Gneiss at Rio das Velhas Granite Contact	2300 Rb-Sr K-feldspar	1

Reference

1. Aldrich et al. 1964.

Barberton

		<u>Ref.</u>
Basaltic Komatiite, Komati Formation	3500 $\pm$ 200 Rb-Sr I.R. 0.70048 $\pm$.5	1
Consort Pegmatite	3030 $\pm$.40 Rb-Sr I.R. 0.766 $\pm$ 0.061	2
Fig Tree Shales and Graywackes	2980 $\pm$ 20 Rb-Sr I.R. 0.712 $\pm$ 0.004	2
New Consort Mine Banded Biotite-Tremolite Schist	2480 $\pm$ 30 Rb-Sr I.R. 0.719 $\pm$ 0.039	2
Onverwacht Acid Lavas	2540 $\pm$ 50 Rb-Sr I.R. 0.719 $\pm$ 0.006	2
Nelspruit Granite and Migmatite	2292 $\pm$ 70 Rb-Sr I.R. 0.7052 $\pm$ 0.0019	4
Mpageni Pluton	2550 $\pm$ 90 Rb-Sr I.R. 0.7065 $\pm$ 0.0016	4
Ancient Gneiss Complex, Mankaiana, Swaziland	3340 Rb-Sr	5
Granodiorite Suite G ₁ Swaziland	3440 $\pm$ 300 Rb-Sr	7
Old G ₄ of Swaziland	3070 $\pm$ 60 Rb-Sr	7
Ngwempisi Pluton, Swaziland	2880 $\pm$ 340 Rb-Sr	7
Felsic Lavas, Onverwacht Sequence	2620 $\pm$ 20 Rb-Sr I.Rs 0.7000, 0.7027, 0.7058 All $\pm$ 0.0003	6
Kaap Valley Granite	3310 $\pm$ 40 U-Pb	8
Theespruit Pluton	3250 $\pm$ 40 U-Pb	8
Nelshoogte Pluton	3220 $\pm$ 40 U-Pb	8
Lekkerloop Spruit Gneisses and Migmatites	3170 $\pm$ 20 U-Pb	8
Lochiel Gneisses and Migmatites	3075 $\pm$ 100 U-Pb	8
Dalmein Pluton	3190 $\pm$ 70 U-Pb Sphene	8
Dalmein Pluton	3290 $\pm$ 80 U-Pb Apatite	8
Mpageni Pluton	2810 $\pm$ 80 U-Pb Zircon	8
Mpageni Pluton	2810 $\pm$ 80 U-Pb Apatite	8
Bosmankop Syenite	3130 $\pm$ 30 U-Pb	8

Middle Marker	3355 $\pm$ 70 Rb-Sr I.R. 0.7015 $\pm$ 0.0018	9
Usushwana Complex	2874 $\pm$ 30 Rb-Sr I.R. 0.7029 $\pm$ 0.0036	10
Quartz Porphyry Lava, Hoeggenoe Formation	3360 $\pm$ 100 Pb-Pb	11
G ₅ of Swaziland	2200 $\pm$ 50 Rb-Sr	7
-	2550 $\pm$ 50 Rb-Sr	7
-	2880 $\pm$ 340 Rb-Sr	7
Onverwacht Pillow Basalts Dalmein-Stream	3230 $\pm$ 30 Common Lead	12
-	3290 $\pm$ 45 Concordia	12
Rosetta	3390 Model Pb	3
-	3400 Model Pb	3
Daylight	3370 Model Pb	3
-	3460 Model Pb	3
Consort	3480 Model Pb	3
French Bobs	3490 Model Pb	3
-	3450 Model Pb	3
Alfstrom	3440 Model Pb	3
-	3440 Model Pb	3
Amo	3250 Model Pb	3
Mica	3150 Model Pb	3
-	3140 Model Pb	3
Swaziland I	2930 Model Pb	3
Swaziland II	2820 Model Pb	3
Fairview	2420 Model Pb	3
Mpageni Granite	2625 $\pm$ 50 Rb-Sr W.R.	4 (13)
Salisbury Kop Granite	2740 Rb-Sr (bi, K-spar)	8 (13)
-	2740 $\pm$ 5 Rb-Sr (Various Minerals)	8 (13)
-	2990 $\pm$ 30 Rb-Sr	8 (13)
Lochiel Migmatite	3075 $\pm$ 100 U-Pb (Zircon)	8 (13)

Badplaas Syenite	3130 $\pm$ 30 U-Pb (Apatite, Zircon)	8 (13)
Nelspruit Granite	3160 $\pm$ 100 U-Pb	8 (13)
Salisbury Kop Granite	3280 $\pm$ 120 U-Pb ^a (Apatite)	8 (13)
Onverwacht Lava	3390 $\pm$ 120 U-Pb (Sulphide)	11 (13)
Acid Lava	3400 U-Pb (Zircon)	11 (13)
Onverwacht Lava	3450 $\pm$ 120 Pb-Pb (Sulphide)	11 (13)
Nelspruit Granite	2990 $\pm$ 30 Rb-Sr	4 (13)
Salisbury Kop Granite	2990 $\pm$ 30 Rb-Sr	4 (13)
Pegmatite (Muscovite)	3040 Rb-Sr	4 (13)

References

1. Jahn and Shih 1974.
2. Allsopp et al. 1968.
3. Ulrych et al. 1967.
4. De Gasparis 1967.
5. Allsopp et al. 1969.
6. Allsopp et al. 1972.
7. Allsopp et al. 1962
8. Oosthuyzen 1970.
9. Hurley et al. 1972
10. Davies et al. 1969
11. Van Niekerk and Burger 1969
12. Sinha 1972
13. Burger and Coertze 1973

Rhodesia

		<u>Ref.</u>
Alfa Farm granite	3020 I.R. 0.705 (assumed)	1
Chirwa Dome Granite	2970 I.R. 0.705 (assumed)	2
Grand Parade Granite	2940 $\pm$ 120 I.R. 0.705 (assumed)	3
Bikita Lepidolite	2760 $\pm$ 150 (M)	4
Pope Tantalum Mine Lepidolite	2820 (M)	5
Benson Mine Mtoko Lepidolite	2520 $\pm$ 60 (M)	6
Forfar Farm Lepidolite	2510 (M)	5
Badze Fly Gate Granite	2760 (W.R.)	7
Bulai and Singelele Granites	2690 $\pm$ 60 I.R. 0.7038 $\pm$ 0.0016	8
Metasediments Marginal to Bulai Granite	3100 (W.R.)	8
Bangawia Hill Granite	3000 $\pm$ 160 (W.R.)	6
Great Dyke Picrite	2550 $\pm$ 410	9
Mushandike Granite	3520 $\pm$ 260 (W.R.) I.R. 0.702 (by inspection)	10
Que Que, Lower Bulawayan Volcanics	2530 $\pm$ 140 I.R. 0.7034 $\pm$ 6	11
Que Que, Maliyami Volcanics	2720 $\pm$ 70 I.R. 0.7010 $\pm$ 2	11
Bulawayo Volcanics	2540 $\pm$ 90 I.R. 0.7015 $\pm$ 2	11
Mashaba Area Gneisses	3580 $\pm$ 200 I.R. Heterogeneous	11
Gwenbro Dam Migmatites	2780 $\pm$ 30 I.R. 0.7011 $\pm$ 1	11
Sesombi Tonalite	2690 $\pm$ 70 I.R. 0.7008 $\pm$ 4	11
Satellites to Great Dyke	2600 $\pm$ 120 I.R. 0.7049 $\pm$ 0.0012	12
Piper Moss Pegmatite	3300 $\pm$ 99 and 3440 $\pm$ 103 av. 3370	13
Pope's Mine Lepidolite	3350 $\pm$ 300	14
Bikita Lepidolite	3340 $\pm$ 300	14

References

1. Unpublished Leeds quoted in Vail and Dodson 1969.
2. Unpublished Oxford.
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4. Herzog et al. 1960.
5. Holmes and Cahen 1957.
6. Snelling et al. 1964.
7. Burger and Coertze 1973.
8. Van Breemen and Dodson 1972.
9. Alsopp 1965.
10. Hickman 1974.
11. Hawkesworth et al. 1975.
12. Robertson and Van Breemen 1970.
13. Ahrens 1955.
14. Nicolaysen 1954.

Robertson (1973) has also provided isotopic analyses of eighty galenas from Rhodesia. He notes that the results can be divided isotopically and geologically into two groups, Que-Que type and Bulawayo type. Most of the Que-Que type leads are associated with the oldest volcanics of the Sebakwian Series or nearby ancient banded gneisses and migmatites. Whereas the Bulawayo type leads are almost always found in shear zones and granite stocks in the younger overlying Bulawayan volcanics. Isotopically they differ: Que-Que leads lie on a straight line above and not intersecting the conformable growth curve; Bulawayo leads fall in a cluster close to the curve, commonly tangential at 2.9 to 2.7 b.y. Robertson interprets the Que-Que date to indicate mineralization at 2.8 b.y., with a paired value of 3.5 b.y. The earlier time is considered to be the depositional time of the Sebakwian lavas, and lavas were then ejected episodically until 2.7 b.y. Granite intrusions mineralized the lead at 2.7 b.y.

Southern India

		<u>Ref.</u>
Ingaldhal Copper Mine Basic Lavas	2345 $\pm$ 60 I.R. 0.7045 $\pm$ 0.0009 Rb-Sr	1
Peninsular Gneiss, South Mysore	2585 $\pm$ 35 I.R. 0.7016 $\pm$ 0.0010	1
- Bangalore s.s.	2580 $\pm$ 50 I.R. 0.7002 $\pm$ 0.0013	1
- s.l.	2590 $\pm$ 35 I.R. 0.7016 $\pm$ 0.0009	1
- All Mysore	2585 $\pm$ 30 I.R. 0.7017 $\pm$ 0.0008	1
Closepet Granite	2380 $\pm$ 35 I.R. 0.7050 $\pm$ 0.0016	1
Chamundi Hill Granite	790 $\pm$ 60 I.R. 0.7050 $\pm$ 0.0013	1
Hyderabad City Gneisses	2490 $\pm$ 265 I.R. 0.7037 $\pm$ 0.0091	1
- + Karimnagar Granites	2490 $\pm$ 115 I.R. 0.7045 $\pm$ 0.0044	1
Nilgiri Charnockite and Gneiss	2615 $\pm$ 80 I.R. 0.7023 $\pm$ 0.0012	1
Madras Charnockites	2580 $\pm$ 90 I.R. 0.7056 $\pm$ 0.0040	1
South India, Oldest Gneisses	3065 $\pm$ 75 I.R. 0.7002 $\pm$ 0.0117	1

Hutti Hornblende Schist	3295 $\pm$ 200 K-Ar	2
Kolar Goldfield Basaltic) Komatiite	3100	3
Kaldurga Gneissic Pebbles in Congl.	3250 $\pm$ 150 I.R. 0.702 $\pm$ 0.003 Rb-Sr	4
Gulbarga, Raichur, Billary, and Shimoga Granites	2990 $\pm$ 120 I.R. 0.707 $\pm$ 0.004	5
Charnockite, Satnur	3100 Rb-Sr	6
N. Mysore Granite (Peninsular Gneiss)	2990 $\pm$ 120 Rb-Sr	7
Bangalore Peninsular Gneiss	2950 $\pm$ 120 Rb-Sr	7
Katriguppe	2950 $\pm$ 110 Rb-Sr	7
Patna, Kolar	2920 $\pm$ 100 Rb-Sr	7
Amphibolite, Kolar	2900 $\pm$ 200 Pb-Pb	8
Kolar, Peninsular Gneiss	2820 $\pm$ 100	9

References

1. Crawford, 1969.
2. Sarkar 1968.
3. Pichamuthu 1971.
4. Venkatasubramanian and Narayanaswamy 1974-2.
5. Venkatasubramanian 1974.
6. Rama Murthy and Sadashiviah 1967.
7. Venkatasubramanian and Narayanaswamy 1974-3.
8. Vinogradov and Tugarinov 1968.
9. Venkatasubramanian et. al. 1971.

Western Australia

(a) <u>Yilgarn</u>	<u>Date m.y.</u>	<u>Ref.</u>
Gneisses Northern	2981 $\pm$ 207 I.R. 0.704 $\pm$ 0.003 Model 2 Rb-Sr	1
Gneisses Armadale and Canning Dam	3161 $\pm$ 791 I.R. 0.702 $\pm$ 0.021 - 3 -	1
Pooled Gneisses	3084 $\pm$ 191 I.R. 0.702 $\pm$ 0.004 - 4 -	1
Gneisses Bowgada and Koolanooka Siding	2931 $\pm$ 127 I.R. 0.706 $\pm$ 0.006 - 4 -	1
Gneisses Koolanooka Hills	2574 $\pm$ 632 I.R. 0.717 $\pm$ 0.016 - 2 -	1
Gneisses Morawa to Mulewa	2828 $\pm$ 71 I.R. 0.704 $\pm$ 0.002 - 4 -	1
Pooled Gneisses	2919 $\pm$ 90 I.R. 0.704 $\pm$ 0.003 - 4 -	1
Gneisses East of Pinjarra	2608 $\pm$ 106 I.R. 0.704 $\pm$ 0.001 - 2 -	1
Gneisses Dumbleyung	2611 $\pm$ 162 I.R. 0.704 $\pm$ 0.003 - 3 -	1
Gneisses Corrigin-Brookton	2639 $\pm$ 2061 I.R. 0.708 $\pm$ 0.055 - 3 -	1
Gneisses Dangin "Low Age" 4 of 6	2679 $\pm$ 297 I.R. 0.714 $\pm$ 0.002 - 2 -	1
- "High Age" 5 of 6	3306 $\pm$ 373 I.R. 0.706 $\pm$ 0.004 - 4 -	1
- All 6	3129 $\pm$ 644 I.R. 0.709 $\pm$ 0.006 - 3 -	1
Gneisses Bruce Rock	2695 $\pm$ 366 I.R. 0.703 $\pm$ 0.004 - 2 -	1
Gneisses York	2688 $\pm$ 211 I.R. 0.712 $\pm$ 0.009 - 4 -	1
Granites, Doodlakine and Merredin	2732 $\pm$ 115 I.R. 0.704 $\pm$ 0.005 - 4 -	1
Granites, Doodlakine - Kellerbarrin	2734 $\pm$ 269 I.R. 0.699 $\pm$ 0.022 - 3 -	1
Granite, Doodlakine Borehole	2765 $\pm$ 92 I.R. 0.700 $\pm$ 0.006 - 3 -	1
Granite Dale Bridge and Yoting	2689 $\pm$ 232 I.R. 0.704 $\pm$ 0.006 - 3 -	1
Granite Bencubbin - Wyalkatchem	2696 $\pm$ 187 I.R. 0.699 $\pm$ 0.012 - 2 -	1
Granite Cadoux - Bonnie Rock	2629 $\pm$ 533 I.R. 0.704 $\pm$ 0.073 - 3 -	1
Granite Williams - Arthur River	2972 $\pm$ 768 I.R. 0.699 $\pm$ 0.026 - 2 -	1
Granite Kondinin	2872 $\pm$ 1560 I.R. 0.701 $\pm$ 0.022 - 2 -	1
Granite Wongan Hills	2808 $\pm$ 565 I.R. 0.686 $\pm$ 0.062 - 3 -	1

Pooled Granites, Wheat Balt Areas	2661 $\pm$ 51 I.R. 0.705 $\pm$ 0.003 - 4 -	1
Granite Wiluna-Leonora- Kookynie	2698 $\pm$ 41 I.R. 0.703 $\pm$ 0.001 - 3 -	1
Granite Cue-Mt. Magnet- Paynes Find	2664 $\pm$ 68 I.R. 0.702 $\pm$ 0.006 - 4 -	1
Granite Perenjori- Paynes Find	2604 $\pm$ 264 I.R. 0.704 $\pm$ 0.010 - 3 -	1
Granite + granite Porph. Koolanooka Hills	2764 $\pm$ 117 I.R. 0.704 $\pm$ 0.005 - 3 -	1
Granite Kalgoorlie Norseman	2617 $\pm$ 20 I.R. 0.703 $\pm$ 0.007 - 4 -	1
Pooled Granites of the Goldfields	2640 $\pm$ 22 I.R. 0.703 $\pm$ 0.0009 - 4 -	1
Pooled Granites all Yilgarn Samples	2667 $\pm$ 27 I.R. 0.704 $\pm$ 0.0012 - 4 -	1
Koolanooka Quartz Porphyry Total Rock	2559 $\pm$ 28 I.R. 0.709 $\pm$ 0.003 - 2 -	1
- Incl. Xenolith and bi	2562 $\pm$ 17 I.R. 0.707 $\pm$ 0.013 - 3 -	1
Granite and Peg. Moorine Rock	2589 $\pm$ 57 I.R. 0.716 $\pm$ 0.010 - 2 -	1
Wardaward Lepidolite	2685 Rb-Sr	1
Dalgaranger Lepidolite	2655 Rb-Sr	1
Mt. Edon Lepidolite	2680 Rb-Sr	1
Mt. Mulgine Muscovite	2689 Rb-Sr	1
Mt. Mulgine Muscovite	2670 Rb-Sr	1
Weelhamby Lake Muscovite	2617 Rb-Sr	1
Granite Waddourring Hill	2287 $\pm$ 65 I.R. 0.725 $\pm$ 0.005 - 2 -	1
Microgranite Dykes Northern	2289 $\pm$ 486 I.R. 0.717 $\pm$ 0.026 - 3 -	1
Koolanooka Hills Late Granite Porphyry	2241 $\pm$ 38 I.R. 0.747 $\pm$ 0.043 - 3 -	1
Radiogenic Pegs etc. S and W Yilgarn	2214 $\pm$ 35 I.R. 0.802 $\pm$ 0.164 - 3 -	1
Gneisses Meckering Quarry	2163 $\pm$ 1128 I.R. 0.724 $\pm$ 0.035 - 3 -	1
Gneisses Lake Grace - Kulin	2073 $\pm$ 724 I.R. 0.708 $\pm$ 0.005 - 3 -	1
Karramindie Soak (Granite)	2705 $\pm$ 35 Pb-Pb	2
Mungari Granite	2640 $\pm$ 35 Pb-Pb	2
Lake Johnston Pluton	2632 $\pm$ 28 Pb-Pb	2
Kambalda Granodiorite	2760 $\pm$ 70 Pb-Pb	2

Karomie Quarry Granite	2684 $\pm$ 98 Pb-Pb	2
	2699 $\pm$ 75 Pb-Pb	2
Stennet Rocks Pluton	2671 $\pm$ 79 Pb-Pb	2
Mungari Granite	2660 $\pm$ 35 Rb-Sr	3
Karramindie Soak (Granite)	2625 $\pm$ 25 Rb-Sr	3
Stennet Rocks	2645 $\pm$ 27 Rb-Sr	3
Buldania Rocks	2660 $\pm$ 20 Rb-Sr	2
	2655 $\pm$ 35 Pb-Pb	2
Paringa Basalt and Golden Mile Dolerite	2675 $\pm$ 35 Rb-Sr	4
Calc-alkaline Granites	2615 $\pm$ 15 I.R. 0.702 to 0.704 Rb-Sr	4
or	2600 to 2690 if all same I.R.	4
Volcanics and Dykes Association IV Williams 1969	2595 $\pm$ 40 Rb-Sr	4
Acid Volcanics	2660 $\pm$ 30 I.R. 0.701 (assumed) Rb-Sr	4
Mount Keith Granodiorite	2689 17 I.R. 0.70149 $\pm$ 15 Rb-Sr	11

(b) Pilbara

12 Granites	3050 $\pm$ 180 Rb-Sr	5
Acid Lavas, Whim Creek	3000 Rb-Sr	5
Pegmatite Cutting Volcanics, Wodgina	2900 Rb-Sr	5
Copper Hills Porphyry	2880 $\pm$ 66 I.R. 0.703 $\pm$ 0.0119 Rb-Sr	6
Older Granite	3125 $\pm$ 366 I.R. 0.7016 $\pm$ 0.0047 Rb-Sr	7
Younger Granite	2670 $\pm$ 95 I.R. 0.7397 $\pm$ 0.0419 Rb-Sr	7
Mt. Newman 13 Mile Granite	2920 Pb-Pb	8
Mt. Newman 40 Mile Granite	2279 and 2245 $\pm$ 36 Pb-Pb	8
Mt. Newman 70 Mile Granite	2882 $\pm$ 60 Pb-Pb	8
Woodstock Granite	2769 $\pm$ 13 and 2961 Pb-Pb	8
Mt. Newman 127 Mile Granite	2961 $\pm$ 7 Pb-Pb	8
Tambourah Granite 1512 and 1514	2938 $\pm$ 33 and 3070 $\pm$ 12 Pb-Pb	8
Cooglagong Granite	2936 $\pm$ 9 Pb-Pb	8
	2951 $\pm$ 83 Rb-Sr	9

Tambourah Granite 1512	2698 $\pm$ 14 I.R. 0.704 $\pm$ 0.0028 Rb-Sr	8
- 1514	2610 $\pm$ 14 I.R. 0.7062 $\pm$ 0.0031	8
Mt. Newman 40 Mile Granite	2207 $\pm$ 66 I.R. 0.8308 $\pm$ 0.0066 Model 2	8
Mt. Newman 70 Mile Granite 1541	2008 I.R. 0.701 (Model)	8
Mt. Newman 70 Mile Granite 1542	2204 I.R. 0.701 (Model)	8
Mt. Newman 13 Mile Granite	2751 $\pm$ 31 I.R. 3.159 $\pm$ 2.383	8
Granite Near Pilbara	3040 I.R. 0.700 (assumed)	10

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4. Turek and Compston 1971
5. Compston and Arriens 1968.
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11. Roddick et al. 1975.

CANADA

Fig. 96
Histograms of Radiometric Dates

dates

10 0 10 0 10 0 10 0 10 0 2.0 2.25 2.5 2.75 3.0 3.25 3.5

Pb-Pb + Rb-Sr + U-Pb

Ar-Ar

U-Pb

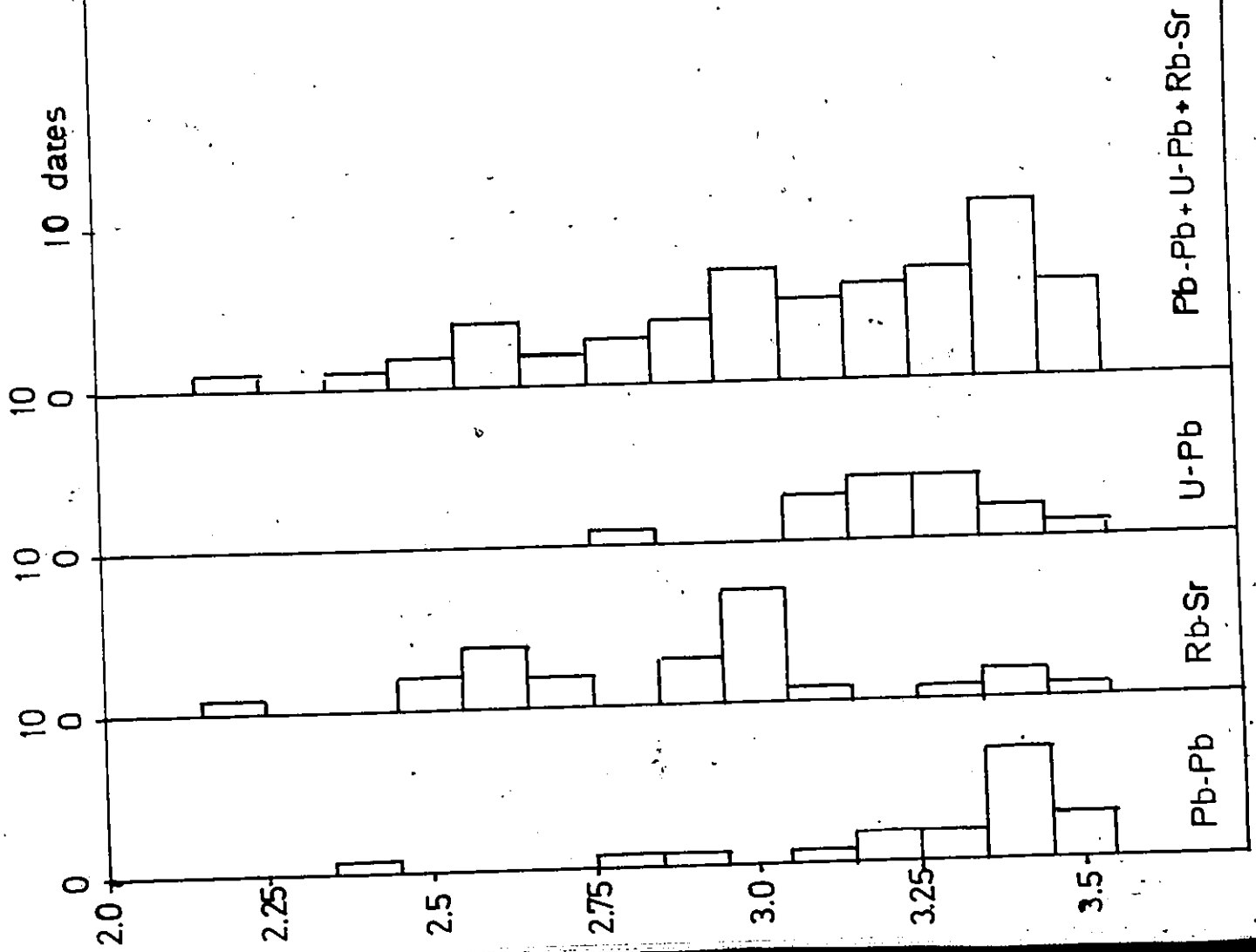
Rb-Sr

Pb-Pb

BARBERTON

Fig. 97

Histograms of Radiometric Dates



RHODESIA

Fig. 98
Histograms of Radiometric Dates

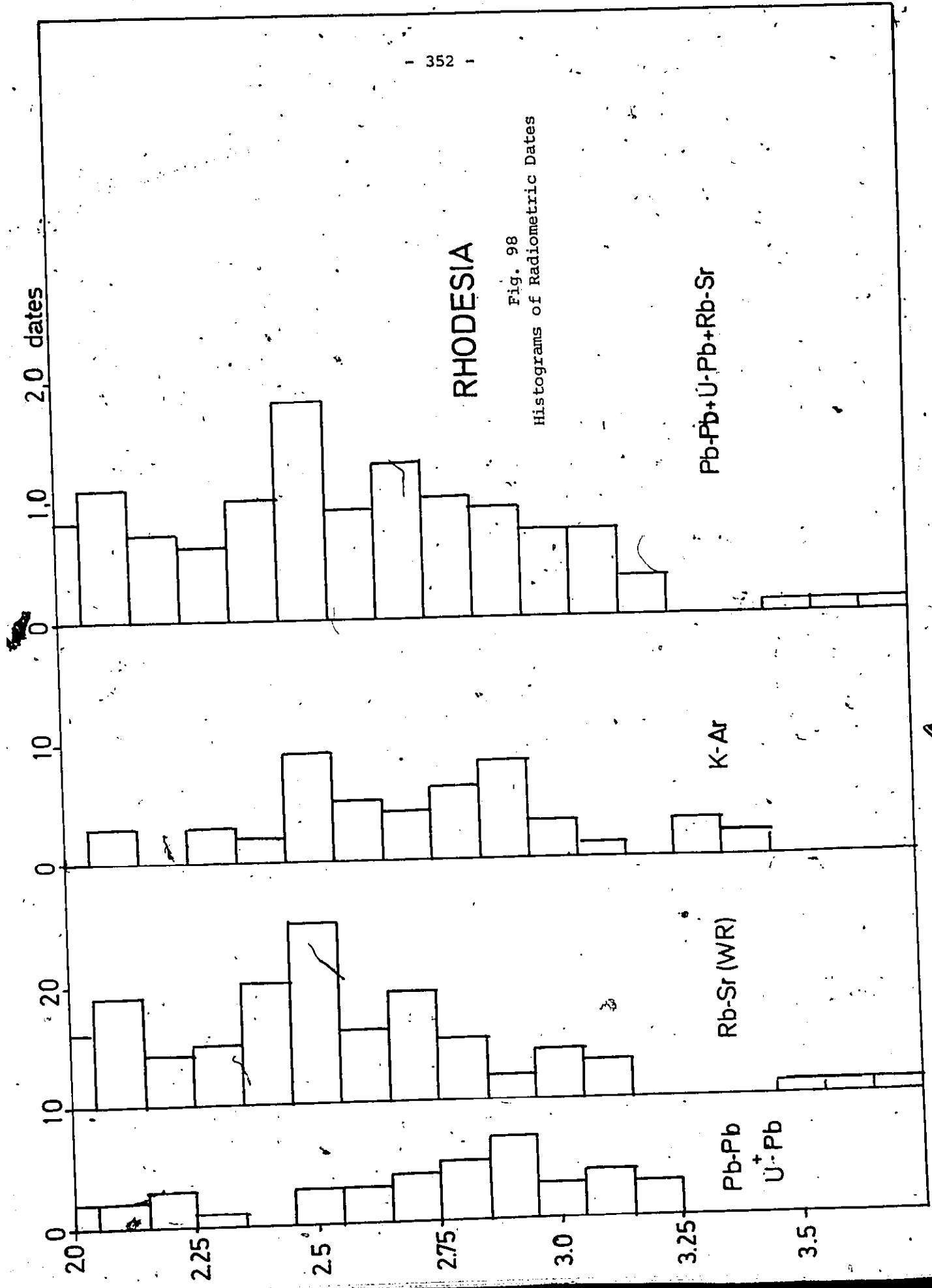
2.0 dates

Pb-Pb+U-Pb+Rb-Sr

K-Ar

Rb-Sr (WR)

Pb-Pb
U-Pb



10 dates

INDIA

Rb-Sr (WR)

b.y.

Fig. 99
Histograms of Radiometric Dates

2.0

2.25

2.5

2.75

3.0

3.25

3.5



Fig. 100
Histograms of Radiometric Dates

PILBARA

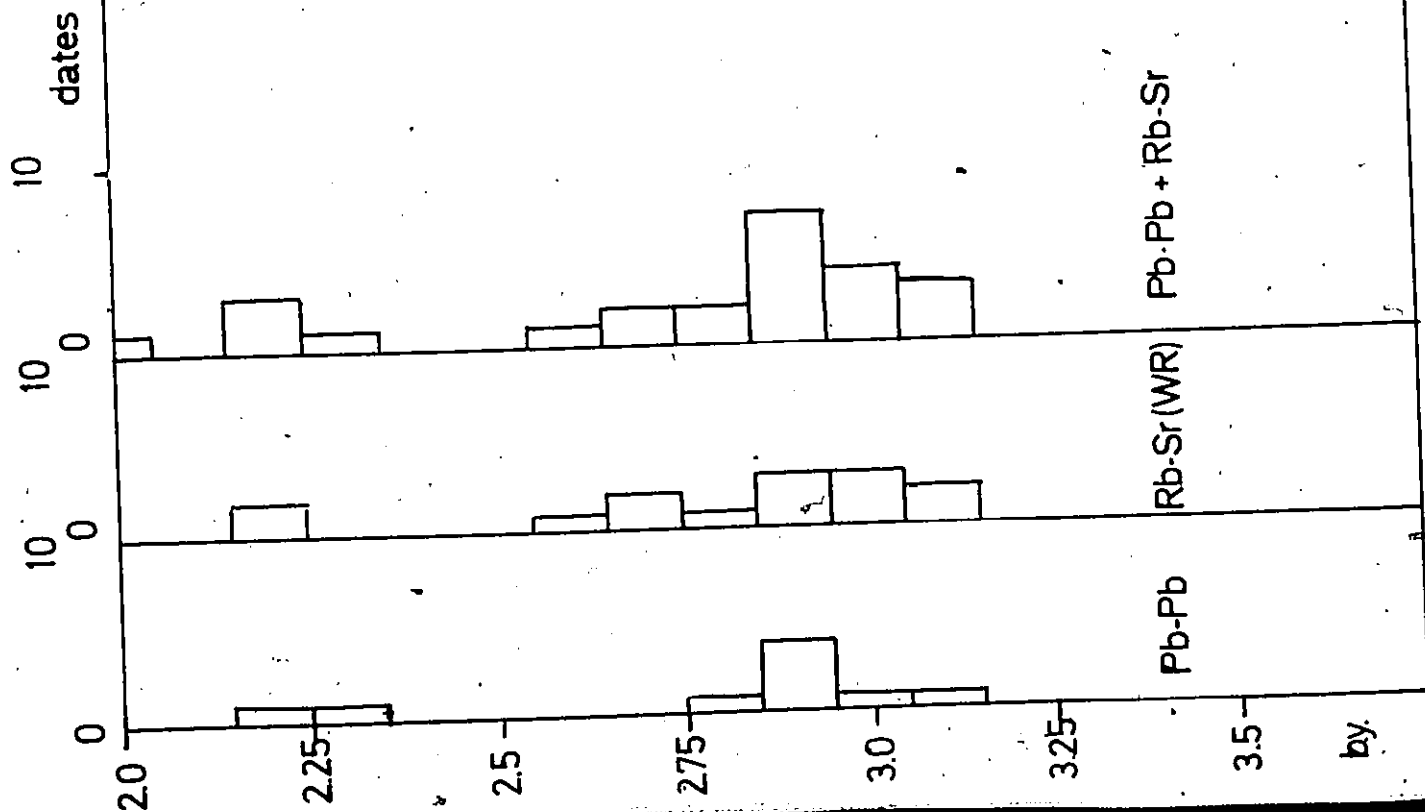


Fig. 101
Histograms of Radiometric Dates

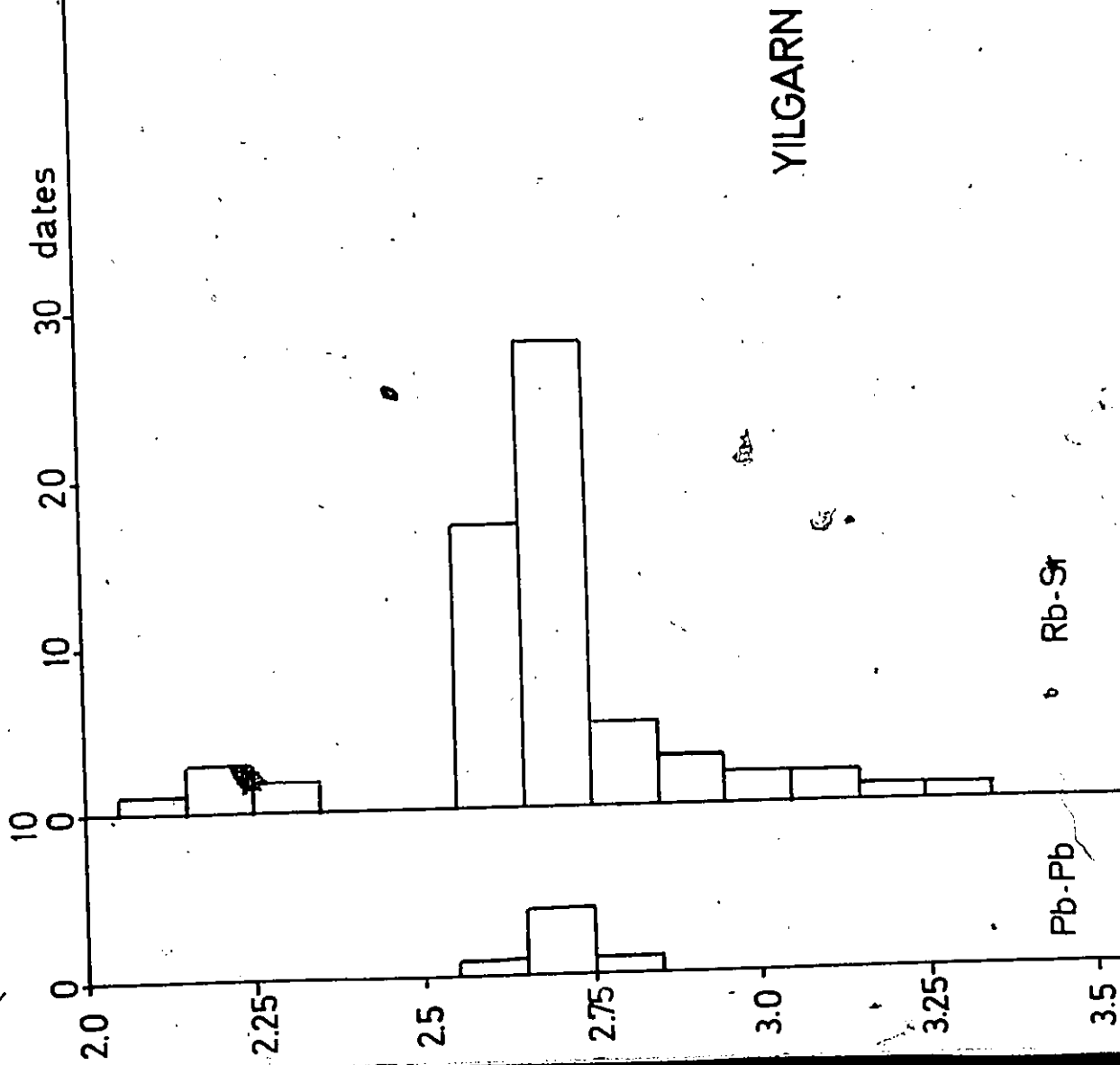
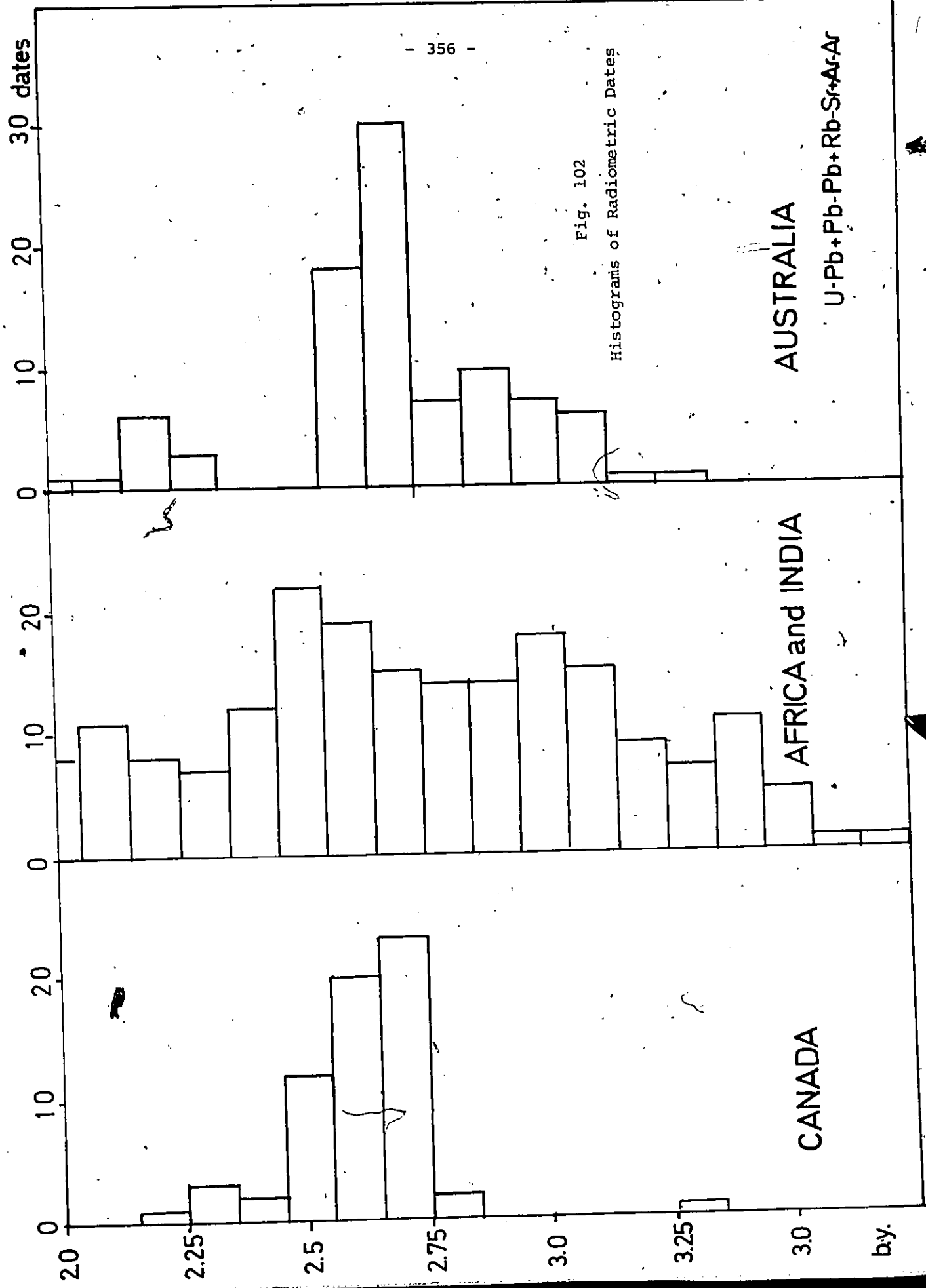


Fig. 102

Histograms of Radiometric Dates



dates

70

60

50

40

30

20

10

20

225

25

275

30

325

35

b.y.

CANADA, AFRICA, INDIA, and AUSTRALIA

Fig. 103

Histograms of Radiometric Dates

U-Pb + Pb-Pb + Rb-Sr + Ar-Ar

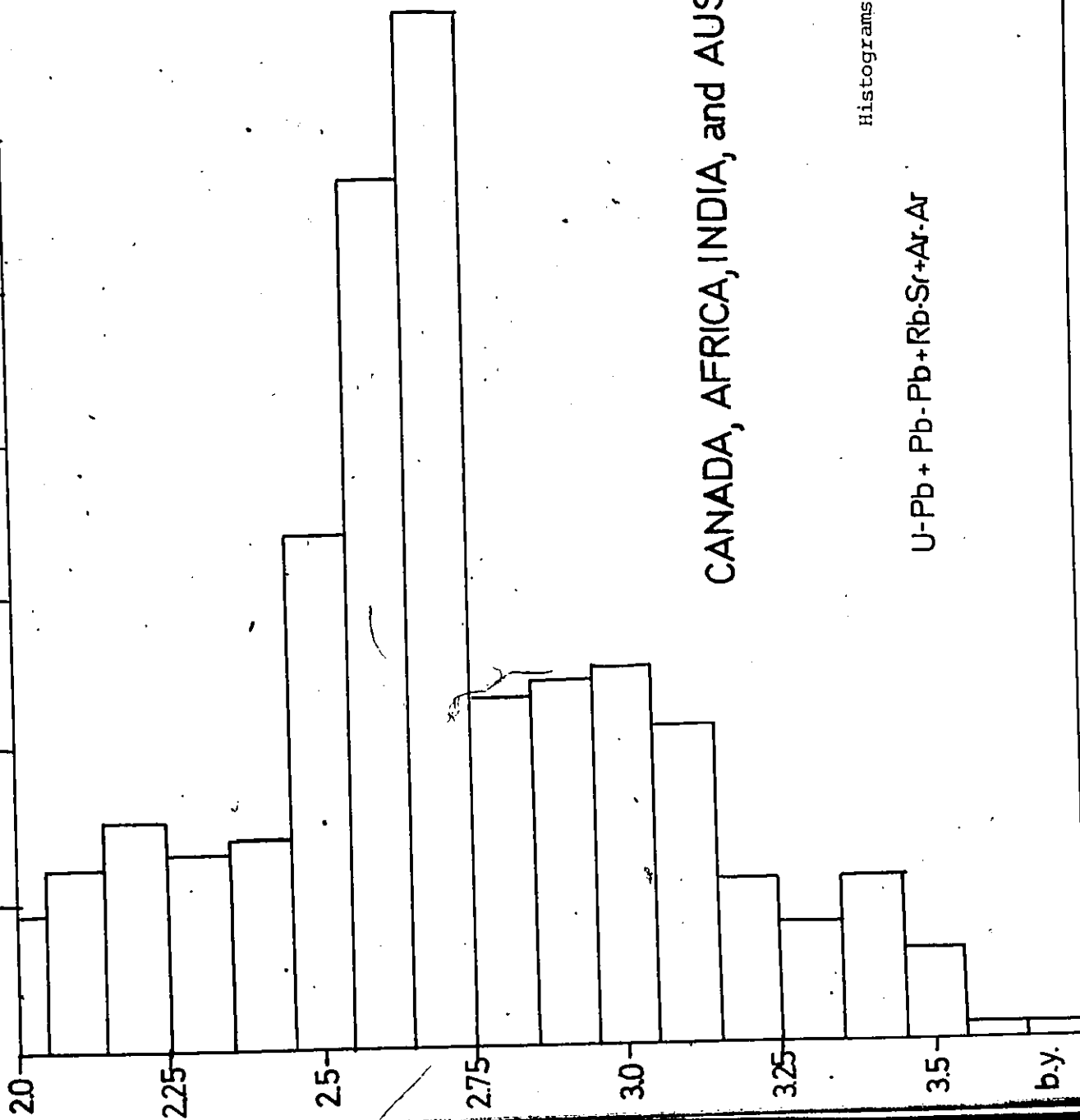


Fig. 104

$^{87}\text{Sr}/^{86}\text{Sr}$ and Rb-Sr Dates

I.R.

.708

Yellowknife +
Flin Flon x
Rice Lake o
Abitibi □

CANADA

Rb-Sr 0.5 (granite)

Rb-Sr 0.24 (andesite = average crust)

Rb-Sr 0.05 (basalt)

.704

.702

.700

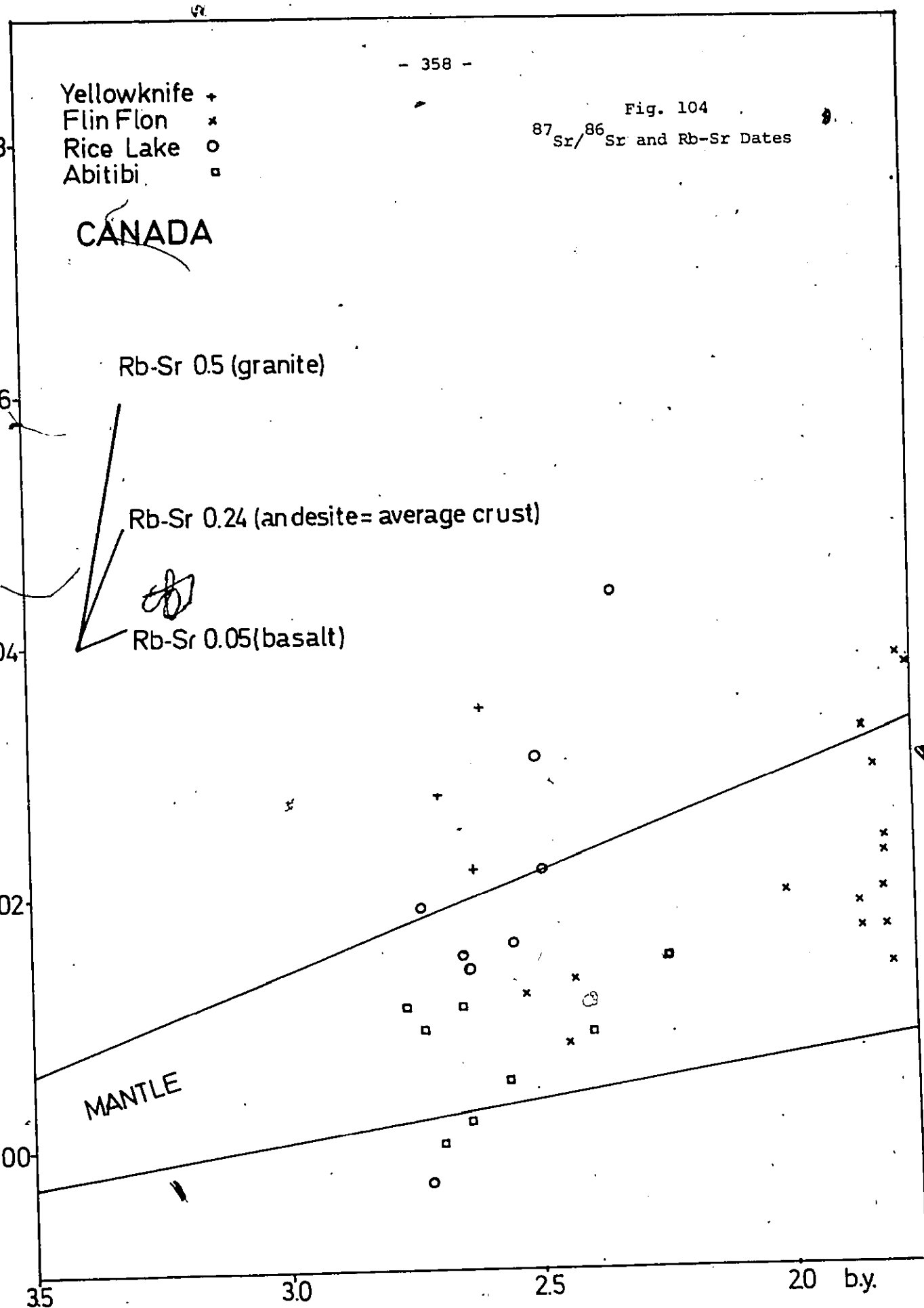
MANTLE

35

30

25

20 by.



I.R.

Rhodesia +
Barberton o

Fig. 105

$^{87}\text{Sr}/^{86}\text{Sr}$ and Rb-Sr Dates

.708

SOUTHERN AFRICA

.706

Rb-Sr 0.5 (granite)

Rb-Sr 0.24 (andesite = average crust)

.704

Rb-Sr 0.05 (basalt)

.702

MANTLE

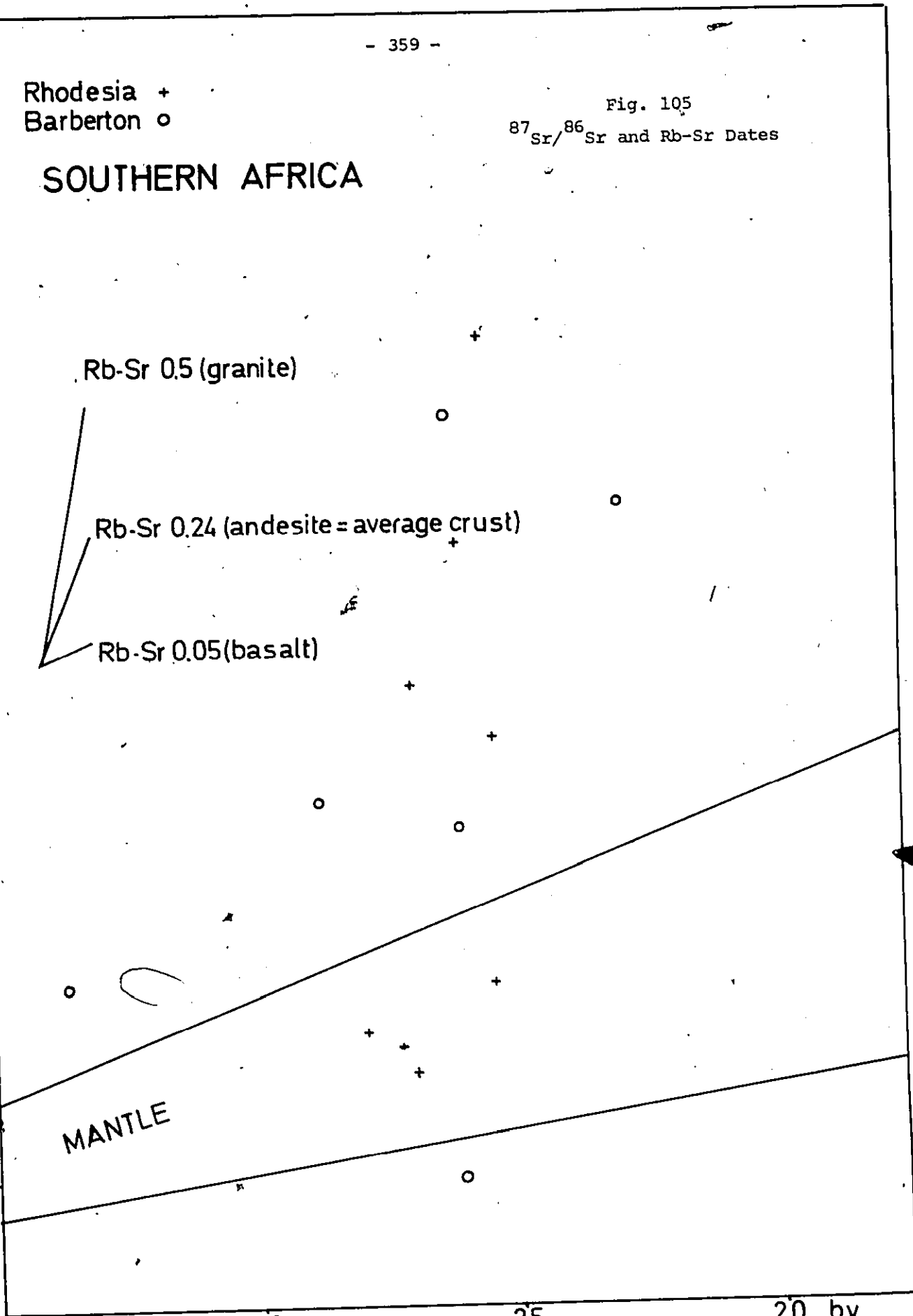
.700

35

30

25

20 by.



I.R.
.708

INDIA

Fig. 106
 $^{87}\text{Sr}/^{87}\text{Sr}$ and Rb-Sr Dates

Rb-Sr 0.5 (granite)
Rb-Sr 0.24 (andesite =
average crust)
Rb-Sr 0.05 (basalt)

.702

MANTLE

.700

3.5

3.0

2.5

2.0 by.



Fig. 107

$^{87}\text{Sr}/^{86}\text{Sr}$ and Rb-Sr Dates

I.R.

Yilgarn
Pilbara

+

o

AUSTRALIA

.708

.706

.704

.702

.700

Rb-Sr 0.5 (granite)

Rb-Sr 0.24 (andesite =
average crust)

Rb-Sr 0.05 (basalt)

MANTLE

35

30

25

2.0 b.y.

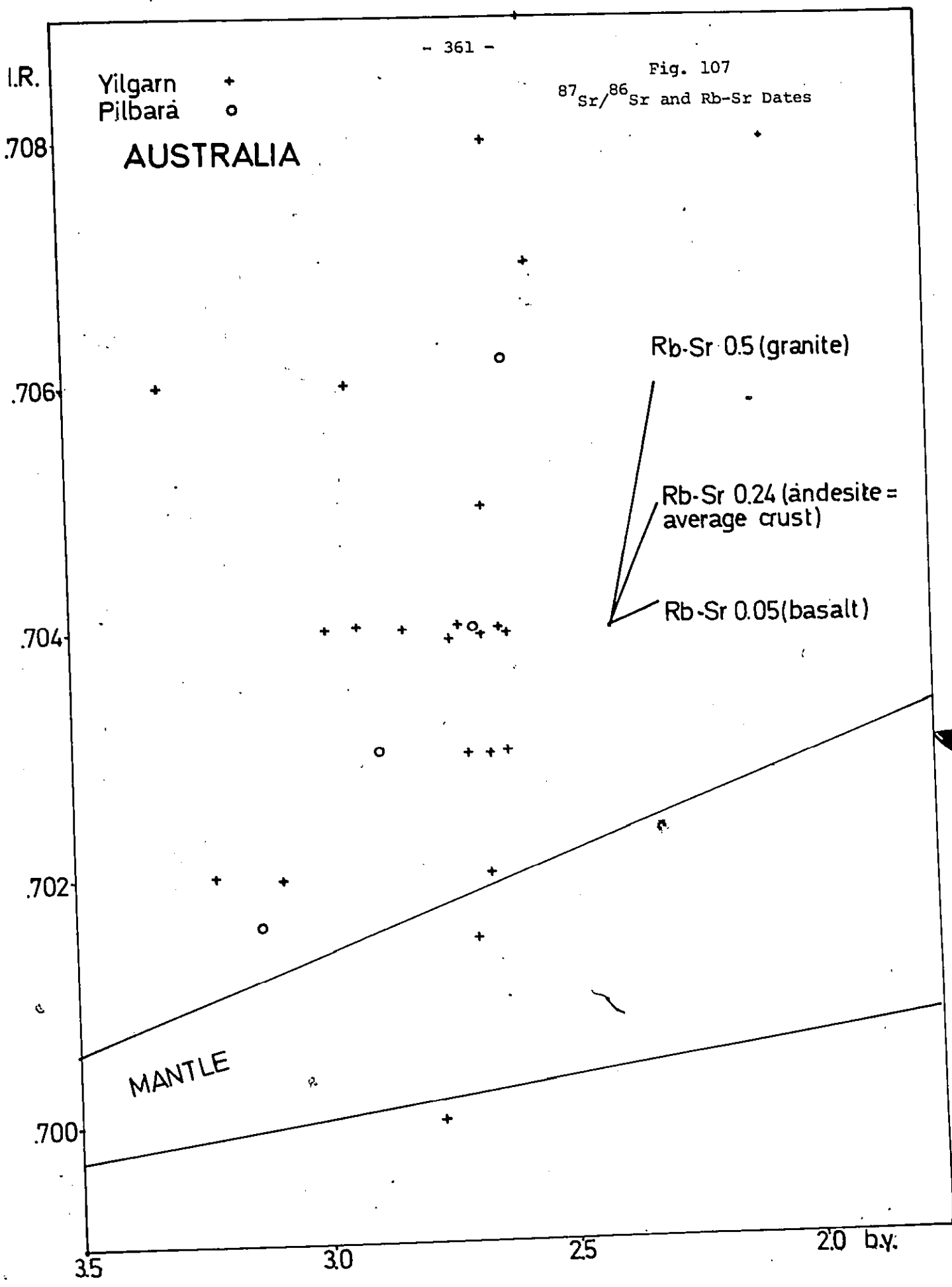
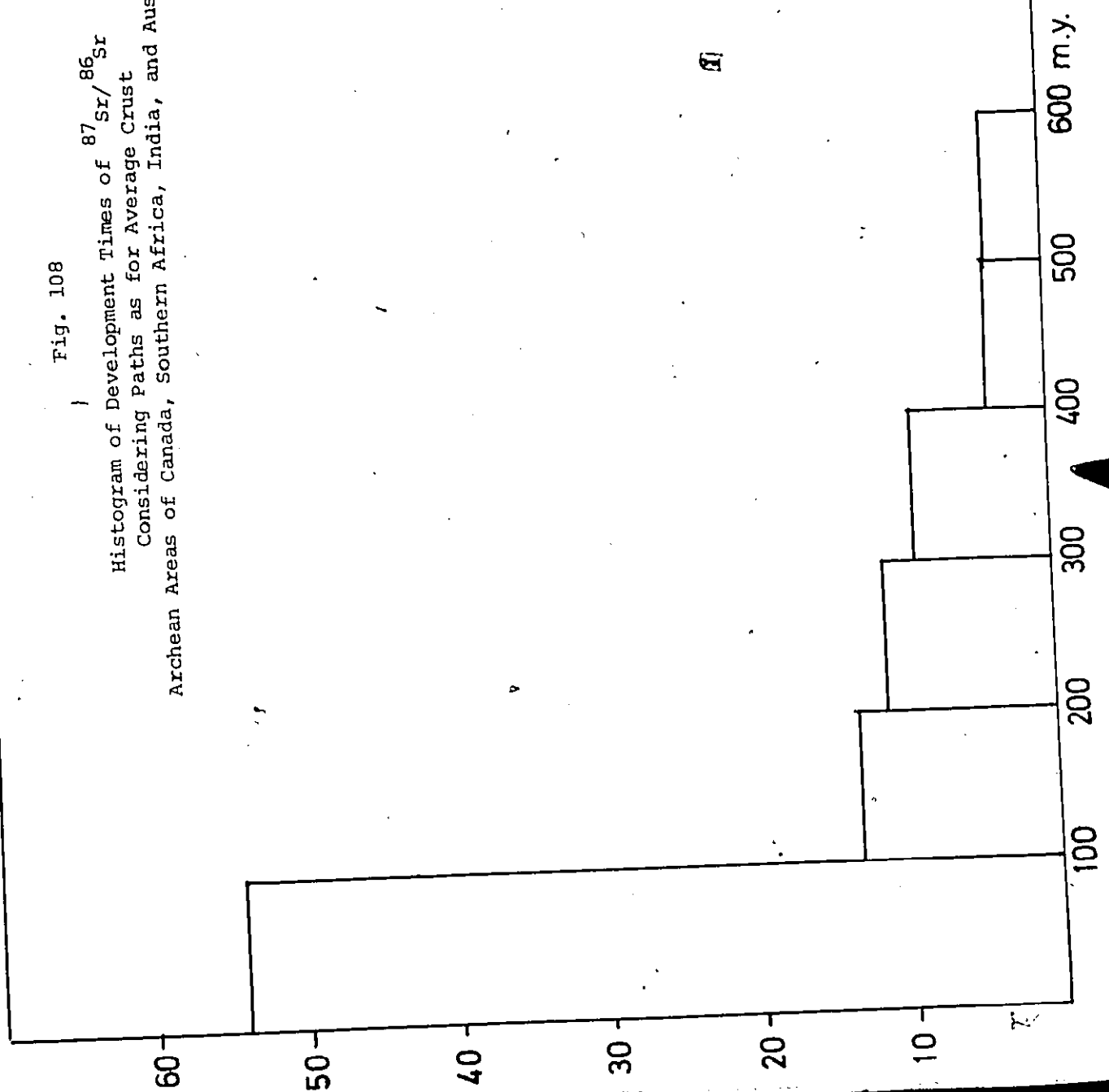


Fig. 108

Histogram of Development Times of $^{87}\text{Sr}/^{86}\text{Sr}$
Considering Paths as for Average Crust
Archean Areas of Canada, Southern Africa, India, and Australia



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