

THE UNIVERSITY OF OTTAWA

SEDIMENTOLOGY AND SEQUENCE STRATIGRAPHY OF THE LOWER
CRETACEOUS CLEARWATER FORMATION, COLD LAKE, ALBERTA

by

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ABSTRACT

The Lower Cretaceous (Aptian to Albian) Clearwater Formation at Cold Lake, Alberta contains a complex assemblage of siliciclastic strata. On the basis of detailed core analyses, Clearwater Formation strata have been subdivided into eight lithofacies and six recurring, facies associations. These facies associations are: 1) Tidal bar, 2) Sand flat, 3) Tidal-fluvial channel, 4) Fluvial channel, 5) Shoreface to foreshore, and 6) Offshore.

Correlation of the facies associations and their bounding time-significant surfaces has led to the interpretation that Clearwater Formation strata are marine and tidally-influenced coastal embayment deposits that comprise four unconformity-bounded depositional sequences (1 to 4). Each sequence is made up of one or more incised valley-fill deposits within a backstepping parasequence set, indicating deposition in the transgressive systems tract. The incised valley-fill deposits of each sequence, however, are interpreted as tide-dominated deltaic deposits emplaced when sediment flux periodically exceeded the relative sea level rise. In addition, each successive sequence indicates a basinward shift of deltaic facies within a larger-scale marine transgression. Together, the four depositional sequences of the Clearwater Formation therefore compose a progradational sequence set.

The Clearwater Formation is the primary reservoir unit at the Cold Lake heavy oil sands area with reserves estimated at $11,050 \times 10^6 \text{ m}^3$ of heavy crude bitumen. The distribution of hydrocarbons is related primarily to the distribution of reservoir quality strata and positive structure. Strata of facies associations 2 (sand flat) and 4 (fluvial channel) are observed to have the best reservoir quality. In the study area these strata occur in each of the upper three depositional sequences but are most abundant in sequences 3 and 4. The spatial distribution of reservoir-quality strata in Sequence 2 is such that additional hydrocarbon deposits are inferred to exist south of the study area,

along the axis of the incised valley trend. Furthermore, northwest of the study area, Sequence 4 probably contains additional reservoir-quality strata along the trend of its incised valleys.

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1. INTRODUCTION AND GENERAL GEOLOGY

1.1 Geologic Setting

The Western Canada Sedimentary Basin is a southwest-dipping, asymmetrical trough of Mesozoic strata overlying cratonic sediments of Paleozoic age and Precambrian granitic rocks (Fig. 1.1). The basin, which covers most of Alberta and southern Saskatchewan, attains a maximum sedimentary thickness of 5800 metres near the deformation front of the Rocky Mountains, and thins to zero along the exposed Precambrian Shield (Fig. 1.2; Masters, 1984). In central Alberta the basin is 500-600 kilometers wide, widening to the south where it extends eastward into Saskatchewan and merges with the cratonic Williston Basin (Cant and Stockmal, 1989).

The Mesozoic succession of the Western Canada Sedimentary Basin is made up of eastward thinning wedges of predominantly siliciclastic rocks (Fig. 1.2). A pronounced angular unconformity separates the Mesozoic succession from Paleozoic carbonate and minor clastic units. In the eastern half of the basin, the Lower Cretaceous Mannville Group overlies Devonian carbonates and evaporites, and in turn is overlain by Lower to Upper Cretaceous shales of the Alberta and Colorado groups (Fig. 1.3).

1.1.1 Structural Framework

The following discussion of basin evolution is based primarily on the work of Cant and Stockmal (1989) and Jackson (1984). The reader is referred to these papers for details regarding the age relationships of the various tectonic elements.

From the Middle Jurassic to Early Tertiary, a number of allochthonous terranes were accreted onto the western margin of North America (Cant and Stockmal, 1989). Allochthonous terrane accretion has been interpreted to involve significant cratonward

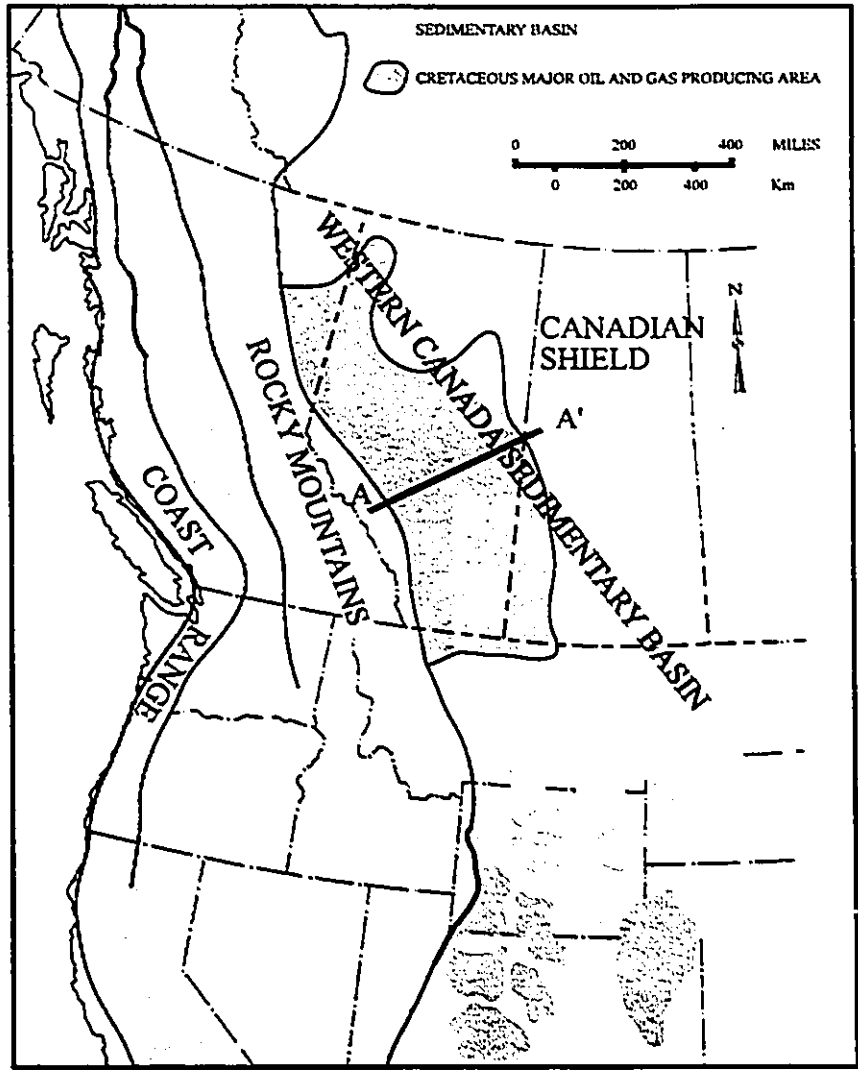


Figure 1.1: Sedimentary basins of western North America. Line A-A' is the line of section in Figure 1.2 (modified after Jackson, 1984).

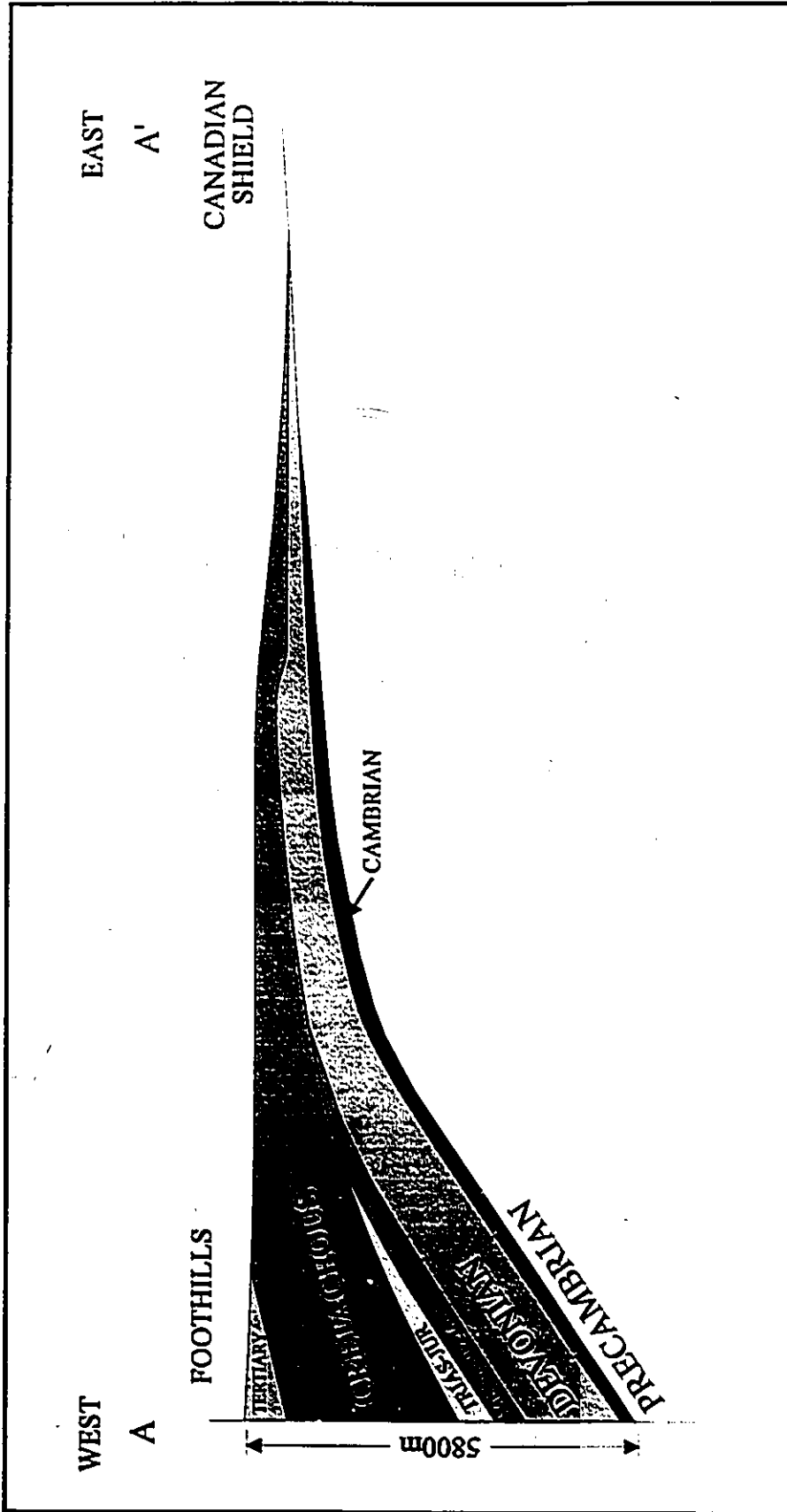


Figure 1.2: Simplified cross-section through the Western Canada Sedimentary Basin showing the eastward-thinning sedimentary fill. The surface trace of this 400 km west-to-east cross-section is shown in Figure 1 (modified after Jackson, 1984).

SERIES	STAGE	STRATIGRAPHY	
LOWER CRETACEOUS	ALBIAN	COLORADO GROUP	VIKING FORMATION
			JOLI FOU FORMATION
		MANNVILLE GROUP	GRAND RAPIDS FORMATION
			UPPER Mbr. LOWER Mbr.
	APTIAN		CLEARWATER FORMATION
		WABISKAW Mbr.	
			McMURRAY FORMATION
DEVONIAN		BEAVERHILL LAKE GROUP	

Figure 1.3: Lower Cretaceous stratigraphic nomenclature for the Cold Lake area of northeastern Alberta (modified after Hayes et al., 1994).

displacement and subsequent tectonic loading on the lithosphere and elevation of sediment sources. The overthrust sedimentary package loaded the western margin of the craton and caused subsidence. This created an elongated, northwest- to southeast-trending foreland trough into which clastic detritus was shed. Basin subsidence, and related accommodation space, was at a maximum immediately adjacent to the overthrust load and decreased eastward (Fig. 1.2). As terrane accretion continued, the foreland basin expanded eastward.

Sediment forming the early part of the basin fill was derived from the emergent granitic craton (Canadian Shield) to the east and from the developing Cordillera to the west. Shield-derived sediment was predominantly quartz whereas the Cordilleran source provided mostly feldspathic and volcanic detritus. As the Cordillera grew, sediment derived from the west overwhelmed the eastern source (Minken, 1974; Harrison *et al.*, 1981; Putnam and Pedskalny, 1983; Jackson, 1984).

The Western Canada foreland basin fill has been subdivided into six northeast-thinning unconformity-bounded clastic wedges: Fernie-Kootenay, Mannville, Dunvegan, Belly River, Edmonton, and Paskapoo (Cant and Stockmal, 1989). Each wedge is interpreted to correlate temporally with one of six major terrane accretion episodes: Intermontane superterrane, Bridge River, Cascadia, Insular superterrane, Pacific Rim-Chugach, and Olympic, respectively (Cant and Stockmal, 1989; Fig. 1.4). Whereas Cordilleran tectonics may account for the large-scale unconformity-bounded clastic wedges (sequences), eustatic sea-level variations and local subsidence events were likely dominant factors controlling the internal stratal architecture of each wedge.

A prominent feature along the eastern margin of the Western Canada Sedimentary Basin is the northwest-trending Athabasca Anticline (Fig. 1.5). Vigrass (1968) associated the occurrence of hydrocarbons in the Athabasca, Cold Lake, and

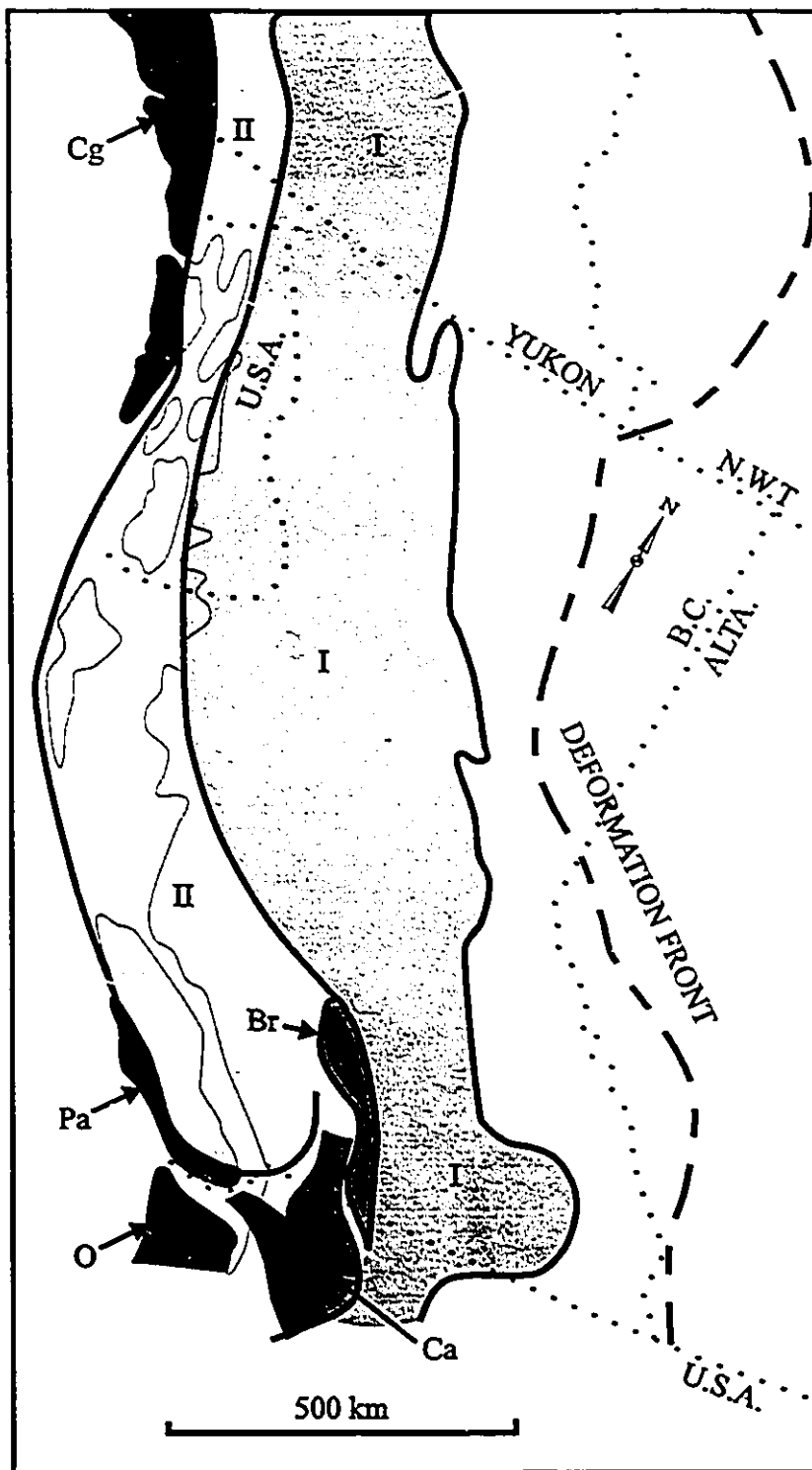


Figure 1.4: Allochthonous terranes of the Canadian Cordillera. I, Intermontane superterrane; II, Insular superterrane; Br, Bridge River terrane; Ca, Cascadia terrane; Pa-Cg, Pacific Rim - Chugach terrane; O, Olympic terrane (modified after Price et al., 1981).

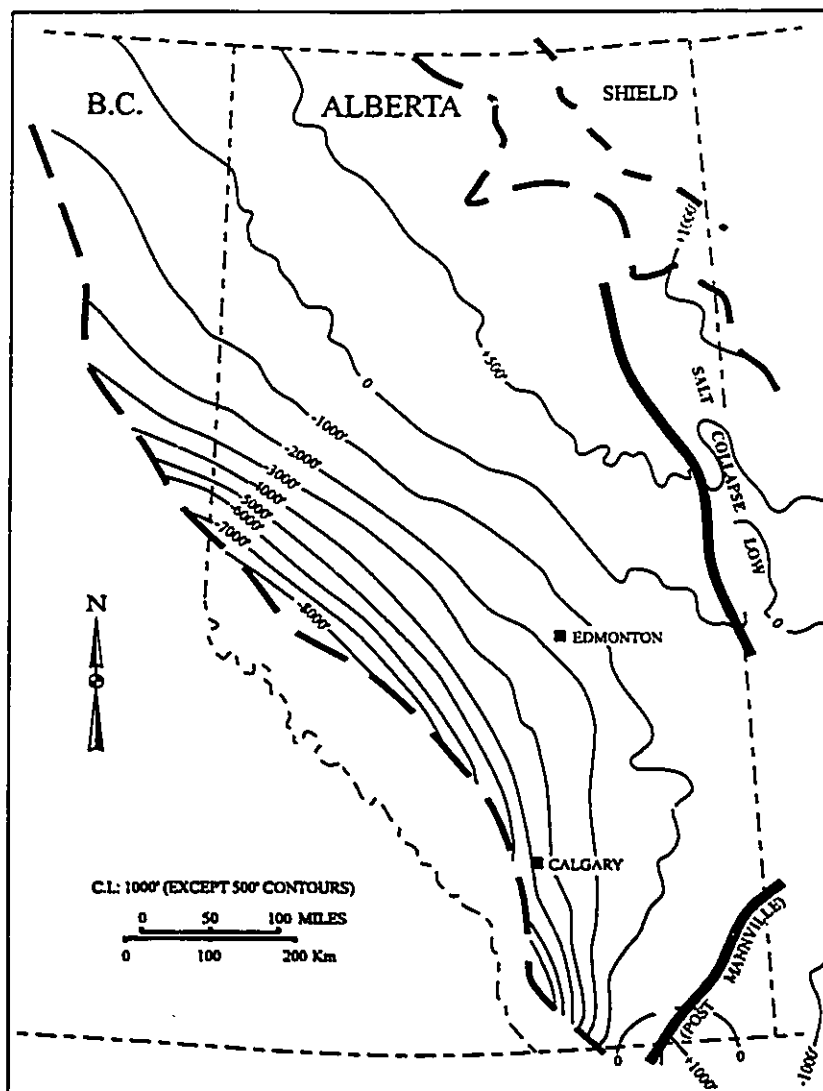


Figure 1.5: Structure map of the pre-Mannville erosional surface showing the location of the Athabasca Anticline (modified after Jackson, 1984).

Lloydminster regions with this structure and related it to the syn- to post Mannville dissolution of Devonian evaporites. In the Cold Lake area the Athabasca Anticline is the most prominent topographical feature on the pre-Cretaceous erosion surface (Fig. 1.6). Here the structure trends northwest to southeast and plunges southeastward. Liquid hydrocarbons accumulated below the structural high in porous sandstones of the Clearwater and Grand Rapids formations, and subsequently were degraded by meteoric-water washing and bacteria (Vigrass, 1968; Masters, 1984; Bachu, 1995).

1.1.2 General Stratigraphy of the Lower Cretaceous

The Lower Cretaceous (Aptian to Albian) Mannville Group is correlated with the Blairmore Group of the foothills area, the Dakota Group in the western United States, and with the Bullhead/Fort St. John groups of northeastern British Columbia (Hayes *et al.*, 1994). The Mannville Group is mostly a subsurface unit, but locally crops out along the Athabasca and Clearwater Rivers in northeastern Alberta and in the Rocky Mountain foothills.

The first geological descriptions of Mannville Group strata were from outcrops along the Athabasca and Clearwater Rivers in north-central Alberta. In the summer of 1882 Robert Bell of the Geological Survey of Canada described the Lower Cretaceous "Tar Sands." He noted that the "Tar Sands" contained a black pitch material that oozed from the outcrop on warm summer days and that it had long been used by local Native peoples and Hudson Bay Company officials as a water repellent useful for lining boats and covering roofed buildings (Bell, 1885). Later, McConnell (1891) assigned the name Clearwater Formation to the thick grey shales above the "Tar Sands" and below sandstones of the Grand Rapids Formation. The "Tar Sands" unit was later formally named the McMurray Formation by McLearn (1917).

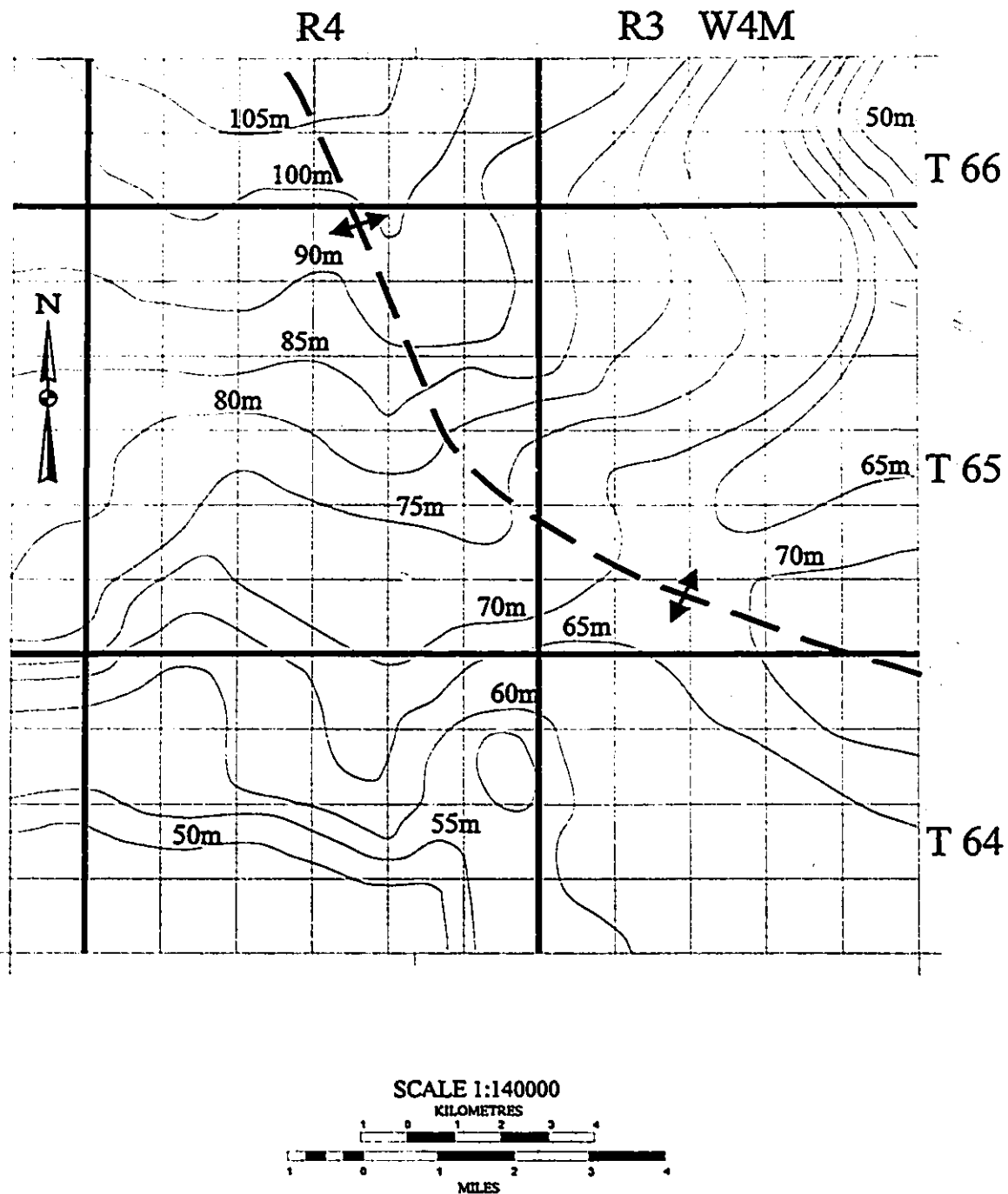


Figure 1.6: Structure map on the top of the pre-Mannville (Devonian) surface in the Cold Lake area. The Athabasca Anticline is shown by the dashed line. Contour interval=5m.

Nauss (1945) used the term Mannville Formation to describe Lower Cretaceous strata in the subsurface of the Vermilion area in central Alberta. Subsequently, Badgley (1952) attempted to extend the Lower Cretaceous stratigraphic nomenclature from the Athabasca River outcrop area into the subsurface of northeast Alberta. Badgley proposed the name Mannville Group for all strata above the Paleozoic unconformity and below the Joli Fou shale (Colorado Group). The Mannville Group of Badgley therefore comprises the present-day McMurray, Clearwater, and Grand Rapids formations (Fig. 1.3). In addition, Badgley (1952) recognized a glauconitic sandstone that occurs locally at the base of the Clearwater Formation (Wabiskaw Member) and the *Metacypris angularis* zone (Ostracod zone equivalent); a fossiliferous unit which occurs locally just below the base of the Clearwater Formation.

In the central and southern Alberta plains, Glaister (1959) subdivided the Mannville Group into upper and lower formations and chose the top of the Ostracod zone as the boundary between the two units. Later, Rudkin (1965) interpreted Glaister's upper and lower Mannville as map units representing two distinct depositional episodes. Lower Mannville strata were deposited in non-marine environments with sediment derived from both the east and west. The Upper Mannville, however, is made up of sediment derived exclusively from the west and deposited in marine and marginal marine environments (Rudkin, 1965).

The current usage of the term Mannville Group was first proposed by Jackson (1984), who subdivided the Mannville Group into three regionally extensive units: Lower, Middle, and Upper Mannville. The Lower Mannville is essentially the same as that described by Rudkin (1965) and consists of continental sandstones and shales derived from either the Cordillera to the west or the Canadian Shield to the east. During this time Paleozoic paleotopography was modified or infilled by fluvial deposition that dominated Lower Mannville deposition. The Middle Mannville of Jackson (1984) was

dominated by transgressive marine, coastal-marine, or non-marine sandstone and shale derived from the Cordillera. Non-marine and marginal-marine sandstone and shale with Cordilleran provenance make up Jackson's Upper Mannville strata. Presently, although formal formation names exist, Mannville Group stratigraphic nomenclature has not yet been formalized regionally.

1.2 Area of Study

The study area lies approximately 300 km northeast of Edmonton, Alberta and occupies an area of 369 km² in the Cold Lake heavy oil deposit (Fig. 1.7). The study was centred on the Imperial Oil Limited Cold Lake Production Project (CLPP, Fig. 1.7) in township 65, range 4 west of the fourth meridian (65-4W4). This area was chosen because of the high density of well control (cores and well logs) and abundance of the hydrocarbon resource.

1.2.1 Mannville Group Stratigraphy at Cold Lake

The Mannville Group at Cold Lake is dominated by sandstone and occurs exclusively in the subsurface. Thickness ranges from 200 to 259 metres. Stratigraphically upward the mineralogical assemblage of the Mannville Group shows a change from an eastern (cratonic) source (Lower Mannville) to a predominantly western (Cordilleran) source (Middle and Upper Mannville; Putnam and Pedskalny, 1983).

Vigrass (1966) subdivided the Mannville Group in the Cold Lake area into four stratal units: A, B, C, and D. He correlated the D unit with the Lower Mannville of Rudkin (1965) and the A, B, and C units with the Upper Mannville. Vigrass also noted that the "C" unit was approximately equivalent to the Clearwater Formation in the Athabasca-Wabasca region. Clack (1967) used the terminology of the Athabasca area and

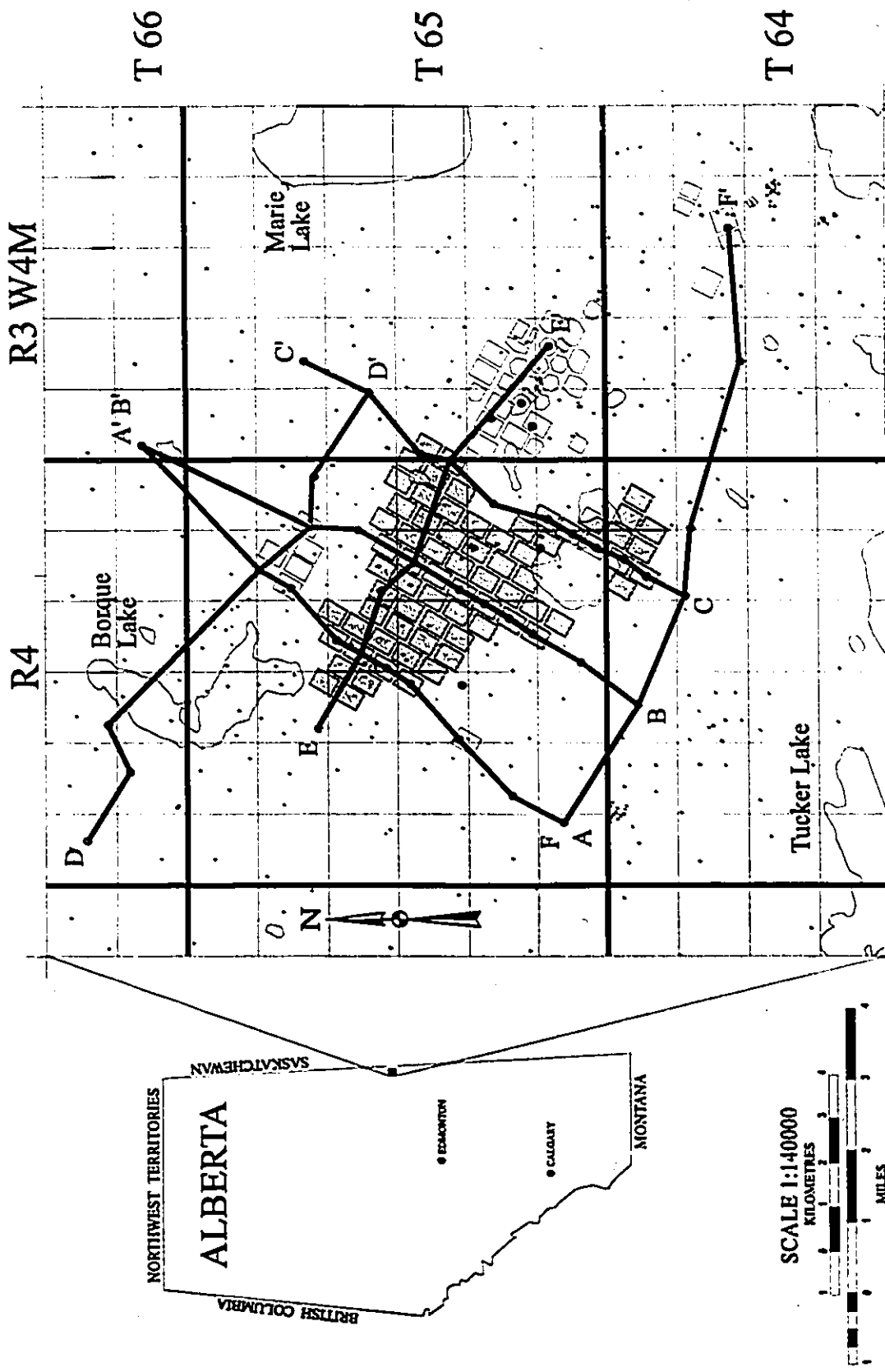


Figure 1.7: Map of study area showing locations of all wells drilled to date. Rectangles denote locations of pad wells (explanation in text). The Cold Lake Production Project (CLPP) area is shaded; large dots represent wells with core utilized in this project.

assigned the names McMurray Formation to unit D, Clearwater Formation to unit C, and Grand Rapids Formation to units B and A. The terminology of Clack (1967) is used widely in the literature and has been adopted in this study.

The following is a brief description of the stratal components that make up the Mannville Group in the Cold Lake area.

McMurray Formation

The McMurray Formation unconformably overlies carbonates and evaporites of the Devonian Beaverhill Lake Group and, in turn, is overlain unconformably by the Clearwater Formation. The McMurray ranges from 13 to 78 metres thick and consists predominantly of very fine- to fine-grained, mature quartz sandstone overlain by an interbedded sandstone and shale unit (Jardine, 1974; Harrison *et al.*, 1981). The basal sandstone consists mostly of fluvial-point-bar and channel-fill deposits (Jardine, 1974). The overlying interbedded sandstone and shale unit, however, was deposited in tidal flat or beach environments during a transgression of the Boreal Sea from the north (Jardine, 1974; Harrison *et al.*, 1981). Subsequently, relative sea-level fall terminated McMurray deposition and subaerially exposed much of the area.

In northeast Alberta, particularly in the Fort McMurray area, the McMurray Formation is an important bitumen reservoir. At Cold Lake, however, only minor amounts of bitumen have been found in the McMurray Formation.

Clearwater Formation

The Clearwater Formation ranges from 40 to 104 metres thick and consists of fine- to medium-grained, moderate- to poorly-consolidated, feldspathic litharenite interbedded with mudstone. The basal Wabiskaw Member (0 to 10 metres thick) consists of glauconitic sandstone with minor shale interbeds. It unconformably overlies the

McMurray Formation and, in turn, is unconformably overlain by younger Clearwater units. These are, in turn, unconformably overlain by strata of the Grand Rapids Formation. The Wabiskaw Member was deposited during a regional transgression of the Boreal Sea (Jardine, 1974) and has been interpreted as beach deposits (Harrison *et al.*, 1981). The overlying Clearwater succession, however, has been interpreted as a river-dominated delta deposited into a generally transgressing sea (Harrison *et al.*, 1981; Hutcheon *et al.*, 1989). A thin, northward thickening marine shale unit caps the Clearwater Formation throughout the Cold Lake area.

The Clearwater Formation is the primary bitumen reservoir at the Cold Lake field. In addition, coeval strata have yielded substantial quantities of heavy oil in the Lloydminster area.

Grand Rapids Formation

The Grand Rapids Formation ranges from 75 to 134 metres thick and comprises well- to poorly-consolidated, fine- to medium-grained, feldspathic and lithic sandstone and interbedded shale. It unconformably overlies the Clearwater Formation and is unconformably overlain by shales of the Joli Fou Formation (Colorado Group).

The Grand Rapids Formation has been informally subdivided into upper and lower members (Minken, 1974). Strata of the Lower Grand Rapids were deposited in a deltaic complex that prograded northward into the Boreal Sea (Minken, 1974). It consists of thin sandstone and siltstone units interbedded with shales and minor coal. The Upper Grand Rapids Member has been interpreted as a transgressive unit consisting of sandstone and shale deposited in beach and shallow-marine bar environments (Minken, 1974). More recently, however, it has been shown that deposition of the Upper Grand Rapids occurred during progradation and in tidally-influenced brackish-bay and channel environments (B. Beynon, personal communication, 1994). A subsequent fall of relative

sea-level created an erosion surface that marks the top of the Grand Rapids succession. A later transgression of the northern Boreal Sea combined with the encroachment of the southern Gulfian Sea led to the formation of the Western Continental Interior Seaway, and deposition of the Joli Fou Shale (Jackson, 1984).

The Grand Rapids Formation contains significant reserves of heavy oil at the Wabasca field and smaller amounts at Lloydminster and Cold Lake. In addition, equivalent units in the Alberta foothills contain large quantities of natural gas (Jackson, 1984).

1.3 Objectives

The Lower Cretaceous Mannville Group of northeastern Alberta contains what may be the world's largest hydrocarbon accumulation in the form of heavy crude bitumen. These deposits occur in the Western Canada Sedimentary Basin along a discontinuous trend from the Lloydminster area of Saskatchewan to the Athabasca and Peace River areas of Alberta (Fig. 1.8). In the Cold Lake area alone the Mannville Group contains heavy oil reserves estimated at $75 \times 10^9 \text{ m}^3$ (Proctor *et al.*, 1984).

In the Cold Lake heavy oil deposit, the Clearwater Formation is the major hydrocarbon reservoir. It occurs at a depth of approximately 425 metres and averages 63 metres thick. In-place bitumen reserves (10° API gravity) for the Clearwater Formation at Cold Lake are estimated at $11,050 \times 10^6 \text{ m}^3$ (ERCB, 1990) and production rates average 90,000 barrels of diluted bitumen per day (Cheadle *et al.*, 1995). Although the Clearwater Formation has been exploited for many years, the distribution of reservoir facies is still poorly understood. One of the principal impediments has been the lack of a consistent stratigraphic model. As a follow up to the recent advances in stratigraphic analysis using sequence stratigraphy (e.g. Van Wagoner *et al.*, 1990), the objective of this thesis has been to develop a more consistent stratigraphic model employing sequence stratigraphic

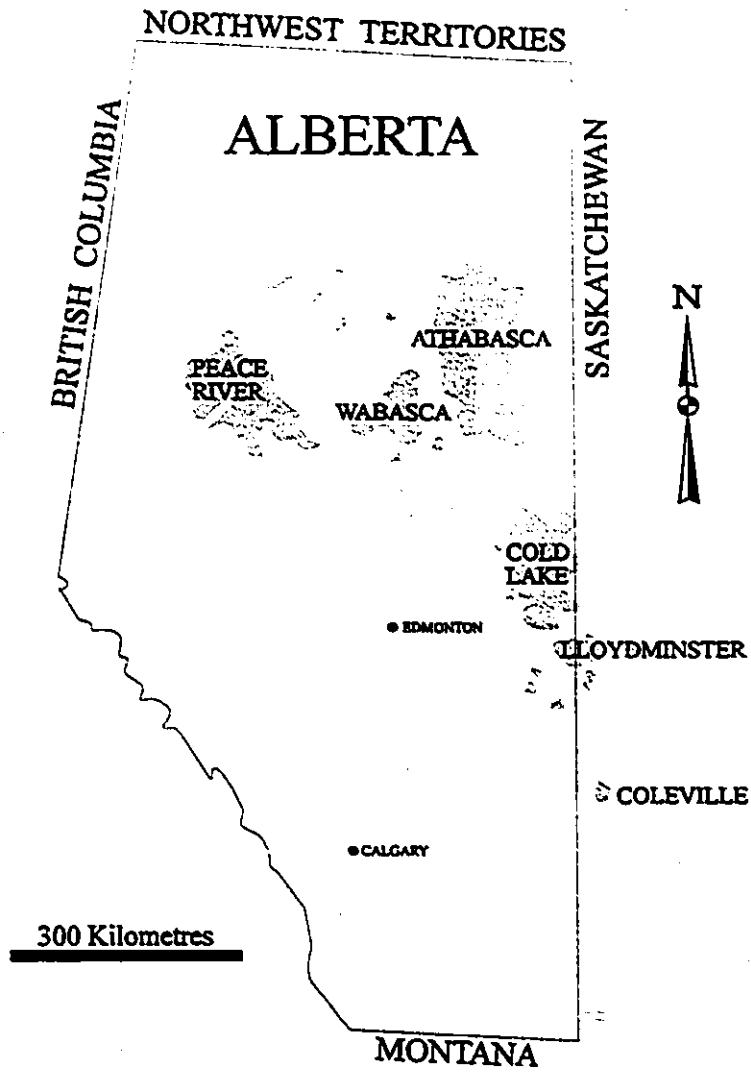


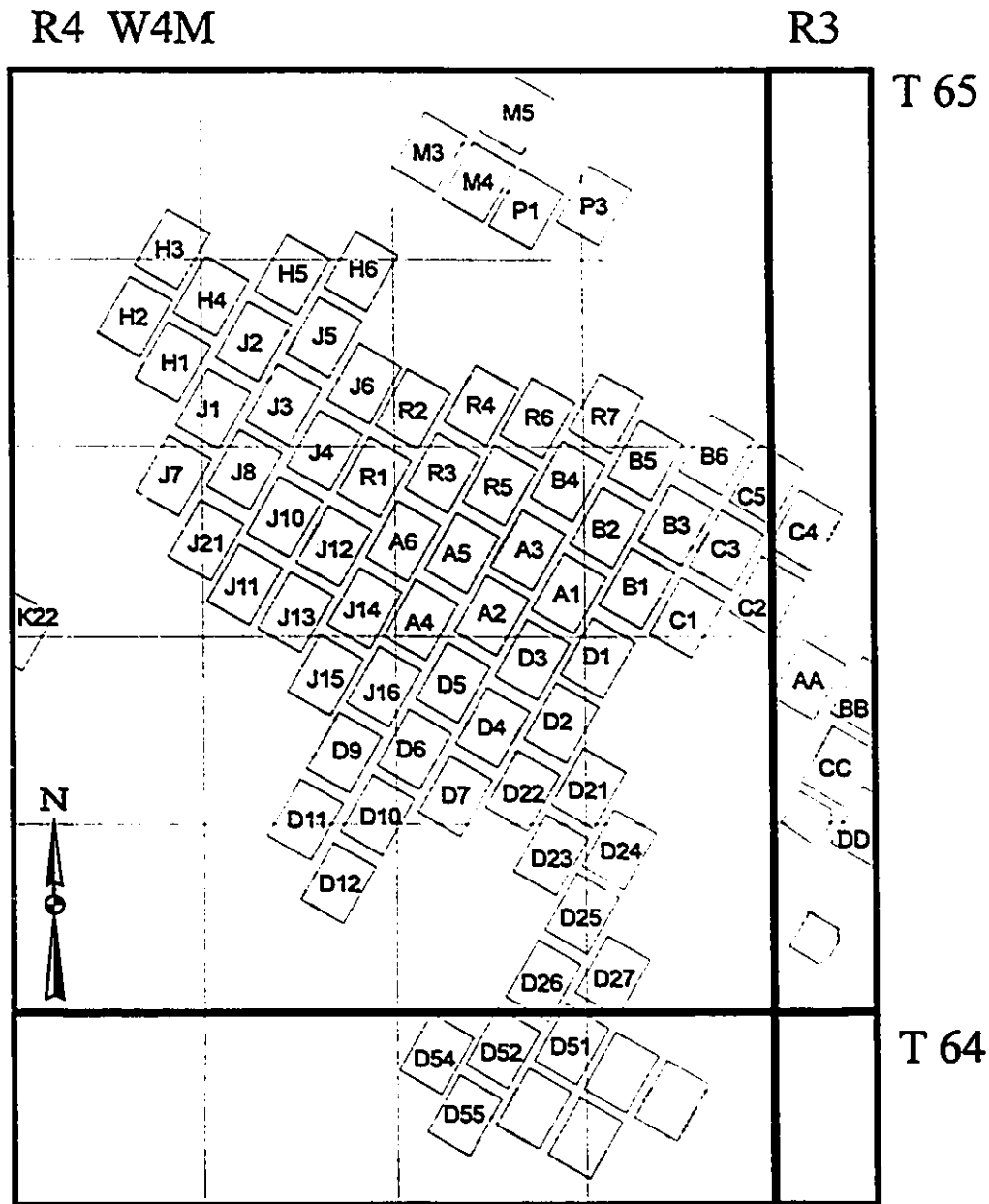
Figure 1.8: Major Lower Cretaceous heavy oil deposits (shaded area; modified after Jardine, 1974).

principles. In large part the impetus for this study is related to the fact that bitumen at Cold Lake is removed from the subsurface by expensive secondary and tertiary steam-flood methods, and, therefore, a more complete understanding of reservoir facies distribution has important economic ramifications.

1.4 Method of Study

Over 2700 wells have been drilled in the study area (Fig. 1.7); the majority are owned by Imperial Oil Resources Limited. Most of the wells in Imperial's CLPP area were drilled from a smaller number of pad locations; each pad is identified by an alphanumeric label (Fig. 1.9). A central platform in each pad is the site from which several deviated wells are drilled (Fig. 1.10). This drilling method reduces the environmental impact and capital cost while allowing the necessary well density for enhanced recovery methods. From each pad two near-vertical wells are drilled (typically numbered 08 and 13, Fig. 1.10). Core from these wells are sub-normal to the stratal boundaries and, therefore, are better suited for gathering sedimentological data than core from the more highly deviated wells.

In this study, cores from 45 vertical and near vertical wells were examined on a bed-by-bed scale. Detailed descriptions of the sedimentary structures and trace fossils were made and are presented with their corresponding lithological striplogs for 37 of the 45 cores in Appendix A. Most core descriptions were logged using AppleCore software (donated by Mike Ranger, University of Alberta) and a Macintosh Classic II computer. Based on the lithological descriptions, eight lithofacies were defined (Chapter 2). Based on stratal characteristics, six lithofacies associations were identified and interpreted in terms of depositional environment (Chapter 3). These interpretations helped to identify time-significant surfaces that were used to correlate geophysical well logs of the Clearwater Formation throughout the study area within a sequence stratigraphic



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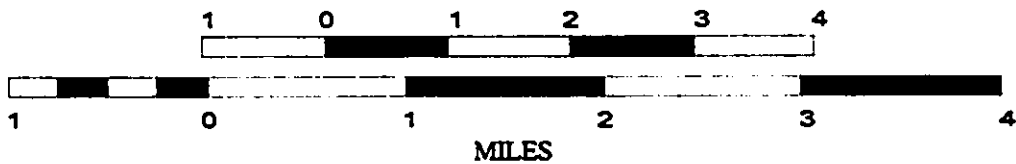


Figure 1.9: Cold Lake Production Project (CLPP) area and pad nomenclature. Each rectangle represents the area covered by one drilling pad. Alphanumeric labels are assigned to each pad as shown.

D24 PAD

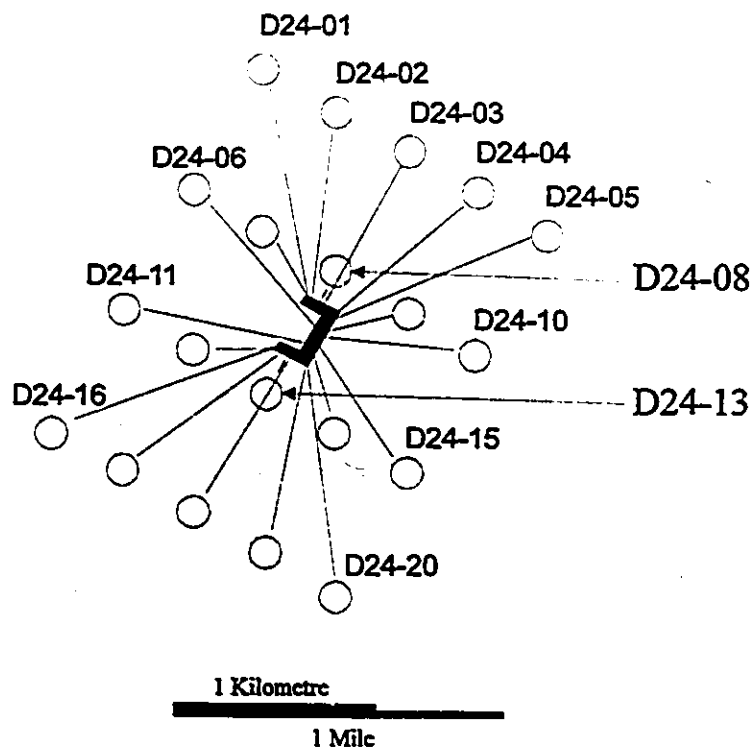


Figure 1.10: Example of pad drilling in Imperial Oil's Cold Lake Production Project area. Each pad is assigned an alphanumeric label (D24 for example) and deviated wells drilled from the pad are numbered from 1 to 20 in the manner shown.

The circles represent bottom-hole locations of the pad wells.

In most cases the wells with the smallest deviation are numbered 08 and 13. Many of the cores examined for this project were from these 'near vertical' pad wells.

framework (Chapter 4). A depositional model was constructed based on the spatial relationships between the facies associations and time-significant surfaces. Because of the typically high mud content of most Clearwater Formation sandstones, differentiating lithological units and identifying time significant-surfaces is difficult, and requires the incorporation of both well log data and core data.

1.5 Tides and tidal processes

Many of the facies defined from Clearwater Formation strata at Cold Lake have been interpreted as being tidally-influenced. Presented below is an introduction to tides and tidal processes and is intended as background information for chapters 2 and 3.

Tides occur as the periodic rise and fall of sea-level due to gravitational interaction between the Sun, Moon, and Earth (Defant, 1958). The stable orbits of the Moon - Earth and Earth - Sun systems create centripetal forces that are equal but opposite in direction to attractive forces between the bodies. The centripetal forces acting on the Earth remain constant, but attractive forces vary depending on position at the Earth's surface. At the closest point (zenith) between the Earth and (for example) Moon, attractive forces are greater than centripetal forces resulting in a (using simple vector addition) resultant force directed away from Earth (Fig. 1.11). At the opposite side of the Earth (nadir), centripetal forces are greater than attractive forces, resulting in a resultant force also directed away from Earth. Along the meridian half way between the zenith and nadir, resultant forces are directed toward Earth. Forces at the zenith and nadir, therefore, pull the deformable ocean surface away from the Earth's surface and create a "tidal bulge." On the other hand, inward directed forces at the half-way meridian pull the ocean surface downward (Fig. 1.11). Finally, due to the Earth's rotation, most locations experience a rise (high tide) and fall (low tide) of sea-level twice daily.

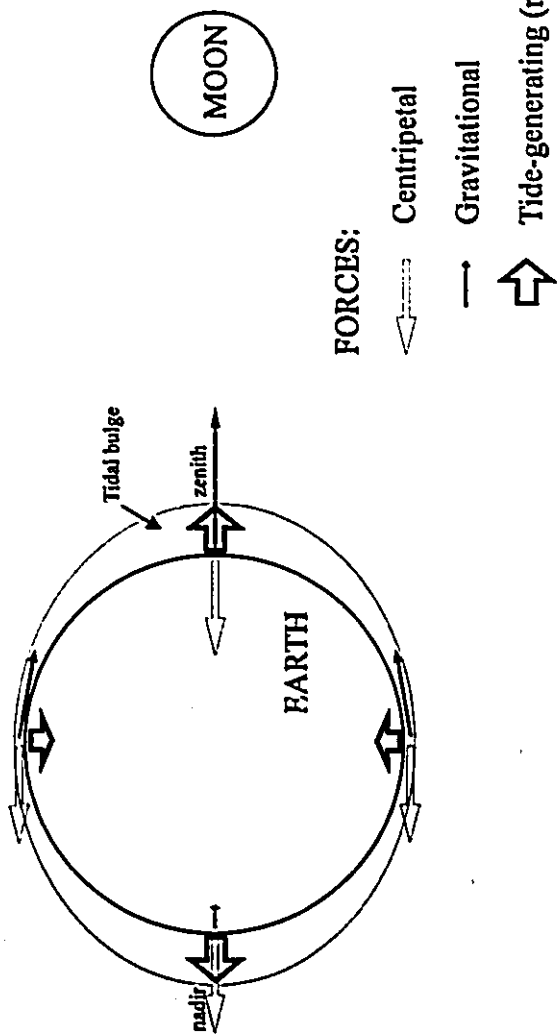


Figure 1.11: Schematic diagram of the Earth-moon system showing the relative magnitude of centripetal, gravitational, and resultant tide-generating forces.

A single rise (flood) and fall (ebb) of the tide is a "tidal cycle." The period of one semidiurnal (twice daily) tidal cycle is 12.42 hours. This is longer than 12 hours because the Moon orbits the Earth in the same direction as the Earth rotates about its axis. Therefore any location on Earth requires slightly more than 1/2 day to travel from the centre of one tidal bulge to the next. When the rotational axis of Earth is inclined with respect to the orbital plane of the Moon (usual case), any point on the surface of the Earth will be closer to the crest of one tidal bulge than the other. This inequity adds a diurnal (once daily) component to the tidal equation, but is only significant in locations where destructive interference dampens the semidiurnal tide (Dalrymple, 1992).

The vertical distance between low and high sea-level at a given location is the "tidal range." Tidal range is dependent on the position on the Earth relative to the Moon and Sun but is enhanced or diminished by the morphology of the ocean basin and coastline as well as Coriolis Effect (due to the rotation of the Earth) and friction along the sea bed (Defant, 1958).

Since the Moon is closer to Earth, it exerts tide-generating forces about two times stronger than the Sun (Ross, 1982). Twice monthly the Moon's orbit about the Earth is in line with the Earth-Sun system causing a combined effect and, therefore, the highest tidal ranges (spring tide). This occurs during full Moon and new Moon. When the Moon is in its quarters the attractive forces of the Moon and Sun are at right angles to each other resulting in reduced tidal ranges (neap tide). Semidiurnal tides have a spring-neap cycle lasting 14.77 days and contain 28 tidal cycles. Diurnal tides, on the other hand, have a spring-neap period of 13.66 days containing 14 tidal cycles (Defant, 1958; Visser, 1980; de Boer *et al.*, 1989; Dalrymple, 1992).

Because of the rise and fall of the ocean surface, currents known as a "tidal currents" are generated. These currents create sedimentary structures that are common in

both modern and ancient tidal environments. In coastal areas the currents tend to flow into and out of embayments generally at high angles to the shoreline. Tidal current speeds are commonly related to the tidal range - a strong current generally results from a higher tidal range. The relationship between the size of an embayment and the cross-sectional area of the embayments mouth, however, can also influence tidal current velocities. Furthermore, coastal morphology and bottom topography can cause inequalities between the flood and ebb tidal currents, which in turn gives rise to a preferred direction of sediment transport. Commonly, areas of flood and ebb current dominance occur as separate channel systems in a single embayment, as is the case with the Bay of Fundy (Dalrymple *et al.*, 1990).

In many tidal environments the dominant tidal current is capable of producing dunes, but the subsequent subordinate tidal current is only strong enough to partially erode the dunes. The scour surface formed is termed a reactivation surface (Fig. 1.12; Nio and Yang, 1991). During slack-water periods, a mud drape is deposited from suspension. Because the subordinate current typically deposits a relatively small amount of sand, the mud drapes deposited after dominant and subordinate tides are normally closely spaced (Fig. 1.12). Field observations (e.g. Reineck and Wunderlich, 1968) and experimental studies (Hawley, 1981; Terwindt and Breusers, 1972) have shown that interbedded sand and mud can result from a single tidal cycle. Whether bounded by reactivation surfaces or mud drapes, the deposit of a single dominant tide is called a tidal bundle. Thicker bundles tend to form during spring tide when tidal ranges, and therefore tidal currents, are stronger. If tides are semidiurnal and current speeds do not drop below the threshold for sand movement during neap tides, there should be 28 tidal bundles within a complete spring-neap cycle. Similarly, there will be 14 or fewer tidal bundles if the tides are diurnal. Beds showing cyclic changes in layer thickness related to spring-neap variations

in tidal current speeds are referred to as tidal rhythmites (e.g. Dalrymple *et al.*, 1991; Williams, 1991).

Other sedimentary structures that are common to, but not necessarily indicative of, tidal deposits are bidirectional cross-stratification (herringbone cross-stratification) and flaser, wavy, and lenticular bedding (Fig. 1.13). Herringbone cross-stratification is the result of alternating ebb and flood tidal current directions. Where current ripples are the dominant bed form, successions of interbedded sand and mud form flaser, wavy, or lenticular bedding. Tidal currents deposit sand during flood and/or ebb tides, while mud settles from suspension during the intervening slack-water stages (Nio and Yang, 1991).

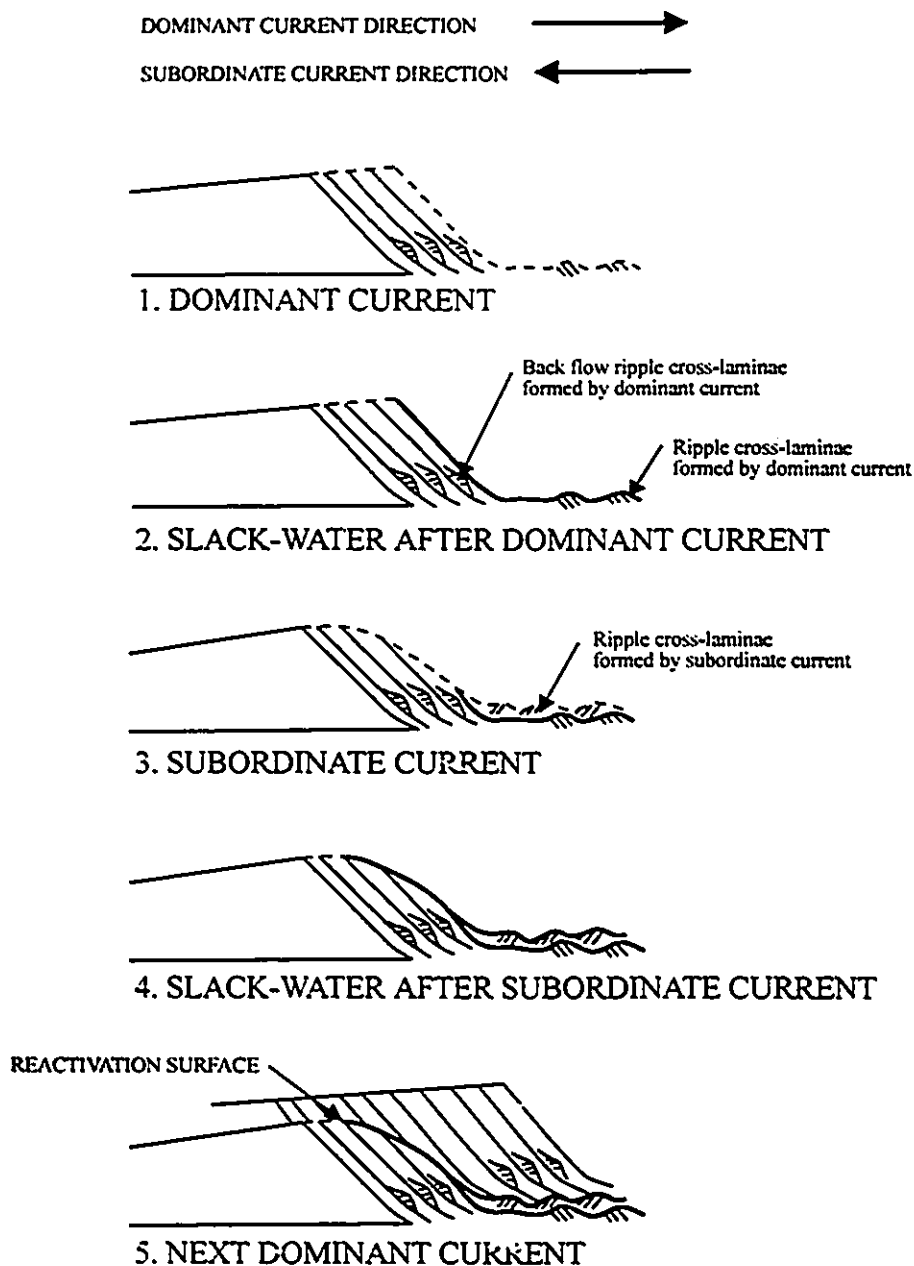


Figure 1.12: Schematic drawing of typical dune behavior during a flood-ebb cycle in which one of the tidal components dominates (i.e. flow speeds are higher and of longer duration). 1: Dunes are constructed during the dominant current stage. 2: Mud drapes are deposited during the initial slack-water stage. 3: Subordinate current erodes part of the dune and mud drape. 4: Mud drapes are again deposited during the next slack-water stage. 5: The dominant current stage of the next cycle constructs another dune that migrates over the reactivation surface (modified after Nio and Yang, 1991; Visser, 1980).

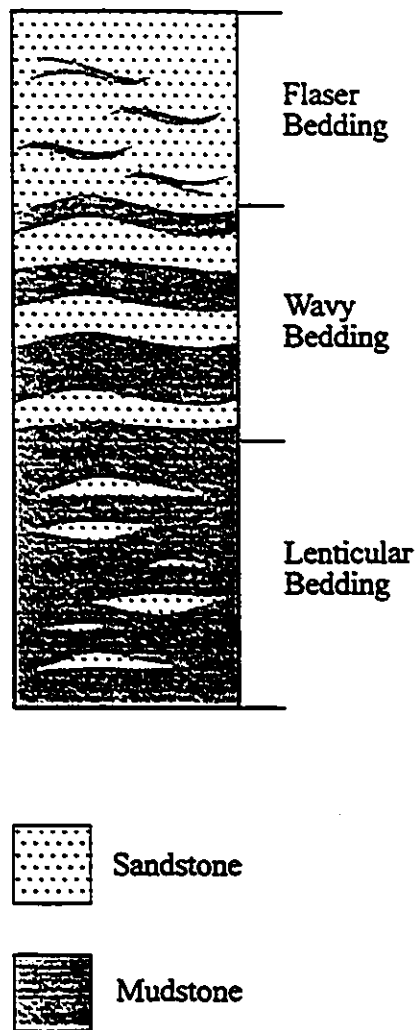


Figure 1.13: Flaser, wavy, and lenticular bedding. The continuum from lenticular to flaser bedding results from an increase in tidal current speed and a corresponding decrease in deposition and preservation of mud drapes and an increased availability of sand (modified after Reineck and Singh, 1980).

2. FACIES DESCRIPTIONS AND INTERPRETATIONS

2.1 Facies

To interpret ancient depositional environments, rock bodies are commonly subdivided into units of similar aspect or facies (Walker, 1992). The modern stratigraphic usage of the term "facies" is attributed to Gressly (1838), who used it to subdivide, in a descriptive sense, rock bodies having similar lithological and paleontological properties. Since then the term facies has been variously used, for example, in an interpretive sense (shoreface facies, fluvial facies, et cetera). However, the essence of the original term was a non-genetic, descriptive subdivision of rock bodies. Nevertheless, implicit in the definition was the understanding that each facies was related to a unique set of depositional processes, which in most instances were interpreted to represent a unique depositional environment or part thereof. Moreover, the vertical and lateral association of facies was then used to interpret the three-dimensional character of the paleoenvironment.

The level of facies subdivision depends in large part on the objectives of the study, the time available for study, the degree of preservation, and the abundance of physical and biological structures in the rocks (Walker, 1992). If the study is a regional analysis, fewer facies subdivisions are normally required in comparison to a more detailed, smaller-scale study (Walker, 1992). Likewise, if time is available, more detailed facies subdivisions can be resolved. The degree of preservation and abundance of primary sedimentary structures are also related to the number of definable facies; if primary sedimentary structures are obscured or show little variation, the definition of unique lithofacies may be difficult or impossible.

In the Cold Lake study area, pervasive black bitumen staining makes the resolution of physical and biogenic sedimentary structures difficult. Notwithstanding, the detailed bed-by-bed description of Clearwater Formation strata in core identified eight

distinct facies and two of the eight comprise two or more subfacies. Lithofacies were defined on the basis of grain-size, type and abundance of sedimentary structures, and ichnofossil assemblage and abundance.

In this study, cross-stratified sandstone sets less than five centimetres thick are regarded as small-scale; sets greater than 5 cm are considered large-scale. In addition, relative bioturbation is described as none, low, moderate, high, very high, and intense after the six ichnofacies classes of Droser and Bottjer (1986: Fig. 2.1). In addition, small trace fossils are regarded as those less than 5 mm in diameter, medium traces are from 5 to 20 mm, and large trace fossils are over 20 mm in diameter.

2.2 Facies Descriptions and Interpretations

In the study area, strata of the Clearwater Formation have been subdivided into eight lithofacies. Calcite-cemented zones up to 3m thick occur in each facies. These bitumen-depleted zones appear randomly distributed, but tend to develop along facies or bedding contacts. They are interpreted as secondary, and are not further discussed here. The eight lithofacies of the Clearwater Formation are:

Facies 1: Glauconitic sandstone

Facies 2: Interbedded sandstone and mudstone

Subfacies 2a: Planar-laminated and small-scale cross-stratified sandstone with interbedded sub-horizontal mudstone

Subfacies 2b: Large-scale cross-stratified sandstone with dipping, interbedded mudstone layers

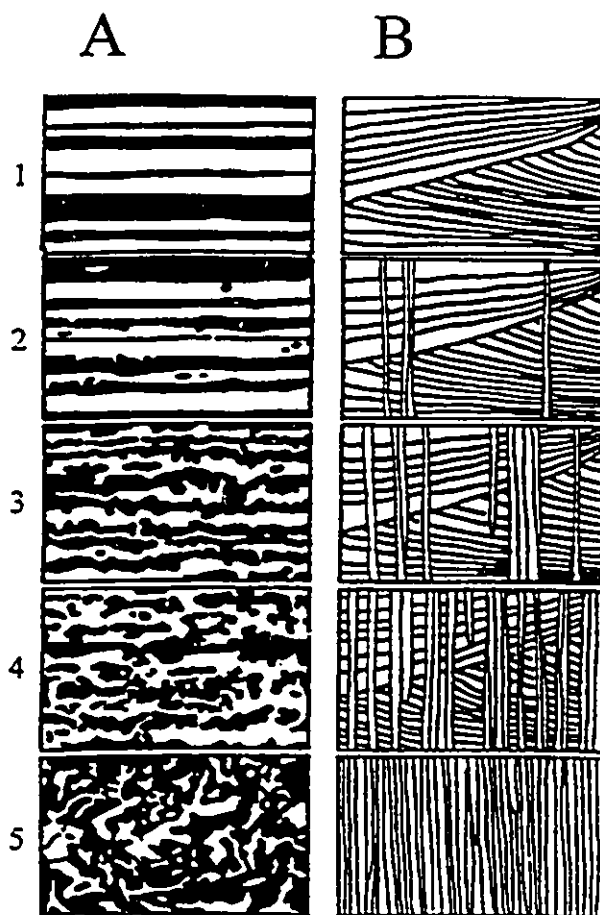


Figure 2.1: Schematic diagram of ichnofabric indices 1 through 5 characteristic of shelf environments (A) and high-energy nearshore environments (B). Ichnofabric indices are defined as follows: 1) None; no bioturbation. 2) Low; up to 10 percent of original bedding disturbed. 3) Moderate; 10-40 percent of original bedding disturbed. 4) High; 40-60 percent of original bedding disturbed. Burrows overlap and are not always well defined. 5) Very high; bedding is completely disturbed, but discrete burrows are detectable and the fabric is not mixed. 6) Intense (not shown); sediment is nearly or totally homogenized (after Droser and Bottjer, 1986).

Subfacies 2c: Large-scale cross-stratified sandstone with abundant mudstone clasts

Facies 3: Sandstone with interbedded bioturbated shaly sandstone

Facies 4: Large-scale cross-stratified sandstone

Facies 5: Planar-laminated sandstone

Facies 6: Small-scale cross-stratified sandstone

Facies 7: Massive (structureless) sandstone

Facies 8: Laminated mudstone

Subfacies 8a: Grey laminated and lenticular mudstone

Subfacies 8b: Parallel-laminated dark-grey mudstone

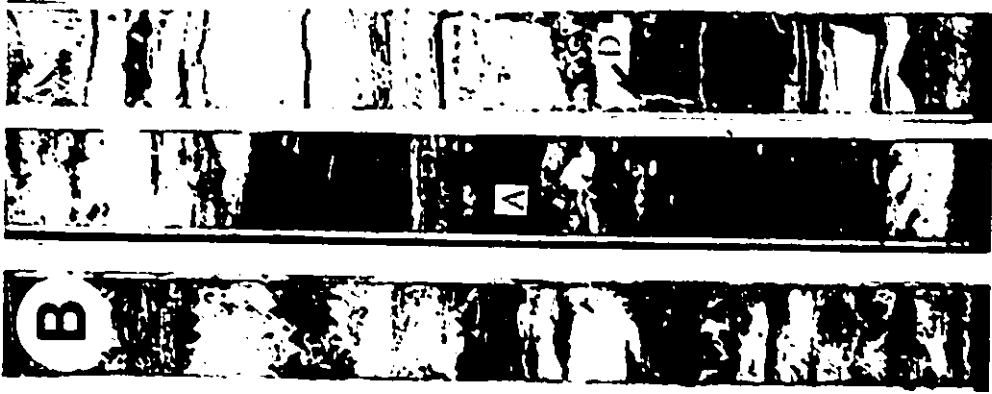
2.2.1 Facies 1: *Glaucconitic sandstone*

Description:

This facies consists of greenish-grey, intensely bioturbated lower-fine to lower-medium shaly sandstone (Fig. 2.2a). It is rich in glauconite, well consolidated, and moderately well sorted. Trace fossils include: *Asterosoma*, *Skolithos*, *Rhizocorallium*, *Teichichnus*, *Zoophycos*, *Palaeophycus*, and *Planolites* that range in size from millimetre-scale to several centimetres (Fig. 2.2b). Locally, bioturbation is so intense that individual ichnofossils cannot be recognized - only a bioturbated texture remains. In addition, physical sedimentary structures are typically destroyed by bioturbation. Rarely, however, planar-laminated beds (2 cm to 15 cm thick) are preserved. In these beds lamination

Figure 2.2: Facies 1

- a) Intensely bioturbated glauconite-rich shaly sandstone with interstratified planar laminated glauconitic sandstone. Several lined *Paleophycus* burrows are visible. Inclination is due to deviation of well bore from vertical. Photograph is from 2-25-65-4W4 (P7-13). Scale bar gradations are in centimetres.
- b) Intensely bioturbated glauconitic shaly sandstone interstratified with zones of weakly bioturbated planar laminated glauconitic sandstone. The thoroughly bioturbated zones are characterized by high density ichnofossil assemblages dominated by *Asterosoma* (*A*), *Skolithos*, *Diplocraterion* (*D*), *Rhizocorallium*, *Teichichnus*, *Zoophycos*, and *Planolites*. The photograph is from 3-9-66-4W4. Scale bar (lower left) is 10 cm.



is defined by alternating layers of glauconite and lithic grains. Where not obliterated by bioturbation, dark grey laminated shale interbeds also occur. These units range from 2 to 30 cm thick and are dispersed throughout Facies 1 strata.

Facies 1 ranges from 0 to 10 metres thick in the study area. In core, the lower and upper contacts of this facies are typically sharp and planar.

Interpretation:

Based on stratigraphic position and abundance of glauconite, this facies is interpreted to be part of the Wabiskaw Member. Abundant glauconite characterizes the Wabiskaw Member and correlative units in the Western Canada Sedimentary Basin (Glaister, 1959; Beynon, 1994; Hayes *et al.*, 1994). Glauconite is produced by a number of processes including: alteration of clay minerals and micas, direct precipitation from sea water, but more typically, alteration of organic matter, for instance fecal pellets (Burst, 1958). The abundance of bioturbation in Facies 1 strata suggests that a low-stress environment prevailed during Wabiskaw deposition, and that organic material was abundant. The Wabiskaw Member glauconite most likely was formed by the alteration of organic matter.

Although generally obscured by intense bioturbation, Facies 1 originally consisted of interbedded sandstones and mudstones that were deposited, respectively, during alternating episodes of high-energy bed-load transport and low-energy suspension deposition. The presence of planar-laminated, non-bioturbated sandstone beds indicates that high-energy events, most likely associated with storms, produced combined-flow plane bed (Arnott, 1993) or oscillatory flat bed conditions (Morton, 1981) at the sea bed. Following these events, suspension deposition returned and the sediment surface became recolonized by benthic tracemakers, resulting in the destruction of many of the primary physical sedimentary structures. The trace fossil assemblage of Facies 1 is typical of the

Skolithos and *Cruziana* Ichnofacies. These assemblages are commonly observed in strata deposited on the lower to middle shoreface, or in environments having similar salinity and energy conditions (Ekdale *et al.*, 1984; Wightman *et al.*, 1987; Pemberton *et al.*, 1992). Facies 1, therefore, is inferred to represent near-shore marine deposition along a storm-dominated coastline.

2.2.2 Facies 2: *Interbedded sandstone and mudstone*

Facies 2 consists of interbedded sandstone and mudstone. Mudstone units are light grey, range from 0.2 to 10 cm thick, and are typically massive to laminated with low to moderate bioturbation dominated by *Planolites* burrows. Sandstone beds are light grey to black (depending on bitumen saturation) and range from lenses less than 1 cm thick to beds up to 30 cm. In addition, sandstone beds are typically stratified, well to moderately well-consolidated, and moderately well sorted (unless otherwise specified below). Based on the nature of the interbedded mudstone and the scale of sedimentary structures in the sandstone, Facies 2 has been subdivided into three subfacies.

2.2.3 Subfacies 2a : *Planar-laminated and small-scale cross-stratified sandstone with interbedded sub-horizontal mudstone*

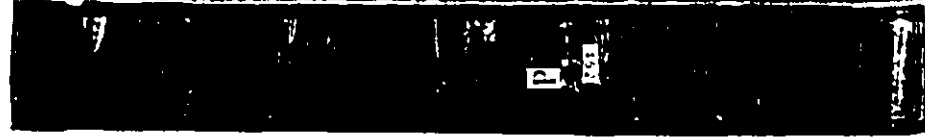
Description:

Subfacies 2a consists of lower to upper fine planar-laminated and small-scale cross-stratified sandstone beds interstratified with 0.2 to 10 cm sub-horizontal light grey to medium grey mudstone laminae and beds (Fig. 2.3a). Typically, centimetre- to tens of centimetres-scale upward-fining successions of interbedded sandstone and mudstone occur within larger-scale (several metres) upward thickening, or less commonly, upward thinning sandstone beds. Sandstone beds range from 1 to 30 cm thick and have sharp,

Figure 2.3: Subfacies 2a

- a) Planar laminated and small-scale cross-stratified sandstone beds with intercalated upward thinning parallel laminated mudstone. Ichnofossils include small *Planolites* (P), and rare larger *Teichichnus* (T), and *Thalassinoides* (Th). The photograph is from 6-29-65-3W4. Scale bar is 10 cm.

- b) Parallel laminated mudstone intercalated with upward thickening planar laminated and small-scale cross-stratified sandstone. A low diversity ichnofossil assemblage dominated by small *Planolites* (P) and *Teichichnus* (T) traces is present. The photograph is from 3-9-66-4W4. Scale bar is 10 cm.



scoured, or less commonly, bioturbated basal contacts. Mudstone makes up 20 to 80% of Subfacies 2a, but typically becomes less abundant upward. Where mudstone predominates (Fig. 2.3b), the most common physical structures are parallel lamination with minor asymmetrical small-scale cross-stratification in the intercalated sandstone. With increasing sandstone abundance, planar lamination, which commonly grades upward into asymmetrical small-scale cross-stratification, is the common sedimentary structure (Fig. 2.4a). Small-scale cross-stratification is occasionally bidirectional (Fig. 2.4a) and is typically associated with millimetre-scale wisps of mudstone.

Mudstone of Subfacies 2a typically exhibits small trace fossils of low to moderate diversity dominated by *Planolites* and *Teichichnus*. Rare larger trace fossils, predominantly *Teichichnus* and *Thalassinoides*, occur locally (Fig. 2.3a). Mudstone laminae and beds less than 2 cm thick are generally more intensely bioturbated than thicker mudstone intervals. In addition, mudstone beds conformably overlie the sandstone units. Soft-sediment deformation structures are uncommon; however, load casts and microfaults do occur (Fig. 2.4b).

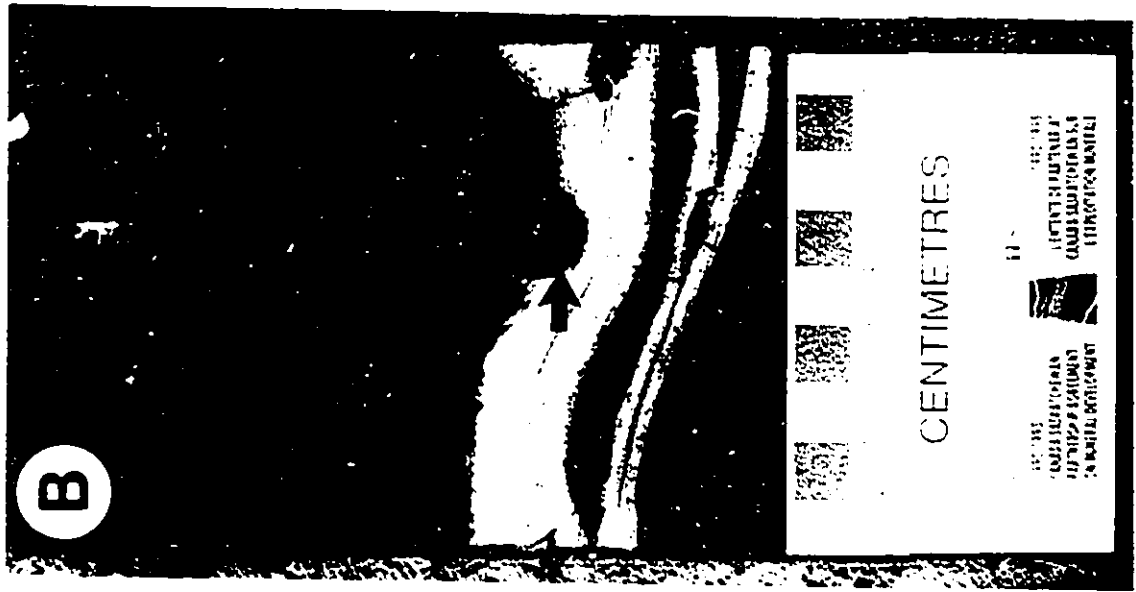
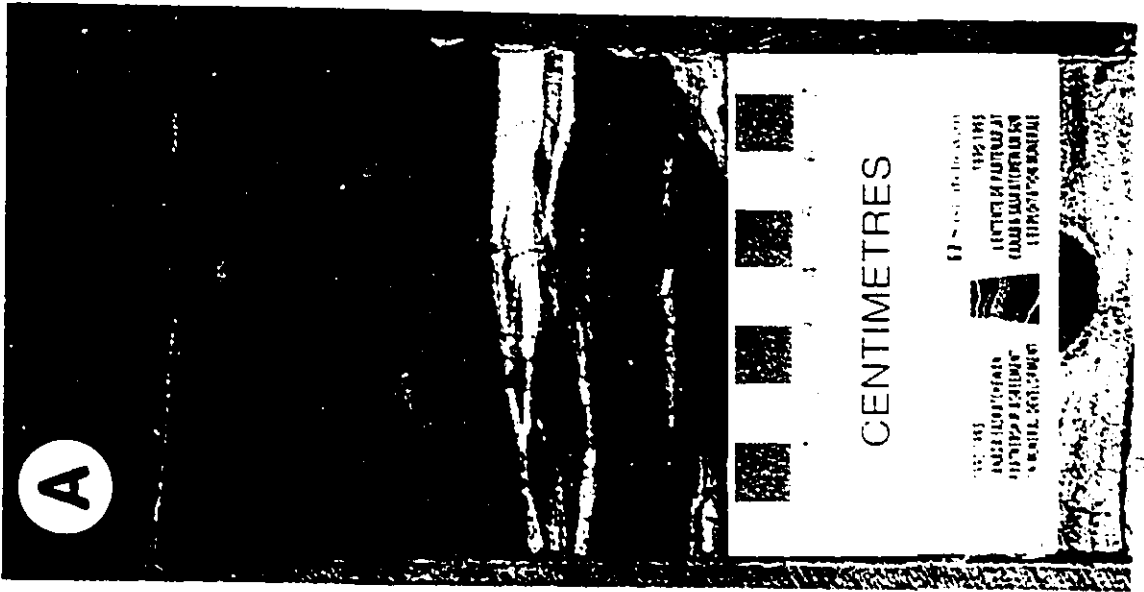
Three samples of Subfacies 2a were prepared for micropaleontological examination by Dr. J. Jansonius of Imperial Oil Limited during the summer of 1993. The restricted assemblage of dinoflagellates, pollen, and other Particulate Organic Matter (POM) are consistent with brackish-water conditions in a swampy, lagoonal or estuarine environment near a fluvial source (J. Jansonius, 1993; personal communication).

Interpretation:

Interbedded sandstone and mudstone of Subfacies 2a indicate the consistent alternation of two depositional processes: bed-load transport and deposition of sand and subsequent suspension settling of mud. Tidal currents (see chapter 1) are interpreted to be the most probable mechanism responsible for the consistent alternation of flow

Figure 2.4: Subfacies 2a

- a) Sandstone interstratified with mudstone. Small-scale cross-stratification shows bidirectional dips. Small arrows indicate paleocurrent flow directions. Photo is from 4-23-65-4W4 (R2-13).
- b) Sandstone interstratified with mudstone showing soft sediment-deformation. Arrow points to a load cast. Photograph is from 4-23-65-4W4 (R2-13).



conditions. Moreover, the consistent alternation of sandstone and mudstone associated with the occurrence of mudstone flasers and bi-directional cross-stratification support the interpretation of tidal influence (Nio and Yang, 1991). Nearshore tidal environments are characterized by abundant sand and mud and by alternating tidal currents that can fluctuate between those capable of depositing sand and those where mud settles from suspension (e.g. Wright *et al.*, 1975; Allen, 1982; Dalrymple *et al.*, 1991).

The typical upward-fining, centimetre- to tens of centimetres-scale succession of planar laminated sandstone grading upward into current-ripple cross-stratified sandstone is the result of repetitive change in tidal flow conditions from upper-flow-regime plane bed to lower-flow-regime current ripples (cf. Harms *et al.*, 1982). Each upward-fining succession thus represents a single tidal event (see section 1.5). Current-ripple cross-stratification dipping in the opposite direction with respect to the predominant dip is interpreted to represent sand transported and deposited by the subordinate tidal current (Nio and Yang, 1991; see section 1.5). The large-scale (several metres) upward increase of sandstone bed thickness indicates increasing sediment input and energy through time. This is interpreted to indicate increased tidal current energy associated with progradation of subtidal deposits. The local upward decrease in sandstone thickness is attributed to a local decrease in tidal current energy related to seasonal or neap-spring tide (see section 1.5) variations.

The small size of trace fossils and the restricted trace fossil and microfossil assemblages suggest an ecologically stressed environment, possibly related to brackish-water conditions (Ekdale *et al.*, 1984; Wightman *et al.*, 1987; Pemberton *et al.*, 1992). Subfacies 2a is therefore interpreted to represent deposition in, or marginal to, a tidally-influenced brackish-water bay.

2.2.5 Subfacies 2b: Large scale cross-stratified sandstone with dipping, interbedded mudstone layers

Description:

Subfacies 2b consists of large-scale and small-scale cross-stratified lower to upper fine sandstone interstratified with inclined (5° to 30°) mudstone veneers and layers (Fig. 2.5a). This subfacies becomes muddier upward on a scale of tens of centimetres (bed scale) to several metres. Sandstone beds are 1 to 30 cm thick, thin stratigraphically upwards, and typically have sharp or scoured basal contacts. The sandstone beds typically grade upward from thick (10 to 30 cm) upper fine, large-scale trough cross-stratified sandstone to thin (1 to 10 cm) lower fine, asymmetrical small-scale cross-stratified sandstone. Each sandstone bed commonly is conformably capped by a mudstone layer. In addition, the mudstone intervals are thin, typically less than 1 cm, and contain a low diversity trace fossil assemblage dominated by *Planolites* (Fig 2.11). Mudstone layers become more abundant and thicken upwards. The distinguishing characteristic of this subfacies is the consistent inclination of both the sandstone and mudstone beds at angles of 5° or greater.

Interpretation:

The consistent interbedding of sandstone and mudstone is best explained by tidally-influenced deposition. The large-scale cross-stratification, however, indicates greater water depths compared with the small-scale structures in sandstones of similar grain size of Subfacies 2a (cf. Harms *et al.*, 1982). Such large-scale structures are the result of migrating dunes or lateral accretion bedding (Harms *et al.*, 1982). The upward change from large-scale to small-scale cross-stratified sandstone is consistent with flow energy reduction related to the waxing-waning cycle of tidal currents (Nio and Yang, 1991). The inclination of mudstone beds sub-parallel to the dip of the sandstone beds

reflects fine-grained suspension deposition during slack-water/subordinate flow conditions on a sloped surface. Thomas *et al.* (1987) termed this style of stratification "Inclined Heterolithic Stratification" or IHS, and noted that it is most commonly associated with tidal point bar deposition. Similar IHS bedding has been interpreted from Lower Cretaceous tidally-influenced point bar deposits (MacEachern, 1989; Smith, 1989). Subfacies 2b is similarly interpreted.

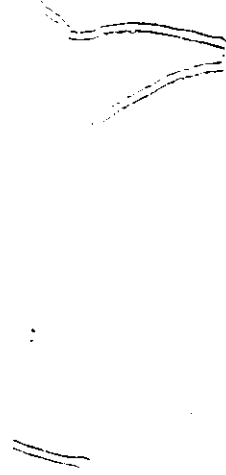
2.2.6 Subfacies 2c: Large-scale cross-stratified sandstone with abundant mudstone clasts

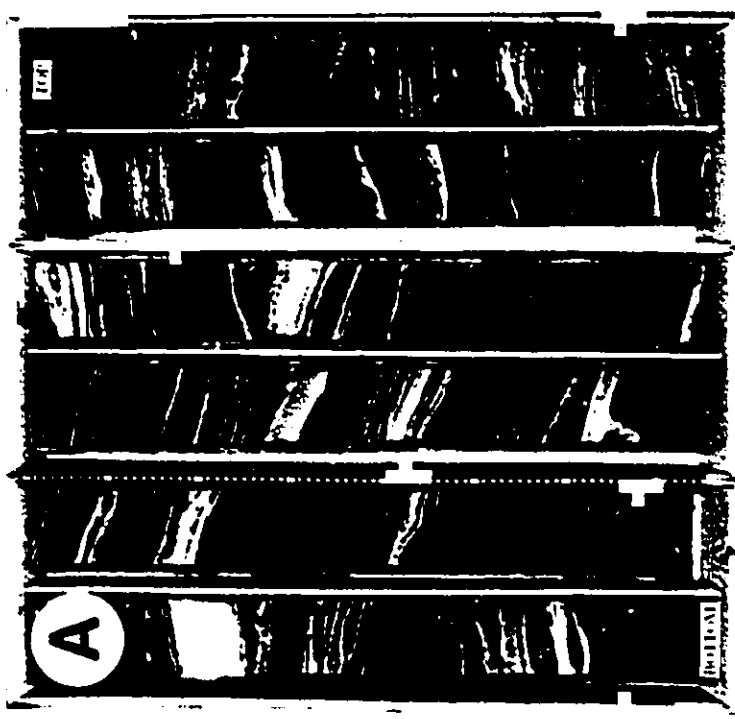
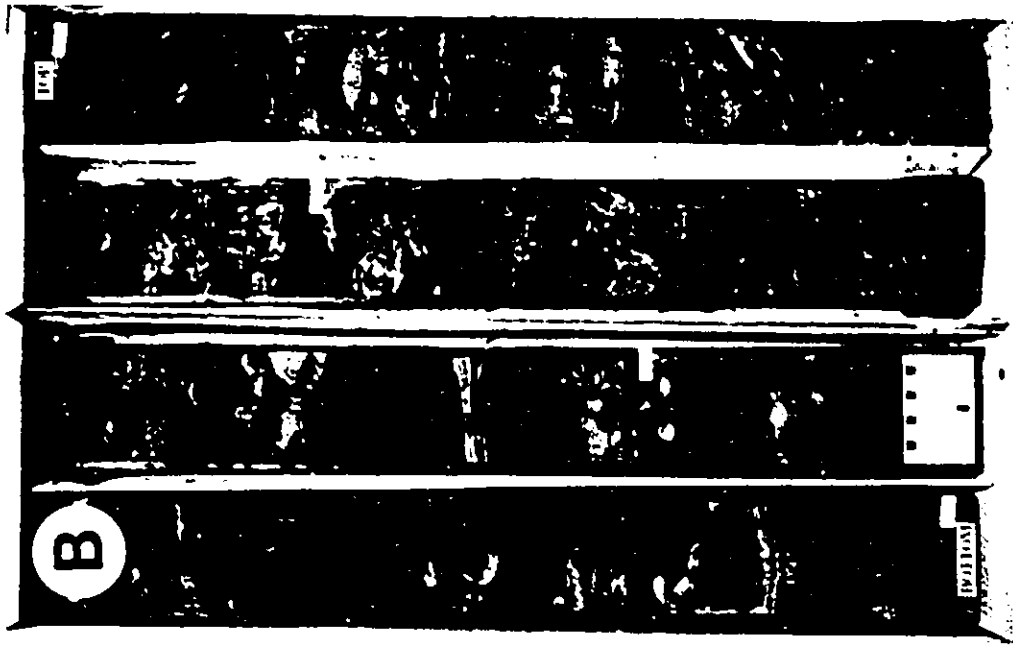
Description:

This subfacies consists of poorly-sorted, lower fine to upper medium cross-stratified sandstone interbedded with zones of abundant angular to rounded mudstone clasts dispersed in a cross-stratified sandstone matrix (Fig. 2.5b). Cross-stratification is large-scale and ranges in dip from 0° to 25°. The sandstones are typically heavily bitumen-saturated and are poorly consolidated. Beds range from 15 cm to over 1 m thick and generally become thinner upward. Mudstone clasts, which are commonly sideritized, occur in zones 5 to 40 centimetres thick. Mudstone clasts locally make up to 80% of the beds. In some beds, intraclasts are relatively uniform in shape and size and range in diameter from a few millimetres (usually angular) to over 10 centimetres (usually rounded and commonly armoured). Because of the limited view afforded by core and the intense bitumen staining, it was difficult to differentiate between different kinds of large-scale cross-stratification. The mudstone clasts, however, are imbricated, and therefore help define the type of cross-stratification; trough cross-stratified sets show an upward increase in the angle of stratification, whereas planar-tabular sets show little upward change in the angle of dip (cf. Harms *et al.*, 1982). Based on this criterion, trough cross-stratified sets predominate in Subfacies 2c. The basal contact of Subfacies 2c is typically erosive and often is characterized by an abrupt increase in grain size.

Figure 2.5: Subfacies 2b and 2c

- a) **Subfacies 2a: large-scale cross-stratified sandstone beds with interstratified inclined mudstone beds and laminae. *Planolites* is the most common trace fossil although rare *Tetlichinus* traces occur. Photograph is from 14-22-65-4W4 (H5-13). Scale bar is 10 centimetres long.**
- b) **Subfacies 2c: large-scale cross-stratified sandstone beds interstratified with zones of abundant mudstone clasts. Photograph is from 12-18-65-4W4. Scale bar gradations are in centimetres.**





Although no recognizable biogenic sedimentary structures are present in the sandstone, a low density and low diversity trace fossil assemblage, dominated by *Planolites*, occurs within some of the mudstone clasts. These burrows, however, show no preferred orientation within the clasts. Micropaleontological analysis of two mudstone intraclasts from Subfacies 2c reveals a Particulate Organic Matter (POM) content (Appendix 3) similar to that of Subfacies 2a, suggesting brackish-water conditions within a swampy, lagoonal or estuarine environment.

Interpretation:

The large-scale cross-stratification of Subfacies 2c is interpreted to be related to the migration of three-dimensional subaqueous dunes. Dunes are lower-flow-regime bedforms that are stable under moderate flow conditions – occurring between ripple and plane bed stability fields in fine- to medium-grained sand and in water over several centimetres deep (Harms *et al.*, 1982). Although dunes are common in a wide variety of depositional environments, the interstratified zones with abundant mudstone clasts (ripped-up from older Subfacies 2a or 2b strata) provide insight into the depositional setting. The lack of distinct mudstone interbeds suggests that slack-water suspension deposition was not associated with deposition of Subfacies 2c. Furthermore, the lack of bioturbation and abundance of large-scale dunes indicates possible fresh-water fluvial or at least highly-stressed tidal-fluvial deposition. This interpretation is based largely on facies associations and correlations discussed in Chapters 3 and 4, respectively.

2.2.7 Facies 3: Sandstone with interbedded bioturbated shaly sandstone

Description:

Facies 3 consists of brown to black, lower to upper fine sandstone interbedded with grey to brown bioturbated shaly sandstone (Fig. 2.6a). Beds of both the sandstone

and shaly sandstone range from 2 to 40 cm thick and are moderately well consolidated. Basal contacts of shaly beds are typically diffuse and bioturbated, whereas sandstone beds have sharp bases. Thin (<1 cm) wavy mudstone interbeds occur rarely. Upward-thickening sandstone beds are well sorted and include symmetrical small-scale cross-stratification, but are predominantly planar-laminated. The shaly beds exhibit a poorly sorted bioturbated texture, with mudstone and shaly sandstone content varying from 5% to over 50% of total bed volume. These interbedded shaly sandstone units typically become less abundant and thinner upward. The interbeds are typically sub-horizontal, but may dip up to 5°.

Shaly sandstone interbeds exhibit a diverse assemblage of large-scale robust trace fossils including *Teichichnus*, *Asterosoma*, *Rhizocorallium*, *Zoophycos*, *Diplocraterion*, *Skolithos*, *Ophiomorpha* and *Planolites* (Figs. 2.6b). The relative abundance of large trace fossils decreases upward, coincident with an increased thickness of coarser-grained beds. Rare, dark grey mudstone intercalations contain *Chondrites* traces. In addition, small shell fragments (less than 5 mm) of gastropods and ostracodes also occur.

Metre-scale upward-coarsening units are stacked and form a succession up to 30 metres thick. Typically, moderate to intensely bioturbated shaly sandstone is interstratified with small-scale symmetrically rippled sandstone beds that show low to no bioturbation, which is then overlain by planar laminated sandstone with minor shaly sandstone interbeds. This grades upward into planar laminated sandstone with rare shaly interbeds and bioturbation.

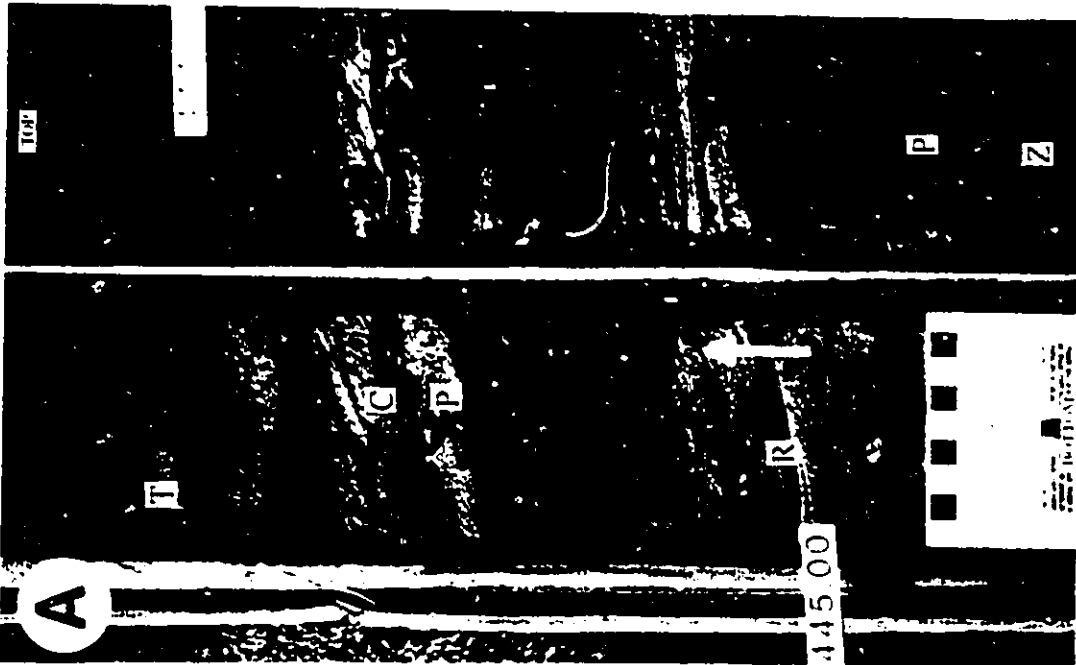
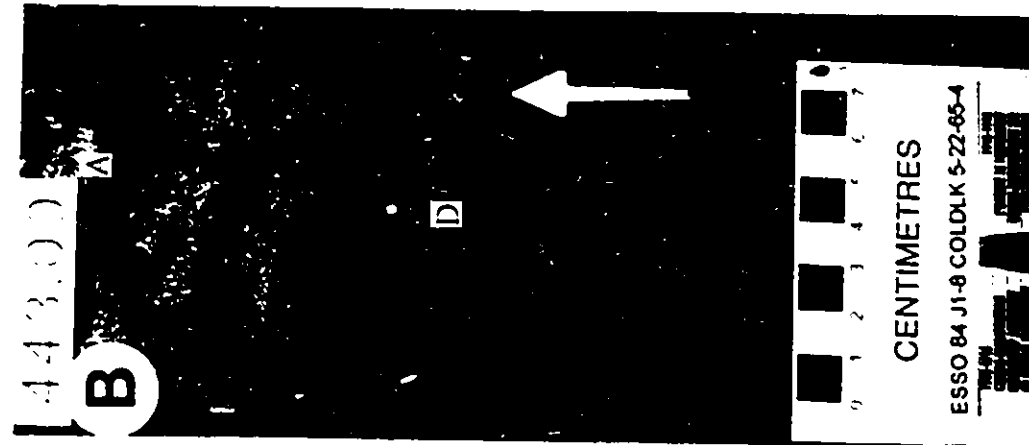
Interpretation:

The interbedding of coarse and fine-grained strata, like that of Subfacies 2a and 2b, indicates alternating episodes of traction and suspension deposition. However, burrowing in Facies 3 is more intense, more diverse, and characterized by larger

Figure 2.6: Facies 3

- a) Planar laminated and small-scale cross-stratified sandstone with interbedded bioturbated shaly sandstone and mudstone. Inclination of beds is due to the deviation of the well. *Rhizocorallium* (R), *Zoophycos* (Z), *Teichichnus* (T), and *Planolites* (P) traces are visible in the shaly sandstone. *Chondrites* (C) and *Planolites* (P) ichnofossils occur in the mudstone laminae. Photograph is from 5-22-65-4W4 (J1-8). Scale bar gradations are in centimetres.

- b) Planar laminated and small-scale cross-stratified sandstone with interbedded bioturbated shaly sandstone and mudstone. Large *Diplocraterion* (D) below a large *Asterosoma* (A). Mudstone laminae contain small *Planolites* and *Chondrites* traces. Photograph is from 5-22-65-4W4 (J1-8). Scale bar gradations are in centimetres.



traces. Collectively these observations suggest less stressed, more normal-marine ecological conditions.

The trace fossil assemblage in Facies 3 is typical of the transition from the *Skolithos* to *Cruziana* Ichnofacies, commonly observed in lower to middle shoreface deposits, or in environments with similar salinity and energy conditions (Ekdale *et al.*, 1984; Wightman *et al.*, 1987; Pemberton *et al.*, 1992). The consistent fluctuation of energy is taken to indicate storm and interstorm periods. Symmetrical small-scale cross-stratification in the sandstone suggests that waves were important. These are interpreted as combined-flow ripples formed during storms. Combined-flow plane bed conditions, however, prevailed during storms and deposited planar-laminated sandstone.

The relatively fine-grained, upward-coarsening succession of nearshore-marine sediment in Facies 3 is inferred to represent deposition in a prograding storm-dominated shoreface environment.

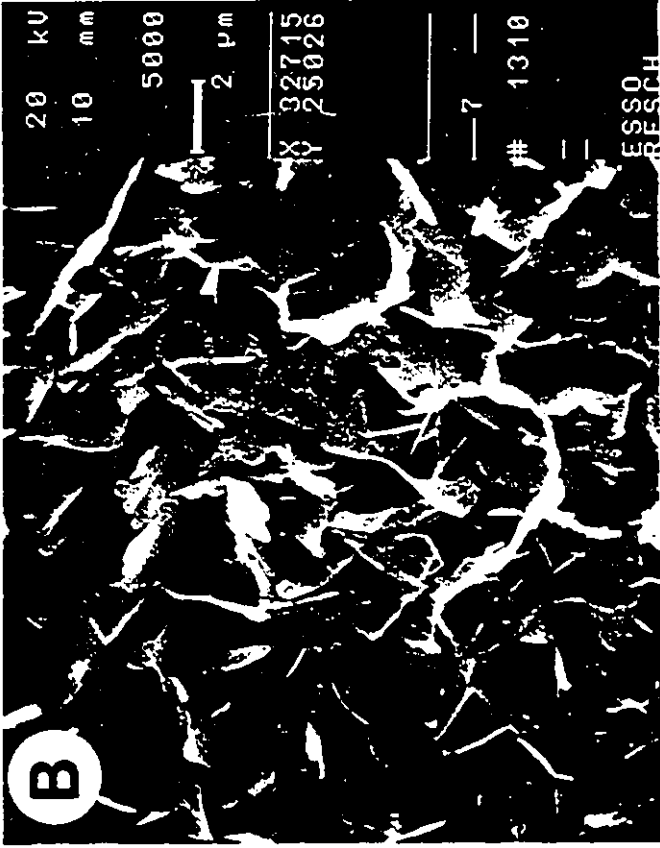
2.2.10 Facies 4: Large scale cross-stratified sandstone

Description:

Facies 4 consists of brown to black, lower fine to lower medium, poorly to well consolidated, and poorly to moderately well-sorted sandstone. Metre-scale trough cross-stratification is the dominant sedimentary structure (Fig. 2.7a) and is intercalated with minor (1 to 10 cm) zones of small-scale asymmetrical cross-stratified sandstone. Beds range from 50 centimetres to 3 metres thick. Mudstone clasts and laminae are common and can make up 10% of the bed in some sections. Regardless of mudstone quantity, however, there is a net decrease in mudstone content stratigraphically upward. A typical metre-scale upward-fining succession begins with large-scale cross-stratification that grades upward to small-scale cross-stratification with interstratified mudstone laminae.

Figure 2.7: Facies 4

- a) Large-scale cross-stratified sandstone. Photograph is from 5-22-65-4W4 (J2-8). Scale bar gradations are in centimetres.
- b) Scanning Electron Microscope photograph (5000 X magnification) of berthierine clay coating the surface of a grain from Facies 4 sandstone. Photograph is from 13-1-65-4W4 (D24-13) at 440.2 m.



The basal contact of each bed is typically sharp or scoured and is commonly overlain by imbricated mudstone clasts. By contrast, the base of the interstratified mudstone laminae are typically conformable.

Facies 4 commonly contains tight intervals which are cemented by chlorite-like clay minerals, such as berthierine (J. Dudley, 1993; personal communication; Fig. 2.7b). Parting along bedding planes and bitumen depletion are common in these zones and, accordingly, physical structures are easily recognized. Dispersed carbonaceous matter, including coal fragments, are common in this facies, but bioturbation is not apparent - except for rare, small *Planolites*-dominated ichnofossils within the mudstone laminae.

Interpretation:

Large-scale trough cross-stratification of Facies 4, as in Subfacies 2c, is related to the migration of three-dimensional subaqueous dunes. Asymmetrical small-scale cross-stratification is related to the migration of current ripples (Harms *et al.*, 1982).

The typical (metre- to several metre-scale) upward-fining succession of large-scale to small-scale cross-stratification interstratified with upward-thickening mudstone laminae indicates an upward decrease of flow energy. Such conditions are common in fluvial systems, particularly associated with lateral point-bar migration (Allen, 1965). The abundance of carbonaceous matter, including coal fragments, is also consistent with a non-marine origin. Carbonaceous matter most likely accumulated in swampy, oxygen-reduced environments of the floodplain (or delta plain). Subsequent erosion associated with lateral point-bar migration or flood episodes incorporated carbonaceous into the channel-fill sand deposits. Facies 4 is therefore interpreted as fluvial point bar deposits.

2.2.11 Facies 5 : Planar-laminated sandstone

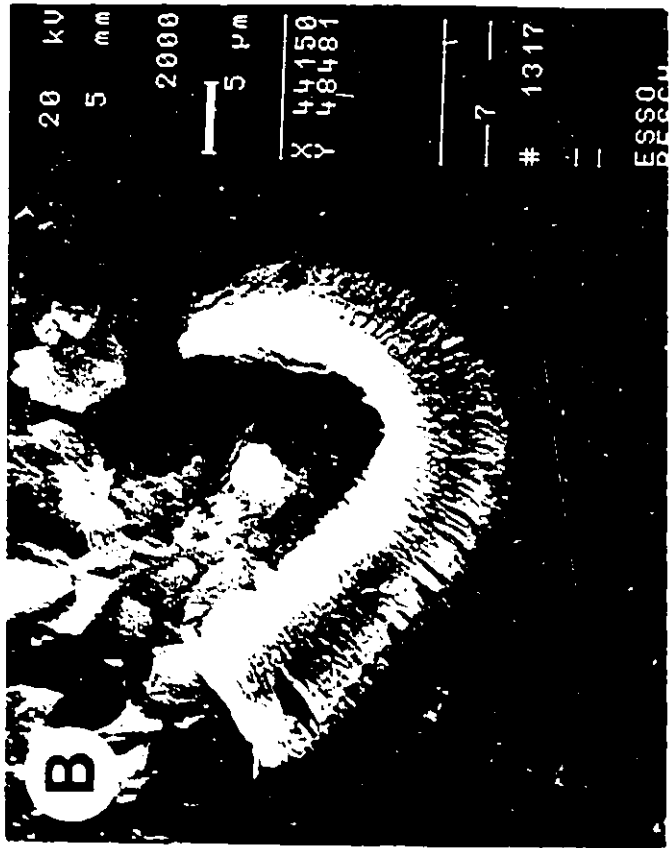
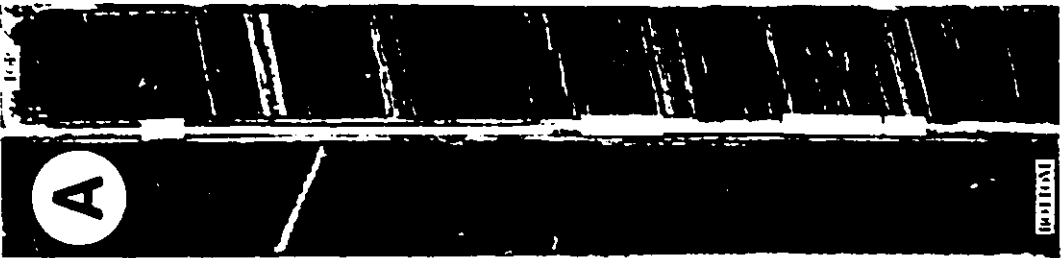
Description:

Facies 5 consists of grey to black, lower fine to lower medium, moderately well consolidated, well-sorted, planar laminated sandstone. Two separate occurrences of Facies 5 have been observed. The first occurs exclusively in the south half of the study area. Here there is no evidence of bioturbation (Fig. 2.8a). Layers of comminuted carbonaceous material, wood fragments, and siderite pellets, typically less than 1 cm but up to 5 cm thick, occur throughout the unit and help to define the planar-lamination. Commonly, asymmetrical small-scale cross-stratification up to 10 cm thick is present between planar-laminated intervals (Fig. 2.8a). The lower contact of Facies 5 is typically sharp to scoured, and beds up to several metres thick are common. In strata below the bitumen-water contact, kaolinite (Fig. 2.8b) is commonly observed. In addition, mudstone laminae and coal fragments occur rarely, and berthierine-cemented zones are common.

The second occurrence of Facies 5 strata occurs stratigraphically higher in the Clearwater Formation. Here the sandstone is fine grained and contains a low abundance of medium to large *Skolithos* burrows (Fig. 2.8c). Beds are typically 20 cm to 1m thick, basal contacts are sharp, and, in contrast to the other occurrence of Facies 5, this sandstone contains little carbonaceous material. Locally, 5 to 15 cm thick beds of low angle large-scale cross-stratified sandstone is interbedded with the planar-laminated sandstone. In deviated cores, however, this type of stratification is difficult to positively identify.

Figure 2.8: Facies 5

- a) Planar laminated sandstone interbedded with asymmetrical small-scale cross-stratified sandstone. Concentrations of carbonaceous material help to define the stratification. The inclination is due to deviation of the well from vertical. Photograph is from 13-1-65-4W4 (D24-13). Scale bar is 10 cm.
- b) Scanning Electron Microscope photograph (2000 X magnification) of vermicular kaolinite from Facies 5 sandstone. Photograph is from 14-22-65-4W4 (H5-13) at 513.6 m.
- c) Planar laminated sandstone with large *Skolithos* burrow. Photo is from 13-1-65-4W4 (D24). Scale bar is 10 cm.



Interpretation:

Planar-laminated, fine to medium sandstone is interpreted to have been deposited under upper-flow-regime plane bed conditions (cf. Harms *et al.*, 1982). The conformable upper contact with small-scale cross-stratification in the first occurrence of Facies 5 indicates deposition under waning flow conditions. The repetitively-stacked successions are inferred to indicate deposition from waning tidal currents on upper-flow-regime sand flats. Broad sand flats are common at the headward end of tide-dominated estuary and delta environments (e.g. Dalrymple *et al.* 1992; Dalrymple, 1992). In such environments, minor coal debris and carbonaceous material are included as part of the flow from the hinterland and deposited with the sand. The lack of ichnofossils is most likely related to high energy and brackish (high-stress) environmental conditions at the time of deposition.

The second occurrence of Facies 5 contains medium to large vertical burrows indicative of high-energy marine conditions (Ekdale *et al.*, 1984; Wightman *et al.*, 1987; Pemberton *et al.* 1992). Such upper-flow-regime conditions are common in foreshore environments where waves swash up and then backwash down the shore. The shallow high-speed backwash commonly creates upper-flow-regime depositional conditions (Clifton, 1969; Clifton *et al.*, 1971). The planar-laminated sandstone is therefore interpreted as upper-flow-regime plane beds deposited on the foreshore. In addition, the large-scale, low angle cross-stratified sandstone is interpreted to represent deposition of asymmetrical dunes in the surf zone. Low angle, large-scale structures are commonly produced as ocean waves break against the shore (Clifton *et al.*, 1971). The association of planar-laminated sandstone with vertical burrows and low angle cross-stratification in the second occurrence of Facies 5 is therefore interpreted to represent foreshore deposition.

2.2.12 Facies 6 : Small scale cross-stratified sandstone

Description:

Tan to black, lower to upper fine, moderately well consolidated, moderately well-sorted, small-scale cross-stratified sandstone with minor upward-thinning mudstone laminae characterizes Facies 6 (Fig. 2.9a). Symmetrical small-scale cross-stratification is the predominant sedimentary structure although rare slightly asymmetrical cross-stratification also occurs. In sandstone beds, bioturbation is moderate to rare and dominated by medium-scale *Skolithos* burrows. The minor dark grey mudstone veneers are sub-horizontal and contain small *Planolites* and *Chondrites* ichnofossils. Beds are typically 10 to 30 cm thick, with sharp basal contacts commonly defined by the occurrence of a mudstone lamina. Bedding dips are sub-horizontal to low angle (5° maximum). Carbonaceous layers up to 3 cm thick are present locally.

Interpretation:

Small-scale trough cross-stratification is interpreted to be formed by oscillatory ripples (Harms *et al.*, 1982). The less common asymmetrical cross-stratified sandstone units are interpreted as asymmetrical wave ripples deposited by shoaling waves. The interbedded mudstone laminae represent periodic fluctuations or reductions in flow velocity; during periods of lower flow energy, mud is deposited from suspension. These flow fluctuations may be related to episodic storm or flood activity.

Irregularity of the mudstone interbeds argues against a tidal origin, instead seasonal events are more likely. The paucity of bioturbation and restriction to *Skolithos* in the sandstone is most likely related to high energy conditions (eliminating horizontal trace makers) or restricted salinity conditions. Facies 6 is therefore interpreted to represent deposition in a restricted bay environment.

2.2.13 Facies 7: Massive (structureless) sandstone

Description:

Facies 7 consists of grey to black, upper fine to upper medium, moderate to poorly consolidated, poorly sorted, massive sandstone (Fig. 2.9b; the term massive implies a lack of recognizable physical sedimentary structures). In addition these strata are devoid of biogenic structures. Rarely, intraclasts of mudstone and sideritized mudstone, similar to those of Subfacies 2c, make up to 80% of the bed, but more typically they are absent. Unlike Subfacies 2c, however, clasts show no preferred orientation and intraclast size varies little within individual beds. In addition, intraclasts are typically elongate, angular and a few millimetres to several centimetres in length. Similarly, grain size varies only slightly within beds, although mudstone intraclasts and coarser grained material are commonly concentrated along the typically sharp or scoured basal contacts.

Although no recognizable physical or biogenic sedimentary structures are present in the sandstone, low density, and low diversity ichnofossils, dominated by *Planolites*, occur in some of the mudstone clasts.

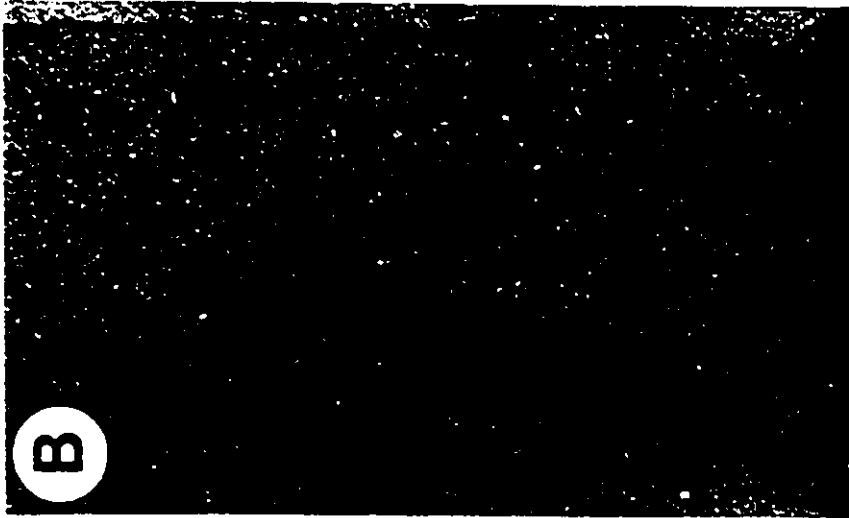
Interpretation:

The origin of massive bedding is poorly understood. Assuming that bitumen saturation has not completely masked all sedimentary structures, processes interpreted to create massive bedding include: liquefaction, reworking by biological activity, or rapid deposition from suspension with limited subsequent traction transport prior to deposition (e.g. Collinson and Thompson, 1982; Ekdale *et al.*, 1984; Arnott and Hand, 1989). Liquefaction is a process whereby granular material is temporarily suspended by the drag of an upward-flowing pore fluid. Such events disturb grain fabric and a massive texture

Figure 2.9: Facies 6 and 7

a) **Facies 6: Small-scale cross-stratified, gas-saturated sandstone overlying bitumen-saturated planar laminated sandstone. Photo is from 13-1-65-4W4 (D24-13). Scale bar is 10 cm.**

b) **Facies 7: Massive sandstone. Photo is from (P7-13). Scale bar gradations are in centimetres.**



typically results (Collinson and Thompson, 1982; Allen, 1984). Shock from seismic activity, increased pore fluid pressure related to a rise in water level, cyclic load associated with storm waves, and rapid sedimentation are common causes of liquefaction. Because of low effective permeability and high porosities, very fine-grained, argillaceous sediments are particularly susceptible to liquefaction. Because of higher permeability, liquefaction is rare in sandstones, however. Moreover, the remobilization of sediment by this process should produce common fluid escape structures. These structures are not present in strata of Facies 7. In conclusion, therefore, the lack of dewatering structures and the coarseness of the sediment precludes an origin related to liquefaction. In addition, the lack of burrows precludes an origin related to extensive infaunal activity.

Rapid deposition from suspension with limited subsequent traction transport can create a massive primary texture. Arnott and Hand (1989) have shown experimentally that under upper-flow-regime plane bed conditions, stratification can become increasingly diffuse as sediment rate, and similarly bed aggradation rate, increases. Furthermore, when sediment aggradation rates are sufficiently high, mud clasts would most likely be buried rapidly, thereby preserving their angularity. Massive sandstones of Facies 7 are therefore interpreted as having been deposited rapidly from suspension under upper-flow-regime conditions.

2.2.14 Facies 8: Laminated Mudstone

Facies 8 consists of laminated mudstone and has been subdivided into two subfacies based on colour, sedimentary structures, and type of bioturbation.

2.2.15 Subfacies 8a: Grey laminated and lenticular mudstone

Description:

Subfacies 8a consists of medium grey mudstone interstratified with light grey siltstone to very fine sandstone (Fig. 2.10a). It occurs stratigraphically above all previously described facies and attains a total thickness of 2m. The mudstone is thinly laminated, whereas coarser-grained layers typically exhibit symmetrical, small-scale cross-stratification and occur as lenses rarely thicker than 1 cm. Low to moderate bioturbation is confined to the mudstone layers and consists of low diversity, low density ichnofossils dominated by *Planolites* and *Chondrites*. The basal contact of Subfacies 8a is typically sharp, planar, or scoured.

Micropaleontological analysis of three separate samples from Subfacies 8a showed a particulate organic matter (POM) distribution consistent with mud deposited on a proximal marine shelf (relatively well sorted and abundant biodegraded tissue) near or just below wave base, and with some terrestrial input from a swampy or treed hinterland (based on the occurrence of pollen and fungal spores; J. Jansonius, 1993, personal communication; Appendix C).

Interpretation:

The fine-grained laminated mudstone of Subfacies 8a reflects quiet-water suspension deposition in a low-energy environment, below fair-weather wave base. Shelf mudstone deposits commonly contain thin sandstone interbeds deposited in response to periodic storms (Walker and Plint, 1992). Interstratified wave-rippled sandstone and siltstone of Subfacies 8a are similarly interpreted. The mudstone was deposited both by suspension settling of fine material originated from rivers, and fines suspended during storms. The biogenic structures are low in diversity and abundance, and indicate stressed

Figure 2.10: Facies 8

- a) **Subfacies 8a: Grey mudstone with interstratified siltstone lenses. Trace fossils include *Planolites* (P) and *Chondrites* (C). The inclination is due to deviation of the well bore from vertical. Photo is from 4-23-65-4W4 (R2-13). Scale bar gradations are in centimetres.**

- b) **Subfacies 8b: Dark grey mudstone. *Helminthopsis* traces (H) are common. The inclination is due to deviation of the well bore from vertical. Photo is from 4-23-65-4W4 (R2-13). Scale bar gradations are in centimetres**

environmental conditions possibly related to reduced salinity. Although *Planolites* and *Chondrites* are not indicative of any particular environment (Pemberton *et al.* 1992) they are common forms of the *Cruziana* ichnofacies (Ekdale *et al.*, 1984; Wightman *et al.*, 1987; Pemberton *et al.*, 1992). This ichnofacies is characteristic of quiet water mud deposition and if in a shallow shelf setting may be associated with interstratified storm beds similar to that observed in Subfacies 8a.

The paleontologic data, considered together with the physical and biogenic structures, suggest that Subfacies 8a was deposited in a storm-influenced, stressed proximal shelf setting below fair weather wave base.

2.2.16 Subfacies 8b: Dark grey parallel-laminated mudstone

Description:

Subfacies 8b consists of parallel-laminated dark grey mudstone with little or no interstratified siltstone (Fig. 2.10b). This subfacies is up to 1m thick and is characterized by a moderately abundant trace fossil suite dominated by small-scale *Helminthopsis* burrows. The basal contact is sharp or planar, and always overlies mudstone of Subfacies 8a. The upper bounding contact is typically sharp and overlain by sandstone or muddy sandstone of the Grand Rapids Formation.

Interpretation:

The dark grey mudstone of Subfacies 8a is attributed to quiet-water deposition on a deep, distal, oxygen-depleted marine shelf. This interpretation is based on the following arguments. Firstly, the dominant mode of deposition is settling from suspension. Secondly, the low abundance of coarse interbeds indicates a distal offshore setting below storm wave base. The dark grey coloration is most likely the result of abundant organic material, suggesting limited oxidation after deposition. And finally, trace fossils of

Subfacies 8b belong to the *Zoophycos* ichnofacies. This ichnofacies has been interpreted as having a broad paleobathymetric range, but occurs most commonly in distal, quiet-water marine successions (Ekdale *et al.*, 1984; Wightman *et al.*, 1987; Pemberton *et al.*, 1992).

3. FACIES ASSOCIATIONS

3.1 Introduction

The facies and subfacies described in Chapter 2 have been grouped into six recurring facies associations. Facies associations are distinct successions of facies which are genetically related to one another, and together have some environmental significance (Collinson, 1969). Grouping facies into facies associations therefore allows each to be considered in context with others.

3.2 Facies Associations









Six facies associations were identified in strata of the Clearwater Formation at Cold Lake. Each is described and interpreted below; refer to Figure 3.1 for the key to symbols used in the schematic diagrams.

3.2.1 Facies Association 1 (*tidal bars*)







Description:

Facies Association 1 (Fig. 3.2) is sharply based and unconformably overlies strata of the McMurray Formation or Wabiskaw Member of the Clearwater Formation. It comprises two interstratified facies consisting of interbedded sandstone and mudstone within a generally upward-coarsening succession. The first is up to 10m thick and contains lower to upper fine, planar-laminated and small-scale cross-stratified sandstone interstratified with upward-thinning beds and laminae of sub-horizontal ($<5^\circ$ dip) mudstone (Subfacies 2a). The second facies, interstratified with the first, is commonly up to 1m thick, and consists of large- and small-scale cross-stratified, lower to upper fine sandstone interstratified with inclined mudstone beds ($>5^\circ$), laminae (Subfacies 2b), and minor mudstone clasts. Bidirectional cross-stratification and flaser bedding are common










SEDIMENTARY STRUCTURES

-  Current ripple
-  Wave ripple
-  Planar-lamination
-  Large-scale, trough cross-stratification
-  Large-scale, high-angle cross-stratification
-  Flaser bedding
-  Lenticular bedding
-  Bidirectional cross-stratification

LITHOLOGICAL ACCESSORIES

-  Rip-up clasts
-  Coal fragments
-  Wood particles
-  Comminuted siderite and carbonaceous material
-  Glauconite
-  Pebble lag

ICHNOFOSSILS

-  *Planolites*
-  *Tetchichnus*
-  *Asterosoma*
-  *Skolithos*
-  *Rhizocorallium*
-  *Zoophycos*
-  *Diplocraterion*
-  *Helminthopsis*
-  *Chondrites*


-  Erosive contact

Figure 3.1: Legend of symbols used in facies association diagrams.

Figure 3.2: Facies Association 1

- a) Planar laminated to small-scale cross-stratified sandstone interstratified with mudstone beds, lamellae and clasts. Photo is from 12-24-65-4W4 (Q6-8). Scale bar is 10 centimetres long.



in sandstone beds of both facies. In sandstone-dominated parts of this facies association, repetitive successions of planar-laminated or large-scale cross-stratified sandstone are gradationally overlain by small-scale cross-stratified sandstone. These occur in packages ranging from a few to tens of centimetres thick, with mudstone laminae commonly intercalated with small-scale cross-stratified sandstone or at upper bed contacts. In mudstone-dominated successions, parallel-laminated mudstone typically contains thin (<1cm) upward-thickening lenses and beds of small-scale, cross-stratified sandstone. Bioturbation is low to moderate and consists of medium- and large-sized burrows dominated by *Planolites*, *Thalassinoides*, and *Teichichnus*.

Interpretation:

The upward-coarsening succession of Facies Association 1 is inferred to represent a tidal bar deposit (Fig. 3.3). Tidal bar deposits typically occur as elongate ridges in subaqueous parts of tide-dominated deltas and estuaries (Meckel, 1975; Wright *et al.*, 1975; Coleman and Wright, 1975; Dalrymple *et al.*, 1990). Bars grow by lateral accretion and progradation, and depending on sea level history and depositional setting, show upward-coarsening or upward-fining trends. These tidal bars are typically composed of planar-laminated (Meckel, 1975) or large-scale cross-stratified sandstone produced by migrating subaqueous dunes of various sizes (Houbolt, 1968; Dalrymple *et al.*, 1990) and are separated by ebb- and flood-dominant channels. In addition, they are typically 15-20 m high, spaced up to 30 km apart, and have lengths of 10-120 km (Houbolt, 1968; Meckel, 1975; Swift, 1975; Dalrymple, 1992).

Regular interbedding of sandstone and mudstone in Facies Association 1 is most likely the result of regular fluctuations of flow velocity related to tides. The occurrence of flaser bedding, bidirectional cross-stratification, and current ripples support the tidal interpretation (Nio and Yang, 1991). The repetitive change from upper-flow-regime plane

FACIES ASSOCIATION 1: TIDAL BAR

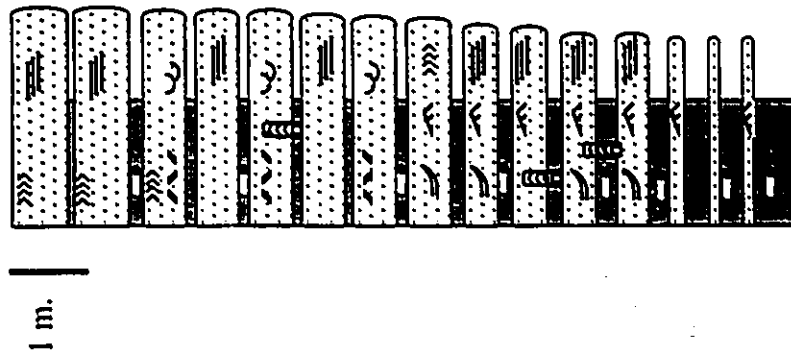


Figure 3.3: Schematic representation of the upward-coarsening succession in Facies Association 1. Refer to the legend (Fig. 3.1) for an explanation of symbols.

bed to lower-flow-regime current ripples throughout Facies Association 1 is related to waning flow during one half of the tidal cycle (most likely the dominant tidal current). The large-scale cross-stratified sandstone and associated inclined mudstone beds up to 1m thick are deposited by the migration of small tidal channels or tidal creeks above and lateral to the tidal bars (cf. Alexander *et al.*, 1991; Dalrymple *et al.*, 1991). The interbedded, small, angular, mudstone clasts originally were partially lithified mud layers in the tidal bar, but were subsequently mobilized and fragmented by tidal currents and incorporated as part of tidal creek deposits.

At river mouths (deltas and estuaries), fresh and marine waters mix to create a stressed, brackish-water environment (Ekdale *et al.*, 1984). The assemblage of *Planolites*, *Teichichnus*, and *Thalassinoides* traces in Facies Association 1 is typical of brackish water conditions, and therefore supports the interpretation of a deltaic or estuarine environment of deposition.

3.2.2 Facies Association 2 (sand flats)

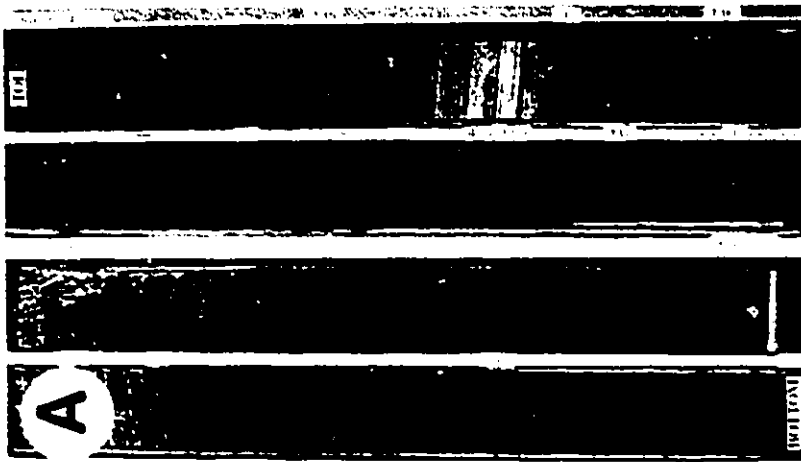
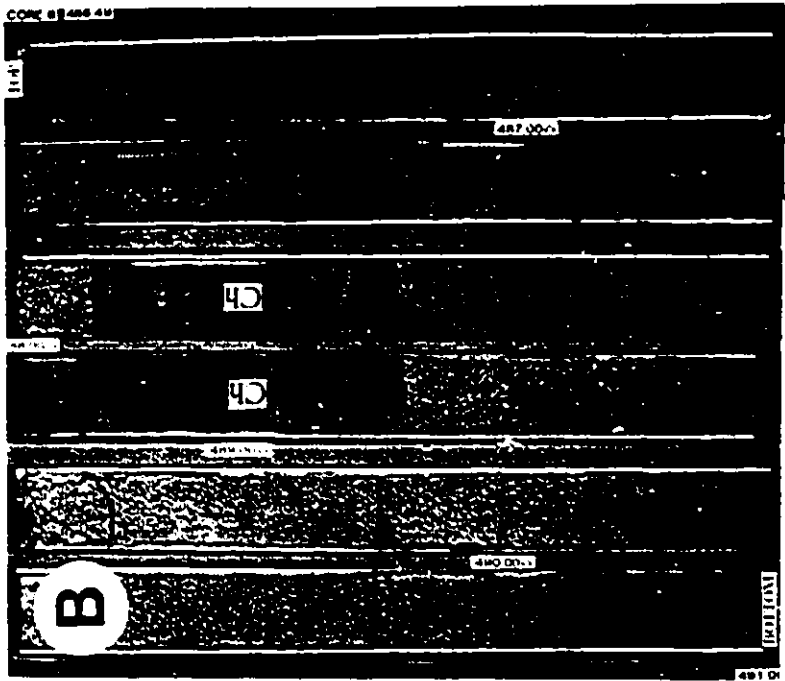
Description:

Facies Association 2 is restricted to the southern half of the study area, and unconformably overlies the McMurray Formation or, where present, the Wabiskaw Member of the Clearwater Formation. In addition, it commonly conformably overlies tidal bars of Facies Association 1. Facies Association 2 varies in thickness from 8 to 30m and consists predominantly of upper fine to lower medium planar-laminated (Facies 5) and massive (Facies 7) sandstone with abundant carbonaceous debris, minor coal fragments, and rare mudstone interbeds (Fig. 3.4). These occur within a subtle upward-coarsening trend and are commonly interbedded with upward-fining, lower medium, large-scale cross-stratified sandstone (Facies 4). Basal contacts of Facies Association 2 and internal facies contacts are typically sharp or erosive.

Figure 3.4: Facies Association 2

- a) Bitumen-saturated planar-laminated sandstone. Lighter coloured zones are bitumen depleted. Photo is from 5-3-65-4W4 (J43-8). Scale bar is 10 cm.

- b) Water-saturated, planar-laminated and large-scale cross-stratified (Ch) sandstone. Large-scale cross-stratified intervals are rich in coal and carbonaceous material. Photo is from 6-35-64-4W4 (D55-13). Scale bar is 10 cm.



Thin laminae or beds of comminuted carbonaceous material and siderite pellets are common in the planar laminated sandstone, as are 5-15cm interbeds of small-scale asymmetrical cross-stratified sandstone. The upward-fining units are rarely thicker than 2m, and typically contain abundant coal and wood fragments in addition to minor mudstone laminae and beds. Mudstone interbeds commonly contain a low diversity of small *Planolites*-dominated ichnofossils.

Interpretation:

The subtle upward-coarsening succession dominated by planar-laminated sandstone is interpreted as an upper-flow-regime sand flat deposit (Fig. 3.5). The proximal region of tide-dominated deltas and estuaries are characterized by broad sand flats cut by small distributary channels (e.g. Dalrymple *et al.*, 1990). Here, because of reduced cross-sectional area and consequent tidal amplification, upper-flow-regime plane bed conditions dominate and deposit planar-laminated sandstone (Nichols and Briggs, 1985; Dalrymple *et al.*, 1992). In the Cobequid Bay-Salmon River estuary, sand flats occur as 0-3m sets of planar-laminated sand interstratified with 10-30mm sets of cbb tide current ripples. The sand flats are up to 9.5m high and are cut by numerous minor distributary channels that locally exhibit a braided pattern (Dalrymple *et al.*, 1990).

The planar-laminated sandstone with minor thin sets of current ripples of Facies Association 2 are, therefore, interpreted as tidal sand flats. Furthermore, the upward-fining, large-scale cross-stratified units are interpreted as distributary channel-fill deposits. Locally, these distributary channels have cut through the sand flats, resulting in large-scale cross-stratified sandstone up to 2m thick containing abundant wood fragments, coal, and other carbonaceous material.

Finally, the consistent spatial distribution of Facies Association 2 in a number of progradational successions (see Chapter 4) supports a proximal tide-dominated deltaic or

FACIES ASSOCIATION 2: UFR SAND FLAT

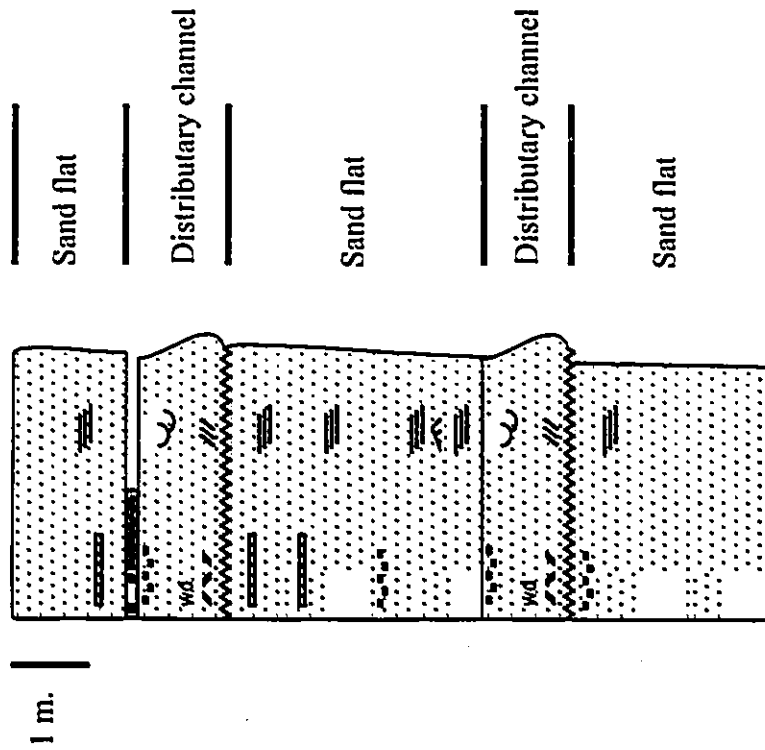


Figure 3.5: Schematic representation of the upward-coarsening succession in Facies Association 2. Refer to the legend (Fig. 3.1) for an explanation of symbols.

estuarine sand flat interpretation. In addition, the low-diversity, small size, and low abundance of trace fossils indicates stressed conditions similar to those in low-salinity deltaic or estuarine environments (Ekdale *et al.*, 1984; Wightman *et al.*, 1987).

3.2.3 Facies Association 3 (tidal-fluvial channel)

Description:

Facies Association 3 erosively overlies strata of facies associations 1 and 2 and comprises two interstratified subfacies of Facies 2 (see Chapter 2). Upper fine to lower medium, large-scale cross-stratified sandstone interbedded with inclined mudstone clasts (Subfacies 2c) occurs interstratified with upper fine to lower medium, large-scale cross-stratified sandstone interbedded with dipping, upward-thickening mudstone laminae and beds (Subfacies 2b). Together these two units make up a series of vertically-stacked, upward-fining successions that range from 0.5 to 5m thick (Fig. 3.6). Although mudstone abundance increases upward in each succession, there is an overall upward decrease in mudstone in Facies Association 3. The total thickness is variable and ranges from 20 centimetres up to 30m.

The base of each upward-fining succession is sharp and contains a concentration of oriented armoured mudstone clasts overlain by mudstone clast-rich sandstone. This then grades upward into sandstone interbedded with inclined, upward-thickening mudstone laminae and beds. In addition, small-scale asymmetrical cross-stratification and flaser bedding occurs in the sandstone where associated with mudstone laminae. Trace fossils occur only in mudstone beds, laminae, and clasts and include a restricted assemblage of *Planolites*, *Thalassinoides*, and *Teichichnus*. In the mudstone clasts, traces are not preferentially oriented.

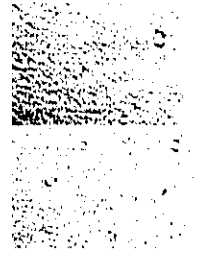


Figure 3.6: Facies Association 3

- a) Planar laminated, large-scale, and small-scale cross-stratified sandstone interstratified with mudstone beds, lamellae, and rip-up clasts. Photo is from 3-9-66-4W4. Scale bar is 10 cm.



Interpretation:

Facies Association 3 is interpreted as a stacked succession of meandering tidally-influenced channel deposits (Fig. 3.7). Upward-fining, large-scale cross-stratified sandstone interbedded regularly with inclined mudstone beds, termed inclined heterolithic stratification by Thomas *et al.* (1987), is commonly observed in ancient and modern tidal point-bar deposits (MacEachern, 1989; Smith, 1989; Rahmani, 1989; Allen, 1991; Nio and Yang, 1991). Current ripple cross-stratification, mudstone flasers, and a lack of overbank deposits are also common features (Allen, 1991). Although not reported elsewhere, abundant mudstone clasts occur in tidal-fluvial point bars of the tide-dominated Colorado River delta (Meckel, 1975).

As channel point bars migrate laterally, sharp-based upward-fining successions are deposited due to the reduction in flow velocity as depth decreases (Allen, 1970). In tidal settings the slack-water periods between ebb and flood tidal currents allow mud to settle out from suspension (see section 1.5). This mud is deposited on the inclined surface of the point bar and is subsequently covered by sand, and therefore is commonly preserved when the tidal current reverses. Thus, the sharp-based successions of inclined heterolithic stratification in Facies Association 3 are interpreted as tidal-fluvial point bar deposits. Mudstone clasts of Facies Association 3 were most likely eroded from partially lithified (and bioturbated) mud deposited on the upper point-bar surface, or as a result of cut-bank erosion. Because flow strength decreases upward along lateral accretion surfaces (Allen, 1970), large mudstone clasts were transported and deposited on the lower parts of each upward-fining point-bar successions. The fact that many of the larger clasts are armored with sand (Chapter 2) indicates moderate transport prior to deposition.

FACIES ASSOCIATION 3: TIDAL-FLUVIAL CHANNEL-FILL

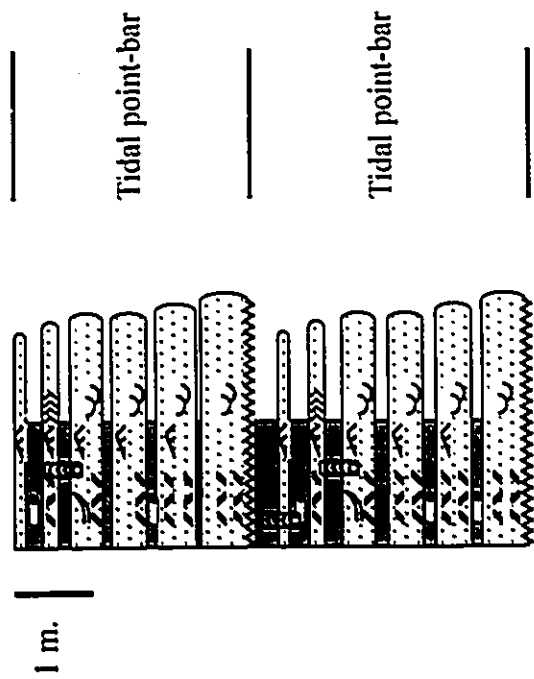


Figure 3.7: Schematic representation of the upward-fining successions in Facies Association 3. Refer to the legend (Fig. 3.1) for an explanation of symbols.

The restricted trace fossil assemblage in the mudstone suggests brackish-water conditions (Ekdale *et al.*, 1984; Wightman *et al.*, 1987; Pemberton *et al.*, 1992), providing support for the interpretation.

3.2.4 Facies Association 4 (fluvial channel)

Description:

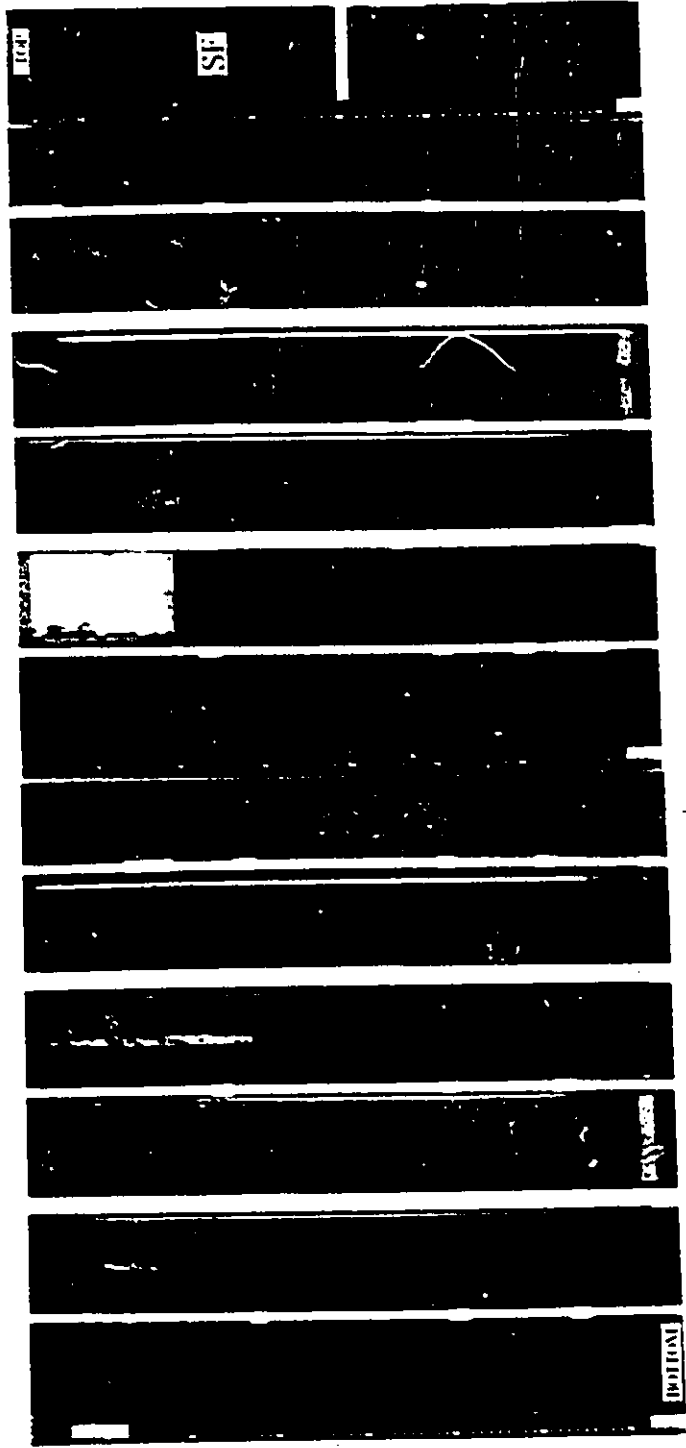
Facies Association 4 (Fig. 3.8) typically consists of sharp based, upward-fining successions of sandstone and mudstone that sharply overlie tidal channel-fill deposits of Facies Association 3. Although thickness varies, ranging from 5 to 30m, three consistent elements make up Facies Association 4. These are a lower upward-fining, large-scale cross-stratified sandstone dominated unit (Facies 4), a middle upward-fining, planar-laminated and small-scale cross-stratified sandstone and mudstone unit (Subfacies 2a), and an upper, homogeneous massive sandstone (Facies 7). Commonly these units occur as stacked successions up to 30 metres thick. Only a portion of the idealized succession is present in some cores.

The base of Facies Association 4 typically consists of a concentration of coarse-grained sandstone, and mudstone clasts and/or siderite clasts, in places aligned parallel to bedding. Medium sandstone with common mudstone and siderite clasts, wood fragments, coal, and carbonaceous debris of the lower unit is gradationally overlain by upward-fining beds of, medium to fine, planar-laminated and small-scale cross-stratified sandstone with interstratified mudstone beds and laminae. The mudstone layers typically become thicker and more abundant upwards. Although the lower large-scale cross-stratified unit is devoid of ichnofossils, in some cores mudstone drapes and layers of the middle unit contain an impoverished assemblage of small *Planolites* burrows. A massive, fine- to medium-grained sandstone unit lacking physical or biogenic sedimentary structures commonly overlies the upward-fining succession sharply. It is important

Figure 3.8: Facies Association 4

- a) Large-scale cross-stratified sandstone overlain by massive sandstone. These are abruptly overlain by shoreface deposits (SF) of Facies Association 5. Photo is from 4-23-65-4W4 (R2-13).





LCP

SF

100-1000

100-1000

100-1000

BOTTOM

to note that the difference between the upward-fining deposits of Facies Associations 3 and 4 is based primarily on the abundance of mudstone (being common in Facies Association 4 and abundant in Facies Association 3) and the lack of massive sandstone deposits in Facies Association 3.

Interpretation:

The upward-fining, sharp-based successions of sandstone and mudstone that characterize Facies Association 4 are interpreted as fluvial channel-fill deposits (Fig. 3.9). The overall upward-fining trend represents the progressive decrease in flow depth and velocity associated with the lateral migration of a meandering river channel. This produces a succession characterized by upward decreases in grain size and scale of cross-stratification (Allen, 1970). A fluvial point-bar succession typically contains a basal lag of coarse-grained sediment overlain successively by large-scale trough cross-stratified sands, current-rippled sands and mud, and finally muddy floodplain deposits (Collinson, 1986; Allen, 1965). Mudstone clasts and coarse sandstone at the base of Facies Association 4 are therefore interpreted as channel lag deposits. The lower, large-scale cross-stratified sandstone unit represents deposition by subaqueous dunes on the lower part of the point bar. Interbedded sandstone and mudstone gradationally overlying the lower point-bar deposits represents deposition on the upper point bar.

During seasonal flooding the channel banks are overtopped, and commonly breached by crevasse splay channels (Gallaway and Hobday, 1983; Collinson, 1986). Subsequently, because of rapid flow expansion, fluid competence and capacity quickly decreases, causing rapid deposition of coarse sediment adjacent to the main channel. Rapid sedimentation, as discussed in Chapter 2, is one mechanism that deposits massive sandstone. The massive sandstone commonly capping Facies Association 3 is therefore inferred to represent proximal floodplain deposits. The lack of mud-dominated

FACIES ASSOCIATION 4: FLUVIAL CHANNEL-FILL

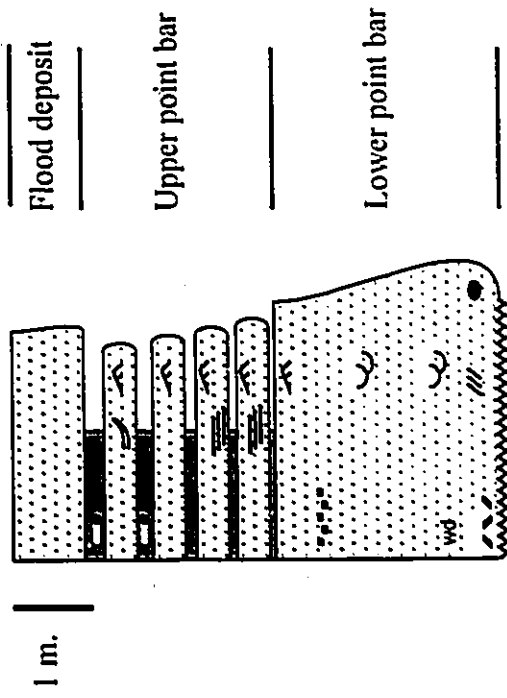


Figure 3.9: Schematic representation of the upward-fining succession in Facies Association 4. Refer to the legend (Fig. 3.1) for an explanation of symbols.

deposits at the top of the fluvial succession is related to the low abundance of fine sediment available for deposition, and to subsequent erosion by channels.

3.2.4 Facies Association 5 (shoreface to foreshore)

Description:

Facies Association 5 (Fig. 3.10), which is up to 25m thick, comprises an upward-coarsening succession of four lithofacies: bioturbated shaly sandstone (Facies 3) or bioturbated glauconitic sandstone (Facies 1), small-scale cross-stratified sandstone (Facies 6), and planar-laminated sandstone (Facies 5). Generally, only part of this idealized succession is observed. Typically, Facies Association 5 sharply overlies tidal bar, sand flat, tidal-fluvial, and fluvial channel-fill facies associations as well as other Facies Association 5 successions. The typical upward-coarsening succession can be subdivided into lower, middle, and upper units. The lowermost unit consists of moderate to intensely bioturbated shaly sandstone or glauconitic sandstone interstratified with upward-thickening, planar-laminated sandstone and small-scale symmetrically rippled sandstone showing low to moderate bioturbation (Facies 1 or 3). Trace fossils in this lower unit include *Teichichmus*, *Asterosoma*, *Rhizocorallium*, *Ophiomorpha*, and *Planolites*, but *Diplocraterion* and *Skolithos* traces become increasingly common upward. In addition, rare mudstone interbeds contain small *Planolites* and *Chondrites* ichnofossils.

The lower unit is gradationally overlain by moderately bioturbated beds of small-scale symmetrically cross-stratified sandstone with minor mudstone intercalations (Facies 6). In this middle unit, moderate to abundant, medium- and large-scale traces dominated by *Skolithos* occur in sandstone strata, whereas intercalated mudstones exhibit a moderately abundant assemblage of small *Chondrites* and *Planolites* traces. The middle

Figure 3.10: Facies Association 5

- a) Upward-coarsening succession of sandstone interbedded with bioturbated shaly sandstone and mudstone. Facies Association 5 overlies sandstone of Facies Association 4 (FA4). Inclination of bedding is due to deviation of the well bore. Photograph is from 5-22-65-4W4 (J1-8). Scale bar is 10 cm.



unit is overlain by weakly bioturbated, planar-laminated sandstone (Facies 5) and minor low-angle, large-scale cross-stratified sandstone. Trace fossils in this upper unit are dominated by large *Skolithos* burrows. In the north part of the study area, bioturbated shaly sandstone of the lower part of Facies Association 5 is more common, whereas planar-laminated sandstone of the upper part of Facies Association 5 is more common to the south.

Interpretation:

Facies Association 5 is interpreted as a northward prograding, low-energy shoreface to foreshore deposit (Fig. 3.11). The lower unit of intensely bioturbated shaly sandstone and interbedded planar-laminated sandstone/bioturbated mudstone reflects deposition on the lower to middle shoreface. The predominance of horizontal trace fossils (*Cruziana* to *Skolithos* ichnofacies) supports this conclusion (Ekdale *et al.*, 1984; Wightman *et al.*, 1987). Less common vertical trace fossil suites were formed by opportunistic organisms that colonized the sea floor after storms. The middle sandstone unit represents upper shoreface deposition where oscillatory waves created small-scale symmetrical ripples (Clifton *et al.*, 1971; Clifton, 1976). In contrast to the lower shoreface, energy conditions on the upper shoreface are such that tracemakers of the *Skolithos* ichnofacies predominate, although horizontal traces are still common (Ekdale *et al.*, 1984).

Finally, planar laminated sandstone that caps the succession is inferred to represent foreshore deposition. Planar lamination is related to shallow-water, high-energy swash-backwash processes that typify the foreshore (Clifton, 1969; Clifton *et al.*, 1971). Furthermore, the predominance of vertical *Skolithos* shafts suggests a high-energy depositional environment, such as the foreshore, in which suspension feeding behavior was favored (Ekdale *et al.*, 1984).

FACIES ASSOCIATION 5: SHOREFACE TO FORESHORE

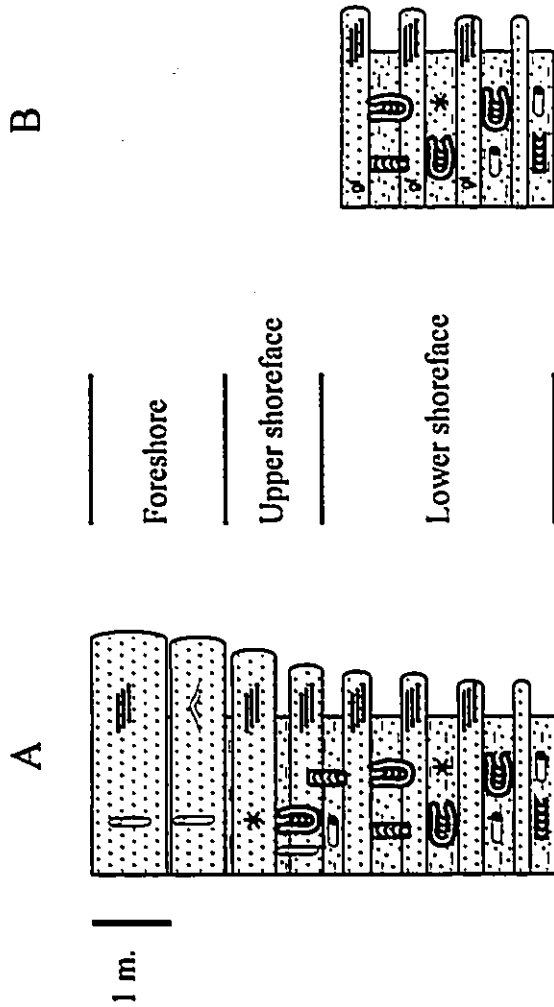


Figure 3.11: Schematic representation of the upward-coarsening succession in Facies Association 5. Succession A is the usual case; succession B is typical of the Wabiskaw Member. Refer to the legend (Fig. 3.1) for an explanation of the symbols.

3.2.6 Facies Association 6 (offshore)

Description:

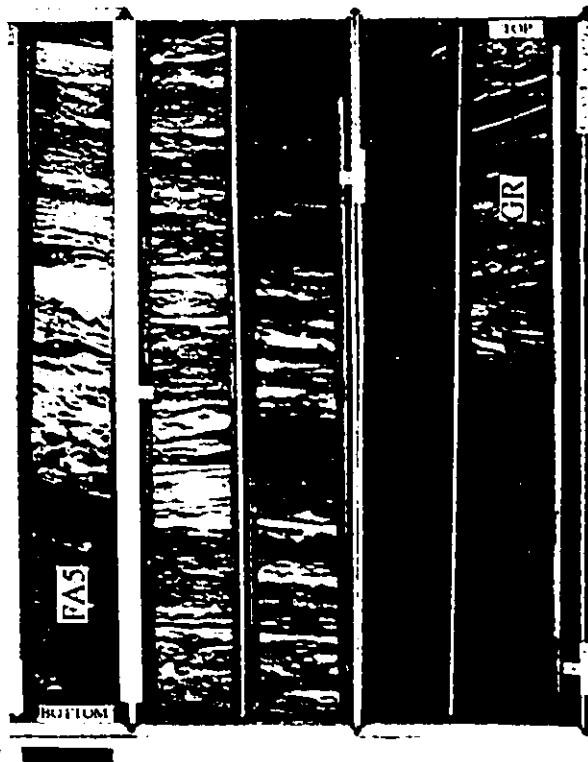
Sharp or erosively based, parallel-laminated beds of grey mudstone intercalated with lenses of symmetrically rippled siltstone (Subfacies 8a) sharply overlain by dark grey parallel-laminated mudstone (Subfacies 8b), collectively make up Facies Association 6 (Fig. 3.12). The basal contact of Facies Association 6, a regionally extensive and easily recognizable marker, was used as the stratigraphic datum for the cross-sections in Appendix 2. This Facies Association overlies strata of facies associations 2, 3, 4, and 5 in the study area. The lower mudstone unit is typically 2 m thick, and contains abundant small *Planolites* and *Chondrites* trace fossils. The upper mudstone is moderately bioturbated, primarily by *Helminthopsis* burrows, and is commonly 1 m thick. This facies association is sharply overlain by bioturbated sandstone and mudstone of the Grand Rapids Formation.

Interpretation:

Mudstones of Facies Association 6 are interpreted as offshore mud deposits (Fig. 3.13) in which parallel-laminated mudstone with *Planolites* and *Chondrites* burrows represents quiet-water suspension deposition of mud below fair-weather wave base (cf. Pryor, 1975; Pickering *et al.*, 1988). Interbeds of wave rippled siltstone are most likely storm deposits (cf. Walker and Flint, 1992). The lower unit of grey mudstone and siltstone probably was deposited on the shallow shelf, where periodic storms supplied coarser grained sediment at frequent intervals. The upper, dark grey mudstone is inferred to have been deposited in deeper, oxygen-depleted water of the distal shelf that supported an impoverished assemblage of grazing *Helminthopsis* tracemakers (cf. Ekdale *et al.*, 1984; Pickering *et al.*, 1988).

Figure 3.12: Facies Association 6

- a) Grey mudstone interstratified with siltstone lenses (Subfacies 8a) overlain by dark grey mudstone with rare siltstone lamellae (Subfacies 8b). Facies Association 6 here overlies Facies Association 5 (FA5), and is overlain by interbedded sandstone and mudstone of the Grand Rapids Formation (GR). Photograph is from 5-22-65-4W4 (J1-8). Scale bar is 10 cm.



FACIES ASSOCIATION 6: OFFSHORE

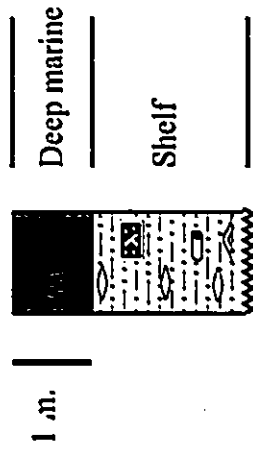


Figure 3.13: Schematic representation of the succession in Facies Association 6. Refer to the legend (Fig. 3.1) for an explanation of symbols.

Regional correlations suggest that this marine unit represents a major transgression of the Clearwater (Boreal) Sea from the north that terminated deposition of the Clearwater Formation (Smith, 1994; Hayes *et al.*, 1994).

4. SEQUENCE STRATIGRAPHY AND DEPOSITIONAL HISTORY

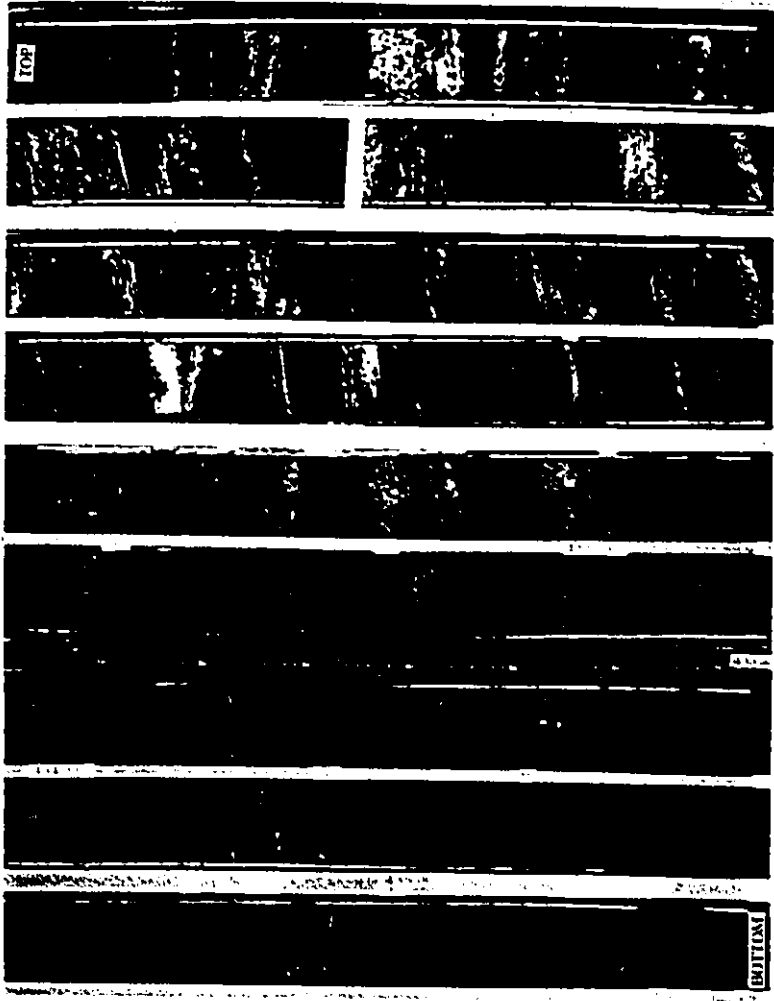
4.1 Sequence Stratigraphy

Sequence stratigraphy is a method of describing relationships between rock bodies within a chronostratigraphic framework. According to the principles of sequence stratigraphy genetically related facies are bounded by surfaces of erosion or nondeposition, or their correlative conformities (Van Wagoner *et al.*, 1988). Subsurface analysis integrating sequence stratigraphic principles and core analysis provide a high-resolution framework for correlating strata. Strata from adjacent wells are correlated by recognizing time-significant bounding surfaces rather than lithology, providing a more realistic interpretation of genetically related stratal packages (Van Wagoner *et al.*, 1990).

The fundamental stratal unit of sequence stratigraphy is the *sequence*, which is defined as "a genetically related succession of strata bounded by unconformities or their correlative conformities." (Mitchum, 1977). Implicit in this definition, sequence boundaries (1) are unconformities related to a fall of relative sea level, (2) separate older strata below from younger strata above, and (3) provide evidence of basinward shifts in lithofacies (i.e. younger, proximal facies overlie older, distal facies).

The fundamental building blocks of sequences are *parasequences*, which stack to form *parasequence sets*. Parasequences are relatively conformable, upward-shoaling successions of genetically related beds or bedsets bounded by time-significant *marine-flooding surfaces* and their correlative surfaces (Van Wagoner *et al.*, 1990). In siliciclastic settings, parasequences are progradational stratal units that occur at a scale mappable in well logs, core, and outcrops (Van Wagoner *et al.*, 1988). In addition, thin transgressive deposits commonly develop between the top of an underlying parasequence and the progradational part of the overlying one (Arnott, 1995; Fig. 4.1). A marine-flooding surface, as defined by Van Wagoner *et al.* (1988) is "a surface that separates

Figure 4.1: Planar-laminated sandstone interbedded with bioturbated shaly sandstone (Facies Association 5). Here the shaly intervals thicken upward and form the transgressive basal part of this shoreface to foreshore parasequence. The white bar marks the transition from transgressive to progradational deposition. The photograph is from 6-35-64-4W4 (D55-13). Scale bar is 10 cm.



younger from older strata, across which there is evidence of an abrupt increase in water depth." In contrast to sequence boundaries, therefore, marine-flooding surfaces form during periods of relative sea level rise when new depositional space is created at a rate exceeding the sediment flux (Posamentier *et al.* 1988). Marine-flooding surfaces are commonly planar (Van Wagoner *et al.* 1988) and are related to erosion associated with shoreface retreat, also termed wave ravinement (Swift, 1975; Davis and Clifton, 1987). Arnott (1995) compared shoreface retreat to a bulldozer blade scouring to a depth approximating fair-weather wave base, which commonly is of the order of 10-15 m.

A parasequence set is a succession of genetically related parasequences that stack in a distinctive pattern and are bounded, in many cases, by major marine-flooding surfaces and their correlative surfaces (Van Wagoner *et al.* 1990). The stacking patterns of parasequence sets can be progradational, retrogradational, or aggradational depending on the relationship between sediment flux and the increase or decrease of accommodation space (Van Wagoner *et al.*, 1990; Fig 4.2). Progradational parasequence sets form when the sediment flux exceeds the rate of new accommodation space creation (Fig. 4.2a). In this case, progressively younger parasequences are deposited farther basinward relative to underlying older ones. Conversely, in retrogradational parasequence sets, progressively younger parasequences are deposited farther landward, because the overall rate of deposition is less than the rate of accommodation (Fig. 4.2b). Aggradational parasequence sets develop when the rate of accommodation is approximately equal to the rate of deposition; progressively younger parasequences are deposited above older ones with little lateral shifting (Fig 4.2c).

Sequences can be further subdivided into systems tracts (Van Wagoner *et al.* 1988) based on the types of bounding surfaces, parasequence set distribution, and stratigraphic position within the sequence. The geometry and association of facies also characterize systems tracts. Sequences deposited in a ramp-margin basin, for instance the

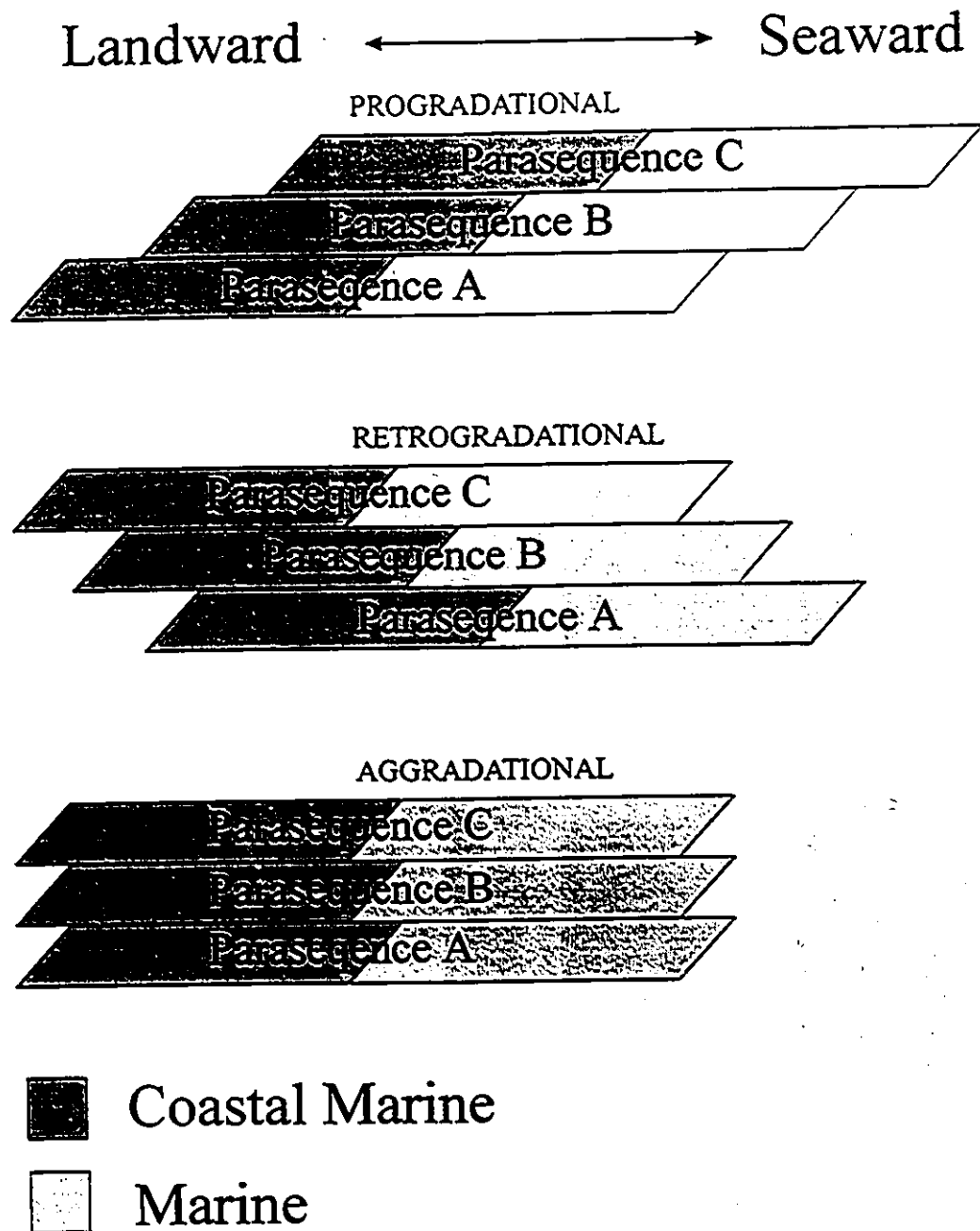


Figure 4.2: Parasequence stacking patterns in parasequence sets (modified after Van Wagoner *et al.*, 1990).

Western Canada Sedimentary Basin, consist commonly of strata deposited during lowstand, transgressive, and highstand systems tracts. During a fall of relative sea level, much of the ramp is subaerially exposed and fluvial valleys are incised as the shoreline is displaced basinward. The lowstand systems tract is composed of parasequence sets that stack in a progradational pattern during the later stages of relative sea level fall. It is bounded on the bottom by the sequence boundary and above by a major flooding surface (transgressive surface) caused by a relative sea level rise. This transgressive surface separates the lowstand systems tract from the transgressive systems tract (Van Wagoner *et al.* 1988). As relative sea level rises, fluvial valleys flood and create coastal embayments. Parasequences show a retrogradational stacking pattern characteristic of the transgressive systems tract. Transgressive environments, such as estuaries, are common in the transgressive systems tract (Zaitlin *et al.* 1994). If transgression is sufficiently slow, only thin deposits, if any, will be preserved above the transgressive surface (Davis and Clifton, 1987). The transgressive systems tract is terminated by the maximum flooding surface onto which highstand systems tract parasequences downlap. The maximum flooding surface is commonly identified by a condensed section of hemipelagic or pelagic sediments. Commonly it is a thin horizon containing abundant and diverse faunal remains and glauconite, representing a surface of slow deposition (Van Wagoner *et al.* 1990).

The highstand systems tract is bounded below by the maximum flooding surface and above by the upper sequence boundary (Van Wagoner *et al.* 1990). It typically contains parasequence sets that stack in aggradational or progradational patterns, and is deposited as the rate of relative sea level rise slows significantly, and during the subsequent relative sea level stillstand. Progradational shoreline and deltaic deposits characterize highstand deposition.

The above discussion is a conceptual model, developed in large part by researchers at EXXON in the early to middle eighties, that is intended to be a framework

for stratigraphic analysis. Note, however, that it is based on a number of simplifying assumptions, and, therefore, represents an idealized model. Also, it is important to note that lowstand, transgressive, and highstand systems tract deposits need not occur in all sequences. Finally, no thickness or temporal (duration of time) connotations are implied for sequences, parasequences, or systems tracts (Van Wagoner *et al.* 1990). In nature, rates of relative sea level change and sediment supply are not necessarily conducive to the uniform development and preservation of stratal successions deposited in the lowstand through transgressive and finally highstand systems tracts.

The strength of sequence stratigraphy is that it provides a framework to organize stratigraphic data. This organization helps to identify and predict the occurrence of reservoir-quality strata. For example, the identification of a lowstand to transgressive incised valley deposit implies the possible existence of a lowstand shoreline farther basinward (a potential hydrocarbon reservoir).

4.2 Coastal Embayments

From the interpretations presented in Chapter 3, it is apparent that strata of the Clearwater Formation at Cold Lake were deposited in a tidally-influenced coastal marine setting, most likely an estuarine or deltaic environment. Such deposits invariably occur in laterally confined coastal embayments.

Coastal embayments are defined here as more or less funnel-shaped coastal deposits that inhabit and fill previously incised valleys. The valleys are the result of fluvial erosion related to a relative sea level fall (Van Wagoner *et al.* 1990). During the subsequent transgression, the valleys flood forming an embayment. The base and walls of an embayment, thus, represent a sequence boundary which can be correlated with an erosional surface outside the embayment (interfleuve). The basal surface of a coastal

embayment deposit must therefore exhibit a basinward shift in facies, truncate older surfaces, and internal markers must onlap the embayment walls (Zaitlin *et al.* 1994).

Estuaries are formed in coastal embayments when fluvial and marine processes interact under conditions of rising relative sea level (Boyd *et al.* 1992), and thus an estuary is a transgressive coastal feature (Reinson, 1992). The most commonly adopted definition of an estuary in the literature is that of Cameron and Pritchard (1963), who stated that "An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage." By this definition, any modern environment where a river enters the sea through a semi-enclosed conduit is an estuary. In a morphological sense, however, river mouth environments where the rate of sediment supply exceeds the rate of relative sea level rise are better classified as deltas (Boyd *et al.* 1992). A definition for estuaries based on physical processes rather than salinity, which is more useful for interpreting the stratigraphic record, was proposed by Dalrymple *et al.* (1992). They defined an estuary as "the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave, and fluvial processes." Deltas, as defined by Elliott (1986), are "discrete shoreline protuberances formed where rivers enter oceans, semi-enclosed seas, lakes or lagoons and supply sediment more rapidly than it can be redistributed by basinal processes." Deltas were described as river, wave, or tide-dominated based on the relative dominance of these three end-member processes (Galloway, 1975).

Some confusion arises, however, when considering tide-dominated deposits. Boyd *et al.* (1992) noted that during evolution of a tide-dominated estuary, a transgressive limit is reached such that subsequent embayment-filling occurs by progradation of the embayment's landward margin. But progradation implies that the rate of sediment supply exceeds the rate of sea level rise. In the literature there is little discussion regarding what

criteria separate tide-dominated deltaic deposits from tide-dominated estuarine deposits (Dalrymple, 1992) and as a result, the interpretation of many tide-dominated deposits as deltaic or estuarine is problematical. For example, the Cobequid Bay-Salmon River estuary (Dalrymple *et al.* 1990) is a transgressive tide-dominated estuarine deposit that has reached its limit of transgression and is now prograding seaward and, as such, may be better described as a delta. Conversely, the Ord delta in Australia (Coleman and Wright, 1975; Wright *et al.*, 1975) may be better described as a tide-dominated estuary (Bhattacharya and Walker, 1992; Dalrymple, 1992). Dalrymple *et al.* (1992) suggested that the distinction between tide-dominated deltas and estuaries can be made by determining the net direction of bed-load transport: this direction is landward in estuaries and seaward in deltas.

In this study any tide-dominated coastal embayment deposit that can be shown to be progradational is defined as a tide-dominated delta. If a retrogradational pattern of facies is observed, the deposit is considered to be estuarine fill. Because of the genetic links between tide-dominated estuaries and deltas, physical morphology and facies distribution within these deposits are similar - the principal difference being the progradational or retrogradational nature of the facies associations. Nevertheless, irrespective of whether the system is an estuary or delta, the wave, tidal, and fluvial processes co-exist in both time and space. As a result, stratal architectures are complex and are typified by rapid vertical and lateral lithofacies changes.

4.2.1 Tide-dominated coastal embayment facies

Tide-dominated environments are characterized by deposition of both sand and mud. These sediments can occur separately, or be rhythmically interbedded, in association with tidal structures such as mud couplets, reactivation surfaces, and flaser bedding (section 1.5).

The typical funnel-shaped morphology of tide dominated estuaries and deltas results in a reduction of cross-sectional area landward through the embayment (Coleman and Wright, 1975). This causes landward amplification of tidal currents, resulting in a high-energy zone characterized by upper-flow-regime conditions where sand flats typically develop (Coleman and Wright, 1975; Dalrymple *et al.*, 1990; Dalrymple *et al.*, 1992). Mud deposition, on the other hand, is volumetrically most significant in the zone of maximum turbidity (Allen, 1991). This zone is characterized by high concentrations of suspended sediment and is the result of two physical processes -- density-driven currents and tidal current asymmetry. Density currents arise because of the salinity difference between fresh and marine water. In an embayment this causes a net landward flow of more dense saline water directly above the bed. This flow, however, is impeded by the seaward flow of less dense fresh water entering the embayment from the fluvial system. These two opposing currents converge and form a null zone coincident with the landward limit of salinity intrusion (Allen, 1991). It is in this null zone that high concentrations of suspended mud occur. During slack-water, this mud settles from suspension. During periods of low river discharge, density circulation is reduced and the turbidity maximum occurs farther landward, approaching the landward limit of tidal-current influence. The location and concentration of the turbidity maximum can therefore vary seasonally along the embayment axis, but does not intrude landward of the tidal current limit (Allen, 1991). During neap tide, weaker tidal currents reduce the axial length of the turbidity maximum but increase its concentration, thereby enhancing mud deposition. On the other hand, during spring tide, stronger tidal currents cause the turbidity maximum to expand and re-suspend much of the previously deposited mud. Nevertheless, some mud drapes are preserved and give rise to the rhythmic interstratification of mud and sand that is characteristic of tidal deposits (Allen, 1991).

Figure 4.3 shows an idealized tide-dominated delta. Tidal sand bars, at the seaward end of the deposit typically contain regularly interbedded upward-coarsening sand and mud. Tidal structures such as, flaser, wavy, and lenticular bedding, bidirectional current ripples, reactivation surfaces, and mud couplets are common features of tidal bar deposits (Coleman and Wright, 1975). The abundance of mud is related to the position of the tidal bar relative to the turbidity maximum. Headward from the tidal bars are the sand flats which consist primarily of upper-flow-regime plane bed sand (Dalrymple *et al.* 1992). Farther headward, meandering tidal-fluvial channels deposit upward-fining point bars that contain large- and small-scale cross-stratified sand interbedded with inclined mud layers and also exhibit tidal structures (Coleman and Wright, 1975). Finally, meandering fluvial channel-fill deposits occur. These also consist of upward-fining point bars, but with less interbedded mud (Coleman and Wright, 1975). Typically, the progradation of meandering tidal and fluvial channels will erode much of the underlying sand flat and tidal bar succession as well as mudflat and salt marsh deposits, if present. In summary, the idealized stratigraphic succession of a prograding tidally-influenced embayment will consist of distal delta tidal bar deposits overlain by proximal delta sand flats that are, in turn, overlain by tidal-fluvial channel-fill strata capped by fluvial channel-fill deposits (Fig. 4.4). This progradational relationship of facies associations is similar to the stratal pattern observed in the Clearwater Formation at Cold Lake. Figure 4.3 is therefore taken to be a conceptual model for the Clearwater Formation in the study area.

4.3 Correlations and Depositional History

Six stratigraphic cross-sections were constructed through the Clearwater Formation at Cold Lake (Fig. 4.5), and are presented in Figures 4.6 - 4.11. Each well contains core, and all were analyzed as part of this study. Here time-significant surfaces (sequence boundaries and flooding surfaces) and the strata sandwiched between them

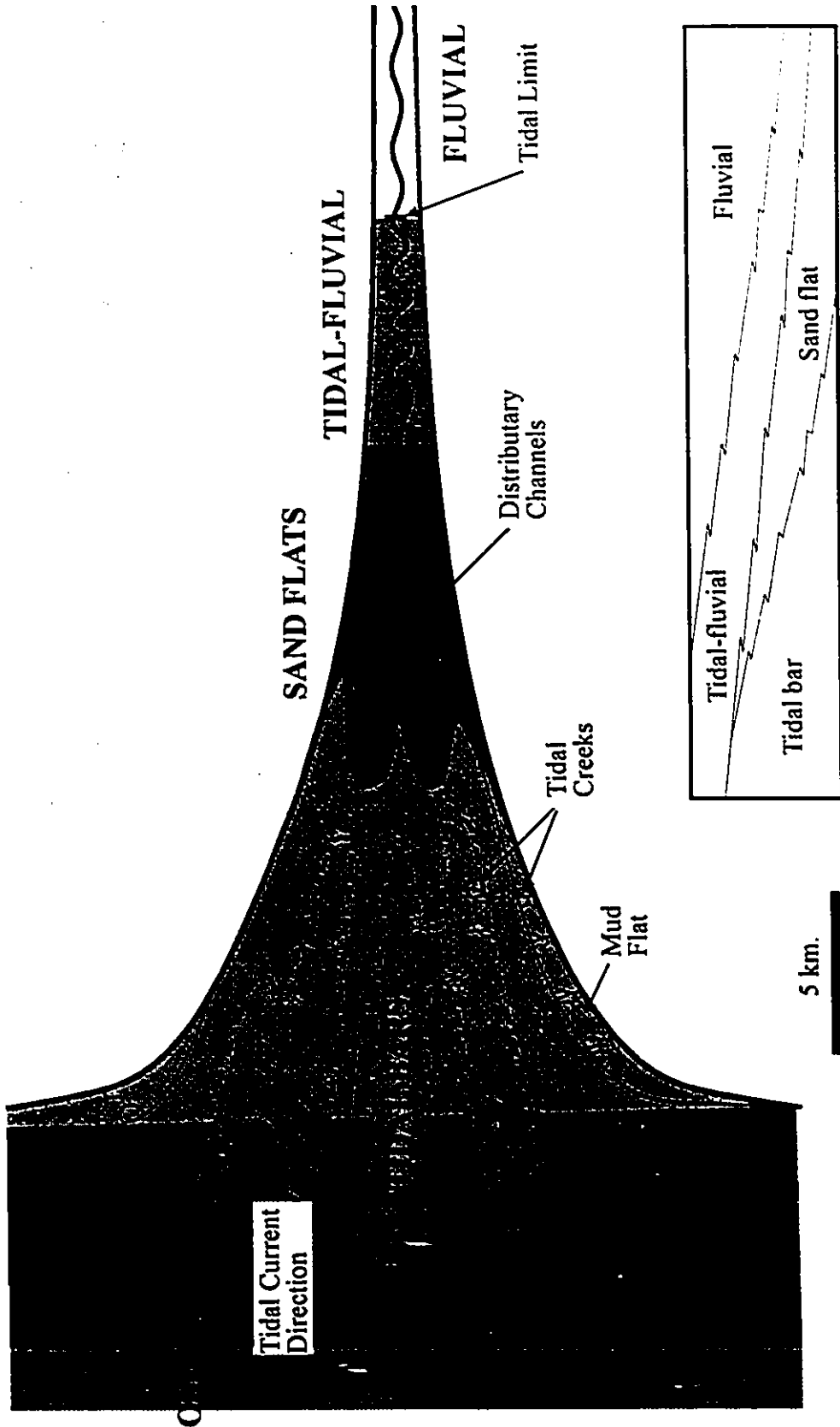


Figure 4.3: Schematic map of a tide-dominated delta, based on the Colorado, Fly, and Cobequid Bay coastal embayments.
Figure 4.4(Inset): Interpreted longitudinal section through the embayment, based on facies relationships observed in the Clearwater Formation.

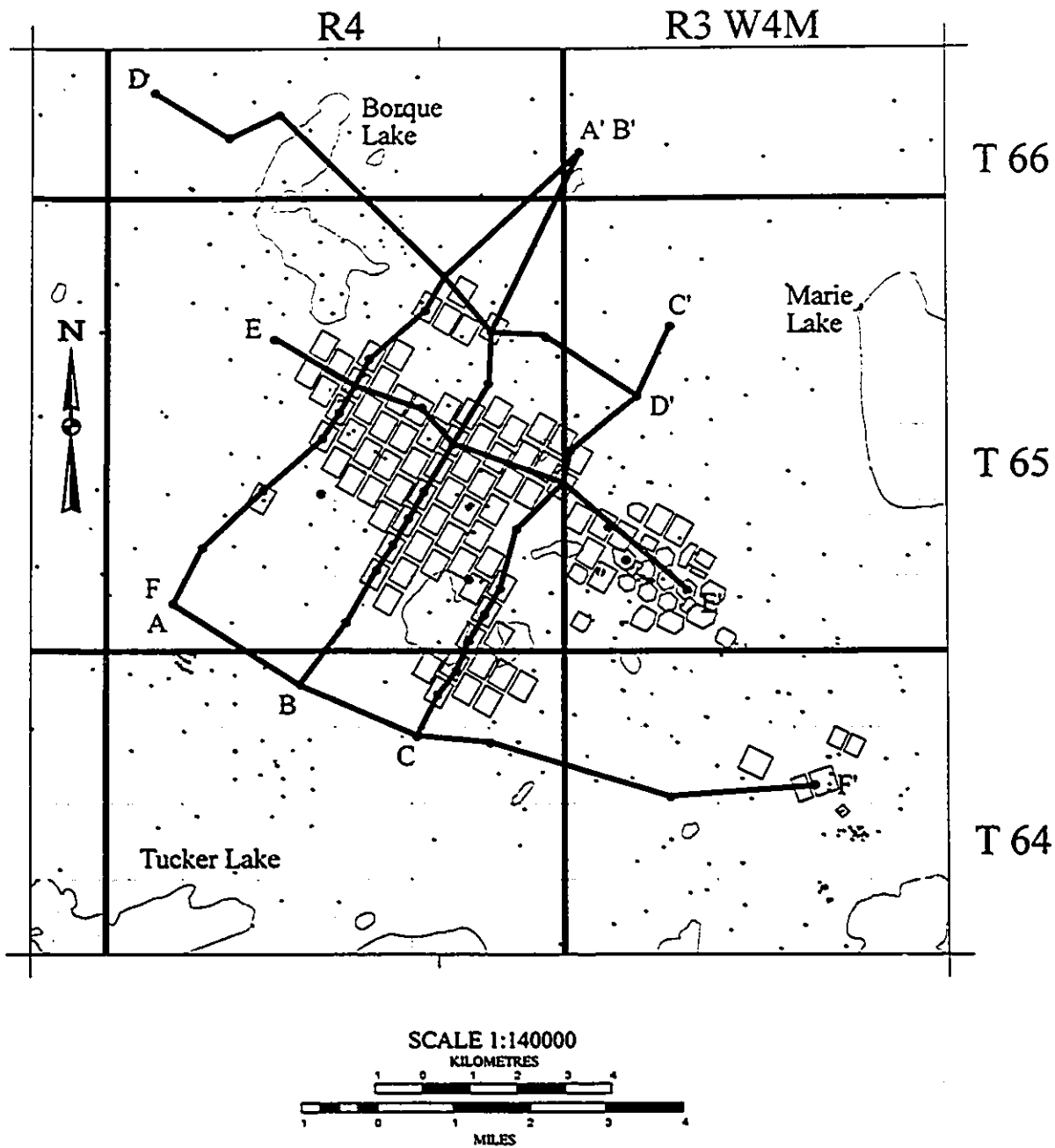


Figure 4.5: Map of study area showing the location of stratigraphic cross-sections. Sections are displayed in figures 4.6 to 4.11 and in Appendix B.

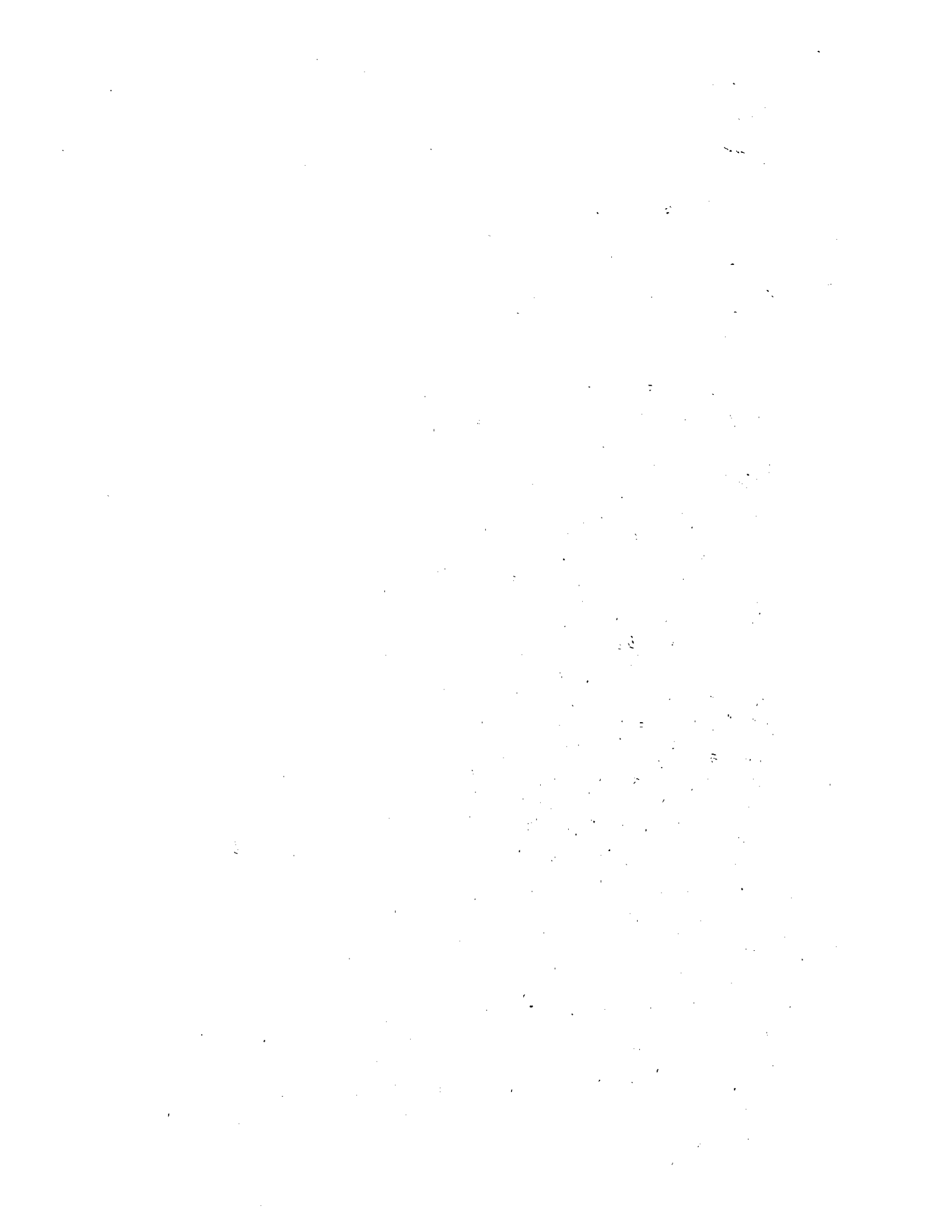
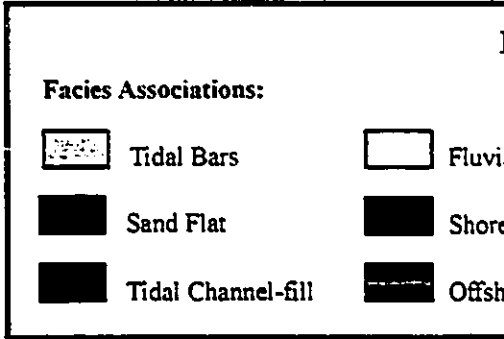
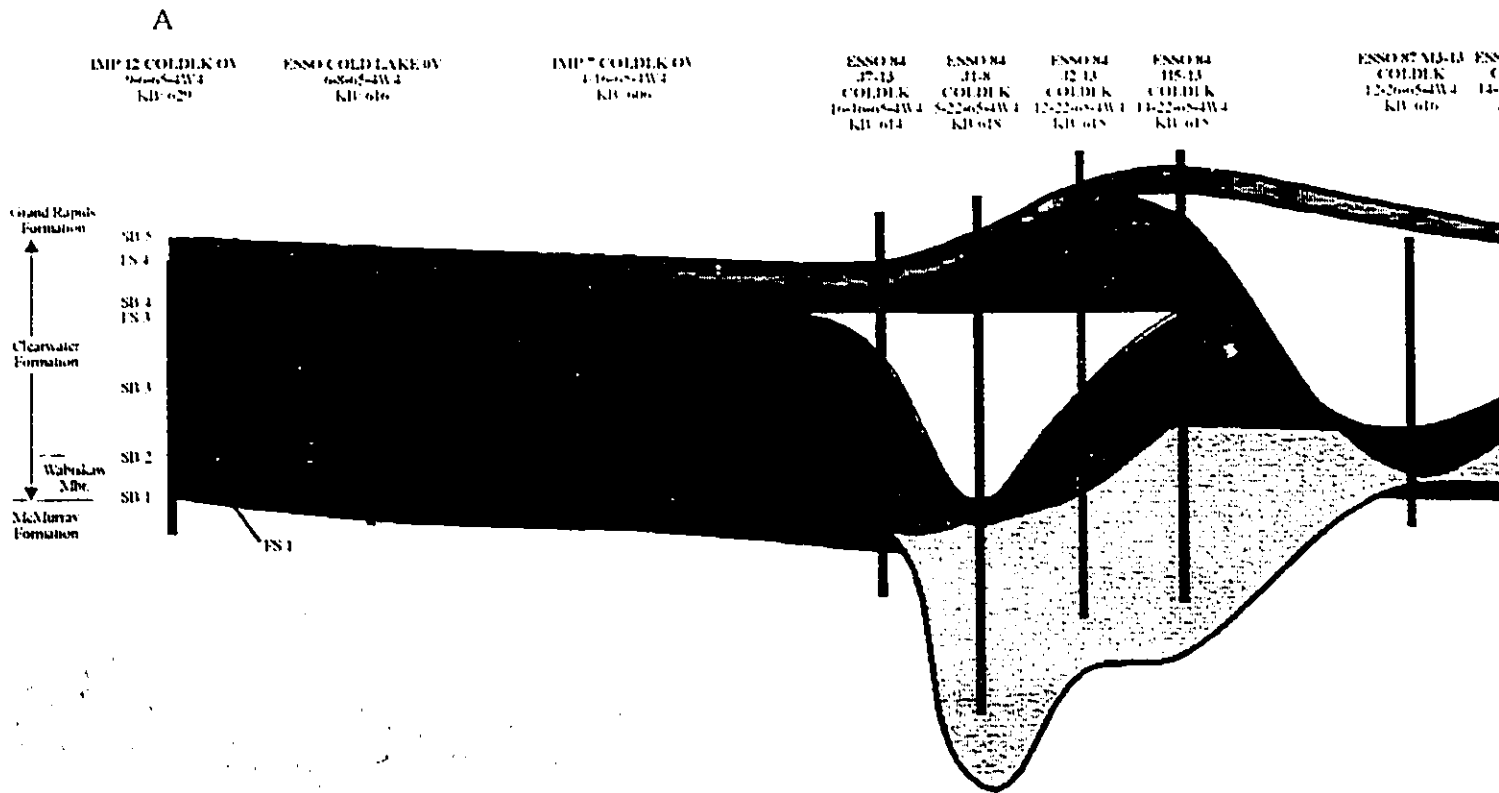
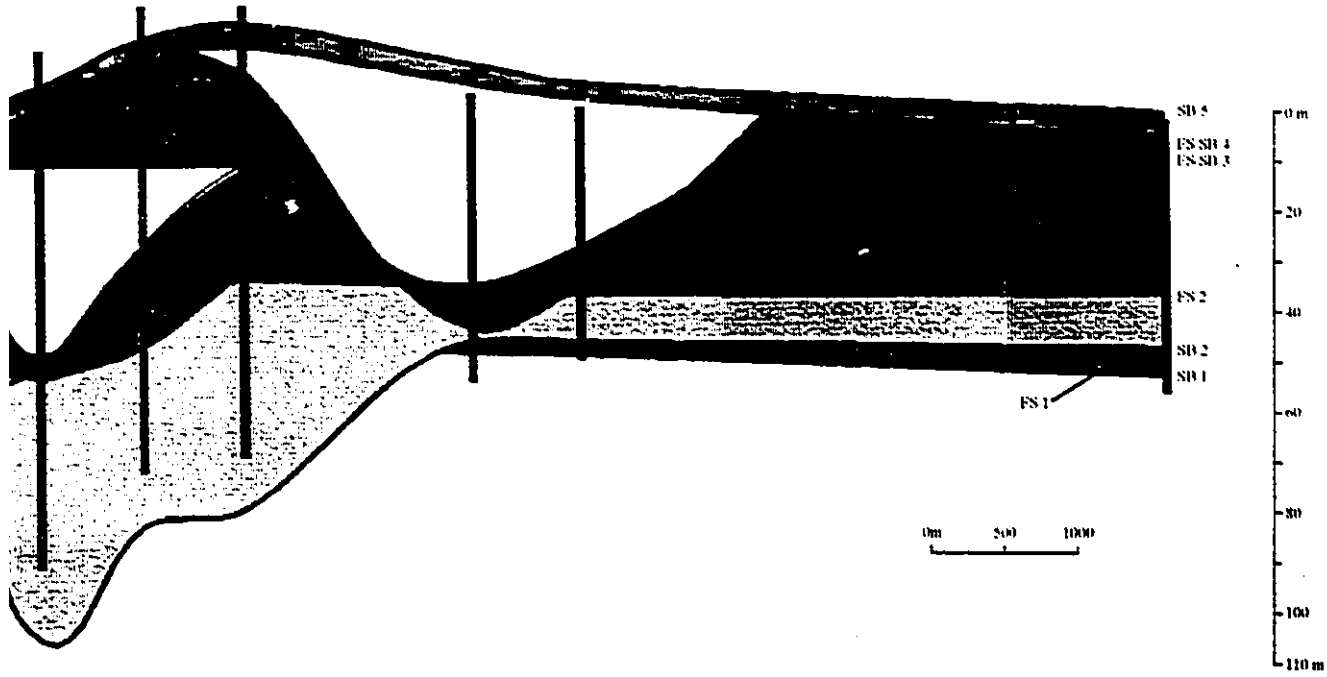


Figure 4.6: Stratigraphic Cross-section A-A'



A'

ENSO 04 31-3 COLDLK 22-26-54W4 KV 615	ENSO 04 32-3 COLDLK 12-22-68-4W4 KV 615	ENSO 04 33-3 COLDLK 13-22-68-4W4 KV 615	ENSO 07 M3-13 COLDLK 12-26-65-4W4 KV 616	ENSO 08 M5-8 COLDLK 14-26-65-4W4 KV 617	ENSO 05 COLDLK OV 12-26-65-4W4 KV 617
---	---	---	---	--	---



Legend

Facies Associations:







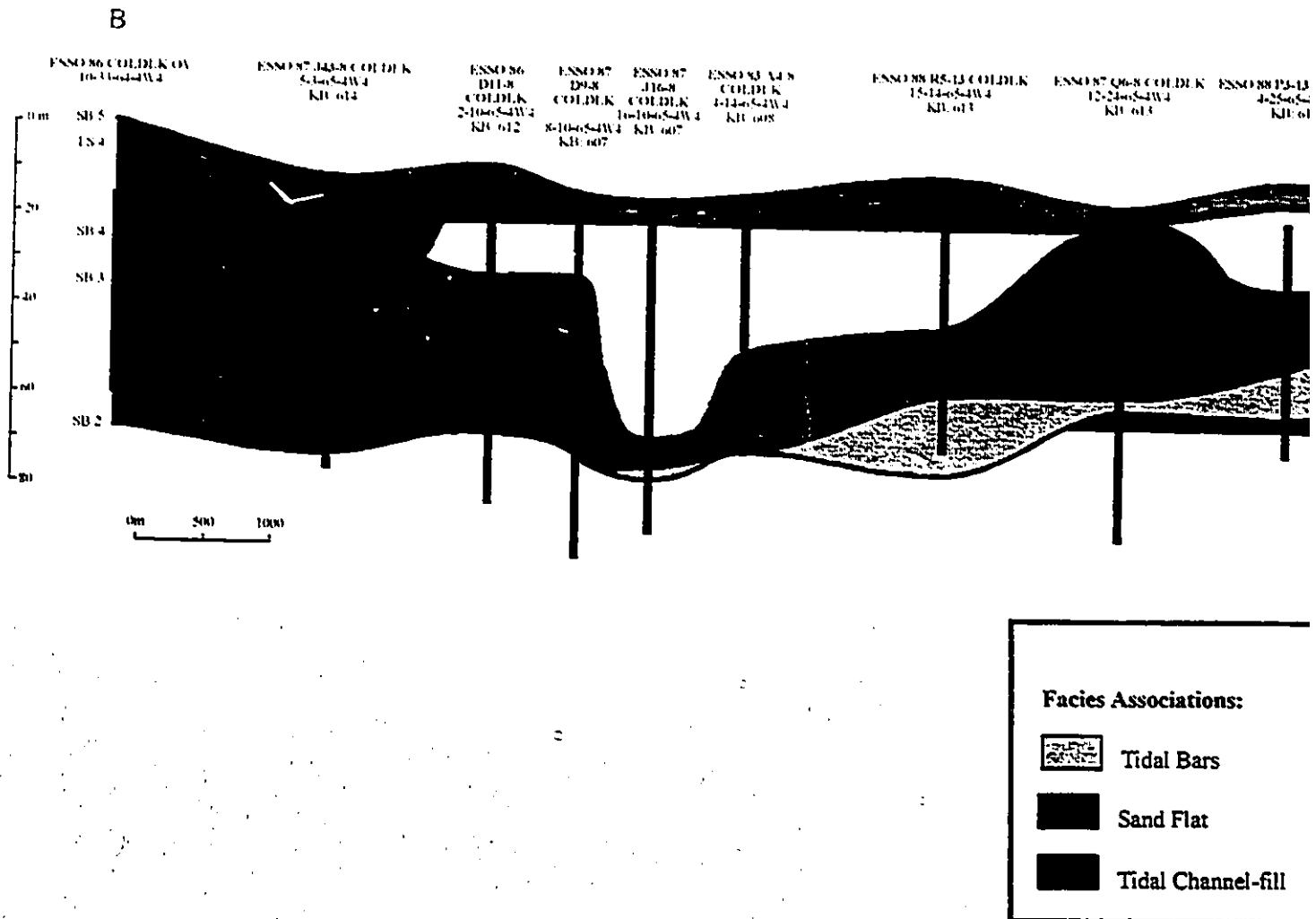
 Tidal Bars	 Fluvial Channel-fill	FS 1: Flooding Surface 1
 Sand Flat	 Shoreface to Foreshore	SB 1: Sequence Boundary 1
 Tidal Channel-fill	 Offshore	

Figure 4.7: Stratigraphic Cross-section B-B'



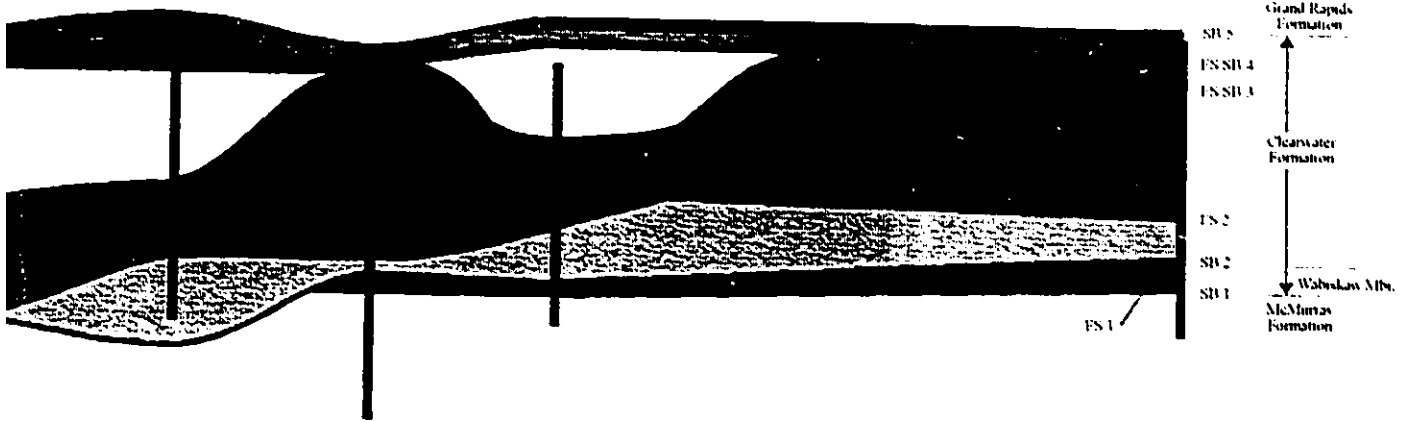
ENSO87R5-L3 COLDEK
15-14-654W4
KU 613

ENSO87Q6-S COLDEK
12-24-654W4
KU 613

ENSO88P3-L3 COLDEK
4-25-654W4
KU 615

B'

ENSO85 COLDEK OV
12-29-654W4
KU 617



Legend

Facies Associations:







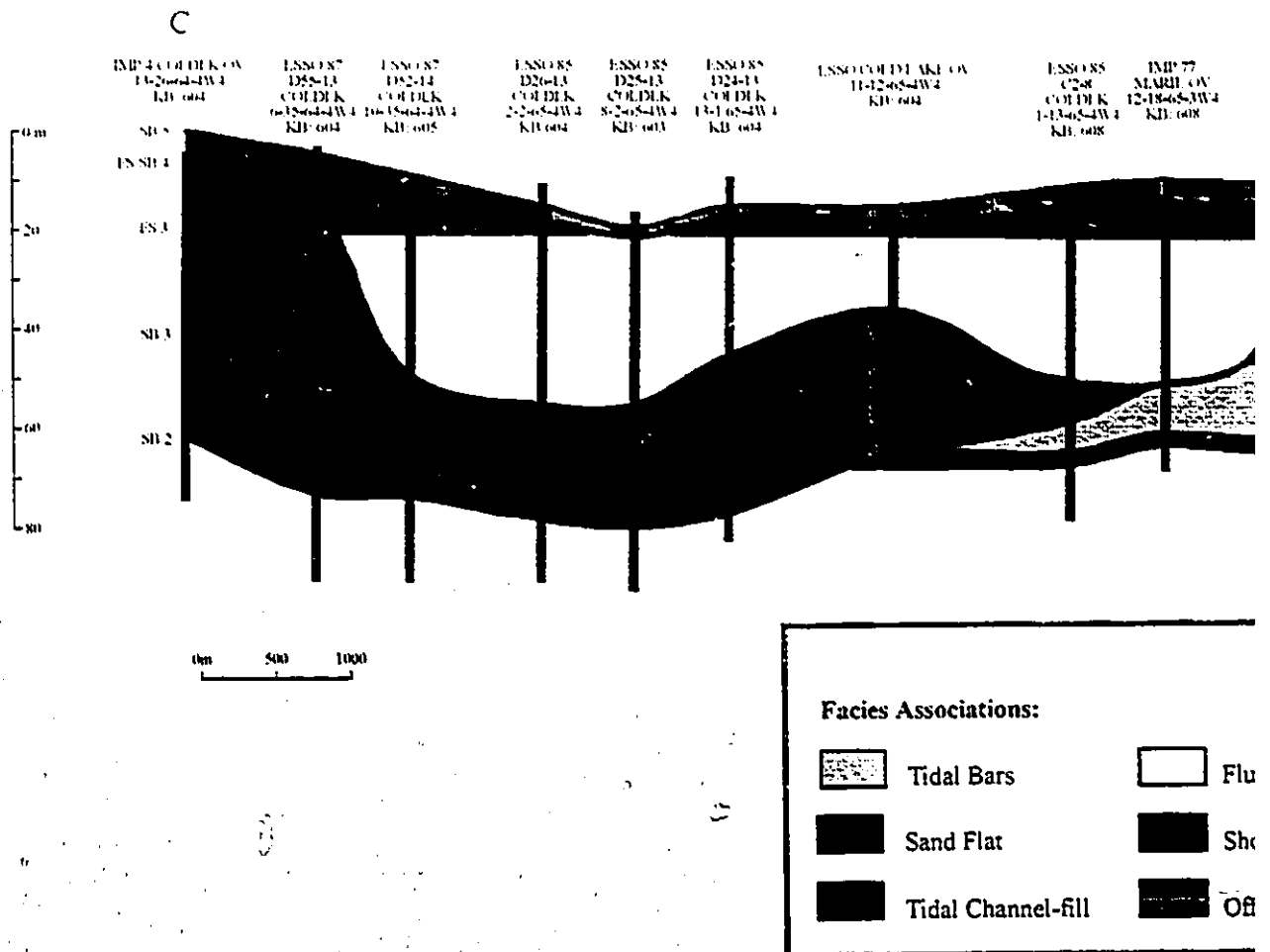
 Tidal Bars	 Fluvial Channel-fill	FS 1: Flooding Surface 1
 Sand Flat	 Shoreface to Foreshore	SB 1: Sequence Boundary 1
 Tidal Channel-fill	 Offshore	

Figure 4.8: Stratigraphic Cross-section C-C'



ESS 4-11
DEK
8-24
604

ESSO COLDLAK OV
11-12-65-3W4
KD: 604

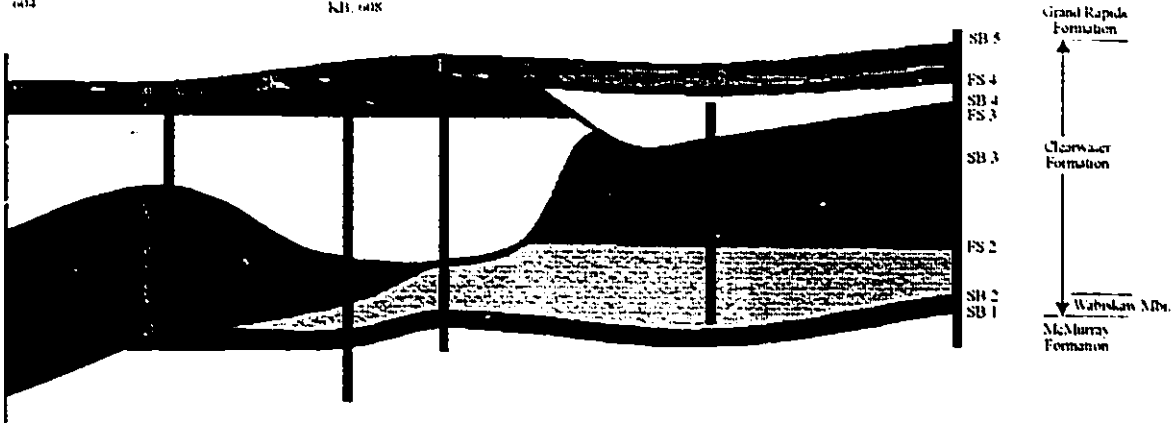
ESSO 85
C28
COLDLAK
1-13-65-3W4
KD: 608

IMP 77
MARE OV
12-18-65-3W4
KD: 608

IMP 9 COLDLAK OV
8-19-65-3W4
KD: 611

ESSO 83 COLDLAK OV
6-29-65-3W4
KD: 609

C



Legend

Facies Associations:







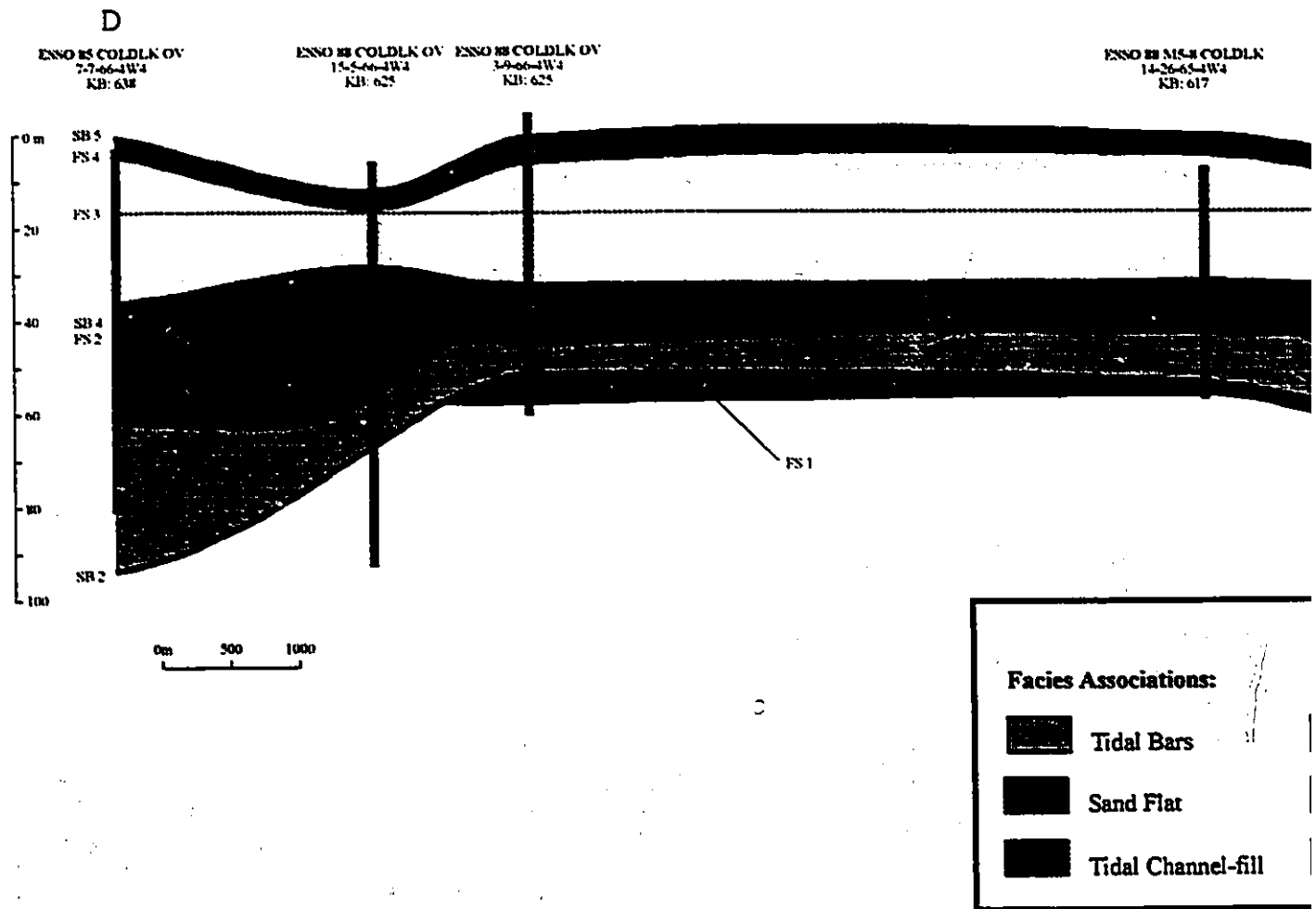
- | | | |
|--|--|----------------------------------|
|  Tidal Bars |  Fluvial Channel-fill | FS 1: Flooding Surface 1 |
|  Sand Flat |  Shoreface to Foreshore | SB 1: Sequence Boundary 1 |
|  Tidal Channel-fill |  Offshore | |

Figure 4.9: Stratigraphic Cross-section D-D'

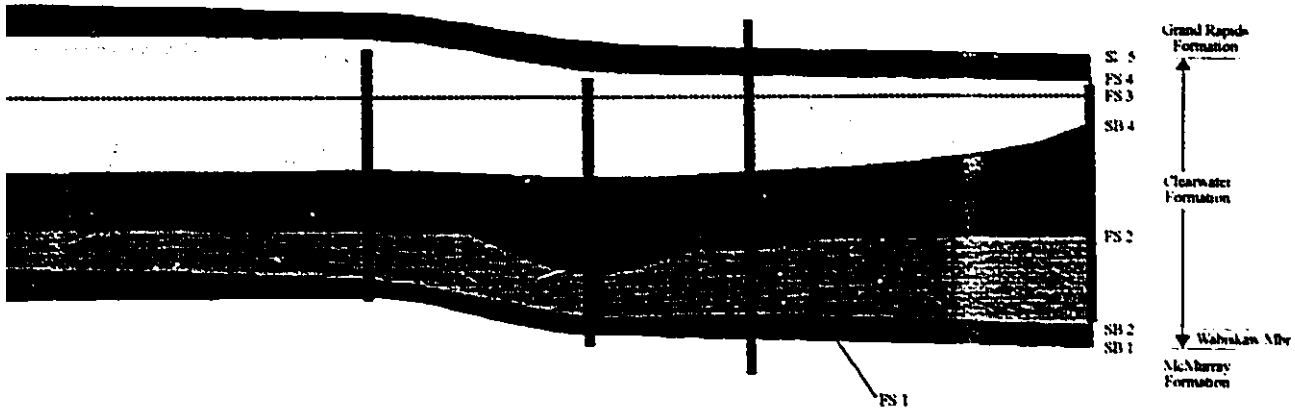


ENSO #1 MS-1 COLDLK
14-25-65-4W4
KB: 617

ENSO #1 P3-13 COLDLK
4-25-65-4W4
KB: 615

ENSO #1 P7-13
COLDLK
2-25-65-4W4
KB: 612

D'
IMP #9 COLDLK OV
2-19-65-1W4
KB: 611



Legend

Facies Associations:







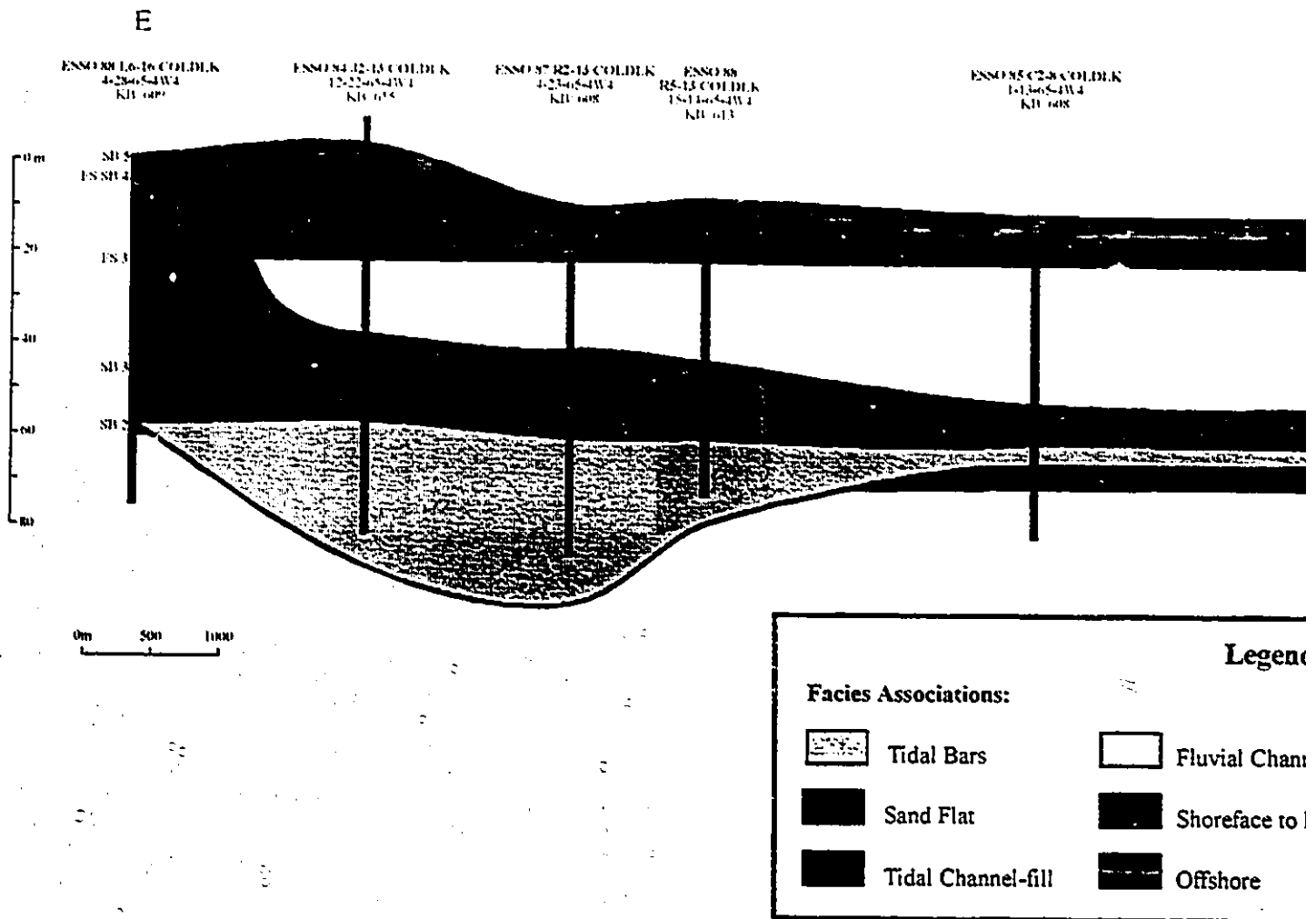
	Tidal Bars		Fluvial Channel-fill	FS 1: Flooding Surface 1
	Sand Flat		Shoreface to Foreshore	SB 1: Sequence Boundary 1
	Tidal Channel-fill		Offshore	

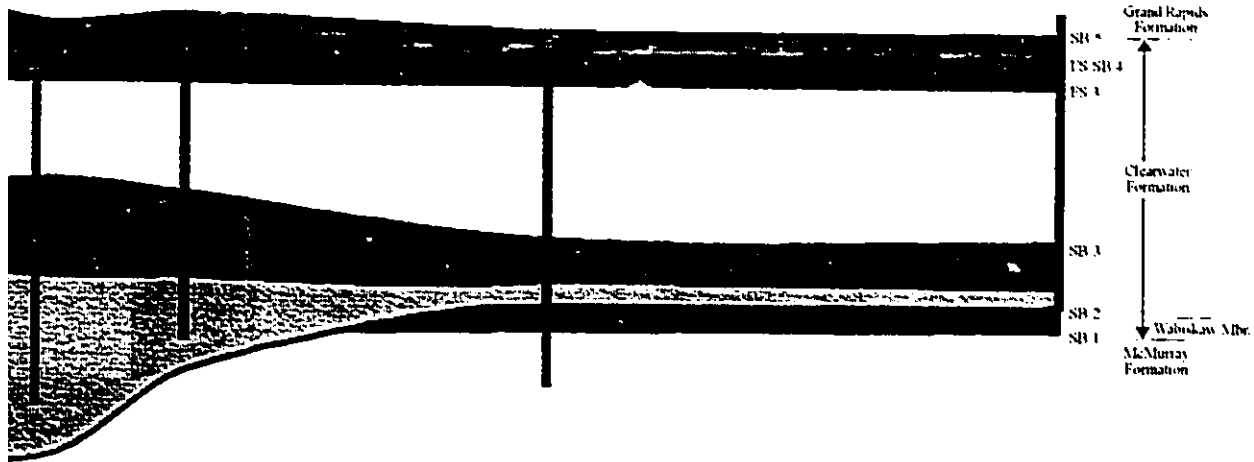
Figure 4.10: Stratigraphic Cross-section E-E'



7R2-13 COLDLK
 25-05-4W4
 KH 608
 ENSO 86
 R5-13 COLDLK
 18-11-05-4W4
 KH 613

ENSO 85 C23 COLDLK
 1-13-05-4W4
 KH 608

E'
 ESSO 79 C-34 ETHELLEN EN
 10-5-05-4W4
 KH 629



Legend

Facies Associations:







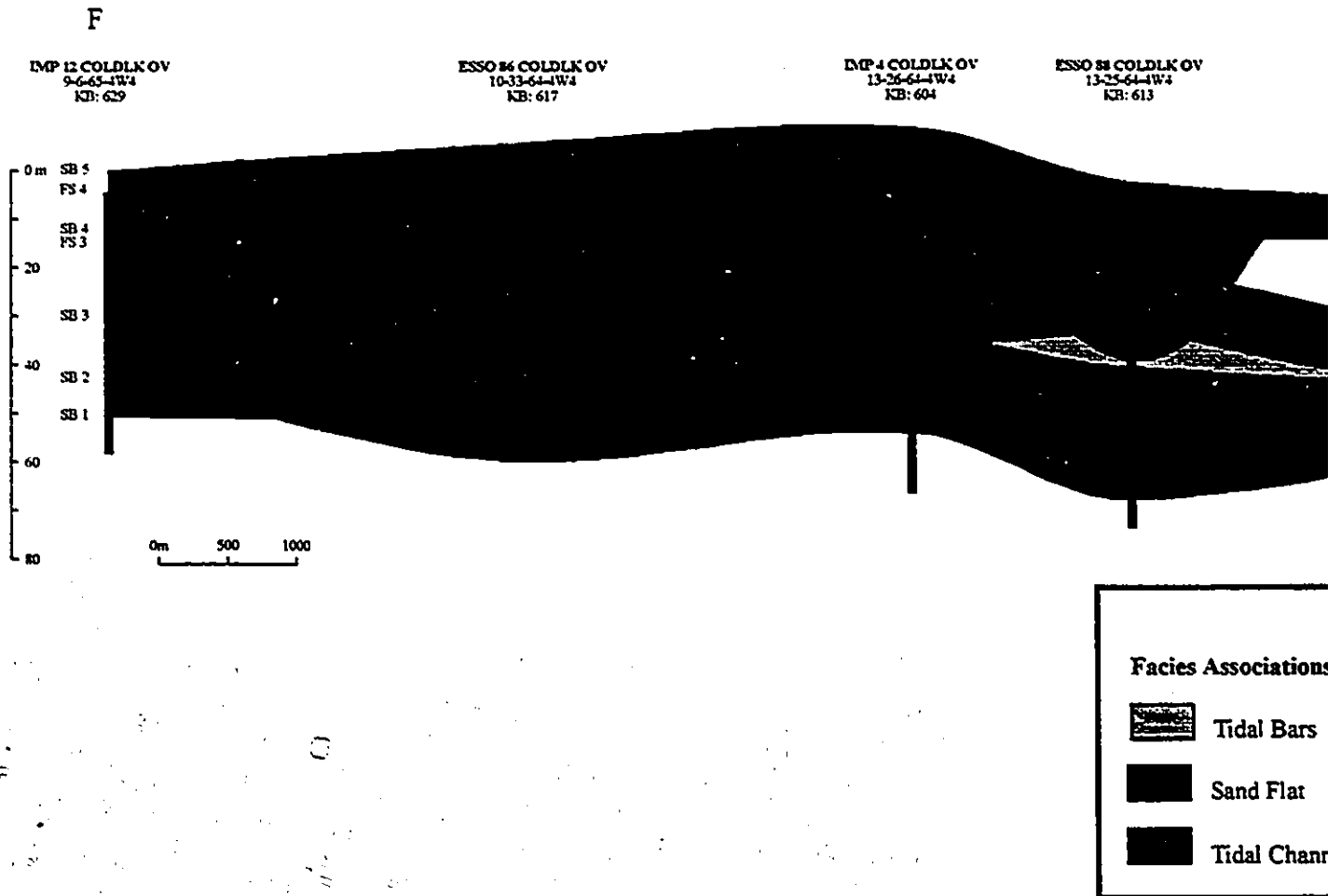
 Tidal Bars	 Fluvial Channel-fill	FS 1: Flooding Surface 1
 Sand Flat	 Shoreface to Foreshore	SB 1: Sequence Boundary 1
 Tidal Channel-fill	 Offshore	

Figure 4.11: Stratigraphic Cross-section F-F'

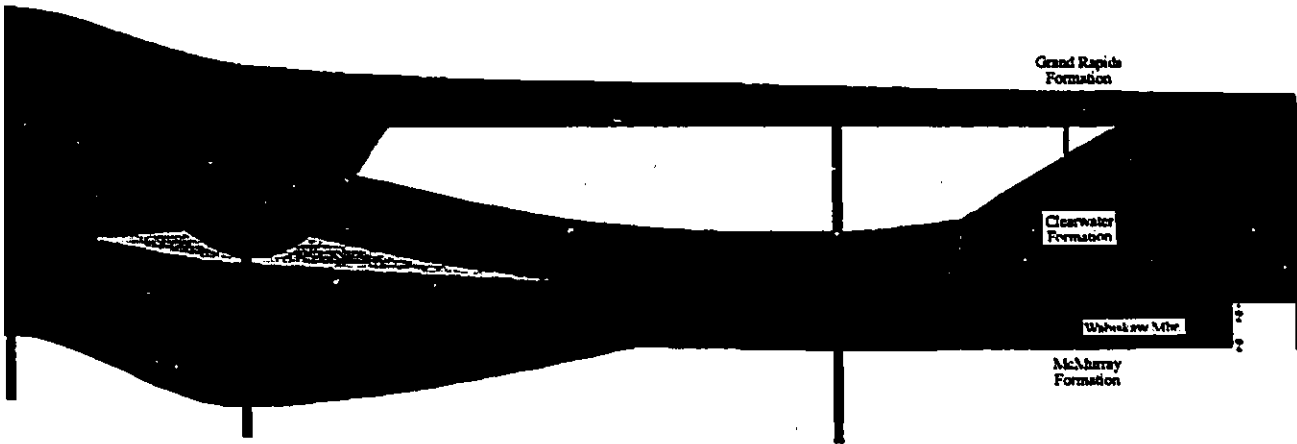


WDLK OV
64-1W4
KB: 604

ESSO 88 COLDLK OV
13-25-64-1W4
KB: 613







ESSO 81 SWD ETHELLK
3-29-64-3W4
KB: 614

F'
ESSO 90 MAYB12A
COLDLK EN
3-27-64-3W4
KB: 613



Legend

Facies Associations:

 Tidal Bars	 Fluvial Channel-fill	FS 1: Flooding Surface 1
 Sand Flat	 Shoreface to Foreshore	SB 1: Sequence Boundary 1
 Tidal Channel-fill	 Offshore	

were correlated. Flooding Surface 3 (FS 3) was used as the stratigraphic datum for these sections; in wells that do not contain FS 3 the stratigraphic position was estimated on the basis of the correlative position of FS 2 and FS 4 in adjacent wells. Locally, some flooding surfaces coincide with a sequence boundary and, therefore, are referred to as flooding surface/sequence boundaries (FS/SB). Appendix B contains the same six cross-sections but shows the geophysical well logs and uses FS 4 (a surface more easily identifiable on well logs) as the stratigraphic datum. Correlation of facies associations within the study area using a sequence stratigraphic framework allowed identification of four depositional sequences in the Clearwater Formation. Each is described in detail below.

4.3.1 Sequence 1 - Wabiskaw Member

Description:

Sequence 1 is bounded below by Sequence Boundary 1 (SB 1), above by SB 2 and is locally absent due to erosion associated with SB 2 (Fig. 4.12). Across SB 1 is an abrupt change in grain size and lithology - from very fine quartz arenite below to upper fine to medium glauconitic litharenite above (Putnam and Pedskalny, 1983). This surface is a regional boundary separating Lower and Upper Mannville Group strata (Rudkin, 1965; Minken, 1974; Harrison *et al.*, 1981; Jackson, 1984). In some cores (e.g. 2-25-65-4W4; P7-13), large robust burrows of the *Glossifungites* ichnofacies (MacEachern *et al.*, 1992; MacEachern and Pemberton, 1994) occur directly below this surface (Fig. 4.13). According to MacEachern *et al.* (1992), the *Glossifungites* ichnofacies indicates burrowing into a semi-consolidated substrate and commonly marks sequence boundaries and transgressive surfaces of erosion (ravinement surfaces).

Sequence 1 comprises two parasequences (A and B) that stack as a retrogradational parasequence set. Parasequence A consists of a glauconite-rich,

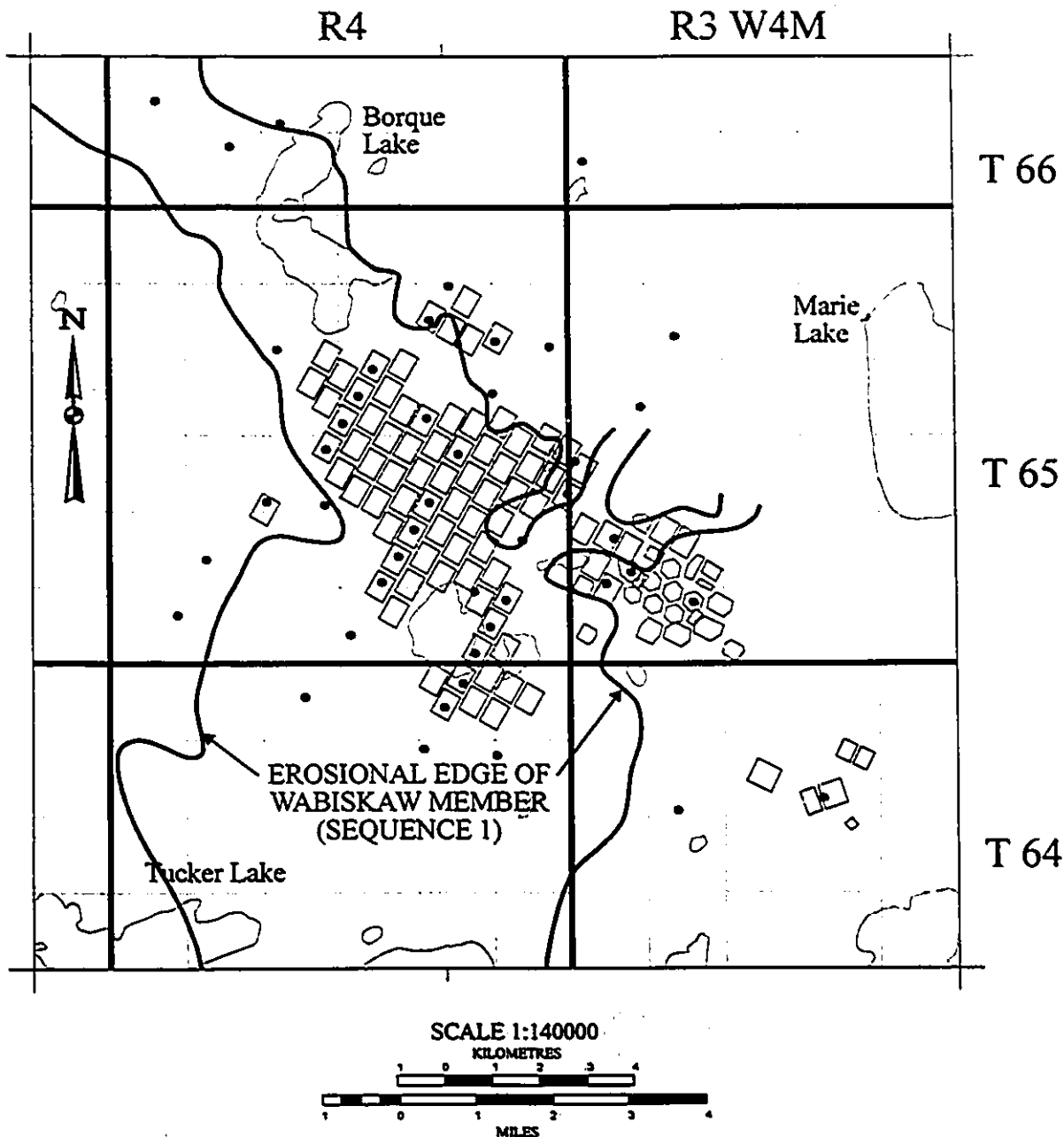


Figure 4.12: Map of study area showing the erosional edge of the Wabiskaw Member (Sequence 1). Boundary drawn on the basis of both core and well log data. Large dots represent wells with core utilized for this project.

Figure 4.13: Boundary (SB 1) between very fine sandstone of the McMurray Formation and glauconitic bioturbated shaly sandstone (Facies Association 5) of the overlying Wabiskaw Member (Clearwater Formation). The sequence boundary (arrow) is characterized by a large *Skolithos* burrow of the *Glossifungites* ichnofacies. The photograph is from 2-25-65-4W4 (P7-13). Scale bar gradations are in centimetres.



shoreface sandstone succession (Facies Association 5) up to 4 m thick that is bounded below by SB 1 and above by Flooding Surface 1 (FS 1). Parasequence B is made up of offshore marine mudstone (Facies Association 6), is bounded below by FS 1 and above by SB 2, and is up to 2 m thick.

Summary:

A fall of relative sea-level, marking the end of McMurray Formation (Lower Mannville) deposition, subaerially exposed a large area and created SB 1. Subsequently, a rise of relative sea-level flooded the study area and deposited two retrogradationally-stacked parasequences of Sequence 1 during the transgressive systems tract. Within the study area these strata make up the Wabiskaw Member of the Clearwater Formation. Sequence 1 deposition was terminated by a fall of relative sea level that formed SB 2.

4.3.2 Sequence 2

Description:

Sequence 2 is bounded below by SB 2 and above by SB 3 or SB 4, attains a maximum vertical thickness of 55 m, and typically overlies glauconite-rich strata of the Wabiskaw Member (Sequence 1). Where the Wabiskaw Member is absent Sequence 2 overlies the McMurray Formation. SB 2 is characterized by a paleovalley of unknown width (13 km minimum; Fig. 4.14). The deepest part of this paleovalley trends northwest-southeast and is considered to reflect the trend of the valley walls. Commonly SB 2 is overlain by a thin layer (up to 30 cm) of chert pebbles, siderite clasts, and other lithic fragments (Fig. 4.15). In addition, a change in lithology is evident across SB 2 – very fine quartz arenite of the McMurray Formation or fine to medium glauconitic sandstone of the Wabiskaw Member below to fine to medium feldspathic litharenite with few

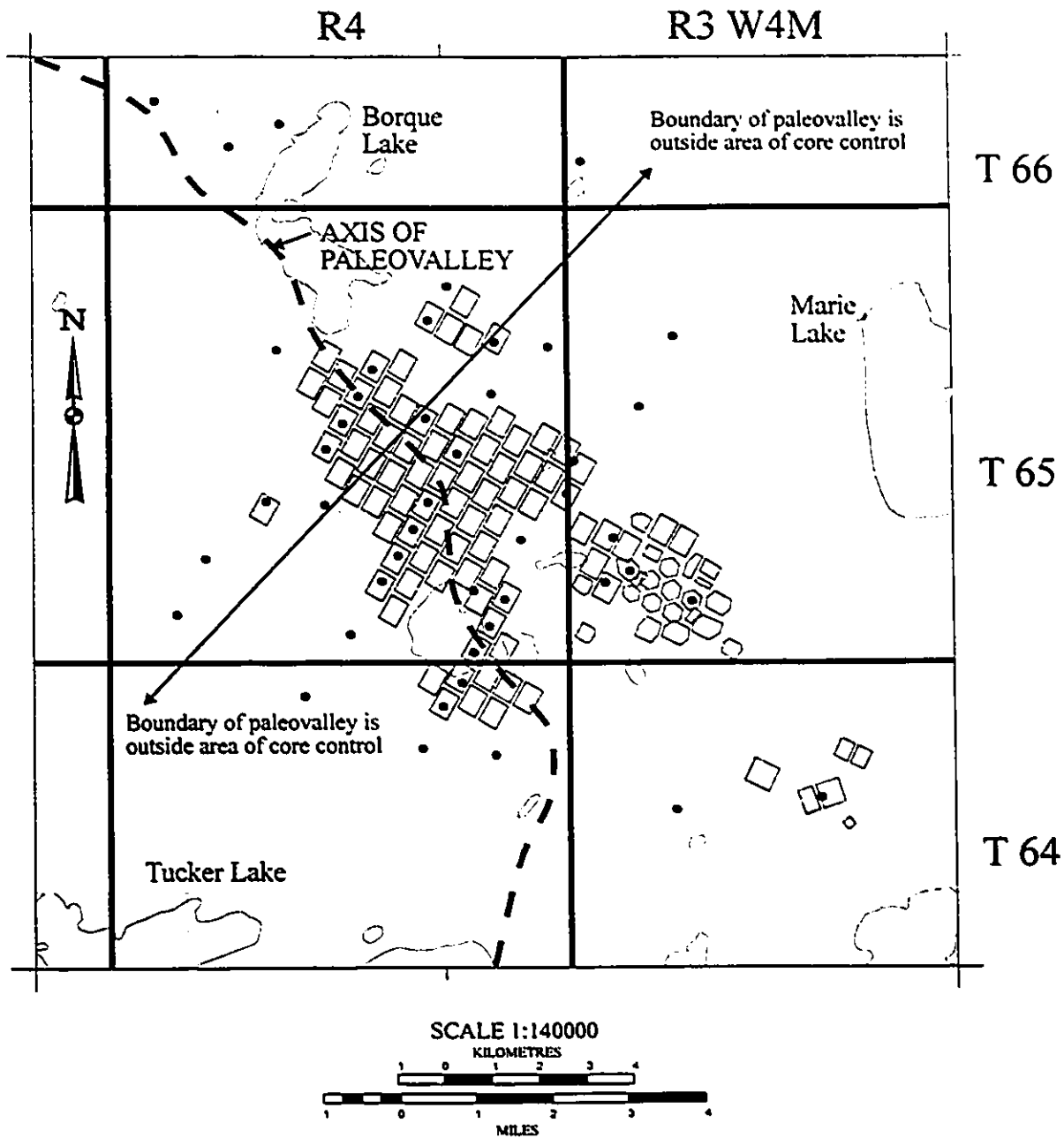
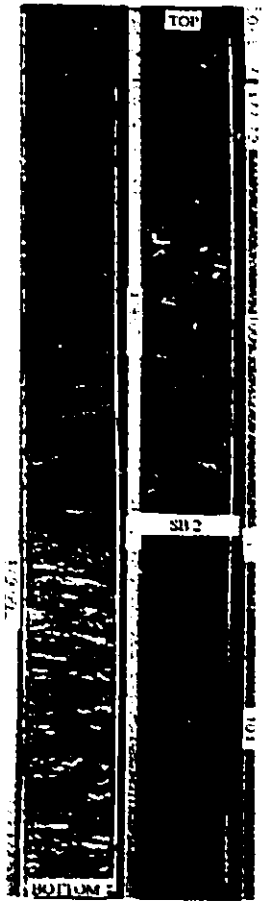


Figure 4.14: Map of study area showing the incised valley axis of Sequence Boundary 2 (SB 2). The axis trend is based on both core and well log data. The walls of the valley lie outside the area of core control. Large dots represent wells with core utilized for this project.

Figure 4.15: Sequence Boundary 2 (SB 2) separates bioturbated sandstone and mudstone of the McMurray Formation from medium sandstone of the Clearwater Formation. Lithic fragments, sideritized mudstone rip-up clasts, and oriented mudstone clasts occur in the zone directly above SB 2. The photo is from 8-10-65-4W4 (D9-18). Scale bar is 10 cm.



TOP

SIR

MILLON

TOP

glauconite grains above (Putnam and Pedskalny, 1982, 1983; Prentice and Wightman, 1987; Hutcheon *et al.*, 1989; Appendix D).

Sequence 2 contains two stacked parasequences (A and B) that form a retrogradational parasequence set. Parasequence A comprises the paleovalley fill, ranges from 10 to 70 m thick, and is bounded below by SB 2 and above by FS 2 or a younger sequence boundary (SB 3 or SB 4). Parasequence A is made up of tidal bar strata (Facies Association 1) gradationally overlain by sand flat deposits (Facies Association 2). These strata are, in turn, erosively overlain by tidal-fluvial deposits (Facies Association 3). Sand flat deposits are mostly confined to the southern part of the study area, whereas tidal bar strata are more common to the north (Figs. 4.6–4.11). These observations indicate a northward progradation of the deltaic system.

Parasequence B consists of a succession of shoreface to foreshore deposits (Facies Association 5) up to 30m thick, bounded below by FS 2 and above by SB 3 or SB 4. A thin upward-fining transgressive unit (Arnott, 1995) occurs at the base of Parasequence B (Fig. 4.1) and is conformably overlain by the remaining upward-coarsening shoreface to foreshore succession.

Summary:

A drop of relative sea level led to fluvial incision and the creation of SB 2. With a subsequent rise of relative sea level, these fluvial valleys flooded and were transformed into coastal embayments. High sediment flux allowed a northward-prograding, tide-dominated delta to develop and infill the embayment (Parasequence A), even as relative sea level continued to rise. Subsequently, however, the filled embayment was flooded (FS 2) and marine shoreface to foreshore deposition ensued (Parasequence B). Due to another drop of relative sea level, these deposits were then erosively overlain by SB 3.

The two parasequences of Sequence 2 stack in a retrogradational pattern, and together represent transgressive systems tract deposition. A similar depositional history has been interpreted from Holocene strata in Papua New Guinea and Australia (Torres Strait and Gulf of Papua: Harris, 1994), where fluvial valleys were incised because of relative sea level fall associated with glaciation. Subsequently, the valleys were partially infilled by fluvial strata of the lowstand systems tract and were later overlain by tide-dominated deltaic strata of the transgressive systems tract related to Holocene transgression. Because of high sediment flux, the embayments in this Holocene example were infilled by deltaic rather than estuarine deposits (Harris, 1994).

4.3.3 Sequence 3

Description:

Sequence 3 is up to 50 m thick (maximum vertical thickness) and is bounded below by SB 3 (or FS/SB 3) and above by SB 4 (or FS/SB 4). SB 3 comprises two paleovalleys: a northwest-southeast trending valley that is a minimum 7km wide, which occurs in the southern two-thirds of the study area, and a second valley of unknown width and orientation in the northeastern part of the study area (Fig. 4.16). The southern paleovalley trend is approximately the same as the paleovalley of Sequence 2. SB 3 is commonly overlain by a 1 to 10cm layer of chert pebbles, shell fragments, and/or sideritized mudstone rip-up clasts. Outside of the paleovalleys, FS 3 merges with SB 3 and is termed FS/SB 3.

Two parasequences (A and B) make up Sequence 3. Parasequence A, which comprises all of the paleovalley fill, is bounded below by SB 3 and above by FS 3 or SB 4. It is up to 45m thick and consists of sand flat deposits (Facies Association 2) erosively overlain by tidal-fluvial strata (Facies Association 3) that are, in turn, erosively overlain by fluvial deposits (Facies Association 4). In one well (13-25-64-4W4), tidal bar deposits

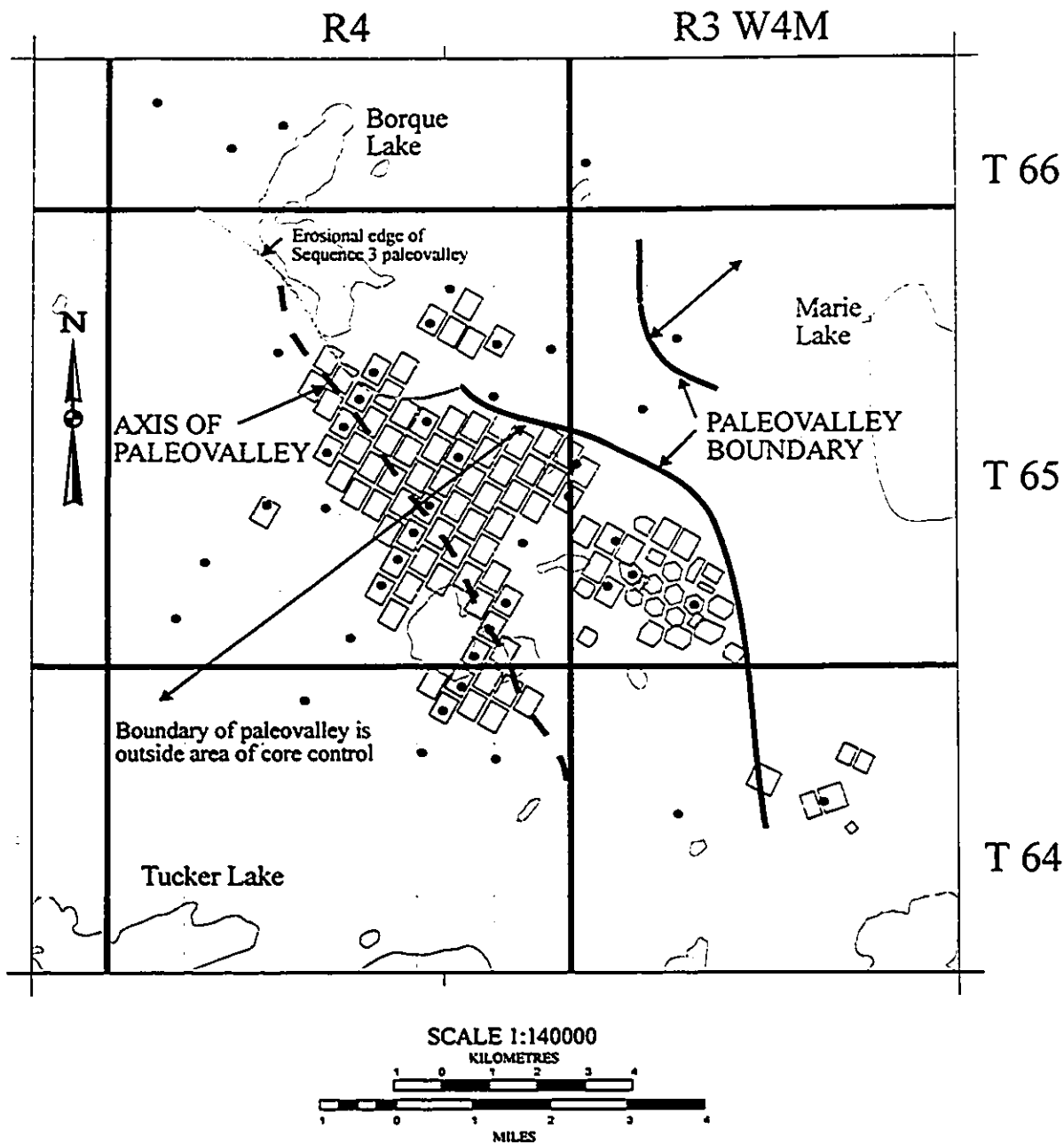


Figure 4.16: Map of study area showing the incised valley axis of Sequence Boundary 3 (SB 3). The axis is based on core data. Some valley walls lie outside the area of core control. Large dots represent wells with core utilized for this project.

(Facies Association 1) occur at the base of the succession. In addition, fluvial deposits of Parasequence A become narrower to the northwest, whereas the tidal-fluvial strata widen.

Parasequence B, up to 20m thick, is bounded below by FS 3 or FS/SB 3 and above by SB 4 or FS/SB 4. It consists of a thin, basal transgressive unit gradationally overlain by upward-coarsening shoreface to foreshore deposits (Facies Association 5).

Summary:

A fall of relative sea level and subsequent fluvial valley incision created SB 3. Subsequent marine transgression flooded the fluvial valleys and created coastal embayments. High sediment flux allowed development of a tide-dominated delta (Parasequence A) that infilled the embayments. Subsequently, continued relative sea level rise flooded the area. This flooding created FS 3. Later progradation deposited the marine shoreface to foreshore strata of the overlying Parasequence B. Similar to sequences 1 and 2, parasequences A and B of Sequence 3 stack in a retrogradational pattern, and therefore represent strata of the transgressive systems tract.

4.3.4 Sequence 4

Description:

Sequence 4 is bounded below by SB 4 or FS/SB 4 and above by SB 5. In the study area, two paleovalleys occur along SB 4: a northern, northwest-southeast trending valley 3km wide, and a southern valley of similar trend and unknown width (Fig. 4.17). Chert pebbles and other lithic fragments commonly occur as a layer up to 10cm thick, just above SB 4 (Fig. 4.18). Three parasequences (A, B, and C) make up Sequence 4 and stack in a retrogradational pattern. Parasequence A is up to 25m thick, is bounded below by SB 4 and above by FS 4, and comprises the fill of the two paleovalleys. The northern paleovalley consists of Parasequence A, which is made up of tidal-fluvial strata (Facies

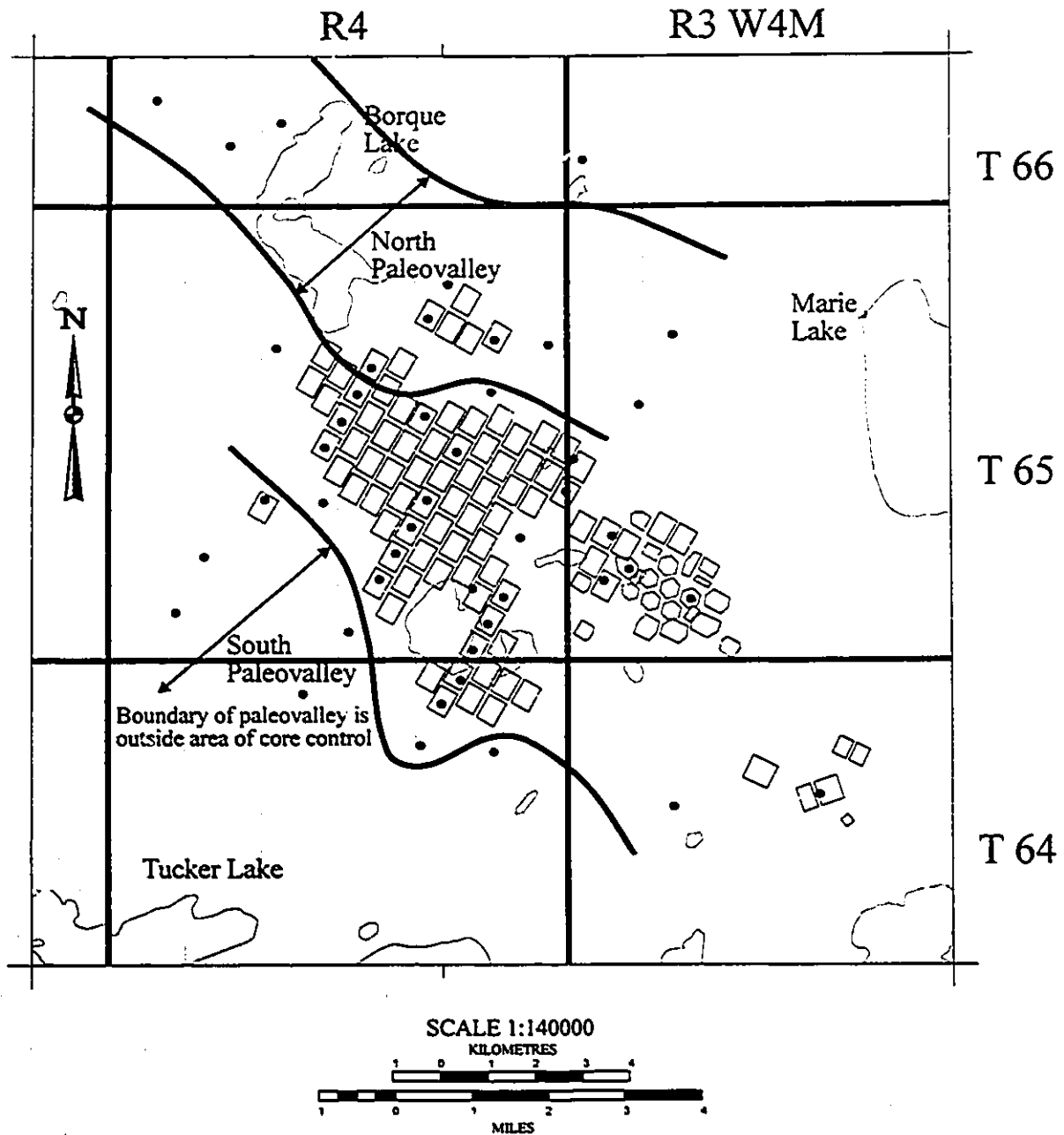


Figure 4.17: Map of study area, showing locations of incised valleys on Sequence Boundary 4 (SB 4). The valley walls were drawn from core data. The southeast wall of the south paleovalley is outside the area of core control. Large dots represent wells with core utilized for this project.

Figure 4.18: Sequence Boundary 4 (SB 4) overlain by a zone of chert pebbles and angular sideritized mudstone clasts. The photograph is from 2-25-65-4W4 (P7-13). Scale bar is 5 cm.



Association 3) are erosively overlain by fluvial deposits (Facies Association 4). In contrast, Parasequence A in the southern paleovalley (at least in the area with core control) contains only tidal-fluvial deposits.

Parasequence B is typically 2m thick and is bounded by FS 4 or FS/SB 4 below and by FS 5 above. Shelf mudstones of Facies Association 6 comprise Parasequence B strata. Distal shelf facies of Facies Association 6 are up to 1m thick, and make up Parasequence C. This unit overlies FS 5 and in turn is erosively overlain by SB 5.

Summary:

As a result of a relative fall of sea level, SB 4 was formed and fluvial valleys were incised. This was followed by relative sea level rise and transgression that flooded the valleys, creating coastal embayments. Due to high sediment flux, progradational tide-dominated deltaic deposition persisted during transgression, but was terminated when relative sea level rise exceeded the rate of sediment input and flooded the embayment fill. Two stacked parasequences consisting of shelf and distal shelf mudstones were then deposited. Another relative sea level fall created SB 5 and terminated deposition of the Clearwater Formation. Similar to earlier sequences, parasequences A, B, and C of Sequence 4 comprise retrogradational transgressive systems tract deposition.

4.4 Summary of Sequence Stratigraphic Model

Within the study area, the Clearwater Formation comprises four unconformably bounded depositional sequences. Sequence 1 consists of shoreface and offshore marine units of the transgressive systems tract, but contains no lowstand or highstand systems tract deposits. Similarly, sequences 2 and 3 are composed of strata accumulated during transgressive systems tract deposition, and consist of tide-dominated deltaic deposits that infill northwest-trending embayments. In both cases these strata are overlain by shoreface

deposits. Deposits of lowstand and highstand systems tracts are also absent in sequences 2 and 3. Sequence 4 consists of tidal-fluvial and fluvial embayment fill deposits overlain successively by shelf and distal shelf parasequences, and together represent transgressive systems tract deposition. Again, lowstand and highstand systems tract deposits are absent.

Alternatively, the stratal patterns of the Clearwater Formation may be interpreted to be the result of (local) autocyclic rather than (regional) allocyclic controls. Each "incised valley" could represent erosion as a result of autocyclic channel avulsion within a deltaic system under conditions of continuously rising relative sea level. Each embayment fill, therefore, could be interpreted as a separate delta lobe deposit. Based on this scenario, strata of the Clearwater Formation represent one depositional sequence, bounded by SB 1 below and SB 5 above. On a local scale, the stratal geometry created by either interpretation would be similar, the principal difference between the two being that the allocyclic interpretation requires each sequence boundary to be correlative regionally, whereas each "avulsion surface" would terminate locally. In this study, the area of investigation is not large enough to make a distinction. However, regional correlations by other workers (D. McPhee, personal communication) suggest that the allocyclic model better fits the Clearwater Formation of north-central Alberta. The interpretation of four unique depositional sequences is therefore regarded as more consistent for this study.

If each depositional sequence is considered to comprise transgressive embayment strata confined laterally within a lowstand incised valley, interesting stratigraphic relationships can be resolved. The embayment infilled by Sequence 2 strata has a minimum width of 13 km (measured perpendicular to its deepest channelized trend; Fig. 4.14). These strata are made up of both distal and proximal delta facies associations. Sequence 3 strata were deposited in two embayments (Fig. 4.16), one of which is at least 7 km wide and consist of proximal tide-dominated deltaic facies overlain by fluvial channel-fill deposits. The youngest sequence, Sequence 4, consists of two embayment

fills (Fig. 4.17) that probably merge to the northwest of the study area. One of the embayments was about 3 km wide, and is filled mostly by fluvial deposits. The other embayment is of uncertain width, and is infilled by tidal-fluvial deposits.

From the foregoing it is apparent that each younger unconformity-bounded embayment fill becomes narrower and progressively less marine in character. Each successive sequence thus exhibits a basinward progradation of similar tide-dominated delta environments. In this model, the Clearwater Formation represents a prograding sequence set made up of four depositional sequences. The depositional sequences probably represent smaller-scale (4th order?) relative sea level fluctuations that are superimposed on a larger-scale (3rd order?) relative sea level rise.

4.5 Controls on Embayment Distribution

Three incised valley fills in the study area are recognized above the Wabiskaw Member. An obvious question is: why were these incised valleys confined to a narrow geographical region? Intuitively, a likely answer is that local tectonic control played an important role. The main structural feature in the study area is the northwest-trending Athabasca Anticline (Chapter 1; Fig. 1.6). This feature has been interpreted to be a positive structural element related to syn- or post Mannville dissolution of Devonian evaporites (Vigrass, 1965, 1968; Orr *et al.*, 1977; Wilmot and *et al.*, 1983; Beynon, 1991). Deep-seated fluids flowing upward through conduits below the pre-Cretaceous unconformity may have been responsible for evaporite dissolution and, consequently, the anticlinal trend (Ranger and Pemberton, 1988).

The map of Devonian structures (Fig. 1.6) shows the general trend of the southeast-plunging, northwest-trending Athabasca Anticline. This structural trend is sub-parallel to the trend of the paleovalleys in Sequences 2 and 3 (Figs. 4.14 and 4.16 respectively). It is reasonable to assume that the same dissolution processes that created

the Athabasca Anticline were responsible for topographic lows that localized valley incision during a fall of relative sea level. Evidence for local tectonic movement is limited to isopach variations between flooding surfaces (see stratigraphic cross-sections, Figs. 4.6 to 4.11). Isopach variation tends to be greatest at or near the thickest trend of sequences 2 and 3.

4.6 Hydrocarbon Occurrence

The hydrocarbon resource at Cold Lake has been interpreted to have originally been a light or medium grade crude (Vigrass, 1968; Masters, 1984). Hydrocarbons were generated from Jurassic and Devonian shales and migrated through Upper Devonian aquifers into Lower Cretaceous strata where they were trapped and subsequently biodegraded (Bachu, 1995). Approximately 90,000 barrels per day (Cheadle *et al.*, 1995) of this highly viscous crude bitumen (API° 10 and 4,000 to 10,000 cP @ 37.8°C; Minken, 1974) are presently produced from the Clearwater Formation at Cold Lake. Because of its viscous nature, *in situ* thermal recovery techniques such as cyclic steam stimulation are required to extract the bitumen (Harrison *et al.* 1981; Hutcheon *et al.* 1989; Cheadle *et al.* 1995).

During the recovery process of steam flooding, the presence of mudstone interbeds and clasts can result in the precipitation of new minerals which in turn significantly reduce the reservoir permeability (Shepherd, 1981; Hutcheon and Abercrombie 1990). In strata of the Clearwater Formation, the best reservoir quality is present in medium cross-bedded and massive sandstones of Facies Association 4, and fine to medium, planar-laminated and massive sandstones of Facies Association 2. Based on visual observation, these coarser-grained facies are more highly bitumen saturated and contain little detrital mudstone. As a result, these strata retain good reservoir quality

because they lack the in-situ source of chemical components that allow diagenetic, pore-filling clay minerals to grow as a result of steaming.

The growth of diagenetic clay minerals is another factor that reduces intergranular porosity and permeability. Moreover, the common occurrence of the Fe-rich clay mineral berthierine, typically as a grain coating, is a major concern at Cold Lake (J. Dudley, personal communication). It is beyond the scope of this study, however, to determine the possible genetic relationship between berthierine growth and primary reservoir sedimentology. Nevertheless, the new model of lithofacies distribution described here will provide an improved framework for evaluating any such relationships.

Reservoir quality strata (facies associations 2 and 4) occur in deltaic and fluvial paleovalley fills of each depositional sequence. Thus, within each paleovalley trend there are two potential zones of reservoir-quality strata. These include the sand flat deposits (Facies Association 2) of coastal embayment strata and fluvial deposits (Facies Association 4) that exist headward of each embayment. In the study area, sand flat reservoir strata occur in the paleovalley fill of Sequence 2, but terminate to the north. South of the study area the incised valley fill of Sequence 2 should contain fluvial deposits and, perhaps, additional reservoir-quality strata. In the paleovalley fill of Sequence 3, extensive sand flat and fluvial reservoir-quality strata occur in the study area. In addition, within the study area, Sequence 4 contains abundant fluvial reservoir strata deposited in northwest-trending paleovalleys. Sand flat strata, however, were not observed in the paleovalleys of Sequence 4, but are interpreted to exist northwest (basinward) of the study area along the paleovalley trend toward Amoco Canada's Wolf Lake Field. Potential reservoir quality strata should occur, therefore, northwest of the study area in Sequence 4 strata.

As stated earlier, during a fall of relative sea level, fluvial valleys incise as the shoreline is displaced basinward. Subsequently, a lowstand shoreline deposit is formed at some distance basinward of the area where valleys are incised (Van Wagoner *et al.*, 1988). The interpreted occurrence of three incised valley fills in the Cold Lake study area thus suggests that three lowstand shoreline deposits could occur to the north-northwest of the study area. To date, these potential hydrocarbon reservoirs have not been discovered, nor adequately interpreted.

5. SUMMARY AND CONCLUSIONS

The Lower Cretaceous (Aptian to Albian) Clearwater Formation at Cold Lake, Alberta contains a complex assemblage of siliciclastic strata. It unconformably overlies sandstone and mudstone of the McMurray Formation and is, in turn, erosively overlain by sandstone and mudstone of the Grand Rapids Formation. Together the McMurray, Clearwater, and Grand Rapids Formations compose the Mannville Group in northeast Alberta. On the basis of detailed core analysis, Clearwater Formation strata have been subdivided into eight lithofacies. These lithofacies, in turn, have been grouped into six environmentally significant facies associations. These recurring facies associations are: 1) Tidal bar, 2) Sand flat, 3) Tidal-fluvial channel, 4) Fluvial channel, 5) Shoreface to foreshore, and 6) Offshore.

Correlation of the facies associations and their bounding time-significant surfaces (sequence boundaries and marine flooding surfaces) has led to the interpretation of Clearwater Formation strata as marine and tidally-influenced coastal embayment deposits that comprise four unconformity-bounded depositional sequences, each of which contains two or more parasequences. Sequence 1 is bounded below by Sequence Boundary 1 (SB 1) and above by SB 2, and is made up of two parasequences separated by a marine flooding surface (FS 1). It comprises strata of the Wabiskaw Member and consists of a shoreface sandstone parasequence (Facies Association 5), overlain by a distal shelf parasequence (Facies Association 6).

Sequence 2 is bounded below by SB 2 and above by SB 3 and consists of two parasequences separated by FS 2. Parasequence A consists of the fill of a northwest-trending incised valley, which consists of northward prograding coastal embayment strata (facies associations 1, 2, and 3). The valley fill is overlain by the marine shoreface to foreshore deposits of Parasequence B (Facies Association 5).

Sequence 3 is bounded below by SB 3 and above by SB 4 and consists of a northwest-trending incised valley and a second coeval paleovalley of unknown orientation. Two stacked parasequences (A and B) compose Sequence 3. Parasequence A forms the fill of both incised valleys, and is made up of northward-prograding coastal embayment strata (facies associations 1, 2, and 3) overlain by fluvial deposits (Facies Association 4). A marine flooding surface (FS 3) separates the valley fill from the overlying shoreface to foreshore deposits of Parasequence B.

Sequence 4 is bounded below by SB 4 and above by SB 5 and consists of two northwest-trending incised valleys and three parasequences. Parasequence A forms the valley fill and consists of tidal-fluvial deposits (Facies Association 3) overlain by fluvial strata (Facies Association 4). A marine flooding surface (FS 4) separates the valley fill below from shelf mudstone of Parasequence B above (Facies Association 6). Another marine flooding surface (FS 5) separates Parasequence B from the overlying distal shelf mudstone of Parasequence C (Facies Association 6).

Each depositional sequence is made up of backstepping parasequence sets, indicating deposition in the transgressive systems tract. The incised valley fills of each sequence, however, are interpreted as prograding tide-dominated deltaic deposits accumulated when sediment flux periodically exceeded the relative sea level rise. Furthermore, each successive sequence indicates a basinward shift of deltaic deposition within a larger-scale marine transgression. Strata of the Clearwater Formation thus make up a progradational sequence set.

The recognition of tide-dominated deltaic strata within the four depositional sequences of the Clearwater Formation significantly improves the predictability of reservoir quality distribution. Strata of facies associations 2 (sand flat) and 4 (fluvial channel) offer the best reservoir quality. In the study area, these strata occur in each of the

upper three sequences, but are most abundant in sequences 3 and 4. The spatial distribution of reservoir quality strata in Sequence 2 is such that additional hydrocarbon deposits are inferred to exist south of the study area, along the axis of the incised valley trend. Furthermore, northwest of the study area, Sequence 4 is interpreted to contain additional reservoir quality strata along the trend of its incised valleys.

REFERENCES

- Allen, G.P. 1991. Sedimentary processes and facies in the Gironde estuary: a recent model for macrotidal estuarine systems. *In*: Smith, D.G., Reinson, B.A., Zaitlin, B.A. and Rahmani, R.A. eds. *Clastic Tidal Sedimentology*. Canadian Society of Petroleum Geologists. Memoir 16. p. 29-40.
- Allen, J.R.L. 1965. A review of the origin and characteristics of recent alluvial sediments. *Sedimentology*. v. 5. p. 98-191.
- Allen, J.R.L. 1970. Studies in fluvial sedimentation: a comparison between fining-upwards cyclothems with special reference to coarse-member composition and interpretation. *Journal of Sedimentary Petrology*. v. 40. p.298-323.
- Allen, J.R.L. 1982. Mud drapes in sand wave deposits: a comparison of fining-upwards cyclothems, with special reference to coarse-member composition and interpretation. *Journal of Sedimentary Petrology*. v. 40. p. 298-323.
- Allen, J.R.L. 1984. *Sedimentary structures: Their Character and Physical Basis*. Amsterdam. Elsevier. 1256p.
- Alexander, C.R., Nittrouer, C.A., Demaster, D.J., Park, Y.-A. and Park, S.-C. 1991. Macrotidal mud flats of the southwestern Korean coast: A model for interpretation of intertidal deposits. *Journal of Sedimentary Petrology*. v. 61. p. 805-824.
- Arnott, R.W.C. 1995. The parasequence definition - are transgressive deposits inadequately addressed? *Journal of Sedimentary Research*. v. B65. No. 1. p. 1-6.
- Arnott, R.W.C. and Hand, B.M. 1989. Bedforms, primary structures and grain fabric in the presence of suspended sediment rain. *Journal of Sedimentary Petrology*. v. 59. p. 1062-1069.
- Arnott, R.W.C. and Southard, J.B. 1990. Exploratory flow-duct experiments on combined-flow bed configurations, and some implications for interpreting storm-event stratification. *Journal of Sedimentary Petrology*. v. 60. p. 211-219.
- Bachu, S. 1995. Synthesis and model of formation-water flow, Alberta Basin, Canada. *American Association of Petroleum Geologists Bulletin*. v. 79. No. 8. p. 1159-1178.
- Badgley, P.C. 1952. Notes on the subsurface stratigraphy and oil and gas geology of the Lower Cretaceous Series in central Alberta: Geological Survey of Canada Paper 52-11. 12 p.

- Bell, R. 1885. Report on part of the Athabasca River, North West Territory. Geological and Natural Survey and Museum of Canada Report of Progress for 1882-1884. p. CC1-CC37.
- Beynon, B.M. 1991. Sedimentology and petroleum geology of the Lower Cretaceous Grand Rapids Formation Cold Lake Oil Sands area, Alberta. Unpublished M.Sc. thesis. University of Alberta. 267p.
- Beynon, B.M. 1994. Sedimentology and depositional history of the McMurray Formation and Wabiskaw Member, northeastern Alberta. *In: C.S.P.G. Mannville Core Conference*. Compiled by: Pemberton, S.G., James, D.P., and Wightman, D.M. Canadian Society of Petroleum Geologists. p. 245-278.
- Bhattacharya, J.P. and Walker, R.G. 1992. Deltas. *In: Walker, R.G. and James, N.P eds. Facies Models, Response to Sea Level Change*. St. John's. Geological Association of Canada. p. 157-177.
- Boer, P.L., de Oost, A.P. and Visser, M.J. 1989. The diurnal inequality of the tide as a parameter for recognizing tidal influences. *Journal of Sedimentary Petrology*. v. 59. p. 912-921.
- Boyd, R., Dalrymple, R.W., and Zaitlin, B.A. 1992. Classification of clastic coastal depositional environments. *Sedimentary Geology*. v. 80. p. 139-150.
- Burst, J.F. 1958. 'Glauconite' pellets; their mineral nature and applications to stratigraphic interpretations. *American Association of Petroleum Geologists Bulletin*. v. 42. p. 310-327.
- Cameron, W.M. and Pritchard, D.W., 1963. Estuaries. *In M.N. Hill ed. The Sea*. New York. John Wiley & Sons. p. 306-324.
- Cant, D.J. and Stockmal, G.S. 1989. The Alberta Foreland Basin: Relationship between stratigraphy and cordilleran terrane-accretion events. *Canadian Journal of Earth Sciences*. 26, p 1964-1975.
- Cheadle, B.A., Dudley, J.S., Eastwood, J.E., Lovell, R.W.W., Reed, K.W., Stancliffe, R.P.W., and Van Wagoner, J.C. 1995. Integrated reservoir description for resource management at Cold Lake, Alberta. Abstract. *In: Exploration, Evaluation and Exploitation 1995: The economic integration of geology and formation evaluation*. Compiled by: Cheadle, B.A., Leggitt, S., Raddysh, H., White, K., and Yeo, C. Joint symposium of the Canadian Society of Petroleum Geologists and Canadian Well Logging Society, 1995 Core Session.
- Clack, W.J.F. 1967. Sedimentology of the Mannville Group in the Cold Lake area, Alberta. Unpublished M.Sc. thesis. University of Calgary, Alberta. 95p.

- Clifton, H.E., 1969. Beach lamination: nature and origin. *Marine Geology*. v. 7. p. 553-559.
- Clifton, H.E. 1976. Wave-formed sedimentary structures - a conceptual model. *In*: Davis, R.A., Jr. and Ethington, R.L. *eds*. Beach and nearshore sedimentation. Society of Economic Paleontologists and Mineralogists. Special Publication No. 24. p. 126-148.
- Clifton, H.E. 1982. Estuarine deposits. *In*: Scholle, P.A. and Spearing, D. *eds*. Sandstone Depositional Environments. American Association of Petroleum Geologists Memoir 31. p. 179-189.
- Clifton, H.E., Hunter, R.E., and Phillips, R.L. 1971. Depositional structures and processes in the non-barred high-energy nearshore. *Journal of Sedimentary Petrology*. v. 41. No. 3. p. 651-670.
- Coleman, J.M. and Wright, L.D. 1975. Modern river deltas: variability of processes and sand bodies. *In*: Broussard, M.L. *ed*. Deltas: models for exploration. Houston. Houston Geological Society. p. 99-149.
- Collinson, J.D. 1969. The sedimentology of the Grindslow Shales and the Kinderscout Grit: a deltaic complex in the Namurian of northern England. *Journal of Sedimentary Petrology*. v. 39. p. 194-221.
- Collinson, J.D. 1986. Alluvial sediments. *In*: Reading H.G. *ed*. Sedimentary environments and facies. Oxford. Blackwell Scientific Publications Ltd. p. 20-62.
- Collinson, J.D. and Thompson, D.B. 1982. Sedimentary structures. London. George Allen and Unwin (Publishers) Ltd. 194p.
- Dalrymple, R.W., Knight R.J., Zaitlin, B.A., and Middleton, G.V. 1990. Dynamics and facies model of a macrotidal sand-bar complex, Cobequid Bay-Salmon River Estuary (Bay of Fundy). *Sedimentology*. v. 37. p. 577-612.
- Dalrymple, R.W., Makino, Y., and Zaitlin, B.A. 1991. Temporal and spatial patterns of rhythmite deposition on mud flats in the macrotidal Cobequid Bay-Salmon River estuary, Bay of Fundy, Canada. *In*: Smith, D.G., Reinson, B.A., Zaitlin, B.A. and Rahmani, R.A. *eds*. Clastic Tidal Sedimentology. Canadian Society of Petroleum Geologists. Memoir 16. p. 137-160.
- Dalrymple, R.W., Zaitlin, B.A., and Boyd, R. 1992. Estuarine facies models: conceptual basic and stratigraphic implications. *Journal of Sedimentary Petrology*. v. 62. no. 6. p 1130-1146.

- Dalrymple, R.W. 1992. Tidal depositional systems. *In: Walker, R.G. and James, N.P eds. Facies Models. Response to Sea Level Change.* St. John's. Geological Association of Canada. p. 195-218.
- Davis, R.A., Jr., and Clifton, H.E. 1987. Sea-level change and the preservation potential of wave-dominated and tide-dominated coastal sequences. *In: Nummedal, D., Pilkey, O.H., and Howard J.D. eds. Sea-level Fluctuations and Coastal Evolution.* Society of Economic Paleontologists and Mineralogists. Special Publication No. 41. p. 223-239.
- Defant, A. 1958. Ebb and flow. The tides of Earth, air, and water. Ann Arbor. University of Michigan Press. 121p.
- Droser, M.L. and Bottjer, D.J. 1986. A semiquantitative classification of ichnofabric. *Journal of Sedimentary Petrology.* v. 56. p. 558-569.
- Dyer, K.R. 1973. Estuaries: A Physical Introduction. London. John Wiley & Sons. 140 p.
- Ekdale, A.A., Bromley, R.G., and Pemberton, S.G. 1984. Ichnology. Society of Economic Paleontologists and Mineralogists. Short Course No. 15. 317p.
- Elliott, T., 1986. Deltas. *In: Reading, H.G. ed. Sedimentary environments and facies.* Oxford. Blackwell Scientific Publications. p. 113-154.
- Energy Resources Conservation Board. 1990. Crude Bitumen Reserves Atlas.
- Galloway, W.E. 1975. Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. *In: Broussard, M.L. ed. Deltas: Models for Exploration.* Houston Geological Society. p. 87-98.
- Galloway, W.E. and Hobday, D.K. 1983. Terrigenous clastic depositional systems. New York. Springer-Verlag. 423p.
- Glaister, R.P. 1959. Lower Cretaceous of southern Alberta and adjoining areas. *American Association of Petroleum Geologists Bulletin.* v. 43. No. 3. p. 590-640.
- Gressly, A. 1838. See Teichart (1958).
- Harms, J.C., Southard, J.B., and Walker, R.G. 1982. Structure and Sequence in Clastic Rocks. Society of Economic Paleontologists and Mineralogists, Short Course 9. 249 p.
- Harris, P.T. 1994. Incised valleys and backstepping deltaic deposits in a foreland-basin setting, Torres Strait and Gulf of Papua, Australia. *In: Dalrymple, R.W., Boyd, R., and Zaitlin, B.A. eds. Incised-valley systems: origin and sedimentary sequences.* Society of Economic Paleontologists and Mineralogists (Society for Sedimentary Geology). Special Publication No. 51. p. 97-108.

- Harrison, D.B., Glaister, R.P. and Nelson, H.W. 1981. Reservoir description of the Clearwater oil sand, Cold Lake, Alberta. *In: Meyer R.F. and Steele C.T. eds. The Future of Heavy Crude Oils and Tar Sands.* McGraw Hill. p. 264-280.
- Hawley, N. 1981. Flume experiments on the origin of flaser bedding. *Sedimentology.* v. 28. p. 699-712.
- Hayes, M.O. 1979. Barrier island morphology. *In: Leatherman, S.P. ed. Barrier Islands from the Gulf of Mexico to the Gulf of St. Lawrence.* New York. Academic Press. p.1-28.
- Hayes, B.J.R., Christopher, J.E., Rosenthal, L., Los, G., McKercher, B., Minken, D., Trembley, Y.M., and Fennell, J. 1994. Cretaceous Mannville Group of the Western Canada Sedimentary Basin. *In: Geological Atlas of the Western Canada Sedimentary Basin.* Compiled by: Mossop, G.D. and Shetsen, I. Alberta Geological Survey/Canadian Society of Petroleum Geologists/Geological Survey of Canada/Alberta Energy. p. 317-334.
- Houbolt, J.J.H.C. 1968. Recent sediments in the southern bight of the North Sea. *Geologie en Mijnbouw.* v. 47. p. 245-273.
- Hutcheon, I. and Abercrombie, H.J. 1990. Fluid-rock interaction in thermal recovery of bitumen, Tucker Lake Pilot, Cold Lake, Alberta. *In: Meshri, I.D. and Ortoleva, P.J. eds. Prediction of reservoir quality through chemical modeling.* American Association of Petroleum Geologists. Memoir 49. p. 161-170.
- Hutcheon, I., Abercrombie, H.J., Putnam, P.E., Gardner, R. and Krouse, H.R. 1989. Diagenesis and sedimentology of the Clearwater Formation at Tucker Lake. *Bulletin of Canadian Petroleum Geology.* v. 37, no. 1, p. 83-97.
- Jackson, P.C. 1984. Paleogeography of the Lower Cretaceous Mannville Group of Western Canada. *In: Masters, J.A. ed. Elmworth - Case Study of a Deep Basin Gas Field.* American Association of Petroleum Geologists. Memoir 38. p. 49-78.
- Jardine, D. 1974. Cretaceous oil sands of Western Canada. *In: Hills, L.V. ed. Oil Sands, Fuel of the Future.* Canadian Society of Petroleum Geologists. Memoir 3. p. 50-67.
- MacEachern, J.A. 1989. Estuarine channel deposition within the Lower Cretaceous Waseca Formation, Upper Mannville Group, Lloydminster area, Saskatchewan. *In: Reinson, G.E. ed. Modern and ancient examples of clastic tidal deposits - A core and peel workshop.* p. 50-59.
- MacEachern, J.A. and Pemberton, S.G. 1994. Ichnological aspects of incised valley fill systems from the Viking Formation of the Western Canada Sedimentary Basin, Alberta, Canada. *In: Dalrymple, R.W., Boyd, R., and Zaitlin, B.A. eds. Incised-*

valley systems: origin and sedimentary sequences. Society of Economic Paleontologists and Mineralogists (Society for Sedimentary Geology). Special Publication No. 51. p. 45-60.

- MacEachern, J.A., Raychauduri, I., and Pemberton, S.G. 1992. Stratigraphic applications of the *Glossifungites* ichnofacies: delineating discontinuities in the rock record. *In: Pemberton, S.G. ed. Applications of Ichnology to Petroleum Exploration.* Tulsa. Society of Economic Paleontologists and Mineralogists (Society of Sedimentary Geology) Core workshop 17. p. 169-198.
- Masters, J.A. 1984. Lower Cretaceous Oil and Gas in Western Canada. *In: Masters, J.A. ed. Elmworth - Case Study of a Deep Basin Gas Field.* American Association of Petroleum Geologists. Memoir 38. p. 1-33.
- Meckel, L.D. 1975. Holocene sand bodies in the Colorado delta area, northern Gulf of California. *In: Broussard, M.L. ed. Deltas: models for exploration.* Houston. Houston Geological Society. p. 239-265.
- McConnell, R.G. 1893. Report on a portion of the district of Athabasca comprising the country between Peace River, and Athabasca River north of Lesser Slave Lake. Geological Survey of Canada Annual Report 1890-91. V 5. Part 1, Section D. p. 1-67.
- McLearn, F.H. 1917. Athabasca River section, Alberta. Geological Survey of Canada. Summary Report, 1916. p. 145-151.
- Minken, D.F. 1974. The Cold Lake oil sands: geology and a reserve estimate. *In: Hills, L.V. ed. Oil Sands, Fuel of the Future.* Canadian Society of Petroleum Geologists. Memoir 3. p. 84-99.
- Mitchum, R.M. 1977. Seismic stratigraphy and global changes of sea level, Part 1: Glossary of terms used in seismic stratigraphy. *In: Payton, C.E. ed. Seismic stratigraphy-applications to hydrocarbon exploration.* American Association of Petroleum Geologists. Memoir 26. p. 205-212.
- Morton, R.A. 1981. Formation of storm deposits by wind-forced currents in the Gulf of Mexico and North Sea. *In: Nio, S.D., Shuttenehm, R.T.E., and van Weering, Tj.C.E. eds. Holocene marine sedimentation in the North Sea Basin.* International Association of Sedimentologists. Special Publication No. 5. p. 385-396.
- Nauss, A.W. 1945. Cretaceous stratigraphy of the Vermilion area, Alberta, Canada. *American Association of Petroleum Geologists Bulletin.* v. 29. No. 11. p. 1605-1629.
- Nichols, M.M., and Briggs, R.B. 1985. Estuaries. *In: Davis, R.A., Jr. ed. Coastal sedimentary environments (2nd ed.).* New York. Springer-Verlag. p. 77-142.

- Nio, S.D. and Yang, C.S. 1991. Diagnostic attributes of clastic tidal deposits: a review. *In: Smith, D.G., Reinson, B.A., Zaitlin, B.A. and Rahmani, R.A. eds. Clastic Tidal Sedimentology. Canadian Society of Petroleum Geologists. Memoir 16. p. 3-27.*
- Orr, R.D., Johnstone, J.R. and Manko, E.M. 1977. Lower Cretaceous geology and heavy-oil potential of the Lloydminster area. *Bulletin of Canadian Petroleum Geology. v. 25. p. 1187-1221.*
- Pemberton, S.G., MacEachern, J.A. and Frey, R.W. 1992. Trace Fossil Facies Models: Environmental and Allostratigraphic Significance. *In: Walker, R.G. and James, N.P. eds. Facies Models, Response to Sea Level Change. St. John's. Geological Association of Canada. p. 47-72.*
- Pickering, K.T., Hiscott, R.N., and Hein, F.J. 1988. Deep Marine Environments: clastic sedimentation and tectonics. London. Unwin Hyman. 416p.
- Posamentier, H.W., Jervey, M.T., and Vail, P.R. 1988. Eustatic controls on clastic deposition I-conceptual framework. *In: Wilgus, C.T., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A. and Van Wagoner, J.C. eds. Sea-level changes: an integrated approach. Society of Economic Paleontologists and Mineralogists. Special Publication No. 42. p. 109-144.*
- Prentice, M. and Wightman, D. 1987. Mineralogy of the Clearwater Formation, Cold Lake oil sands deposit. *Geological Association/Mineralogical Association of Canada. Program with Abstracts. v. 12. p. 82.*
- Price, R.A., Monger, J.W.H., and Muller, J.E. 1981. Cordilleran cross-section, Calgary to Victoria. *In: Thompson, R.I. and Cook, D.G. eds. Field guides to geological and mineralogical deposits: Calgary. Geological Association of Canada.*
- Pritchard, D.W. 1967. What is an estuary: a physical viewpoint? *In Lauff, G.H. ed. Estuaries. Washington, D.C. American Association for Advancement of Science. Publication 83. p. 3-5.*
- Proctor, R.M., Taylor, G.C., and Wade, J.A. 1984. Oil and natural gas resources of Canada. *Geological Survey of Canada. Paper 83-31.*
- Pryor, W.A. 1975. Biogenic sedimentation and alteration of argillaceous sediments in shallow marine environments. *Geological Society of America Bulletin. p. 1244-1254.*
- Putnam, P.E. and Pedskalny, M.A. 1983. Provenance of Clearwater Formation sandstones, Cold Lake, Alberta, with comments on feldspar compositions. *Bulletin of Canadian Petroleum Geology. v. 31. p.148-160.*

- Putnam, P.E. and Pedskalny, M.A. 1982. Lithic sandstones with a large Volcanic component: the Mannville Group (Lower Cretaceous) of the Tucker Lake area, east-central Alberta, Canada. Proceedings of the International Association of Sedimentologists Meeting, August 22-28, Hamilton, Ontario, Abstracts with program. p. 88.
- Rahmani, R.A. 1988. Estuarine tidal channel and nearshore sedimentation of a late Cretaceous epicontinental sea, Drumheller, Alberta, Canada. *In*: de Boer, P.L., Van Gelder, A., and Nio, S.D. eds. Tide-influenced Sedimentary Environments and Facies. Dordrecht. D. Reidel Publishing Company. p. 433-471.
- Ranger, M.J. and Pemberton, S.G. 1988. Marine influence on the McMurray Formation in the Primrose area, Alberta. *In*: James, D.P. and Leckie, D.A. eds. Sequences, stratigraphy, sedimentology: surface and subsurface. Canadian Society of Petroleum Geologists. Memoir No. 15. p. 439-450.
- Reineck, H.E. and Singh, I.B. 1980. Depositional sedimentary environments. New York. Springer-Verlag. 549 p.
- Reineck, H.E. and Wunderlich, F. 1968. Classification and origin of flaser and lenticular bedding. *Sedimentology*. v. 11. p. 99-104.
- Reinson, G.E. 1992. Transgressive barrier island and estuarine systems. *In* Walker, R.G. and James, N.P. eds. Facies Models, Response to Sea Level Change. St. John's. Geological Association of Canada. p. 179-194.
- Rennie, J.A. 1987. Sedimentology of the McMurray Formation on the Sandalta project study area, northern Alberta, and implications for oil sands development. *In*: Tillman, R.W. ed. Reservoir Sedimentology. Society of Economic Paleontologists and Mineralogists. Special Publication No. 40. p. 169-189.
- Ross, D.A. 1982. Introduction to oceanography (third edition). Englewood Cliffs, New Jersey. Prentice-Hall Inc. 544p.
- Rudkin, R.A. 1964. Lower Cretaceous. *In*: McCrossan, R.G. and Glaister, R.P. eds. Geological History of Western Canada. Calgary. Alberta Society of Petroleum Geologists. p. 156-168.
- Shepard, D.W. 1981. Steam stimulation recovery of Cold Lake bitumen. *In*: Meyer R.F. and Steele C.T. eds. The Future of Heavy Crude Oils and Tar Sands. McGraw Hill. p. 349-360.
- Smith, D.G. 1989. Comparative sedimentology of mesotidal (2 to 4 m) estuarine channel point bar deposition from modern examples and ancient Athabasca Oil Sands (Lower Cretaceous), McMurray Formation. *In*: Reinson, G.E. (ed.) Modern and ancient examples of clastic tidal deposits - A core and peel workshop. p. 60-65.

- Smith, D.G. 1994. Paleogeographic evolution of the Western Canada Sedimentary Basin Foreland Basin. *In: Geological Atlas of the Western Canada Sedimentary Basin.* Compiled by: Mossop, G.D. and Shetsen, I. Alberta Geological Survey/Canadian Society of Petroleum Geologists/Geological Survey of Canada/Alberta Energy. p. 277-296.
- Swift, D.J.P., 1975. Barrier-island genesis: evidence from the central Atlantic Shelf, eastern U.S.A. *Sedimentary Geology.* v. 14. p. 1-43.
- Teichert, C. 1958. Concepts of Facies. *American Association of Petroleum Geology. Bulletin.* v. 42. p. 2718-2744.
- Terwindt, J.H.J. and Breusers, H.N.C. 1972. Experiments on the origin of flaser, lenticular and sand-clay alternating bedding. *Sedimentology.* v. 19. p. 85-98.
- Thomas, R.G., Smith, D.G., Wood, J.M., Visser, J., Calverley-Range, E.A. and Koster, E.H. 1987. Inclined heterolithic stratification - terminology, description, interpretation and significance. *Sedimentary Geology.* v. 53. p. 123-179.
- Van Wagoner J.C., Posamentier, H.M., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S. and Hardenbol, J. 1988. An overview of sequence stratigraphy and key definitions. *In: Wilgus, C.T., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A. and Van Wagoner, J.C. eds. Sea-level changes: an integrated approach.* Society of Economic Paleontologists and Mineralogists. Special Publication No. 42. p. 39-45.
- Van Wagoner J.C., Mitchum, R.M., Campion, K.M., and Rahmanian, V.D., 1990. Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high-resolution correlation of time and facies. *American Association of Petroleum Geologists. Methods in Exploration Series.* No. 7. 55 p.
- Vigrass, L.V. 1965. General geology of Lower Cretaceous heavy oil accumulations in western Canada. *Journal of Canadian Petroleum Technology.* v. 4. p. 168-176.
- Vigrass, L.V. 1968. Geology of Canadian heavy oil sands. *American Association of Petroleum Geologists Bulletin.* v. 52. No. 10. p. 1984-1999.
- Visser, M.J. 1980. Neap-spring cycles reflected in Holocene subtidal large-scale bedform deposits: a preliminary note. *Geology.* v. 8. p. 543-546.
- Walker, R.G. 1992. Facies, Facies Models and Modern Stratigraphic Concepts. *In: Walker, R.G. and James, N.P eds. Facies Models, Response to Sea Level Change.* St. John's. Geological Association of Canada. p. 1-14.

- Walker, R.G. and Plint, A.G. 1992. Wave- and Storm-Dominated Shallow Marine Systems. *In: Walker, R.G. and James, N.P eds. Facies Models. Response to Sea Level Change.* St. John's. Geological Association of Canada. p. 219-238.
- Wightman, D.M., Pemberton, G. and Singh, C. 1987. Depositional Modeling of the Upper Mannville (Lower Cretaceous), east central Alberta: Implications for the recognition of brackish water deposits. *In: Tillman, R.W. ed. Reservoir Sedimentology. Society of Economic Paleontologists and Mineralogists. Special Publication No. 40.* p. 189-220.
- Williams, G.E. 1991. Upper Paleozoic tidal rhythmites, South Australia: sedimentary features, deposition, and implications for the earth's paleorotation. *In: Smith, D.G., Reinson, B.A., Zaitlin, B.A. and Rahmani, R.A. eds. Clastic Tidal Sedimentology. Canadian Society of Petroleum Geologists. Memoir 16.* p. 161-177.
- Wilmot, B. and Oliver, T.A. 1984. Computer applications to salt solution and deposition of the Mannville Group, Edam, west central Saskatchewan. *abs. In: Stott, D.F. and Glass, D.J. eds. Mesozoic of Middle North America. Canadian Society of Petroleum Geologists. Memoir No. 9.* p. 565.
- Wright, L.D., Coleman, J.M. and Thom, B.G. 1975. Sediment transport and deposition in a macrotidal river channel, Ord River, Western Australia. *In: Cronin, L.E. ed. Estuarine research. v. II.* New York. Academic Press. p. 309-322.
- Zaitlin, B.A., Dalrymple, R.W. and Boyd, R. 1993. The stratigraphic organization of incised-valley systems associated with relative sea-level changes. *In: Dalrymple, R.W., Boyd, R., and Zaitlin, B.A. eds. Incised-valley systems: origin and sedimentary sequences. Society of Economic Paleontologists and Mineralogists (Society for Sedimentary Geology). Special Publication No. 51.* p. 45-60.

APPENDIX A. CORE DESCRIPTIONS

Core from 45 wells were described in detail for this study. This section includes the graphical strip-logs from each cored well. The strip-logs were produced from AppleCore computer software (courtesy M. Ranger, University of Alberta) and have been plotted out at a vertical scale of 1:100. Due to hardware and software problems, some files were lost or overwritten. As a result only 37 of the original 45 strip-logs are included here. The strip-logs presented here include:

3 -29 -64 -3 W4
12 -18 -65 -3 W4
8 -19 -65 -3 W4
6 -29 -65 -3 W4
12 -6 -66 -3 W4
13 -25 -64 -4 W4
13 -26 -64 -4 W4
10 -33 -64 -4 W4
6 -35 -64 -4 W4 (D55-13)
10 -35 -64 -4 W4 (D52-14)
13 -1 -65 -4 W4 (D24-13)
2 -2 -65 -4 W4 (D26-13)
8 -2 -65 -4 W4 (D25-13)
5 -3 -65 -4 W4 (J43-8)
9 -6 -65 -4 W4
6 -8 -65 -4 W4
2 -10 -65 -4 W4 (D11-8)
8 -10 -65 -4 W4 (D9-8)
16 -10 -65 -4 W4 (J16-8)
1 -13 -65 -4 W4 (C2-8)
4 -14 -65 -4 W4 (A4-8)
15 -14 -65 -4 W4 (R5-13)
1 -16 -65 -4 W4 (J22-13)
4 -16 -65 -4 W4
16 -16 -65 -4 W4 (J7-13)
5 -22 -65 -4 W4 (J1-13)
12 -22 -65 -4 W4 (J2-13)
14 -22 -65 -4 W4 (H5-13)
4 -23 -65 -4 W4 (R2-13)
12 -24 -65 -4 W4 (Q6-8)
4 -25 -65 -4 W4 (P3-13)
12 -26 -65 -4 W4 (M3-13)

14 -26 -65 -4 W4 (M5-8)
4 -28 -65 -4 W4 (L5-8)
15 -5 -66 -4 W4
7 -7 -66 -4 W4
3 -9 -66 -4 W4

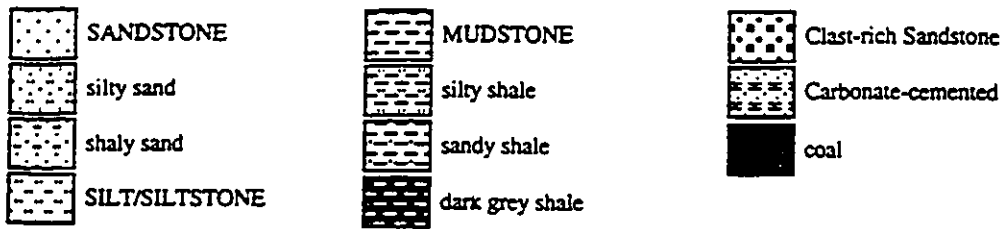
Wells that were analyzed but not presented here include:

3-27-64-3W4 (MAY B12A)
10-5-65-3W4 (CA4)
1-7-65-3W4 (GOB3)
3-7-65-3W4 (DDOB6)
10-7-65-3W4 (BB29)
11-12-65-4W4
16-12-65-4W4 (D23-6A)
2-25-65-4W4 (P7-13)

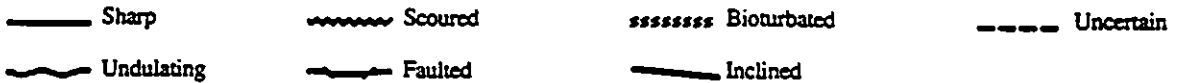
A legend of symbols used for the strip-logs is presented in Figure A.1. In addition, a key to strip-logs is given in Figure A.2.

Figure A.1: LEGEND

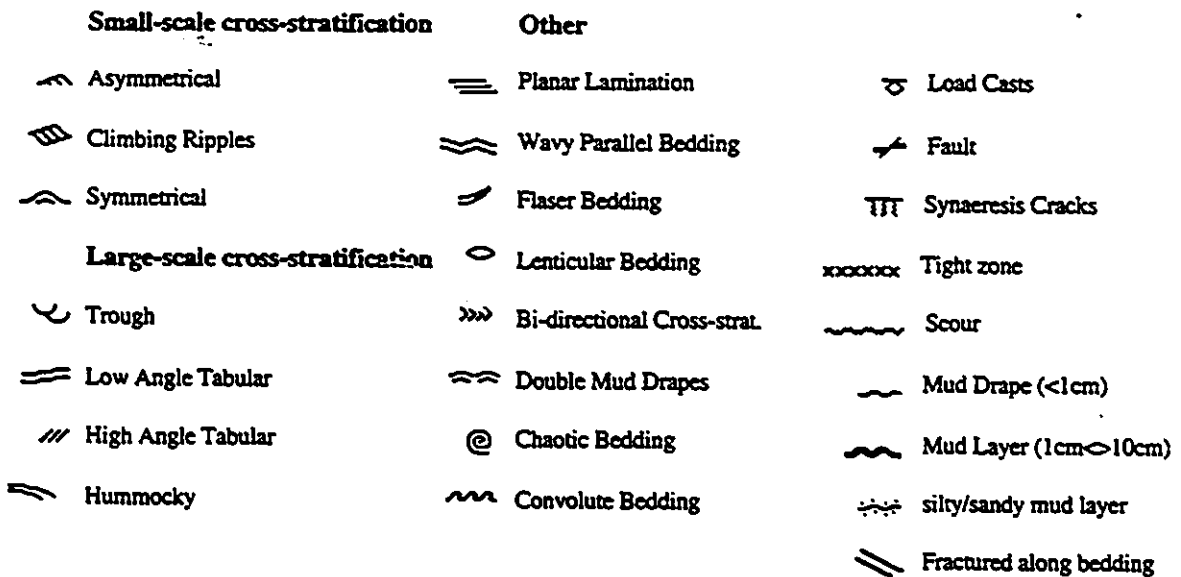
LITHOLOGY



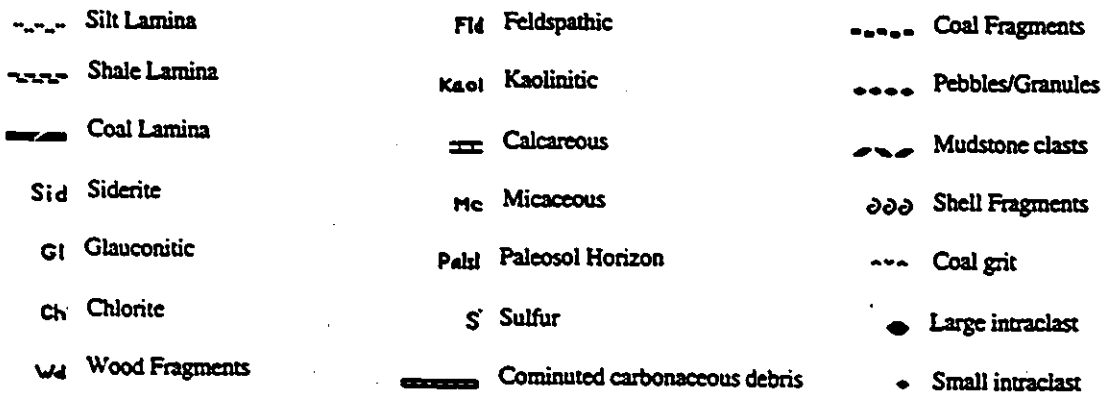
CONTACTS












PHYSICAL STRUCTURES



















LITHOLOGIC ACCESSORIES



Legend continued

	Rootlets
	Planolites
	Diplocraterion
	Ophiomorpha
	Rhizocorallium
	Conichnus
	Asterosoma
	Chondrites
	Zoophycos

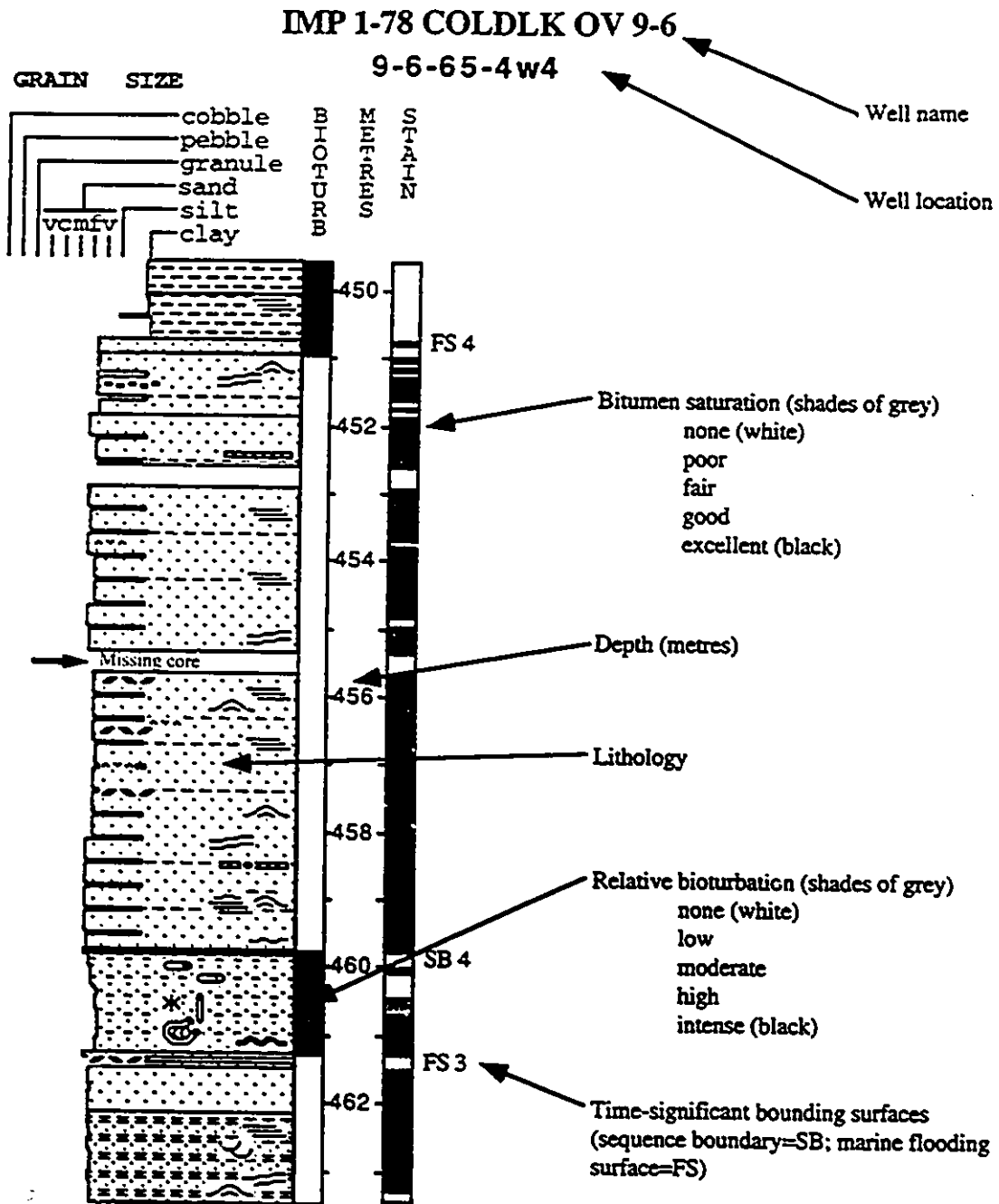
ICHNOFOSILS

	Skolithos		Monocraterion
	Palaeophycus		Gyrolithes
	Arenicolites		Macaronichnus
	Escape Trace		Trichichnus
	Cylindrichnus		Bergaueria
	Rosselia		Helminthopsis
	Terebellina		Thalassinoides
	Subphyllochorda		Teichichnus

FOSSILS

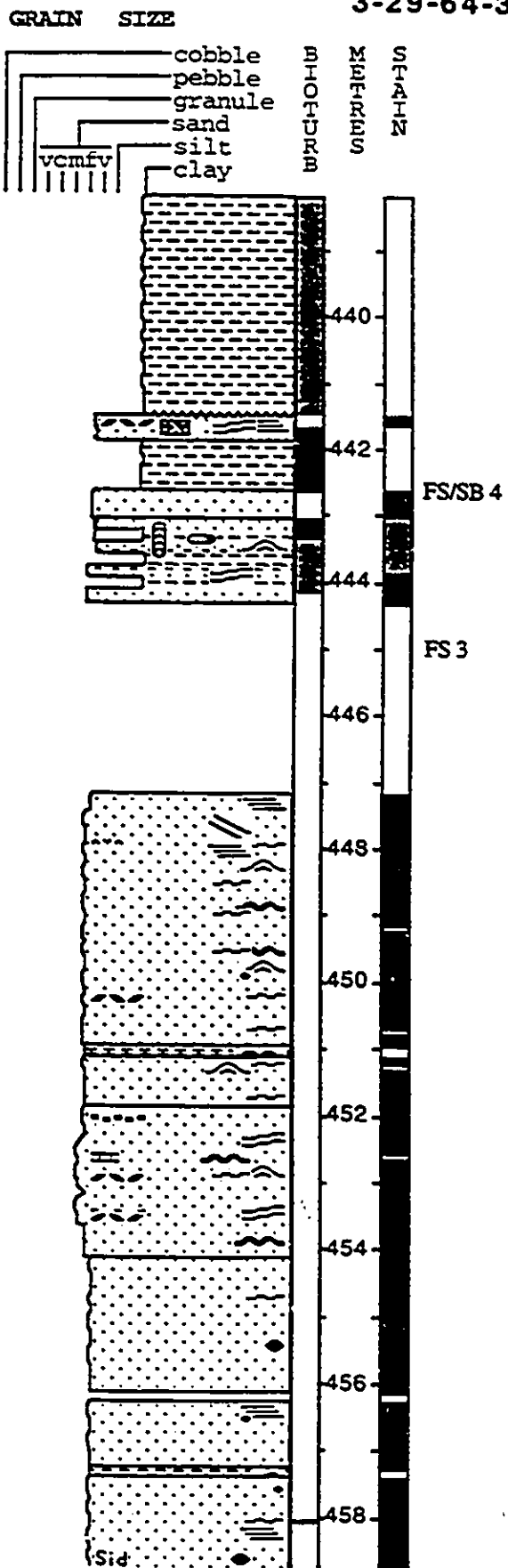
	Pelecypods		Brachiopods
	Ostracods		Gastropods

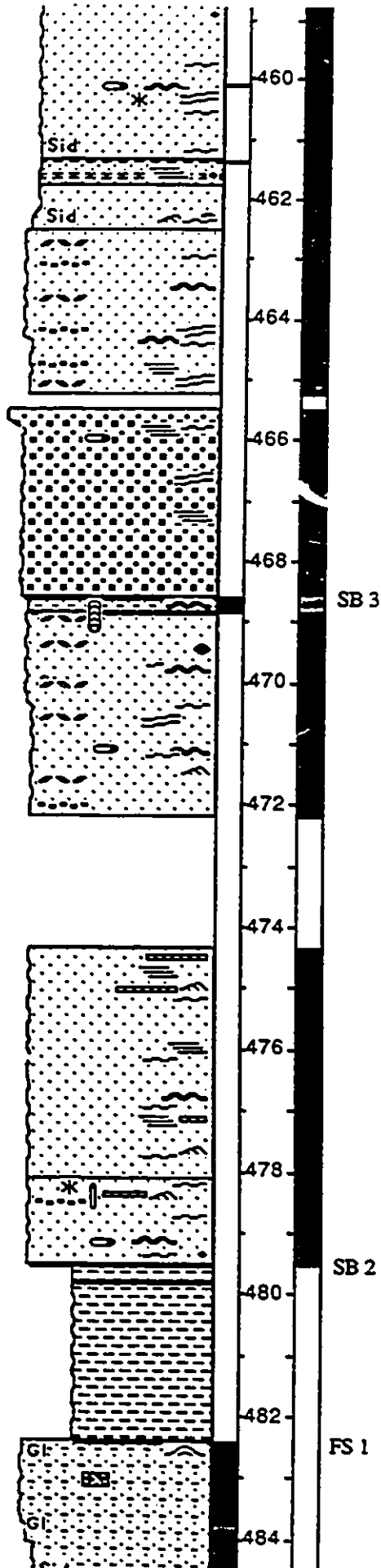
Figure A.2: Sample strip-log

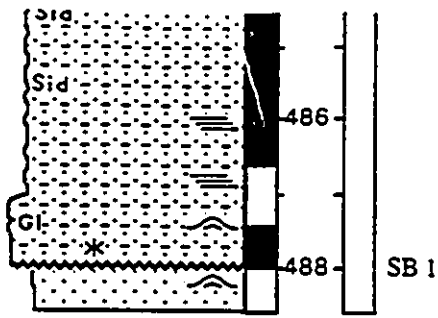


ESSO ETHEL LK 3-29-64-3W4

3-29-64-3w4

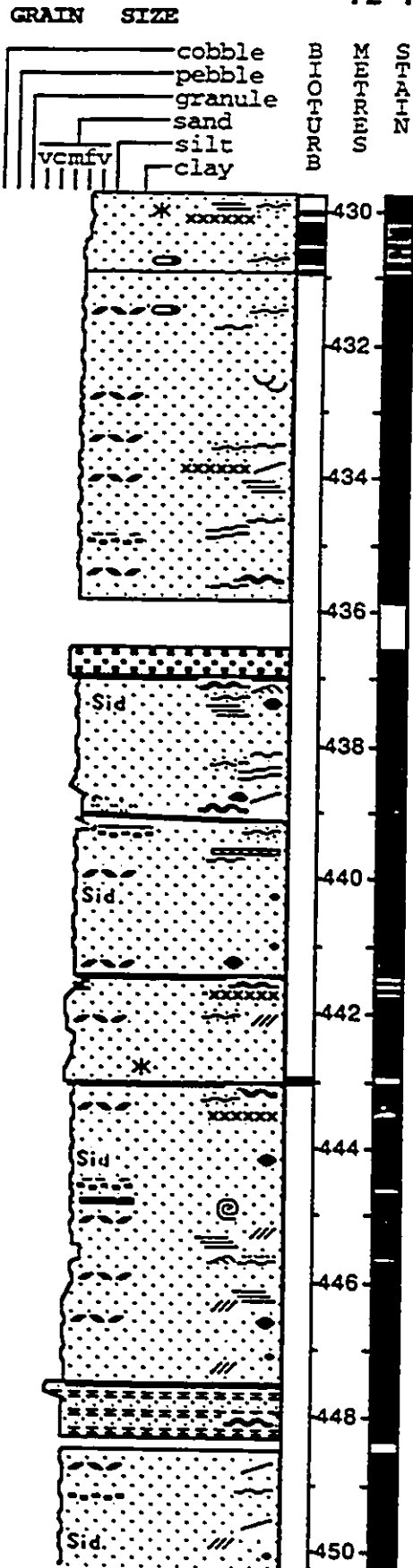




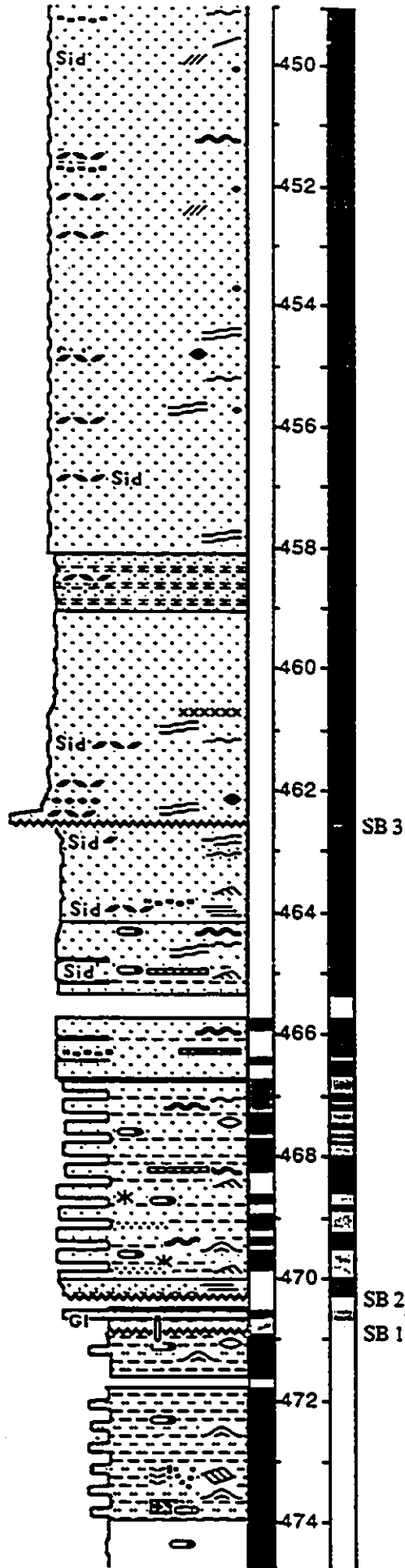


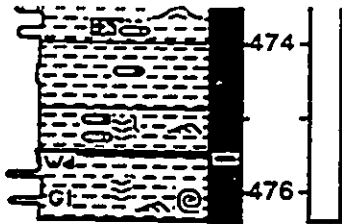
IMP 77 MARIE OV 12-18

12-18-65-3w4



Continued from previous page



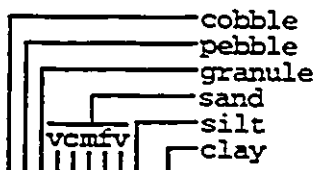


Continued from previous page

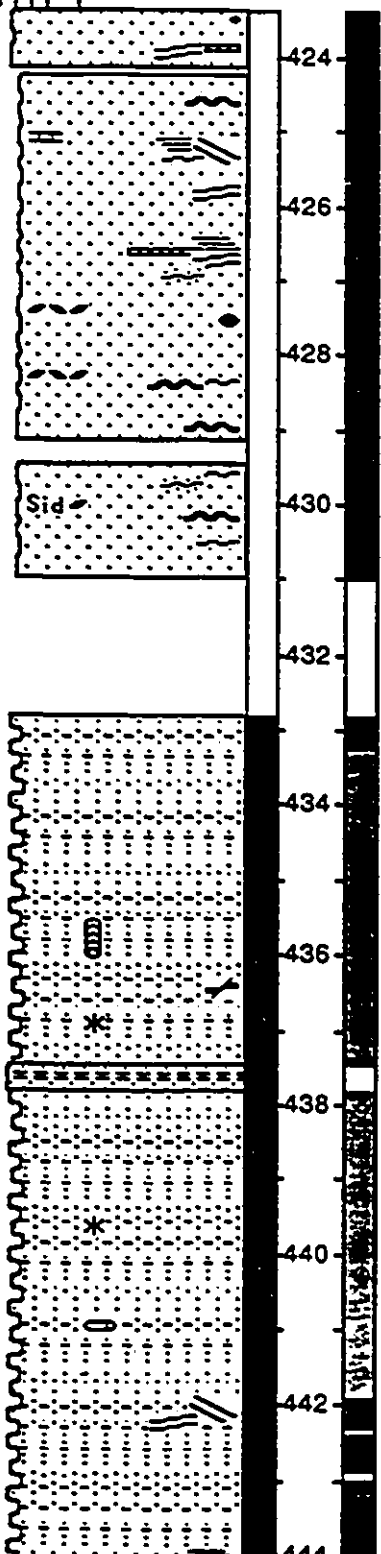
IMP COLDLK OV 8-19

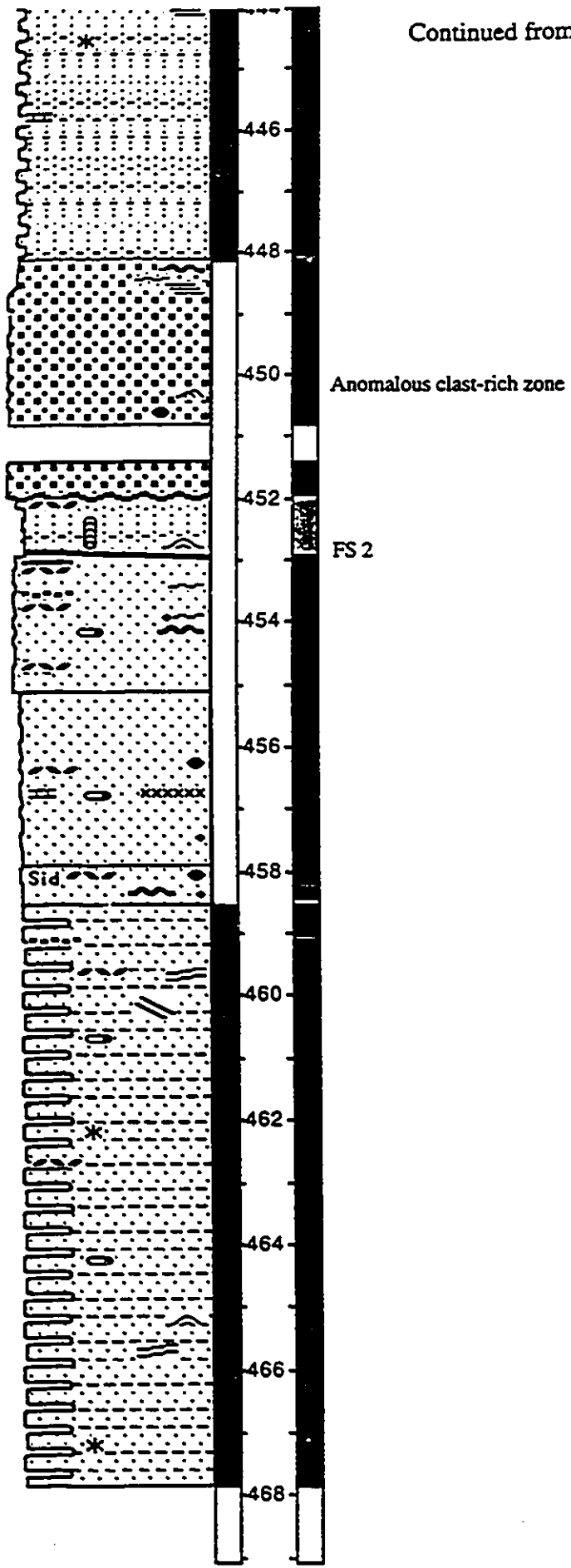
8-19-65-3w4

GRAIN SIZE



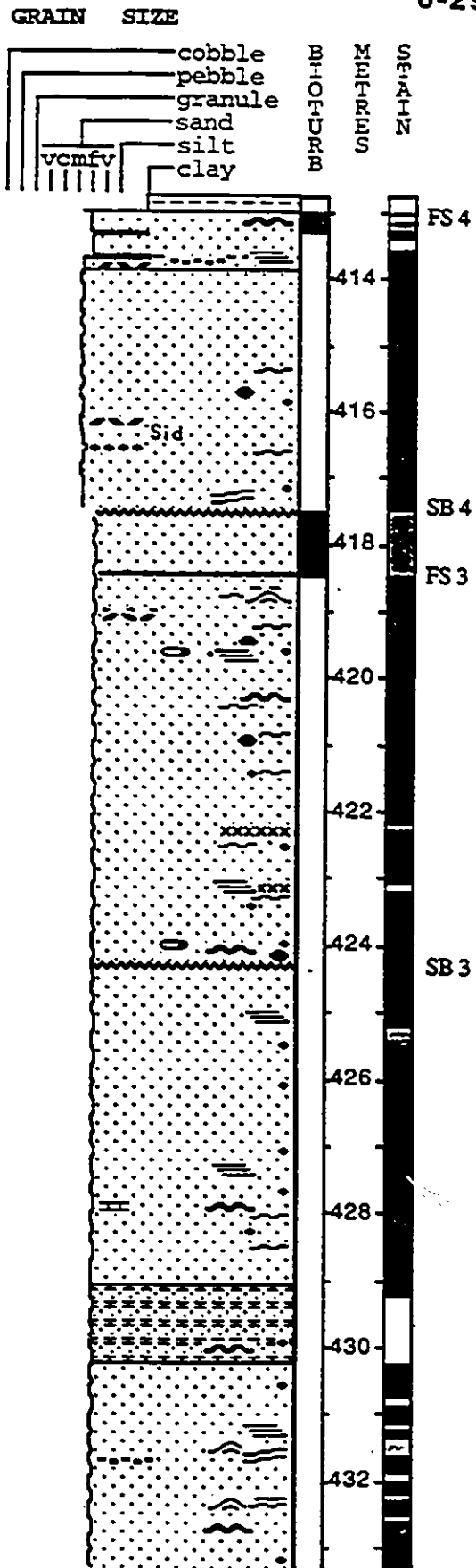
SHOULDER
MARKERS
STAIN

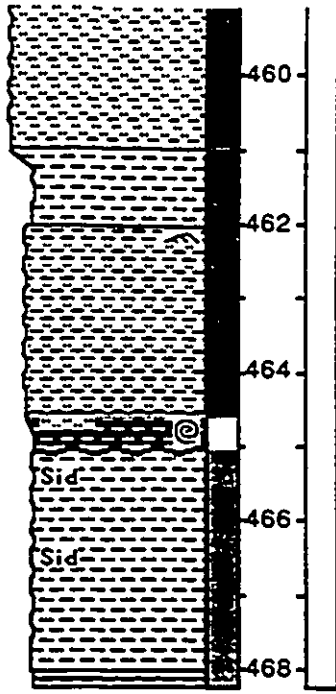




ESSO 85 COLDLK OV 6-29

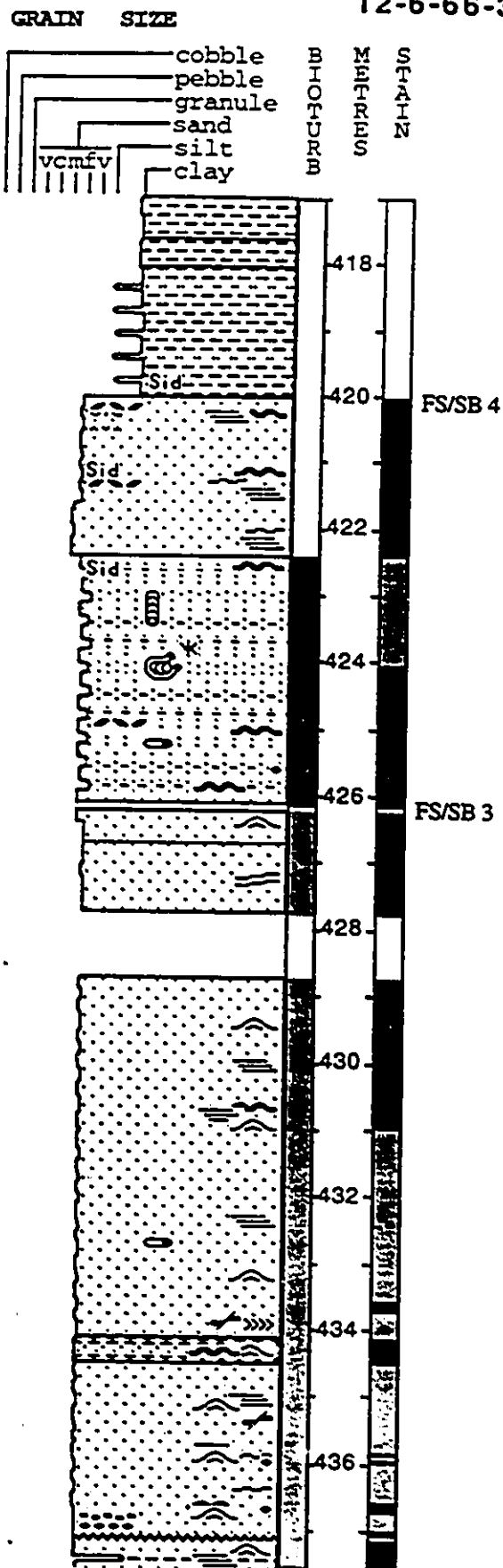
6-29-65-3w4

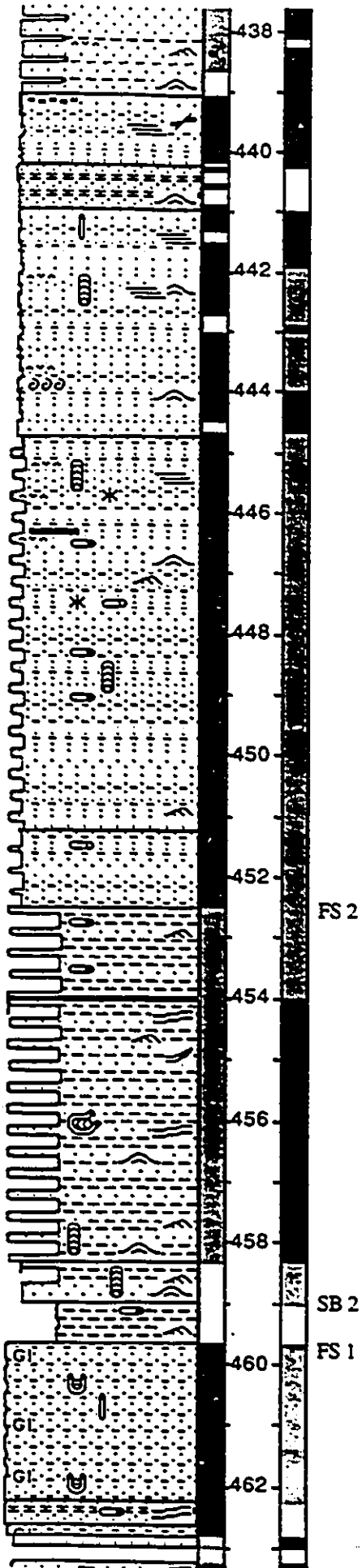




ESSO 85 COLDLK 0V 12-6

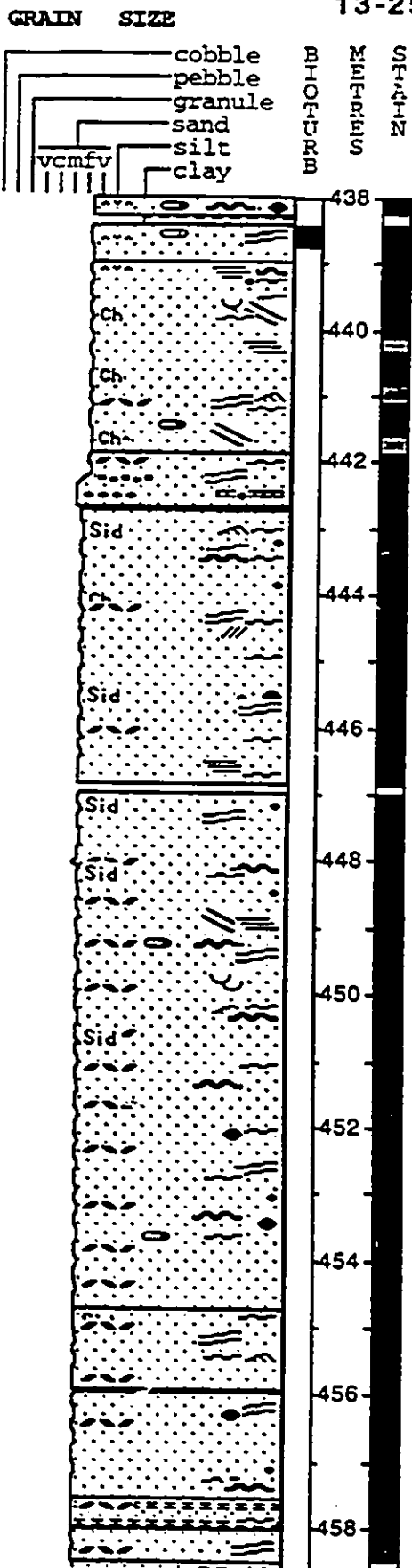
12-6-66-3w4

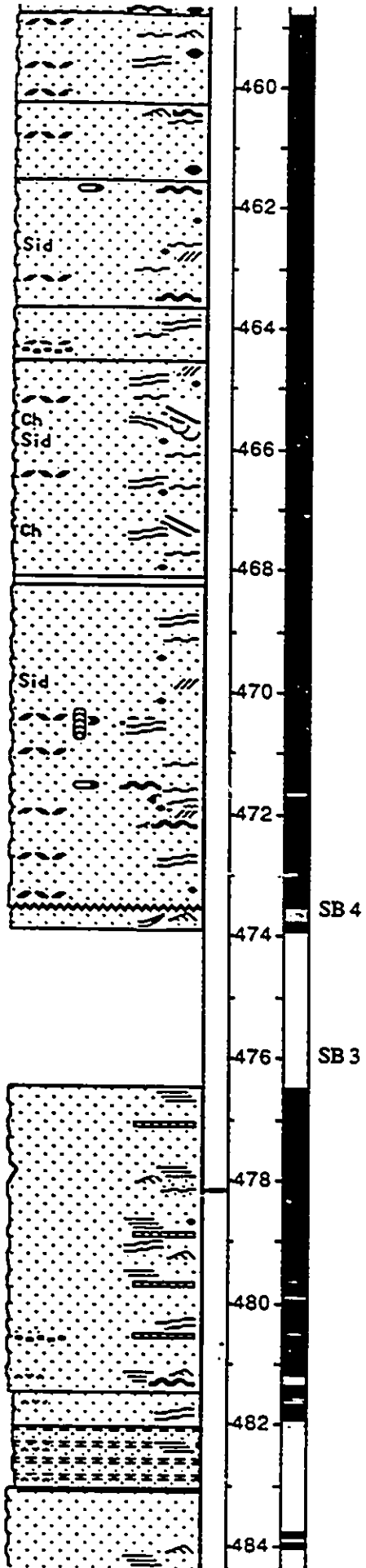


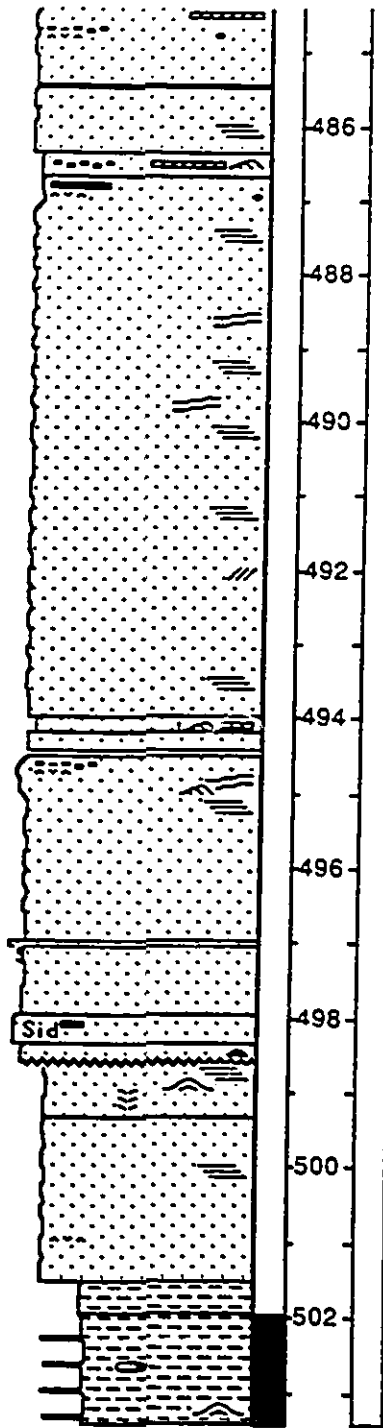


ESSO 88 COLDLK OV 13-25

13-25-64-4w4



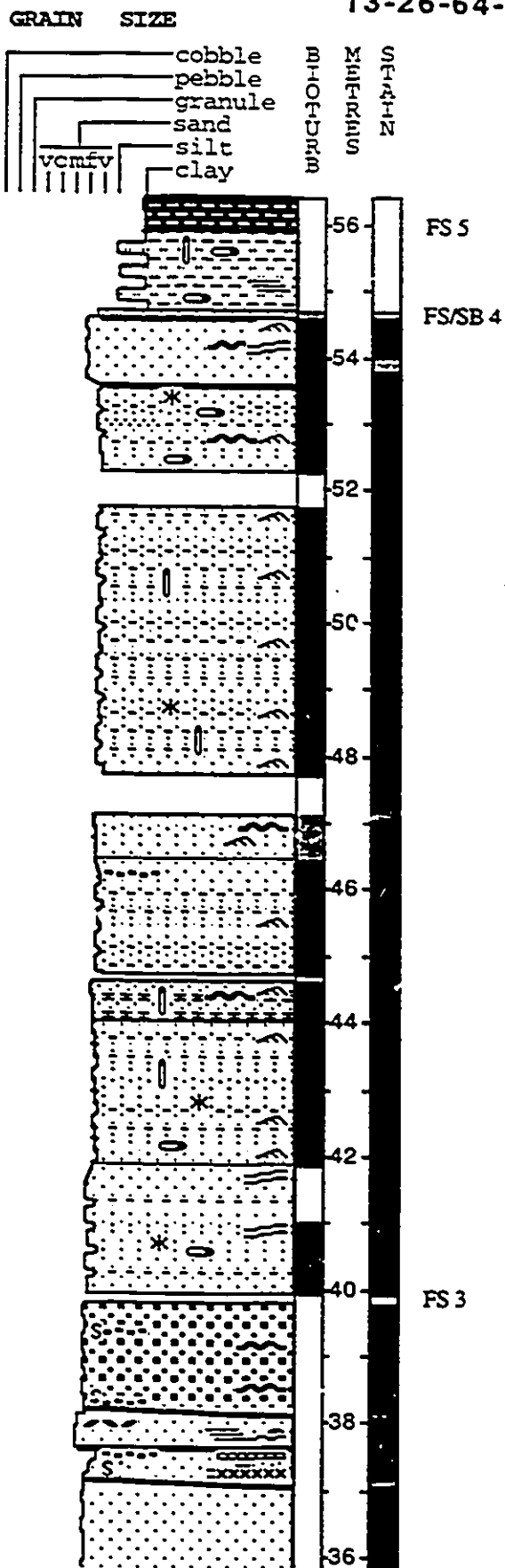


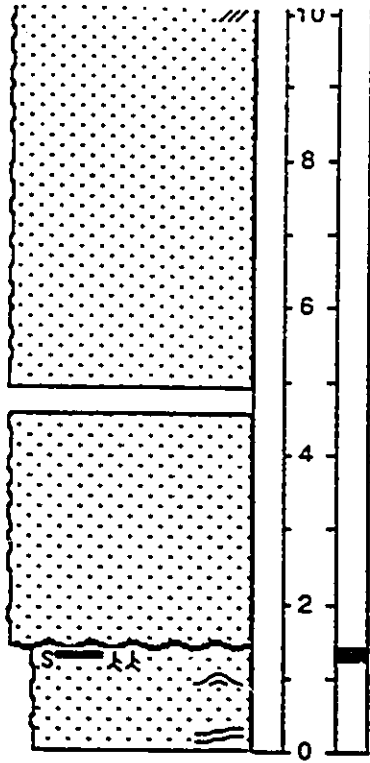


SB 2

IMP COLDLK OV 13-26

13-26-64-4w4



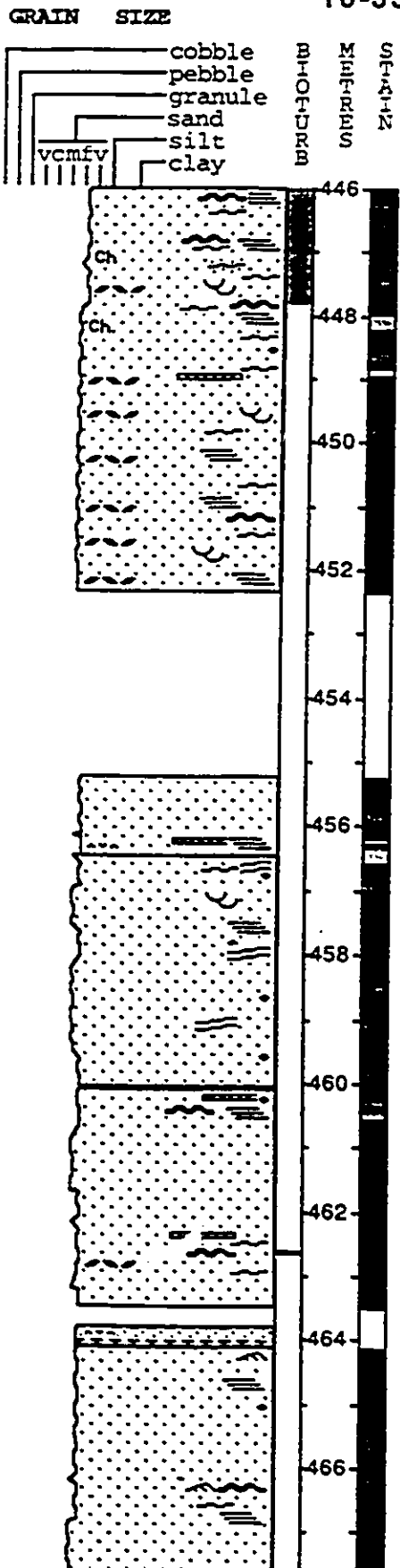


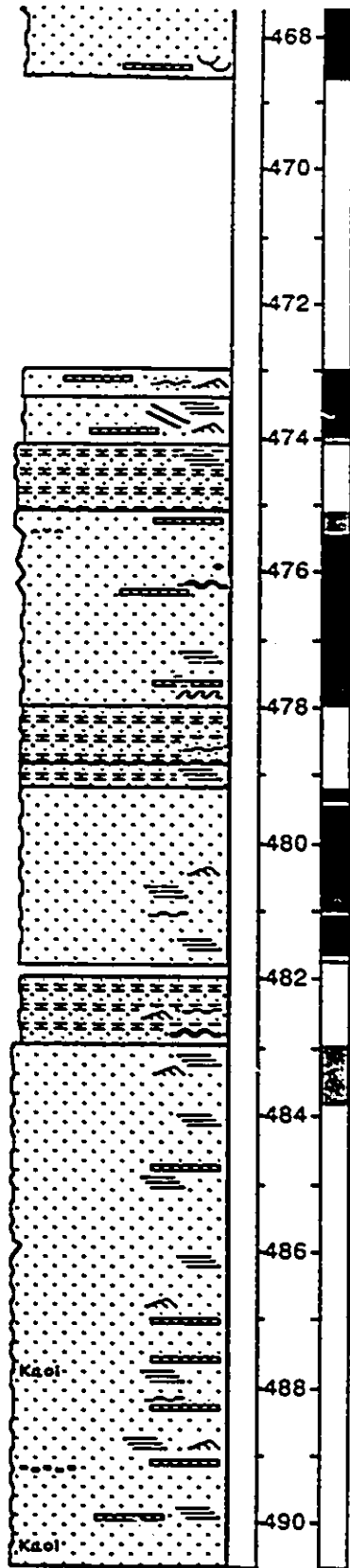
SB 2

McMurray Formation

ESSO 85 COLDLK OV 10-33

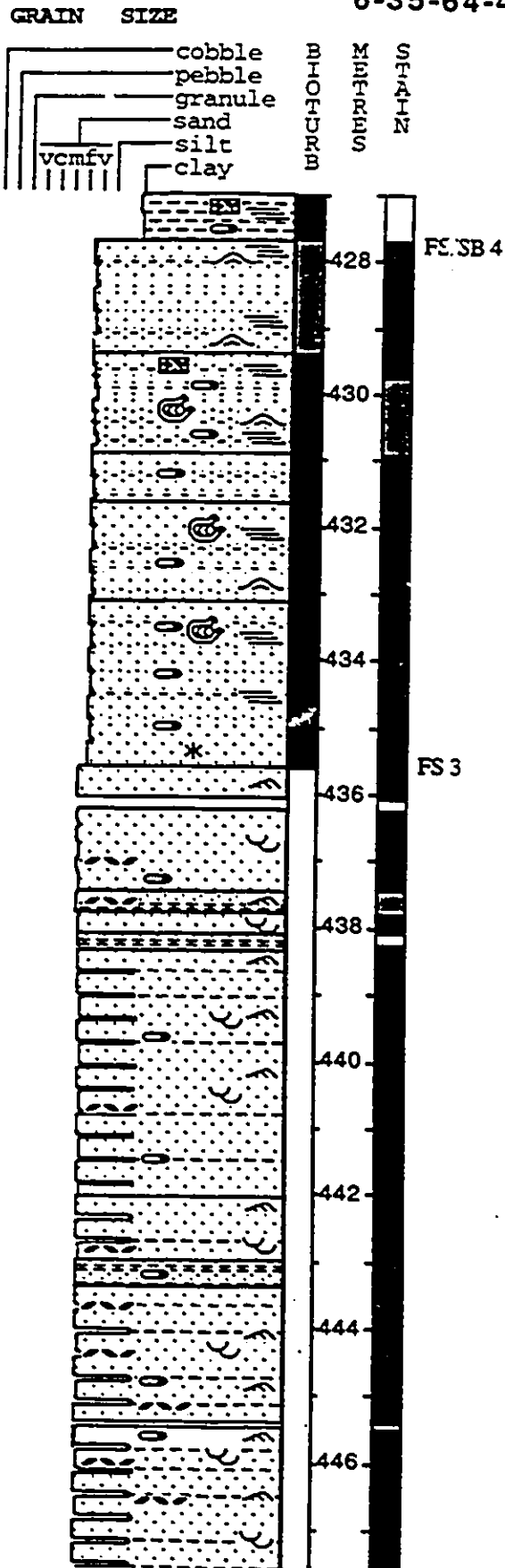
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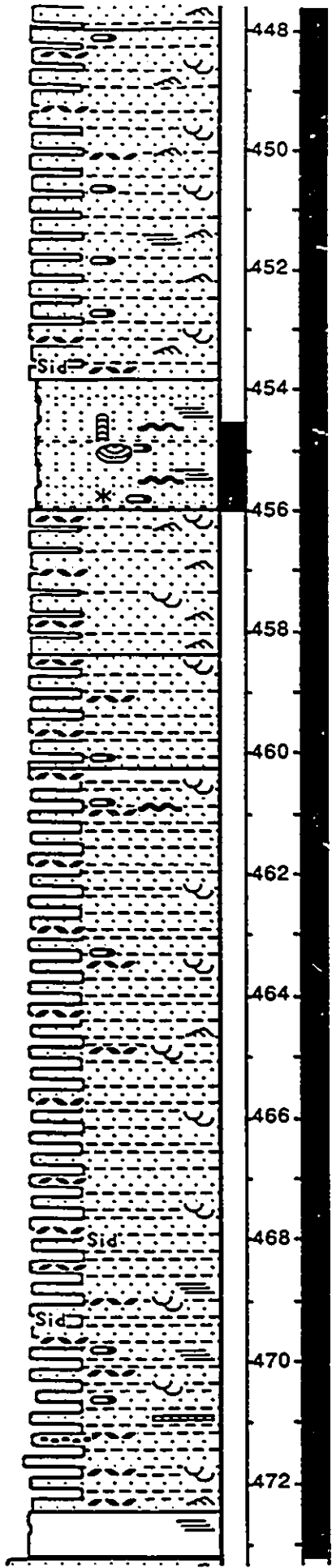


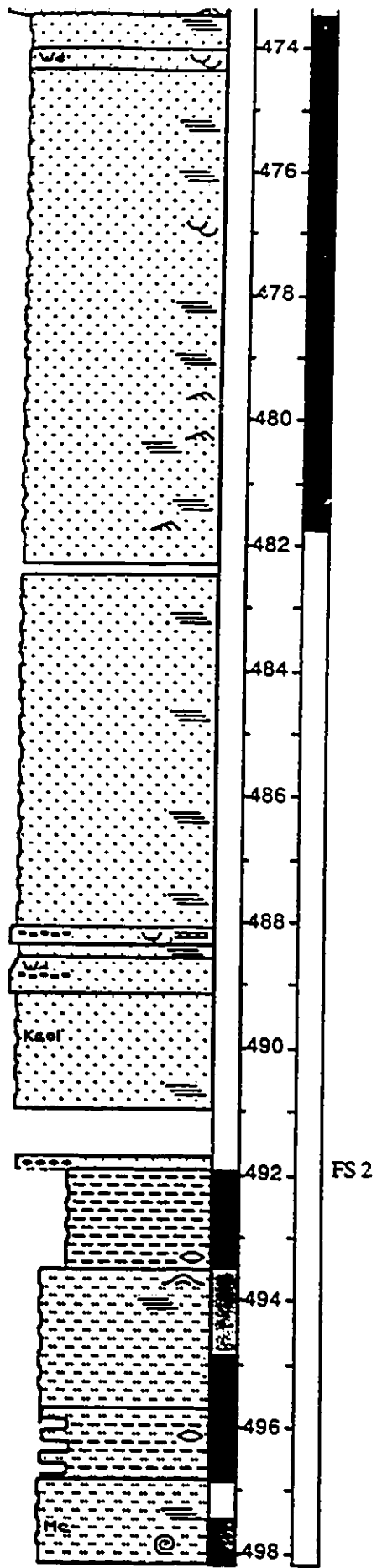


ESSO 87 D55-13 COLDLK 6-35

6-35-64-4w4



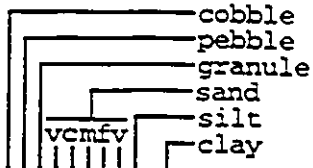




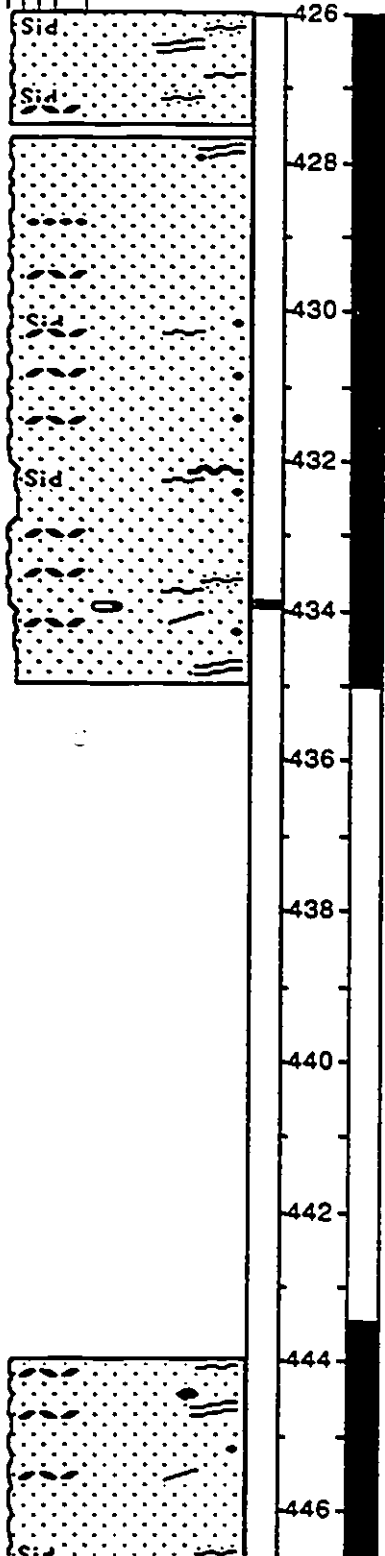
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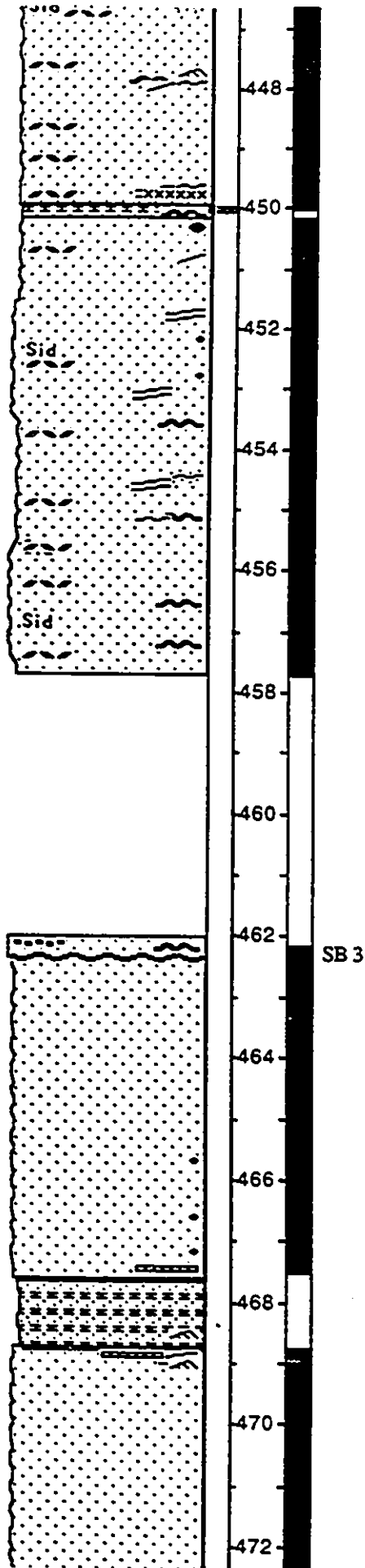
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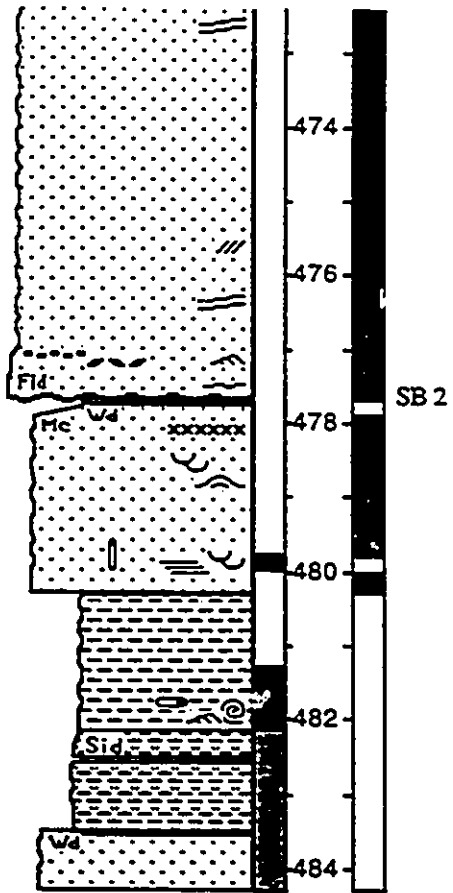
GRAIN SIZE



SHOALS
M
S
N

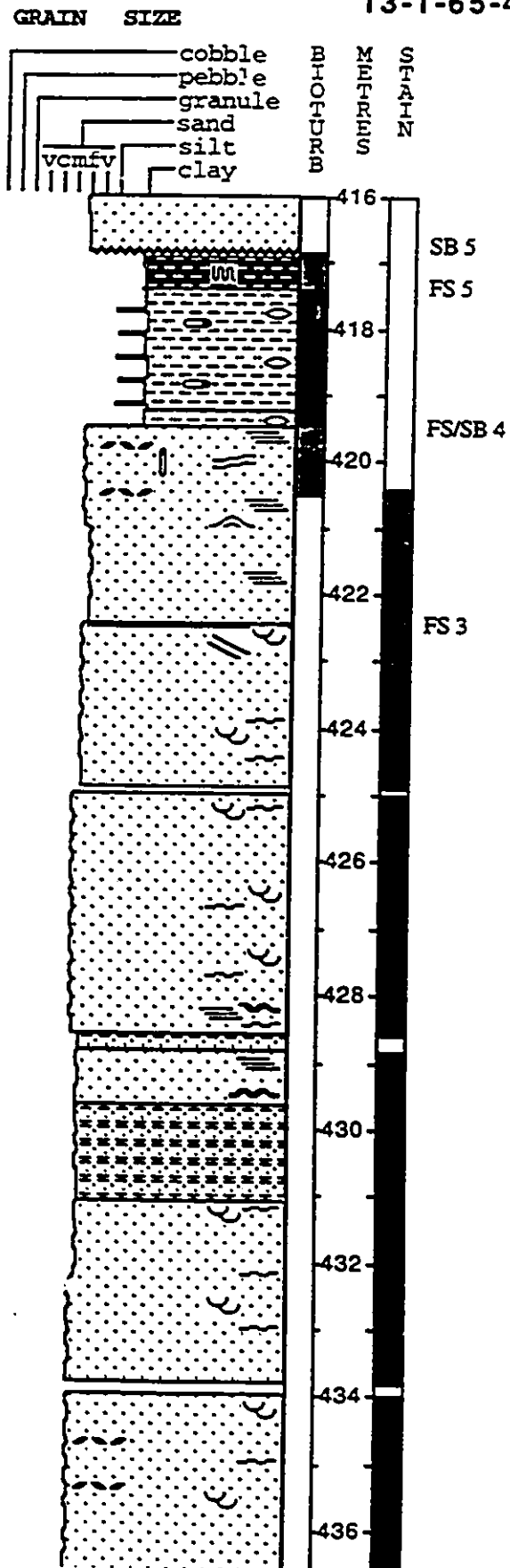


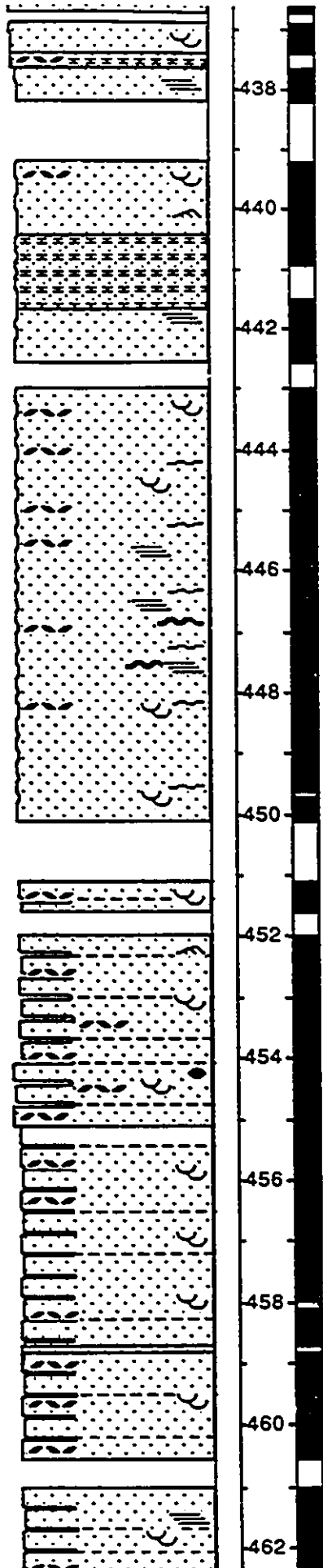




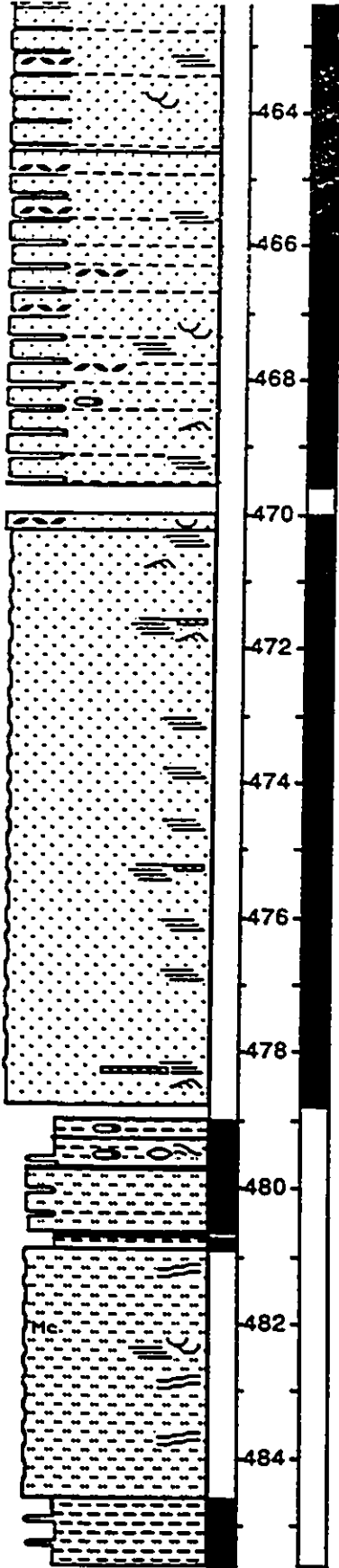
ESSO 85 D24-13 COLDLK 13-1

13-1-65-4w4





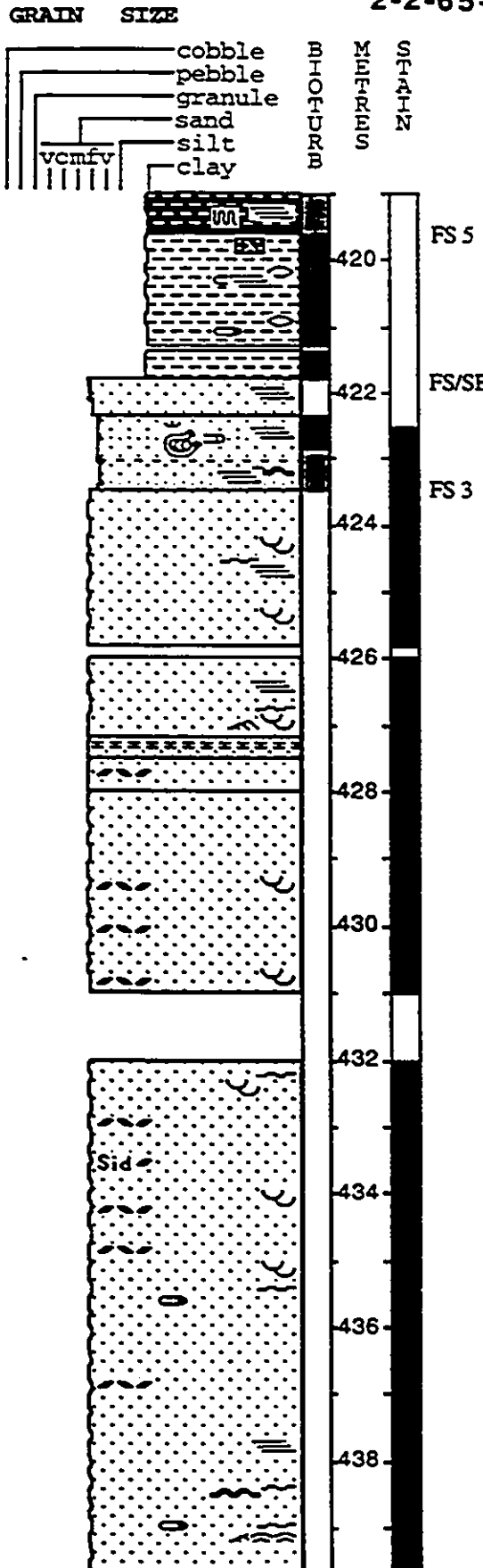
SB 3

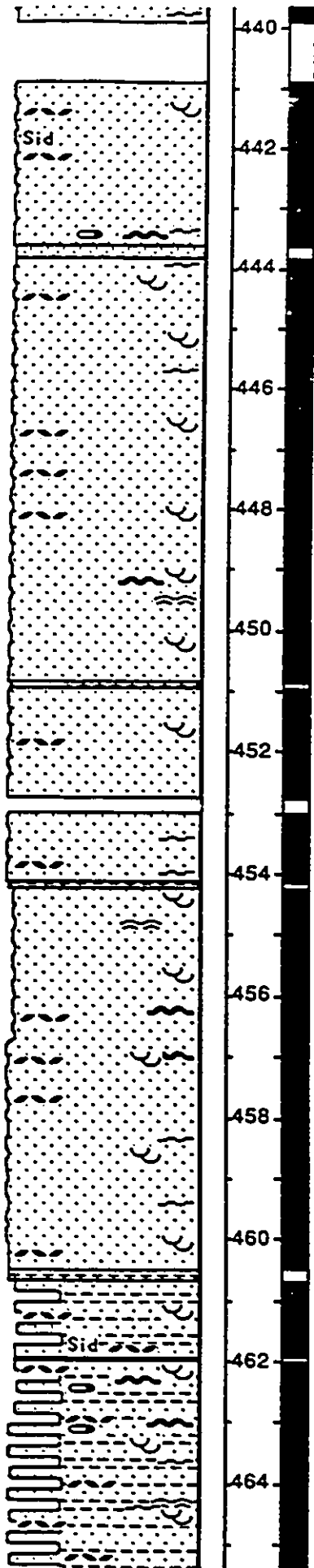


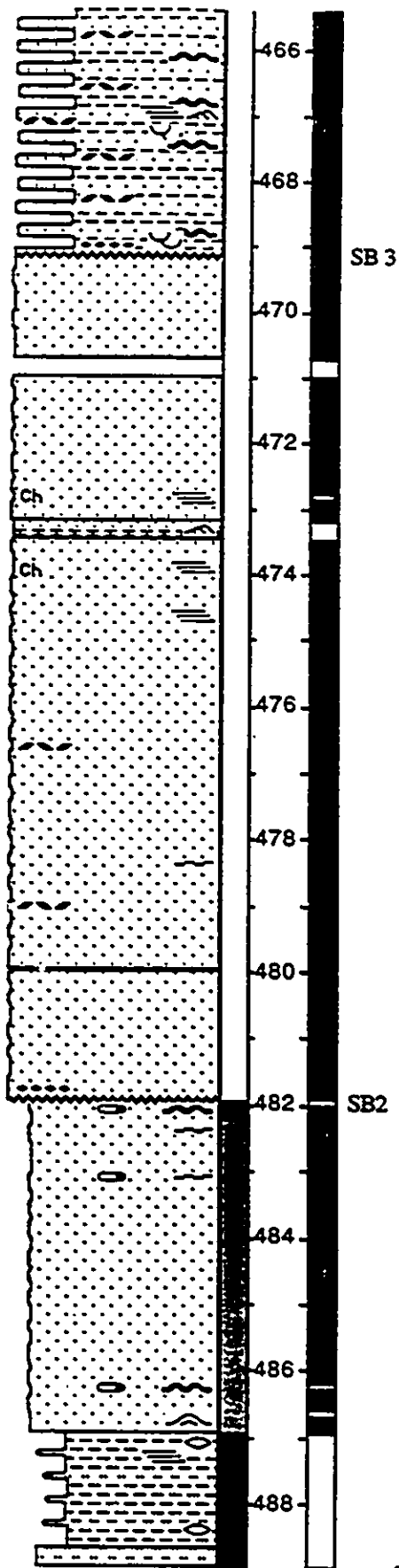
SB 2

ESSO 85 D26-13 COLDLK 2-2

2-2-65-4w4

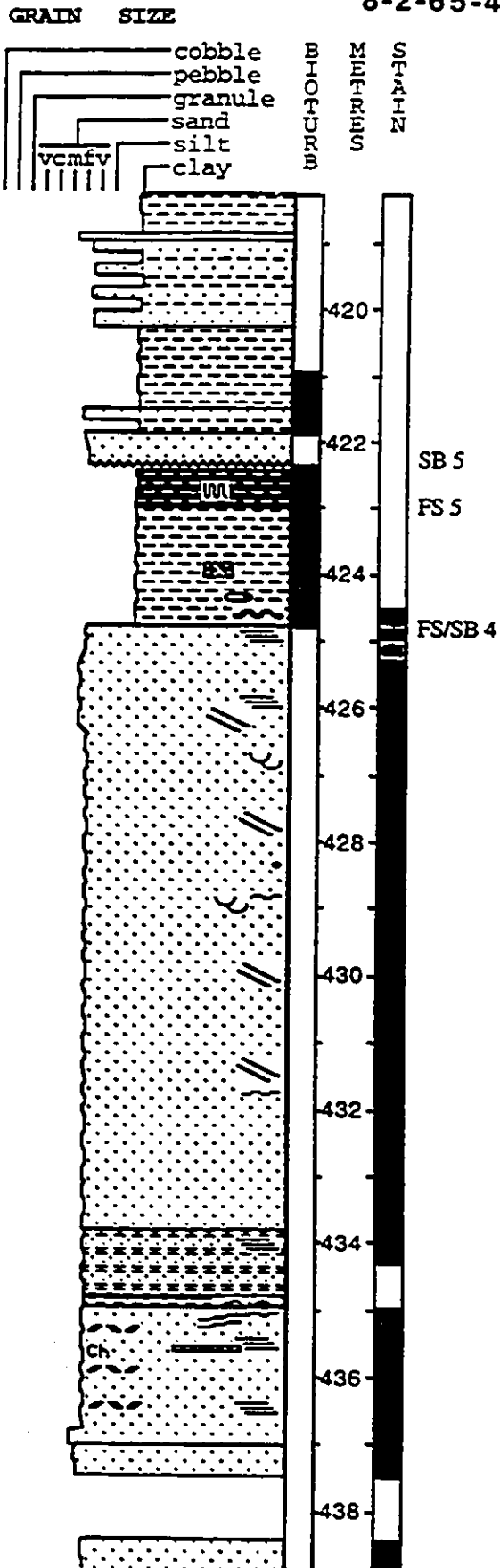


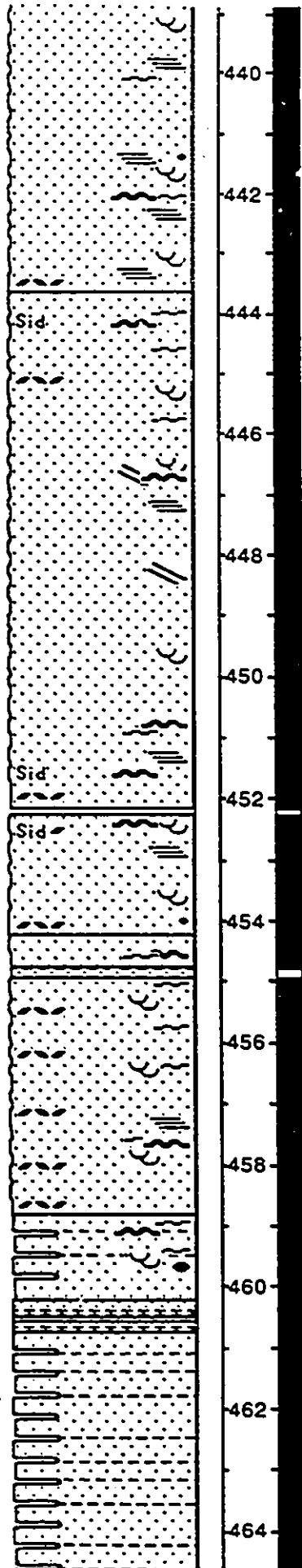


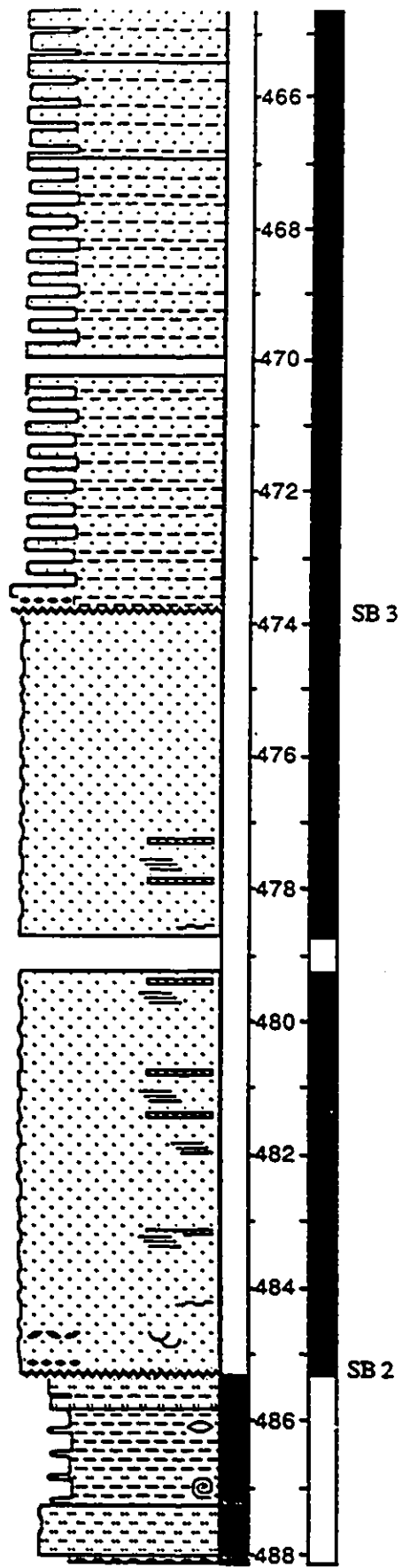


ESSO 85 D25-13 COLDLK 8-2

8-2-65-4w4

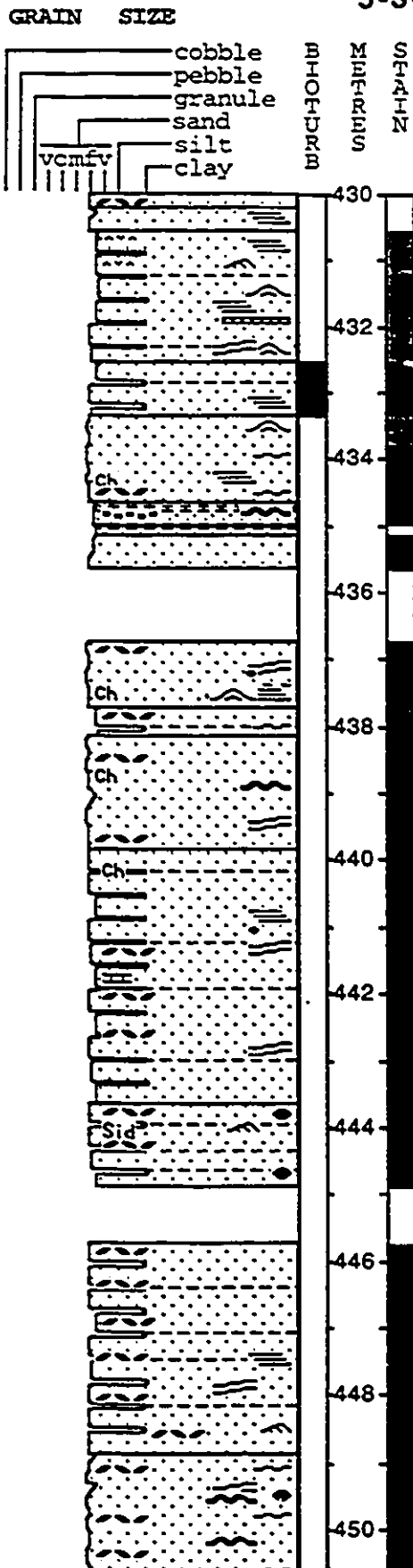


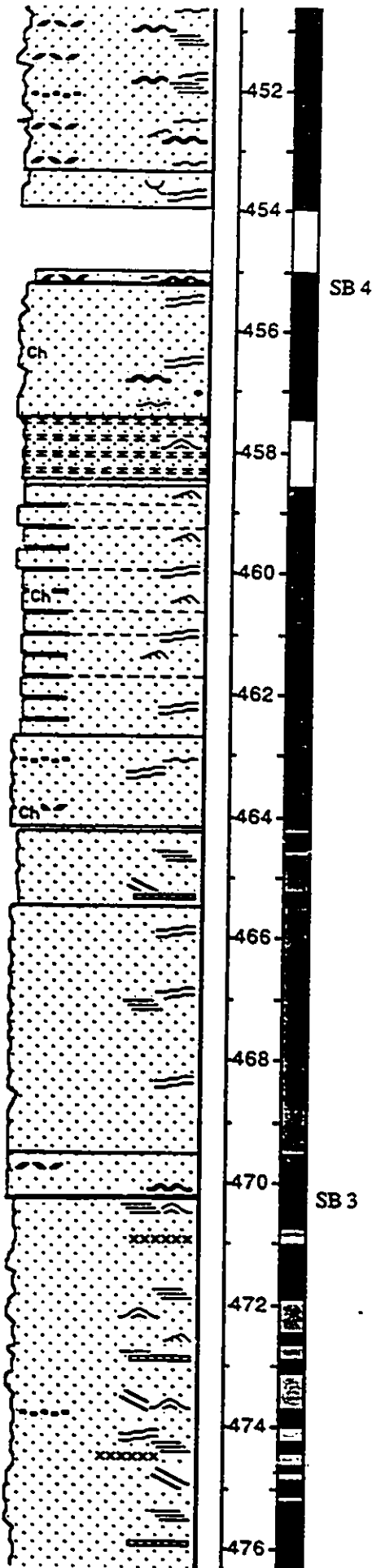




ESSO 87 J43-8 COLDLK 5-3

5-3-65-4w4

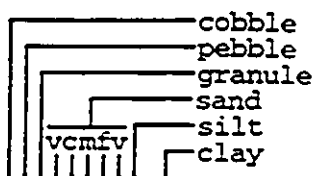




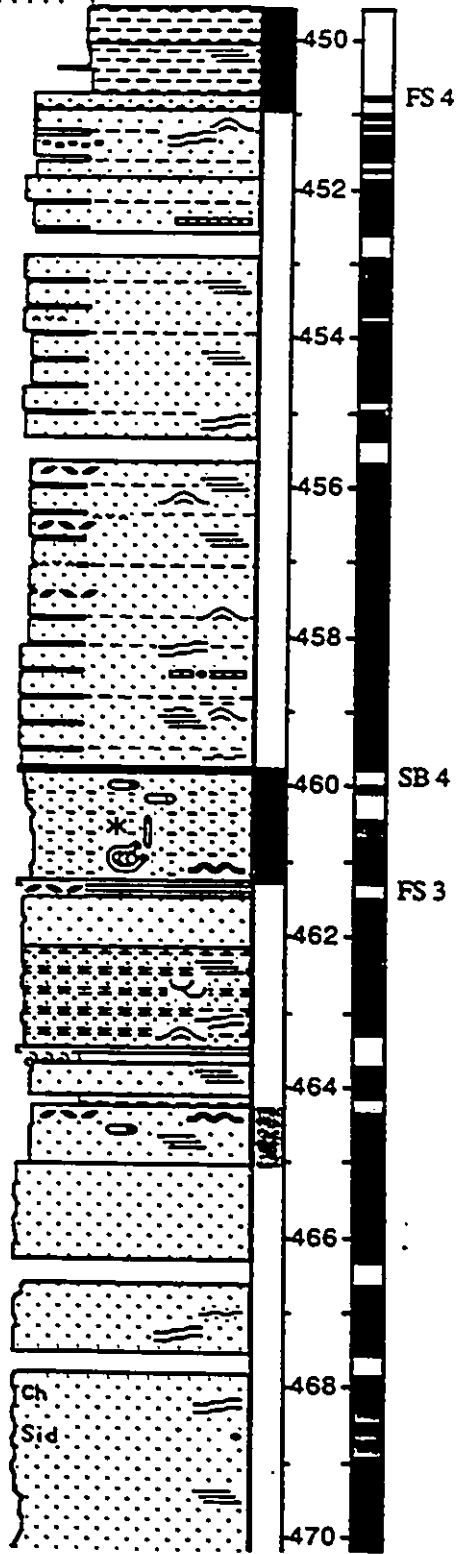
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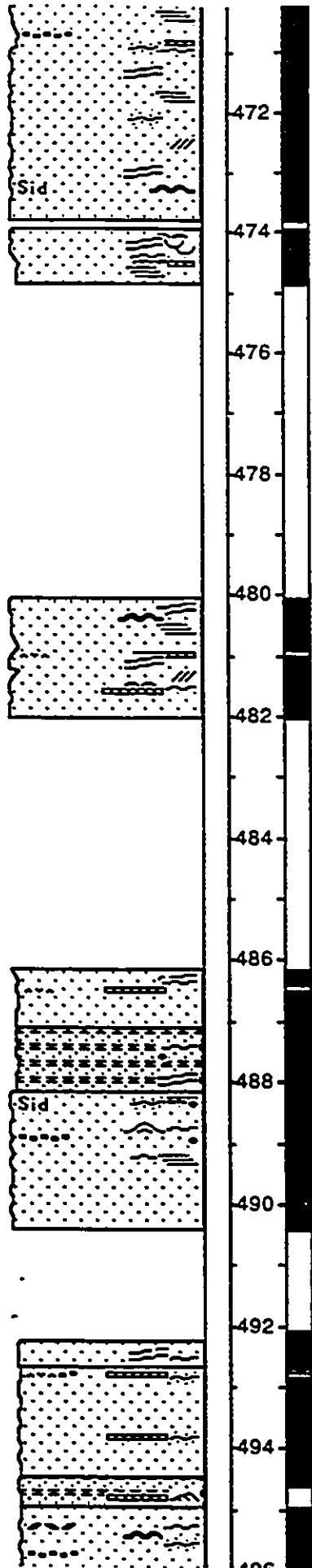
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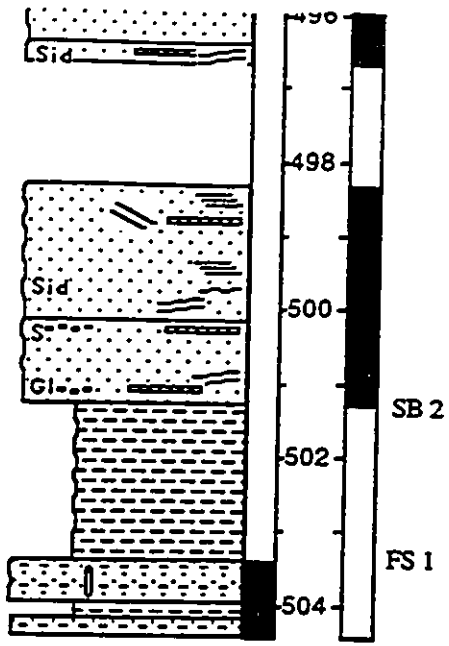
GRAIN SIZE



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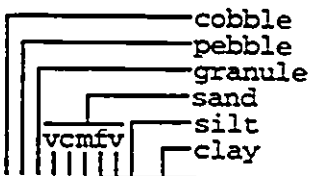




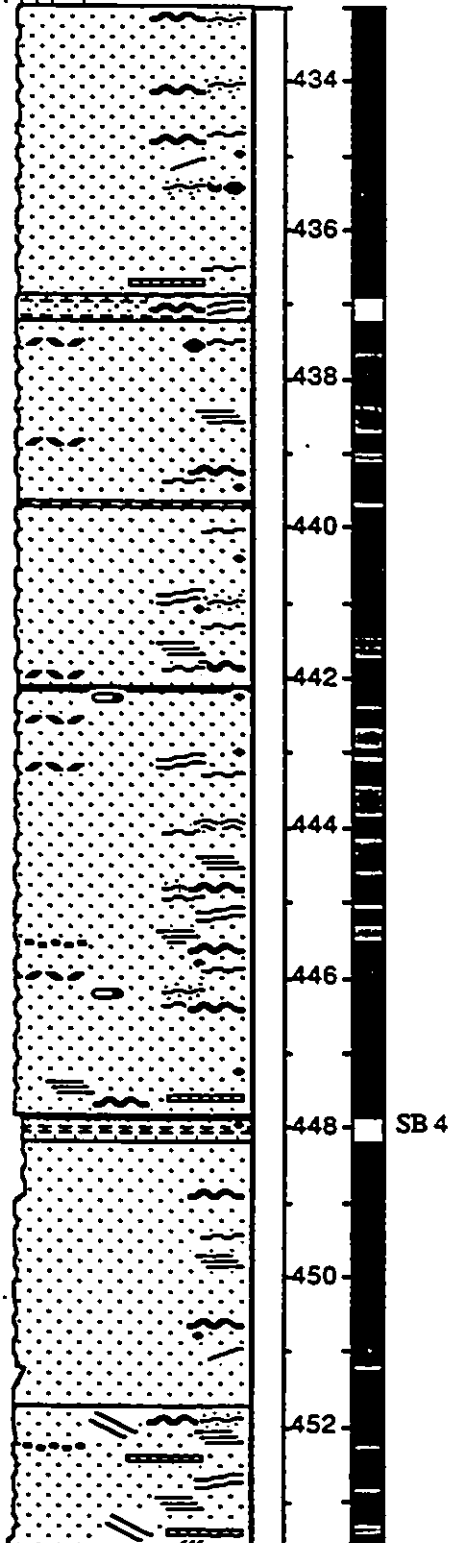
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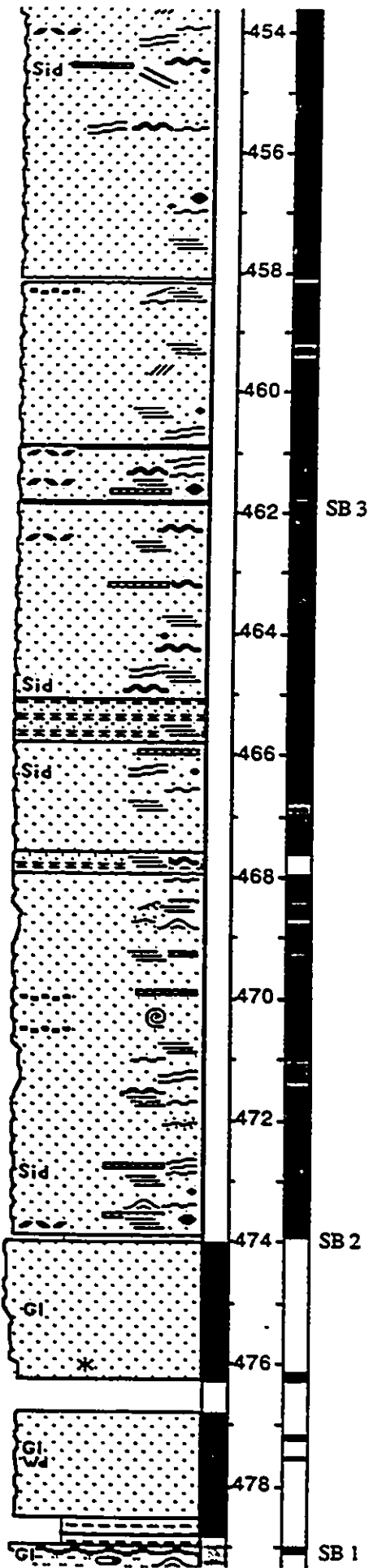
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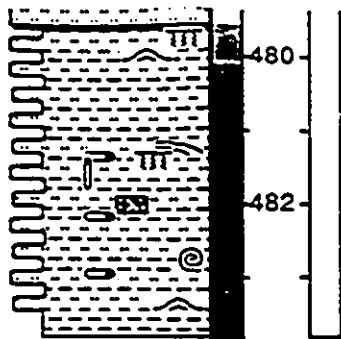
GRAIN SIZE



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MATERIALS
STAIN

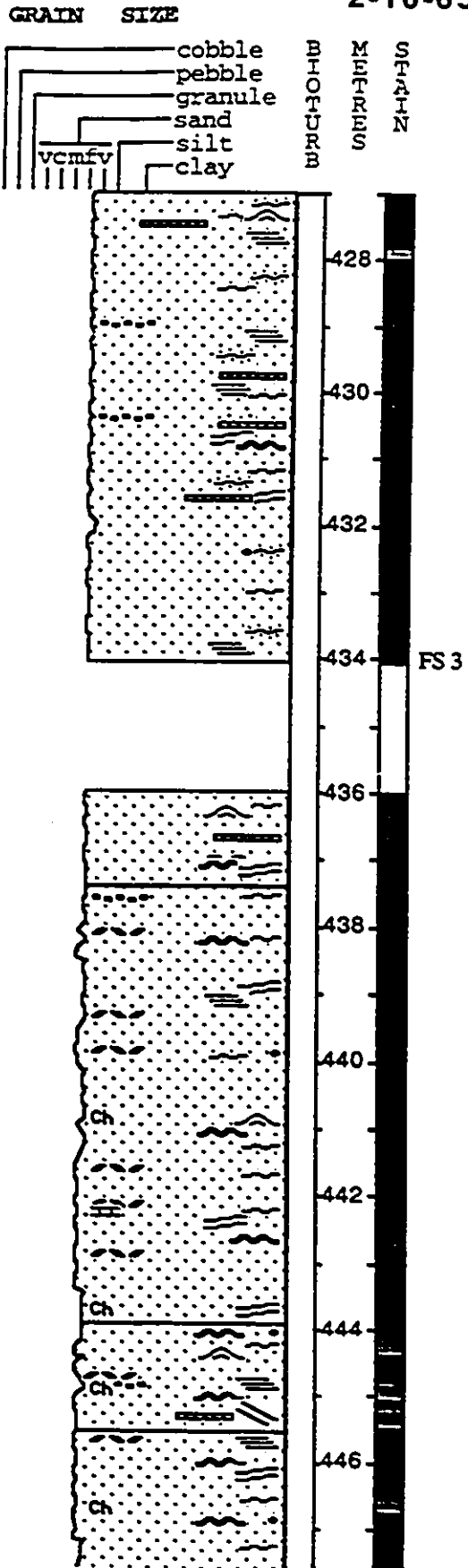


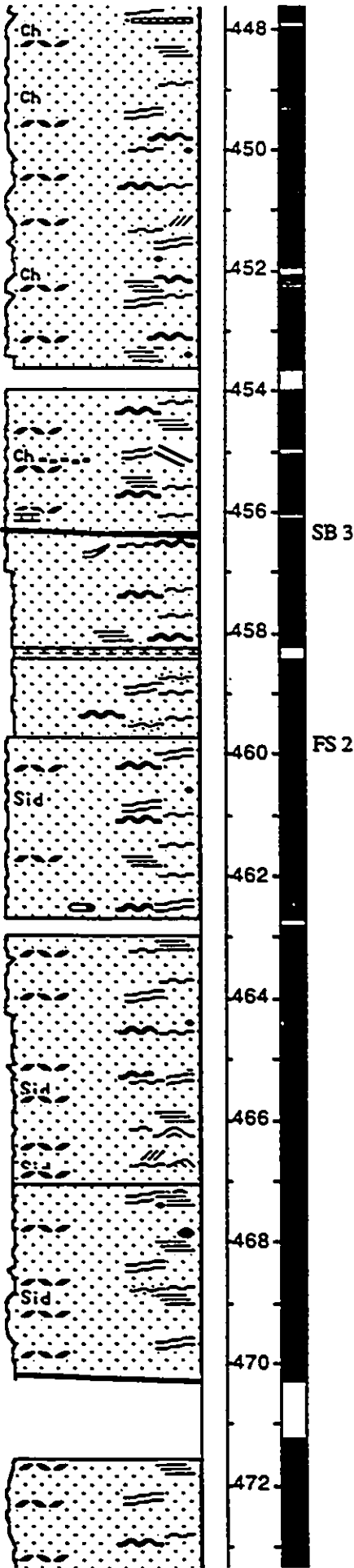


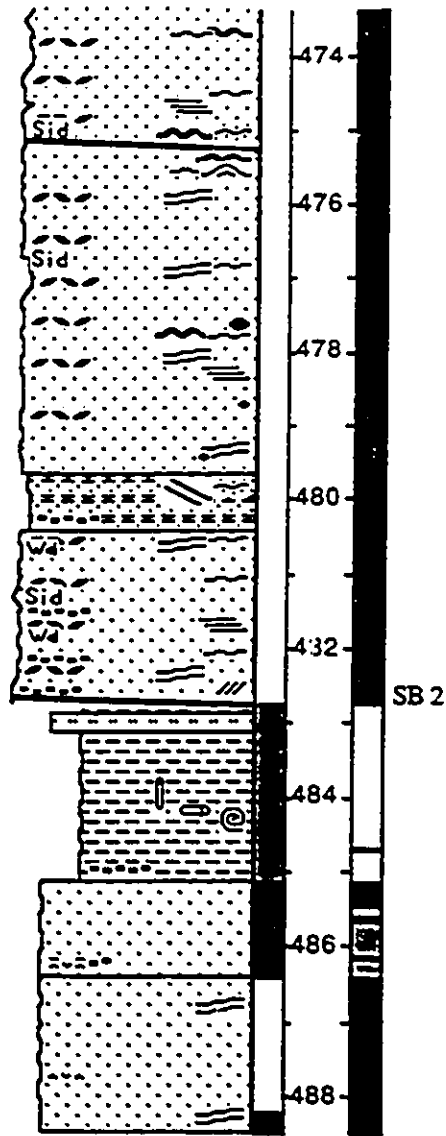


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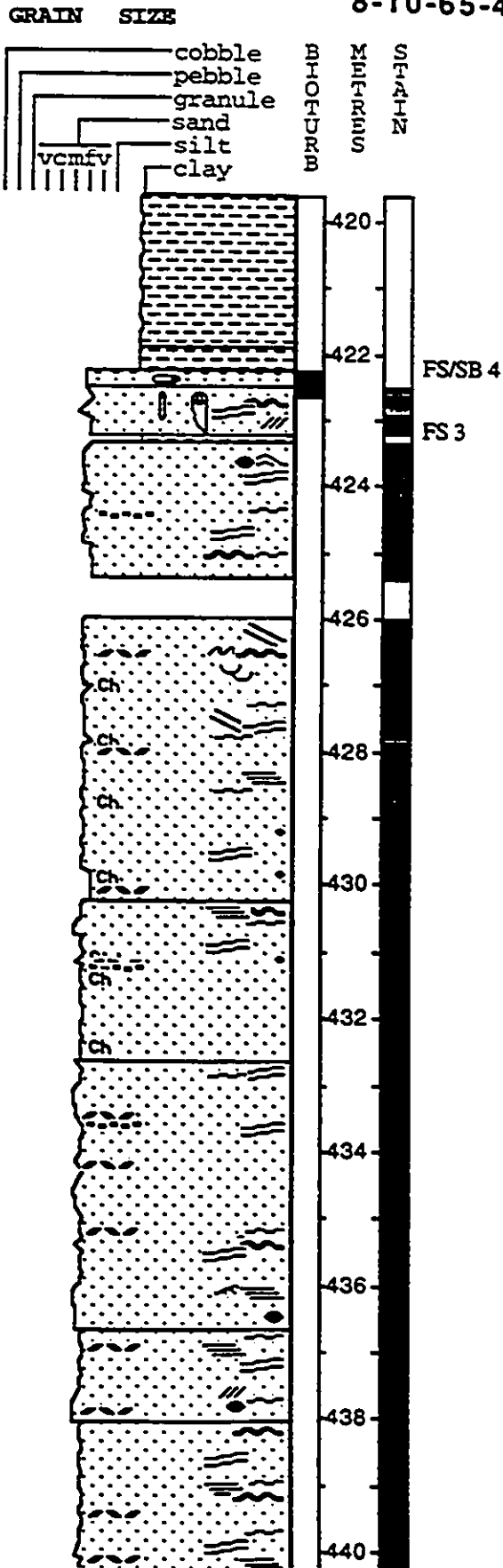


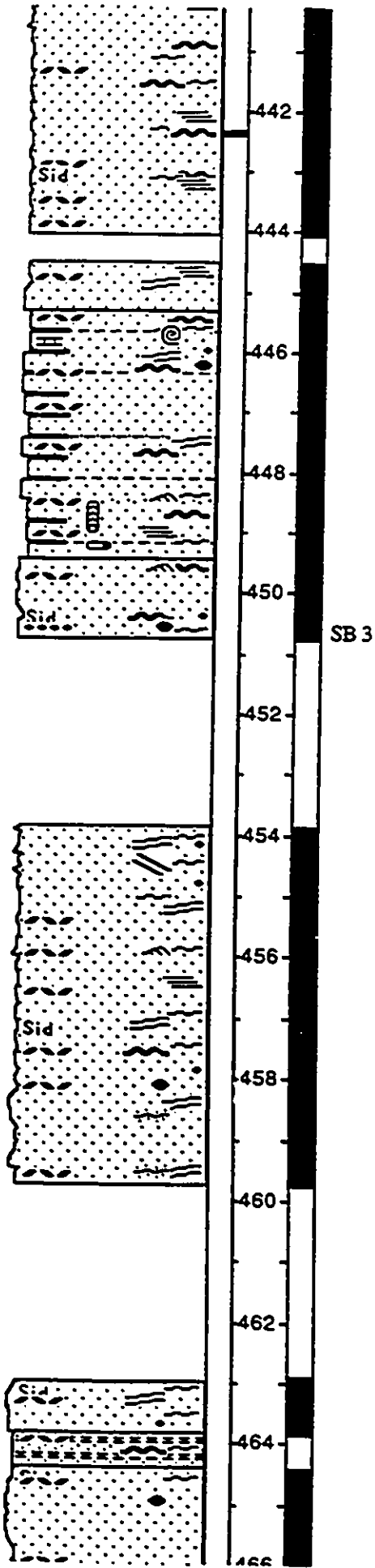


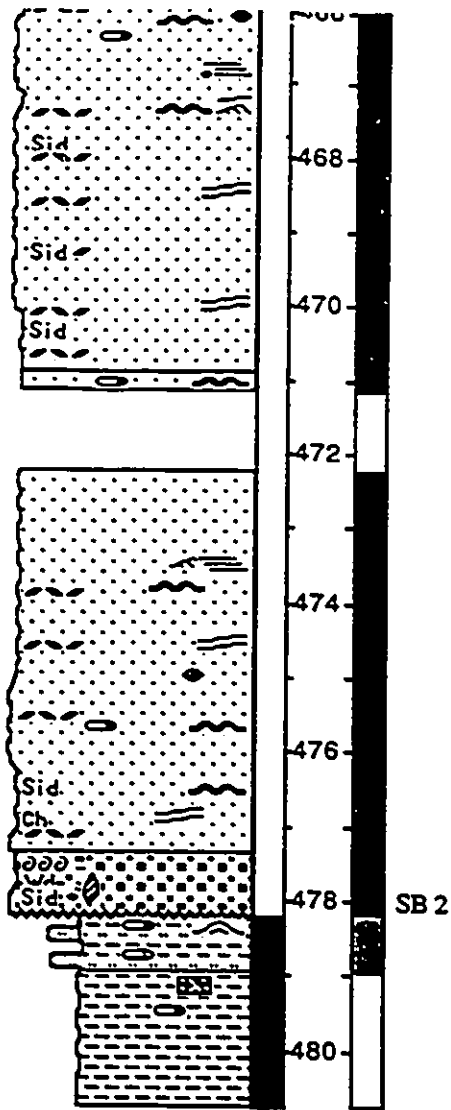


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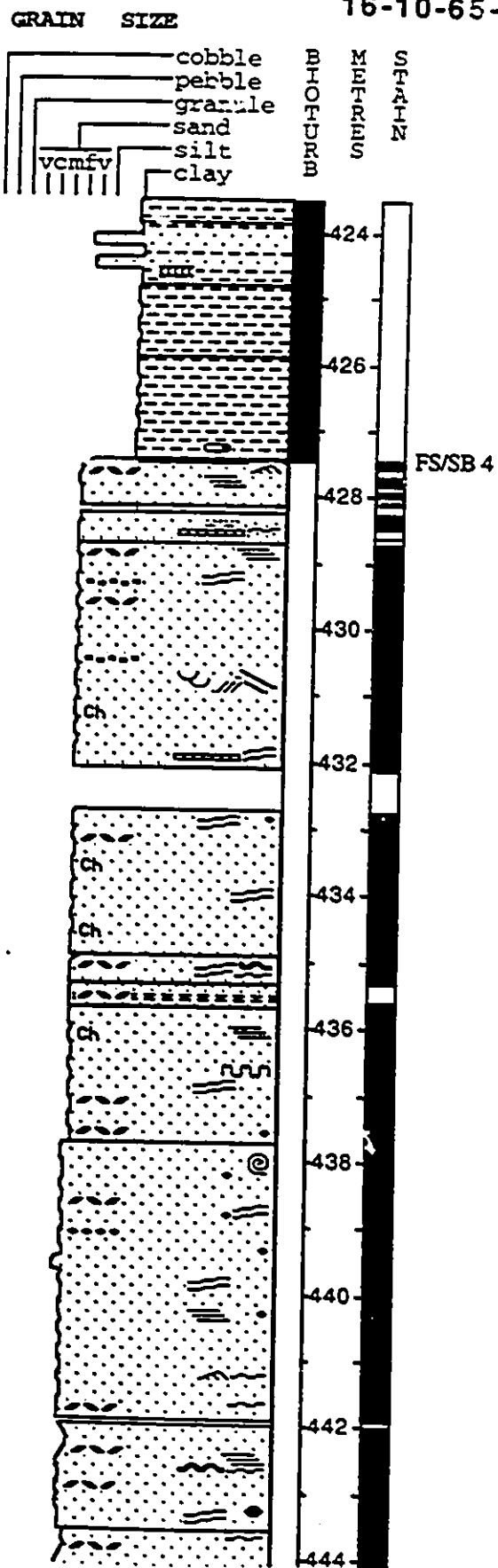


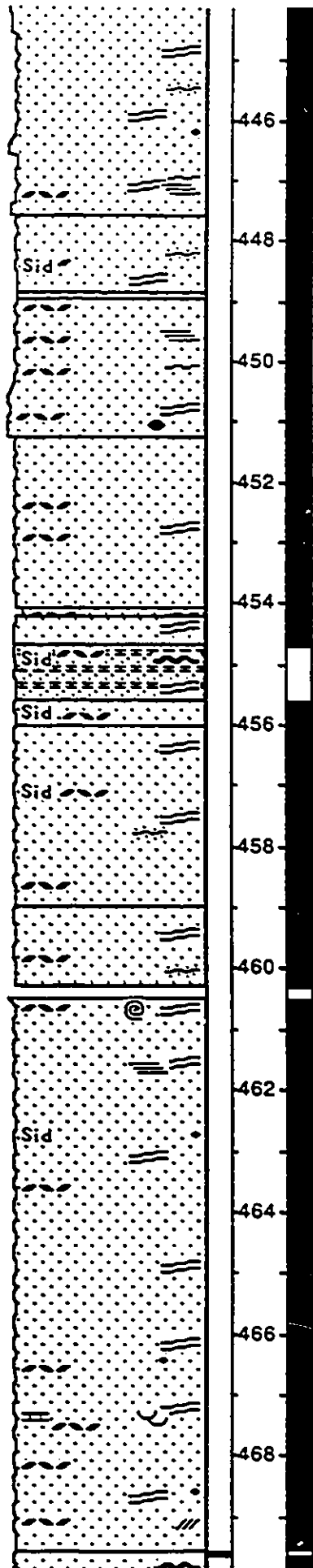


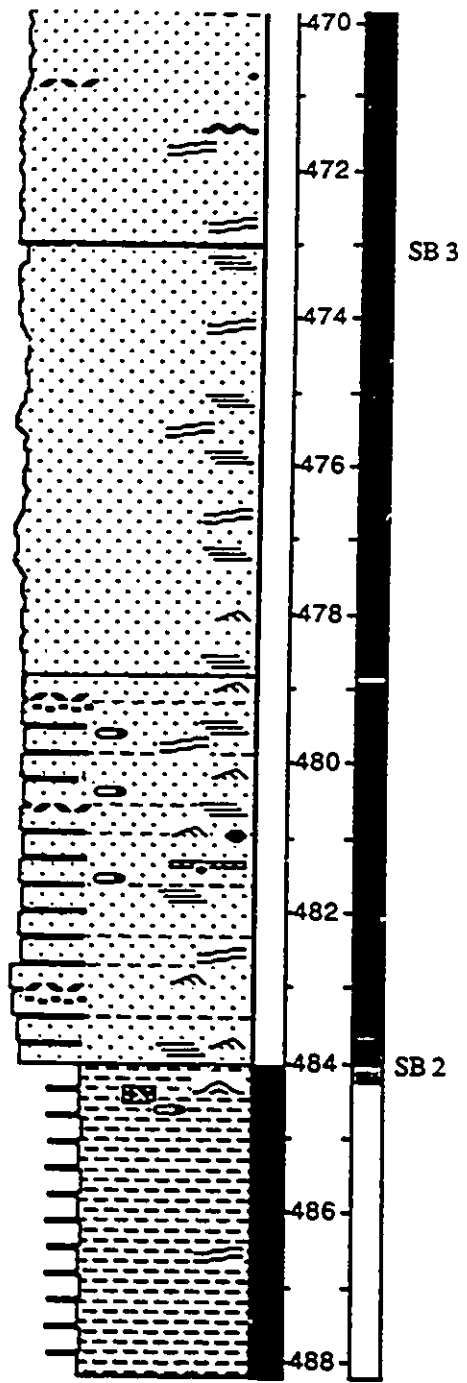


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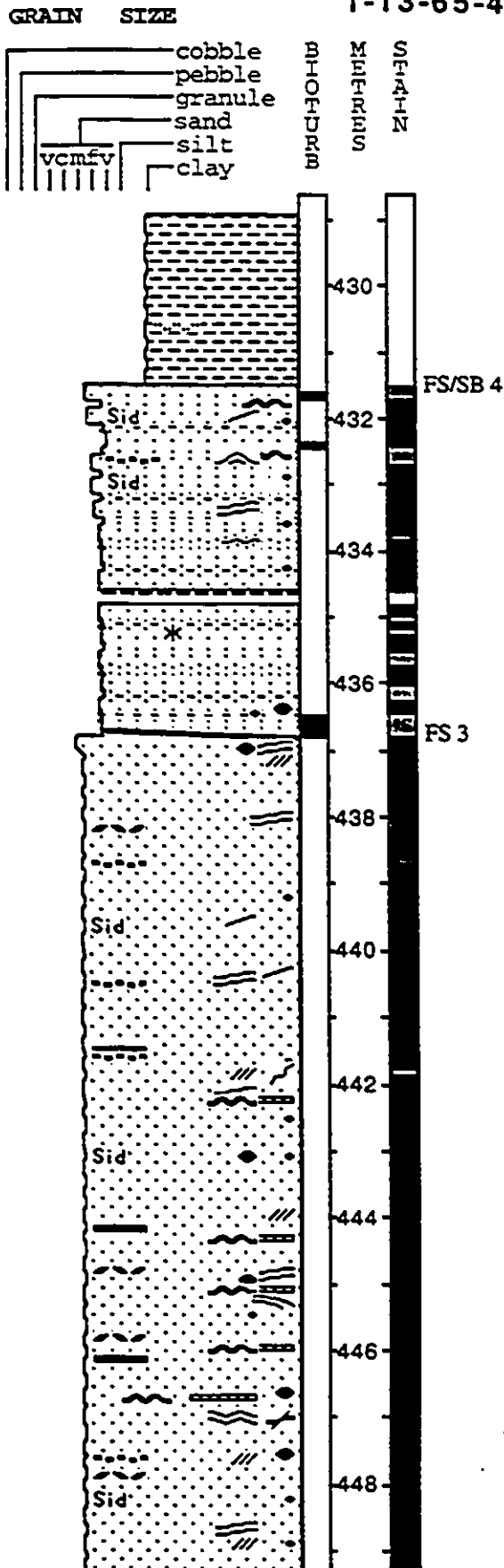


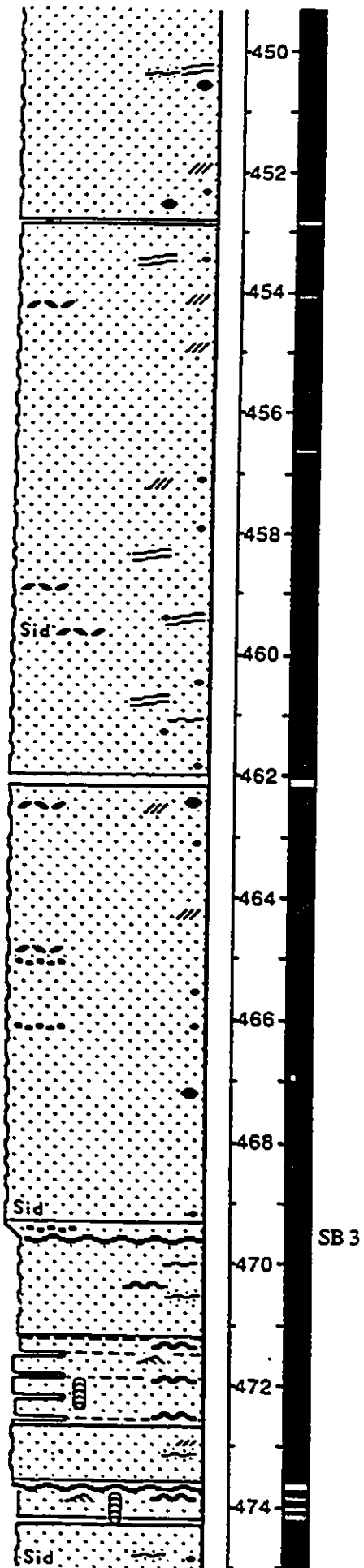


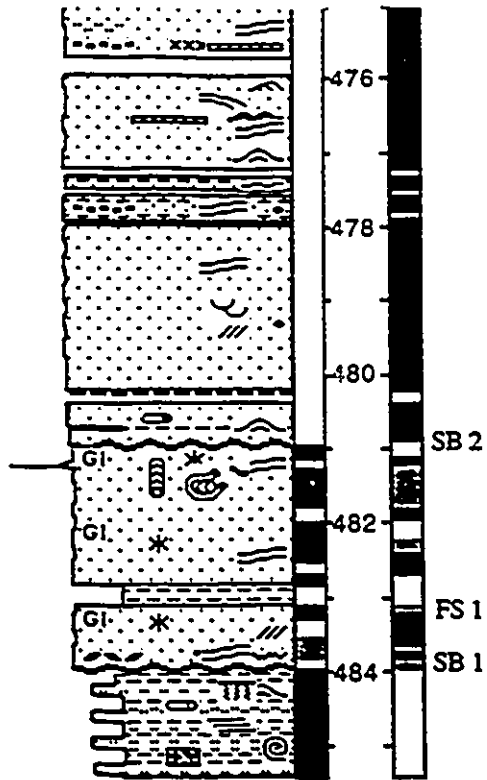


ESSO 85 C2-8 COLDLK 1-13

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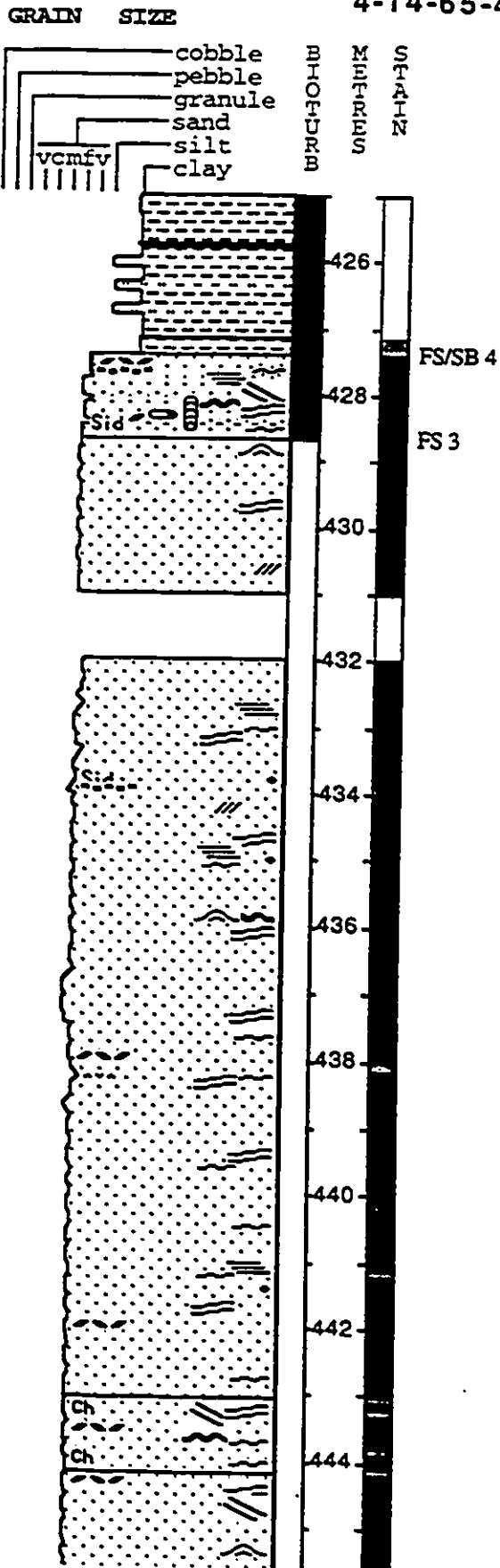


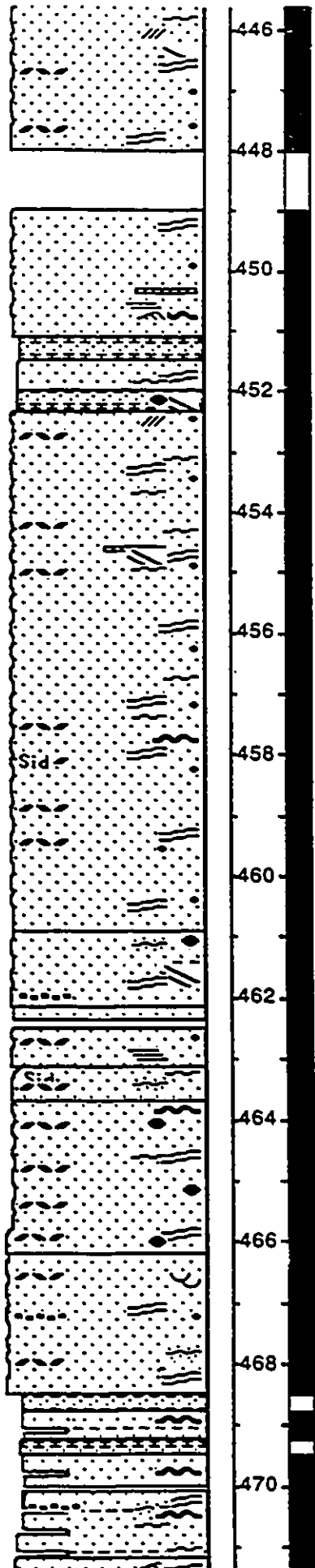


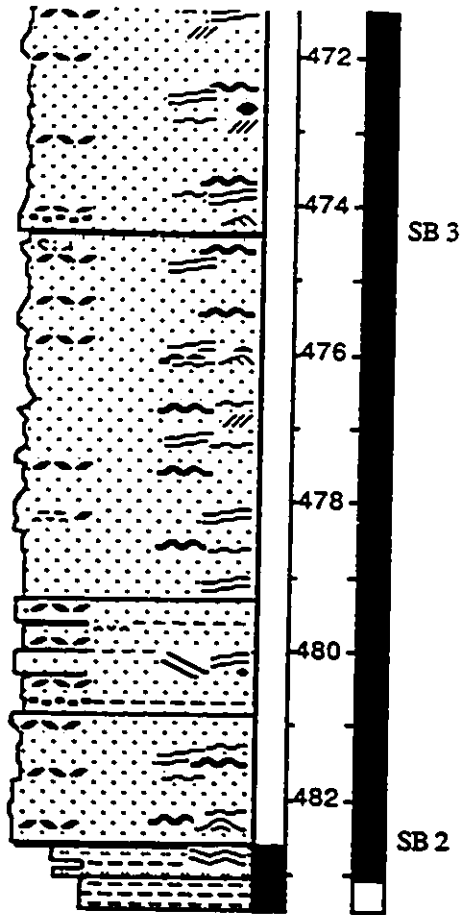


ESSO 83 A4-8 COLDLK 4-14

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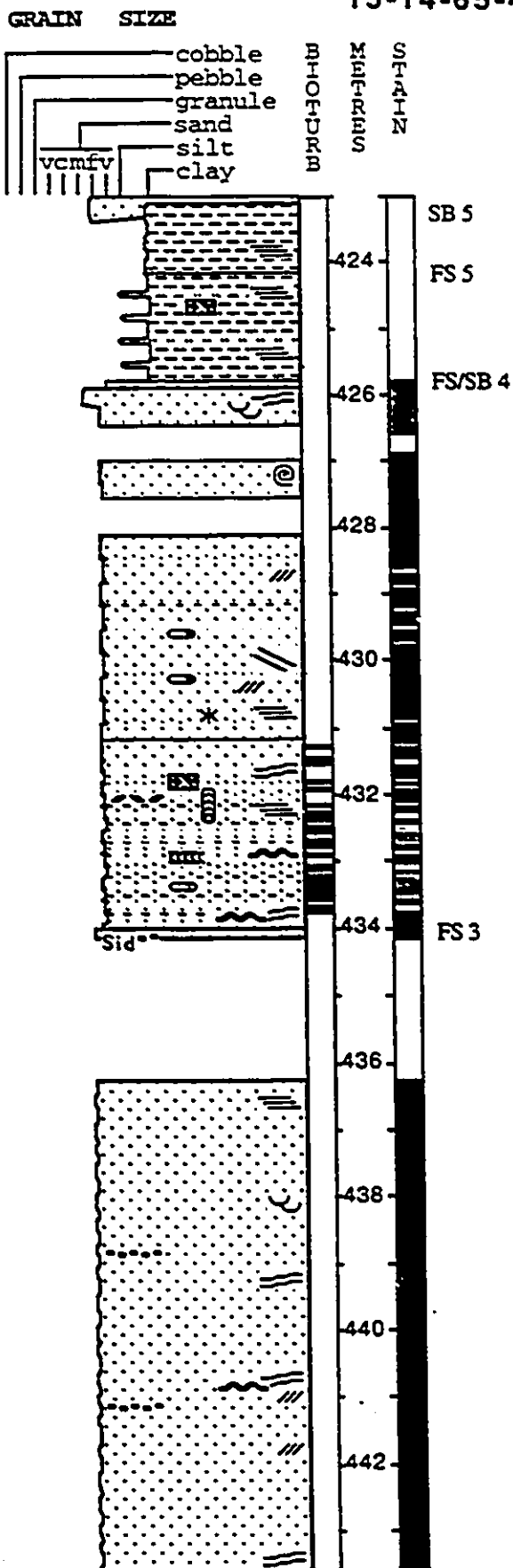


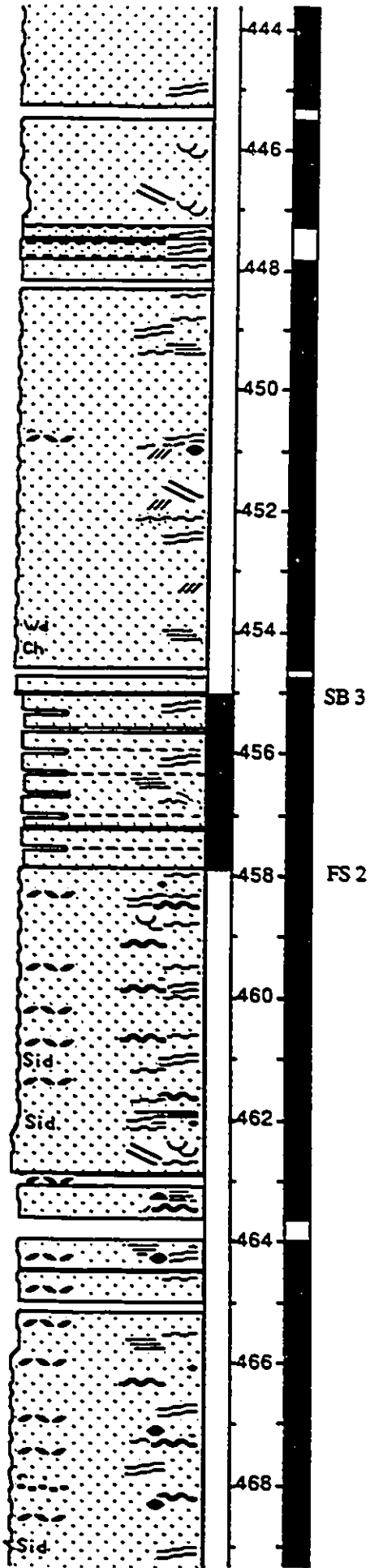


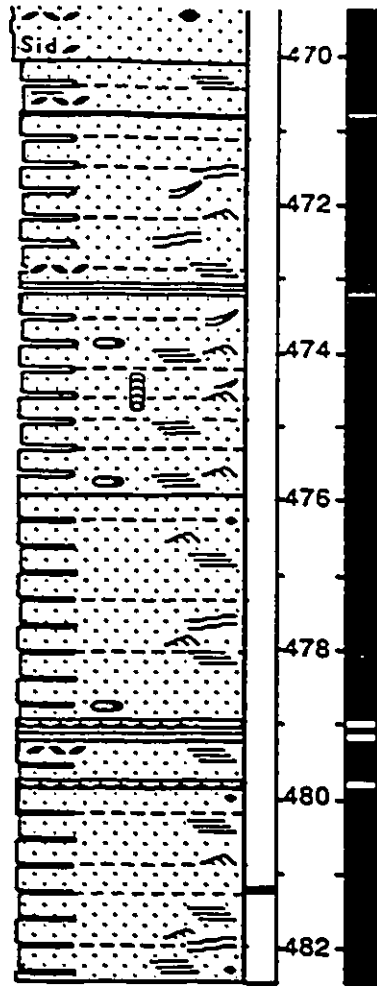


ESSO 88 R5-13 COLDLK 15-14

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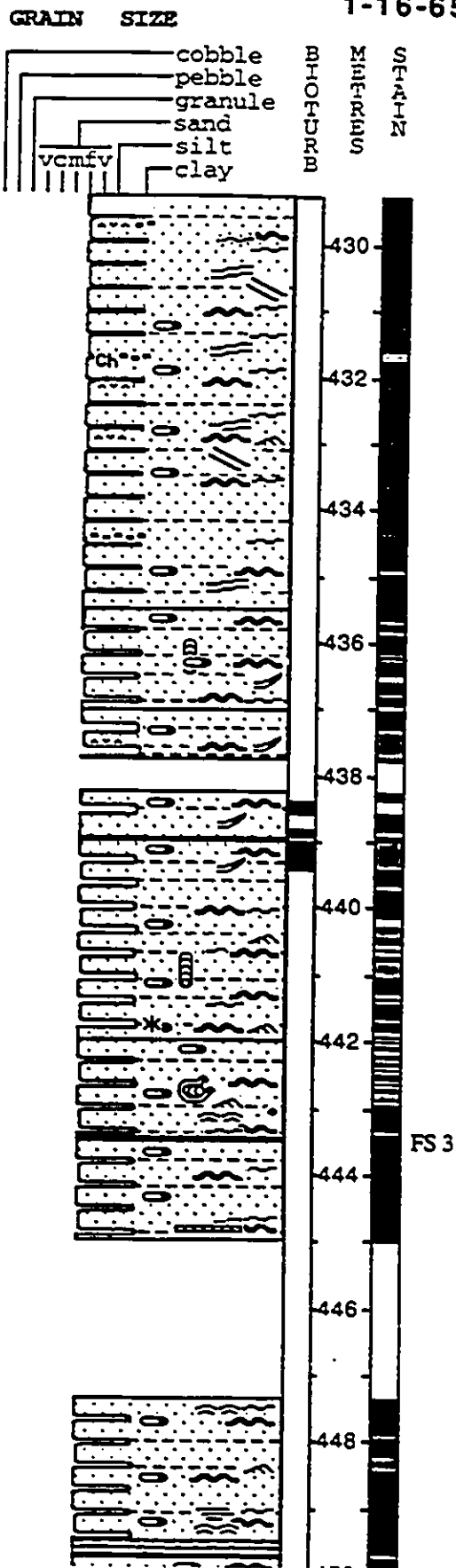


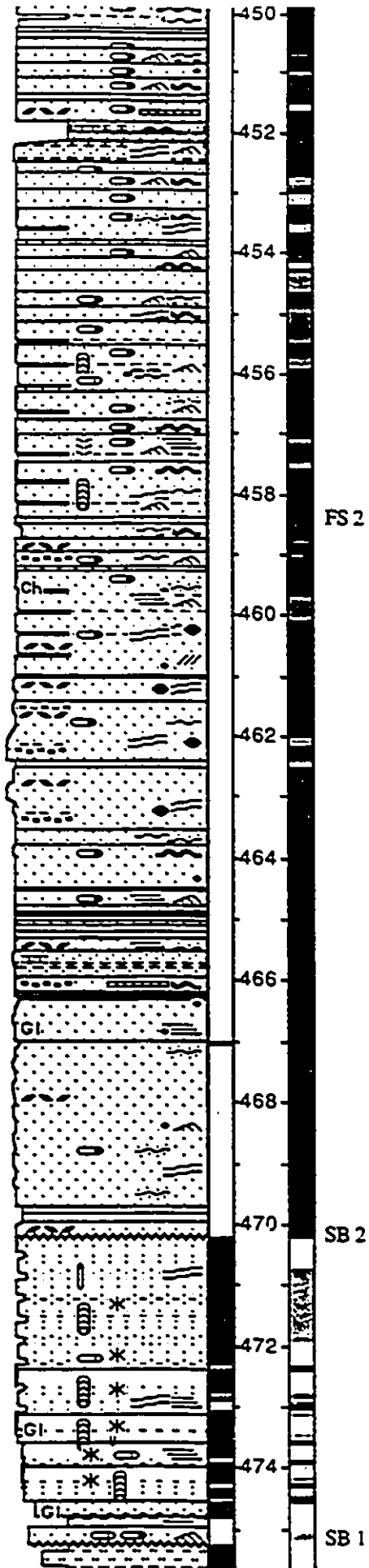


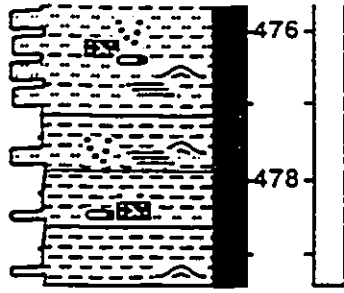


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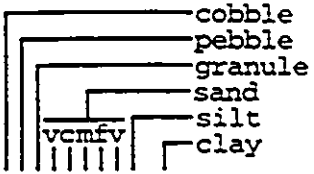




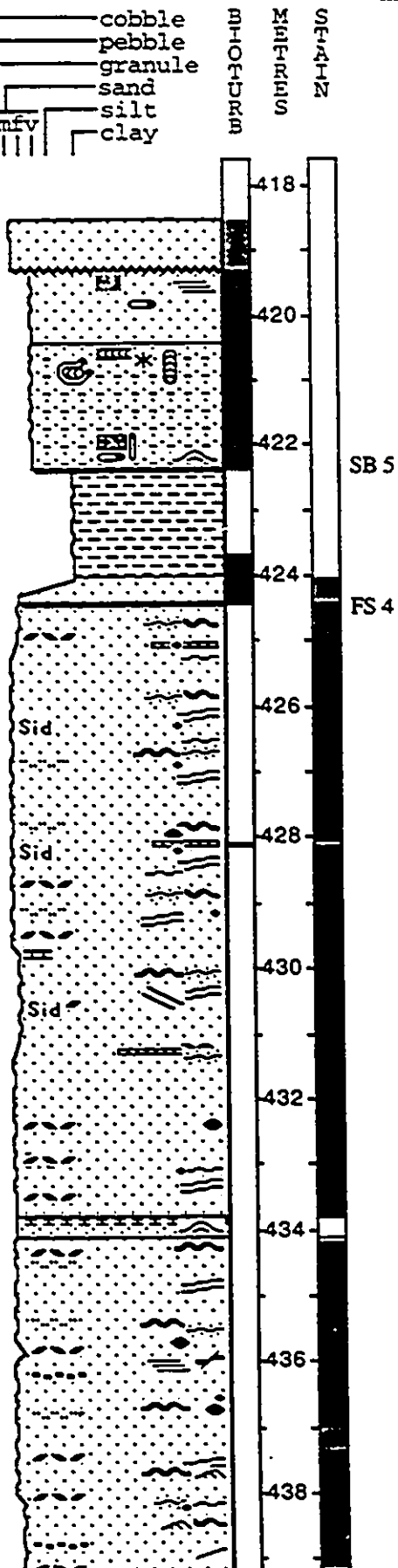


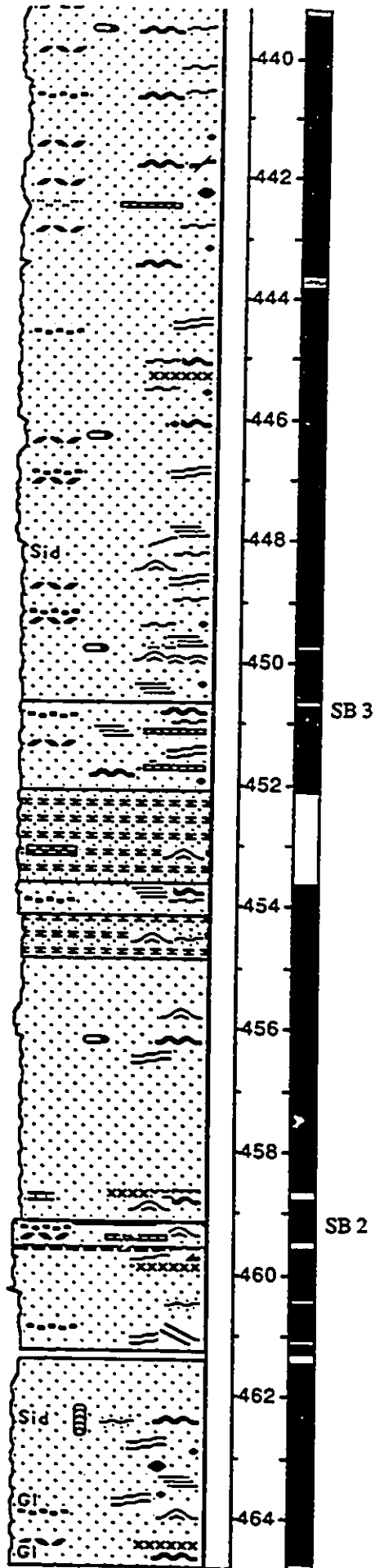
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GRAIN SIZE



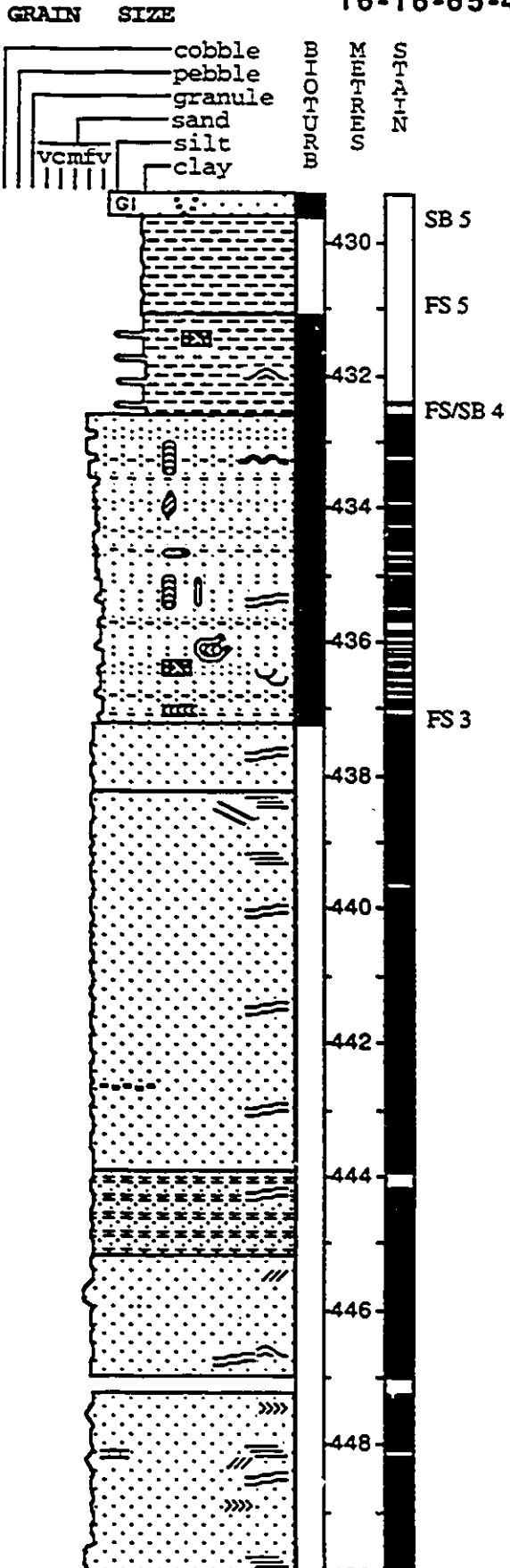
IMP 7 COLDLK OV 4-16
4-16-65-4w4

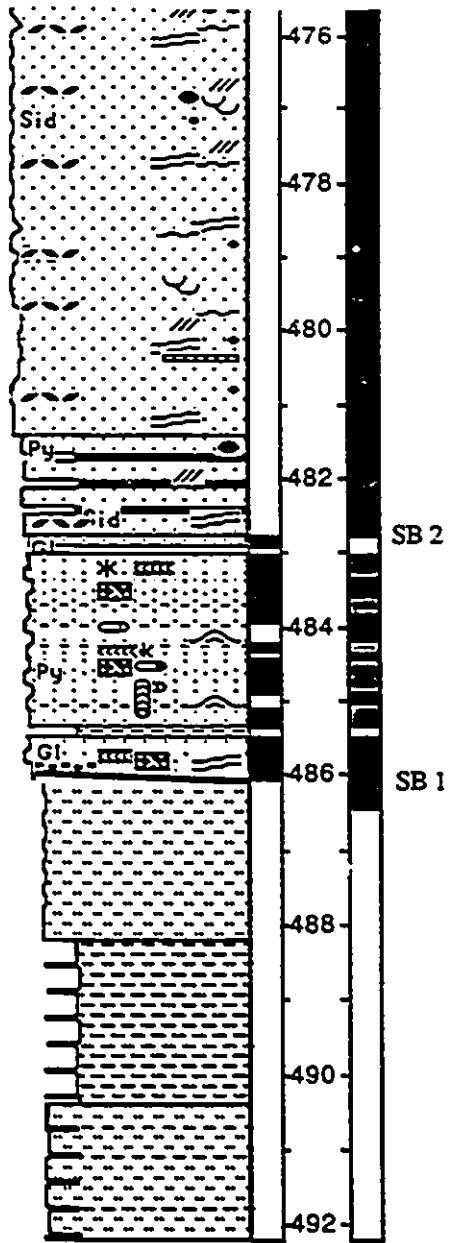


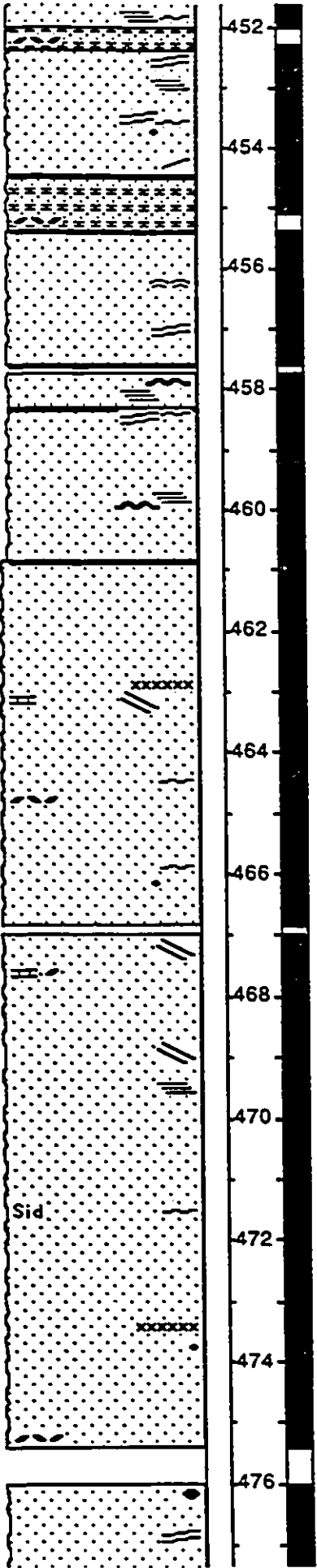


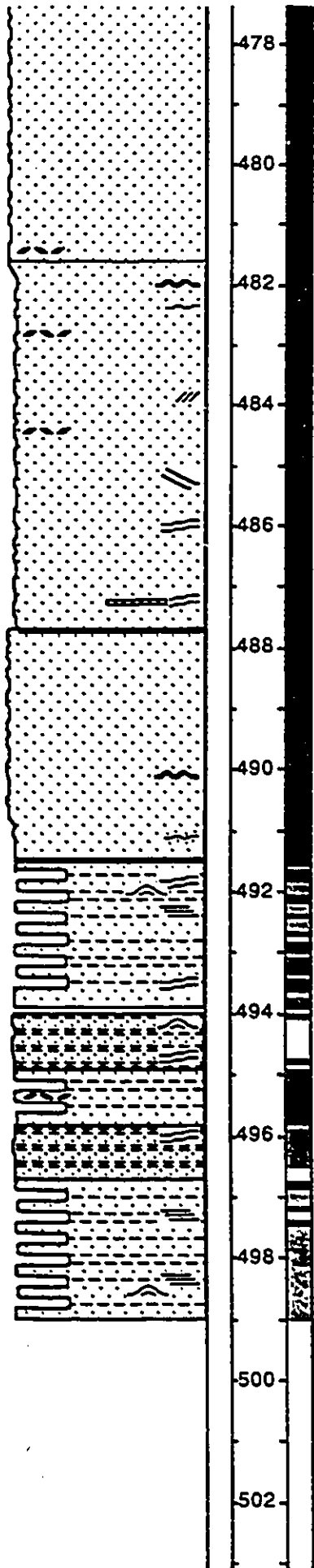
ESSO 84 J7-13 COLDLK 16-16

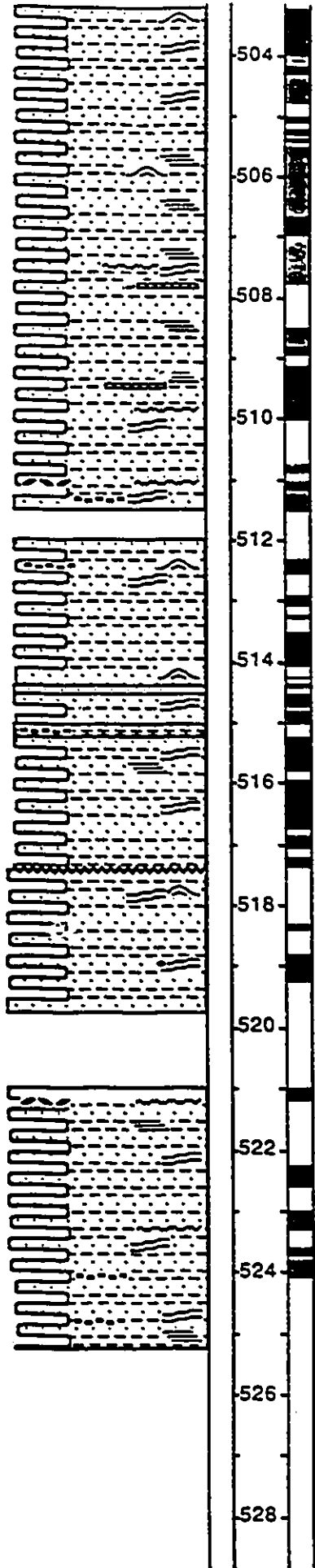
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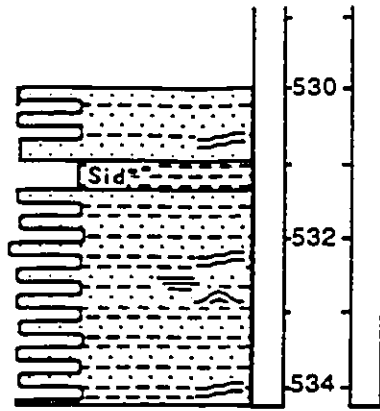






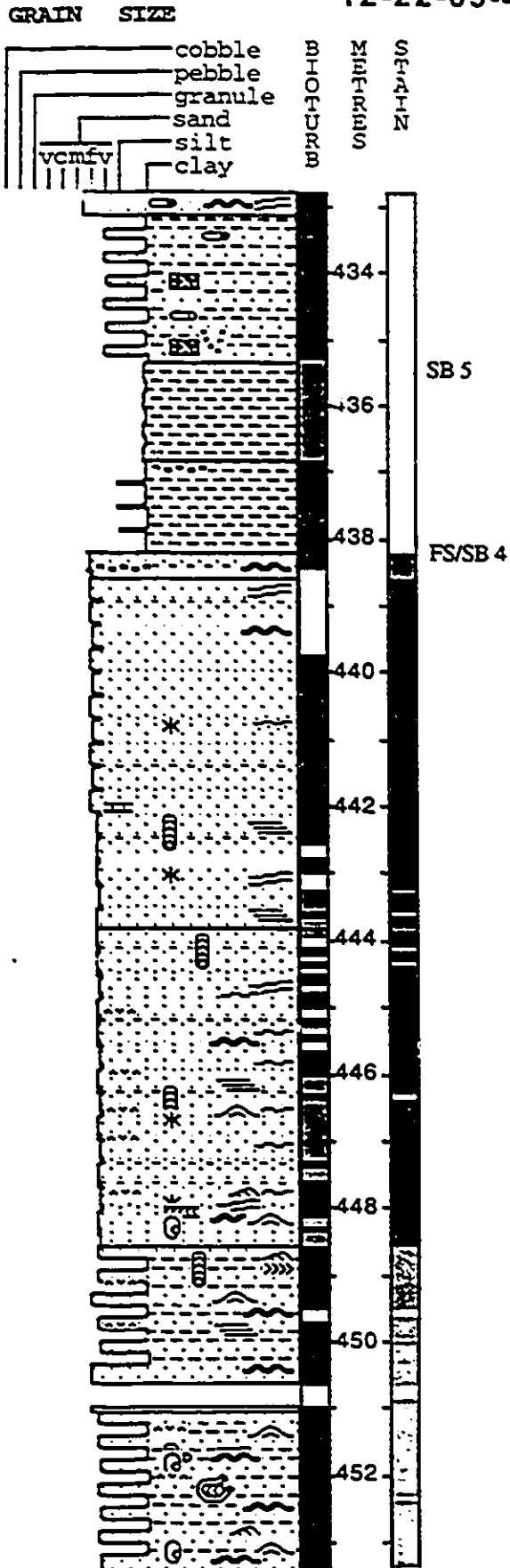


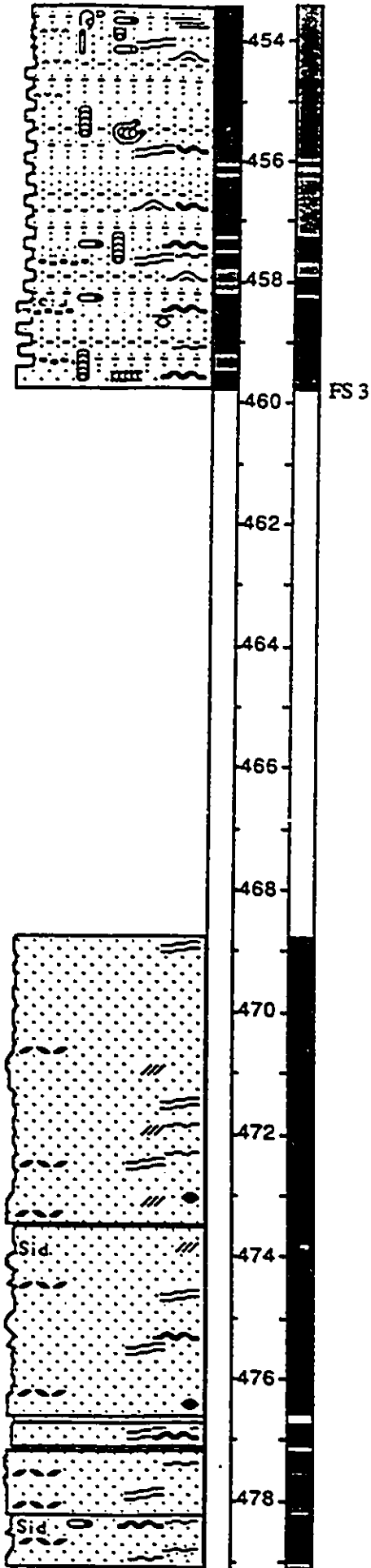


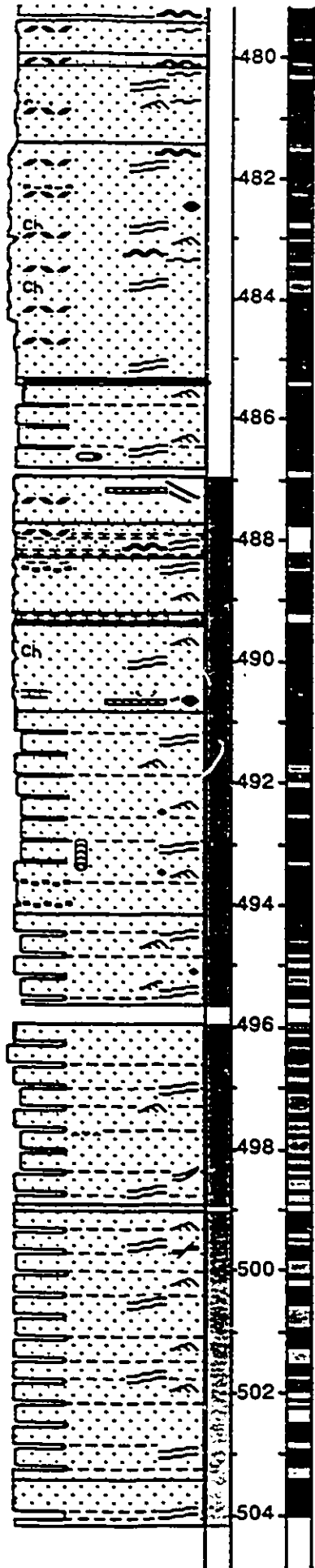


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12-22-65-4w4



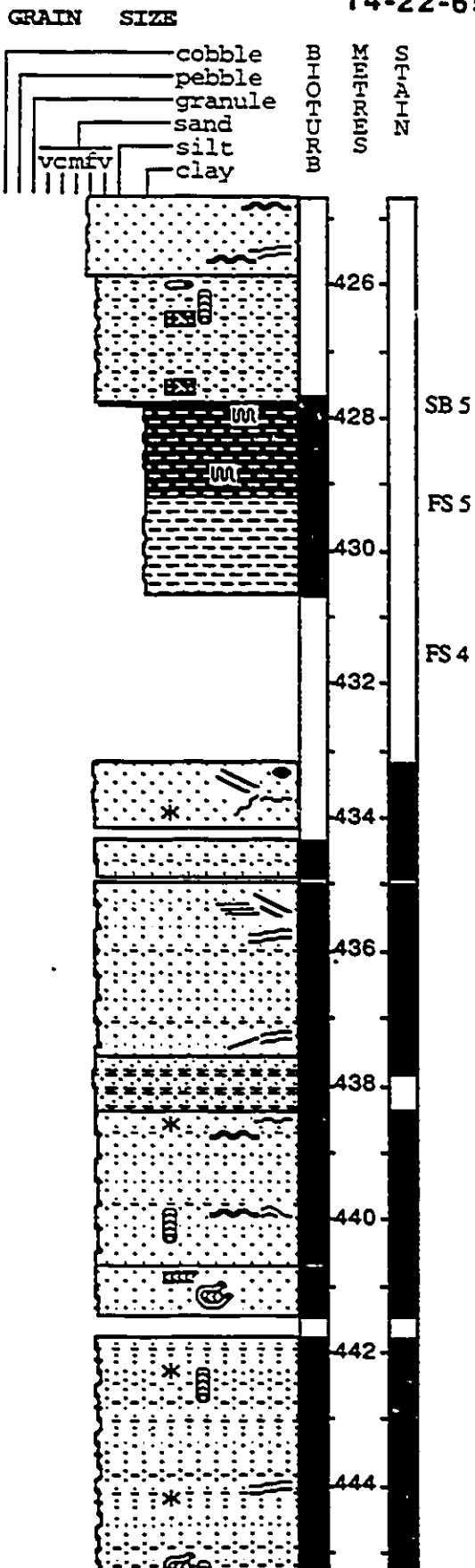


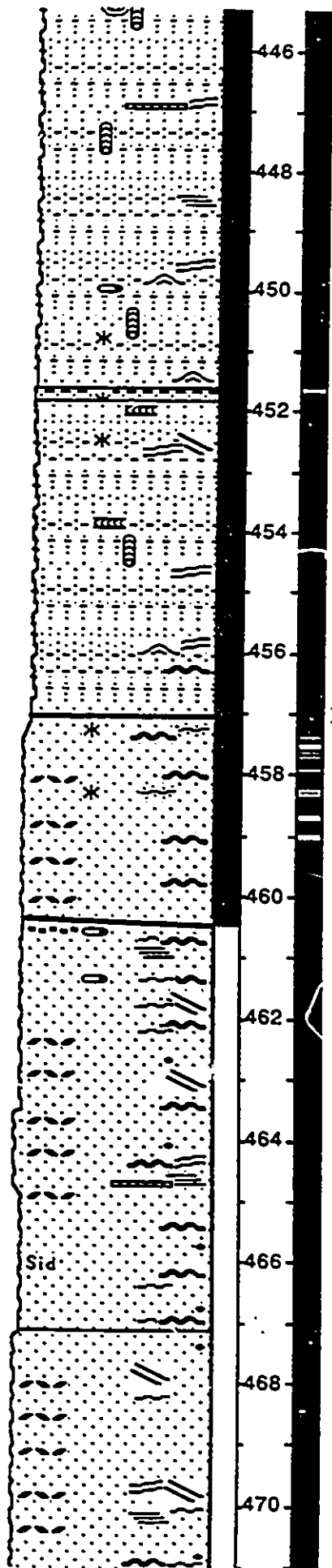


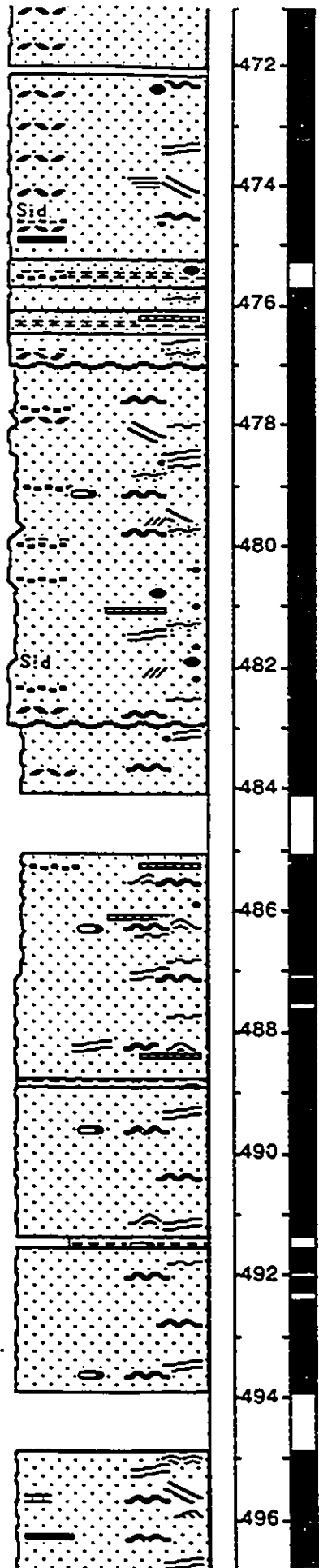
SB 3

ESSO 84 H5-13 COLDLK 5-22

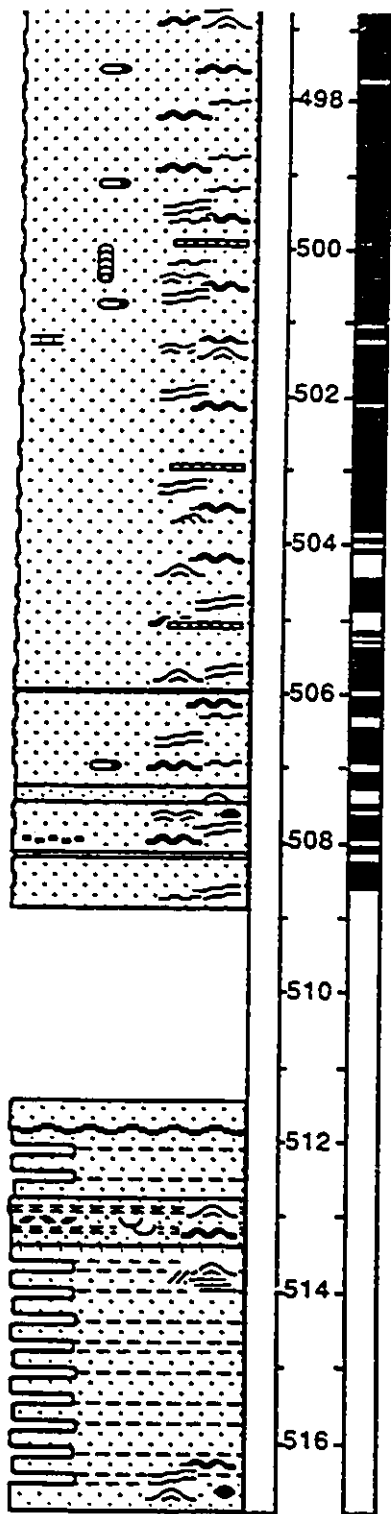
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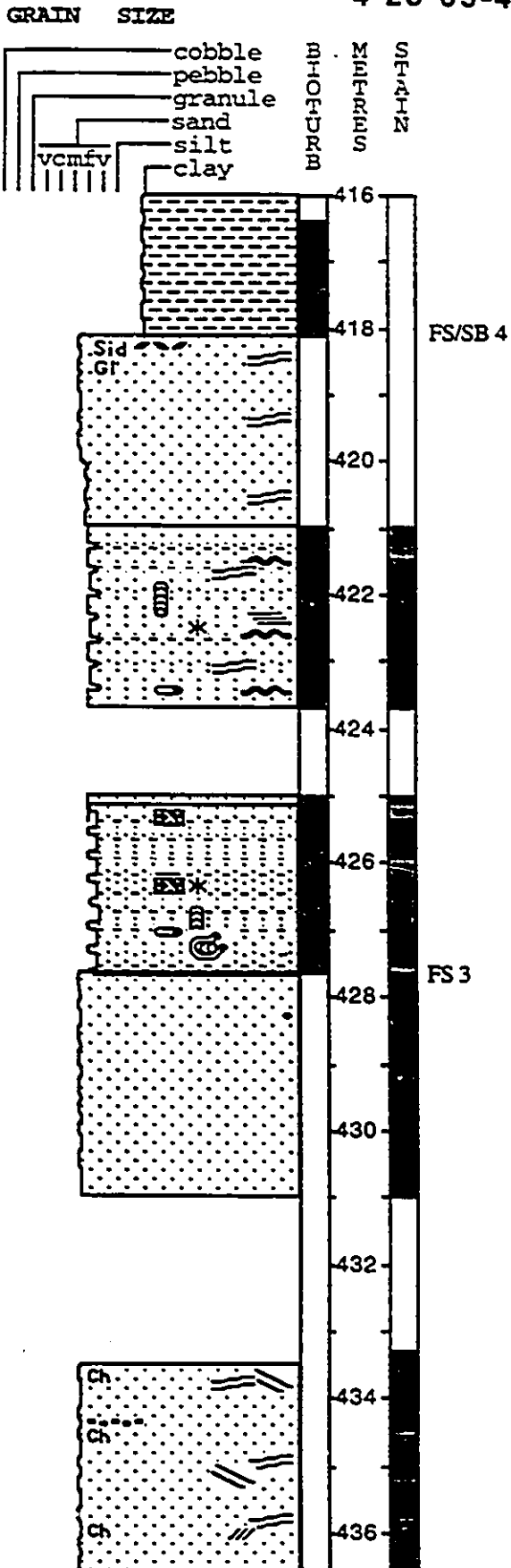


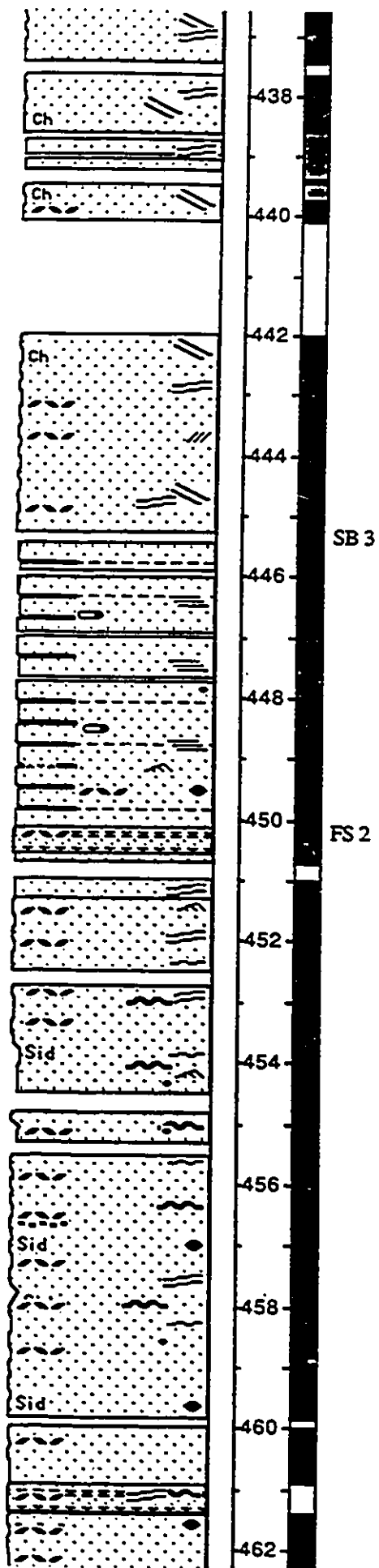
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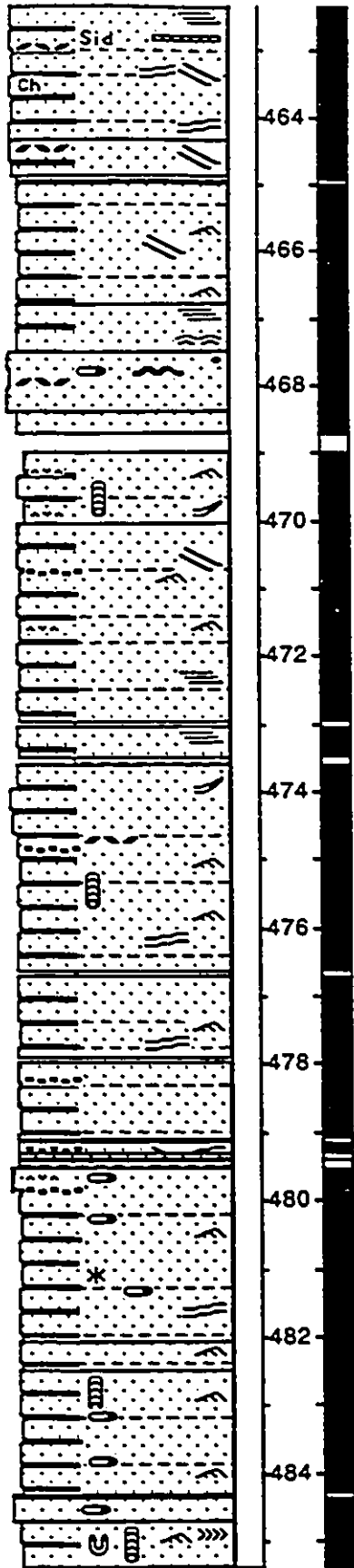


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4-23-65-4w4



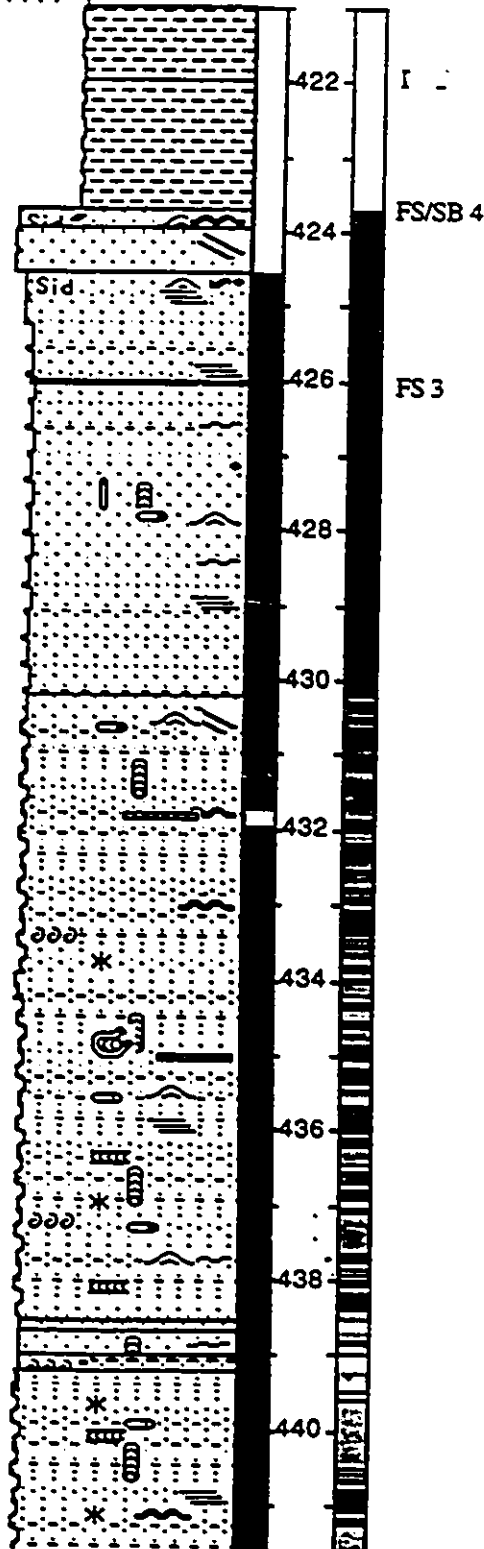


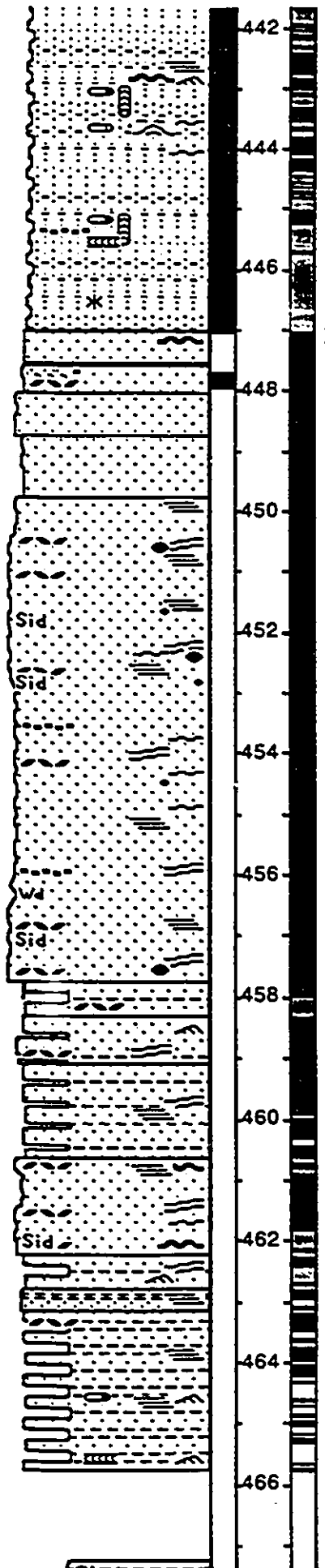


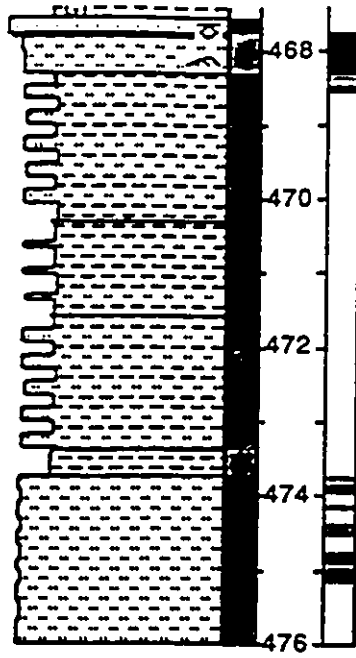
ESSO 87 Q6-8 COLDLK 12-24

12-24-65-4w4

GRAIN SIZE





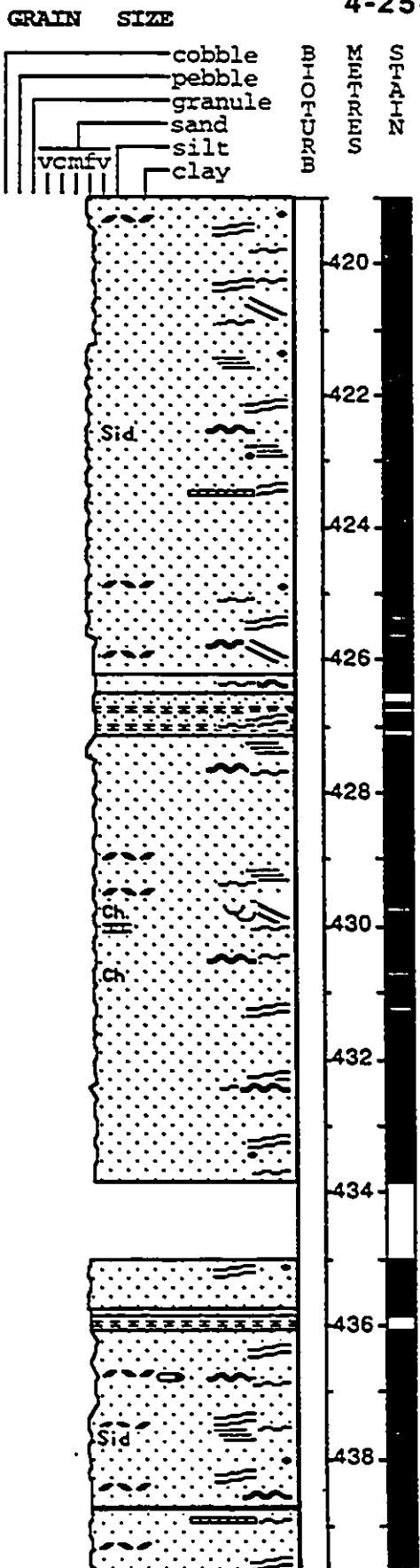


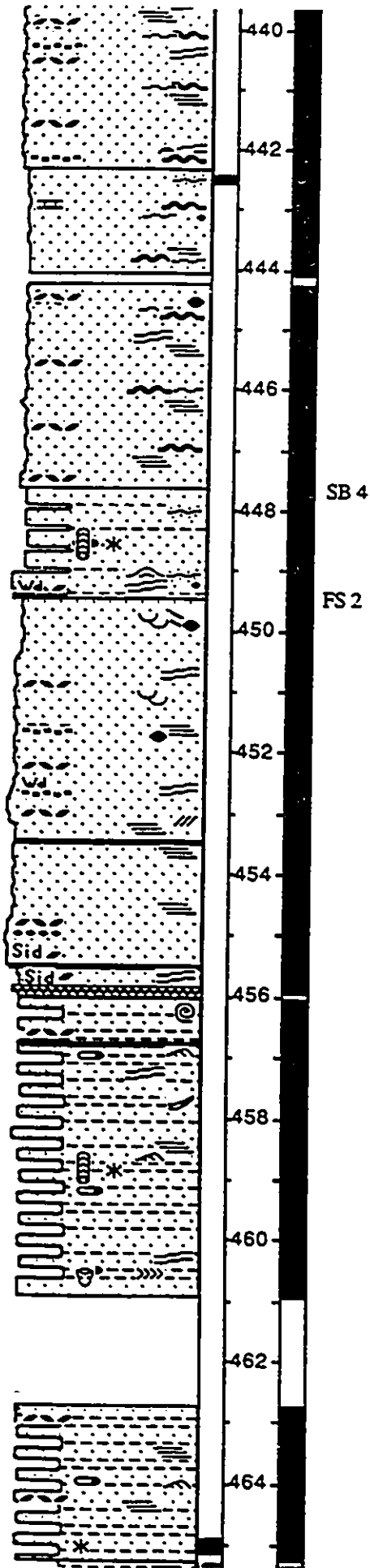
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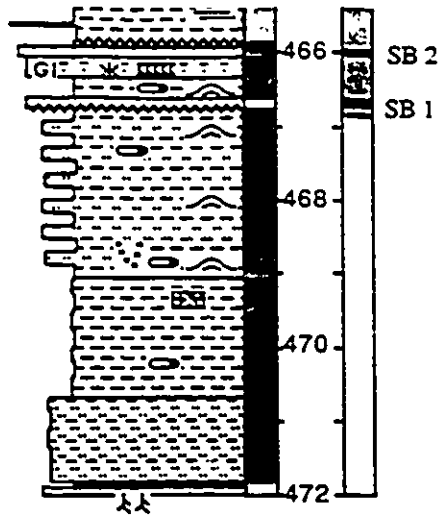
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ESSO 88 P3-13 COLDLK 4-25

4-25-65-4w4

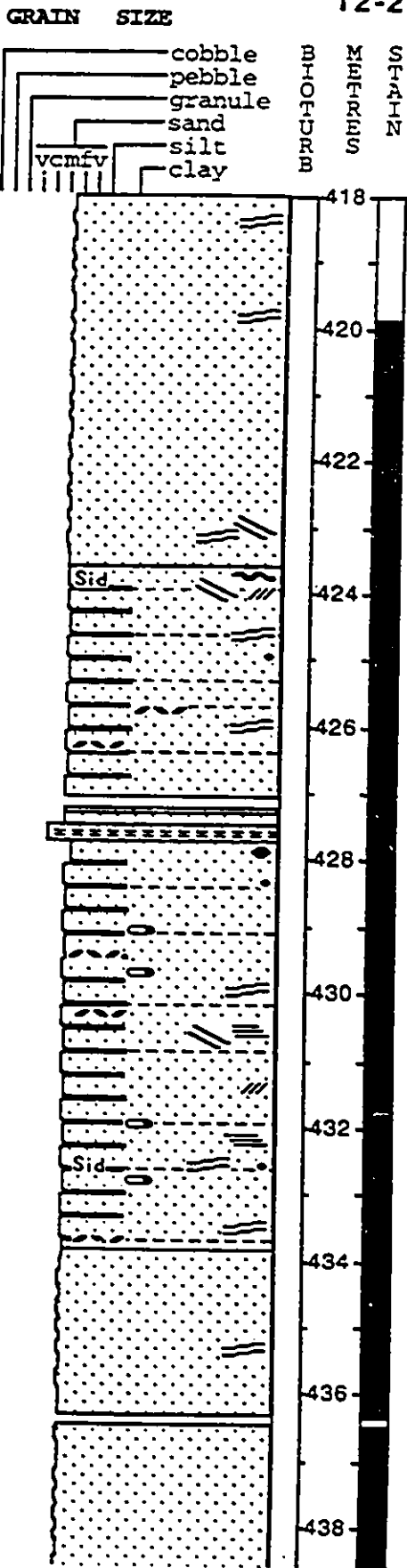


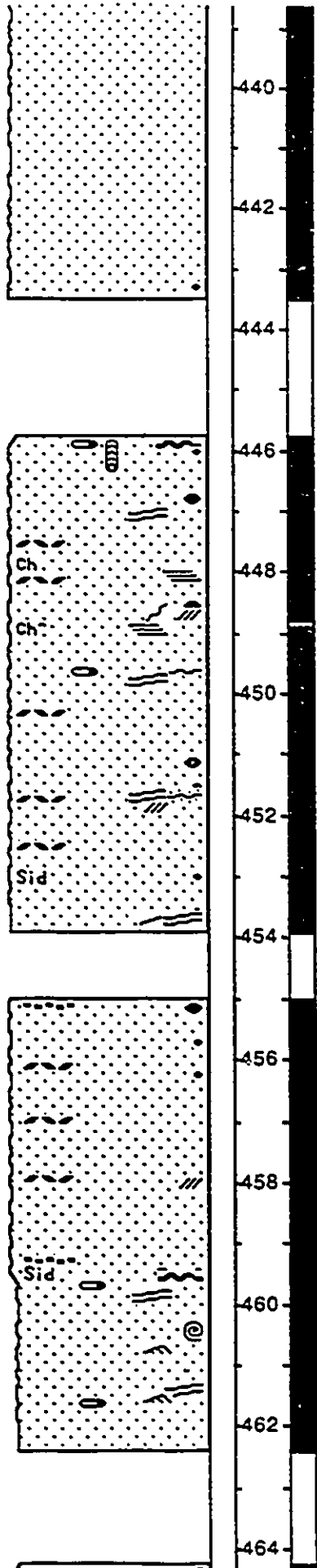




ESSO 87 M3-13 COLDLK 12-26

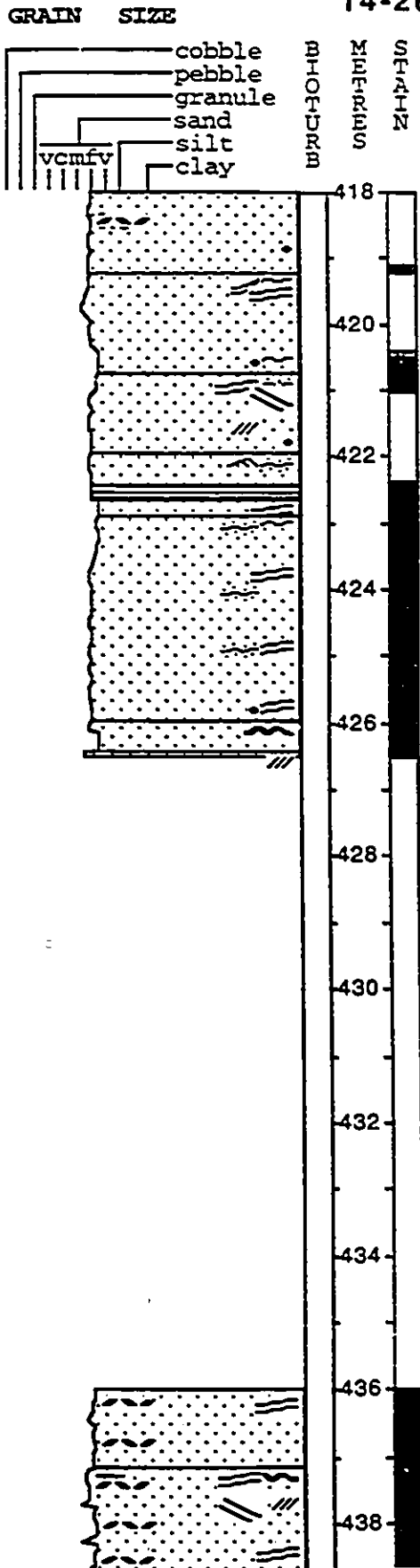
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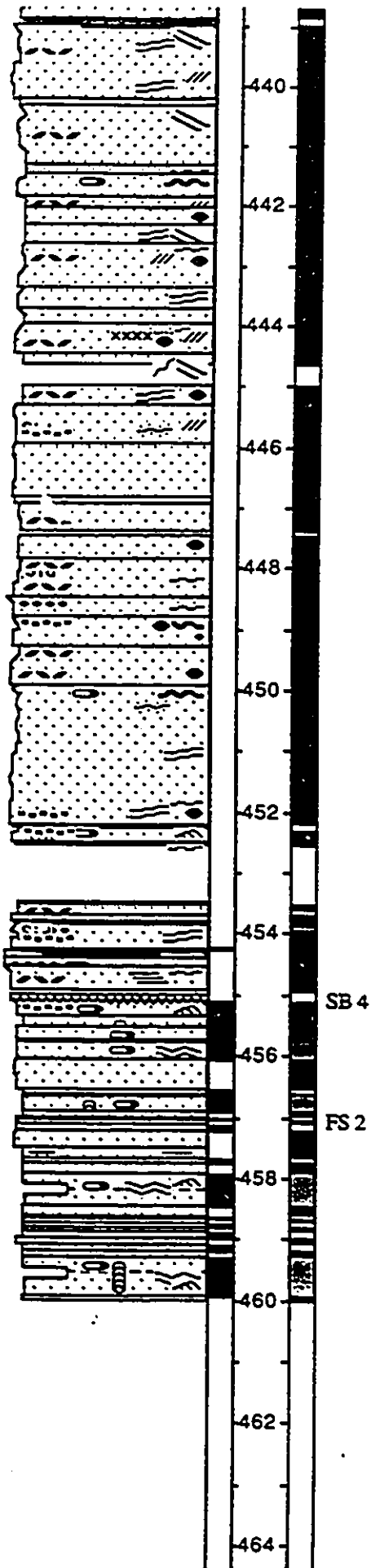


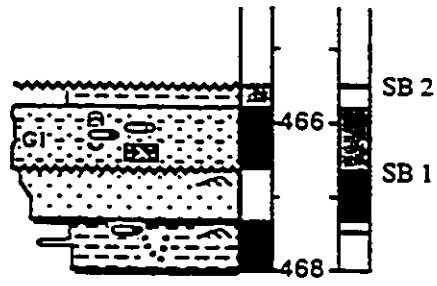


ESSO 88 M5-8 COLDLK 14-25

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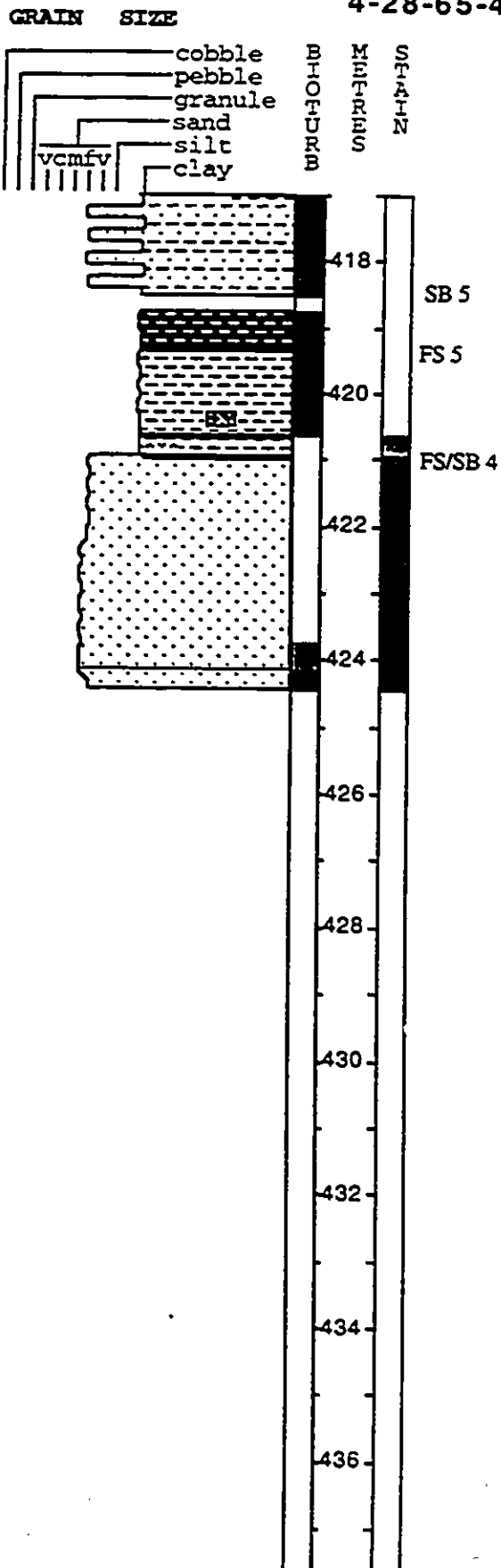


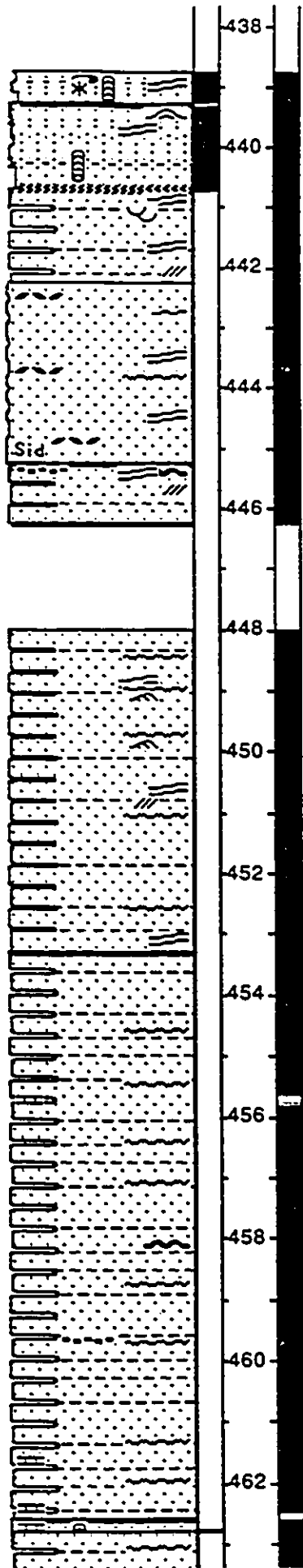




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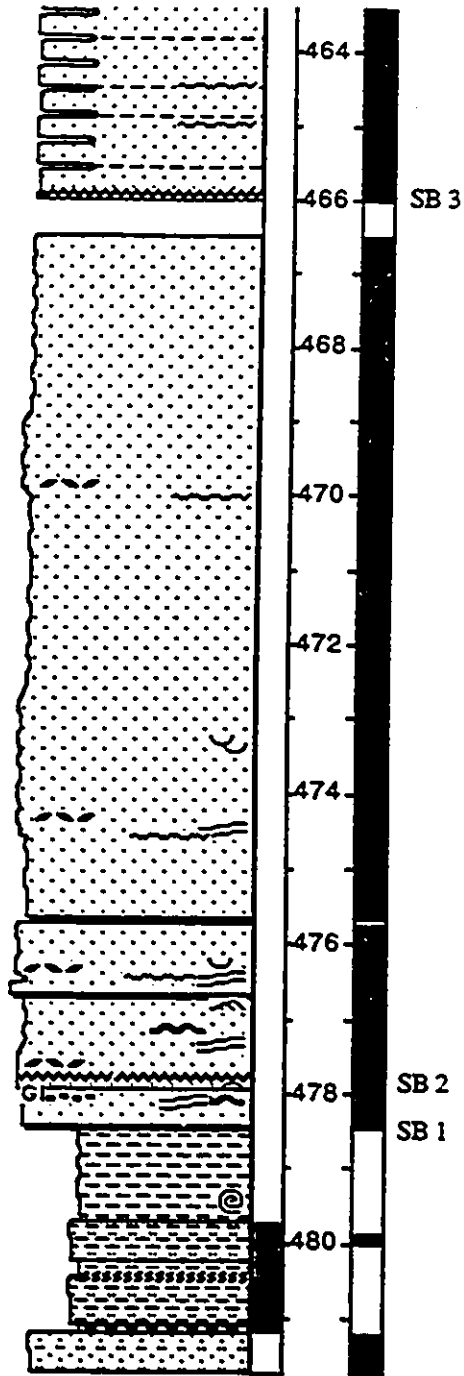
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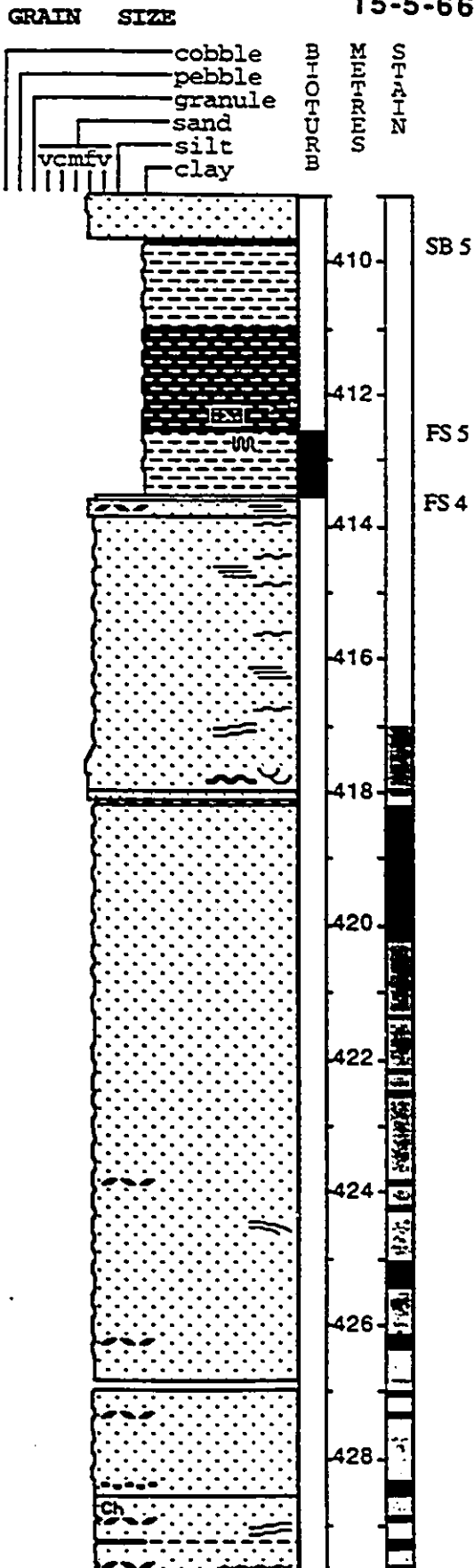
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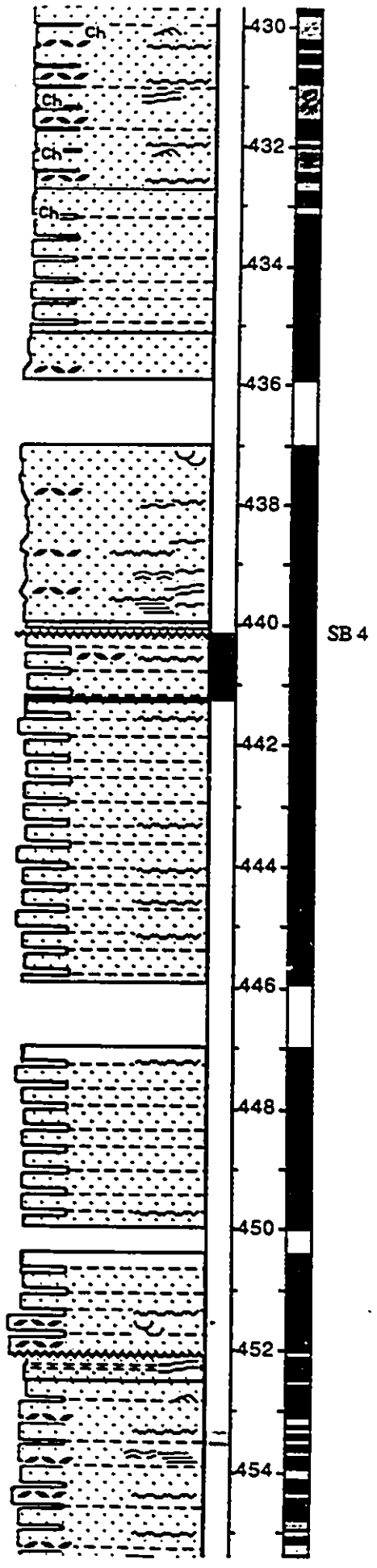
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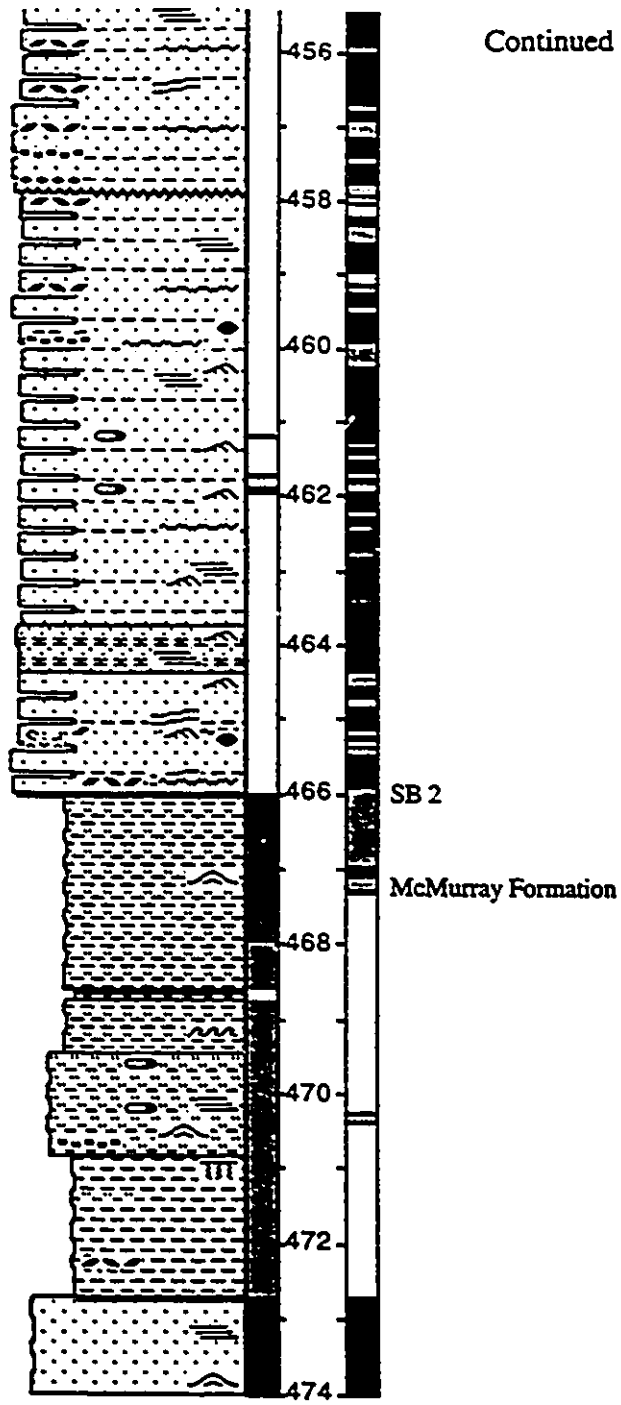


ESSO 88 COLDLK OV 15-5

15-5-66-4W4

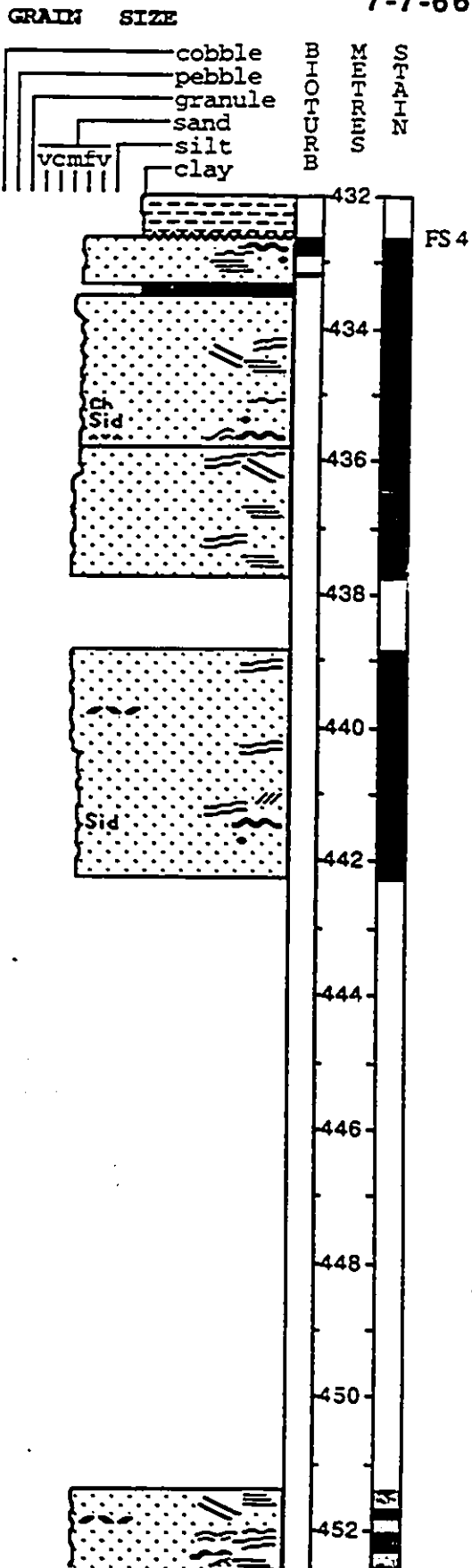


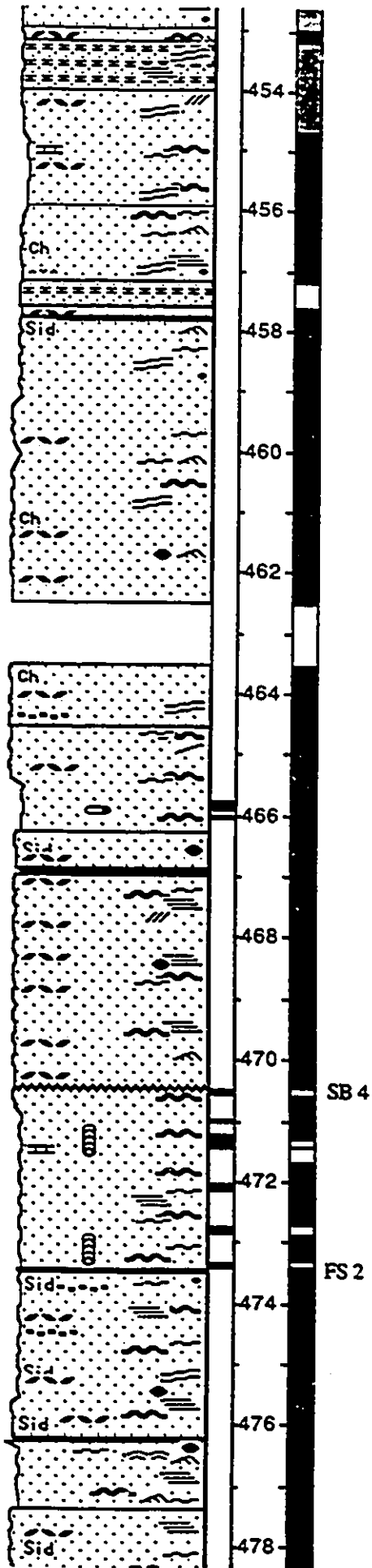


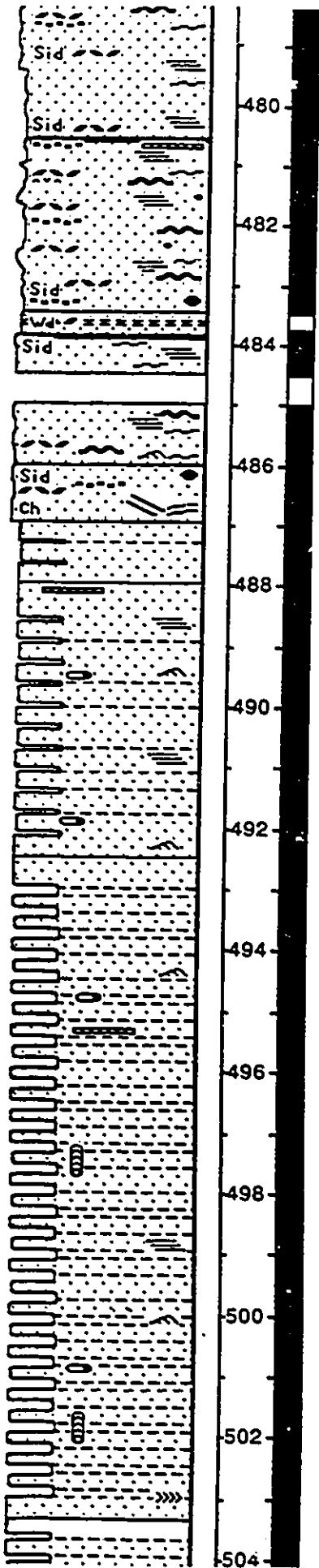


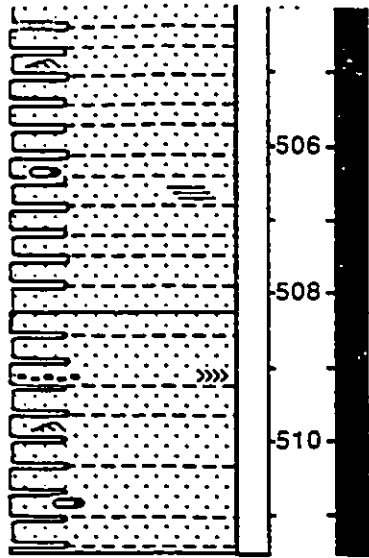
ESSO 85 COLDLK OV 7-7

7-7-66-4w4





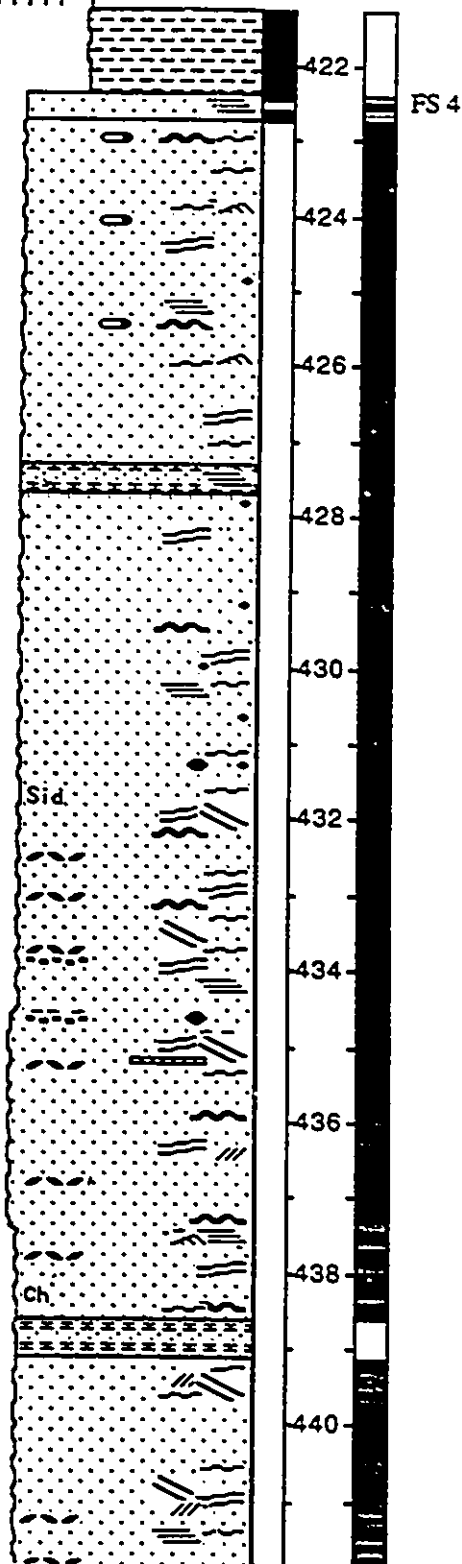
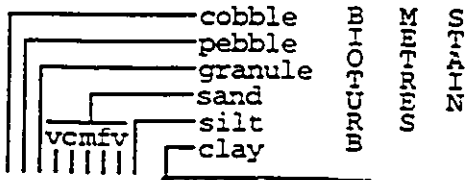


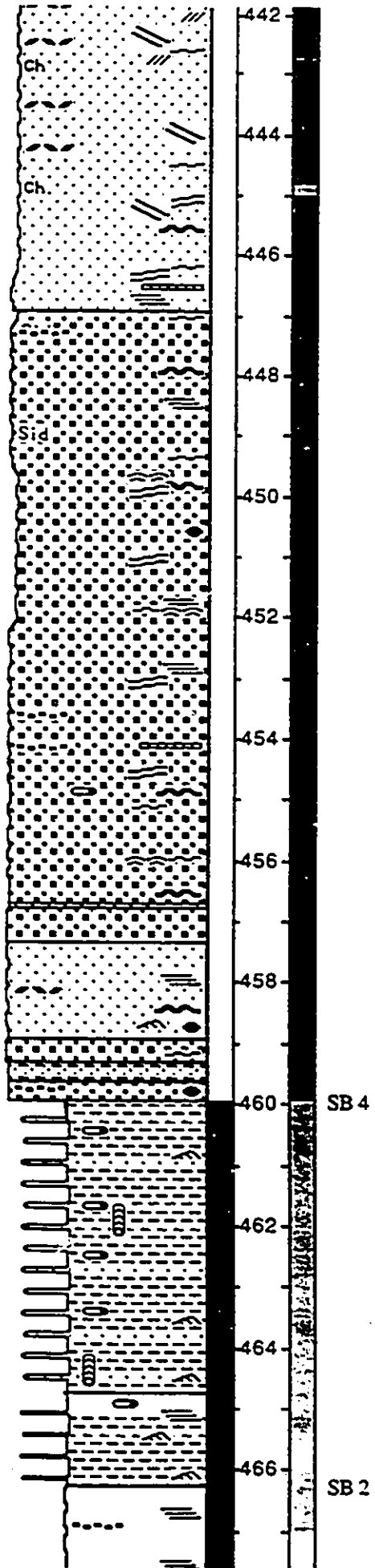


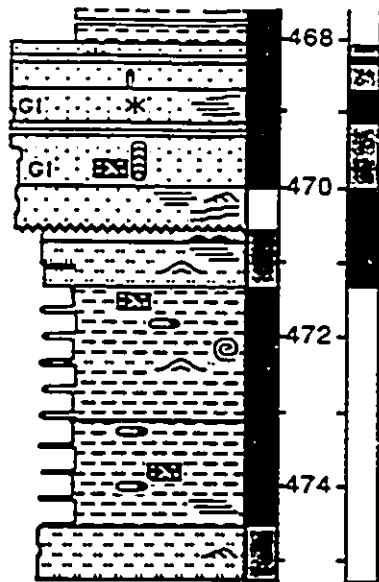
ESSO 88 COLDLK OV 3-9

3-9-66-4w4

GRAIN SIZE







FS 1

Continued from previous page

SB 1

472

474

APPENDIX B. STRATIGRAPHIC CROSS-SECTIONS

Six stratigraphic cross-sections through the Clearwater Formation and their corresponding geophysical well logs are included (pocket at back). Vertical scale is 1:480, but the sections are not to scale horizontally. Each well log comprises two vertical tracks: the left track contains gamma ray (GR) and spontaneous potential (SP) curves; the right track contains deep induction (ILD), medium induction (ILM), and Spherically Focused Log (SFLU) resistivity curves or Laterlog (LL8, LLU, or LLS), and dual induction (resistivity) curves.

Gamma ray curves (dashed lines), measured in API (American Petroleum Institute) units, are a measure of the natural radioactivity in rock formations. A shift of the gamma ray curve to the right represents an increase in the formation's natural radioactivity. Because shales typically contain a higher concentration of radioactive minerals than sandstone or carbonate, the gamma ray response curve will shift to the right for shales and to the left for 'clean' sandstone or carbonate.

The spontaneous potential logs (solid lines) are plotted in millivolts and provide a measure of differences in direct current voltage between the natural electrical potential of a moveable electrode in the well bore and the potential of a fixed electrode at the surface. The salinity differences (resistivity) between the drilling mud and formation water create voltage differences that are recorded on the SP log. Typically, a shift to the right represents impermeable shale, whereas a shift to the left represents sandstone or carbonate. On occasion, oil company officials will calibrate the SP curve in reverse so that a shift to the left represents shale and a shift to the right represents sandstone. Some of the SP curves included here (J1-8; J43-8; J16-8; R5-13; Q6-8) have such reversed SP curves.

The right tracks of the included well logs contain various curves of electrical resistivity. The resistivity logs measure the conductive nature of formation fluids. More resistive fluids, such as hydrocarbons, are less conductive and therefore are more highly resistive than formation water. A shift to the right indicates higher resistivities.

Together, the response curves in the left and right tracks of each well log provide useful information about the rock formations lithology and fluid content.

APPENDIX C. MICROPALAEONTOLOGY

During the summer of 1993, ten samples were taken from core in the study area. Of these, seven were from the Clearwater Formation (samples 5, 6, and 10 were from McMurray or Grand Rapids formations, and are not described here). The samples were sent to Dr. J. Jansonius at Imperial Oil Resources Limited in Calgary, Alberta for analysis of microfossils. The following is a brief statement of background information followed by a summary of the analyses:

The analysis of samples was carried out in two stages:

A- The proportions, size distribution, and quality of Particulate Organic Matter (POM) particles of an untreated thin-section slide was examined. This gives a general indication of paleoenvironment. For example, particles from more proximal areas are less well sorted than those from more distal areas. In addition, woody particles are often blade shaped near river mouths, whereas more equidimensional or rounded particles result from wave action in more distal areas. Furthermore, in oxygen-depleted conditions, much amorphous material is preserved.

The categories of POM used here are: 'dinos' (including algal cysts); saccate 'pollen'; small 'spores' (ferns *et cetera*, which usually settle closer to their source than saccate pollen); 'opaque' woody (indicating exposure to oxygen during transport); 'fresh' woody (indicating limited transport); 'soft' tissues (epithelial and parenchymous material, which cannot be transported far); 'biodegraded' tissue (initial stages of purification, under reduced oxygen conditions); 'amorphous' material (generally indicating anoxic conditions). These categories are given with their relative percentages.

2- Here, two size fractions (one oxidized with Schulze solution and one of the sieved residue) are mounted on the same slide for examination. Oxidation solubilizes

partly decayed plant material and helps to concentrate fossils on the slide; the sieving helps to concentrate fossils that are smaller than the more common species on the slide. With this method the presence or absence of dinoflagellate and marine algal cysts can be verified, and help to document the marine or terrestrial character of a given sample.

Sample 1: 14-22-65-4W4 (H5-13) 497.7m (Facies Association 1)

A: Dinos trace; pollen 13; spores 1; opaque 2; fresh 80; soft 3; biodegraded 1; amorphous trace. The pollen are mostly of taxodiaceous type, similar to swamp cypress, which indicates a swampy, possibly lagoonal or estuarine (mangrove) environment. The fresh woody component has a large proportion of blades, indicating nearness to a fluvial source, and is poorly sorted and generally rather coarse.

B: Dinoflagellates are very rare, and show little diversity, with most types thought to be tolerant of subsaline conditions, some appearing to be washed in, rather than to have thrived locally: *Palaeoperidinium cretaceum*, *Circulodinium* sp., single *Comasphaeridium whitei*, *Coronifera* cf. *oceanica*, *Oligosphaeridium* complex, *Apteodinium* sp., and *Odontochitina costata*. In addition, some fragments of clitellate cocoons (leeches) were observed, which are indicators of fresh water, but may wash out into saline water.

Sample 2: 12-18-65-4W4 1540.8' (496.6m; Facies Association 1)

A: Dinos trace; pollen 3; spores 2; opaque 2; fresh 91; soft 2; biodegraded trace; amorphous trace. The spores include varied fungal spores; the pollen are mostly of taxodiaceous type, similar to swamp cypress, which indicates a swampy, possibly lagoonal or estuarine (mangrove) environment. The fresh woody component is rather coarse and consists mostly of blades, indicating nearness to a fluvial source.

B: Dinoflagellates are very rare, and show little diversity, with most types thought to be tolerant of subsaline conditions, some appearing to be washed in, rather than to have

thrived locally: *Palaeoperidinium cretaceum*, indeterminate round peridinioid cysts, *Circulodinium* sp., single *Kleithrasphaeridium simplicispinium*.

Sample 3: 13-1-65-4W4 (D24-13) 419.0m (Facies Association 6)

A: Dinos trace; pollen 1; spores 1; opaque 10; fresh 88; soft trace; biodegraded trace; amorphous trace. The fresh woody fragments contain a fair number of blades, but much more equidimensional than in samples 1 and 2. In addition, sorting is rather poor and particle size is fairly large.

B: The spores include some fungal spores; the pollens include about equal amounts of bisaccate and taxodiaceous pollen, as well as a few *Classopollis*. Dinoflagellates include *Nummus similis*, *Fromea fragilis*, *Odontochitina operculata*, *O. costata*, and individual specimens of *Pterospermopsis* sp., *Canningia chabaca*, *Palaeoperidinium* sp., *Oligosphaeridium* complex, *Spiniferites ramosus*, and others. This sample is more indicative of an open marine connection than samples 1 and 2.

Sample 4: 13-1-65-4W4 (D24-13) 454.0m (Facies Association 3)

A: Dinos trace; pollen 3; spores 3; opaque 3; fresh 6; biodegraded 4; amorphous 81. Unusual POM assemblage in that the amorphous particles have a definite outline, showing that each particle comprises many algal cysts that have been biodegraded, or converted to amorphous matter under (nearly) anoxic bottom conditions. None of the cysts (possibly from a bloom - not uncommon in estuarine environments) were well preserved enough to allow identification.

B: Rare round peridinioid cysts, *Canningia*, *Comasphaeridium whitei*, *Palaeoperidinium cretaceum*, *Pseudoceratium* cf. *interiorensis*.

Sample 7: 11-12-65-4W4 458.6m (Facies Association 3)

A: Dinos 1; pollen 6; spores 3; opaque 30; fresh 10; biodegraded (terrestrial) 50; amorphous (marine) trace. Terrestrial material poorly sorted; opaque/dark woody fragments are generally fine and sub-angular, the fresh woody particles are fine to medium in size and include scattered blades. The biodegraded fraction is fine to coarse; preservation is fair. Environment of deposition is proximal, close to estuarine conditions.

B: Bisaccate pollen slightly exceeded the taxodiaceous pollen in numbers. Dinoflagellates include common small, thin, round, non-descript peridinioid cysts, rare *Canningia chabaca*, *Palaeoperidinium cretaceum*, *P. sp.*, *Ellipsoidictyum sp.*

Sample 8: 11-12-65-4W4 451.1m (Facies Association 3)

A: Dinos 1; pollen 10; spores 4; opaque 15; fresh 45; biodegraded 25; amorphous trace. Sorting slightly better than in sample 7, with more elongate particles tending towards blades. Rare microthyroid fungal fructifications. Environment a bit more estuarine than sample 7.

B: Rare *Palaeoperidinium cretaceum*, *P. sp.*, *Circulodinium sp.*, *Canningia sp.*, thin round cysts, *Filisphaeridium*.

Sample 9: 11-12-65-4W4 416.2m (Facies Association 5)

A: Dinos 1; pollen 3; spores 1; opaque 15; fresh 20; biodegraded 55; amorphous (terrestrial) 5. The POM shows fair sorting; the opaque material is mostly fine and abraded, the fresh material is fine to medium with scattered medium to coarse blades, and the biodegraded material is fine to medium. The overall assemblage indicates a somewhat distal or shelf position, near or just below wave base.

B: Common small chorate (spiny) dinoflagellate cysts (*Cleistosphaeridium*, et cetera); scattered *Odontochitina operculata*, *Canningia sp.*; rare *Palaeoperidinium sp.*,

Circulodinium brevispinosum, and *Oligosphaeridium* complex occur as well. The spores include a few fungal spores, and there are some microthyriaceous fructifications, which indicates a treed or swampy type of hinterland.

APPENDIX D. MINERALOGY

Two representative samples of Clearwater Formation sandstone from 2-18-65-3W4 (C21-08) were selected for petrographic analysis. Sample 1 (Fig. D.1, a and b) is from the fluvial facies association (FA 4) and its composition is typical of Clearwater Formation sandstone in the study area (excluding the Wabiskaw Member). Sample 2 (Fig. D.1, c and d) is typical of sandstone from the Wabiskaw Member of the Clearwater Formation.

Due to the poorly consolidated nature of Clearwater Formation sandstones, a blue epoxy was injected into the samples before the thin-sections were cut. As a result of this injection, the original fabric of the grains was disturbed. In addition, the epoxy injection typically removes most grain-coating clay minerals. What remains is essentially a grain mount of framework grains within a matrix of blue epoxy.

Sample 1 (feldspathic litharenite, Fig. D.2):

Sample 1 was taken from core at a depth of 455.2 m.

Grain Size: upper fine to upper medium.

Sorting: poor

Constituent grains:

Rock fragments compose 35% of this sample with volcanic rock fragments (20%) being the most common; sedimentary rock fragments make up

15% of this sample. The volcanic rock fragments are typically subangular to subrounded and are identified by the presence of randomly oriented plagioclase feldspar laths. Sedimentary rock fragments are primarily composed of massive and laminated shale clasts which typically occur as subrounded grains that are a deep brown colour under plane polarized light.

Quartz is a major detrital constituent, making 25% of this sample and mainly occurs as monocrystalline grains. The quartz grains exhibit angular to subrounded grain shapes.

Feldspars compose 25% of this sample and occur as subangular to subrounded grains. Plagioclase is the most common feldspar (15%), but alkali feldspars, such as orthoclase (5%) and microcline (5%), also occur. Alteration of feldspar grains to illite and chlorite is common. In addition, many plagioclase grains have undergone secondary dissolution.

Chert makes up 15% of this sample and occurs as angular to subangular grains that typically are light brown in colour under plane polarized light.

Trace amounts of mica (predominantly biotite), heavy minerals, and carbonaceous material are also present throughout the sample.

Sample 2 (glaucinitic subarkose or sublitharenite, Fig. D.2):

Sample 2 was taken from core at a depth of 471.3 m.

Grain size: lower fine to lower coarse.

Sorting: moderate to poor.

Constituent grains:

Quartz is the predominant framework grain in this sample, making up 50% this sample. It occurs as rounded to subangular clear grains.

Glauconite makes up 35% of this sample. It occurs as light to dark green, rounded to subrounded grains that are typically medium or coarse sized. Because glauconite is very soft relative to the other constituent grains it is commonly deformed around more competent grains. In addition, glauconite grains are typically larger than the other constituents. This is because they have a low specific gravity and can be transported in similar energy systems as smaller quartz, chert, or feldspar grains.

Feldspars, predominantly plagioclase compose 5% of this sample and occur as subrounded grains.

Chert makes up 5% of this sample and occurs as sub angular to subrounded grains.

Mica, predominantly muscovite occurs as small elongate grains and make up 5% of this sample.

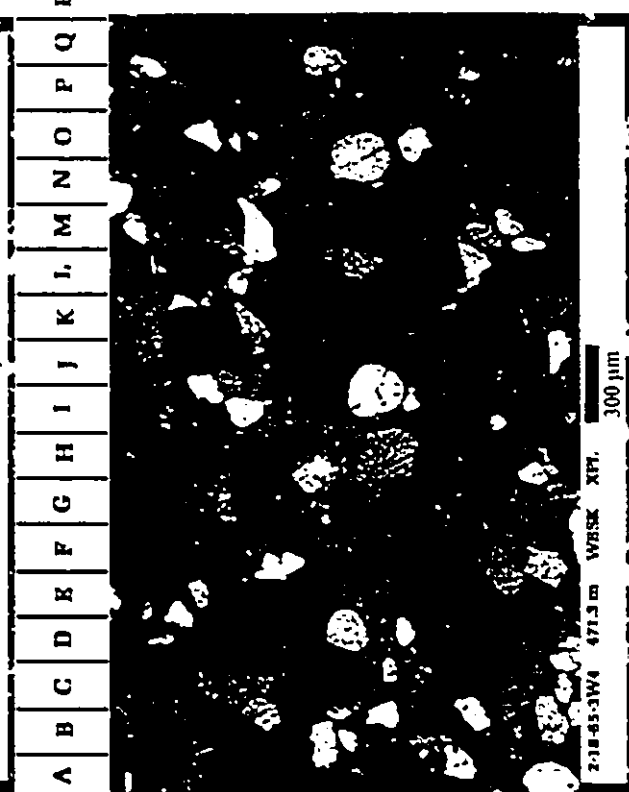
Trace amounts of rock fragments and heavy minerals occur throughout this sample.

Figure D.1: Photomicrograph

- a) **Sample 1 (25x, plane polarized light). Upper fine to upper medium feldspathic litharenite. Major constituents include volcanic rock fragments (C2, M7), sedimentary rock fragments (E10, N4), quartz (D5, I7), Plagioclase (O7, C3), Potassium feldspar (M2), and chert (Q6).**
- b) **Sample 1 (25x, cross polarized light). Same as a but with polars crossed.**
- c) **Sample 2 (25x, plane polarized light). Lower fine to lower coarse glauconitic arkose. Major constituents include quartz (I6), glauconite (E5), chert (O5), and muscovite (H6).**
- d) **Sample 2 (25x, cross polarized light). Same as c but with polars crossed.**



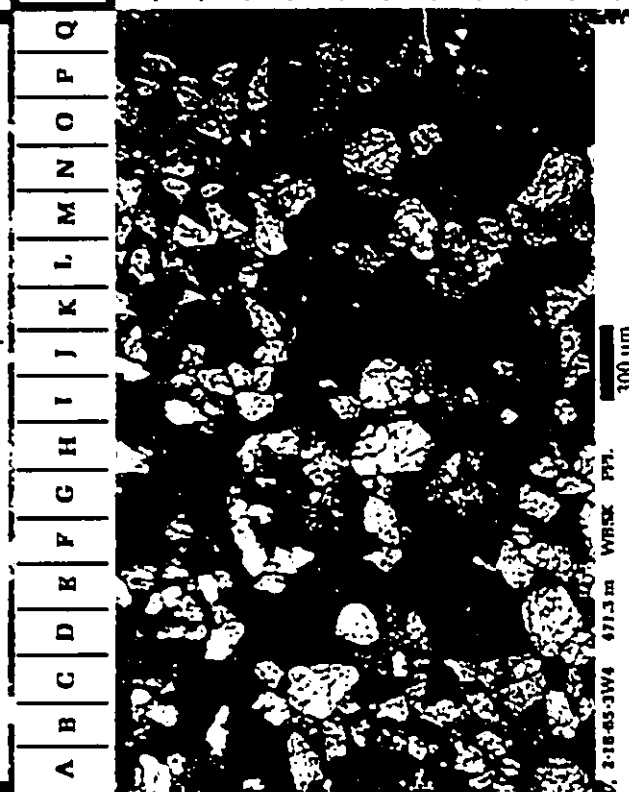
1
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12



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10
11
12

A B C D E F G H I J K L M N O P Q R

A B C D E F G H I J K L M N O P Q

a/b
c/d

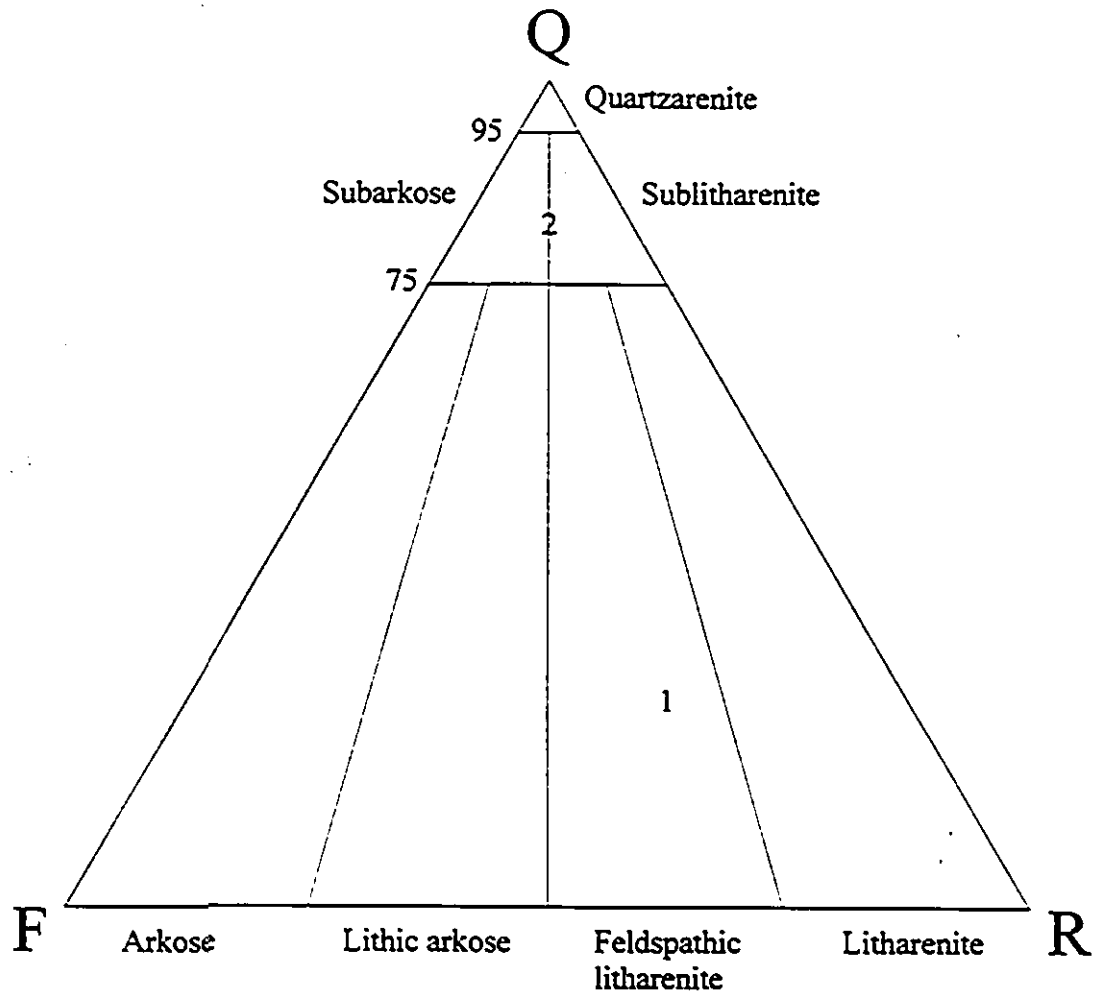


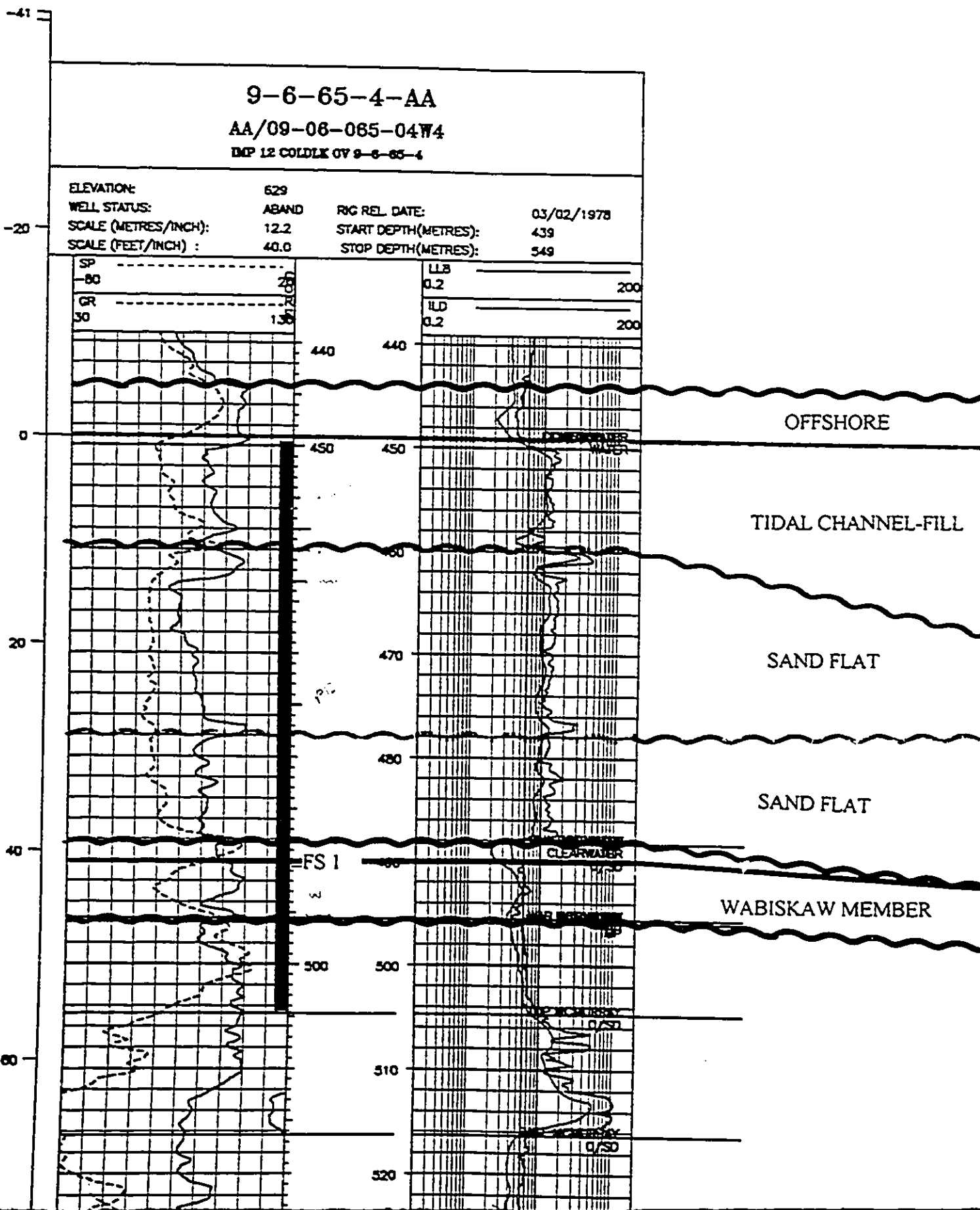
Figure D.2: Ternary diagram showing the classification (after Folk, 1974) of the two thin-section samples (1 and 2). Sample 1 plots in the feldspathic litharenite category; sample 2 plots on the line between subarkose and sublitharenite.

9-6-65-4-AA

AA/09-08-065-04W4

DMP 12 COLDEX CV 9-6-65-4

ELEVATION: 629
WELL STATUS: ABAND RIG REL DATE: 03/02/1978
SCALE (METRES/INCH): 12.2 START DEPTH(METRES): 439
SCALE (FEET/INCH) : 40.0 STOP DEPTH(METRES): 549

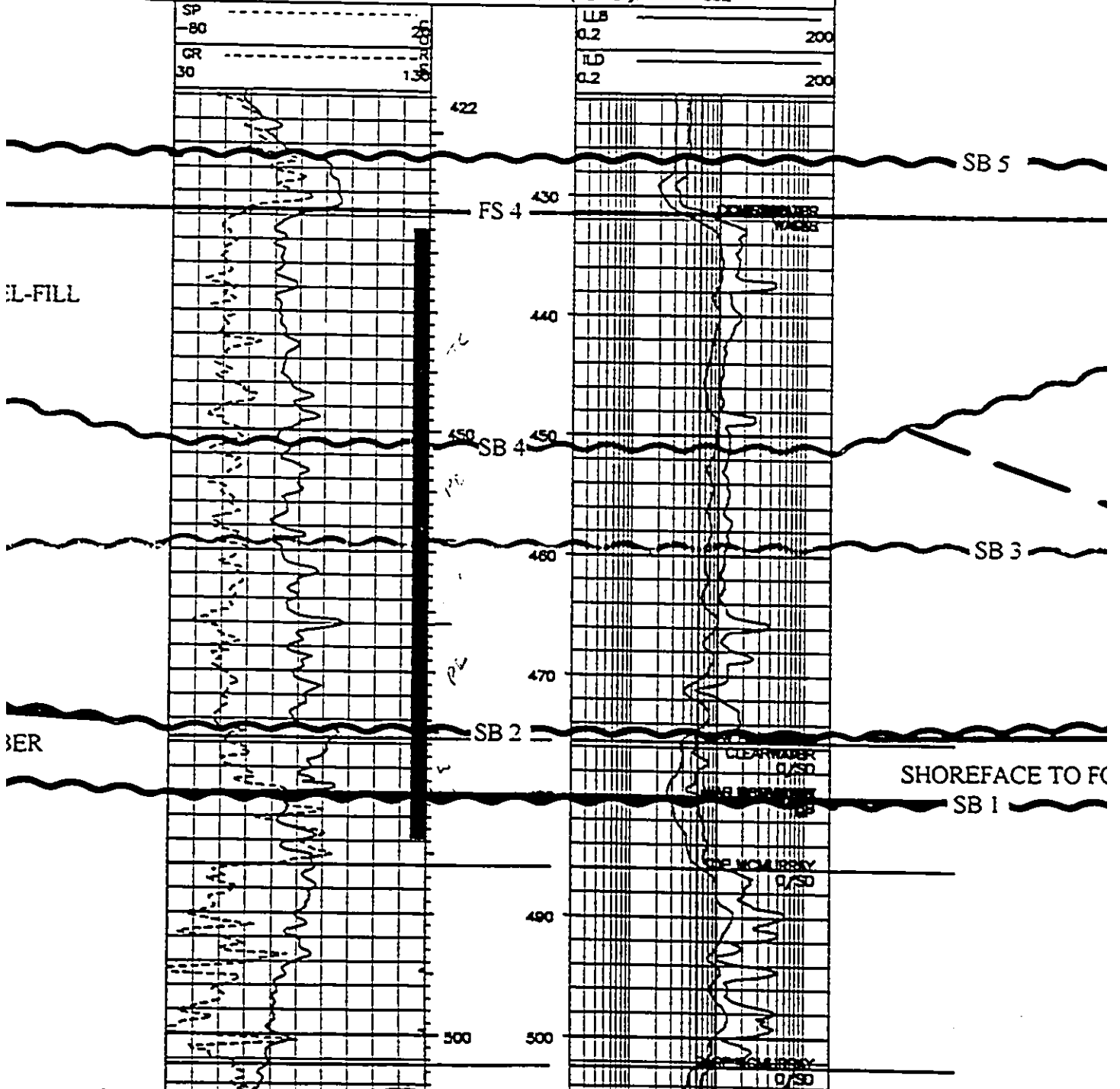


6-8-65-4-AA

AA/06-08-065-0474

ESSO COLD LAKE CV 6-8-65-4

ELEVATION:	516	RIG REL. DATE:	23/02/1979
WELL STATUS:	ABAND	START DEPTH(METRES):	422
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	532
SCALE (FEET/INCH) :	40.0		

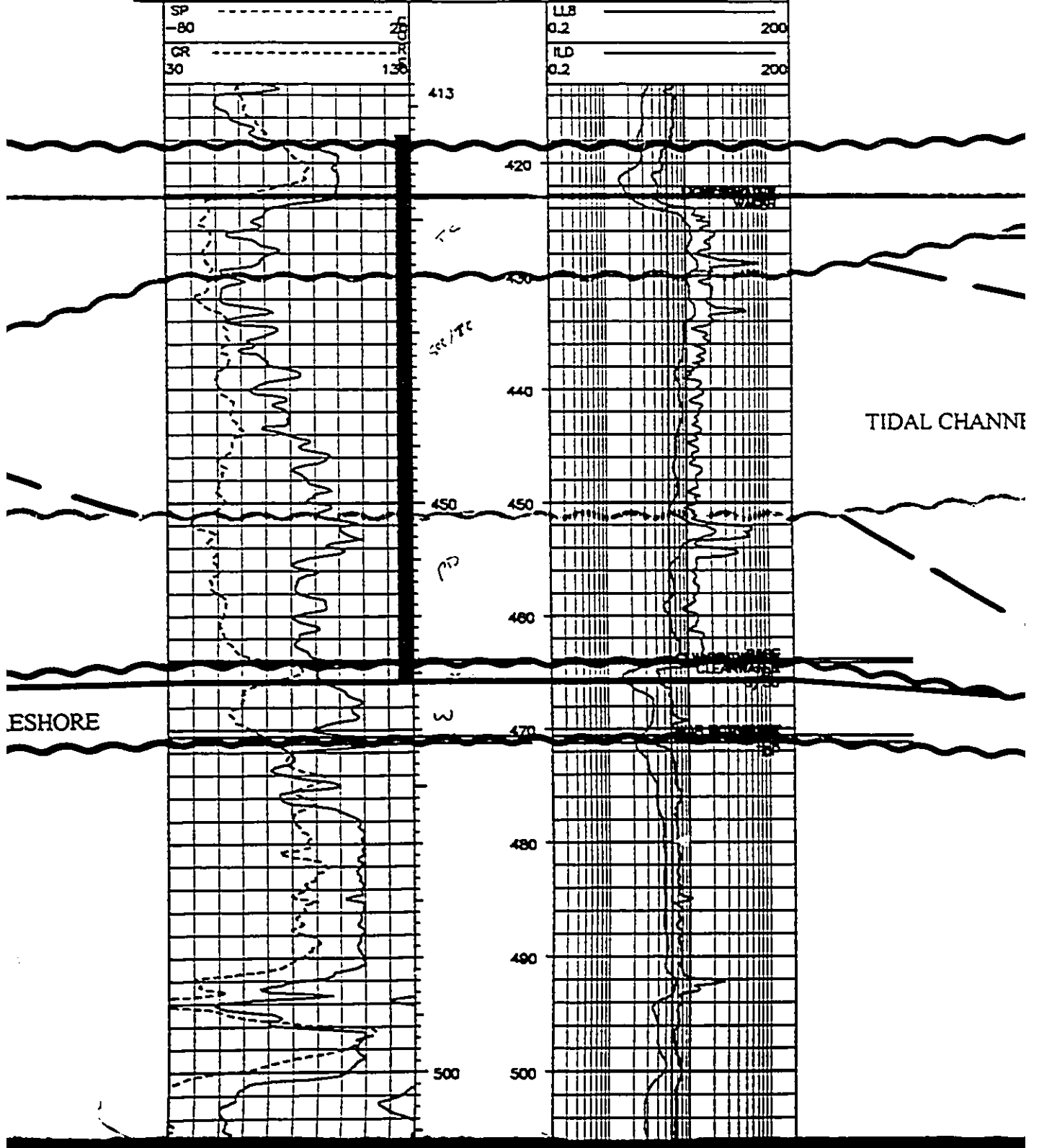


4-16-65-4-AA

AA/04-18-085-04W4

DMP 7 COLDLX OV 4-16-65-4

ELEVATION:	606	R/C REL. DATE:	02/01/1978
WELL STATUS:	ABAND	START DEPTH(METRES):	413
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	523
SCALE (FEET/INCH) :	40.0		

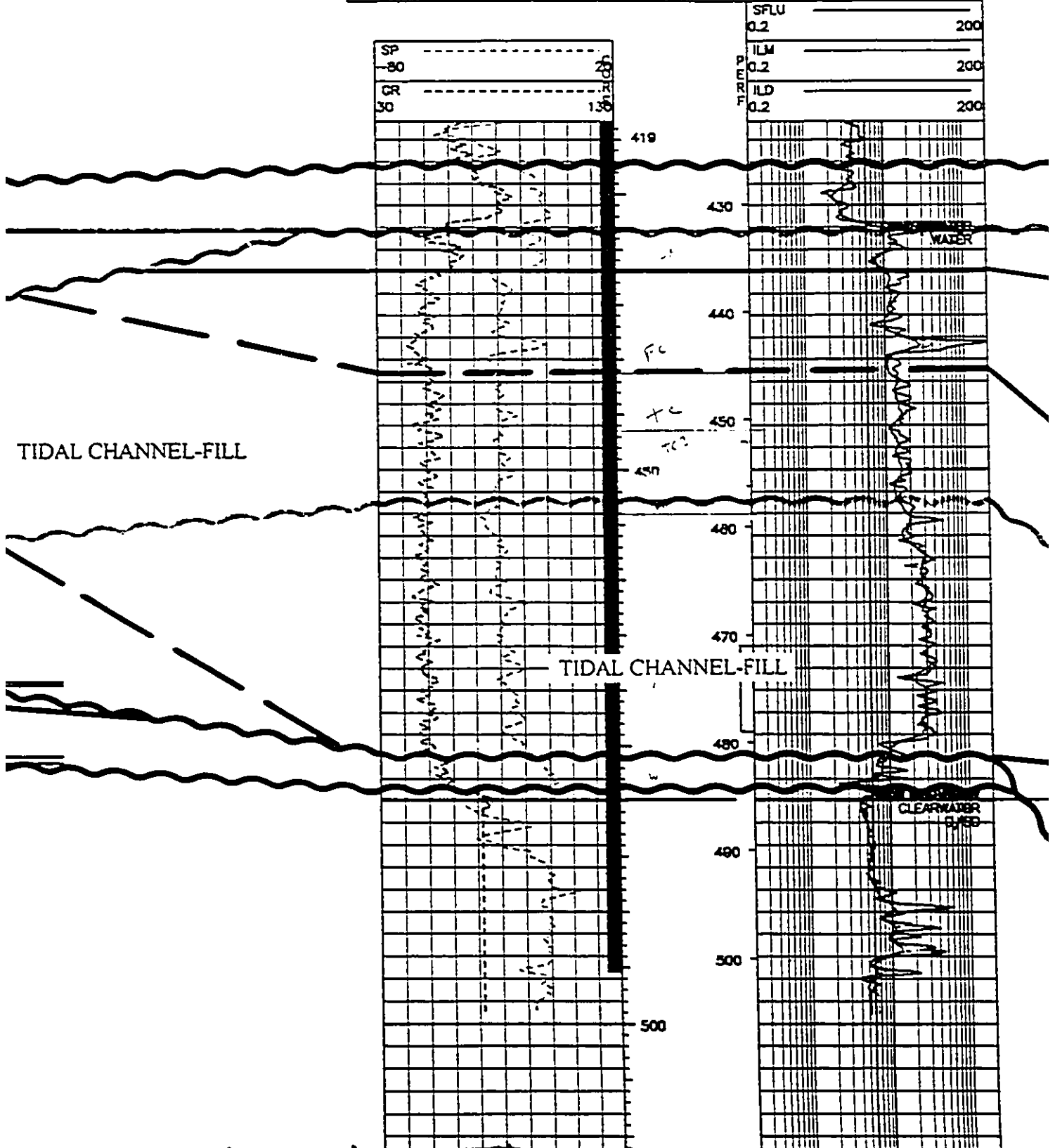


J07-13

09/18-16-085-04W4

ESSO 84 J7-13 COLDLK 16-16-85-4

ELEVATION:	614	RIG REL. DATE:	09/02/1985
WELL STATUS:	CB	START DEPTH(METRES):	418
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SCALE (FEET/INCH) :	40.0		

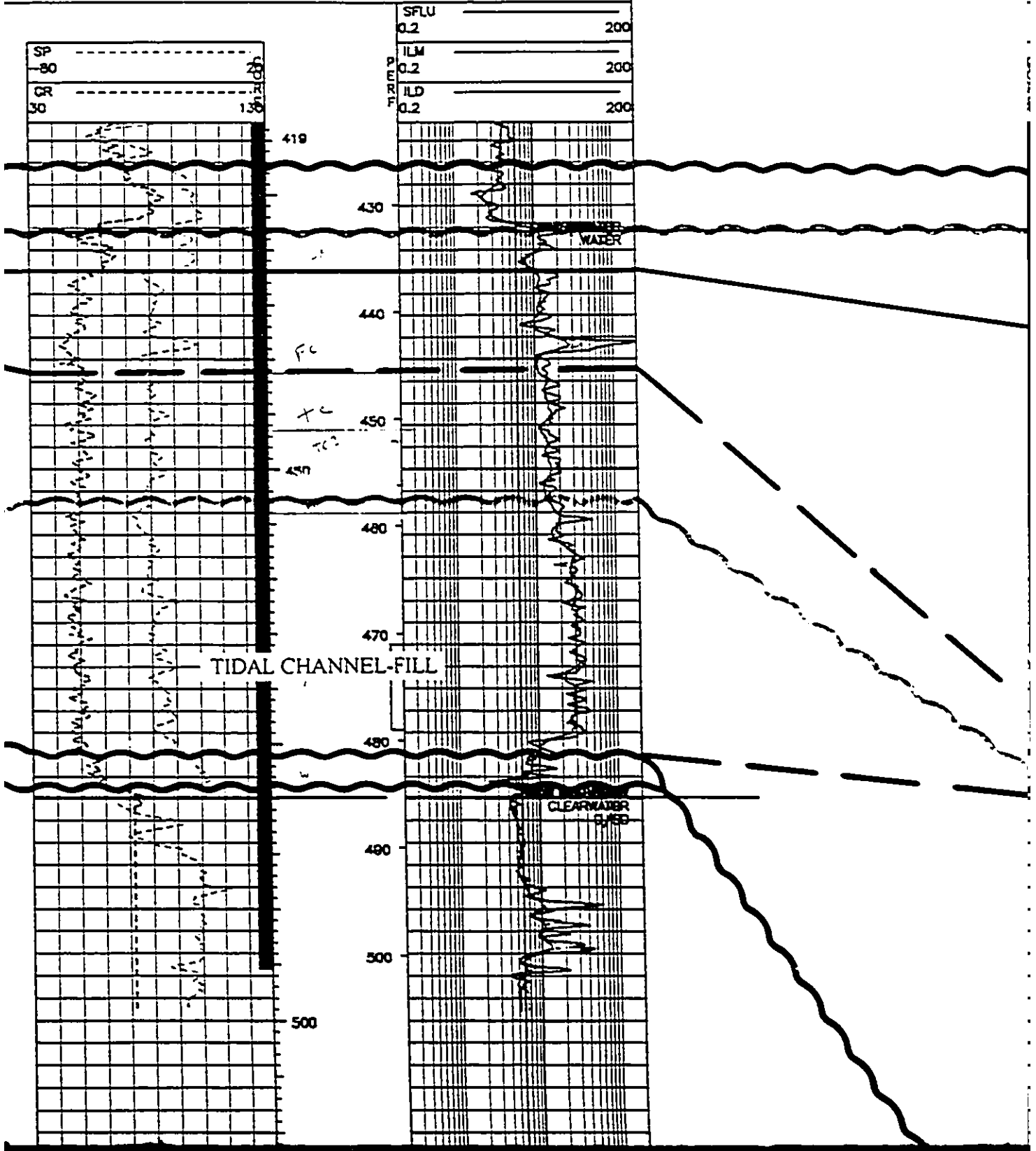


J07-13

09/16-16-085-04W4

ESSO 64 J7-13 COLDLK 16-16-85-4

ELEVATION:	614	RIG REL. DATE:	08/02/1985
WELL STATUS:	CB	START DEPTH(METRES):	418
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	528
SCALE (FEET/INCH) :	40.0		

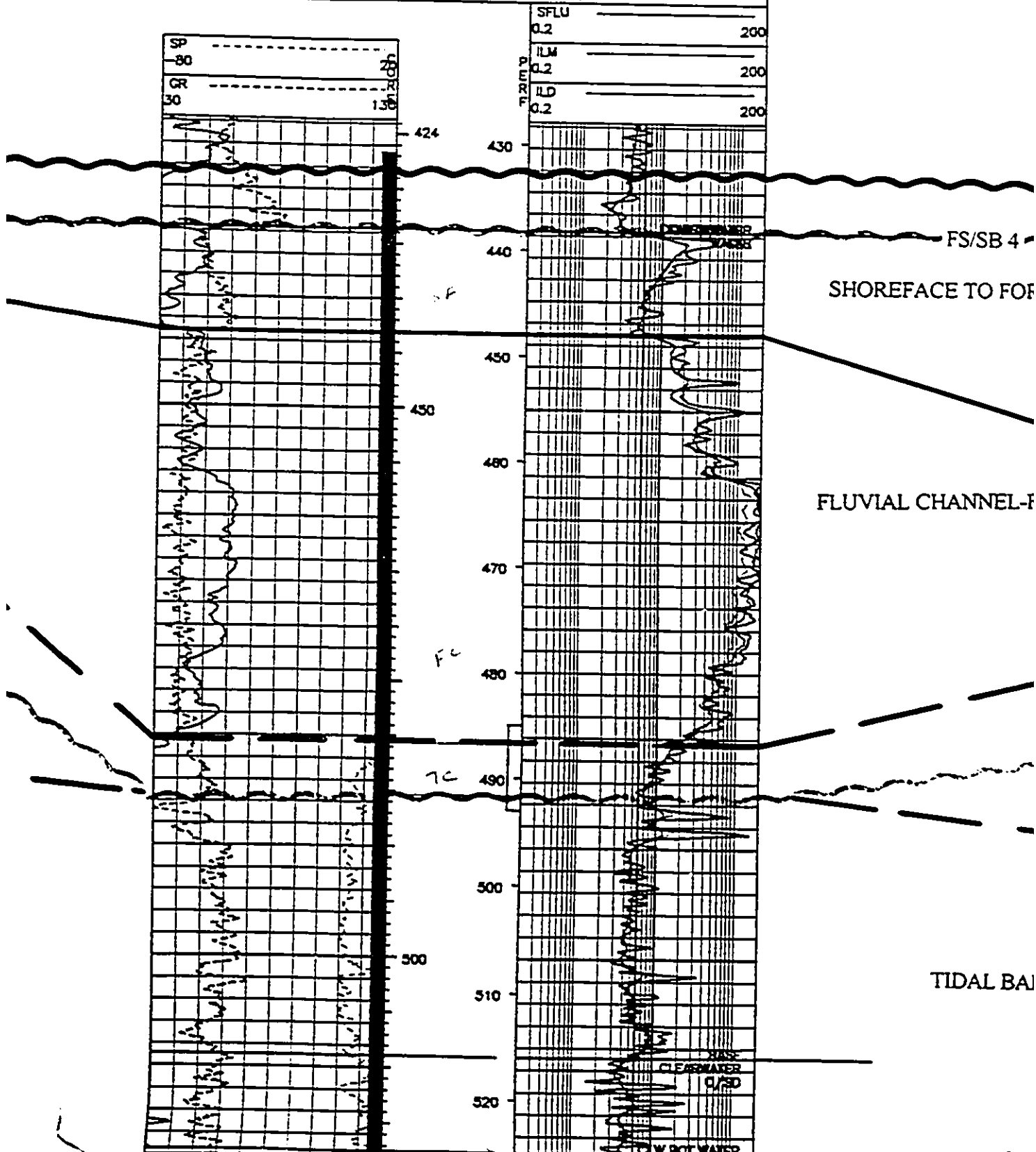


J01-08

12/05-22-065-04W4

ESSO 64 J1-8 COLDLK 5-22-65-4

ELEVATION:	618	RIG REL. DATE:	05/11/1984
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SCALE (FEET/INCH) :	40.0		

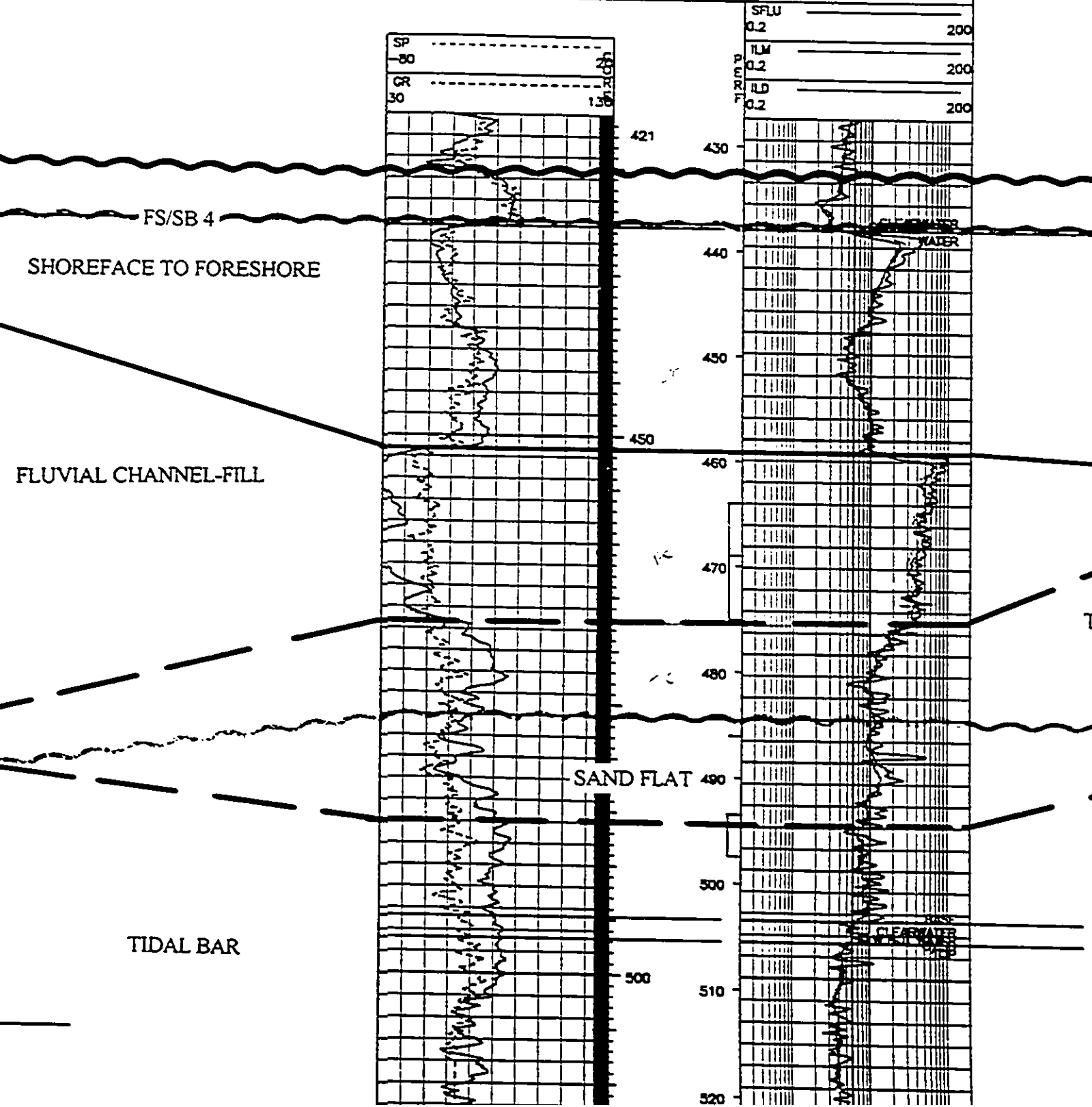


J02-13

05/12-22-065-04W4

ESSO 84 J2-13 COLDEX 12-22-65-4

ELEVATION:	815	RIG REL DATE:	12/09/1984
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SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	530
SCALE (FEET/INCH) :	40.0		

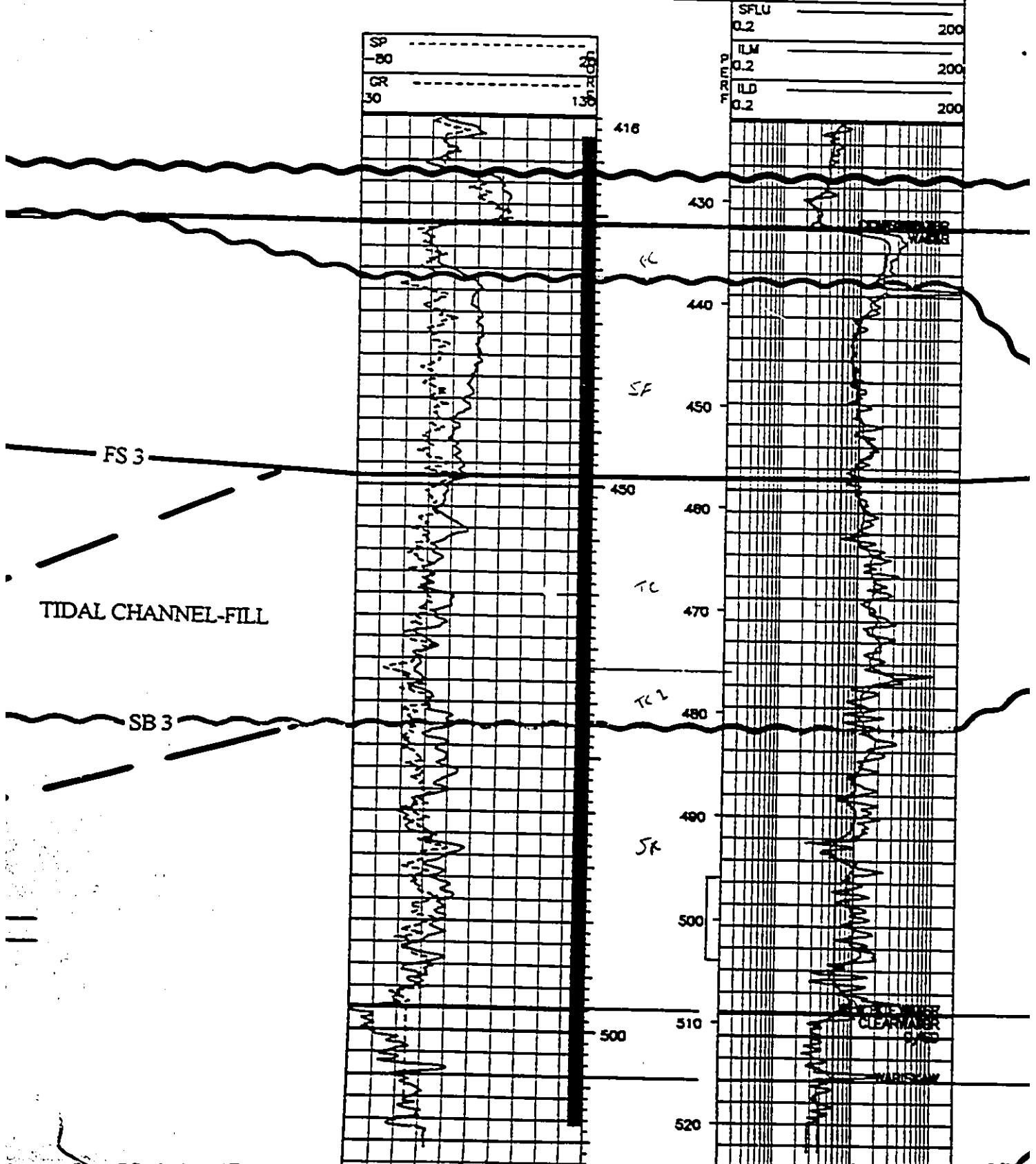


H05-13

03/14-22-065-04W4

ESSO 84 H5-13 COLDLX 14-22-65-4

ELEVATION:	815	RIG REL DATE:	08/11/1984
WELL STATUS:	S-CN-THX	START DEPTH(METRES):	416
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SCALE (FEET/INCH) :	40.0		

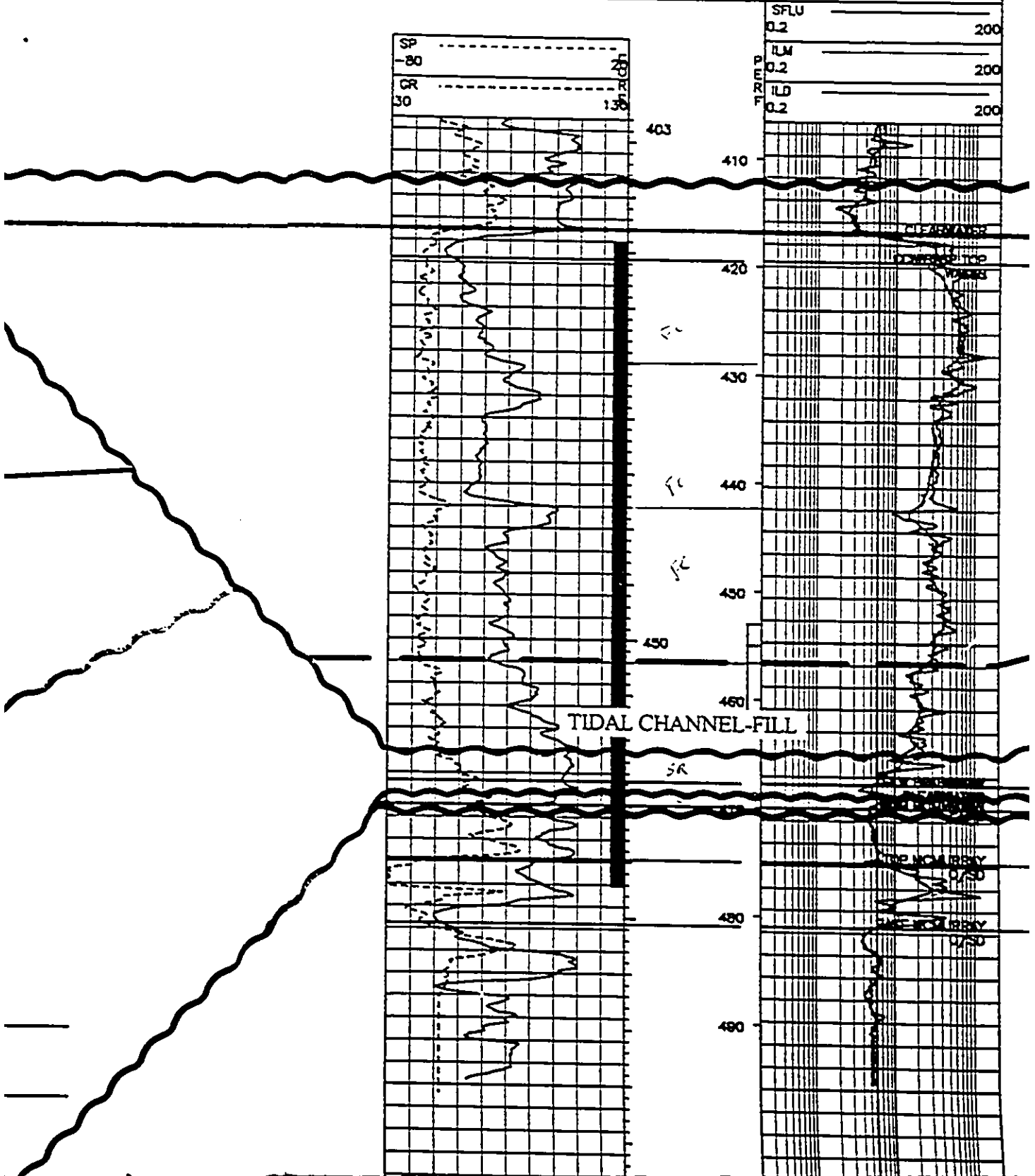


M03-13

08/12-26-065-04W4

K390 87 M3-13 COLDLK 12-26-065-4

ELEVATION:	816	RC REL DATE:	13/03/1988
WELL STATUS:	CB	START DEPTH(METRES):	403
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	513
SCALE (FEET/INCH) :	40.0		

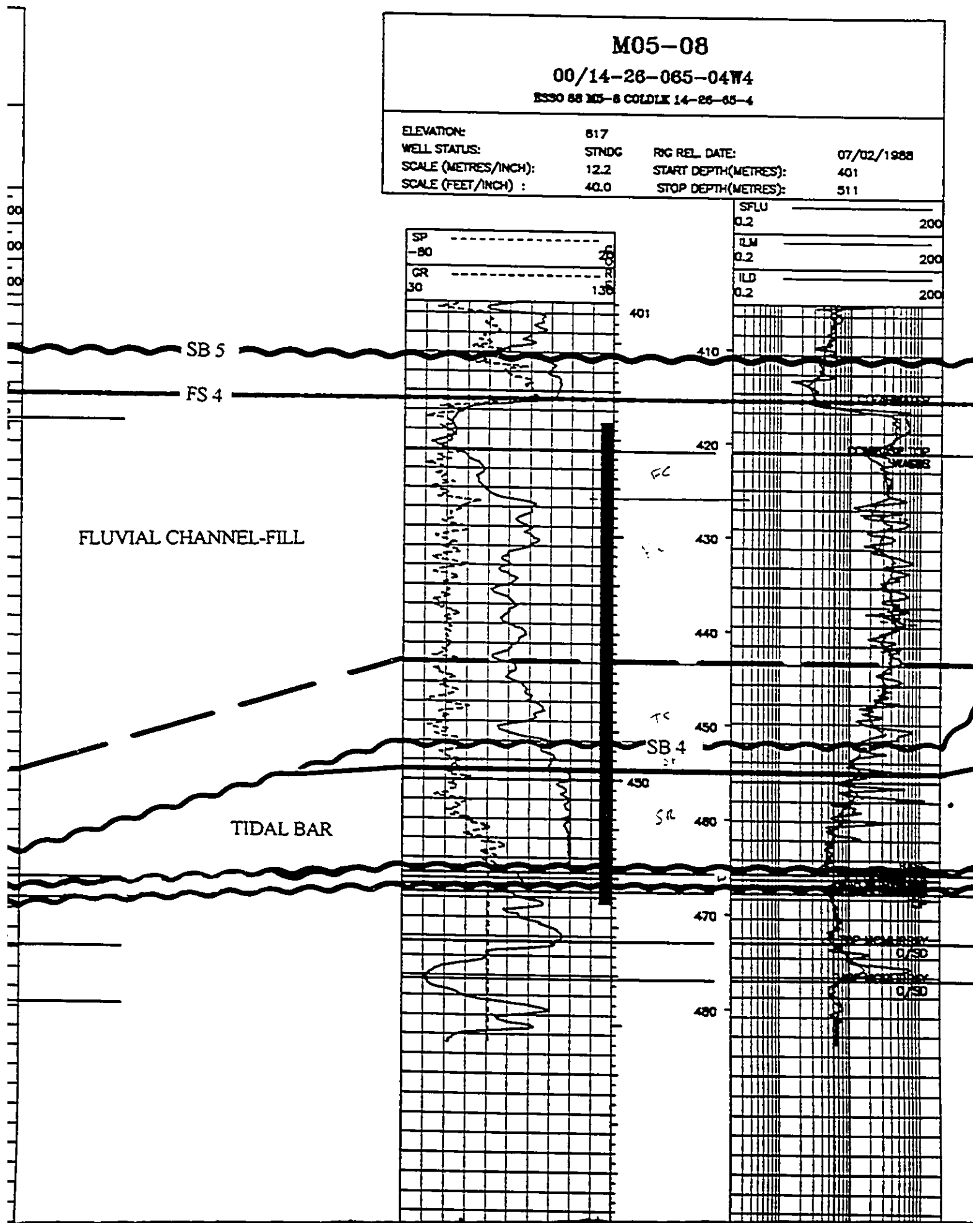


M05-08

00/14-26-065-04W4

ESSO 88 M3-8 COLDLK 14-26-65-4

ELEVATION:	817	RIG REL. DATE:	07/02/1988
WELL STATUS:	STNDC	START DEPTH(METRES):	401
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	511
SCALE (FEET/INCH) :	40.0		

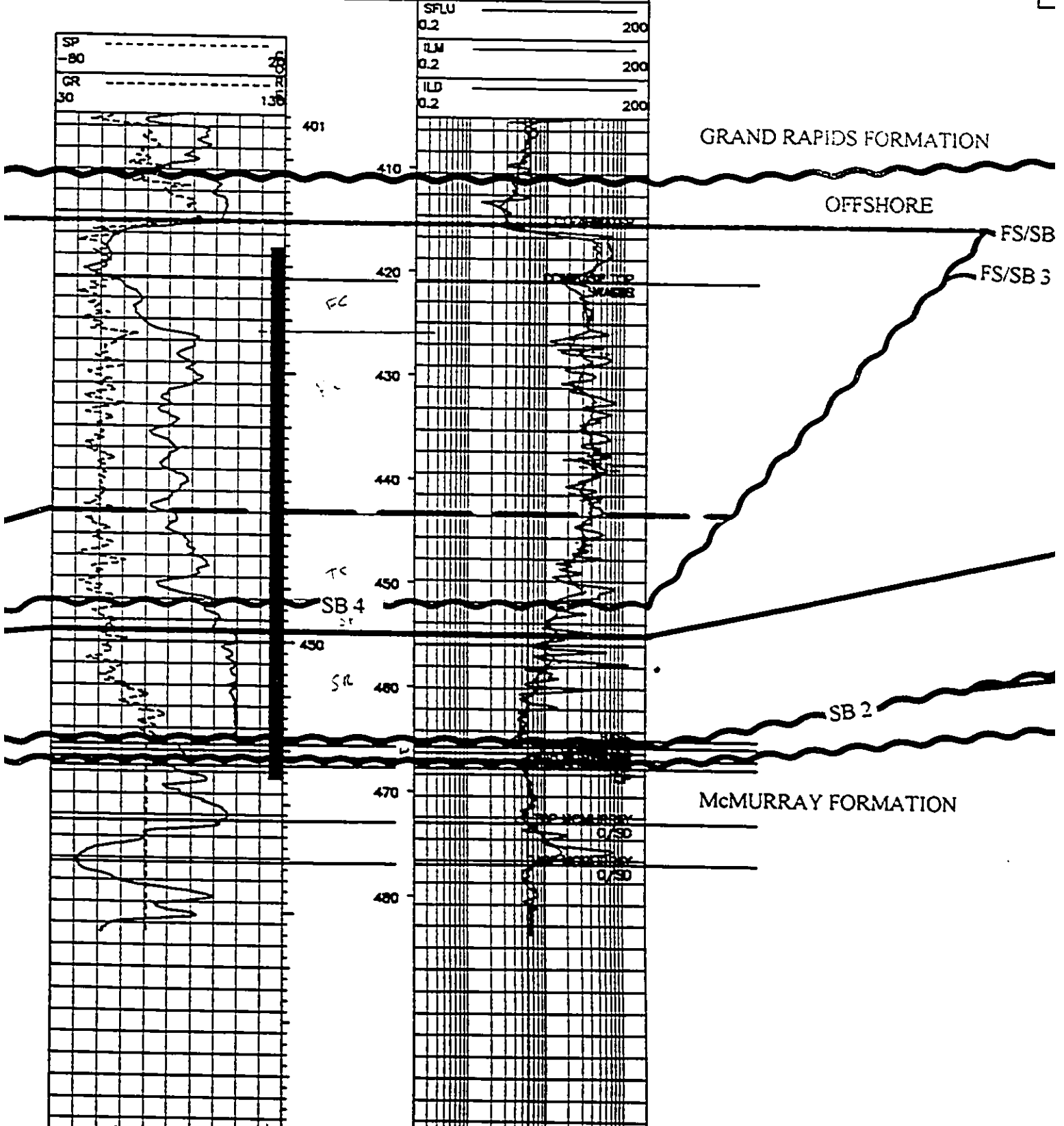


M05-08

00/14-26-065-04W4

ESSO 88 M5-8 COLDLK 14-26-05-4

ELEVATION:	517	RIG REL DATE:	07/02/1988
WELL STATUS:	STNDC	START DEPTH(METRES):	401
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	511
SCALE (FEET/INCH) :	40.0		



12-6-66-3-AA

AA/12-08-066-03W4

ESSO 85 COLDLK 07 12-6-66-3

ELEVATION:	817	RIG REL. DATE:	08/03/1985
WELL STATUS:	ABAND	START DEPTH(METRES):	412
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	522
SCALE (FEET/INCH) :	40.0		

GRAND RAPIDS FORMATION

OFFSHORE

FS/SB 4

FS/SB 3

SHOREFACE TO FORESHORE

SHOREFACE TO FORESHORE

FS 2

SR

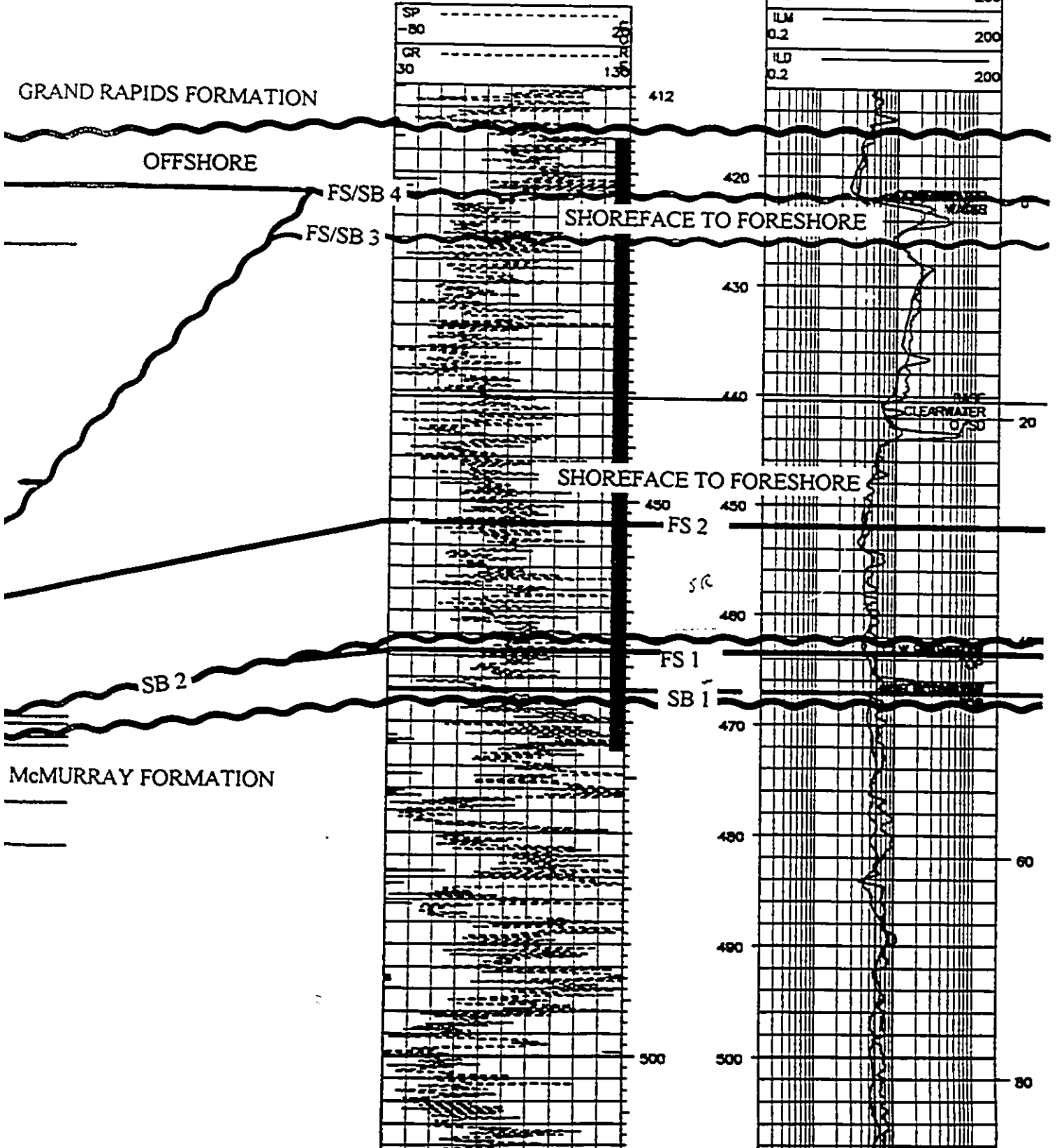
FS 1

SB 1

SB 2

McMURRAY FORMATION

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ILM	0.2	200
ILD	0.2	200

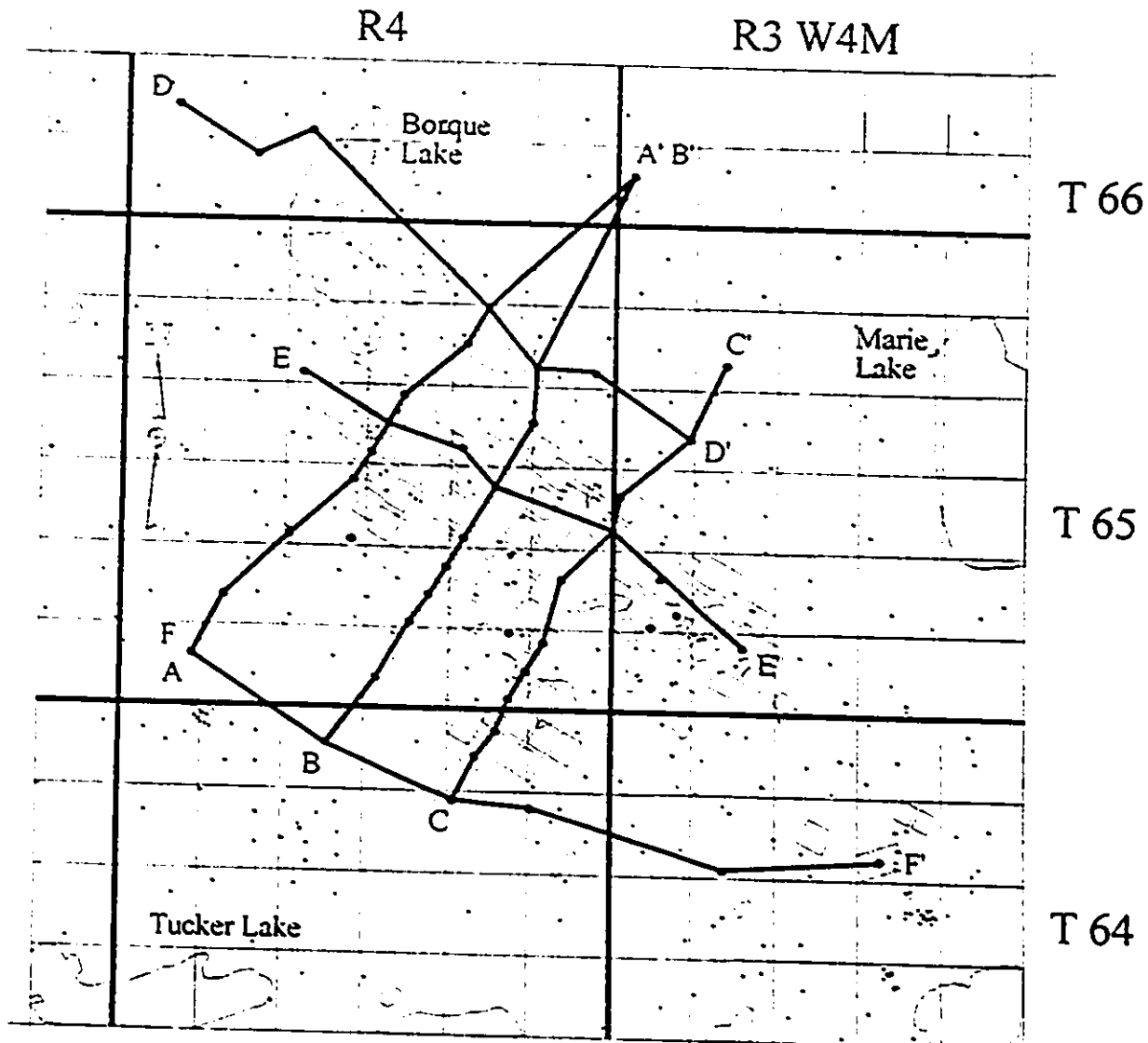
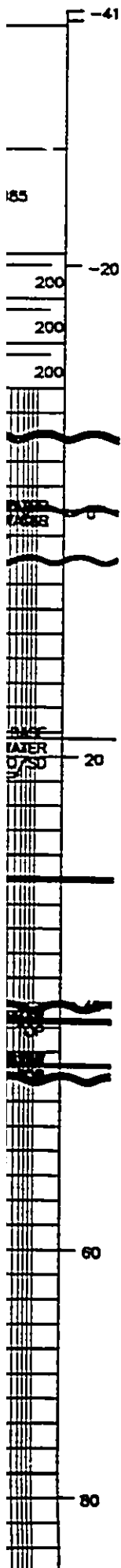


STRATIGRAPHIC CROSS-SECTION A-A'

VERTICAL SCALE: 1:480
HORIZONTAL SCALE: NOT TO SCALE
DATUM: FLOODING SURFACE 4 (FS 4)

WELL LOGS COURTESY IMPERIAL OIL RESOURCES LIMITED, CALGARY

SECTION DRAWN BY: G. Glen McCrimmon August, 1995



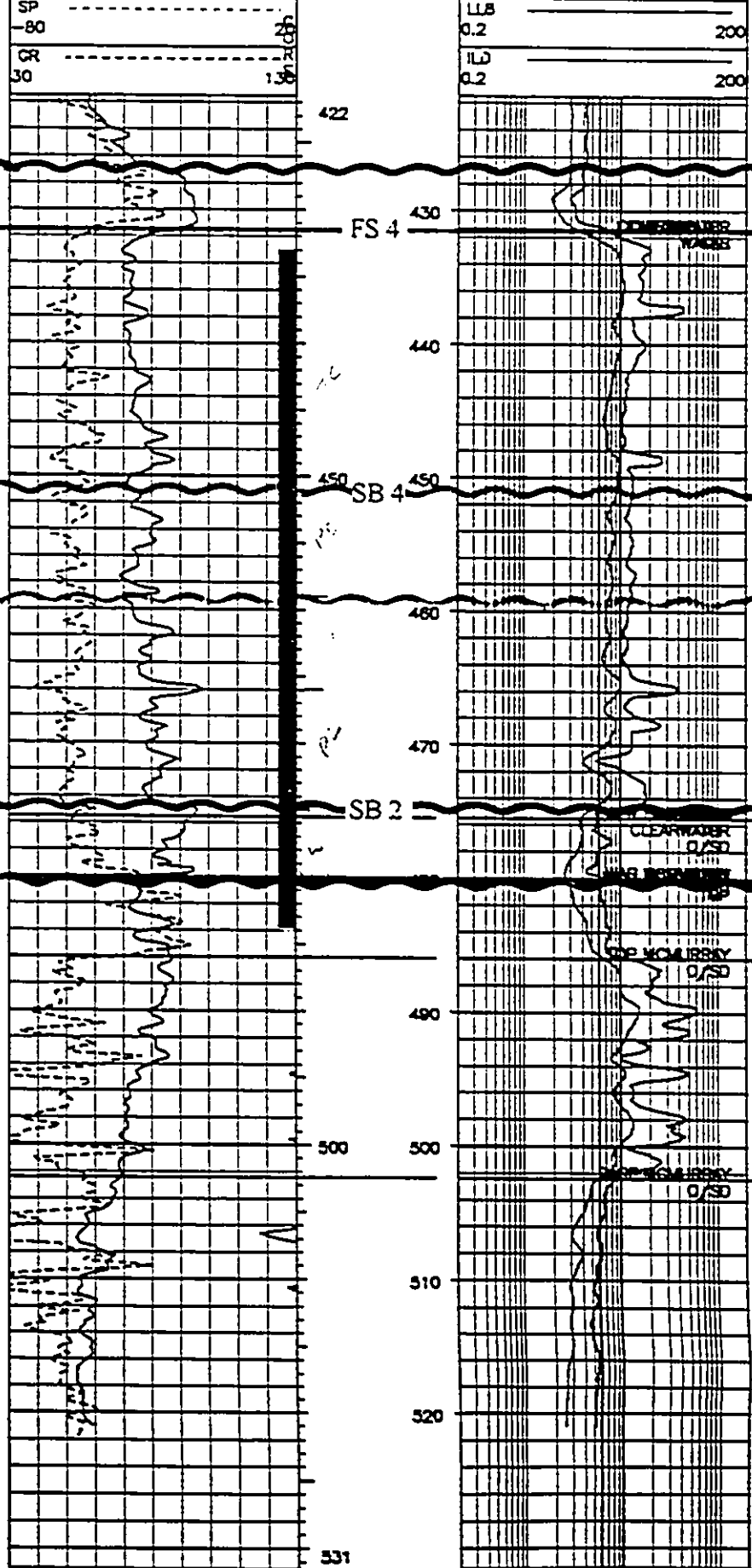
SCALE 1:140000

KILOMETRES



MILES

WELL STATUS:	ACARD	NO. REL. DATE:	25/02/1978
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SCALE (FEET/INCH) :	40.0	STOP DEPTH(METRES):	532



ORE

CHANNEL-FILL

SANDSTONE

SANDSTONE

MEMBER

422

430

440

450

460

470

480

500

510

520

531

SB 5

FS 4

SB 4

SB 2

SHOREFACE TO FC

SB 1

COMBINATION OF SANDS

CLEARWATER

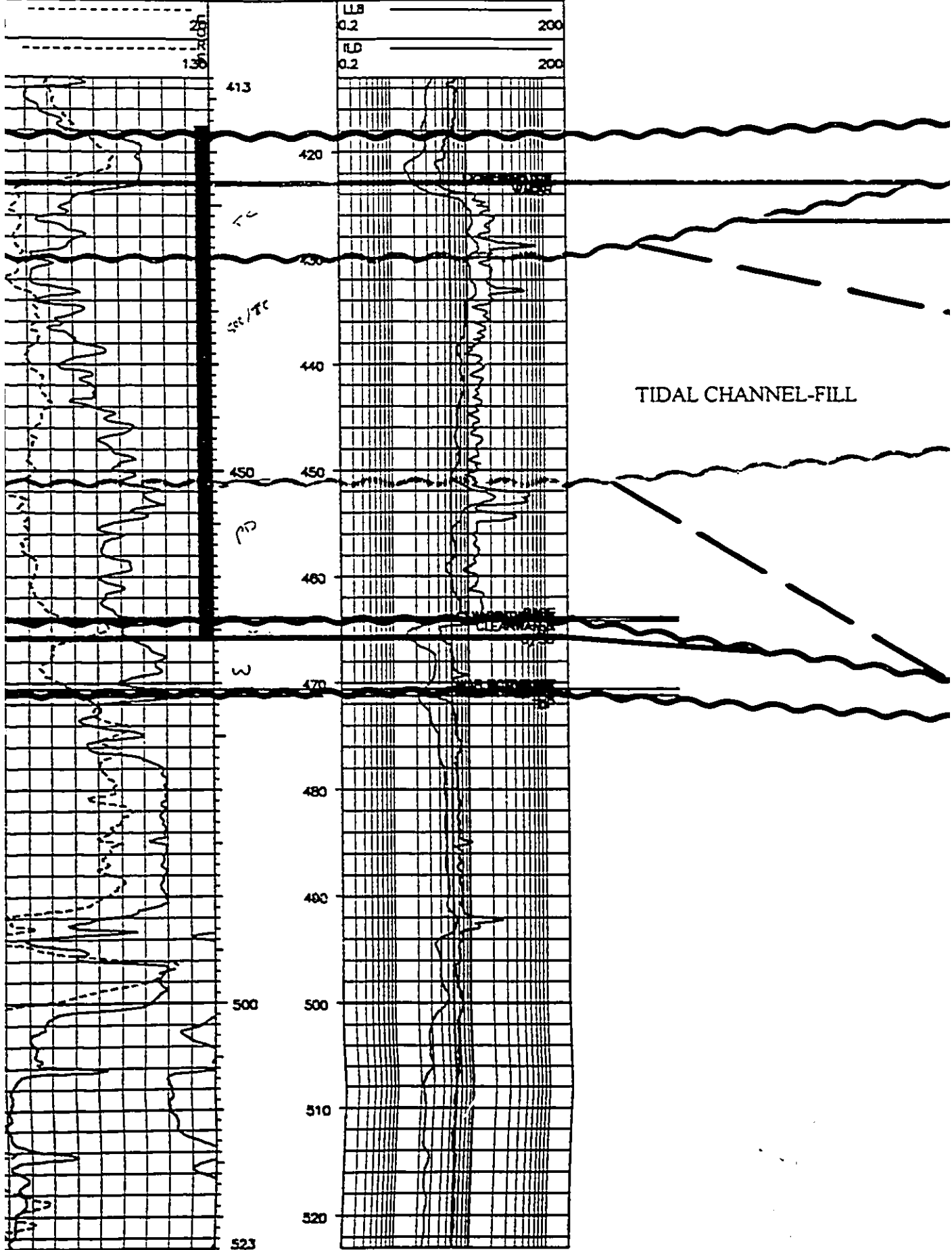
TOP MCM LIBBY

TOP MCM LIBBY

LLB	0.2	200
ILD	0.2	200

SP	80
GR	30

STATUS:	ABAND	RIG REL. DATE:	02/01/1978
E (METRES/INCH):	12.2	START DEPTH(METRES):	413
E (FEET/INCH) :	40.0	STOP DEPTH(METRES):	523



SCALE (FEET/INCH) :

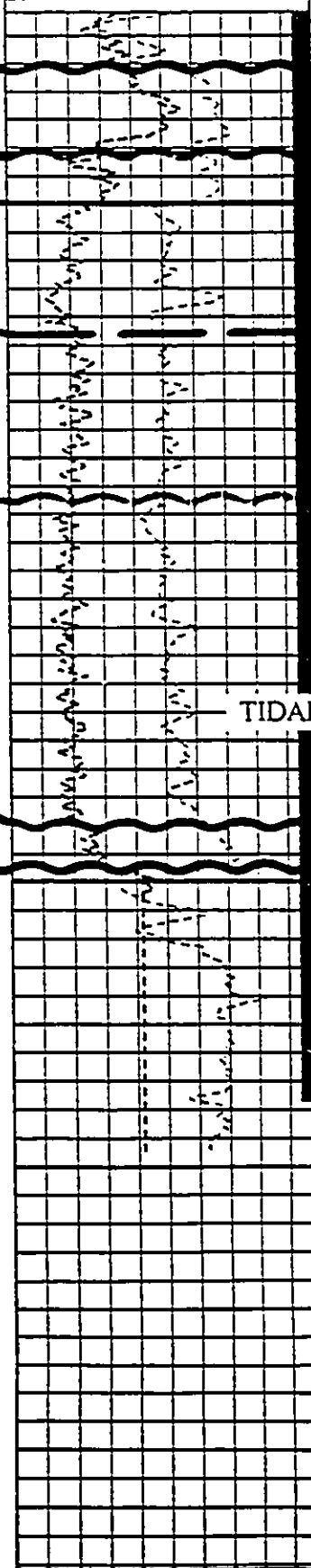
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0.20

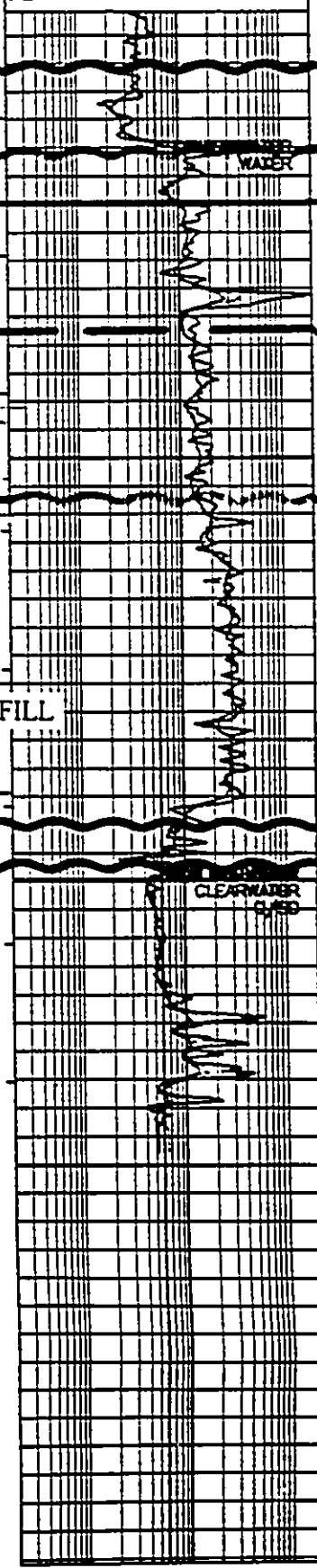
SP
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 200
 0.2
 200
 0.2
 200

DEPTH

SFLU
 0.2
 200
 ILM
 0.2
 200
 ILD
 0.2
 200



410
 430
 440
 FC
 TC
 450
 455
 460
 470
 TIDAL CHANNEL-FILL
 480
 490
 500
 520

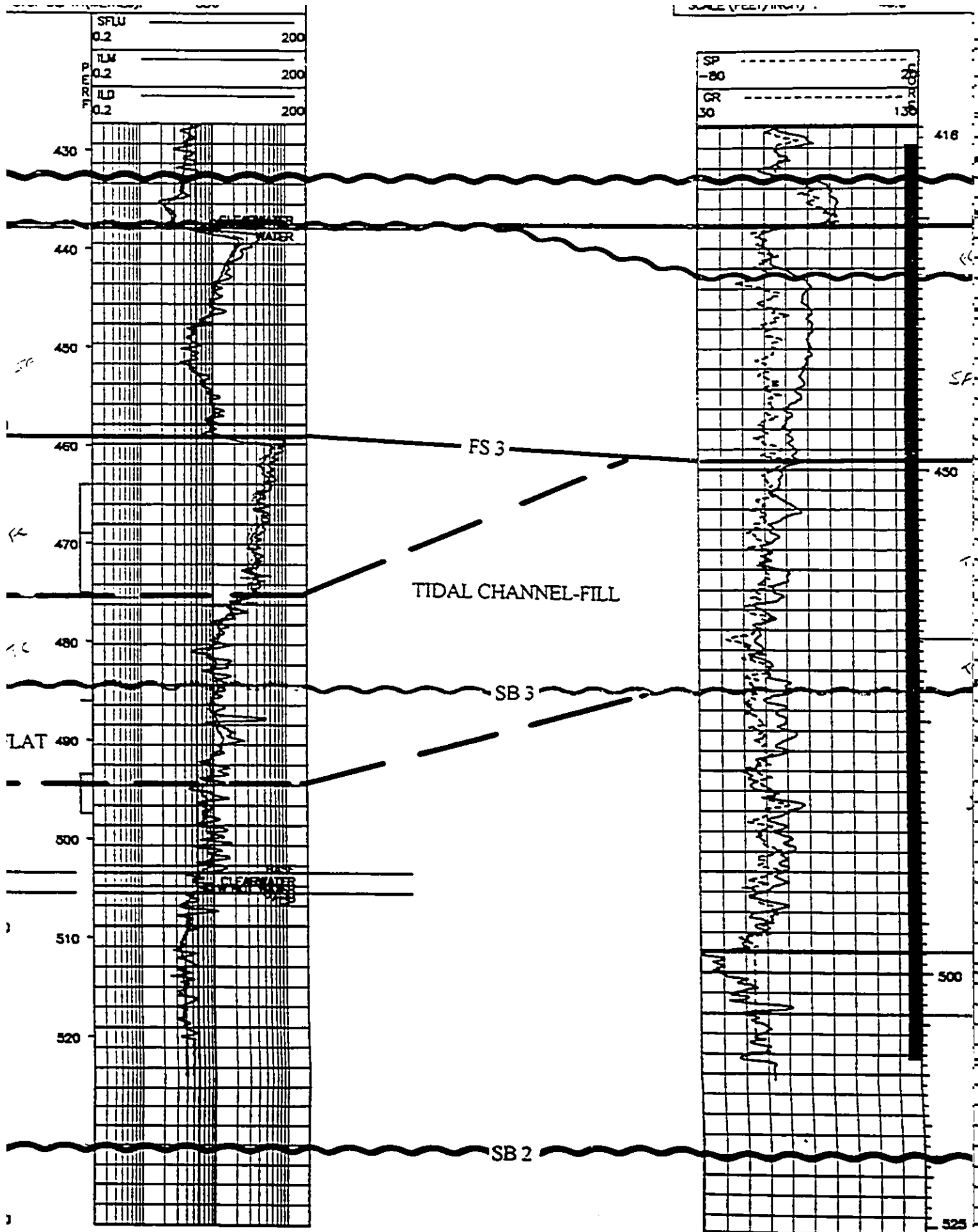


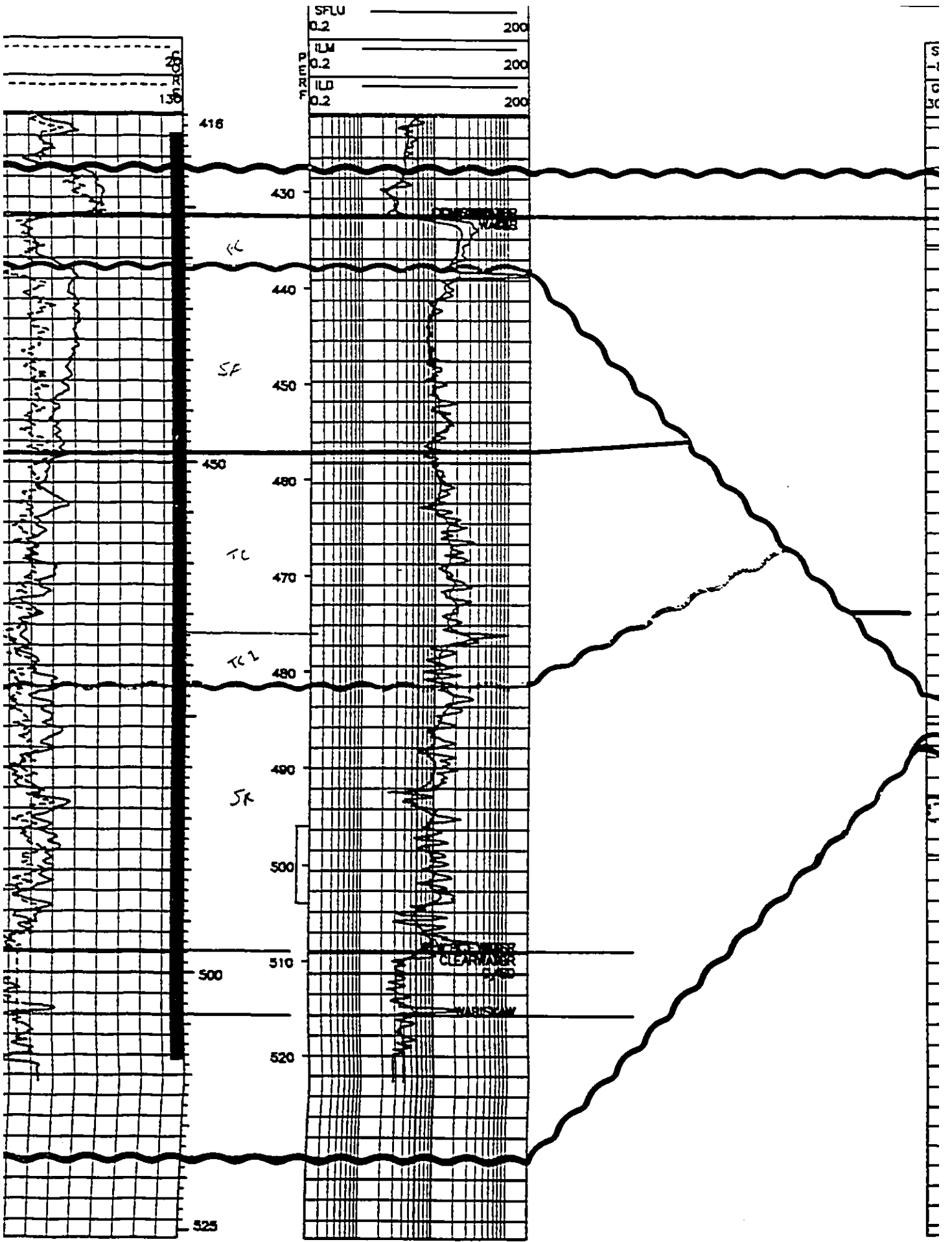
WATER

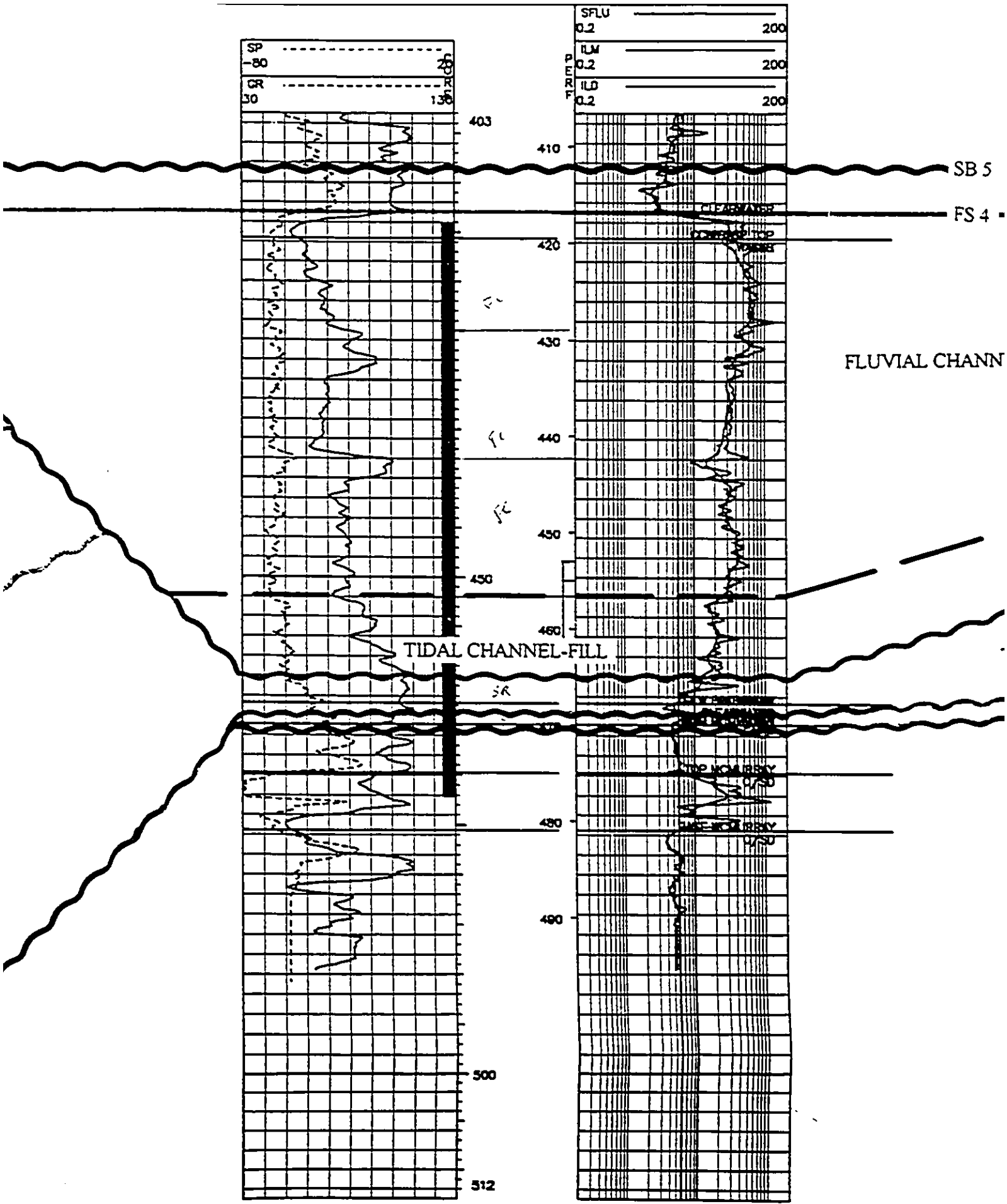
CLEARWATER

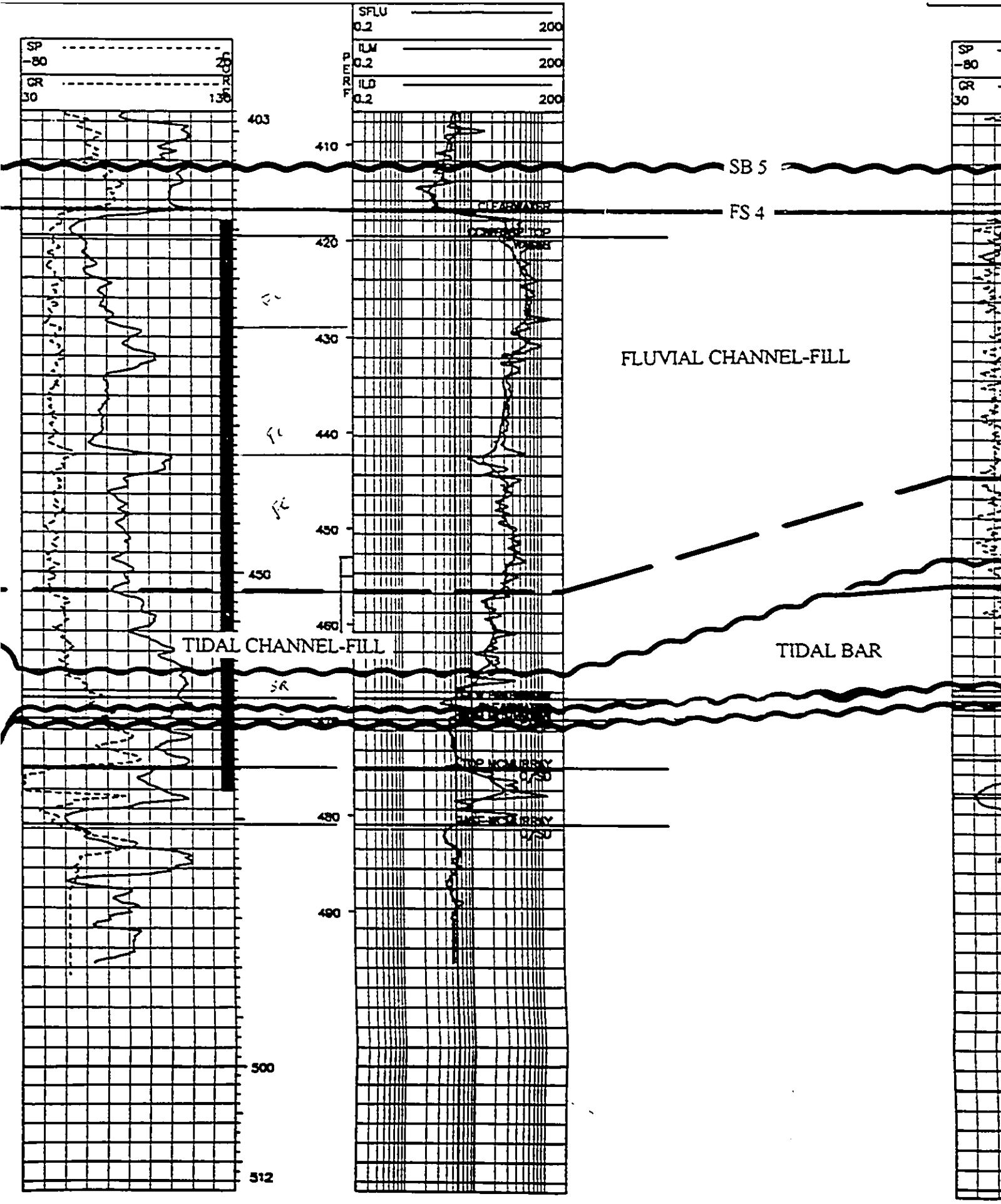
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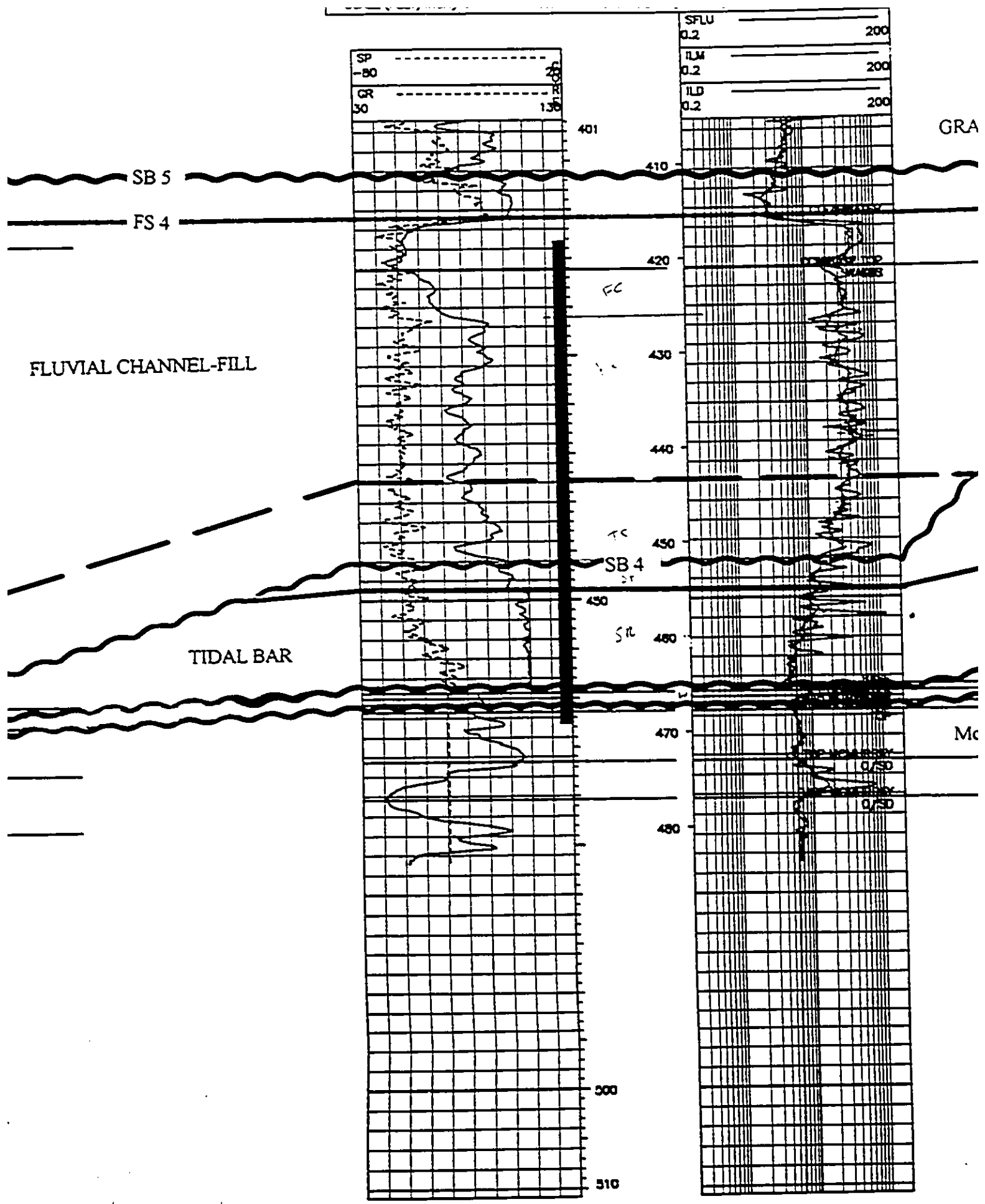
TIDAL CHANNEL-FILL











SP
-80
GR
50

SFLU
0.2 200
TLM
0.2 200
ILD
0.2 200

SB 5
FS 4

FLUVIAL CHANNEL-FILL

TIDAL BAR

GRA

Mc

401

410

420

430

440

450

460

470

480

500

510

FC

TC

SB 4

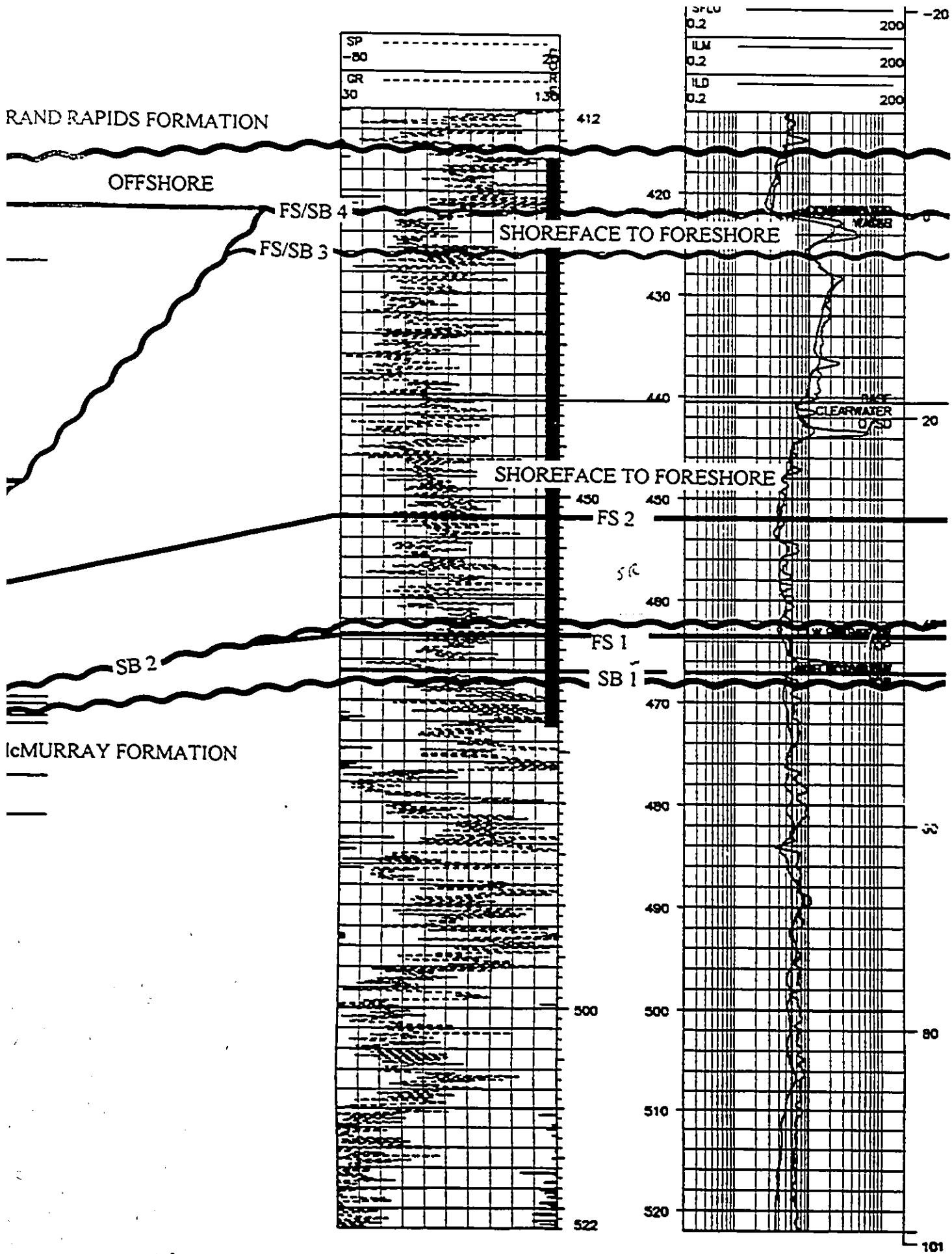
450

SR

460

O/SB

O/SB

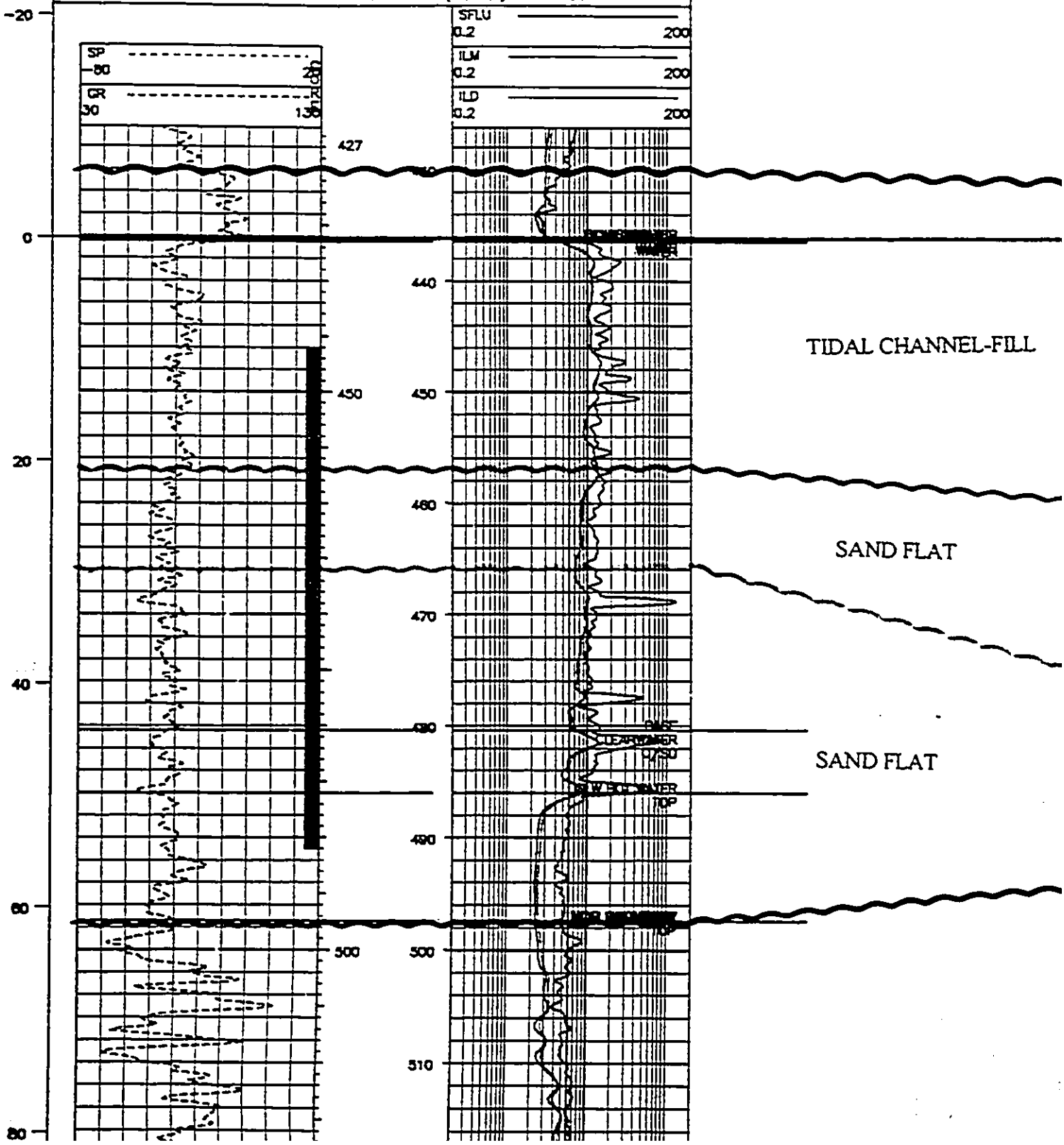


10-33-64-4-AA

AA/10-33-064-04W4

ISSO 06 COLDEX 07 10-33-64-4

ELEVATION: 617
WELL STATUS: ABAND RIG REL. DATE: 19/02/1988
SCALE (METRES/INCH): 12.2 START DEPTH (METRES): 426
SCALE (FEET/INCH) : 40.0 STOP DEPTH (METRES): 536

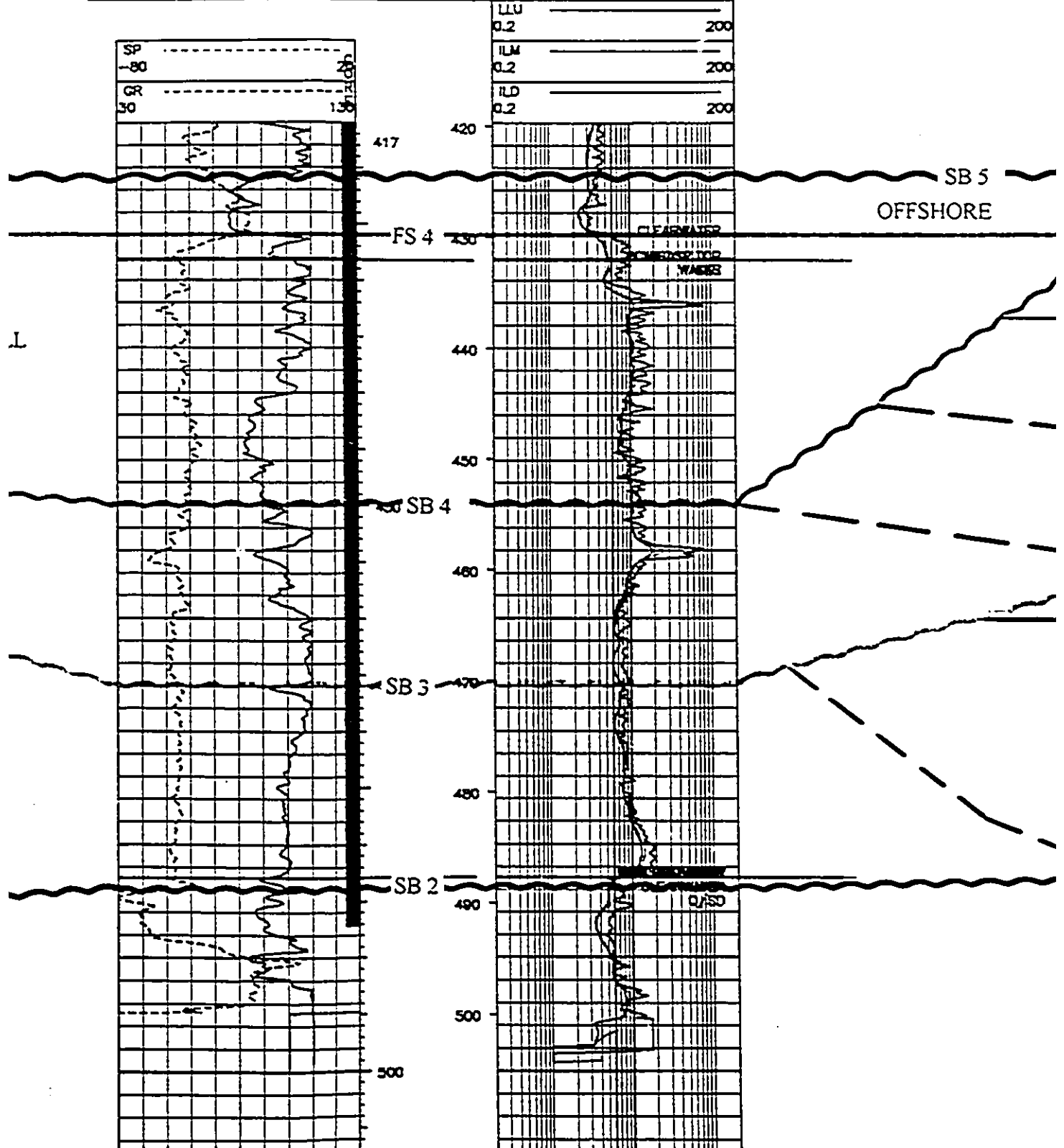


J43-08

00/05-03-085-04W4

XSSO 87 J43-8 COLDLK 3-3-88-4

ELEVATION:	514	RIG REL. DATE:	05/10/1987
WELL STATUS:	STNDG	START DEPTH(METRES):	416
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	528
SCALE (FEET/INCH) :	40.0		

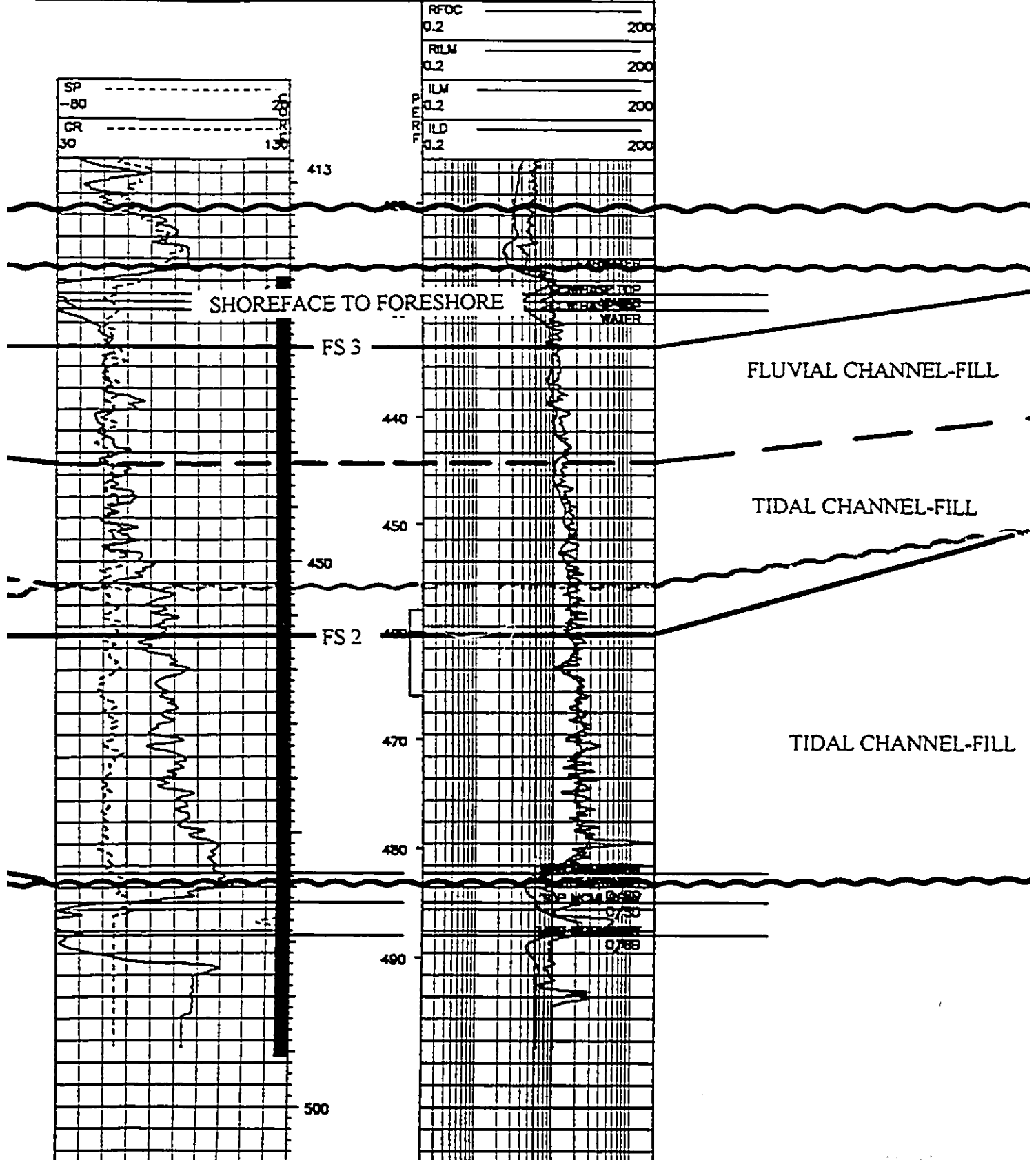


D11-08

07/02-10-085-04W4

ESSO 86 D11-8 COLDLK 2-10-85-4

ELEVATION:	812	RIG REL DATE:	27/10/1988
WELL STATUS:	S-CN-THX	START DEPTH(METRES):	413
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	523
SCALE (FEET/INCH) :	40.0		

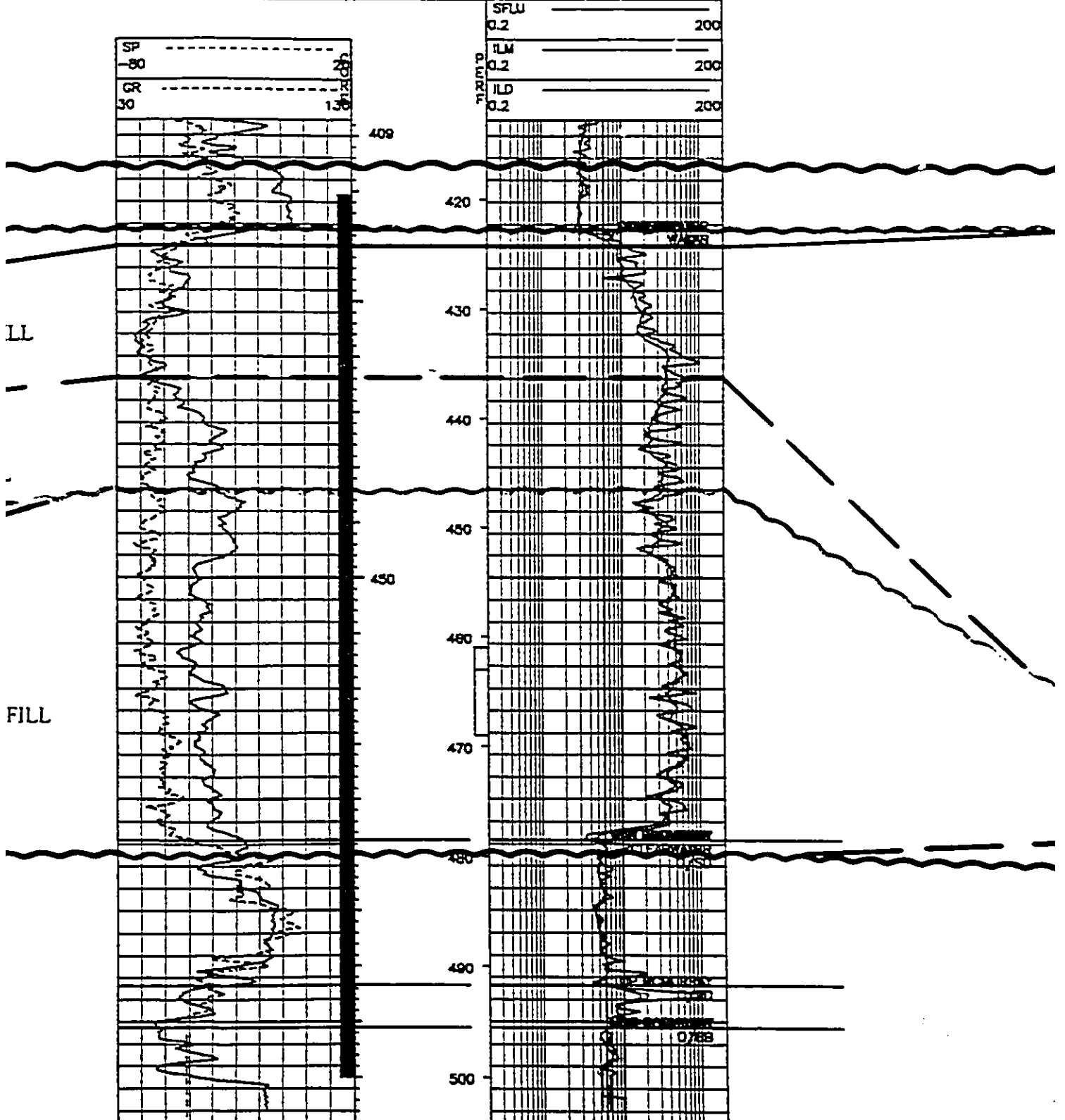


D09-08

06/08-10-065-04W4

ESSO 67 D9-8 COLDK 8-10-65-4

ELEVATION:	507	RIG REL. DATE:	24/07/1967
WELL STATUS:	CB	START DEPTH(METRES):	409
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	519
SCALE (FEET/INCH) :	40.0		

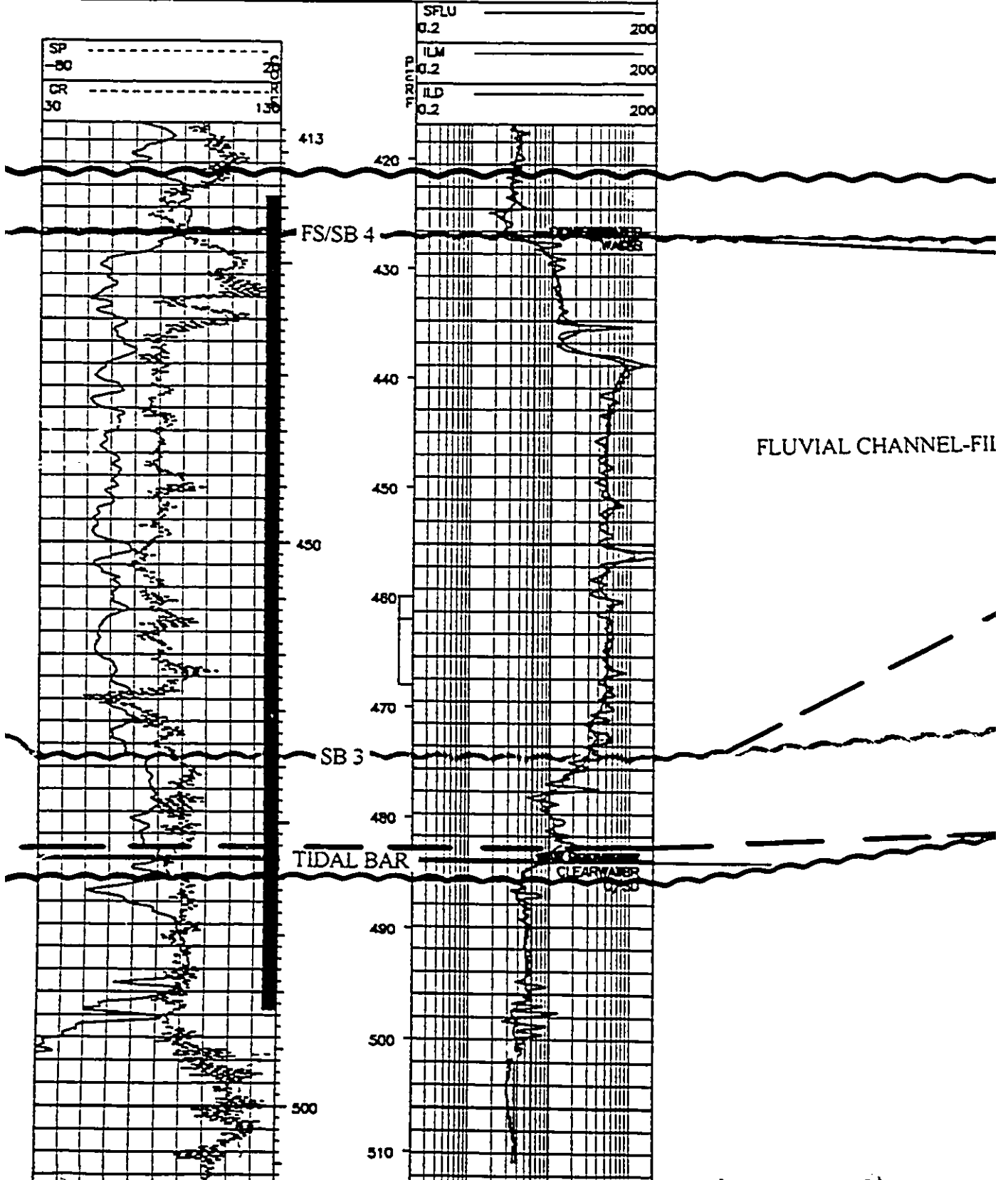


J16-08

07/16-10-065-04W4

ESSO 87 J16-8 COLDLK 16-10-65-4

ELEVATION:	507	RIG REL. DATE:	29/09/1987
WELL STATUS:	CB	START DEPTH(METRES):	412
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	522
SCALE (FEET/INCH) :	40.0		

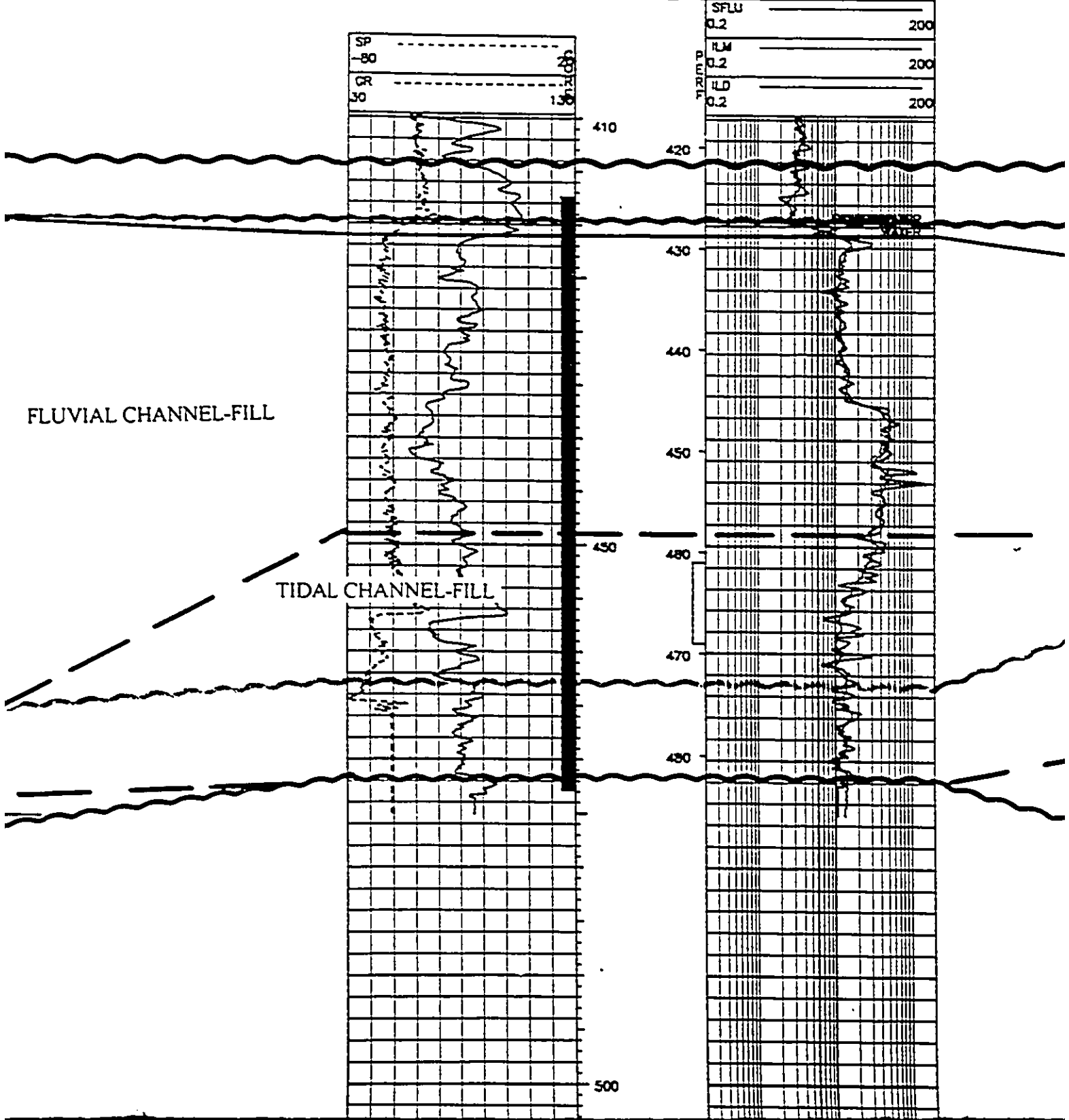


A04-08

05/04-14-065-0474

ESSO 83 A4-8 COLDLE 4-14-83-4

ELEVATION:	808	RIG REL. DATE:	05/12/1983
WELL STATUS:	CB	START DEPTH(METRES):	410
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	520
SCALE (FEET/INCH) :	40.0		



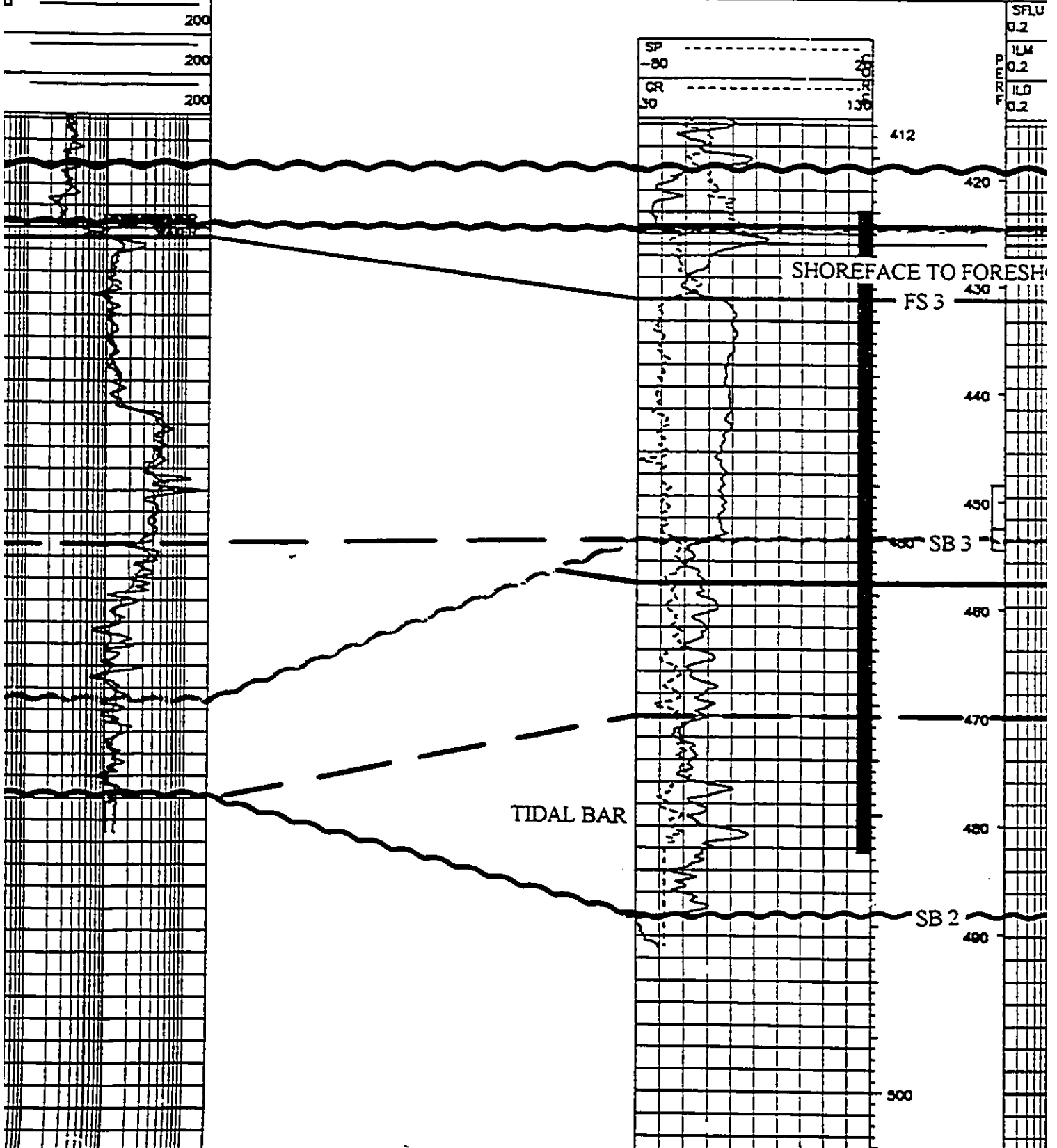
R05-13

10/15-14-065-04W4

ISSO 88 85-13 COLDEX 15-14-65-4

ELEVATION:	813	RIG REL. DATE:
WELL STATUS:	CYCLICAL	START DEPTH(METR
SCALE (METRES/INCH):	12.2	STOP DEPTH(METR
SCALE (FEET/INCH) :	40.0	

05/12/1983
ES): 410
ES): 520

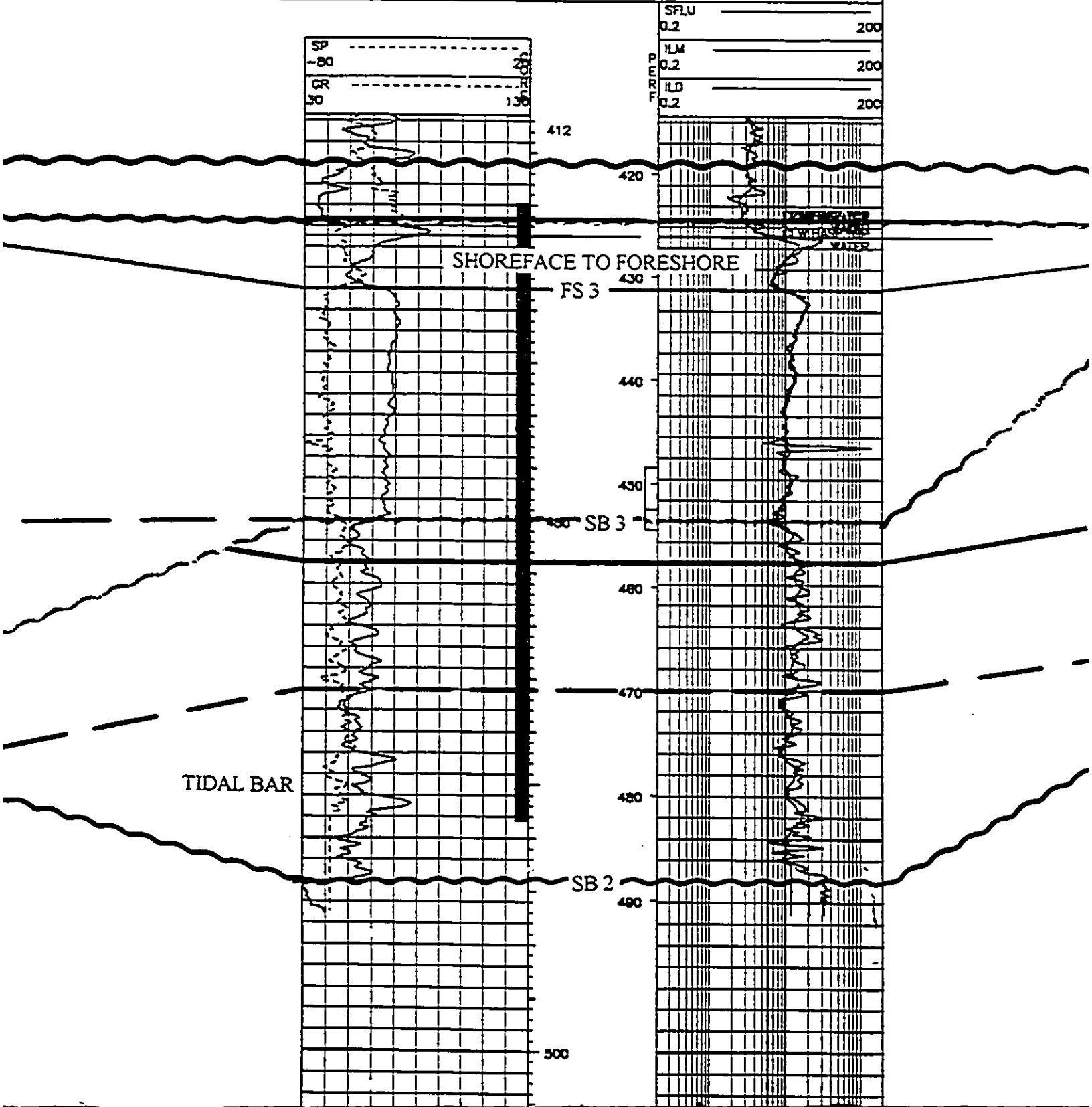


R05-13

10/15-14-065-04W4

ESSO 85 85-13 COLDEX 15-14-85-4

ELEVATION:	813	RIC REL. DATE:	22/05/1988
WELL STATUS:	CYCLICAL	START DEPTH(METRES):	411
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	521
SCALE (FEET/INCH) :	40.0		

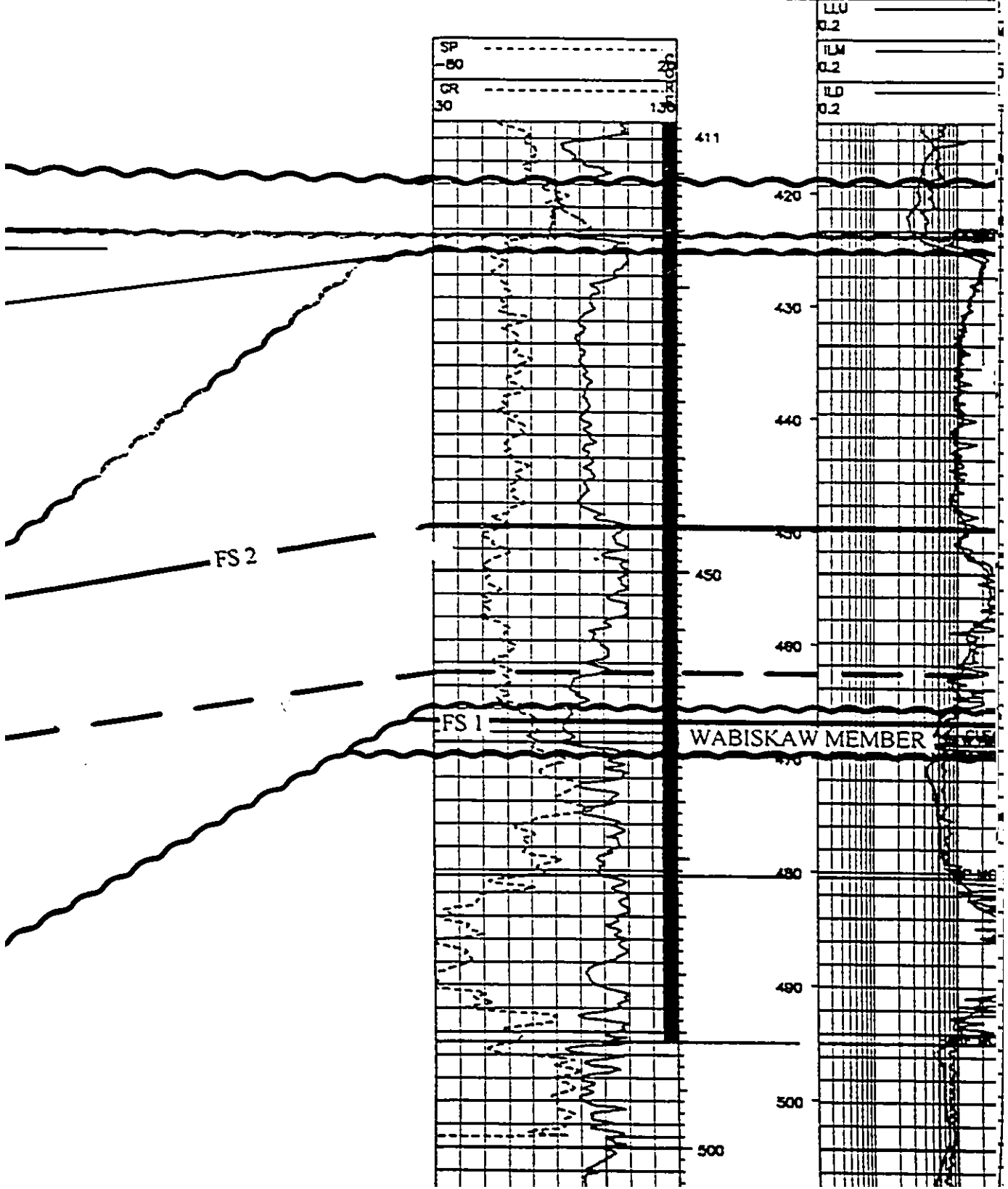


Q06-08

00/12-24-065-0474

ESSO 87 Q6-8 COLDLK 12-24-85-4

ELEVATION:	813	RIG REL. DATE:	28/10/11
WELL STATUS:	STRUC	START DEPTH(METRES):	411
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	521
SCALE (FEET/INCH) :	40.0		



Q06-08

2-24-085-04W4

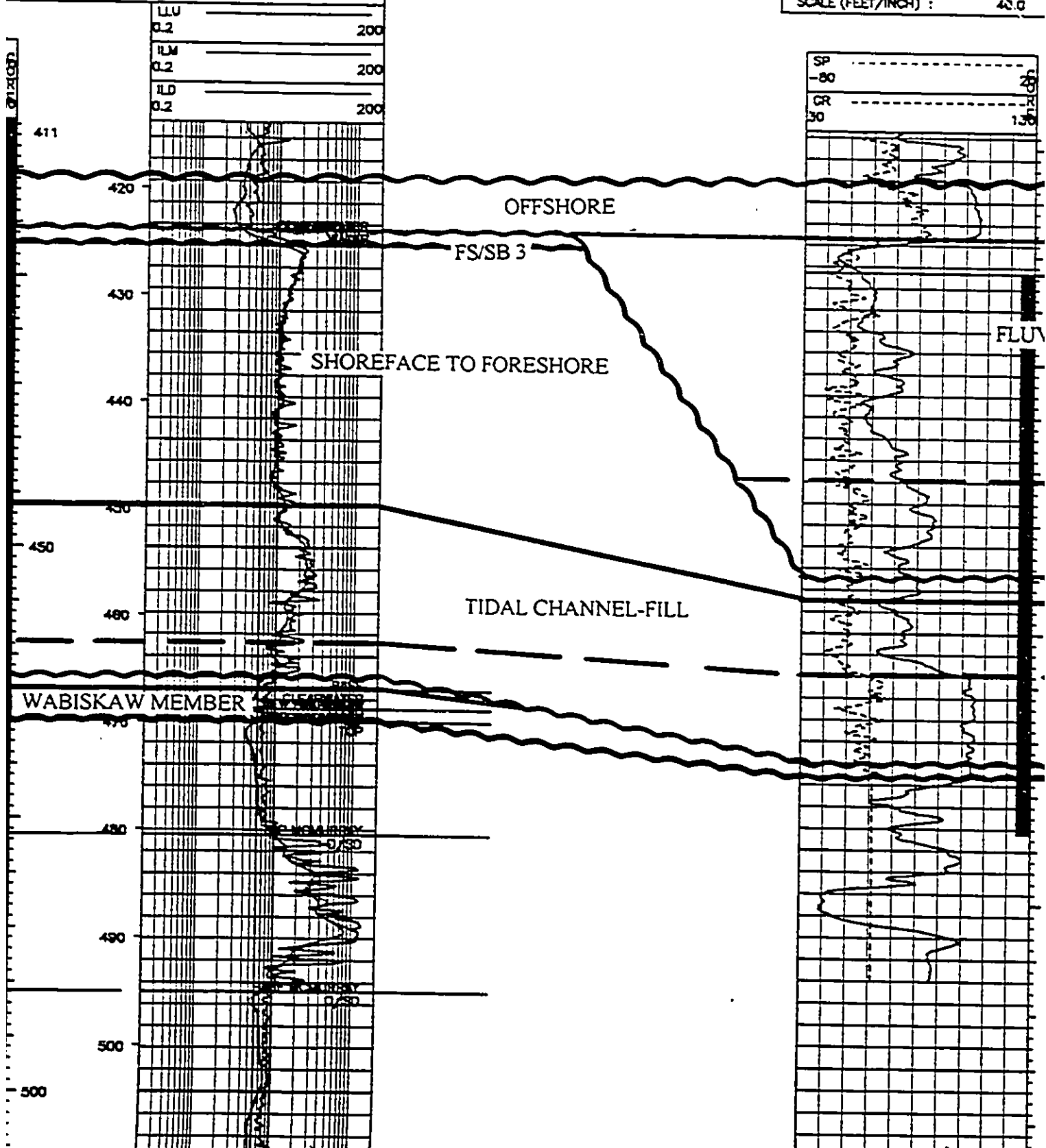
-8 COLDLX 12-24-88-4

1	LOG REL DATE:	28/10/1987
2	START DEPTH(METRES):	411
0	STOP DEPTH(METRES):	521

00/04-

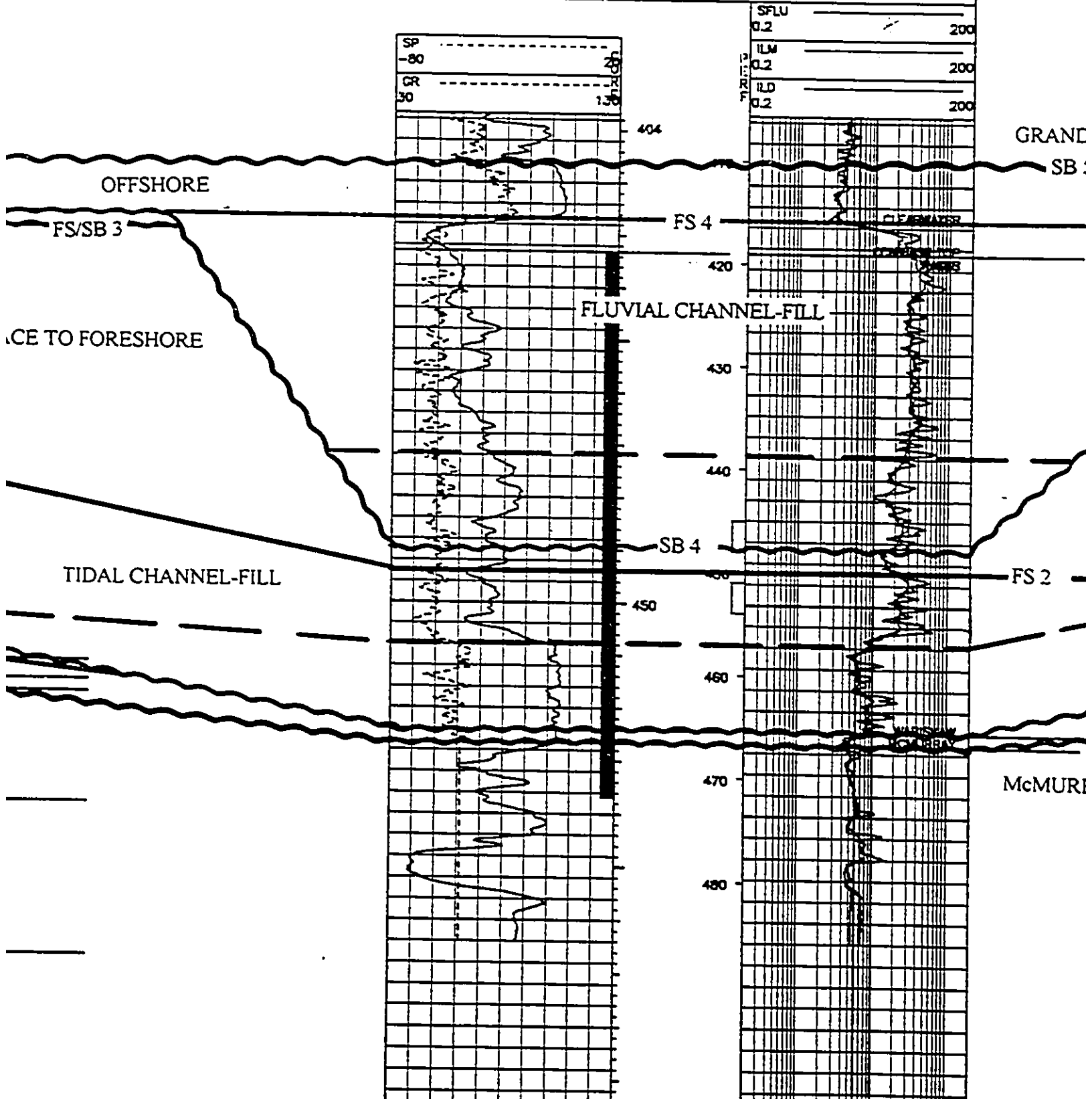
ESSO 88 P3-1:

ELEVATION:	815
WELL STATUS:	CYCLIC
SCALE (METRES/INCH):	12.2
SCALE (FEET/INCH) :	40.0



P03-13
00/04-25-085-04W4
ESSO 68 P3-13 COLDLE 4-25-85-4

ELEVATION:	615	RIG REL DATE:	21/01/1988
WELL STATUS:	CYCLICAL	START DEPTH(METRES):	403
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	513
SCALE (FEET/INCH) :	42.0		



13

5-04W4

1-25-85-4

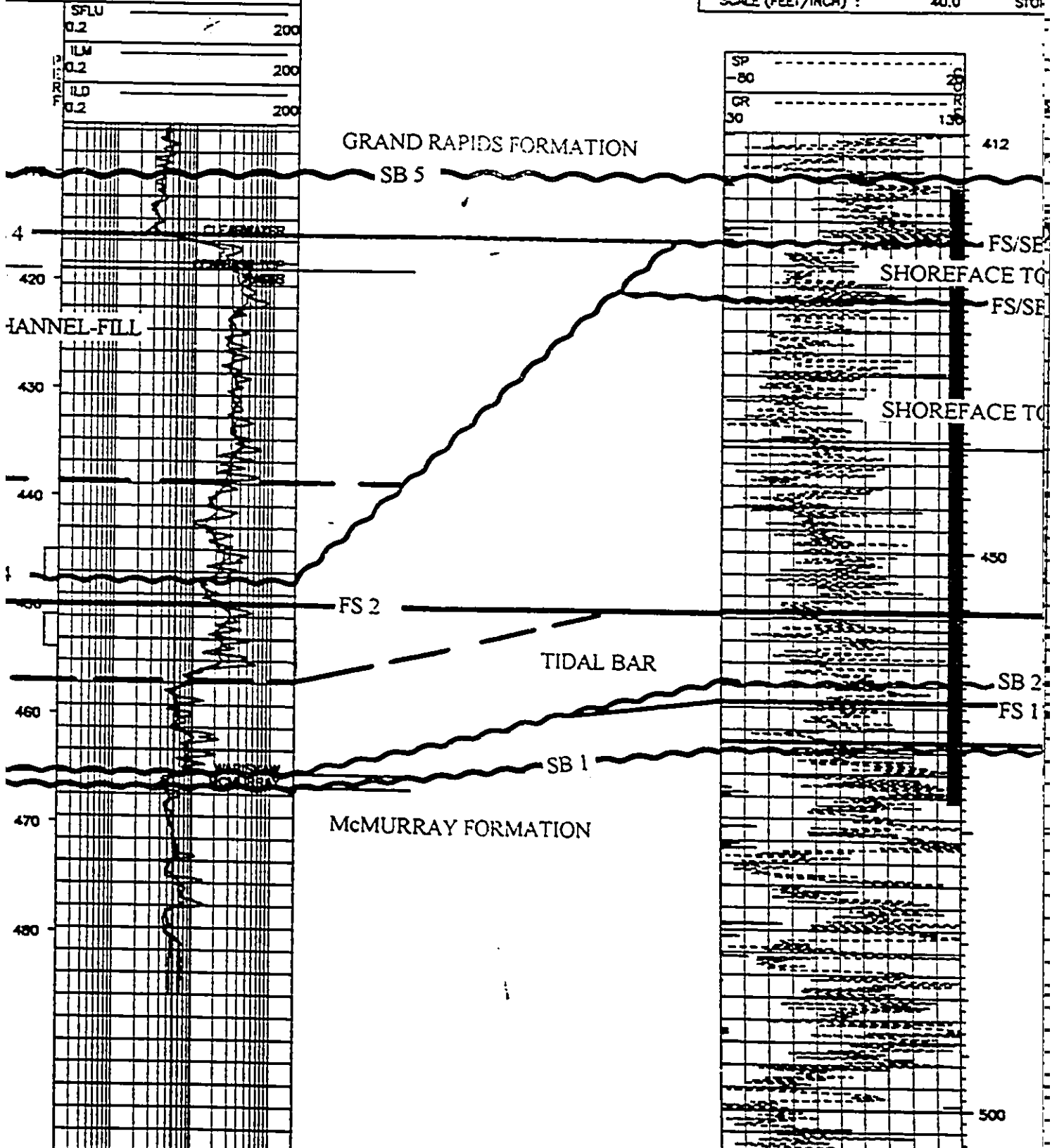
REL DATE: 21/01/1988
 RT DEPTH(METRES): 403
 XP DEPTH(METRES): 513

12-6-66-0

AA/12-06-08

ESSO BS COLDLK CV 12

ELEVATION: 817
 WELL STATUS: ABAND R/C F
 SCALE (METRES/INCH): 12.2 STAR
 SCALE (FEET/INCH) : 40.0 STOP



12-6-66-3-AA

AA/12-06-066-03W4

ISSO 85 COLDLK 0V 12-6-66-3

ELEVATION:	817	RIG REL DATE:	08/03/1985
WELL STATUS:	ABAND	START DEPTH(METRES):	412
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	522
SCALE (FEET/INCH):	40.0		

GRAND RAPIDS FORMATION

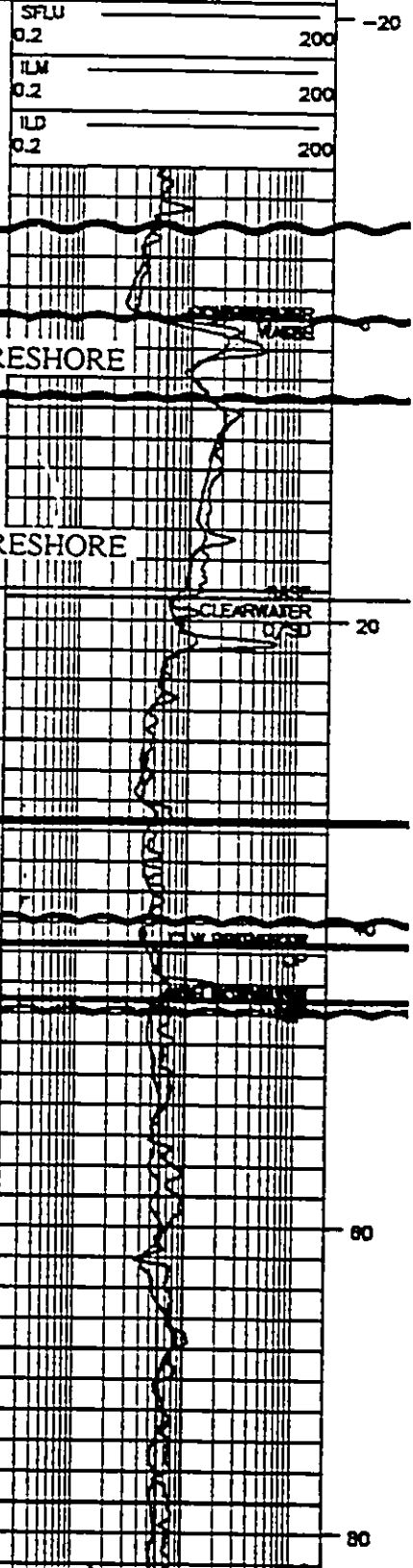
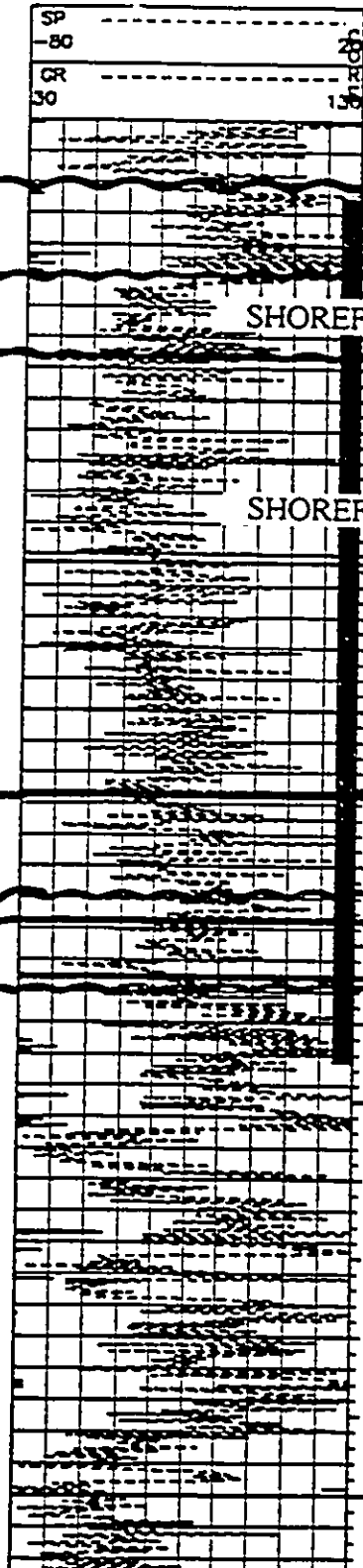
SB 5

FS 2

TIDAL BAR

SB 1

McMURRAY FORMATION

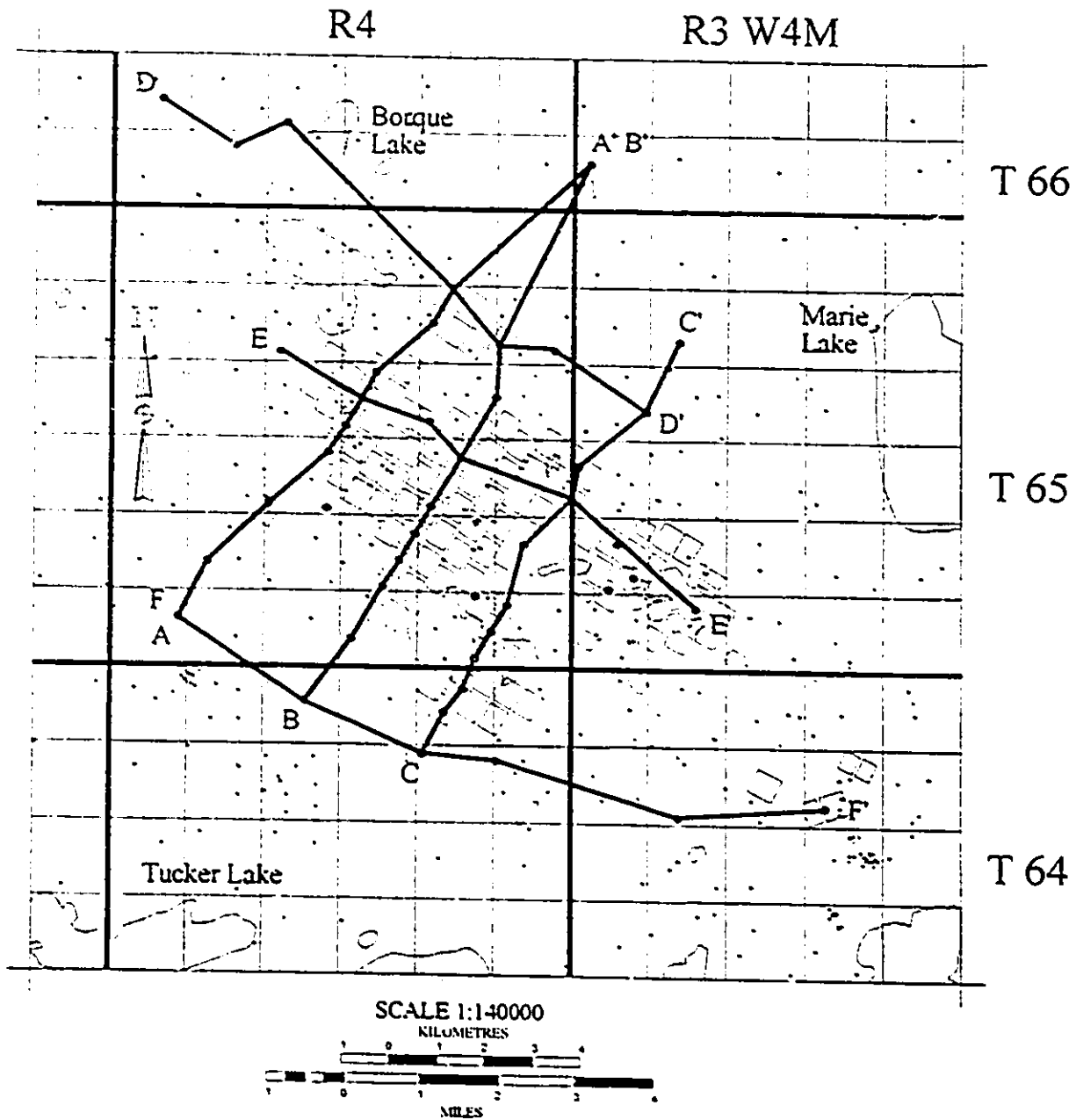


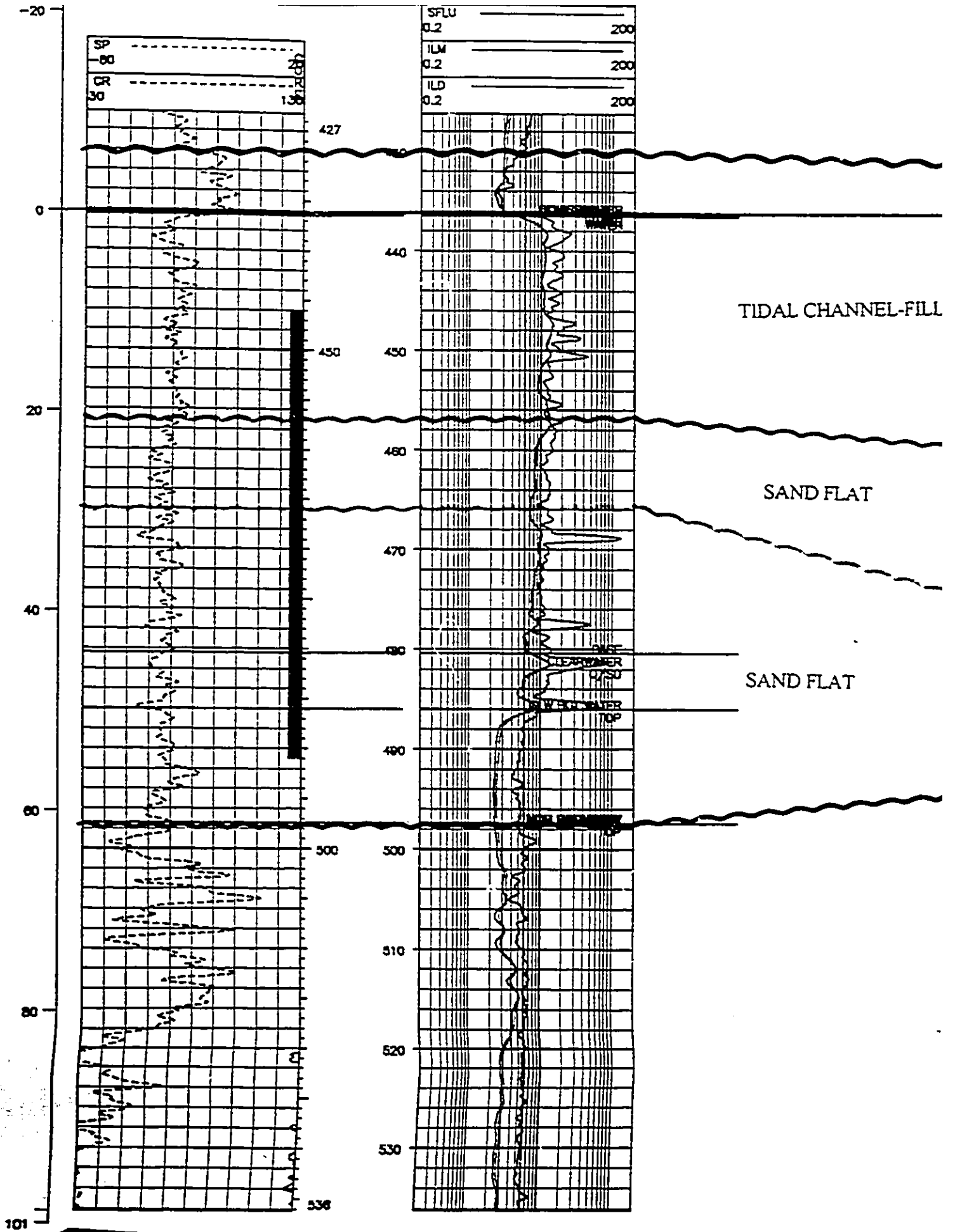
STRATIGRAPHIC CROSS-SECTION B-B'

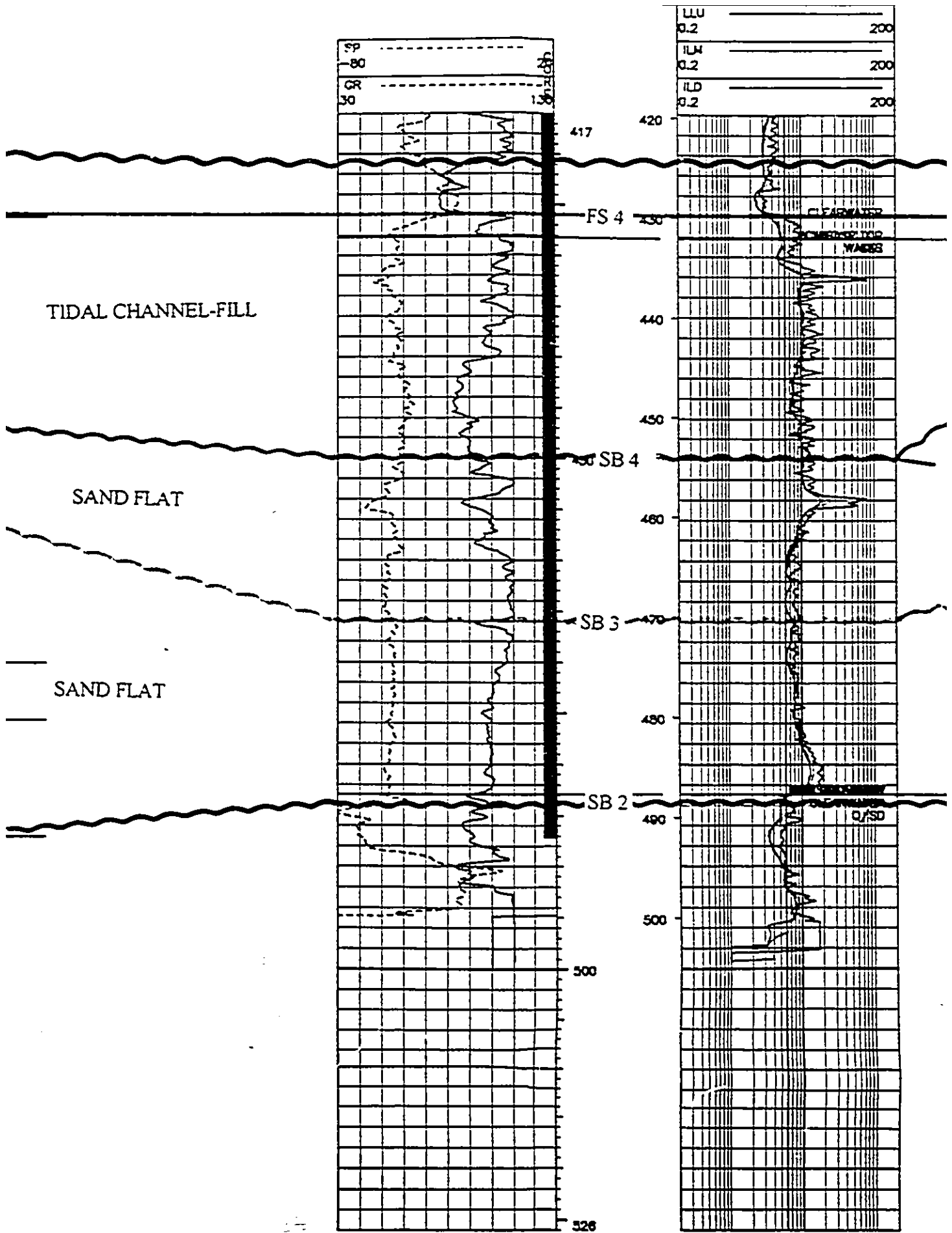
VERTICAL SCALE: 1:480
 HORIZONTAL SCALE: NOT TO SCALE
 DATUM: FLOODING SURFACE 4 (FS 4)

WELL LOGS COURTESY IMPERIAL OIL RESOURCES LIMITED, CALGARY

SECTION DRAWN BY: G. Glen McCrimmon August, 1995







SP
80
GR
50

LU
0.2
200
IL
0.2
200
LD
0.2
200

TIDAL CHANNEL-FILL

SAND FLAT

SAND FLAT

417

420

FS 4

430

440

450

SB 4

460

SB 3

470

480

SB 2

490

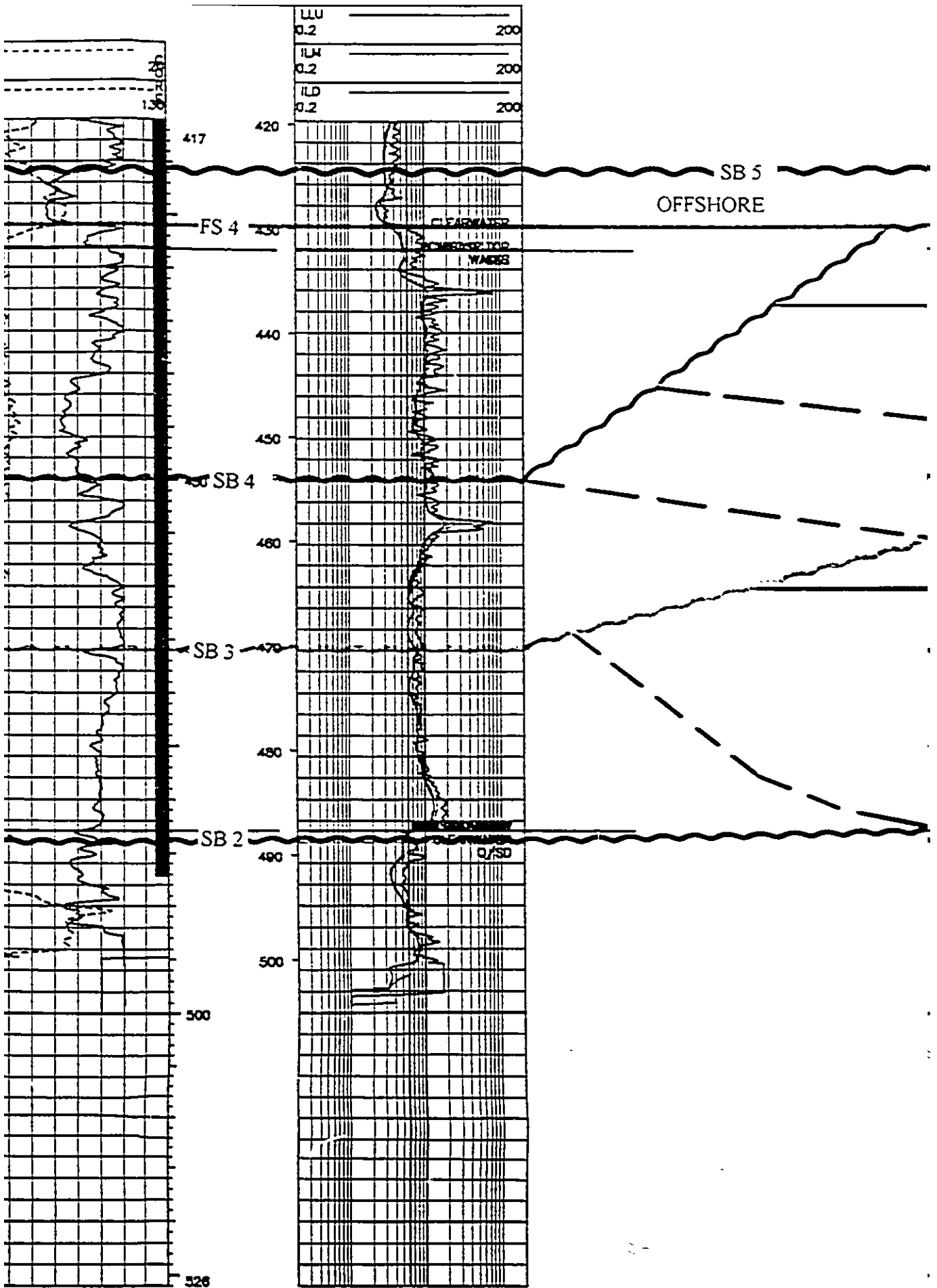
500

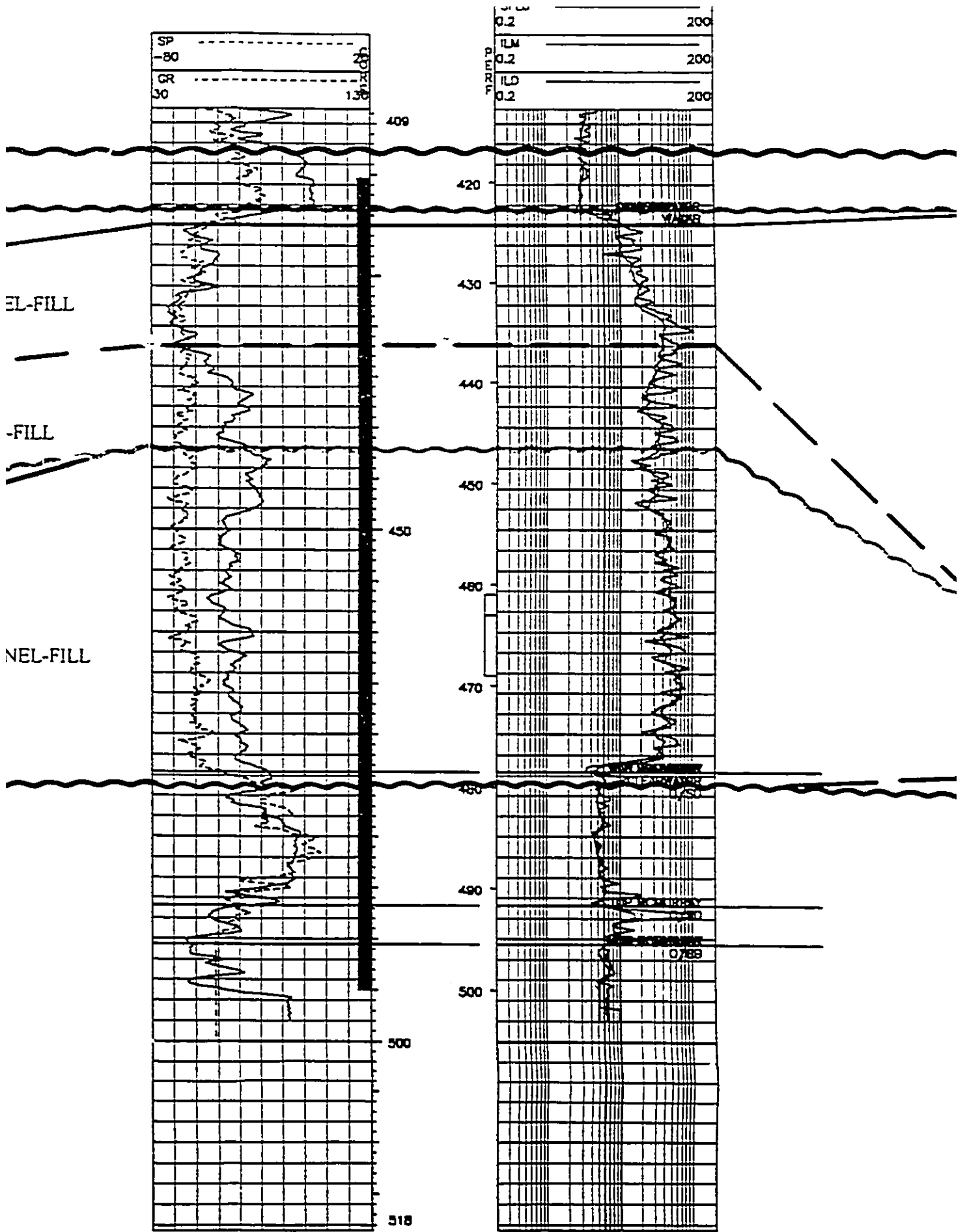
500

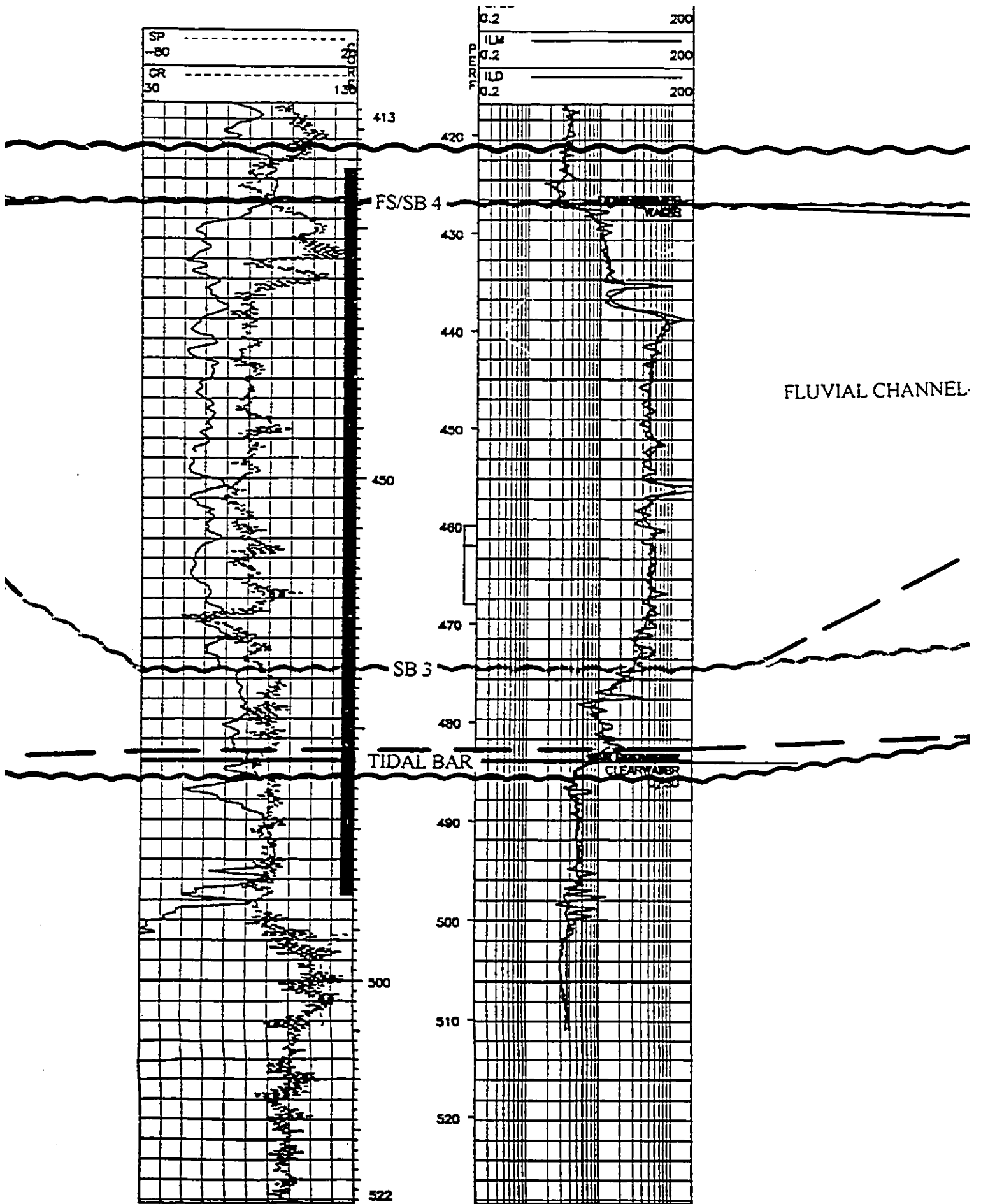
526

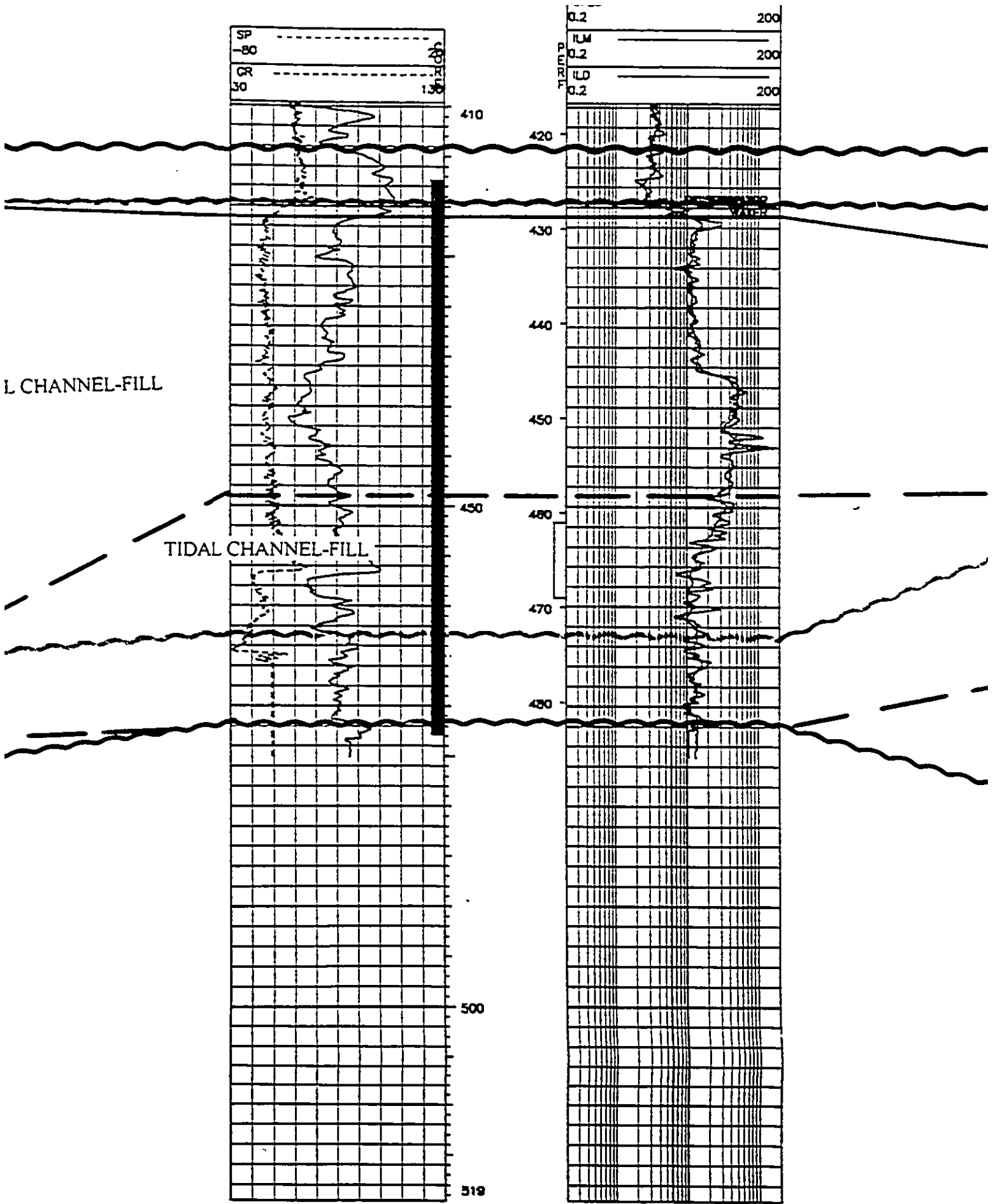
CLEARWATER
SOUNDING TOP
WAGES

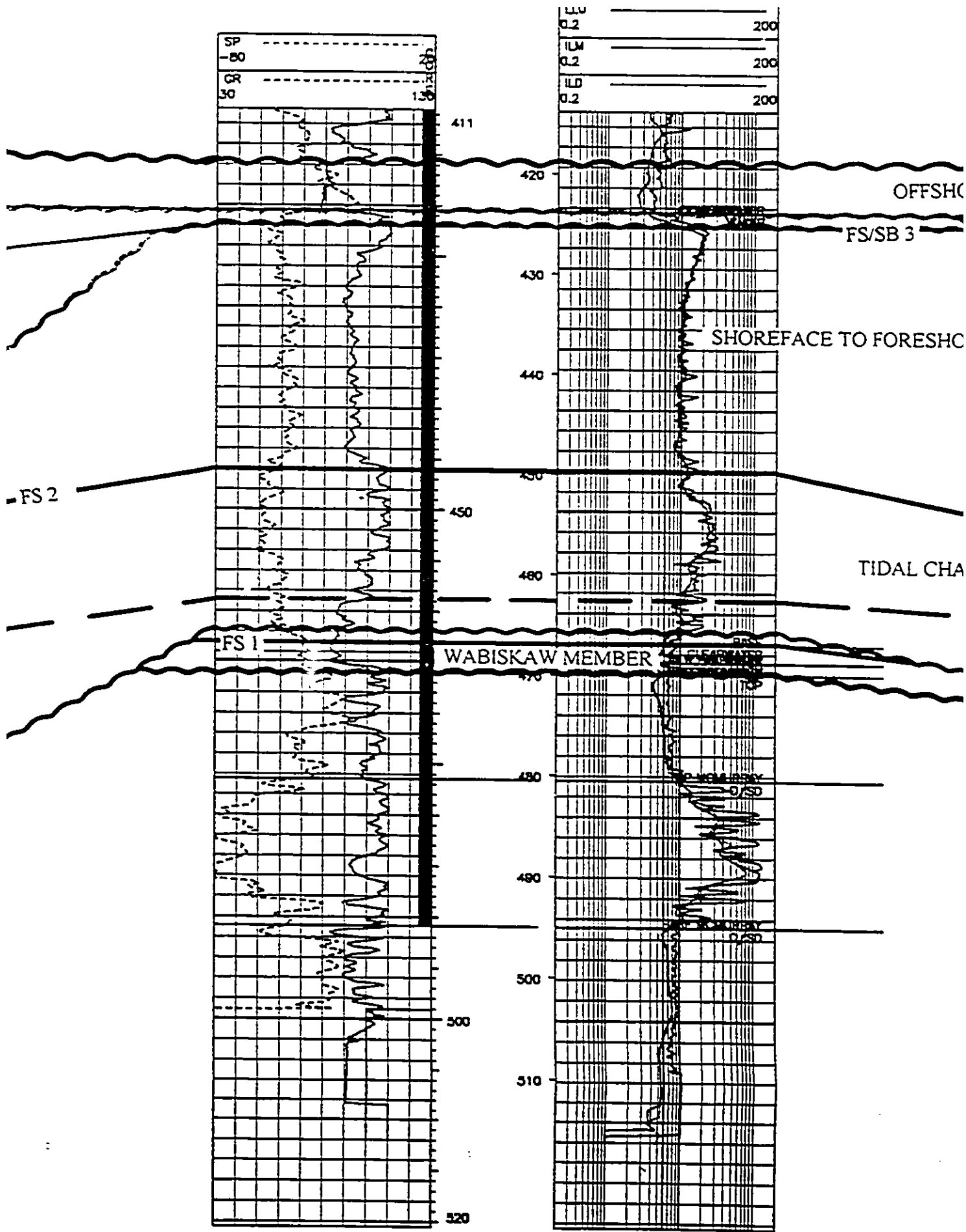
Q/SD

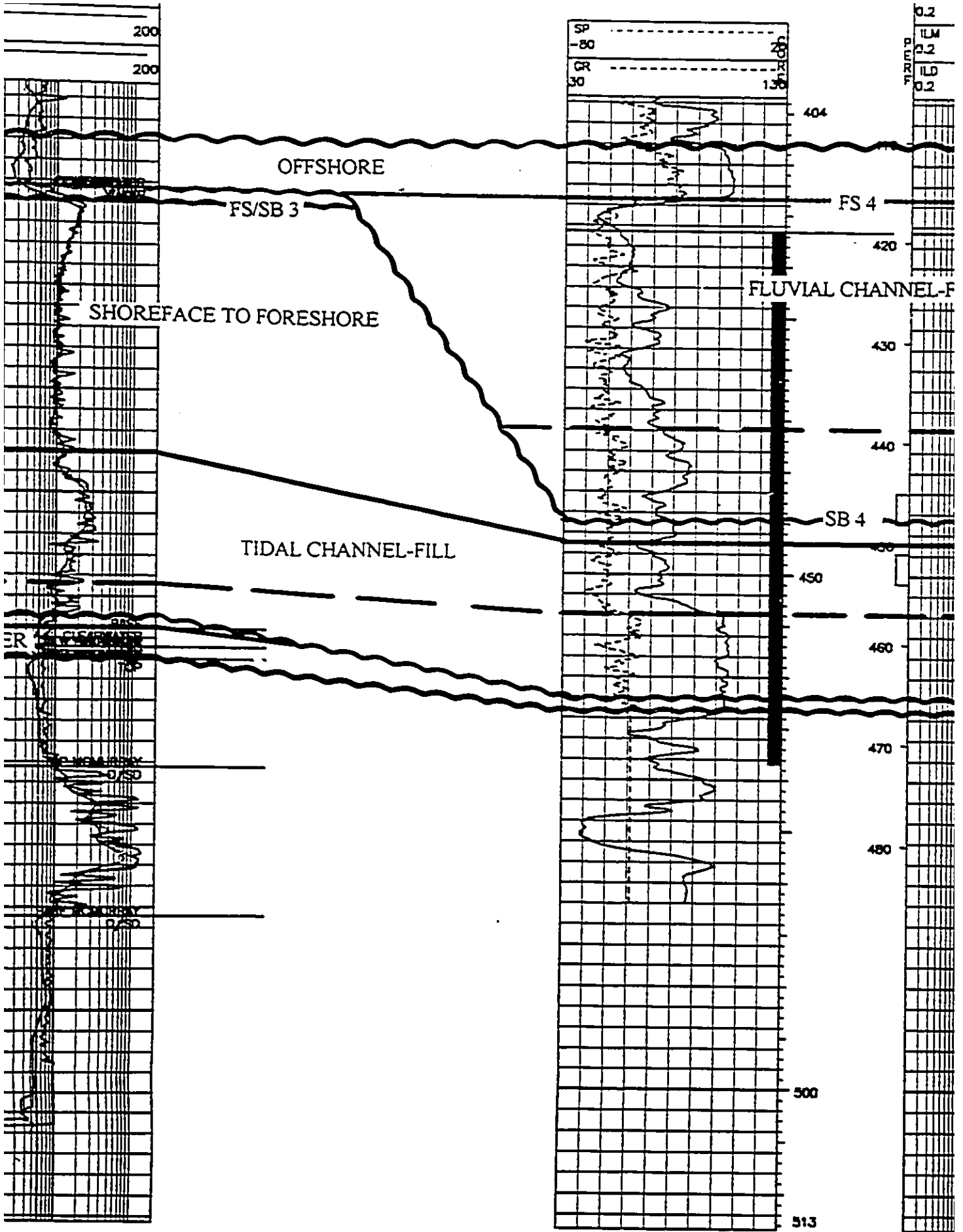


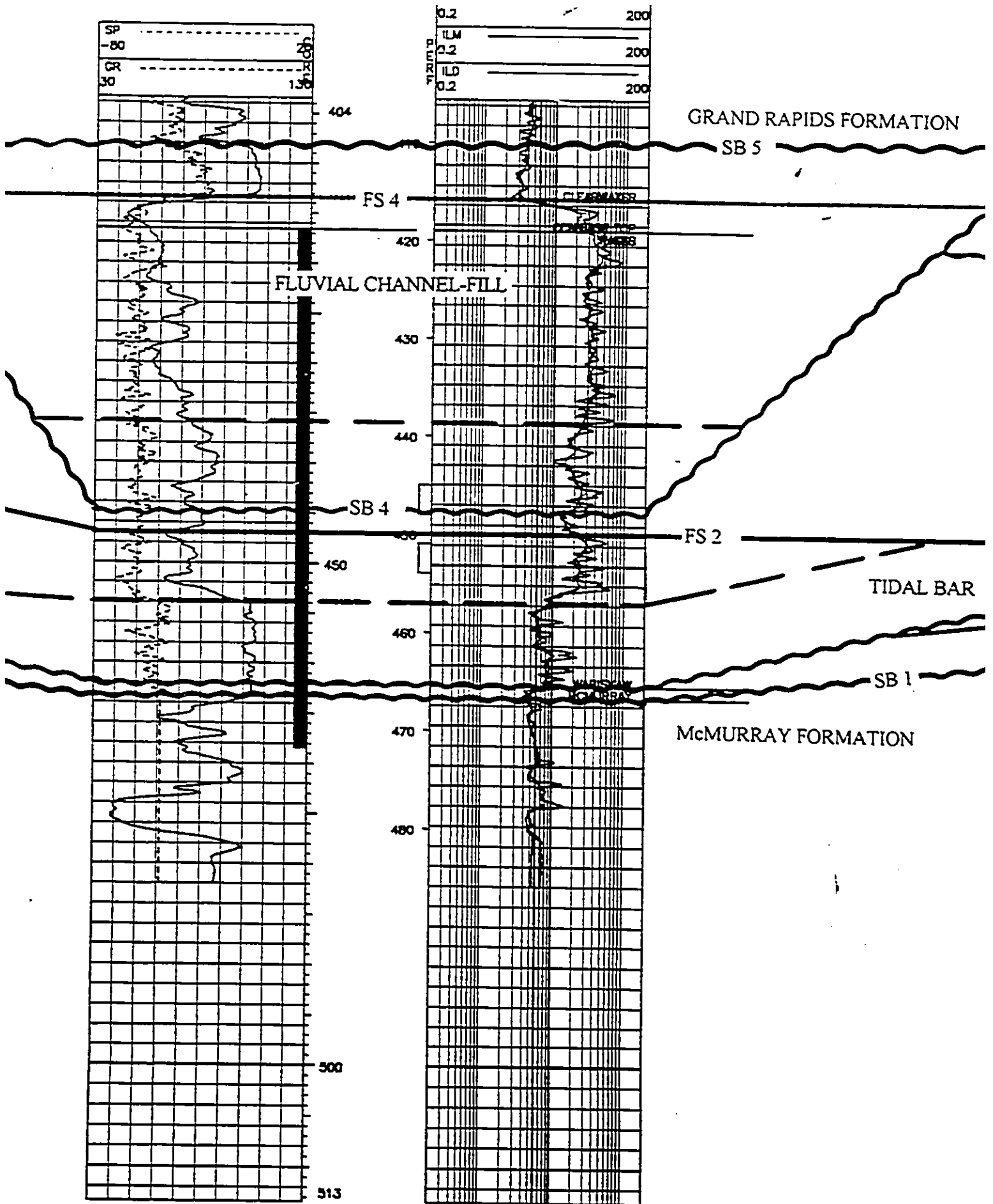


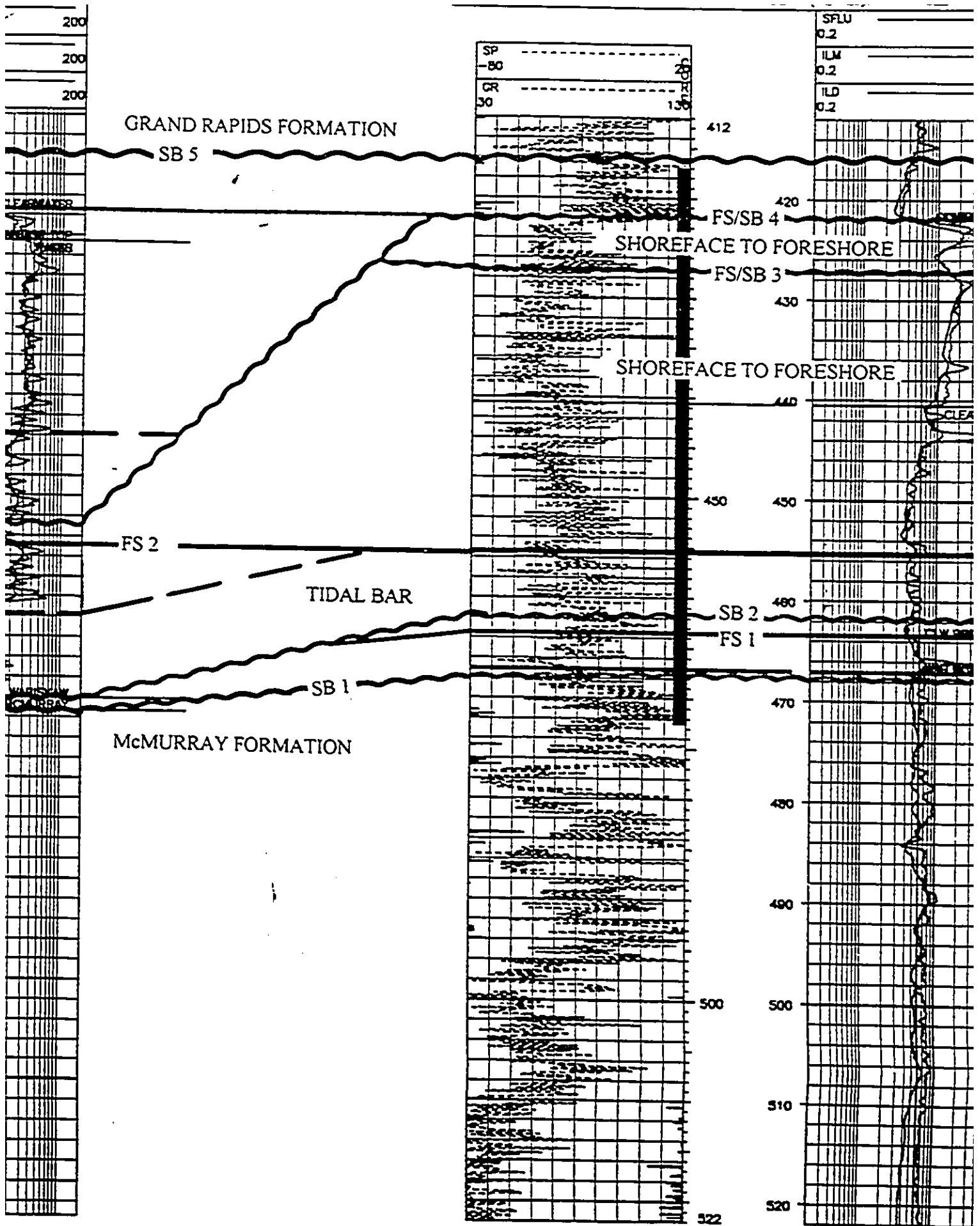






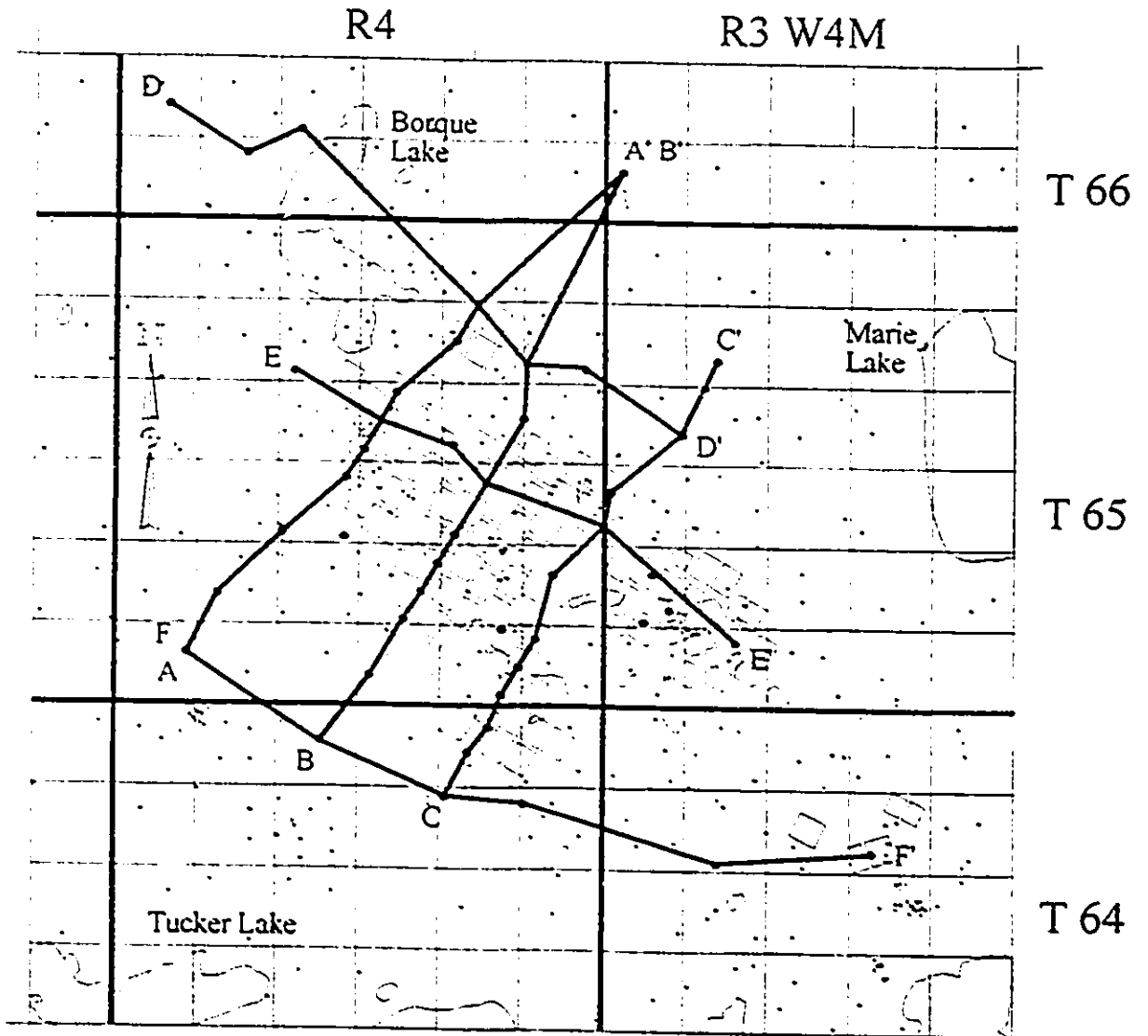
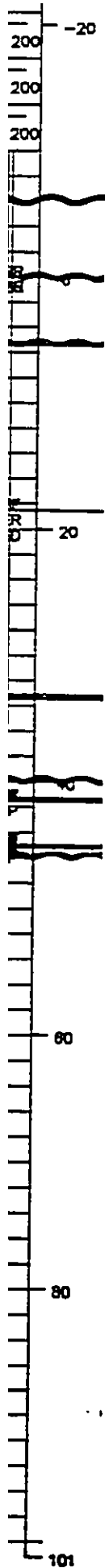




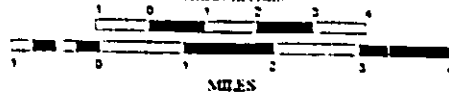


WELL LOGS COURTESY IMPERIAL OIL RESOURCES LIMITED, CALGARY

SECTION DRAWN BY: G. Glen McCrimmon August, 1995



SCALE 1:140000
KILOMETRES

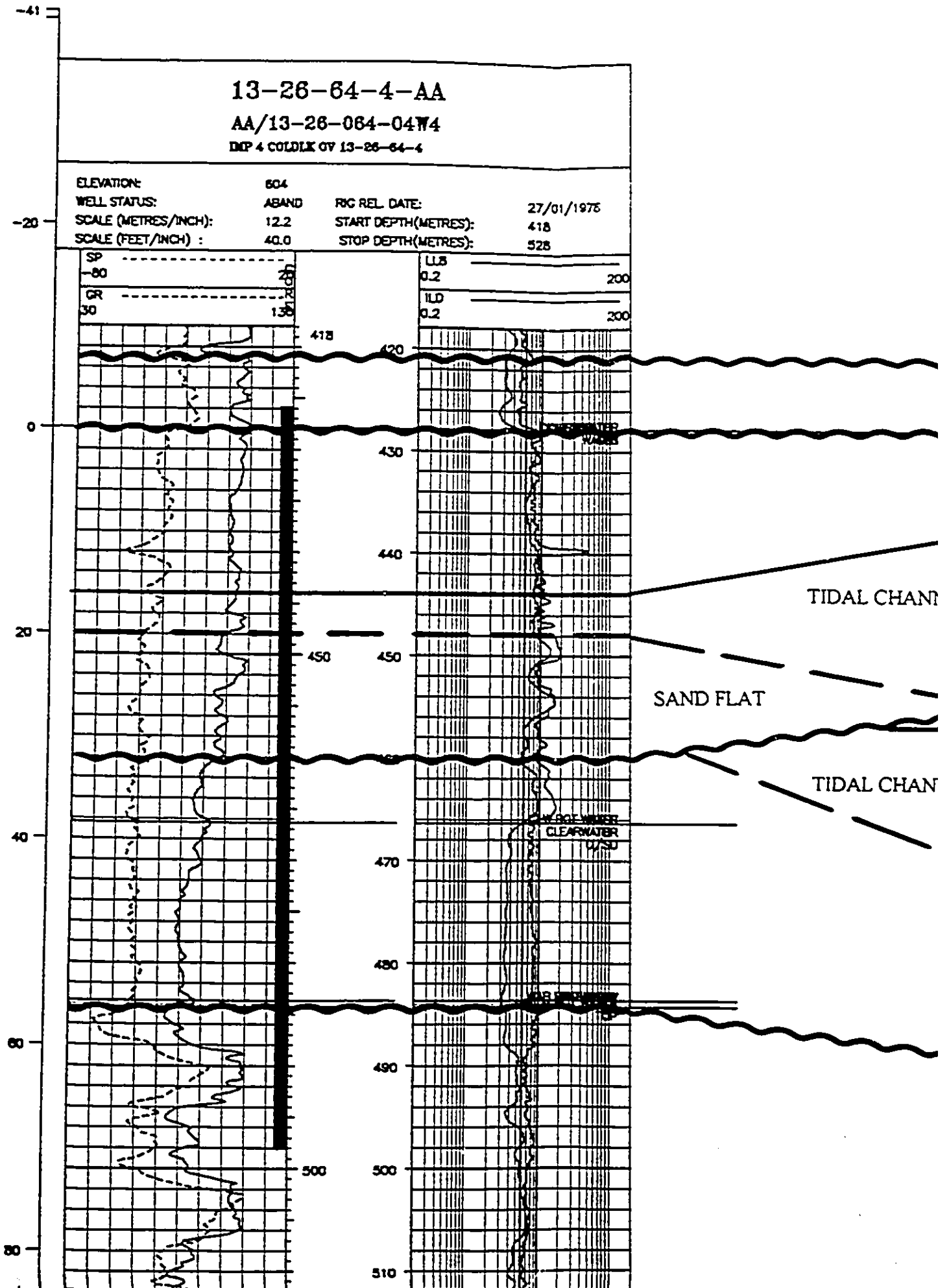


13-26-64-4-AA

AA/13-26-064-04W4

DIP 4 COLDLK OV 13-26-64-4

ELEVATION:	604	RIG REL DATE:	27/01/1976
WELL STATUS:	ABAND	START DEPTH(METRES):	418
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	528
SCALE (FEET/INCH) :	40.0		

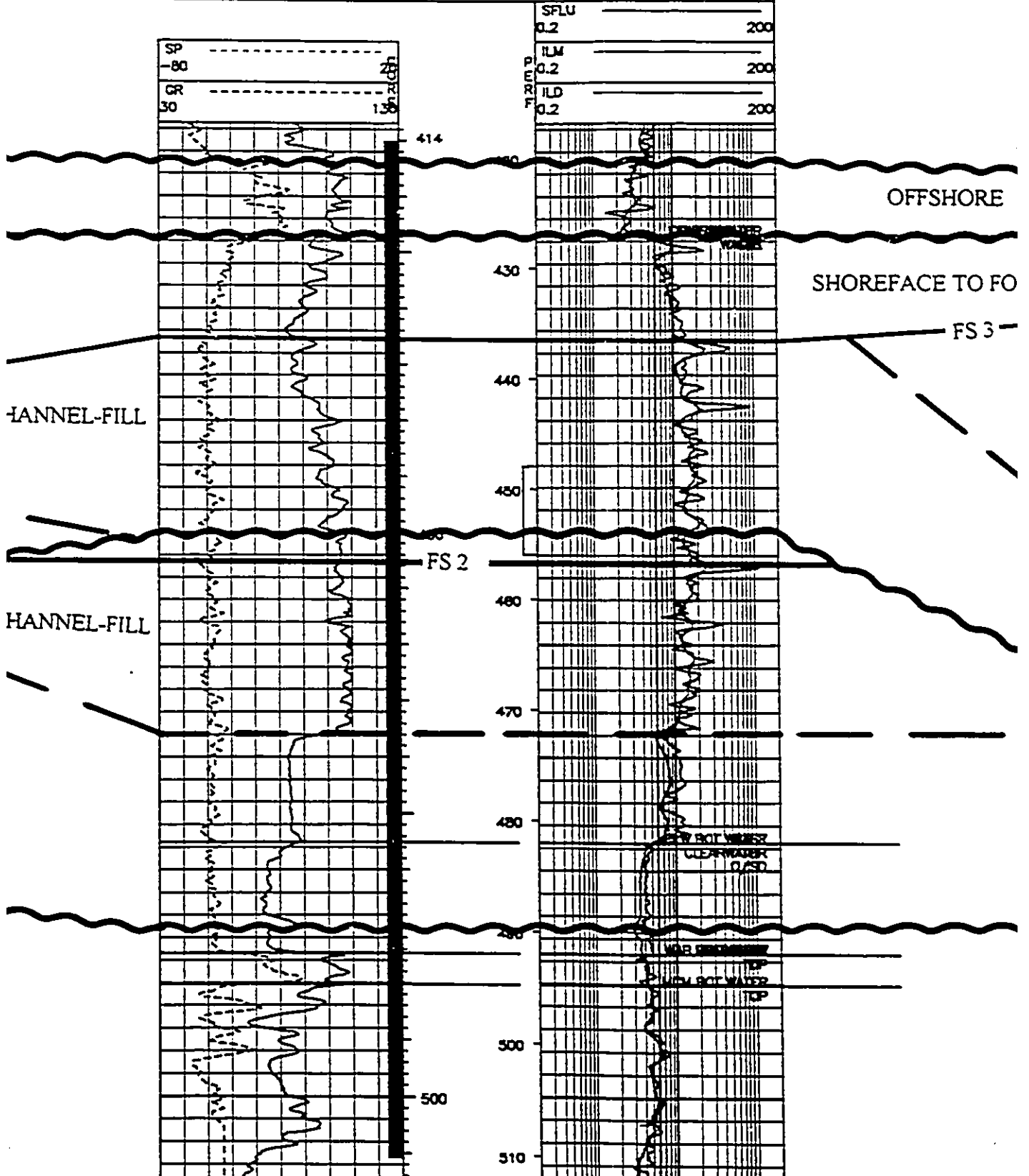


D55-13

04/06-35-084-04W4

ESSO 87 D55-13 COLDLX 6-35-64-4

ELEVATION:	604	RIG REL DATE:	08/08/1987
WELL STATUS:	CB	START DEPTH(METRES):	413
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	523
SCALE (FEET/INCH) :	40.0		

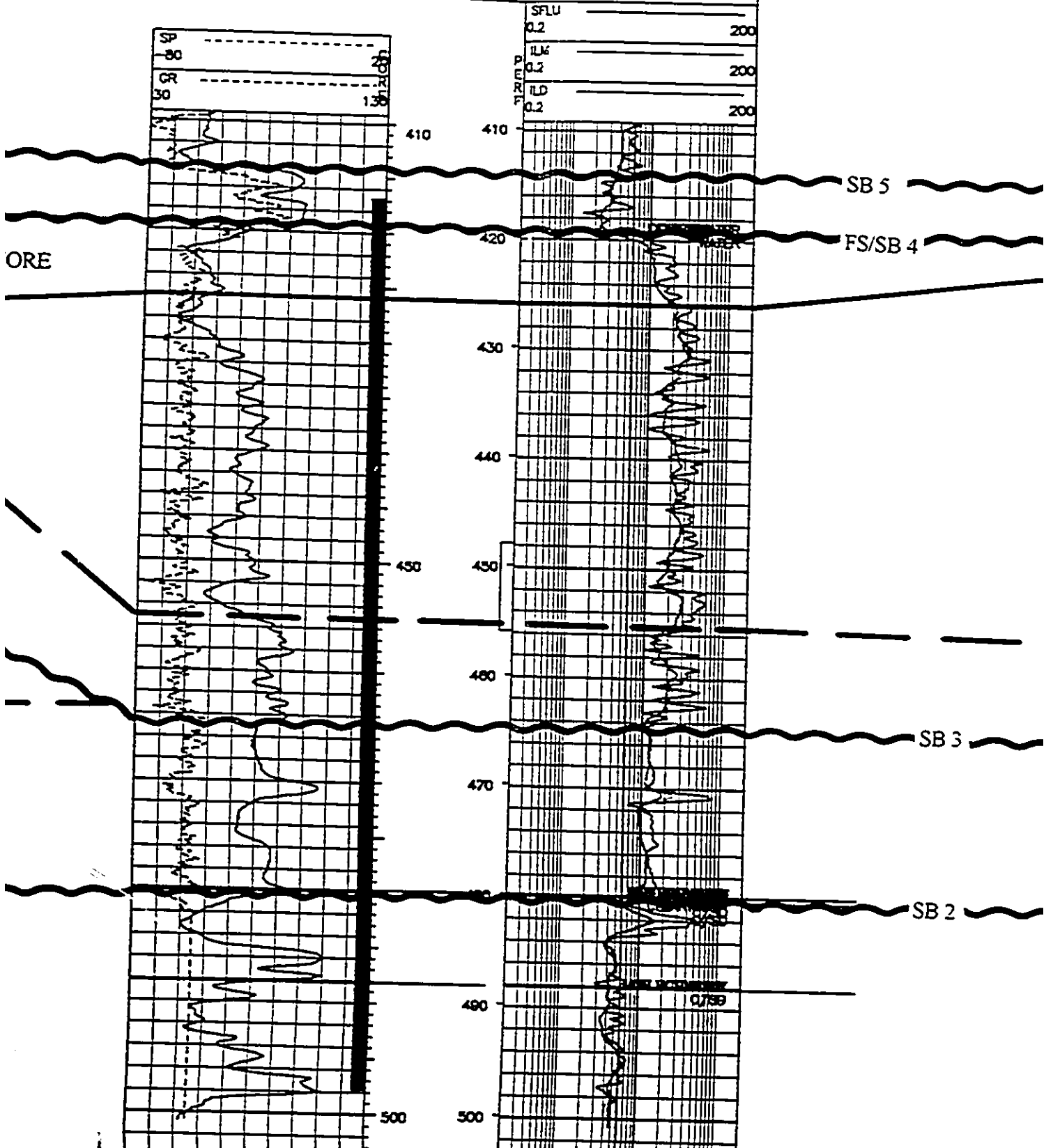


D52-14

00/10-35-084-04W4

K350 87 D52-14 COLDLK 10-35-04-4

ELEVATION:	605	RIG REL. DATE:	01/07/1987
WELL STATUS:	CB	START DEPTH(METRES):	409
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	519
SCALE (FEET/INCH) :	40.0		



-0474
35-64-6

DATE: 01/07/1987
DEPTH(METRES): 409
DEPTH(METRES): 519

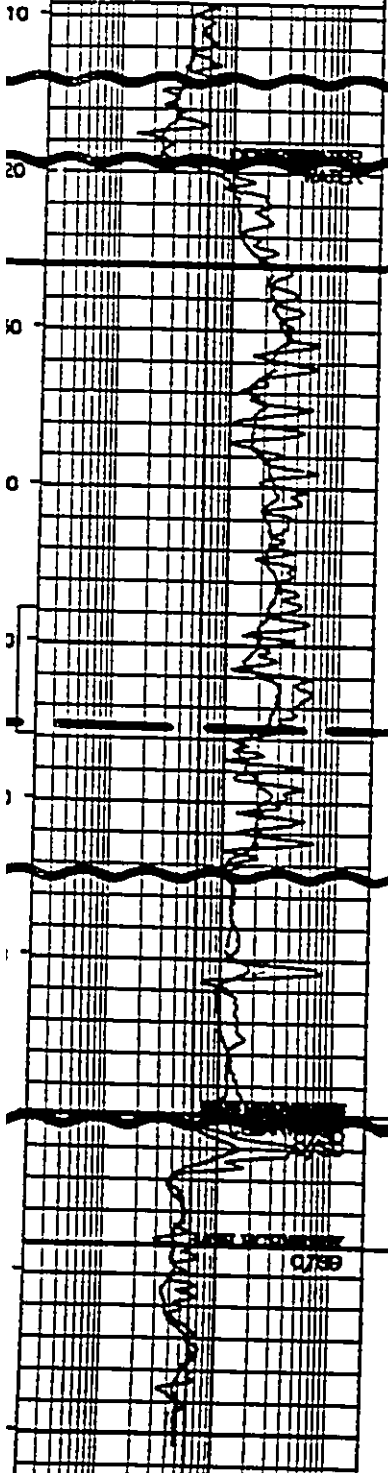
D26-13

03/02-02-085-04

ESSO 85 D26-13 COLDUK 2-2-0

ELEVATION: 804
WELL STATUS: CB RIG REL. DATE:
SCALE (METRES/INCH): 12.2 START DEPTH:
SCALE (FEET/INCH) : 40.0 STOP DEPTH:

SFLU	200
ILK	200
ILD	200



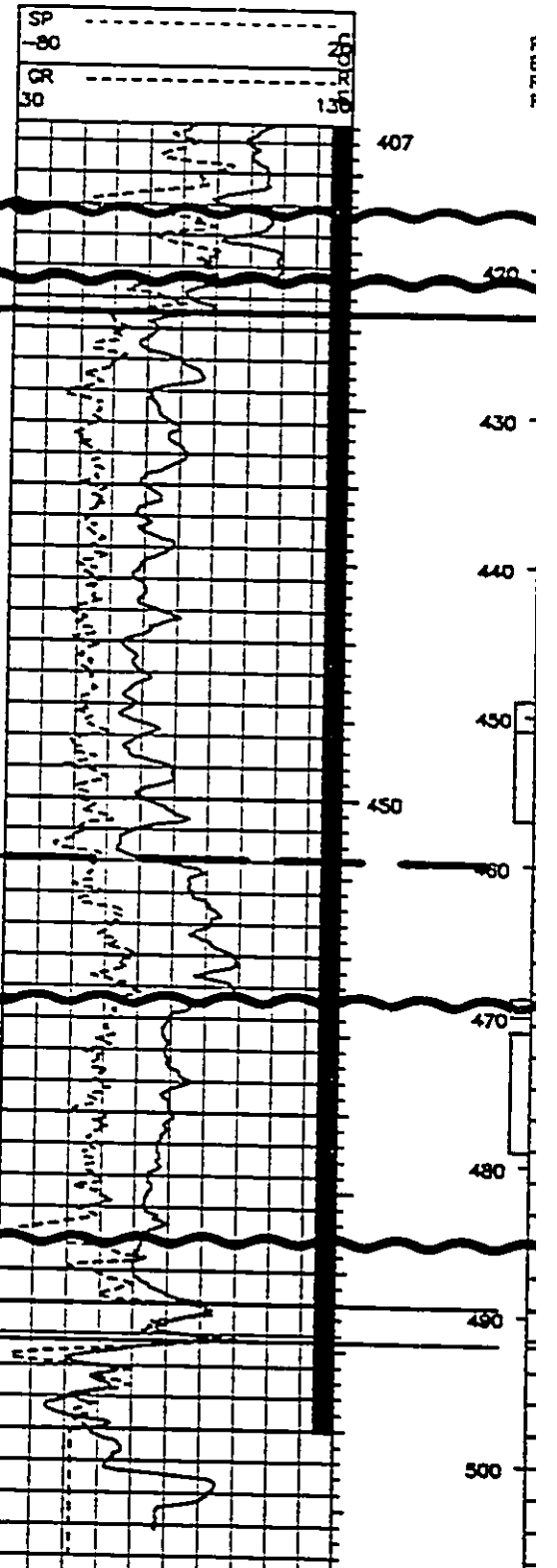
SB 5

FS/SB 4

SB 3

SB 2

0.759



407

430

440

450

450

460

470

480

490

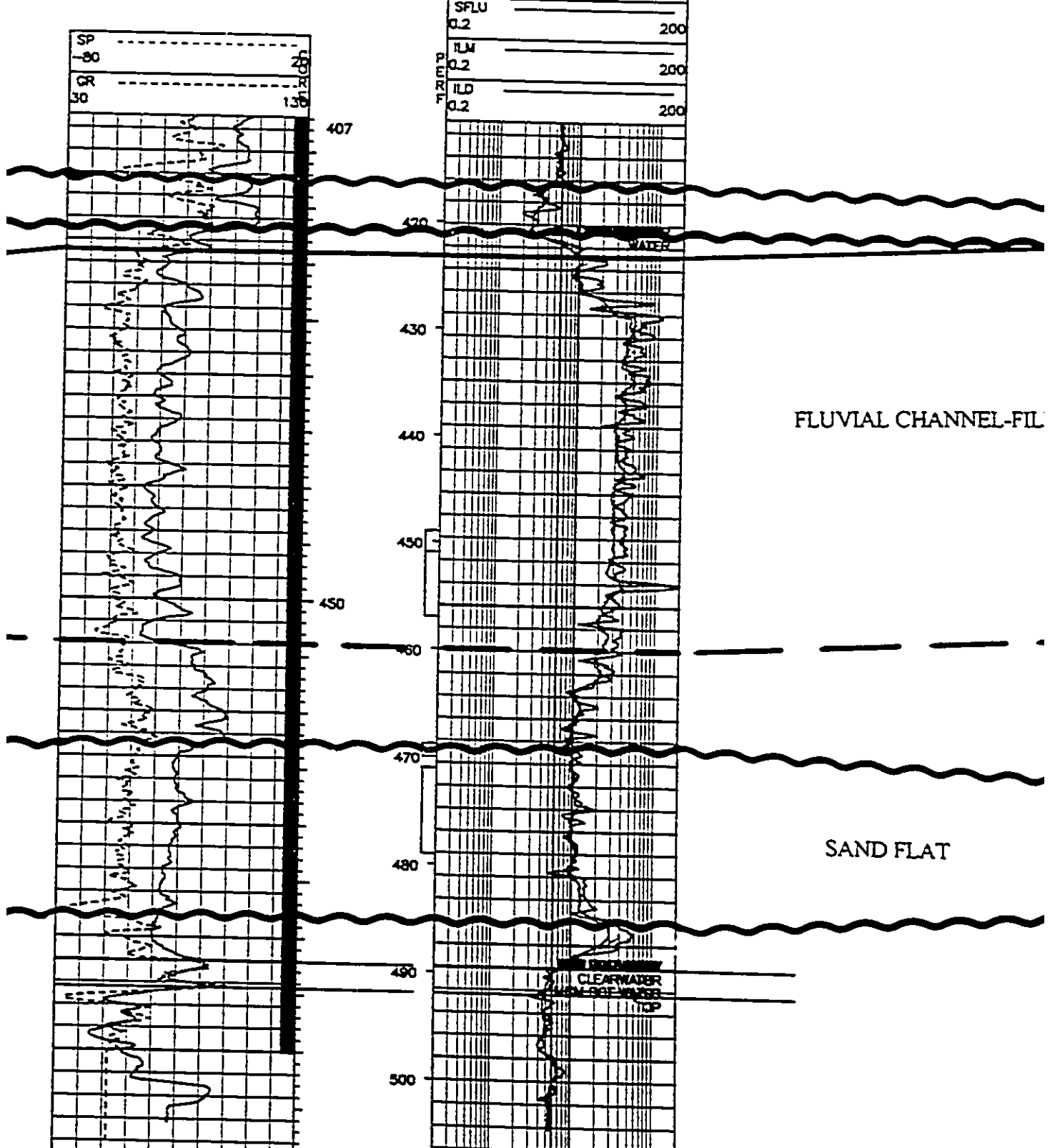
500

D26-13

03/02-02-085-04W4

ESSO 85 D26-13 COLDLX 2-2-85-4

ELEVATION:	804	RIG REL. DATE:	08/07/1985
WELL STATUS:	CB	START DEPTH(METRES):	407
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	517
SCALE (FEET/INCH) :	40.0		

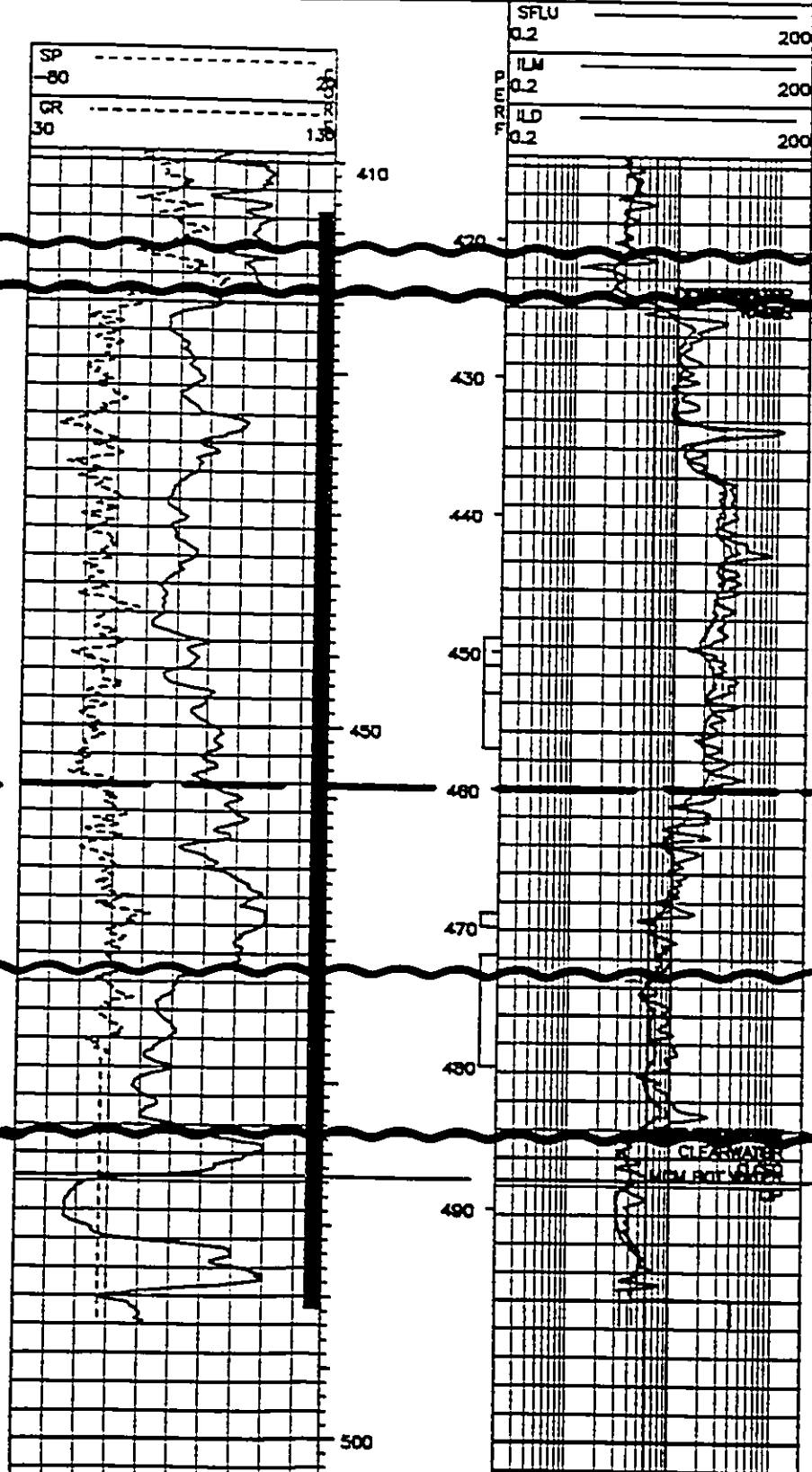


D25-13

05/08-02-085-04W4

ESSO 85 D25-13 COLDLK 8-2-85-4

ELEVATION:	803	RIG REL DATE:	15/07/1985
WELL STATUS:	CB	START DEPTH(METRES):	409
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	519
SCALE (FEET/INCH) :	40.0		



EL-FILL

TIDAL CHANNEL-FILL

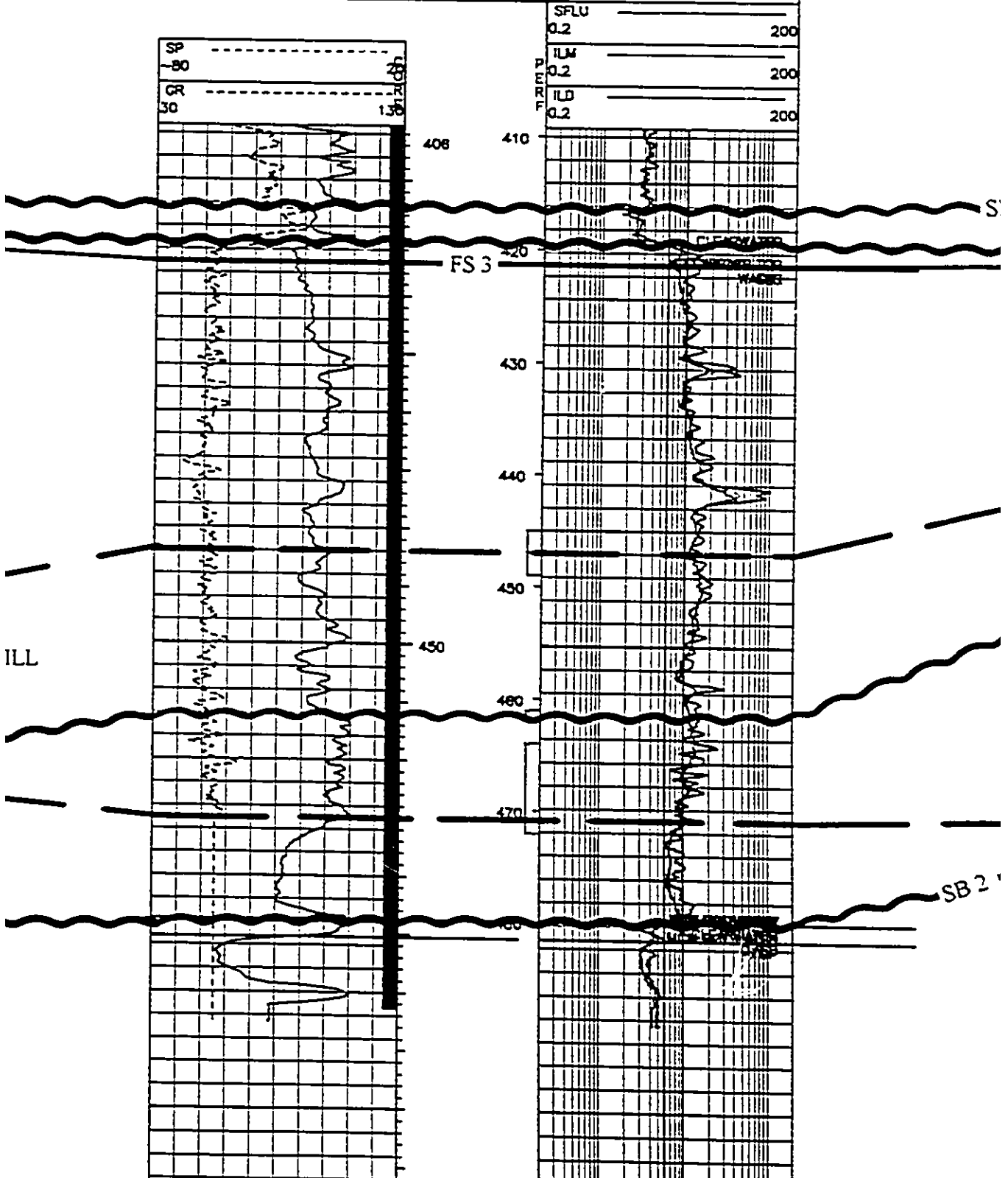
CLEARWATER

D24-13

06/13-01-065-04W4

ESSO 85 D24-13 COLDEX 13-1-65-4

ELEVATION:	804	RIG REL DATE:	02/08/1985
WELL STATUS:	CB	START DEPTH(METRES):	405
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	515
SCALE (FEET/INCH) :	40.0		



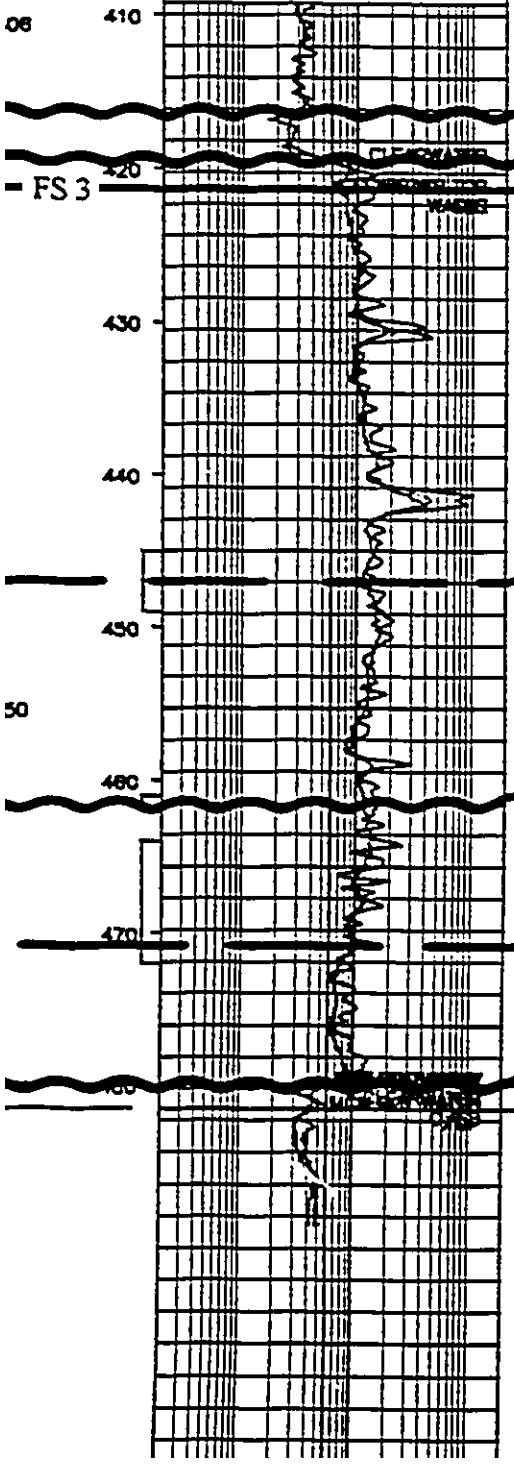
24-13

1-065-04W4

COLDEX 13-1-65-4

RIG REL. DATE: 02/08/1985
 START DEPTH(METRES): 405
 STOP DEPTH(METRES): 515

SFLU	0.2	200
ILM	0.2	200
ILD	0.2	200



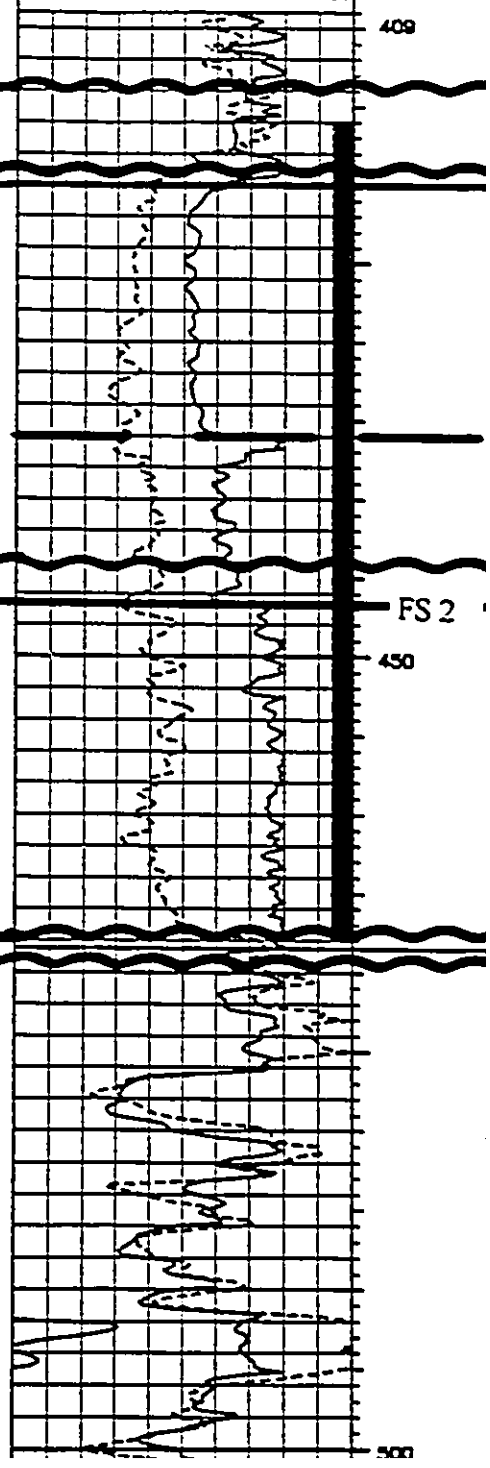
11-12-65-

AA/11-12-065-

ESSO COLD LAKE CV 11-1

ELEVATION: 804
 WELL STATUS: ABAND RIG REL
 SCALE (METRES/INCH): 12.2 START D
 SCALE (FEET/INCH) : 40.0 STOP D

SP	-80	200
GR	30	130

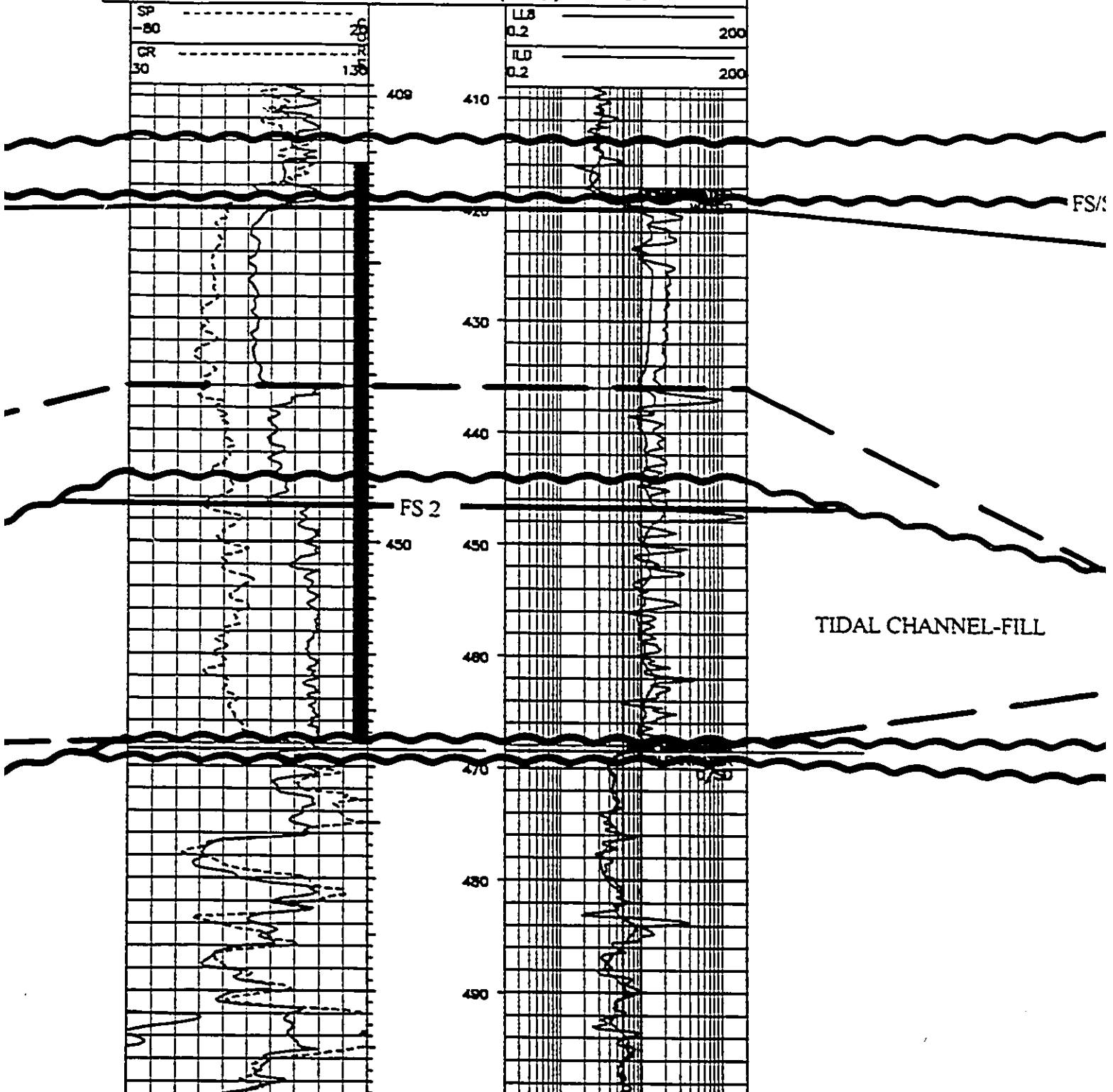


11-12-65-4-AA

AA/11-12-065-04W4

ESSO COLD LAKE CV 11-12-65-4

ELEVATION:	804	RIG REL. DATE:	15/01/1979
WELL STATUS:	ABAND	START DEPTH(METRES):	409
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	519
SCALE (FEET/INCH) :	40.0		



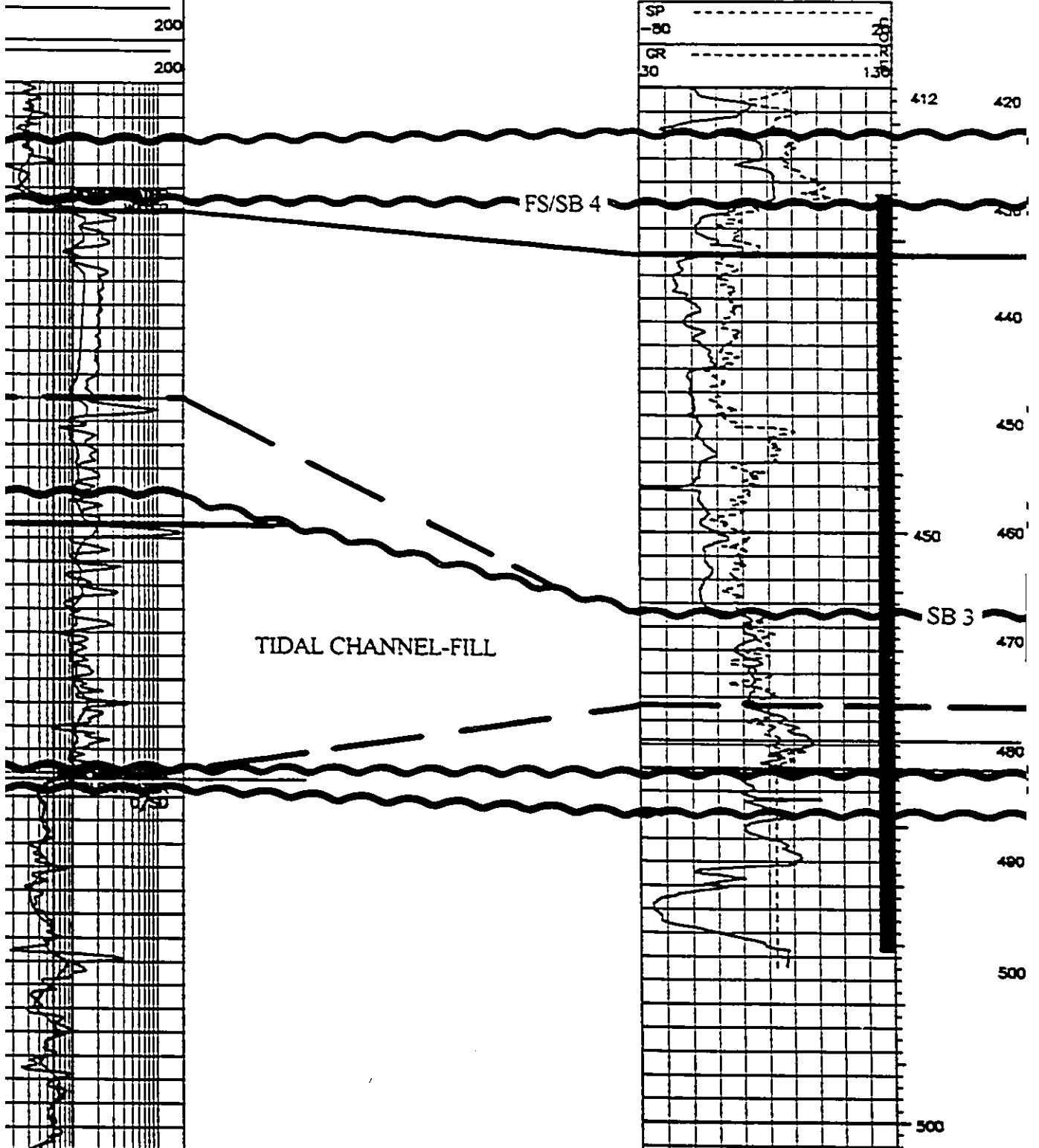
C02-08

00/01-13-065-04

ESSO 85 C2-8 COLDLK 1-13-6

ELEVATION:	808	
WELL STATUS:	CB	RIG REL DAT
SCALE (METRES/INCH):	12.2	START DEPTH
SCALE (FEET/INCH) :	40.0	STOP DEPTH

15/01/1979
409
519

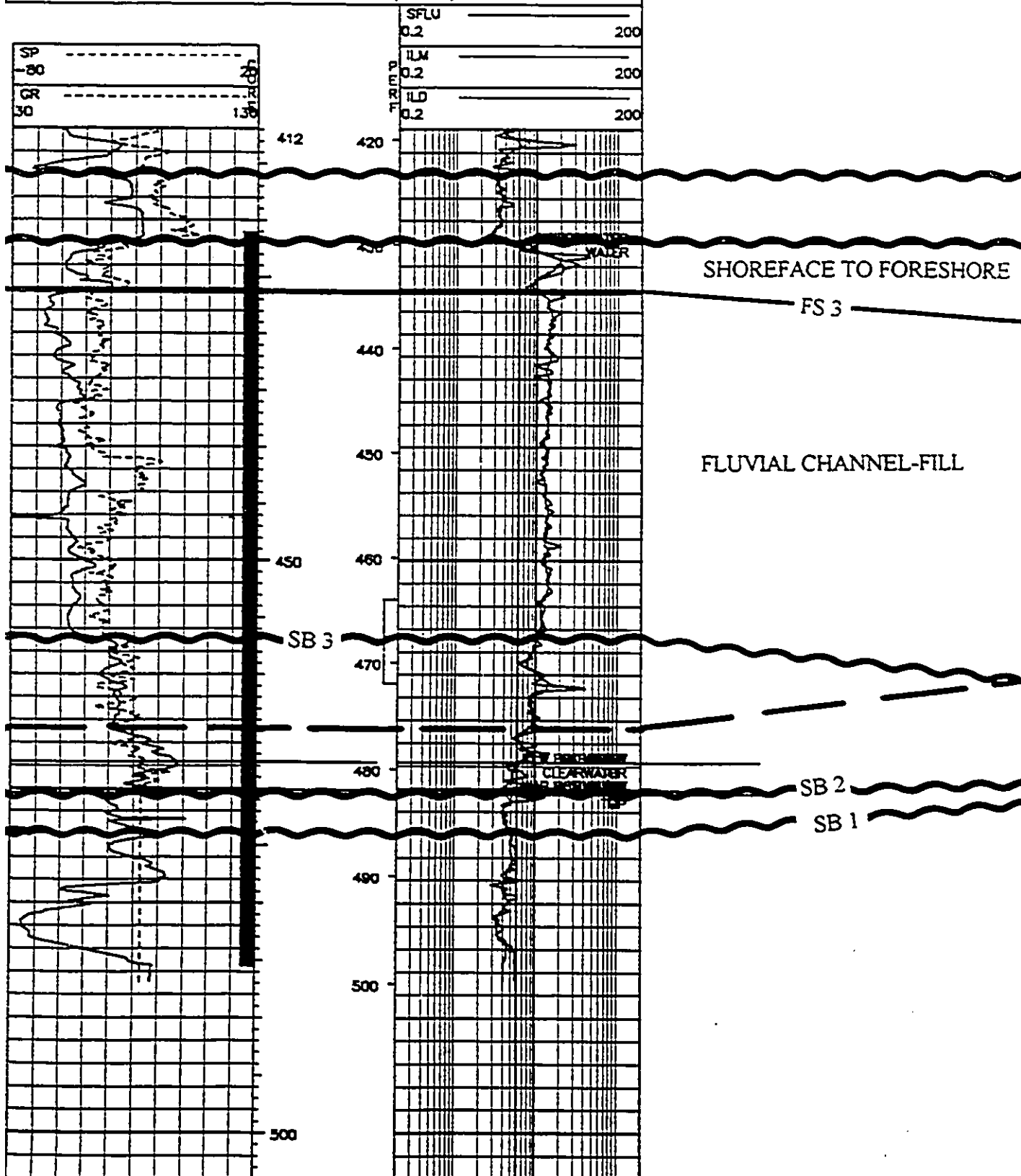


C02-08

00/01-13-065-04W4

Z330 85 C2-8 COLDLK 1-13-65-4

ELEVATION:	808	REG REL DATE:	28/06/1985
WELL STATUS:	CB	START DEPTH(METRES):	412
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	522
SCALE (FEET/INCH) :	40.0		

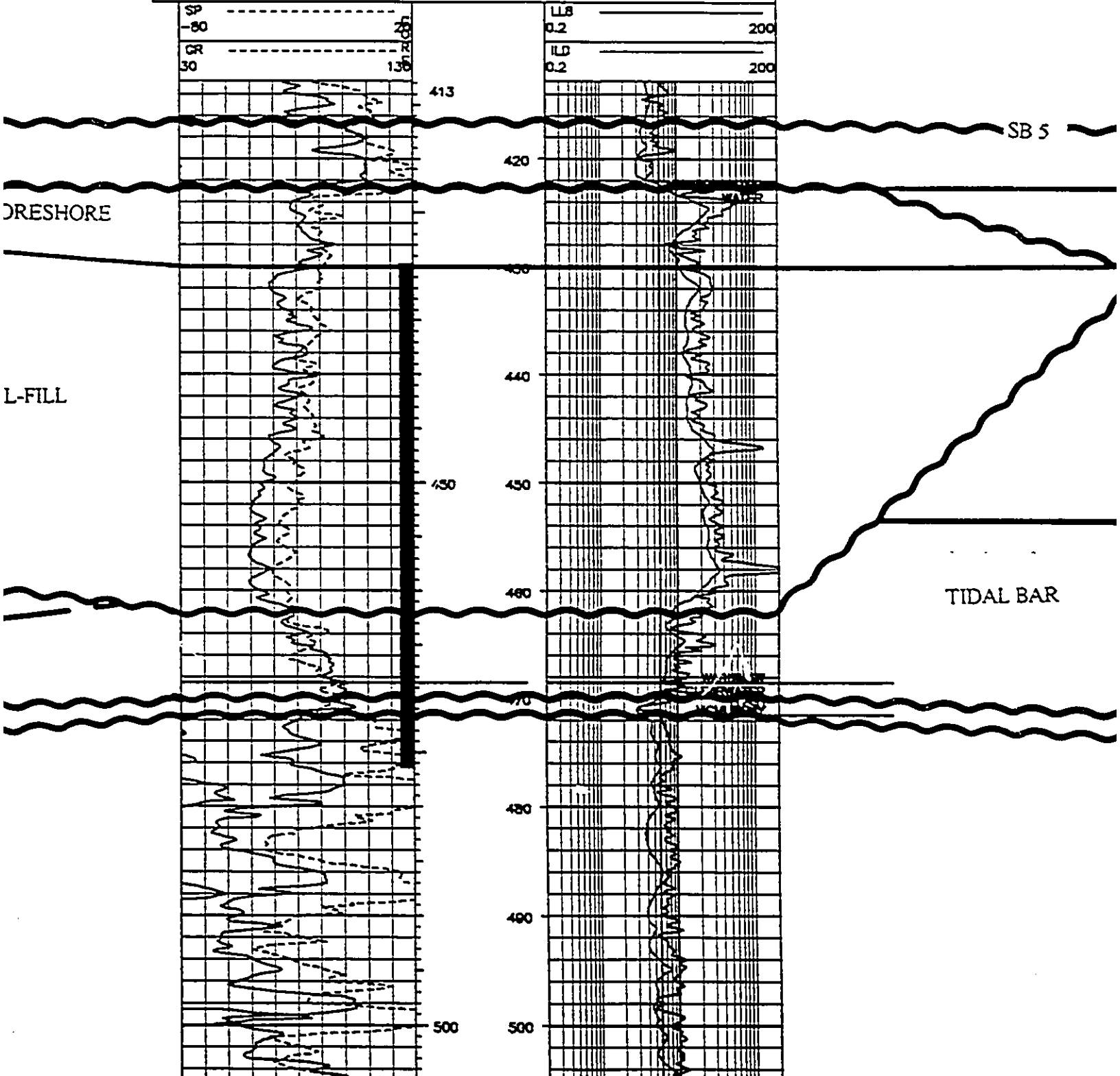


12-18-65-3-AA

AA/12-18-065-03W4

DOP 77 MARIE OY 12-18-65-3

ELEVATION:	808	ROG REL. DATE:	14/02/1977
WELL STATUS:	ABAND	START DEPTH(METRES):	413
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	523
SCALE (FEET/INCH) :	40.0		



19-65-3-AA

08-19-065-03W4

P 9 COLDEX OV 8-19-65-3

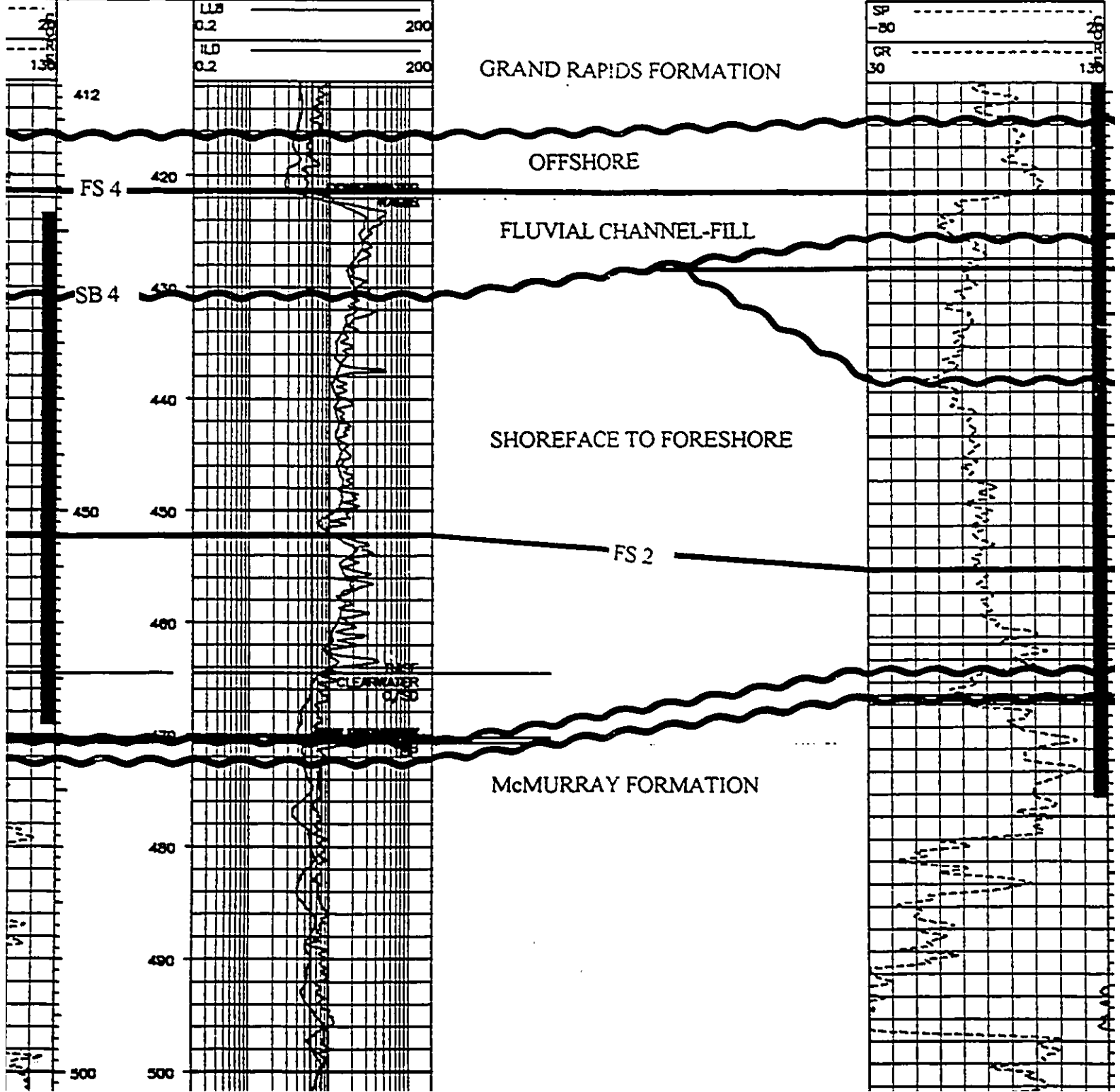
6-29

AA/06-

ES90 85 COLL

511		
ABAND	RIG REL. DATE:	18/02/1978
12.2	START DEPTH(METRES):	412
40.0	STOP DEPTH(METRES):	522

ELEVATION:	609
WELL STATUS:	ABAND
SCALE (METRES/INCH):	12.2
SCALE (FEET/INCH) :	40.0

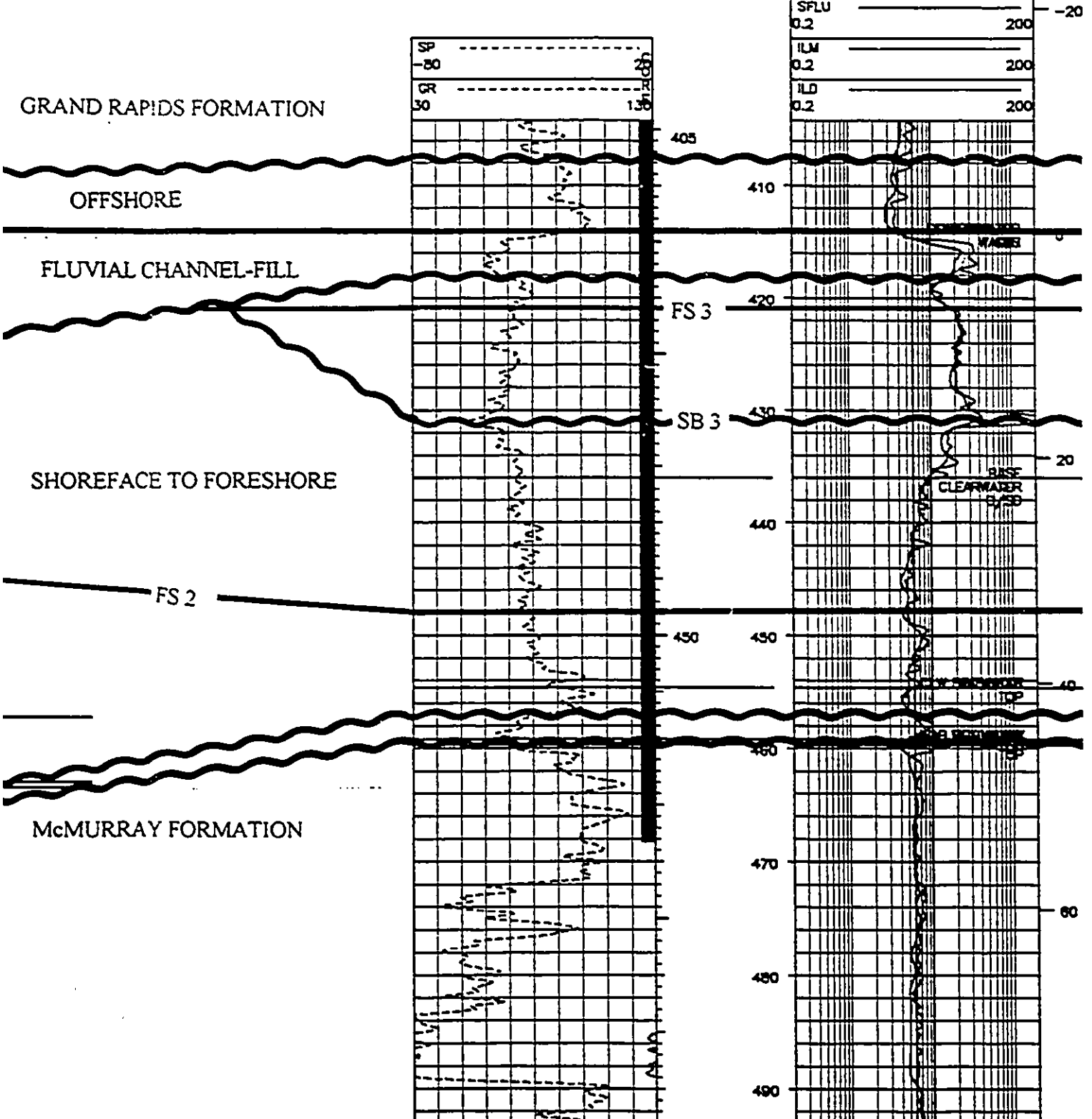


6-29-65-3-AA

AA/06-29-065-03W4

ESSO 85 COLDLK 07 6-29-65-3

ELEVATION:	809	ROG REL. DATE:	02/03/1985
WELL STATUS:	ABAND	START DEPTH(METRES):	404
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	514
SCALE (FEET/INCH) :	40.0		

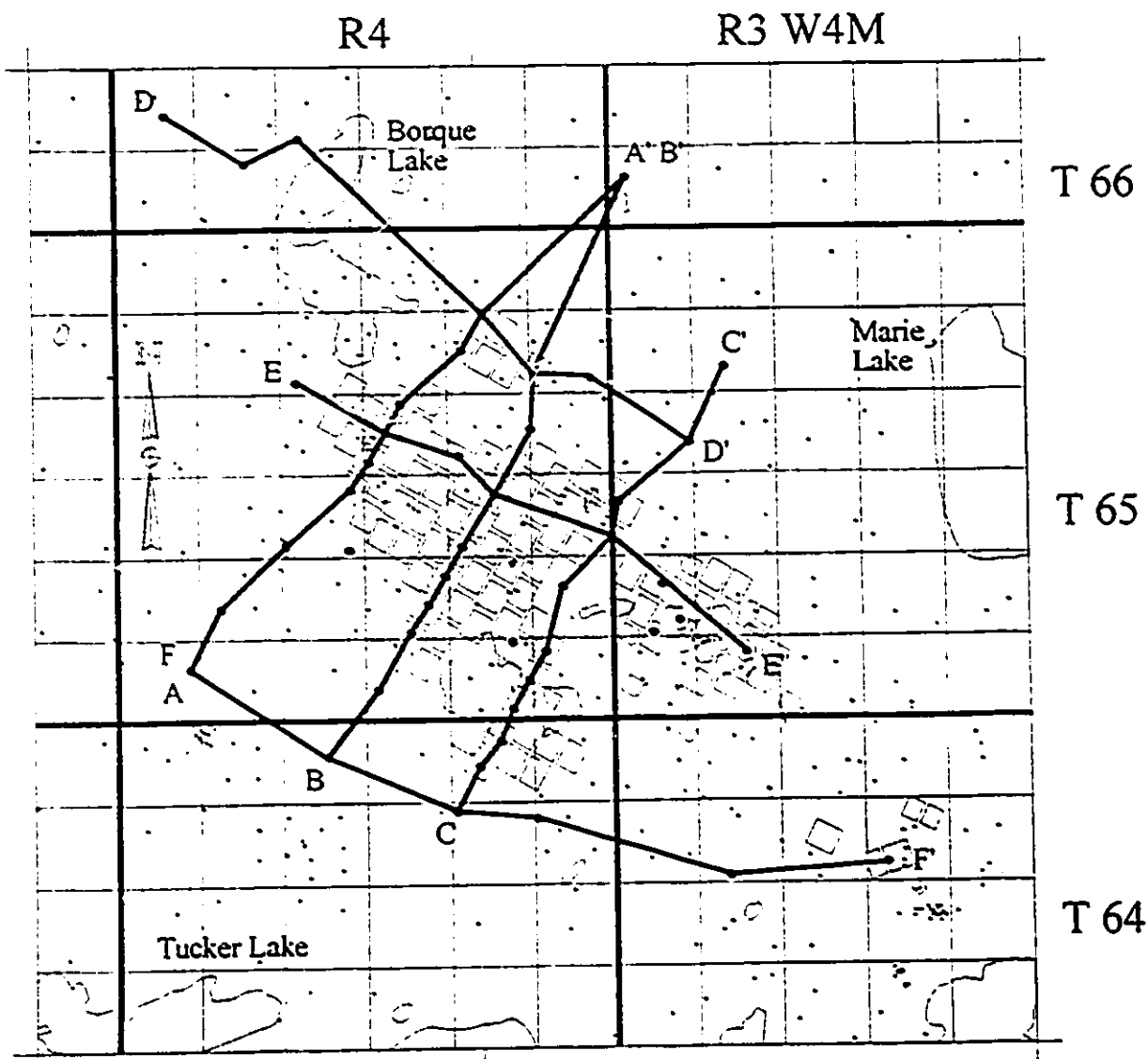
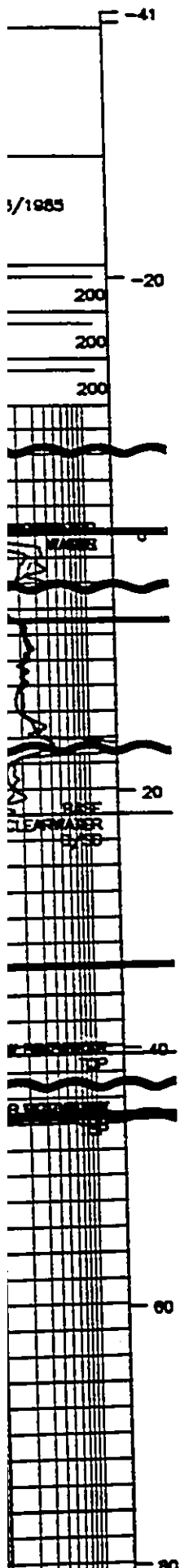


STRATIGRAPHIC CROSS-SECTION C-C'

VERTICAL SCALE: 1:480
HORIZONTAL SCALE: NOT TO SCALE
DATUM: FLOODING SURFACE 4 (FS 4)

WELL LOGS COURTESY IMPERIAL OIL RESOURCES LIMITED, CALGARY

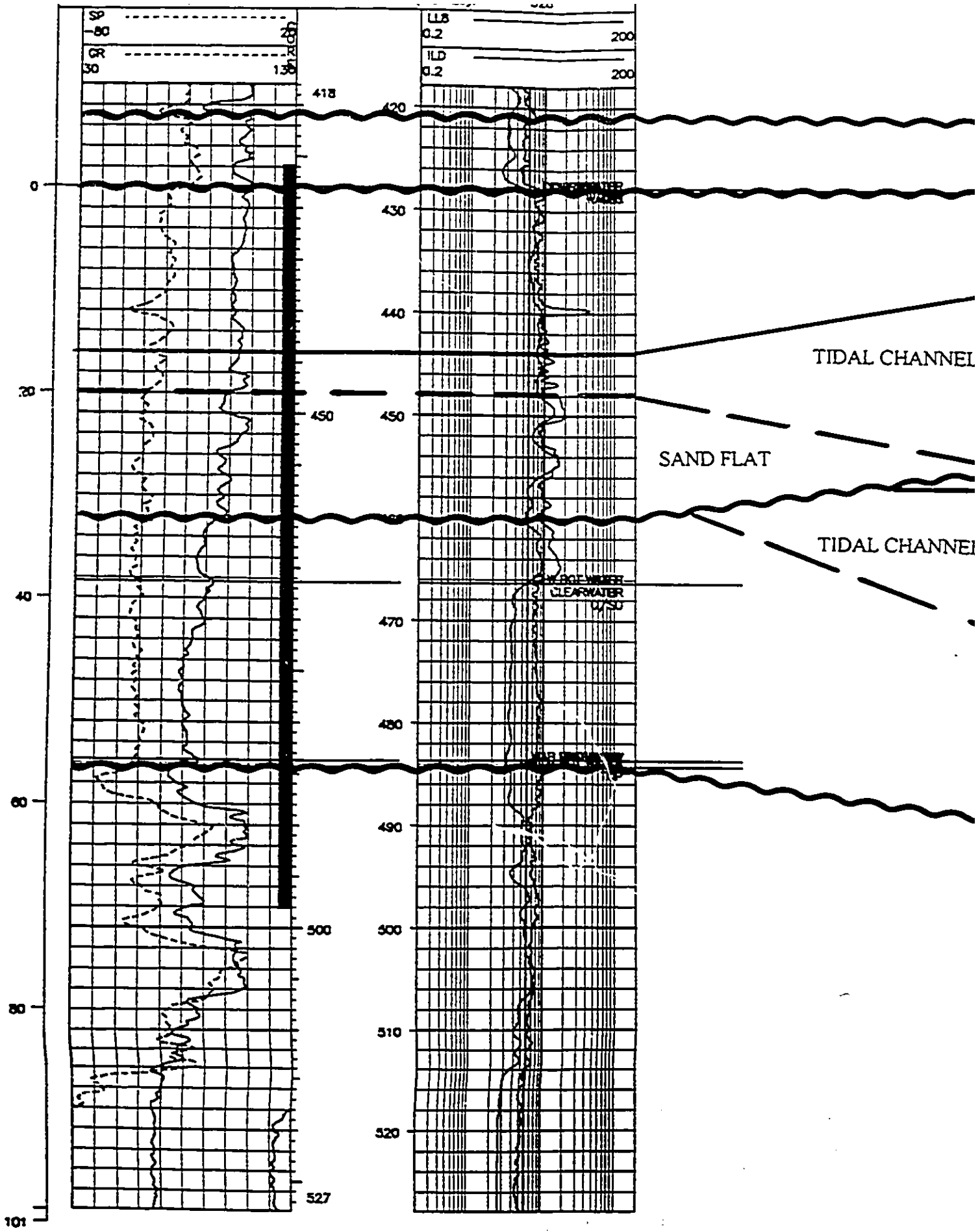
SECTION DRAWN BY: G. Glen McCrimmon August, 1995

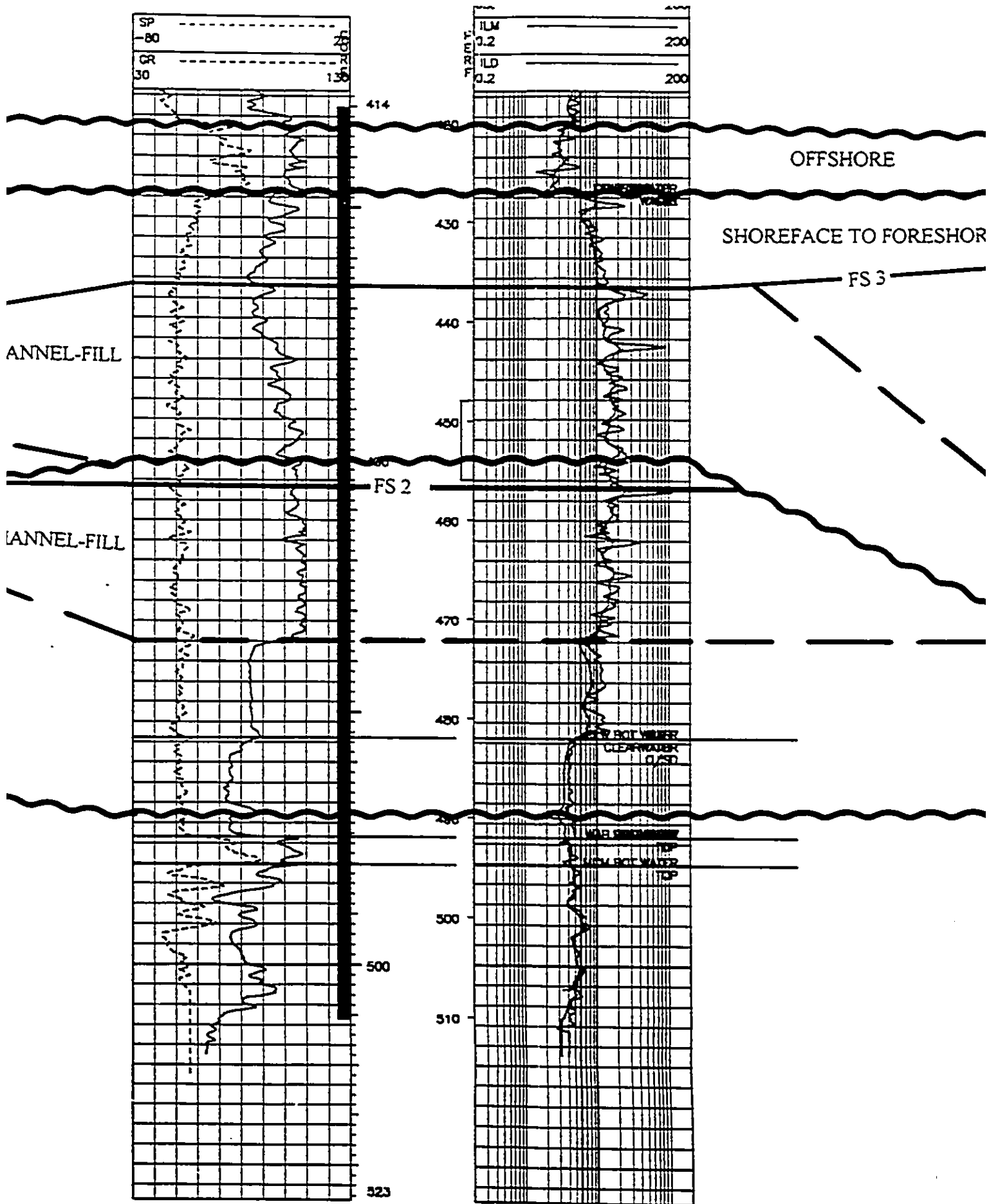


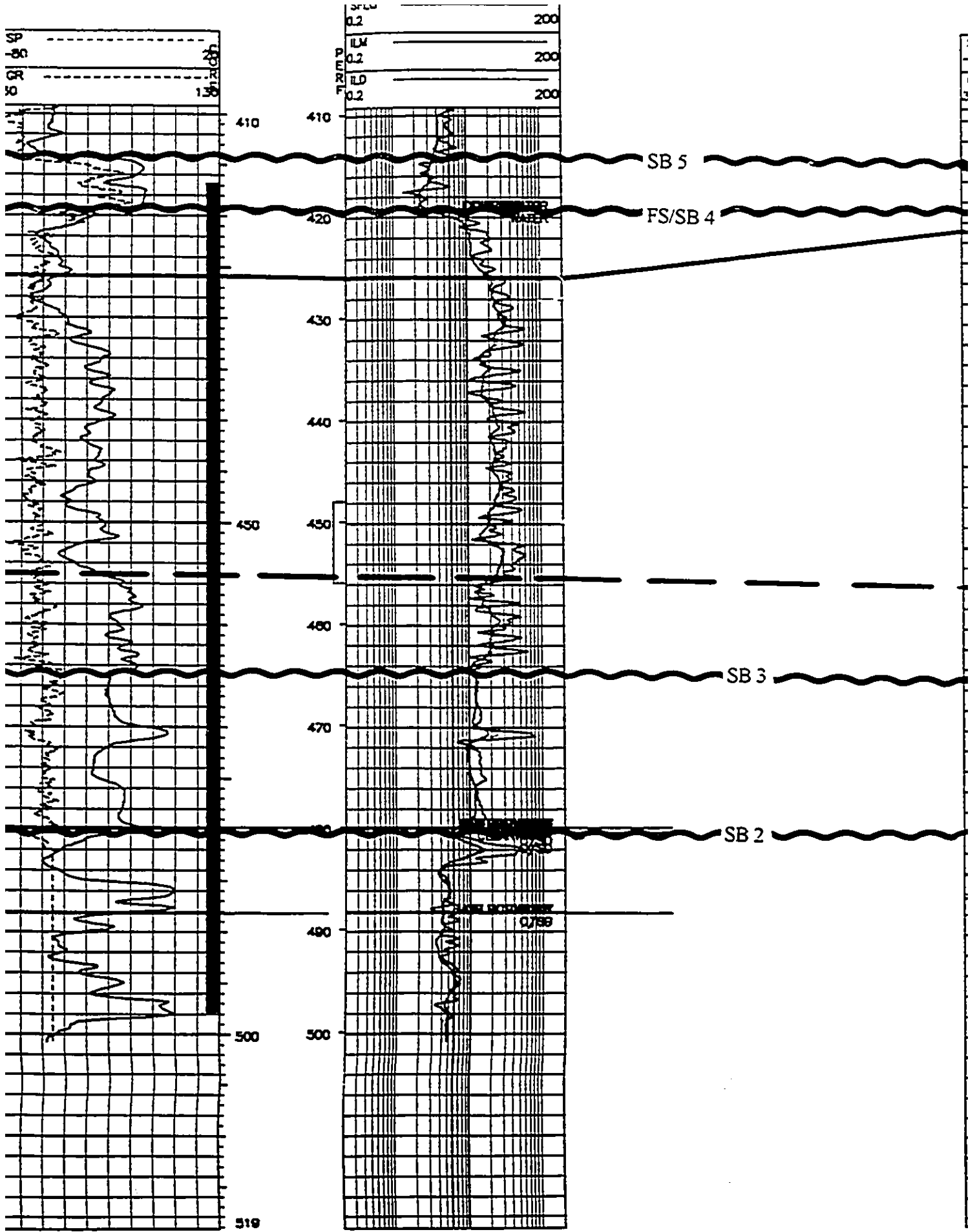
SCALE 1:140000

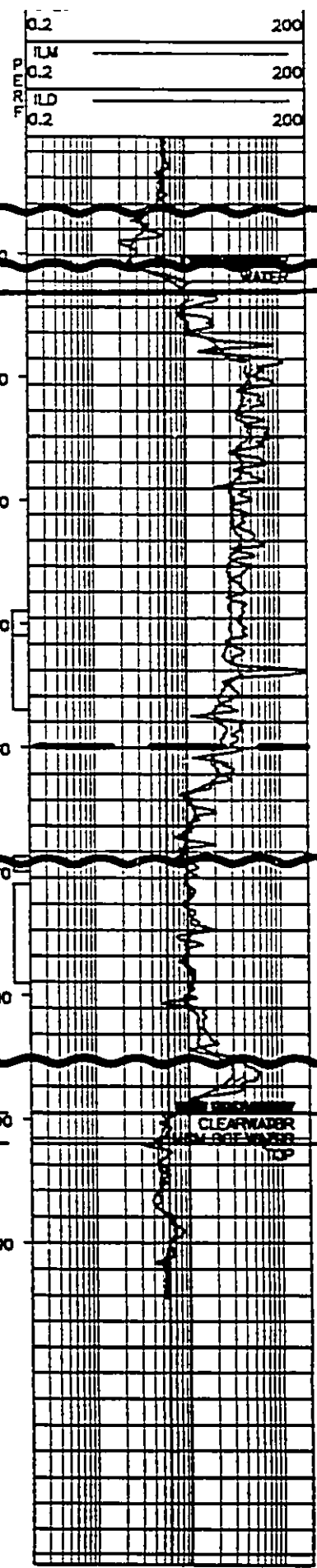
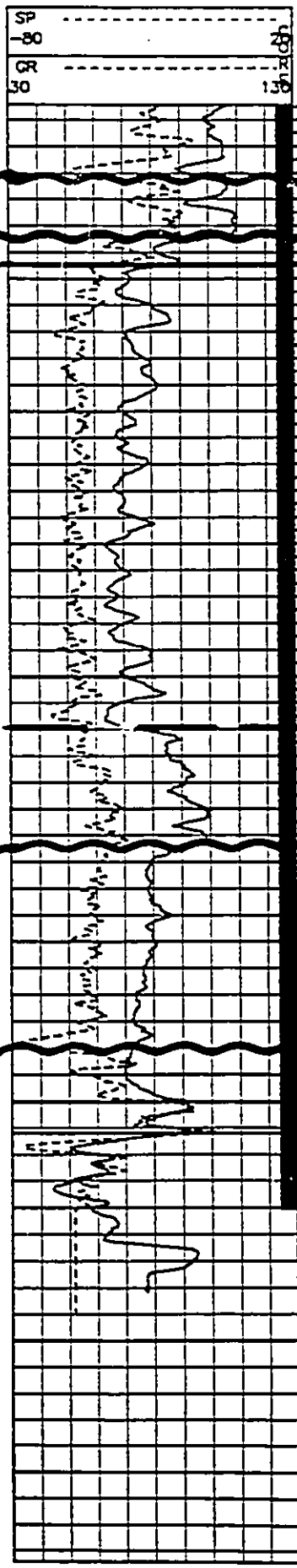
KILOMETRES







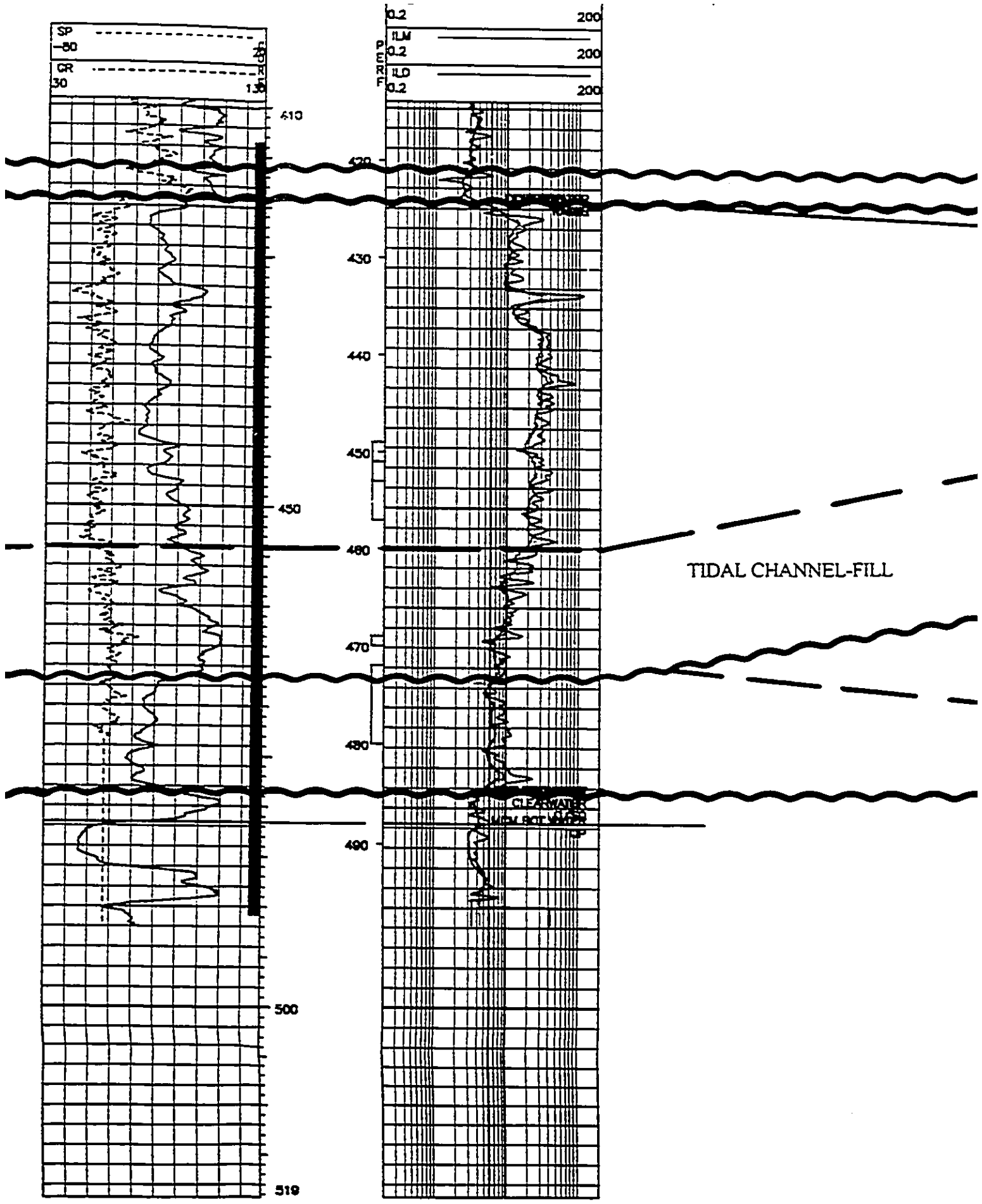


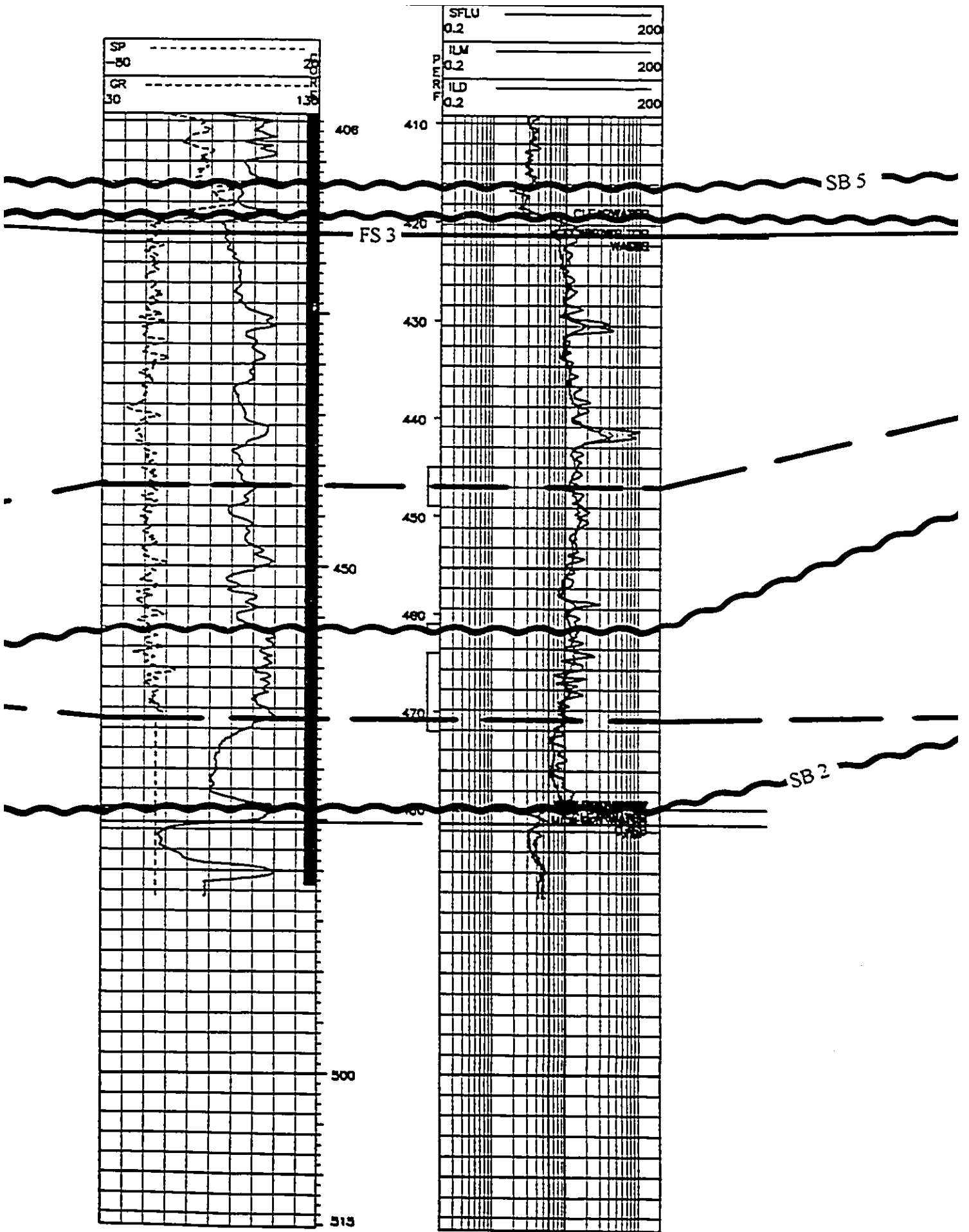


FLUVIAL CHANNEL-FILL

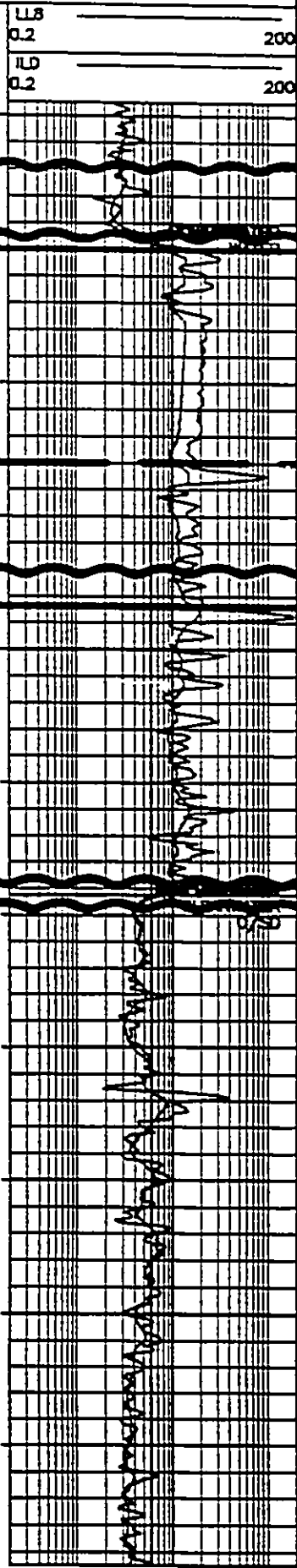
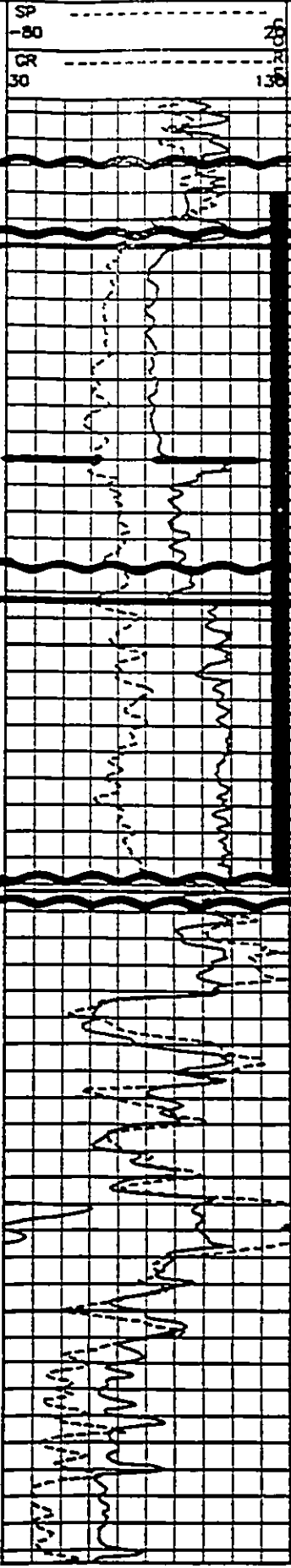
SAND FLAT

CLEARWATER
TOP





SCALE (FEET/INCH) : 40.0 STOP DEPTH(METRES): 519



SB 5

FS 2

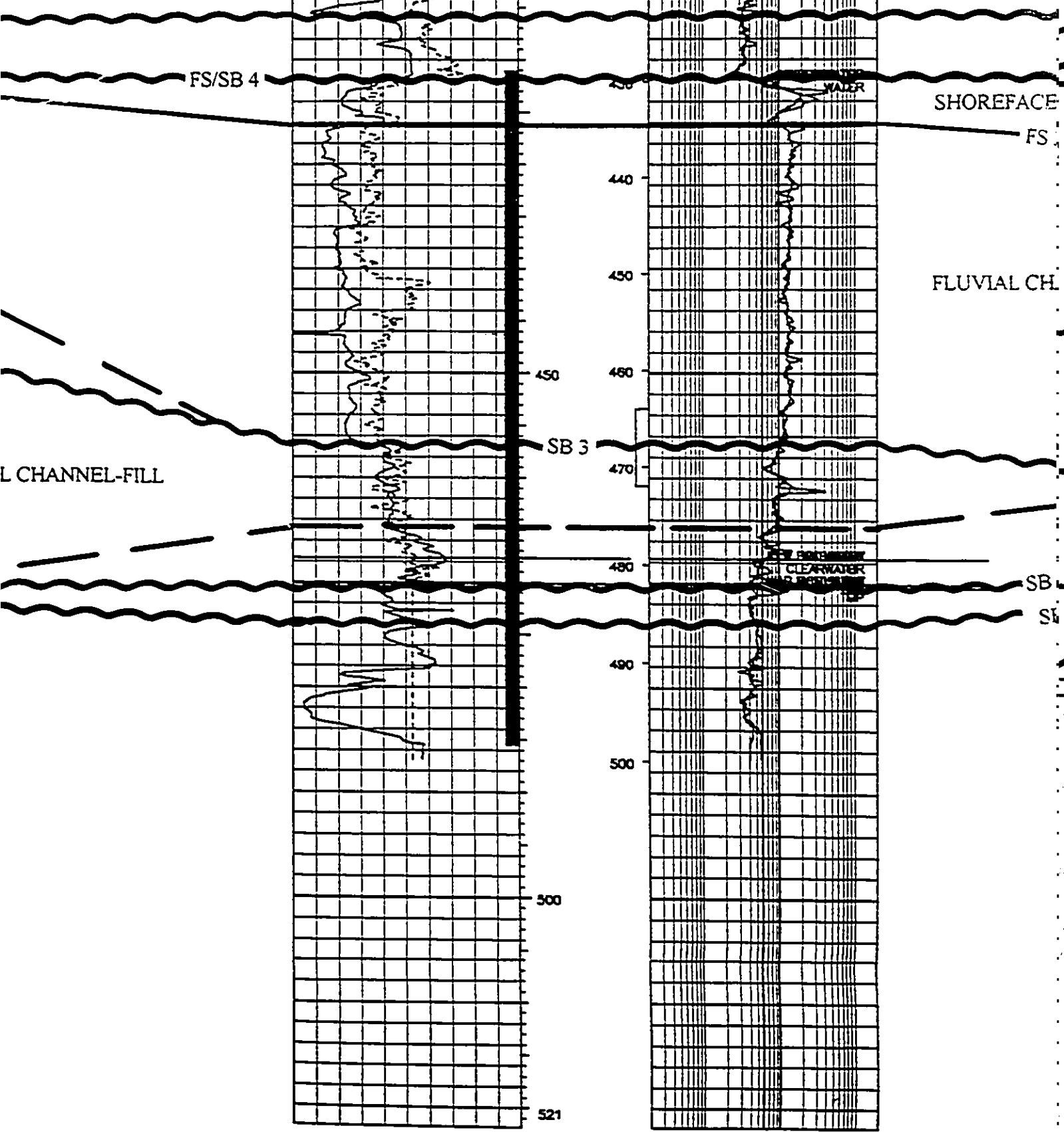
SB 2

TIDAL C

SP
80
GR
30

412
420
430
440
450
460
470
480
490
500
521

SFLU
0.2
200
ILM
0.2
200
ILD
0.2
200



SCALE (METRES/INCH): 12.2
SCALE (FEET/INCH) : 40.0

START DEPTH(METRES): 412
STOP DEPTH(METRES): 522

SP -80
GR 30

LLS 0.2
ILD 0.2

SB 5

GRAND RAPIDS F

OFFSHORE

FS 4

FLUVIAL CHAN

SB 4

SHOREFACE TO

450

FS 2

DAL BAR

CLEARWATER
0.50

McMURRAY FOR

480

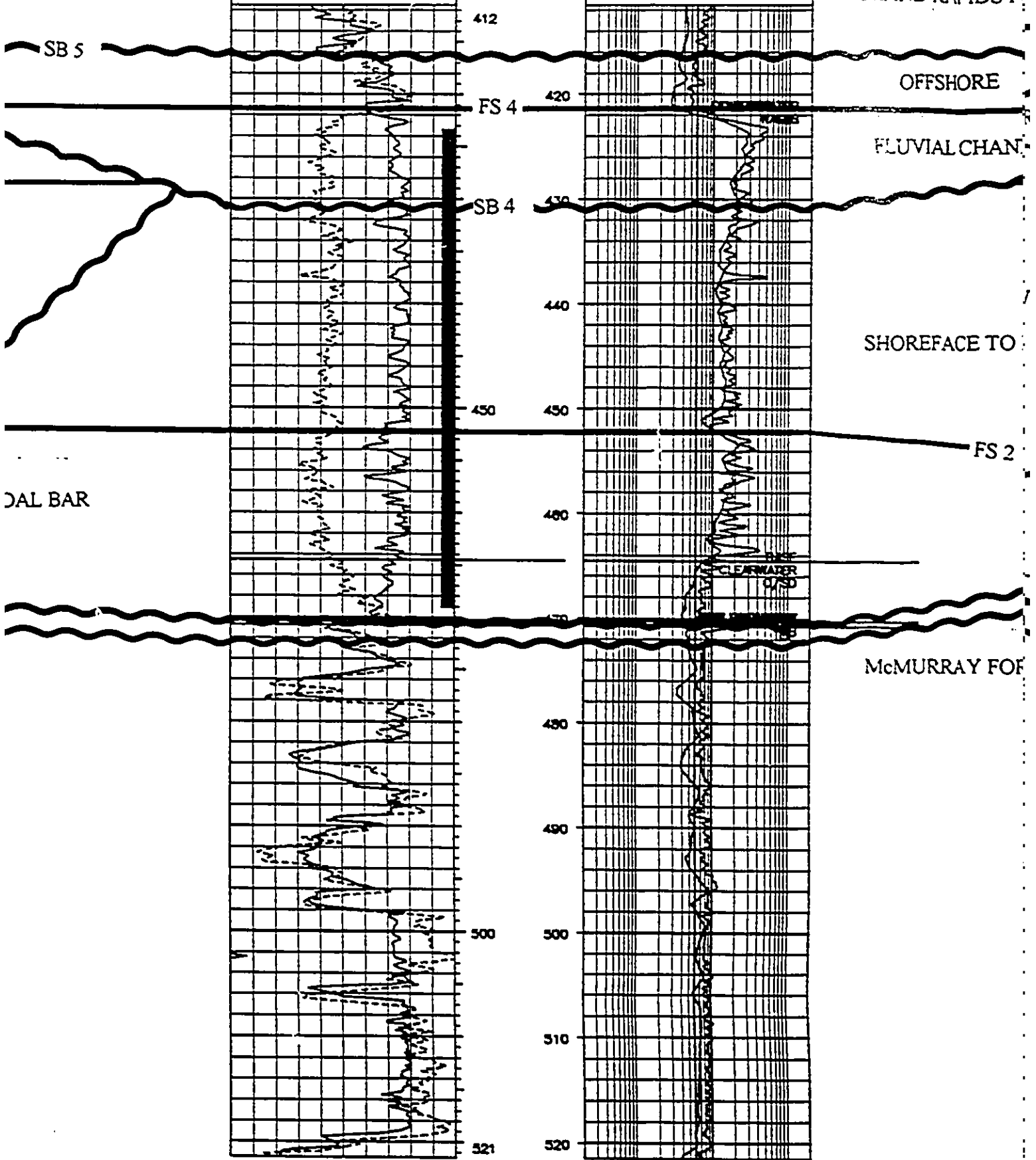
490

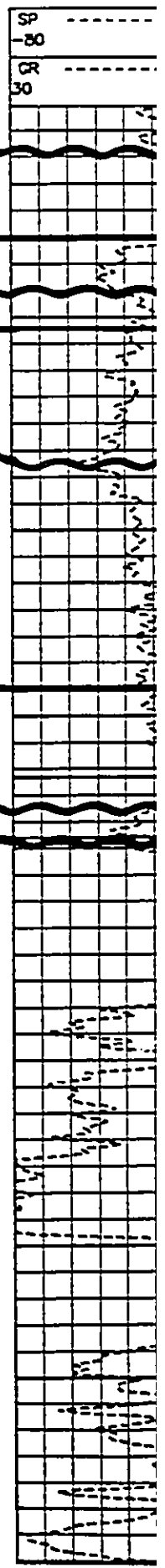
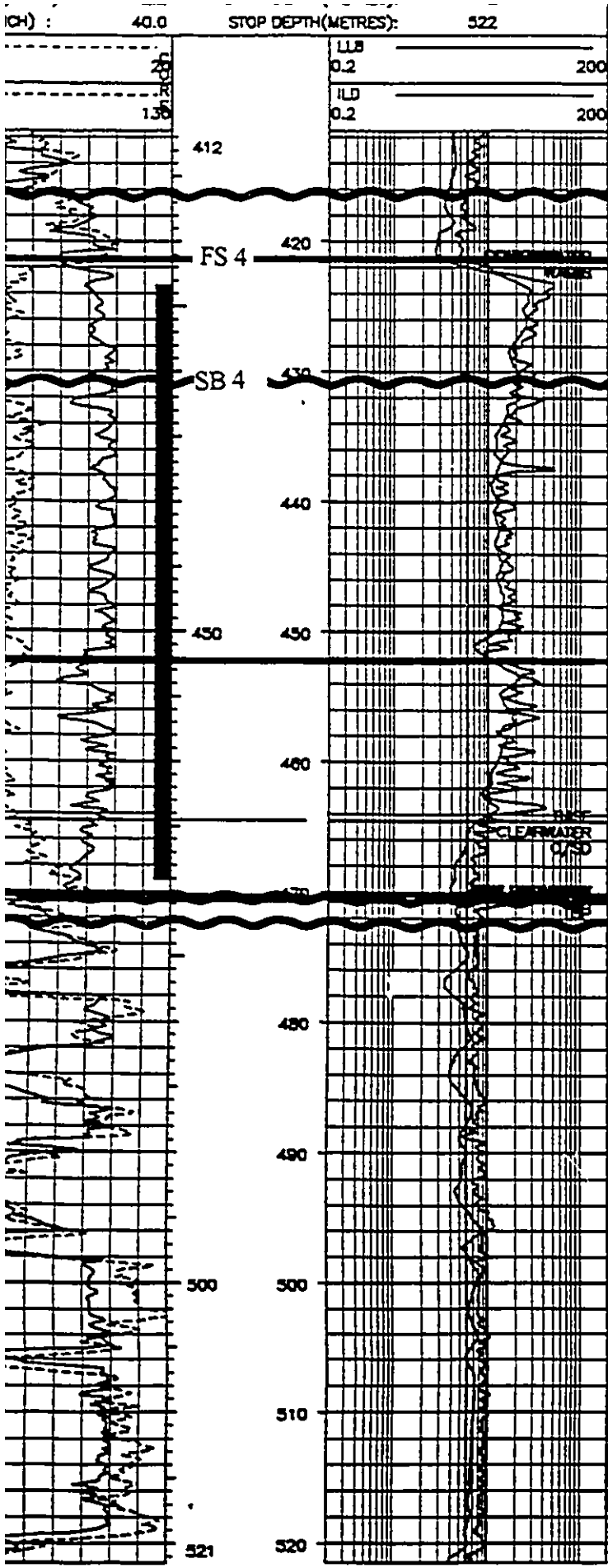
500

510

521

520





GRAND RAPIDS FORMATION

OFFSHORE

FLUVIAL CHANNEL-FILL

SHOREFACE TO FORESHORE

McMURRAY FORMATION

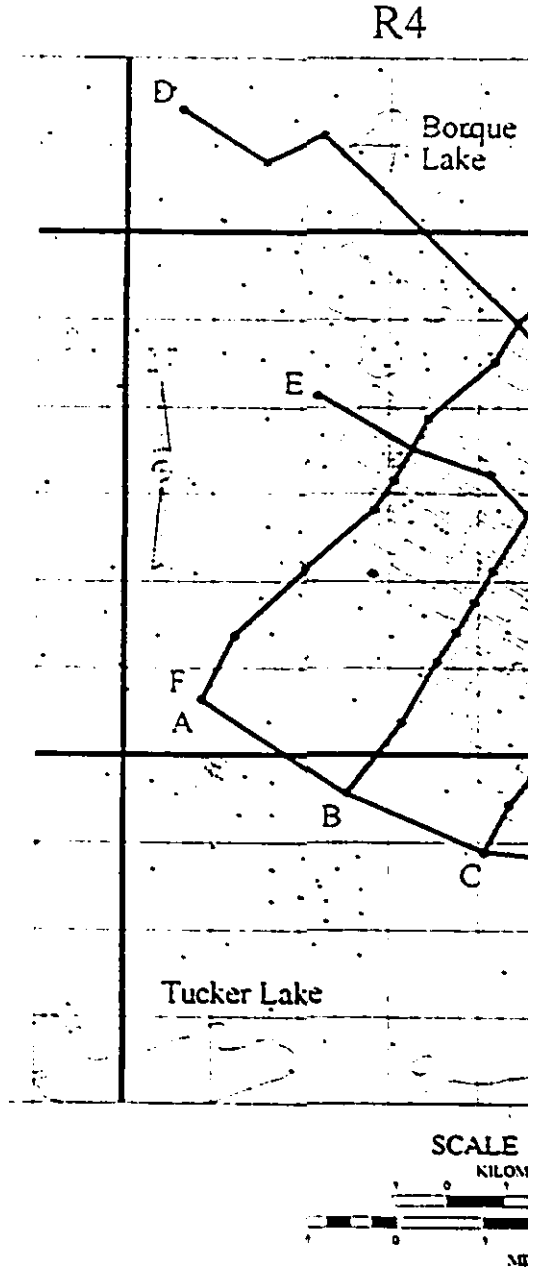
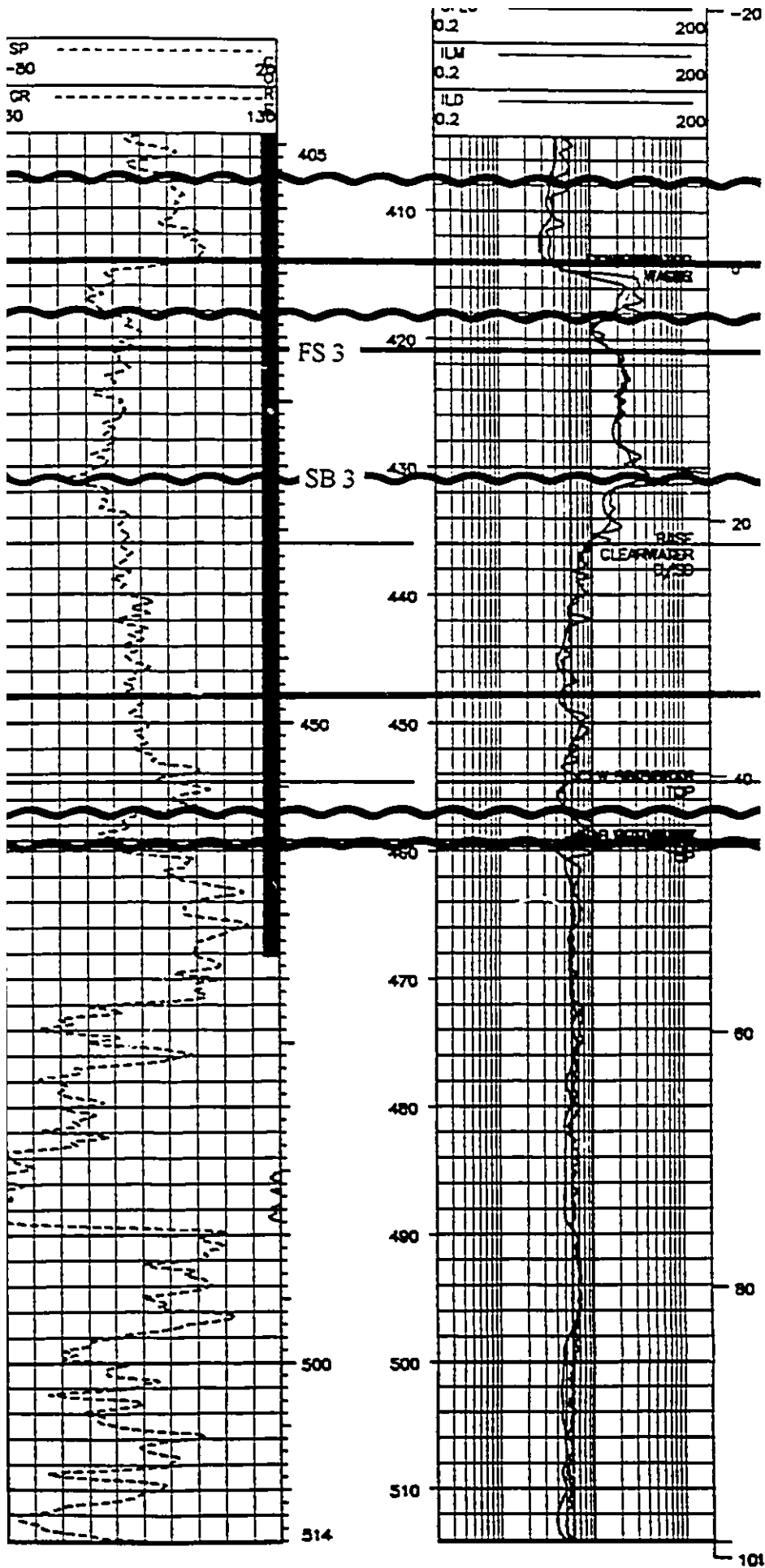
FS 4

SB 4

FS 2

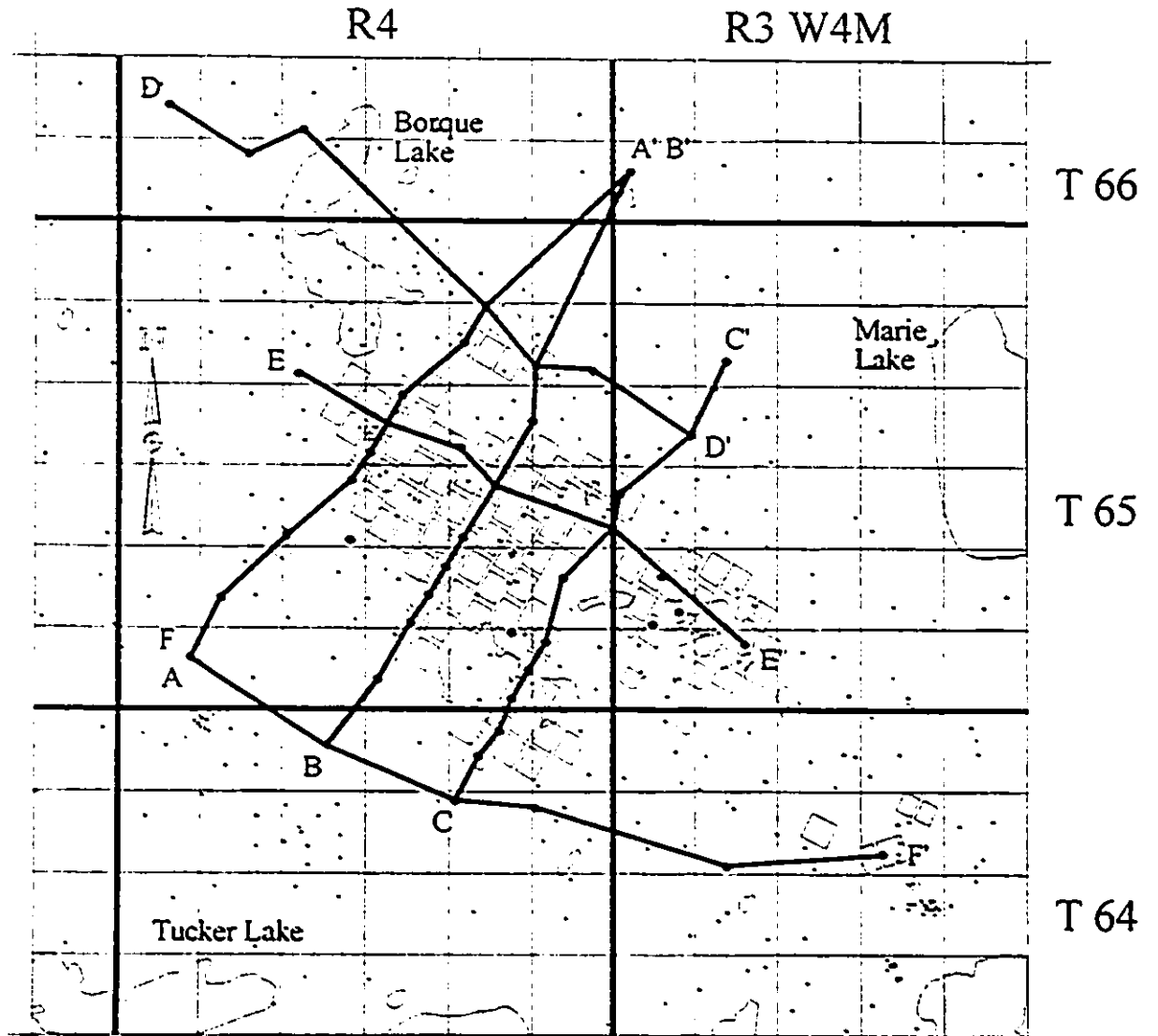
CLEARWATER

WELL LOGS COURTESY IMPERIAL OIL RE
SECTION DRAWN BY G. Glen McCrimmon



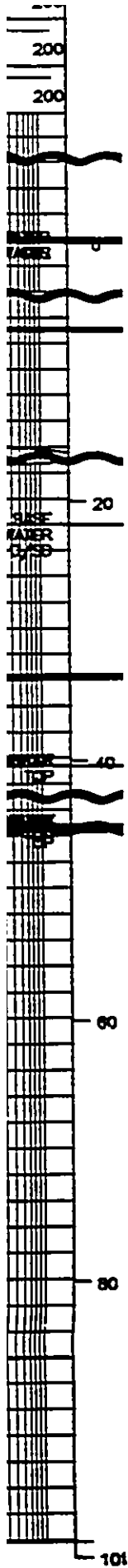
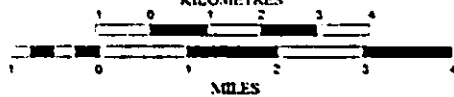
SECTION DRAWN BY: G. Glen McCrimmon

August, 1995



SCALE 1:140000

KILOMETRES

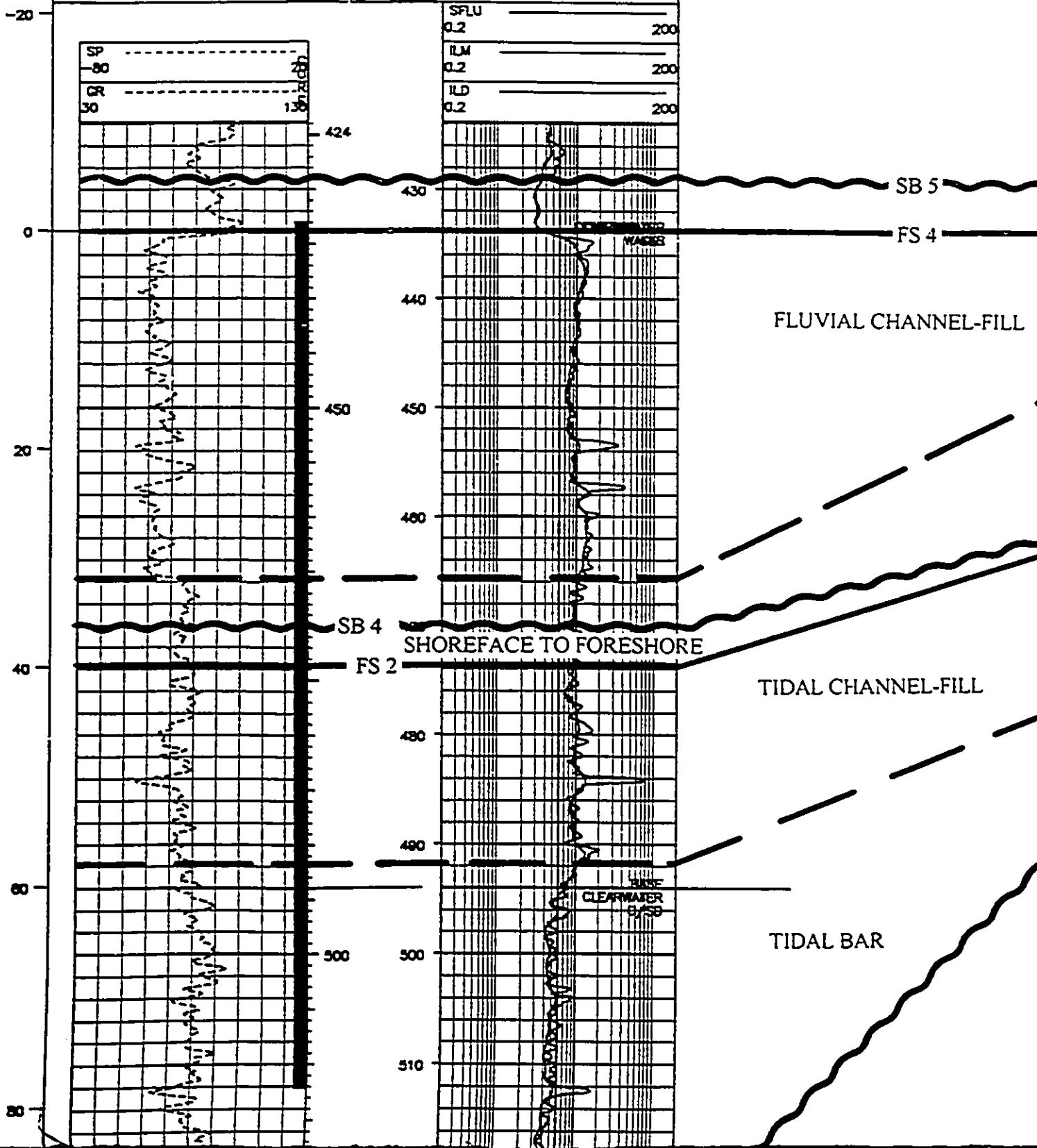


7-7-66-4-AA

AA/07-07-086-04W4

ISSO 85 COLDLK OV 7-7-66-4

ELEVATION:	638	RIG REL. DATE:	03/03/1985
WELL STATUS:	ABAND	START DEPTH(METRES):	424
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	534
SCALE (FEET/INCH) :	40.0		

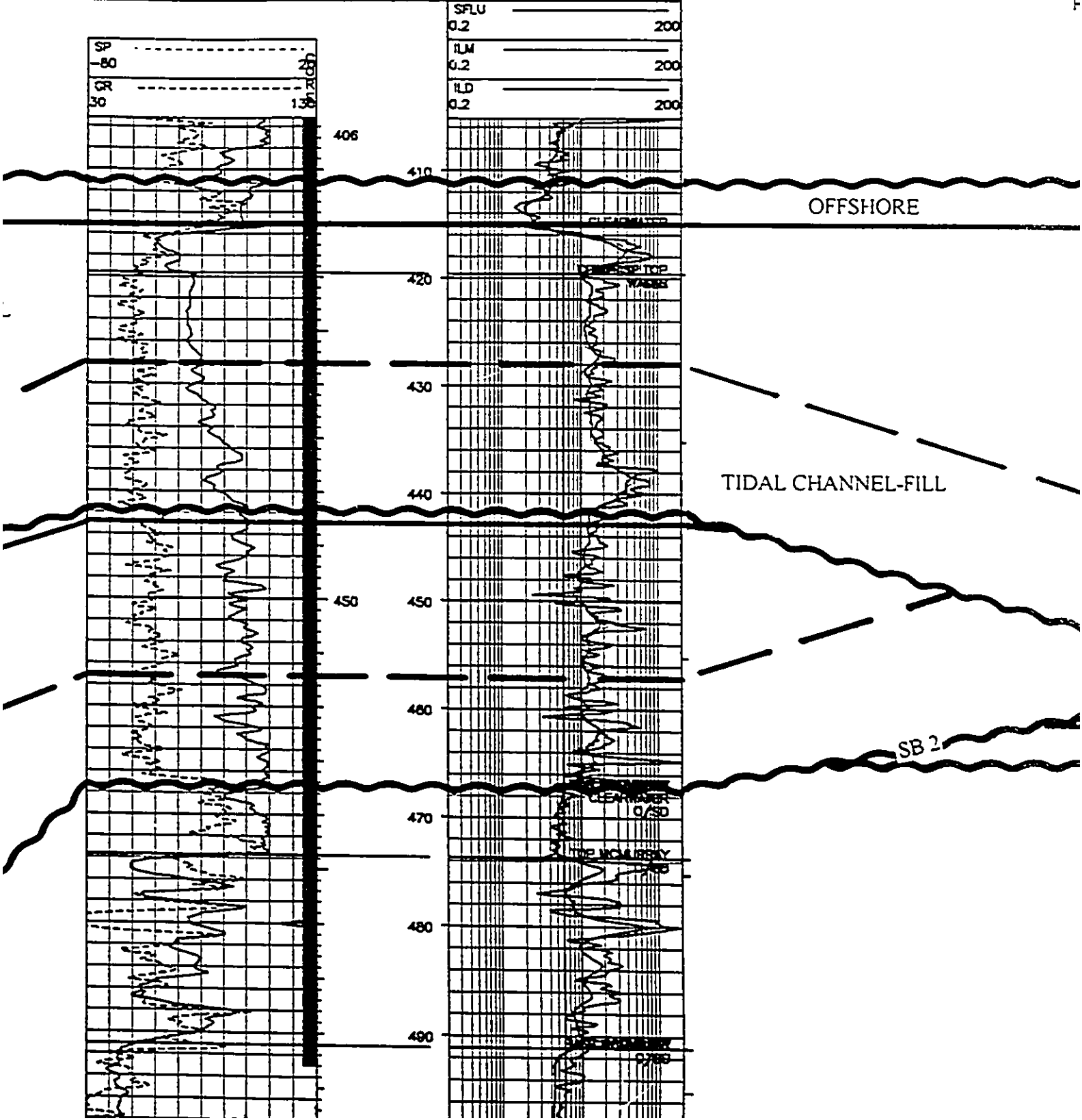


15-5-66-4-AA

AA/15-05-088-04W4

ESSO 88 COLDLX CV 15-5-66-4

ELEVATION:	825	RIG REL. DATE:	08/02/1988
WELL STATUS:	ABAND	START DEPTH(METRES):	405
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	515
SCALE (FEET/INCH) :	40.0		

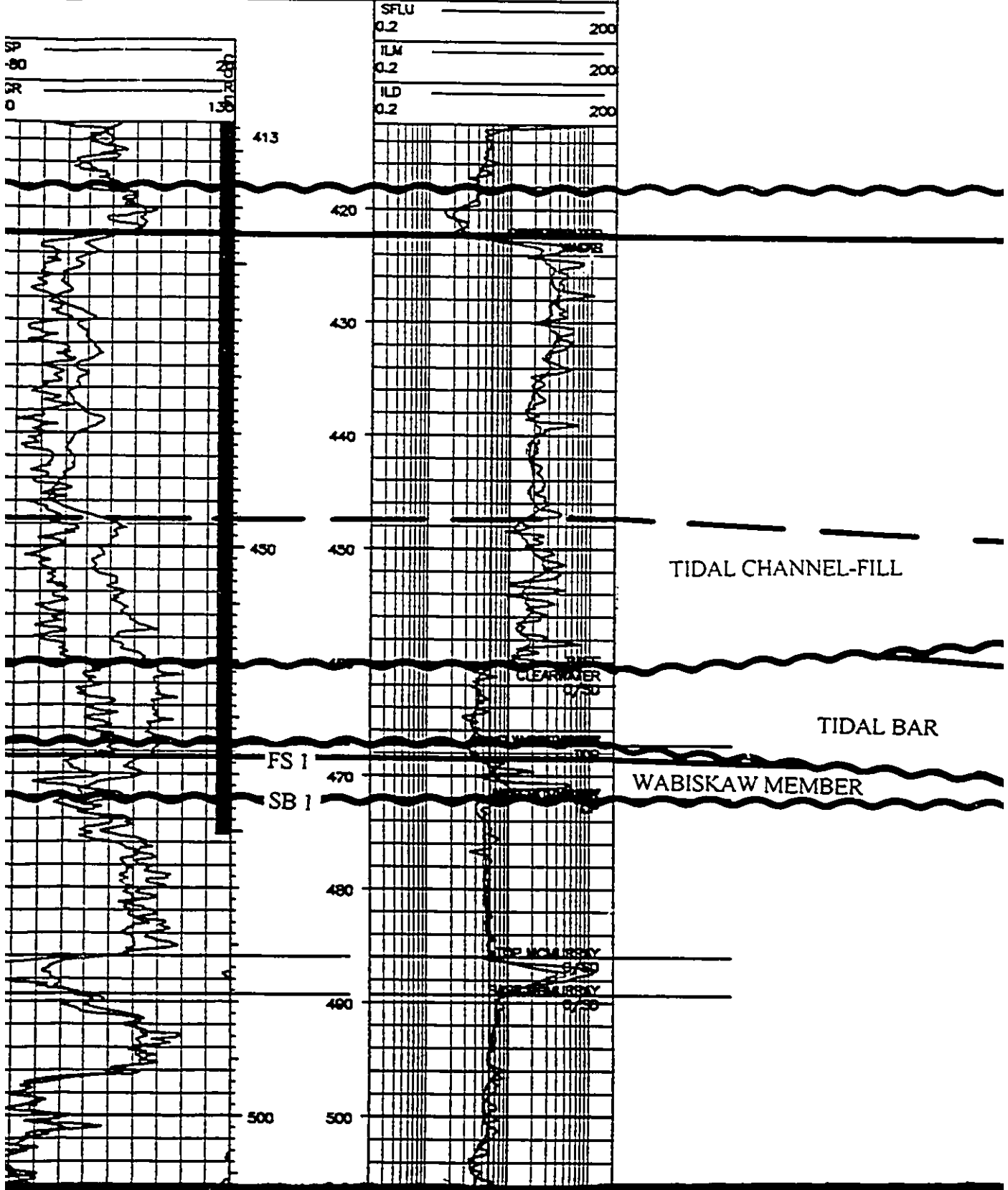


3-9-66-4-AA

AA/03-09-088-0474

ESSO 88 COLDLK CV 3-9-66-4

ELEVATION:	625	ROG REL. DATE:	15/02/1988
WELL STATUS:	ABAND	START DEPTH(METRES):	413
WELL DIA (METRES/INCH):	12.2	STOP DEPTH(METRES):	523
WELL DIA (FEET/INCH) :	40.0		

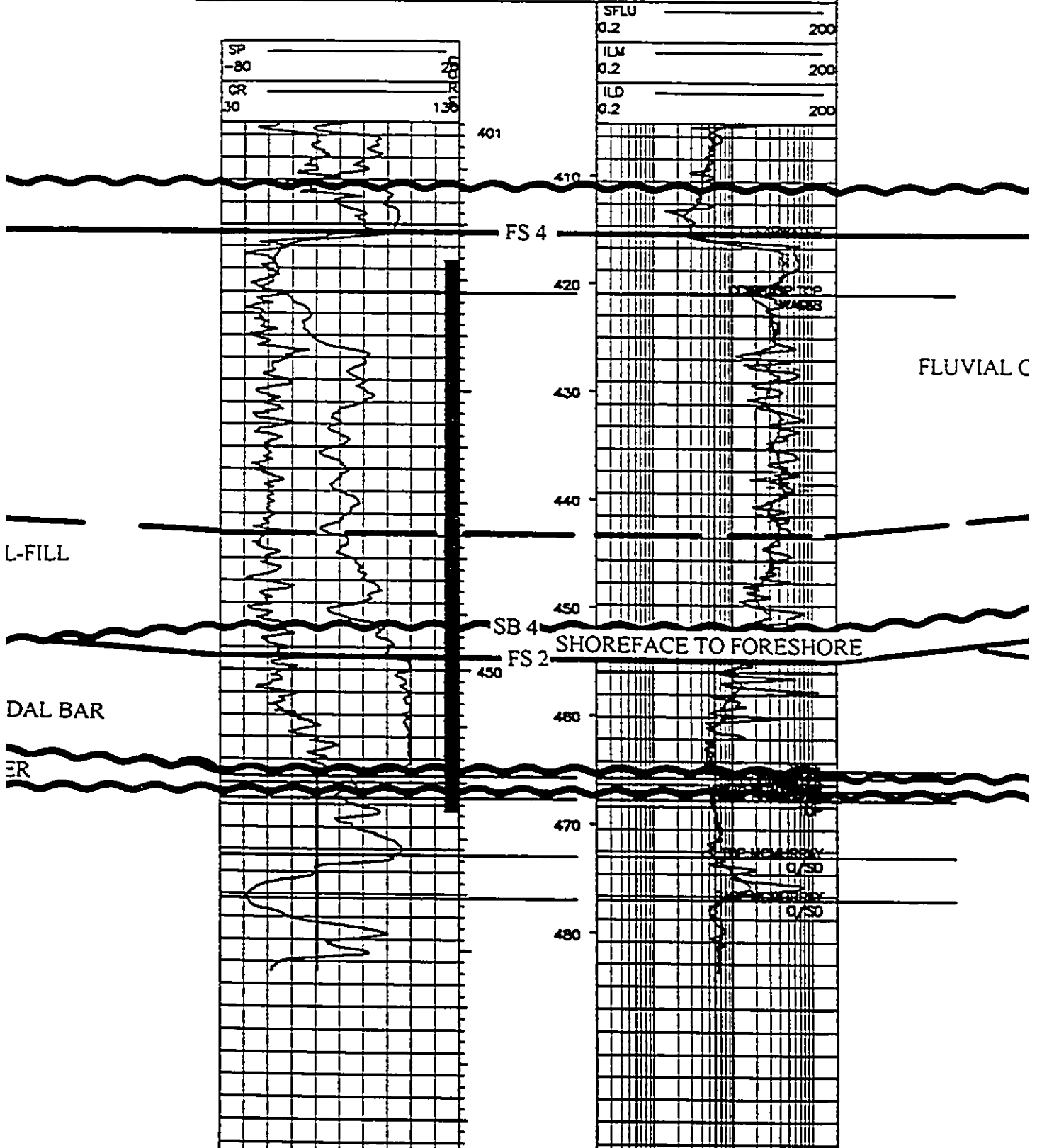


M05-08

00/14-26-085-04W4

ESSO 88 M5-8 COLDLK 14-26-85-4

ELEVATION:	617	R/C REL DATE:	07/02/1988
WELL STATUS:	STNDC	START DEPTH(METRES):	401
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	511
SCALE (FEET/INCH) :	40.0		

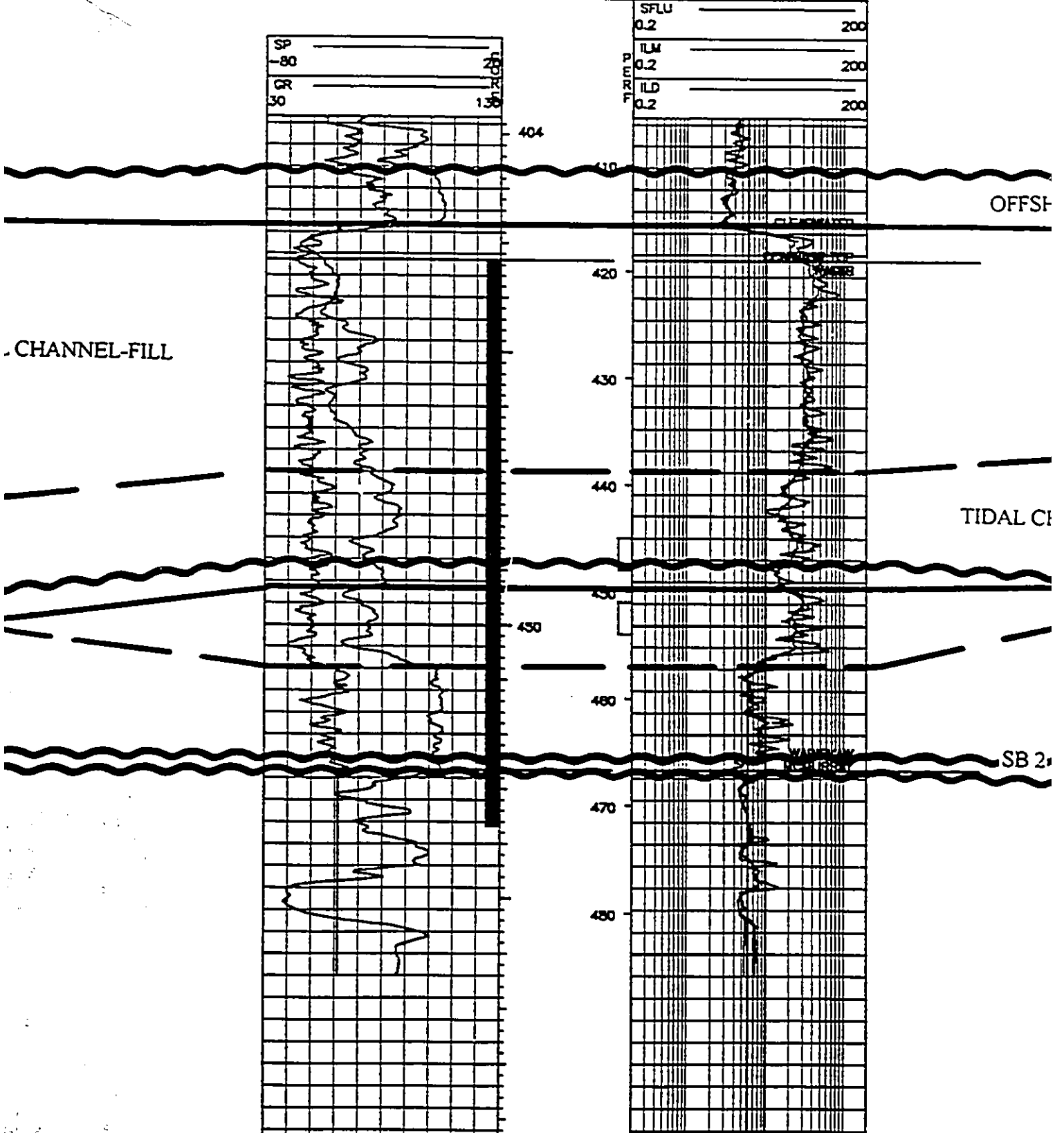


P03-13

00/04-25-085-04W4

ESSO 88 P3-13 COLDLK 4-25-85-4

ELEVATION:	815	RIG REL. DATE:	21/01/1988
WELL STATUS:	CYCLICAL	START DEPTH(METRES):	403
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	513
SCALE (FEET/INCH) :	40.0		

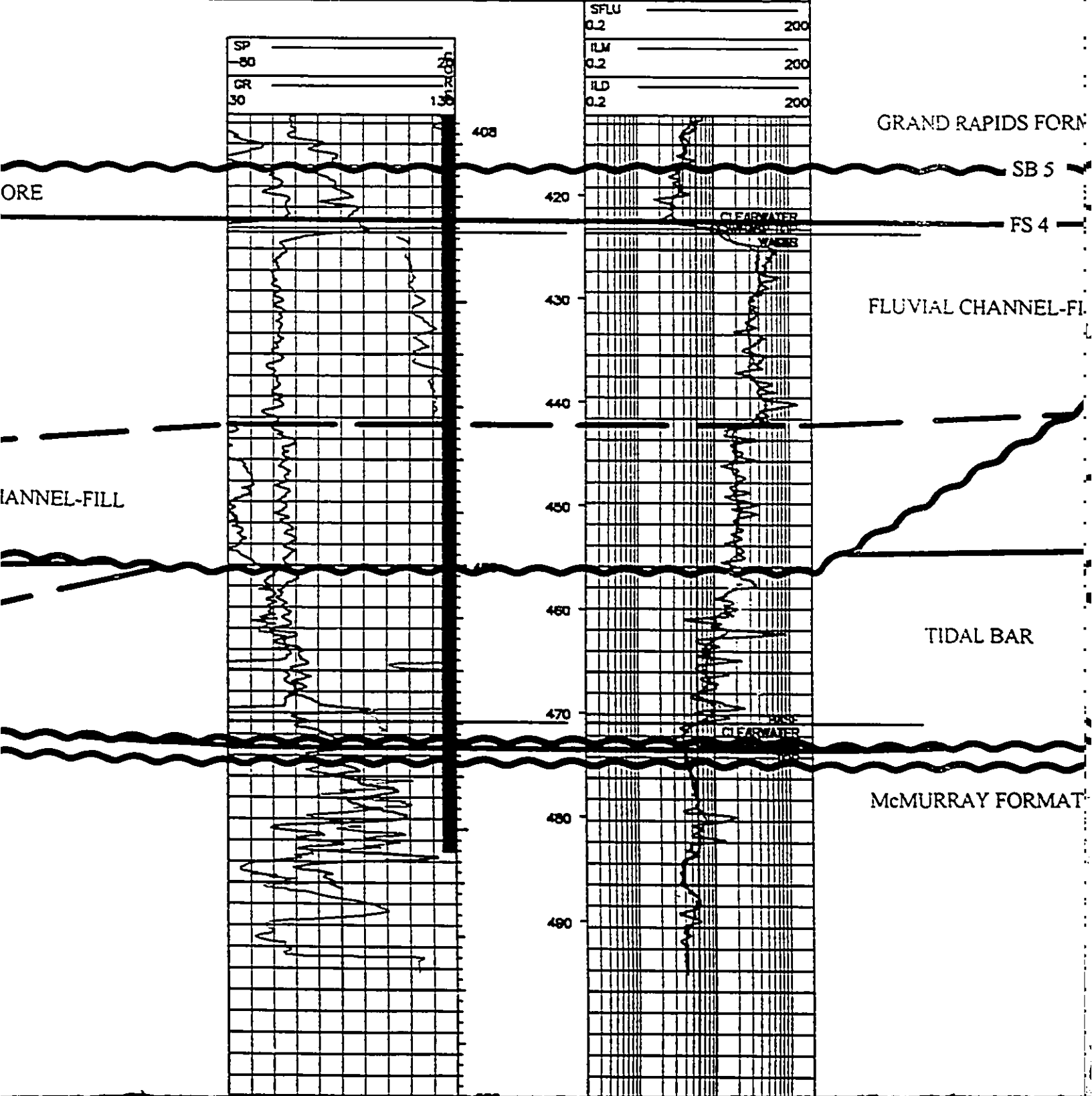


P07-13

00/02-25-065-04W4

ESSO 88 P7-13 COLDLK 2-25-85-4

ELEVATION:	515	RIG REL. DATE:	03/07/1988
WELL STATUS:	STNDC	START DEPTH(METRES):	407
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	517
SCALE (FEET/INCH) :	40.0		

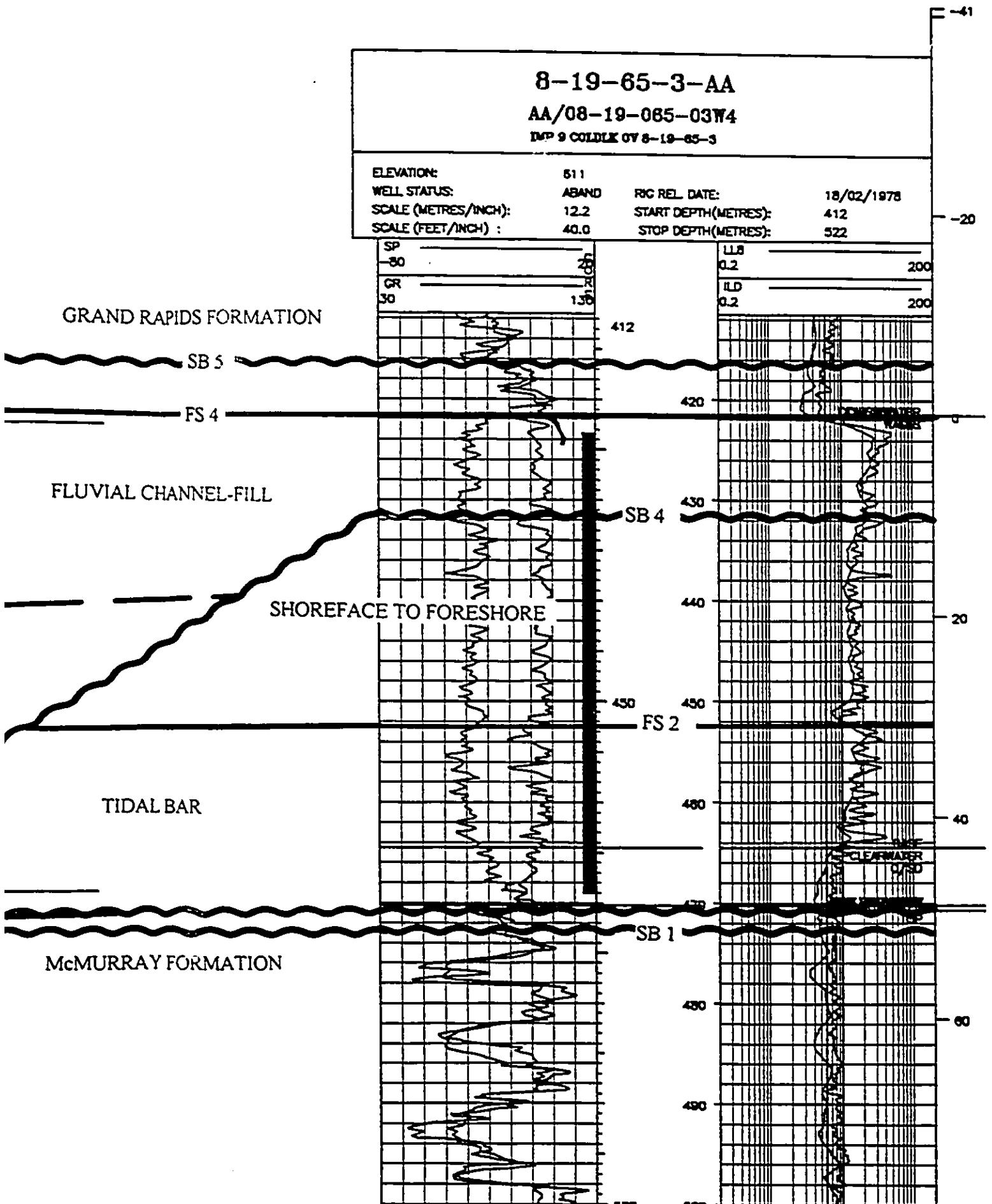


8-19-65-3-AA

AA/08-19-085-03W4

IMP 9 COLDLK OV 8-19-65-3

ELEVATION:	511	RIG REL. DATE:	18/02/1978
WELL STATUS:	ABAND	START DEPTH(METRES):	412
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	522
SCALE (FEET/INCH) :	40.0		

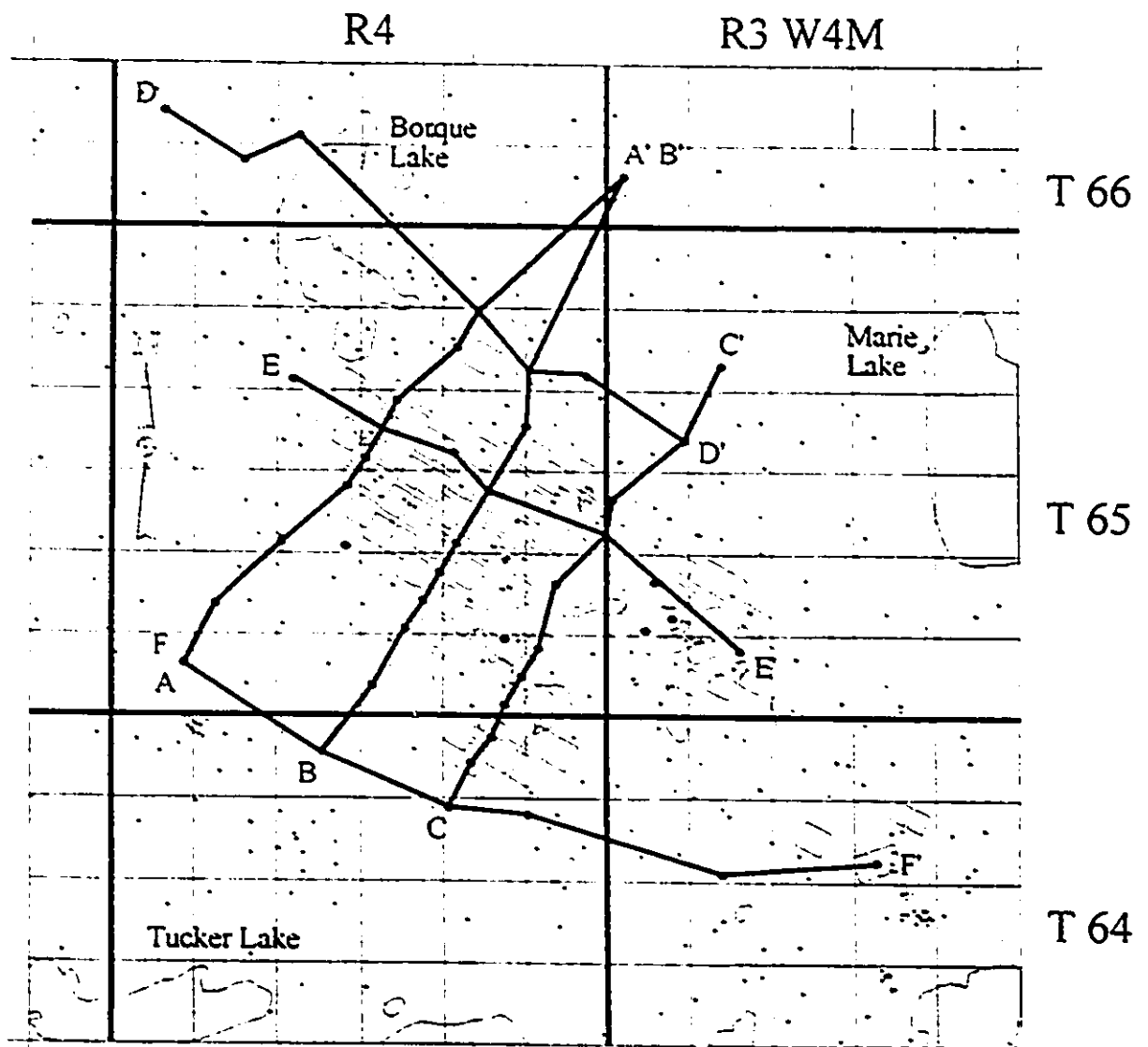
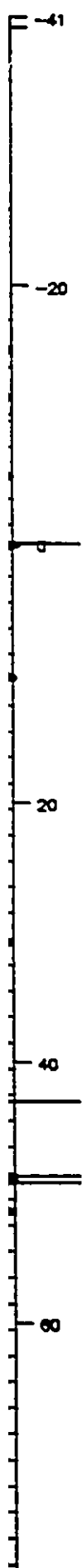


STRATIGRAPHIC CROSS-SECTION D-D'

VERTICAL SCALE: 1:480
HORIZONTAL SCALE: NOT TO SCALE
DATUM: FLOODING SURFACE 4 (FS 4)

WELL LOGS COURTESY IMPERIAL OIL RESOURCES LIMITED, CALGARY

SECTION DRAWN BY: G. Glen McCrimmon August, 1995



SCALE 1:140000
KILOMETRES



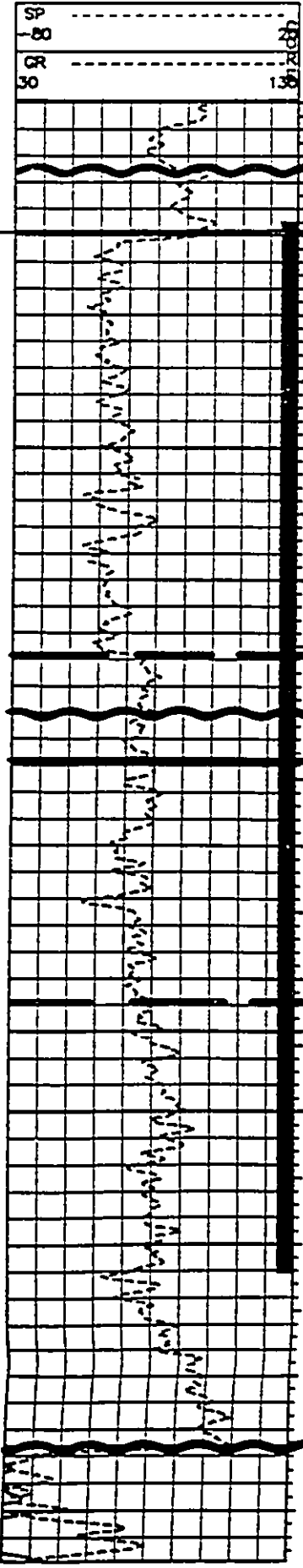
SCALE (FEET/INCH) :

40.0

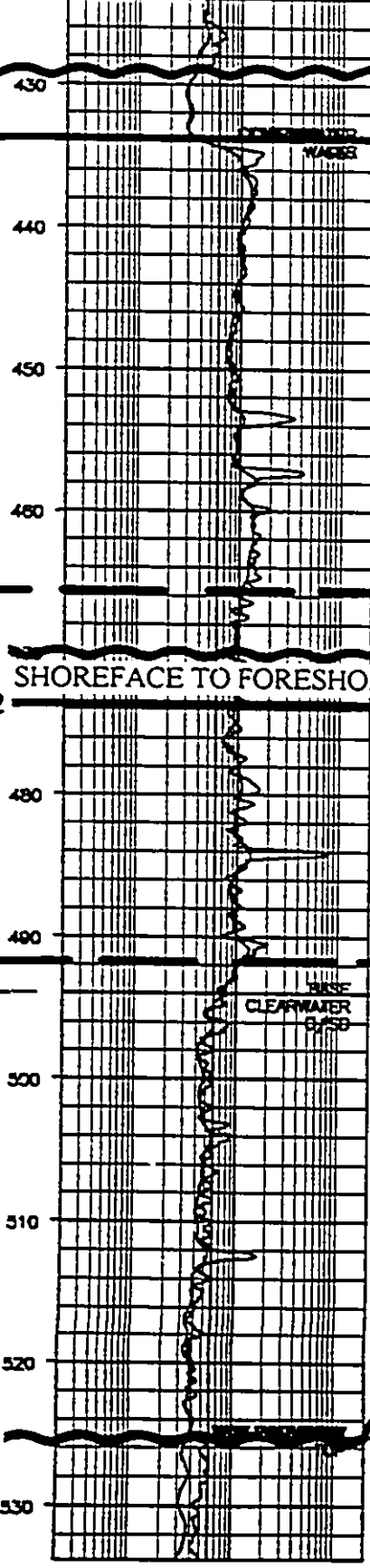
STOP DEPTH (METRES):

534

-20
0
20
40
60
80
101



SFLU	0.2	200
ILM	0.2	200
ILD	0.2	200



SB 5
FS 4

FLUVIAL CHANNEL-FILL

SB 4
SHOREFACE TO FORESHORE
FS 2

TIDAL CHANNEL-FILL

BASE
CLEARWATER
9/59

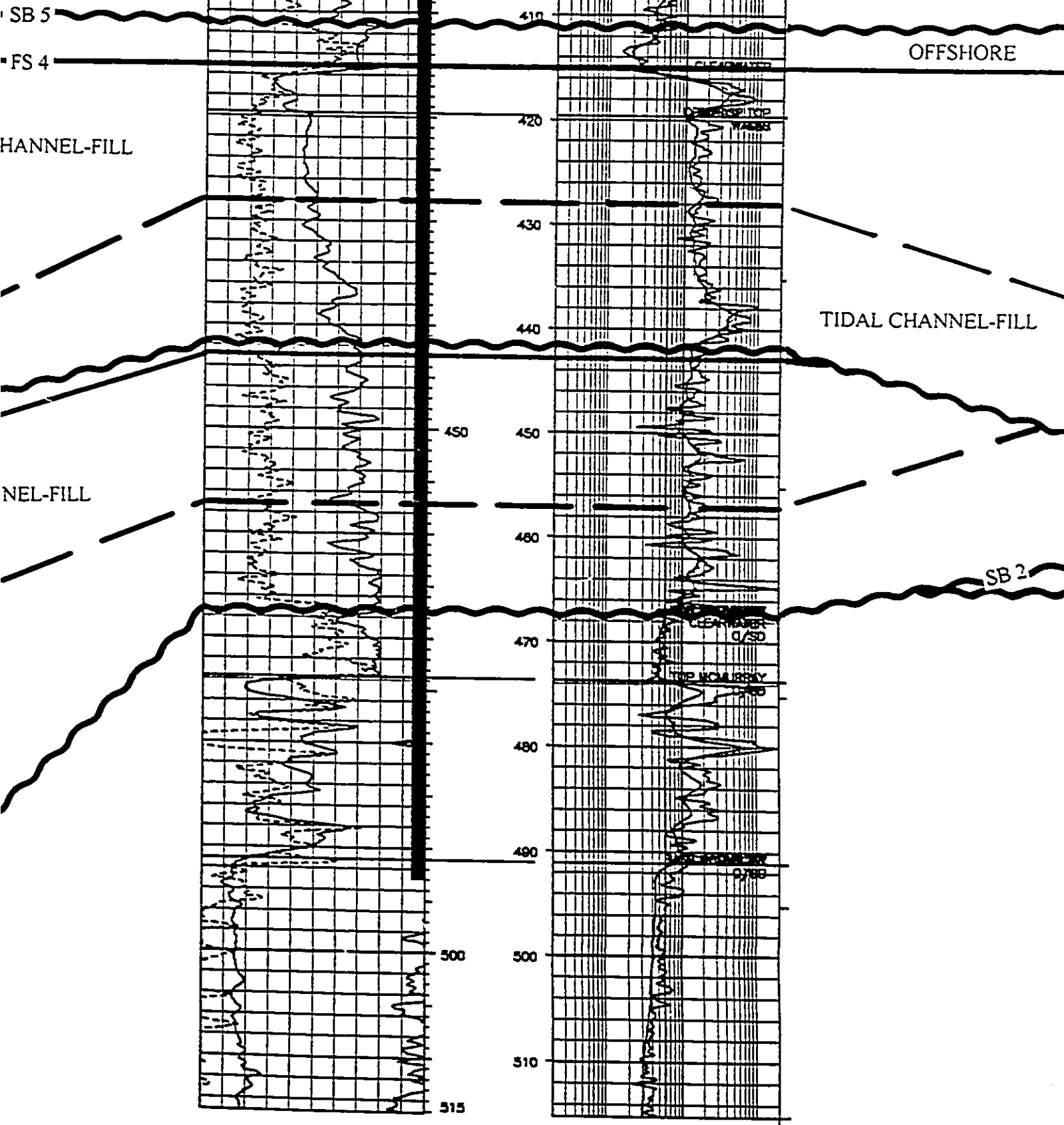
TIDAL BAR

SB 2

SCALE (FEET/INCH) : 40.0 STOP DEPTH (METRES): 515

SP
-80
GR
30
1.5

SFLU
0.2
200
ILM
0.2
200
ILD
0.2
200

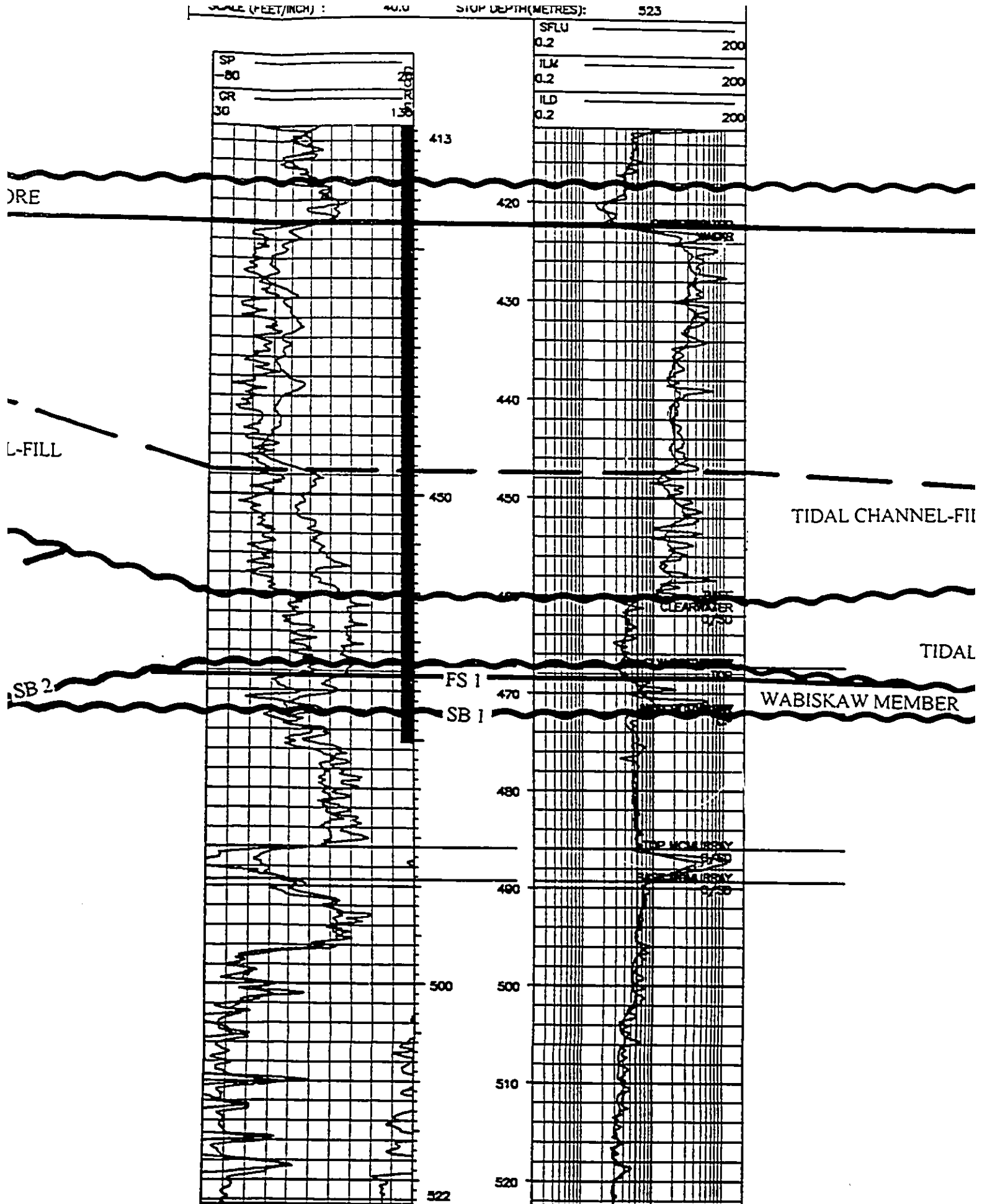


SCALE (FEET/INCH) :

40.0

STOP DEPTH(METRES):

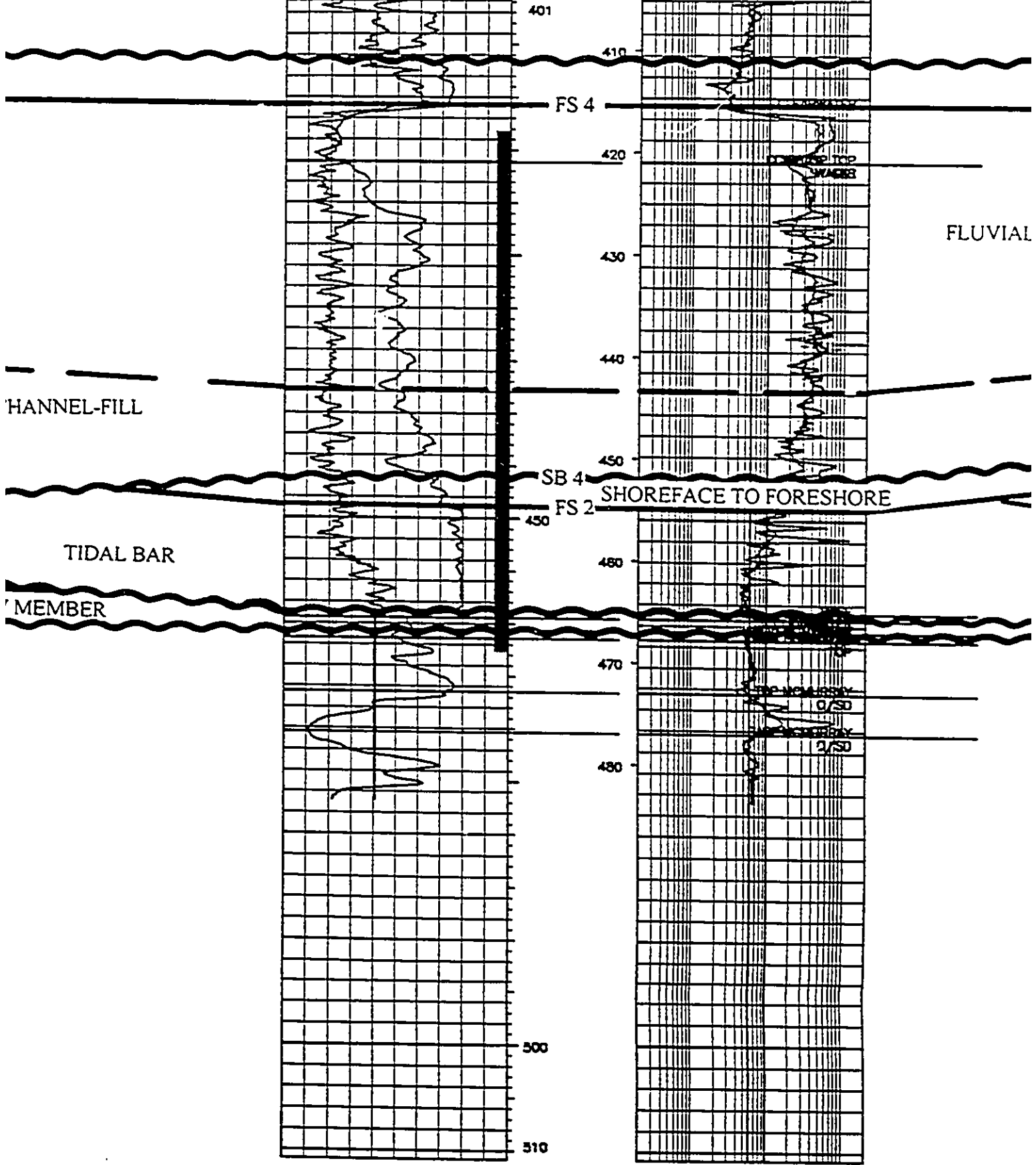
523



SCALE (FEET/INCH) : 40.0 STOP DEPTH(METRES): 511

SP
-80
GR
30

SFLU
0.2
200
ILM
0.2
200
ILD
0.2
200



SCALE (FEET/INCH) :

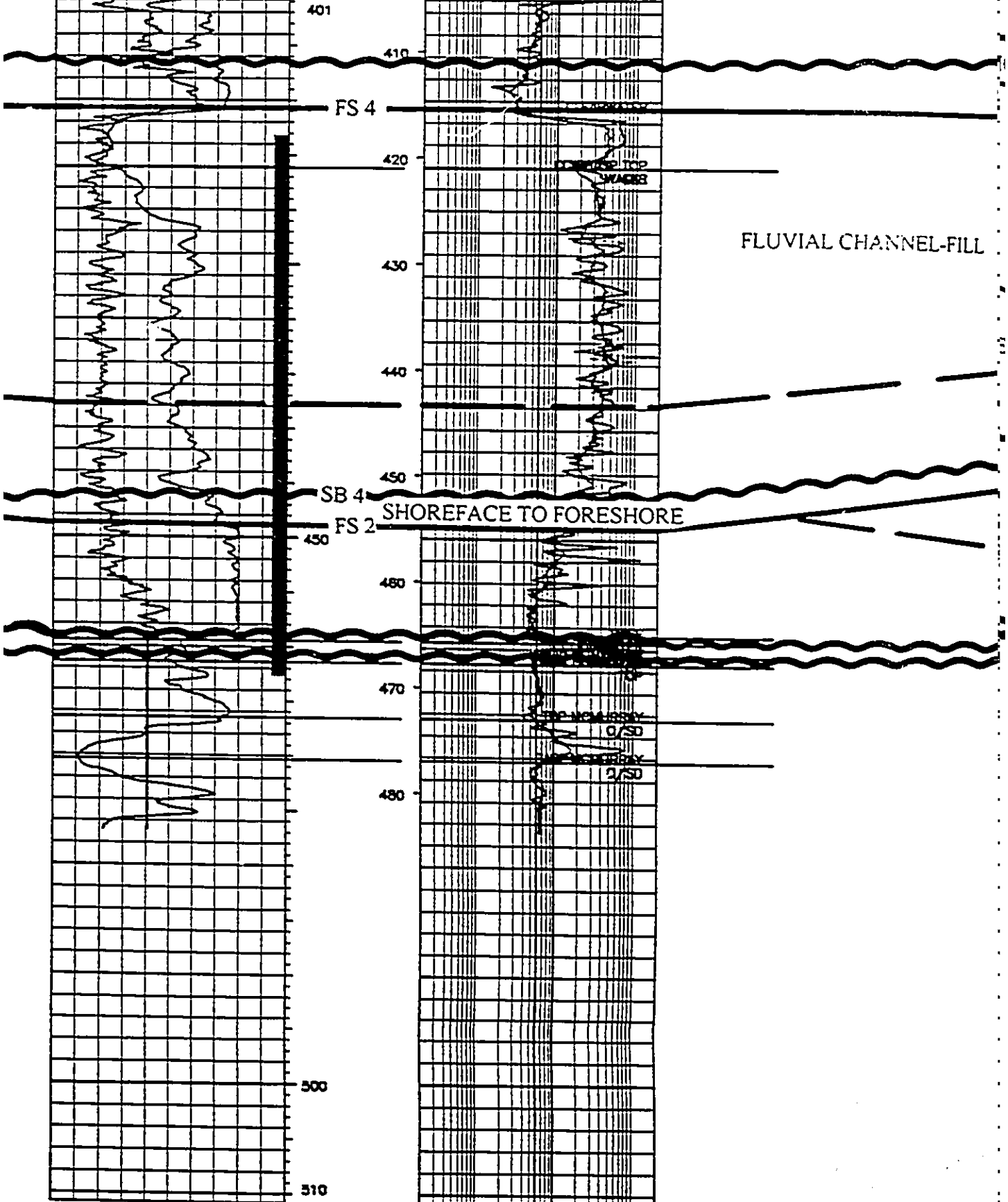
40.0

STOP DEPTH (METRES):

311

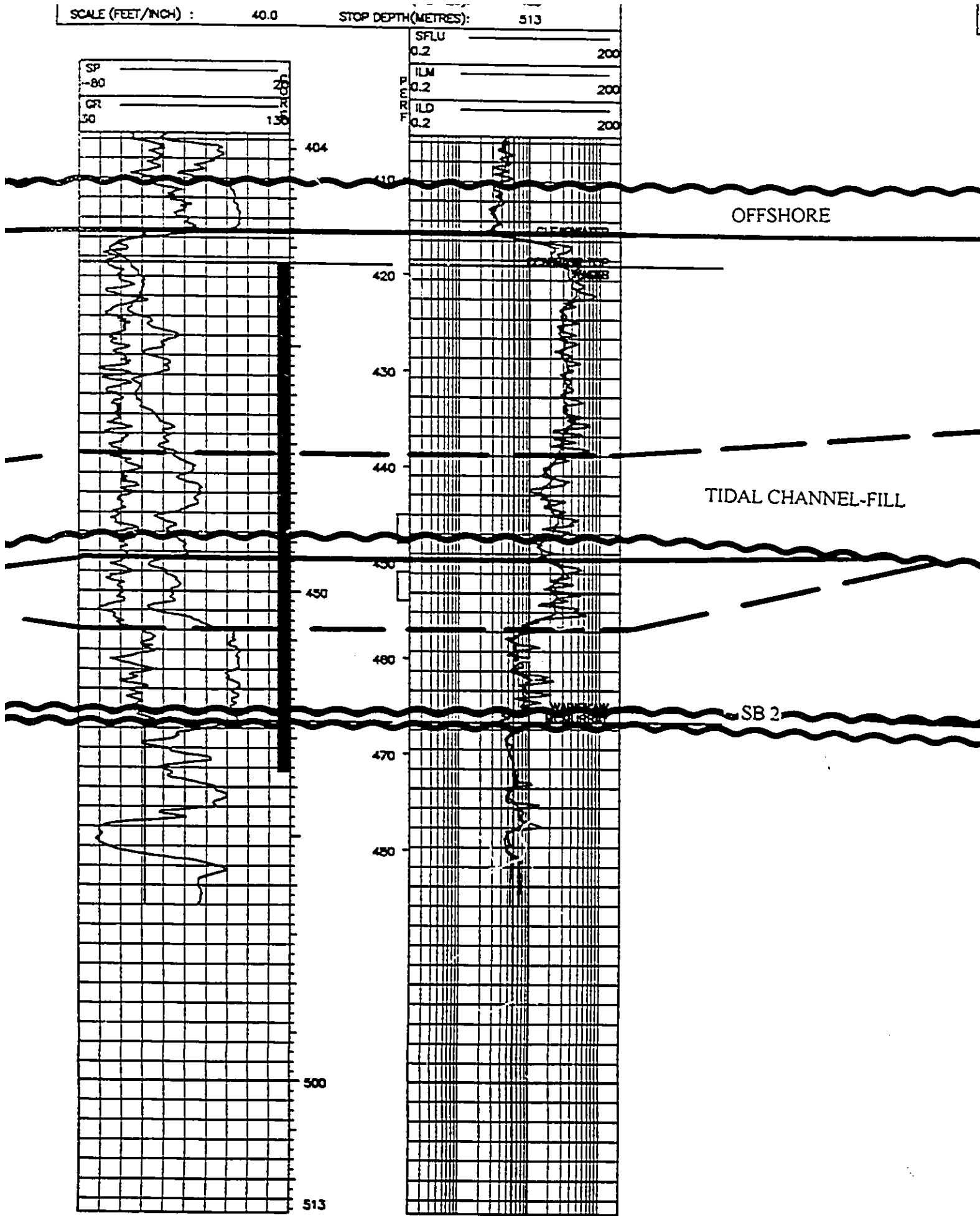
SP _____
 -80 _____
 GR _____
 30 _____

SFLU _____
 0.2 _____ 200
 ILM _____
 0.2 _____ 200
 ILD _____
 0.2 _____ 200



SCALE (FEET/INCH) : 40.0

STOP DEPTH (METRES): 513



SCALE (METRES/INCH): 1:2.2

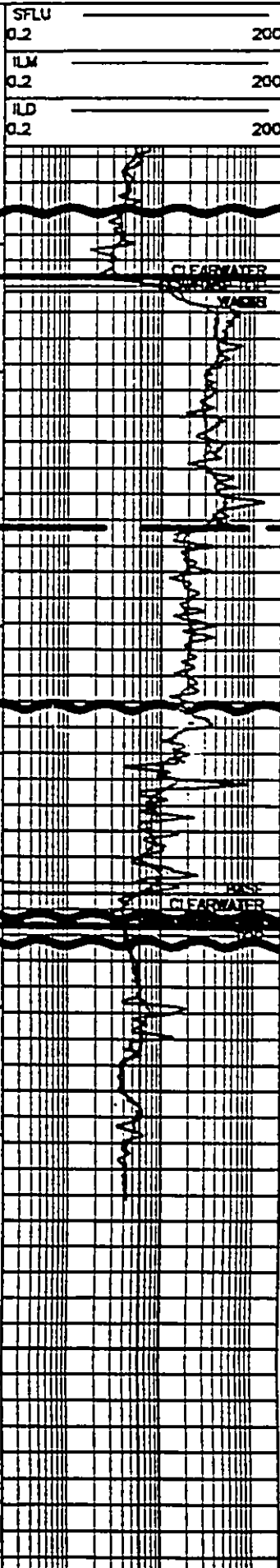
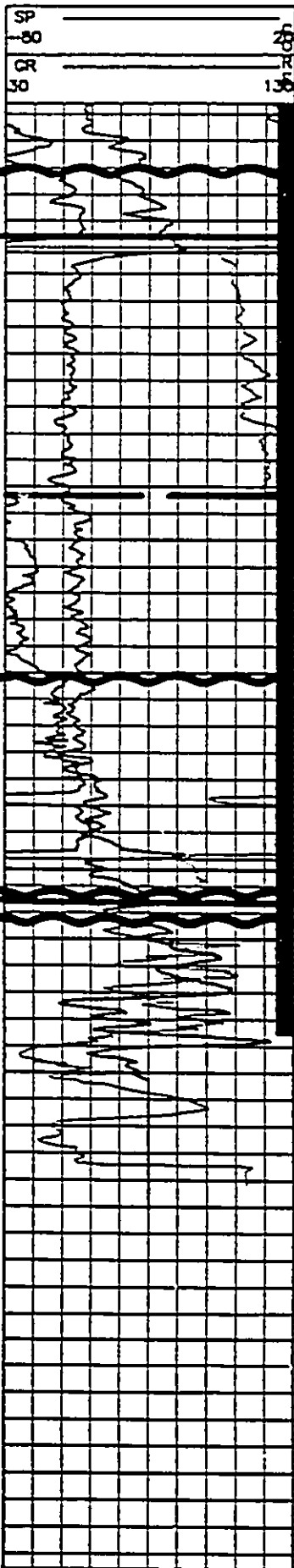
START DEPTH (METRES): 407

STOP DEPTH (METRES): 517

SCALE (FEET/INCH): 40.0

START DEPTH (METRES): 407

STOP DEPTH (METRES): 517



GRAND RAPIDS FORMATION

SB 5

FS 4

FLUVIAL CHANNEL-FILL

SHOR

TIDAL BAR

McMURRAY FORMATION

400

420

430

440

450

460

470

480

490

500

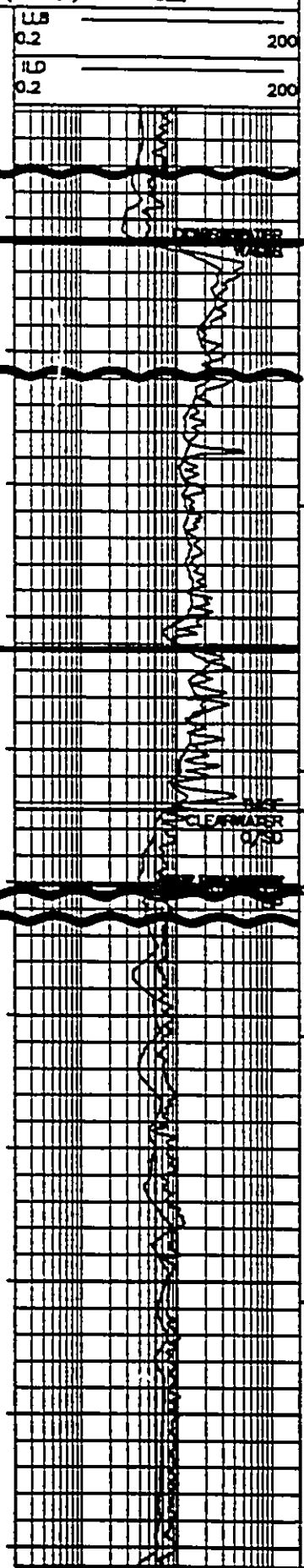
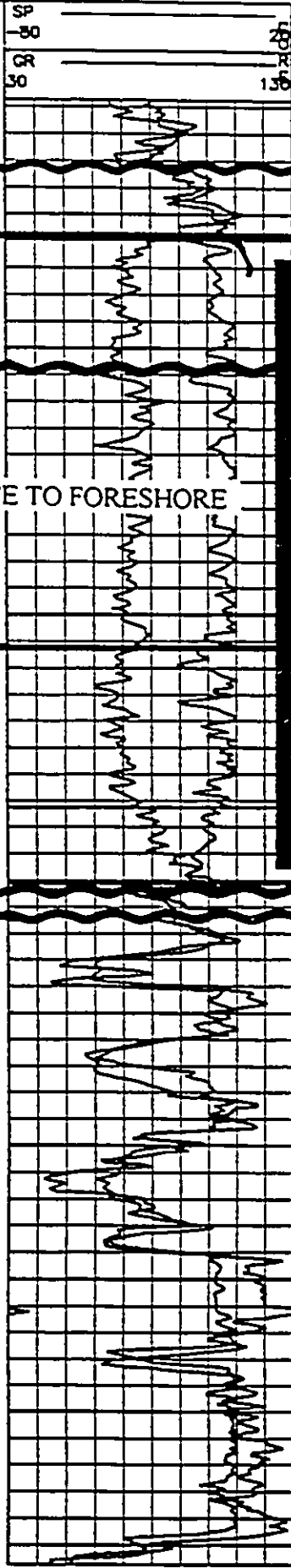
517

CLEARWATER
BASE

CLEARWATER
BASE

SCALE (METRES/INCH): 12.2
SCALE (FEET/INCH) : 40.0

START DEPTH(METRES): 412
STOP DEPTH(METRES): 522



GRAND RAPIDS FORMATION

SB 5

FS 4

FLUVIAL CHANNEL-FILL

SHOREFACE TO FORESHORE

SB 4

FS 2

TIDAL BAR

McMURRAY FORMATION

SB 1

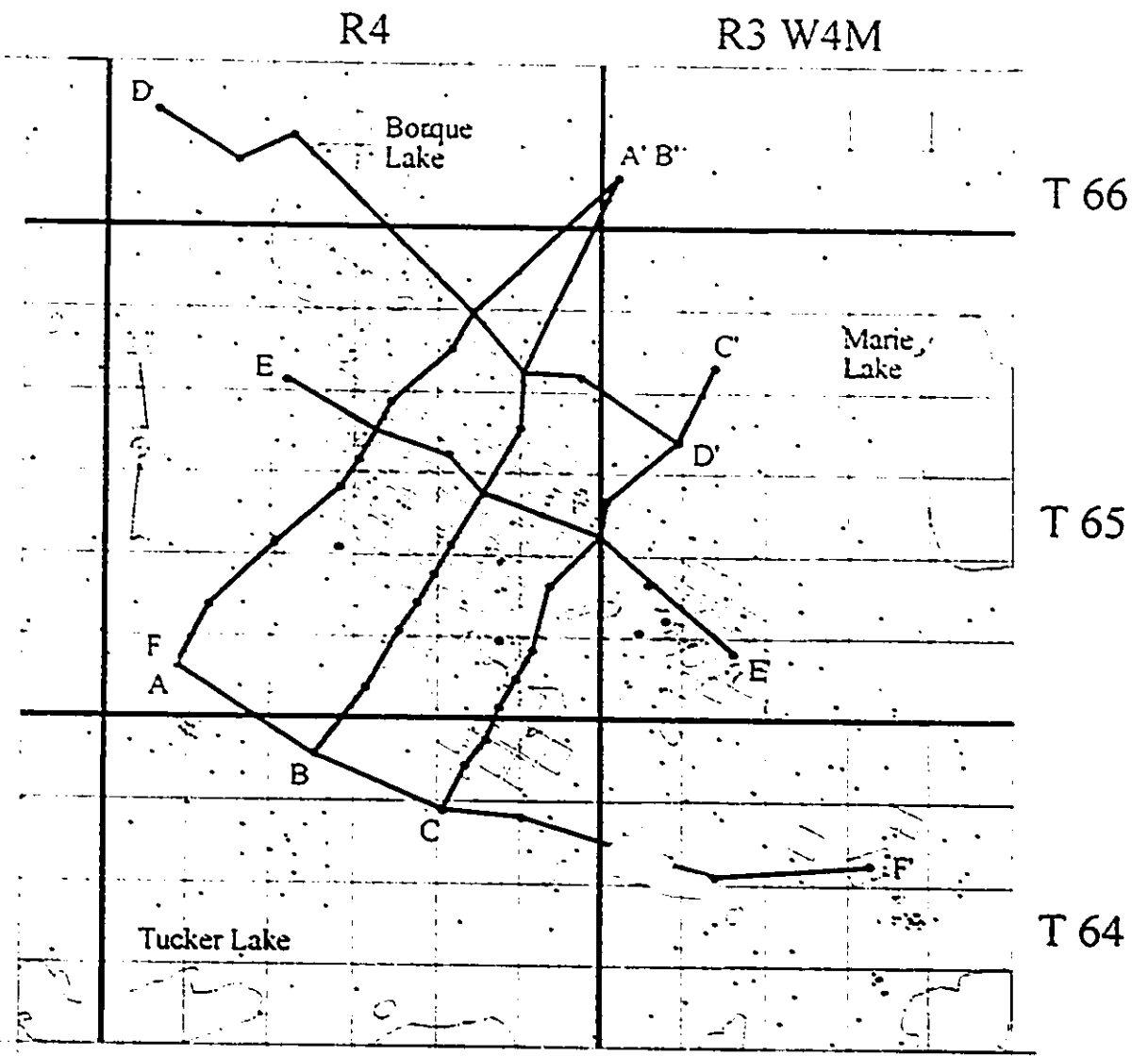
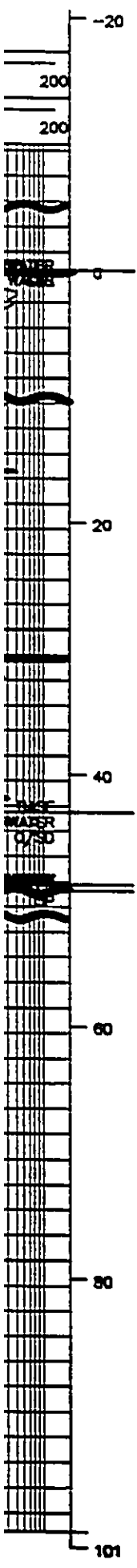
CLEARWATER

-20
0
20
40
60
80
100

HORIZONTAL SCALE: NOT TO SCALE
DATUM: FLOODING SURFACE 4 (FS 4)

WELL LOGS COURTESY IMPERIAL OIL RESOURCES LIMITED, CALGARY

SECTION DRAWN BY: G. Glen McCrimmon August, 1995



SCALE 1:140000

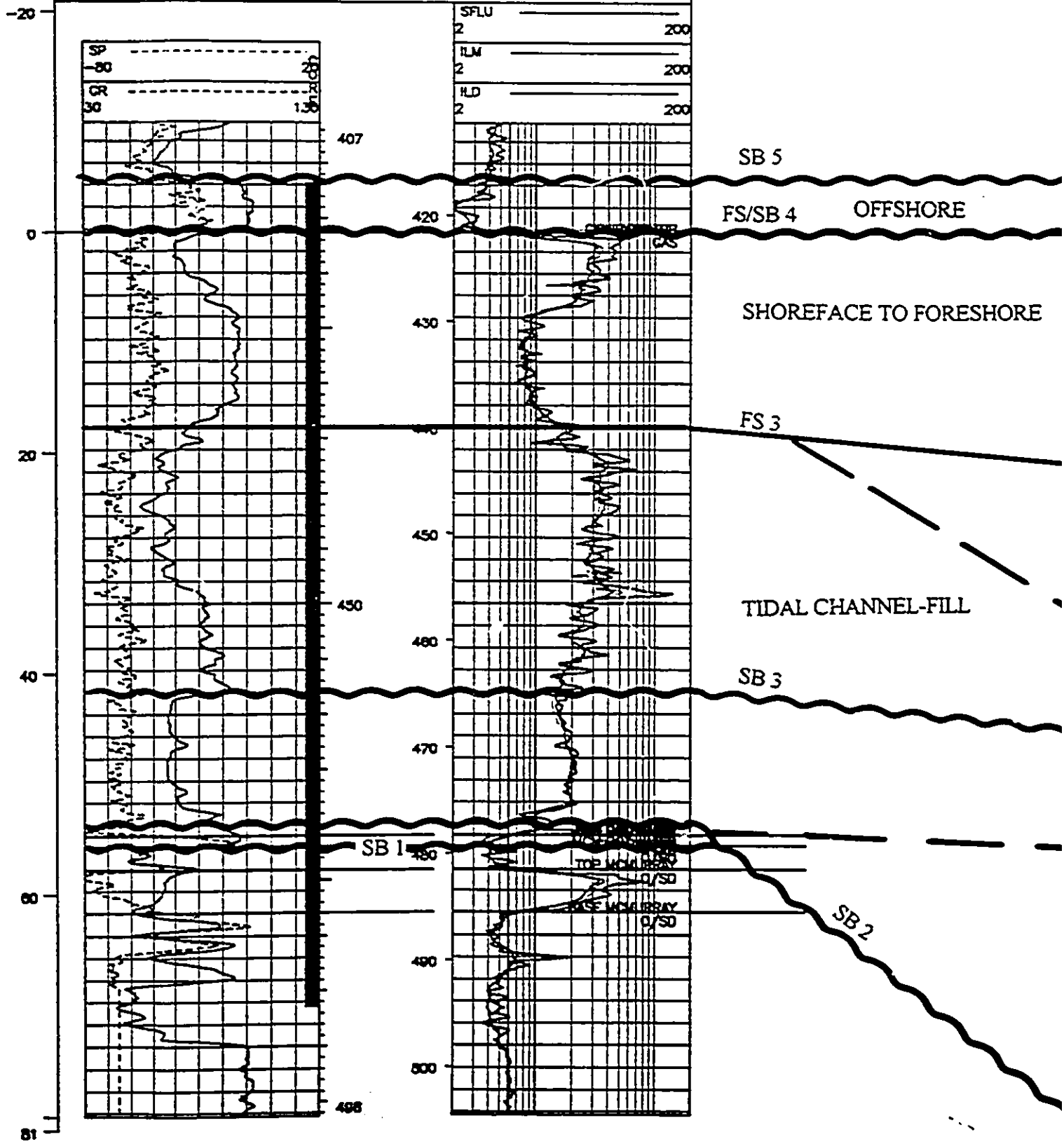
KILOMETRES



MILES

00/04-20-003-04#4
 ESSO 55 106-16 COLDK 4-25-65-4

ELEVATION:	509	RIG REL. DATE:	06/03/1988
WELL STATUS:	STNDG	START DEPTH(METRES):	406
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	496
SCALE (FEET/INCH) :	40.0		

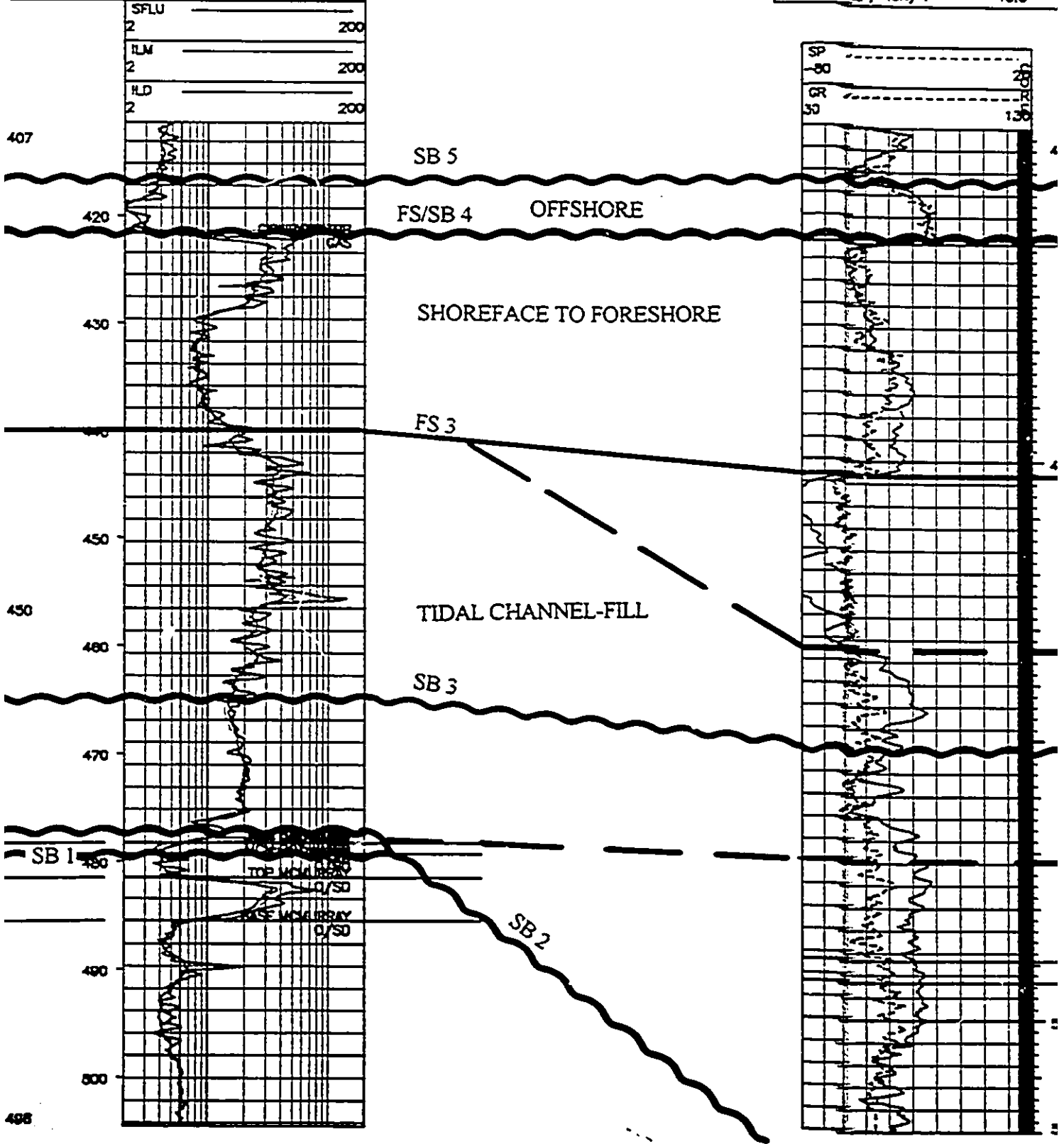


CG-003-U474
 COLDLK 4-25-63-4

05/12-2:
 ESSO 84 J2-13 CO

RIG REL. DATE: 06/03/1968
 START DEPTH(METRES): 408
 STOP DEPTH(METRES): 498

ELEVATION: 615
 WELL SURFUS: CB
 SCALE (METRES/INCH): 12.2
 SCALE (FEET/INCH) : 40.0

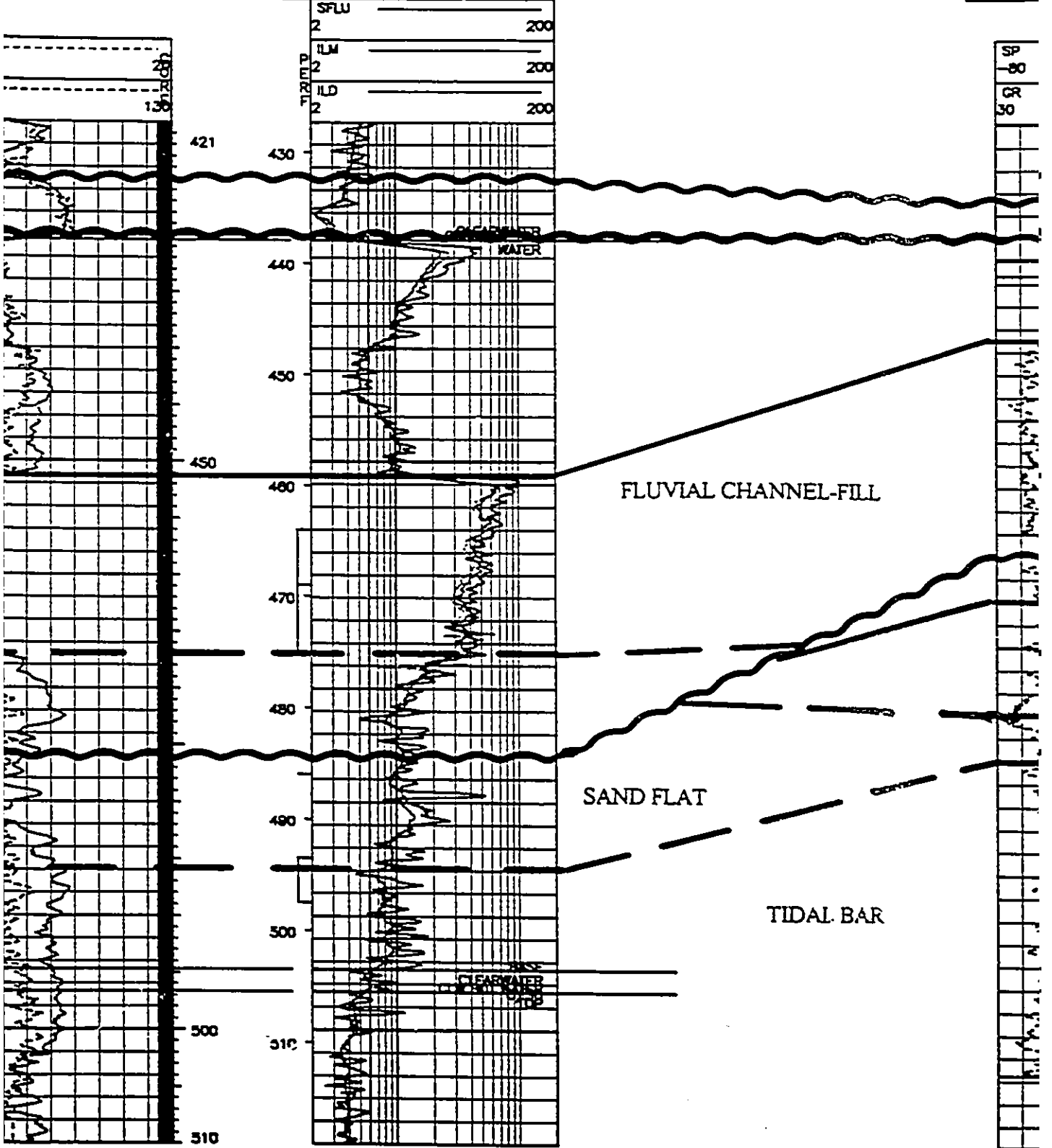


05/12-22-065-04W4

ESSO 84 J2-13 COLDLK 12-22-65-4

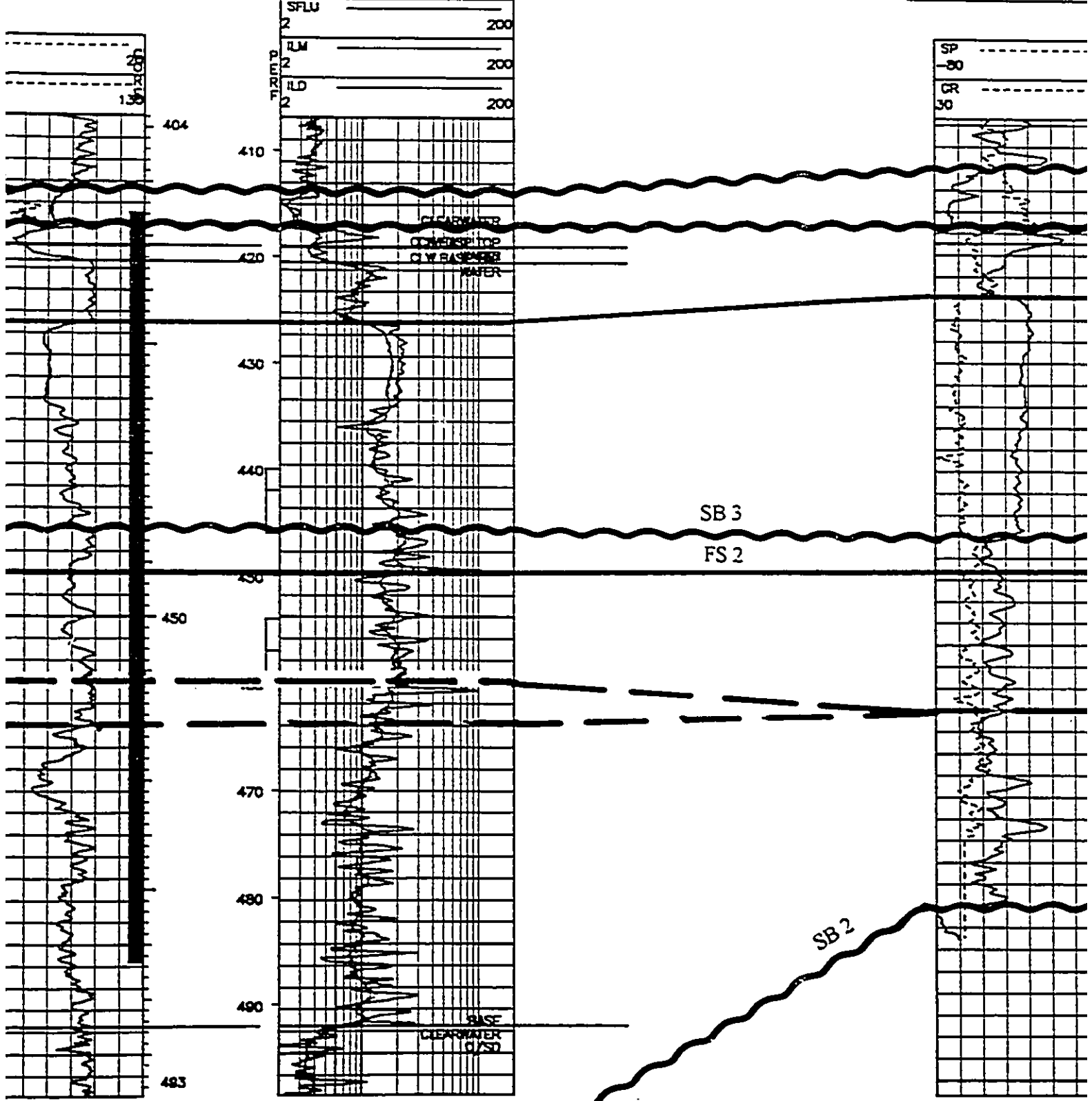
SR	815	RIG REL DATE:	12/09/1984
RES/INCH):	CB	START DEPTH(METRES):	420
T/INCH) :	40.0	STOP DEPTH(METRES):	510

ELEVATION	
WELL SURFACE	
SCALE	
SCALE	

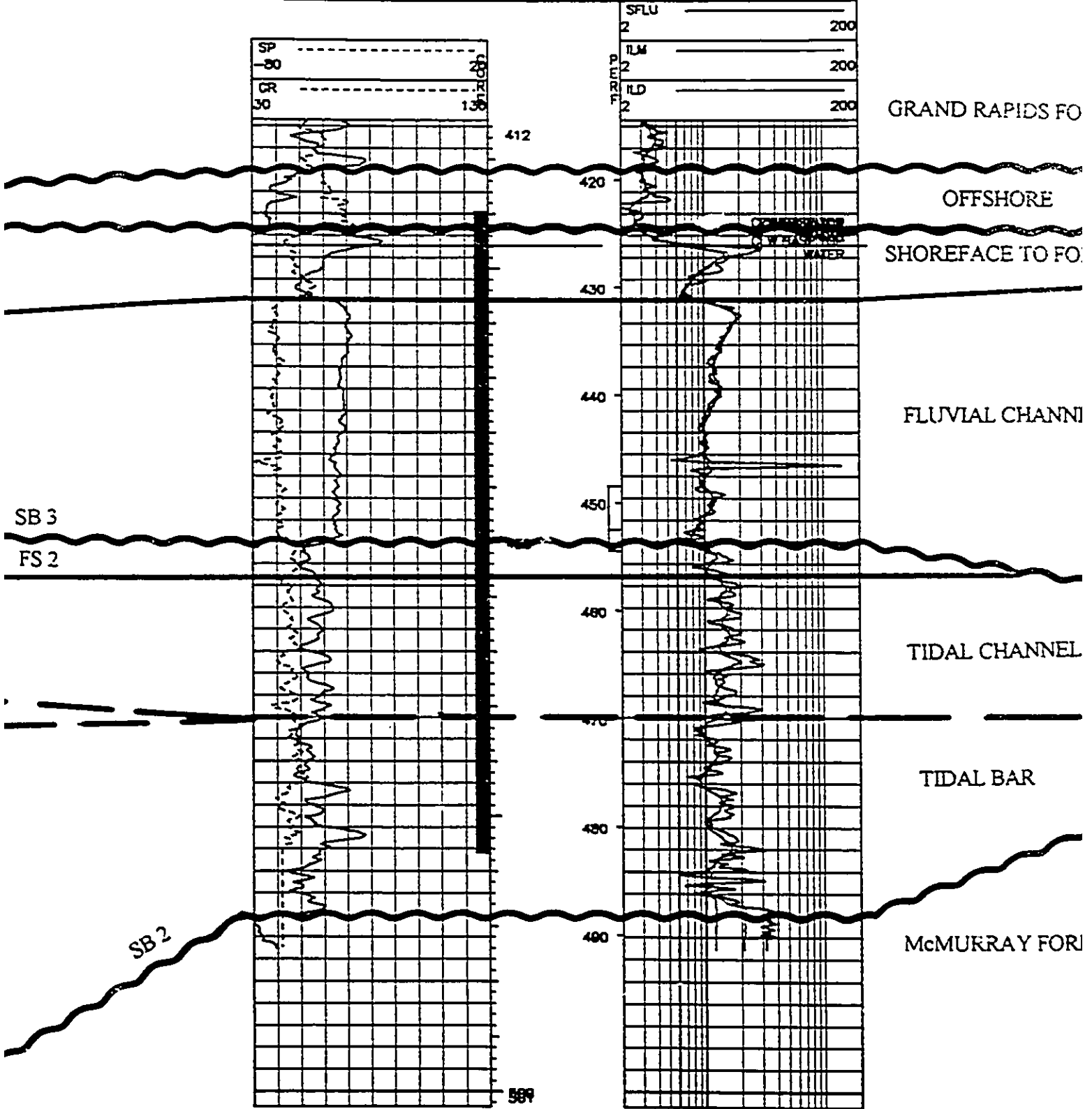


608	RIG REL DATE:	09/07/1988
CB	START DEPTH(METRES):	404
/INCH): 12.2	STOP DEPTH(METRES):	494
CH) : 40.0		

ELEVATION:
 WELL STATUS:
 SCALE (METRES/INCH):
 SCALE (FEET/INCH) :

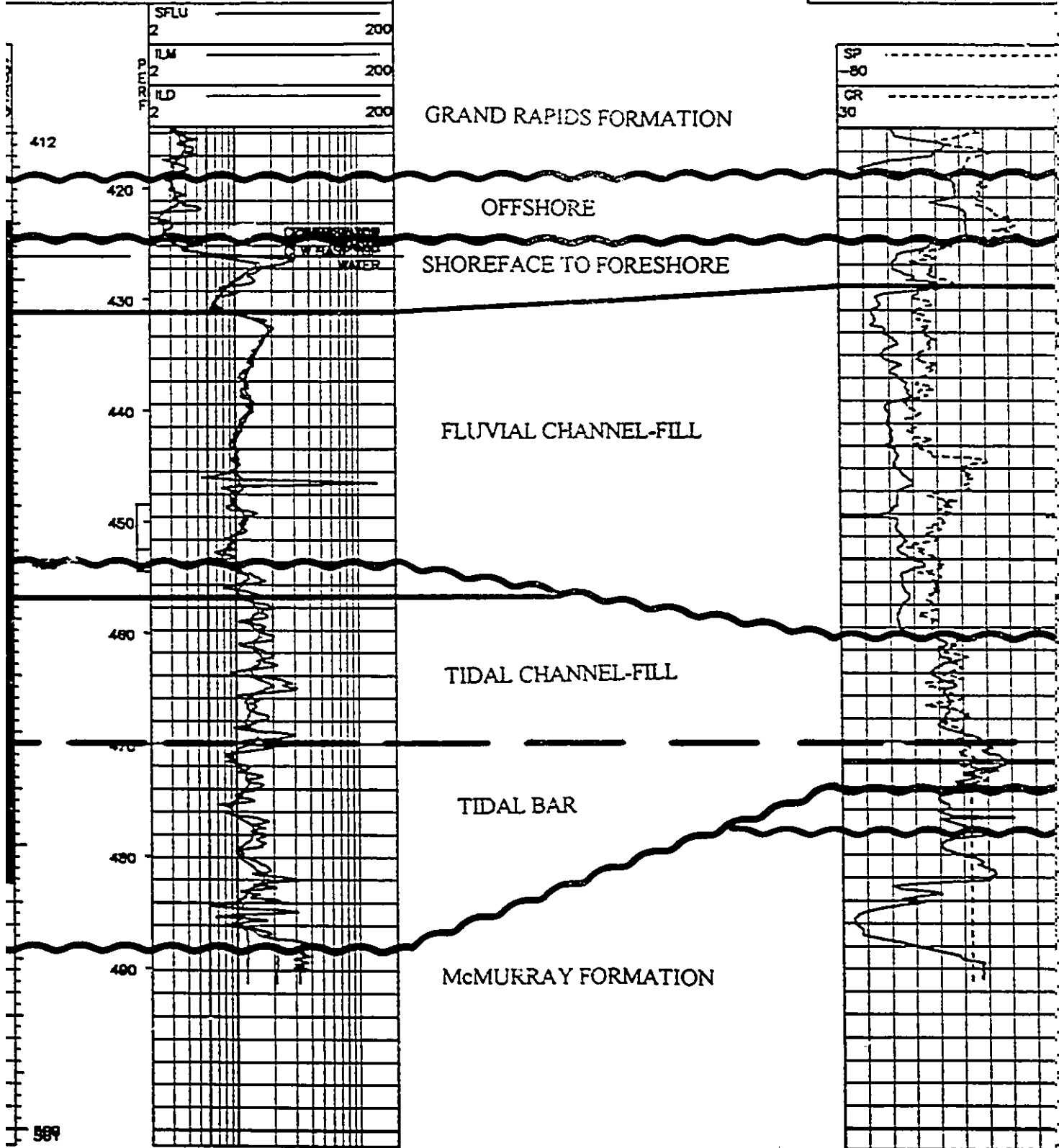


ELEVATION:	613	RIG REL. DATE:	22/05/1985
WELL STATUS:	CYCLICAL	START DEPTH(METRES):	411
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	501
SCALE (FEET/INCH) :	40.0		



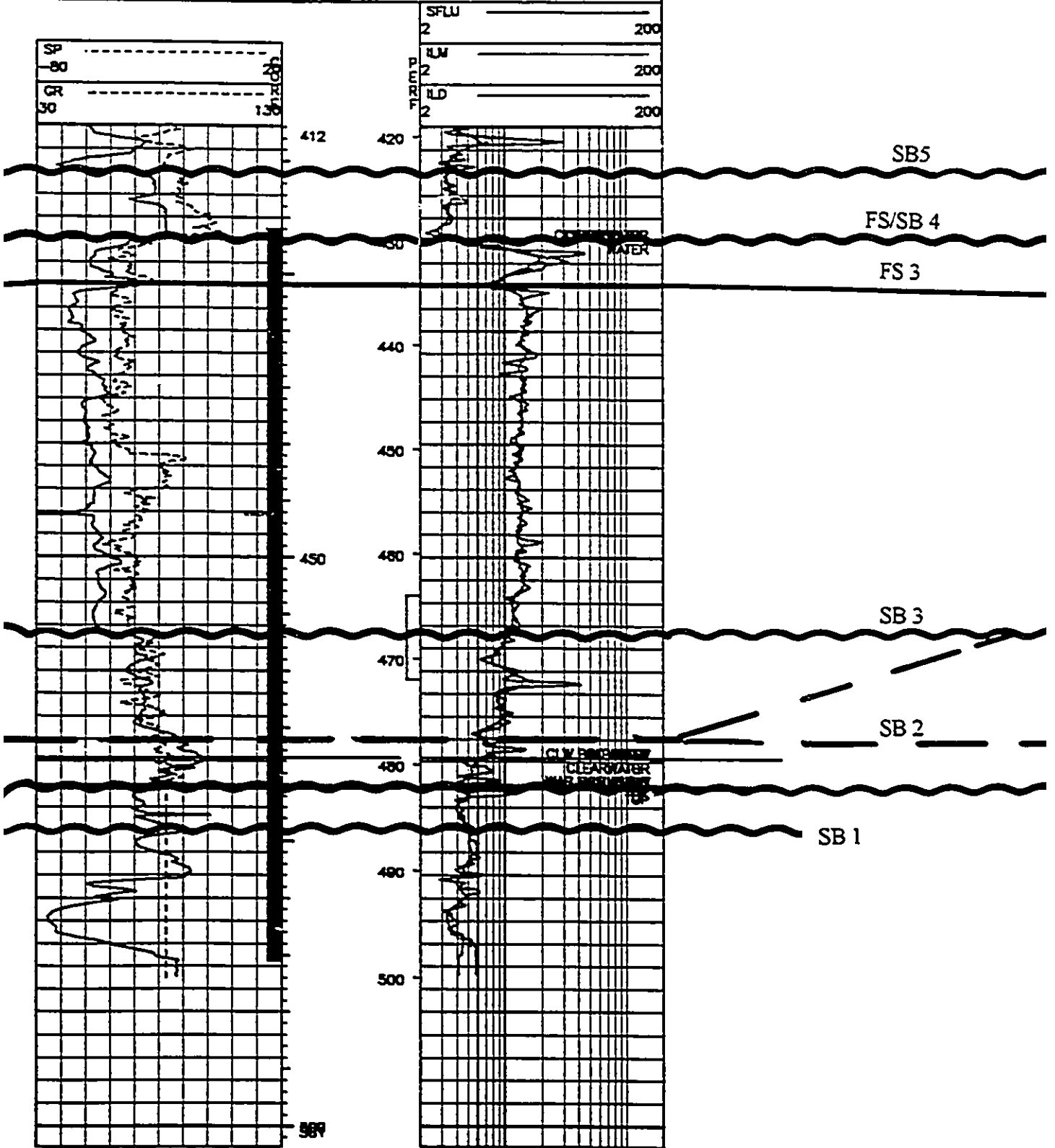
CAL RIG REL DATE: 22/05/1988
 START DEPTH(METRES): 411
 STOP DEPTH(METRES): 501

ELEVATION: BK
 WELL STATUS: CI
 SCALE (METRES/INCH): 1:5
 SCALE (FEET/INCH) : 4:1



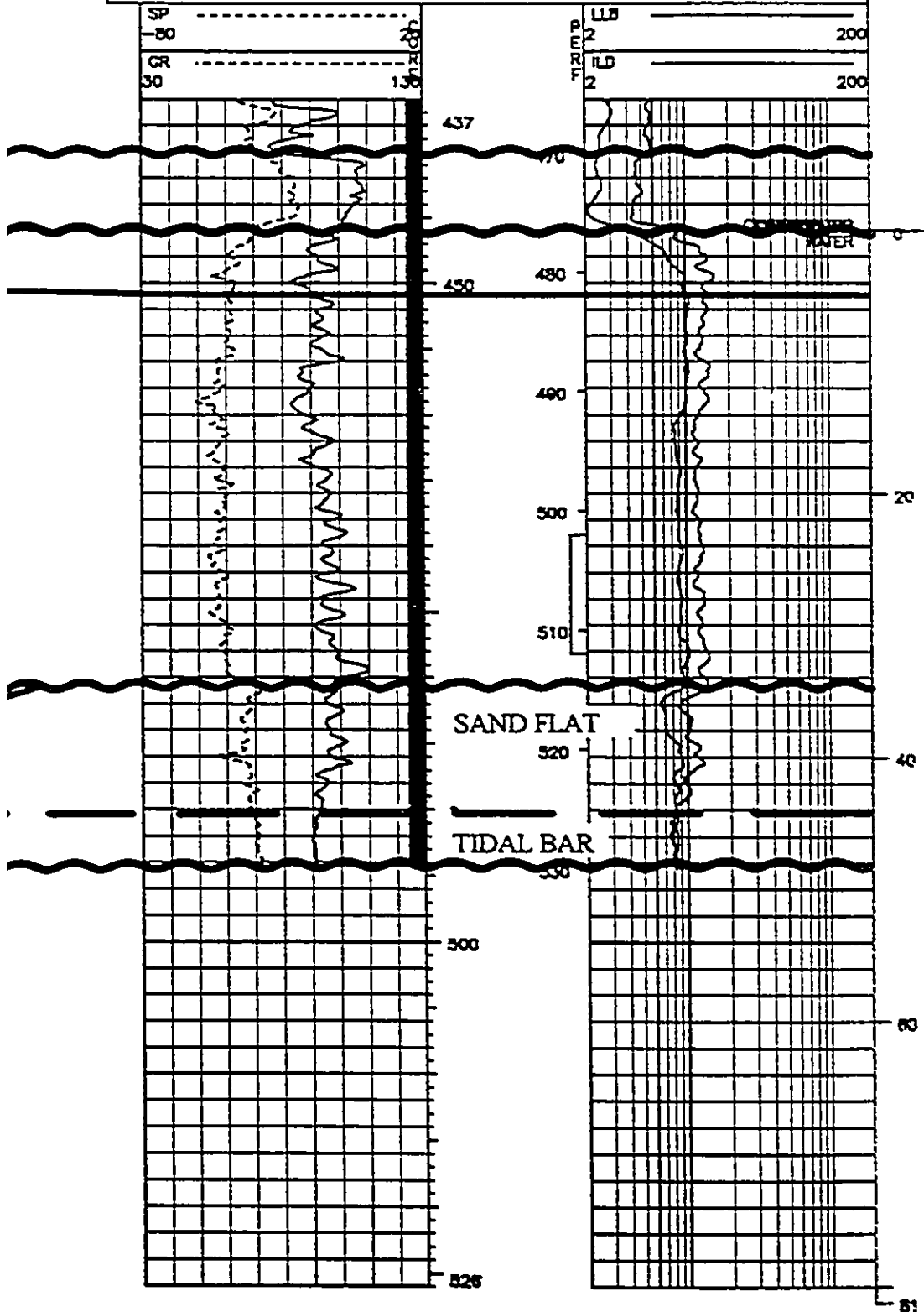
ES30 85 CE-8 COLDLK 1-13-85-4

ELEVATION:	808	ROC REL DATE:	28/08/1985
WELL STATUS:	CB	START DEPTH(METRES):	412
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	502
SCALE (FEET/INCH) :	40.0		



AA/10-05-065-03W4
 ESSO 79 C-44 STRAHLK EX 10-3-85-3

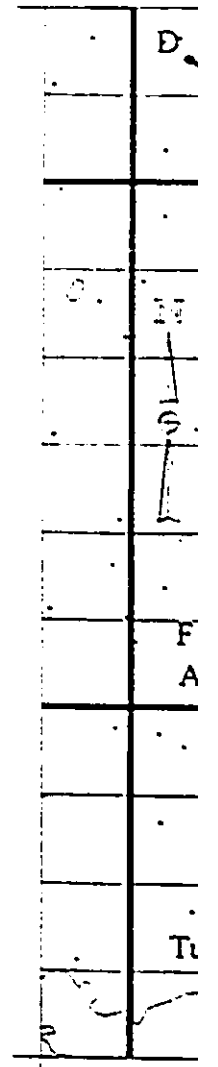
ELEVATION: 829
 WELL STATUS: S-CYC RIG REL. DATE: 03/11/1979
 SCALE (METRES/INCH): 12.2 START DEPTH(METRES): 438
 SCALE (FEET/INCH) : 40.0 STOP DEPTH(METRES): 528



STRAI

VERTICAL:
 HORIZONTAL:
 DATUM:

WELL LOGS CO
 SECTION DRAW

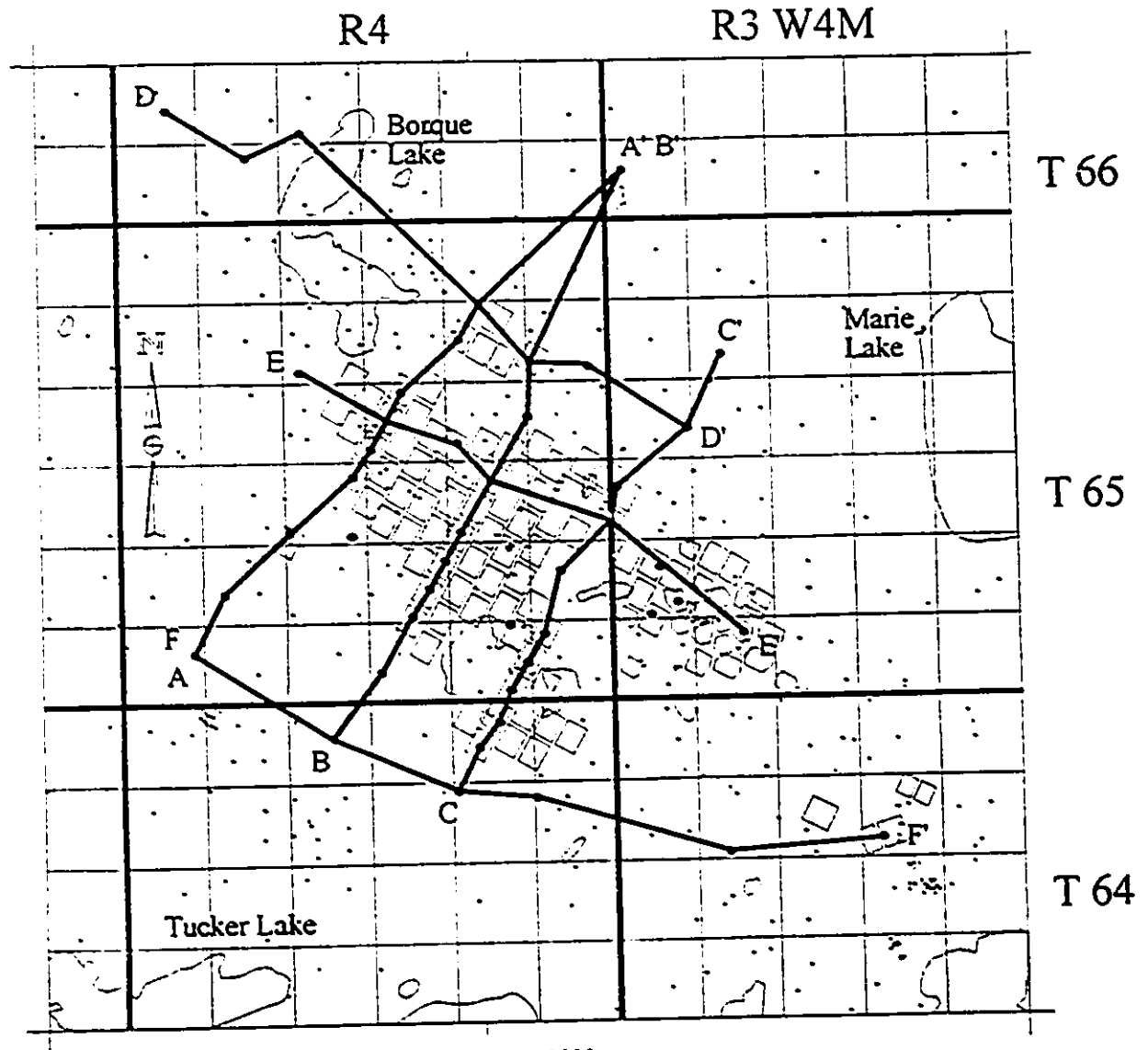
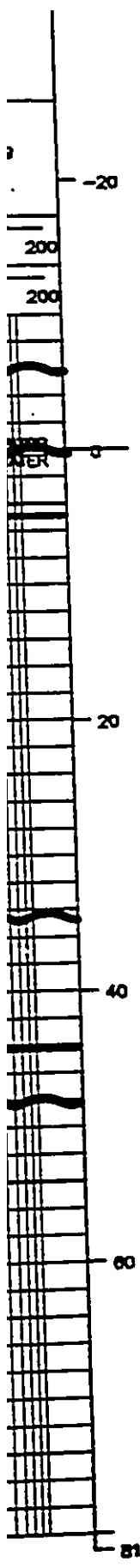


STRATIGRAPHIC CROSS-SECTION E-E'

VERTICAL SCALE: 1:480
HORIZONTAL SCALE: NOT TO SCALE
DATUM: FLOODING SURFACE 4 (FS 4)

WELL LOGS COURTESY IMPERIAL OIL RESOURCES LIMITED, CALGARY

SECTION DRAWN BY: G. Glen McCrimmon August, 1995



SCALE 1:140000
KILOMETRES

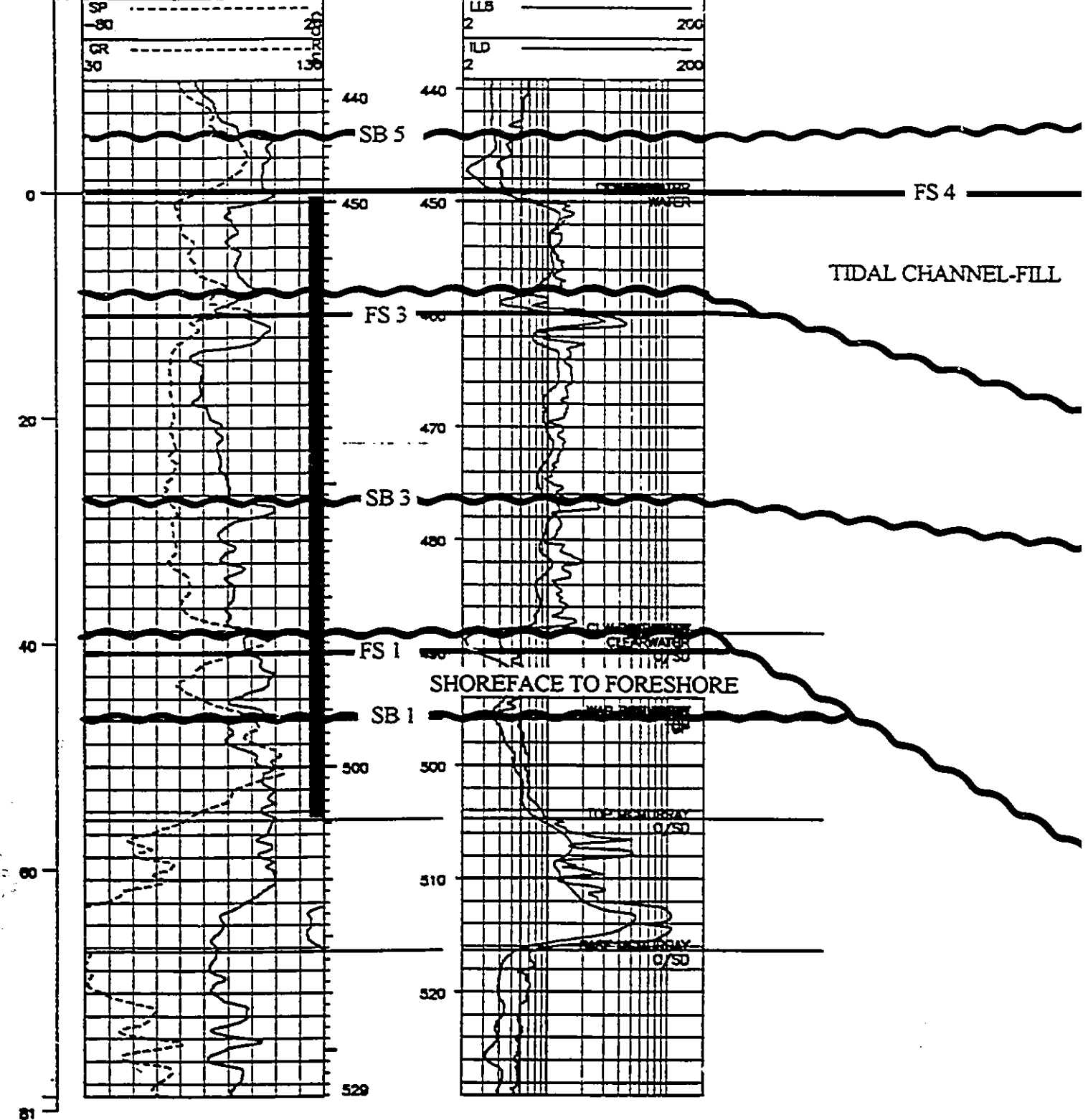


9-6-65-4-AA

AA/09-06-065-0474

DWP 12 COLDLK OV 9-6-65-4

ELEVATION: 629
WELL STATUS: ABAND
RIG REL. DATE: 03/02/1978
SCALE (METRES/INCH): 12.2
SCALE (FEET/INCH) : 40.0
START DEPTH (METRES): 438
STOP DEPTH (METRES): 529

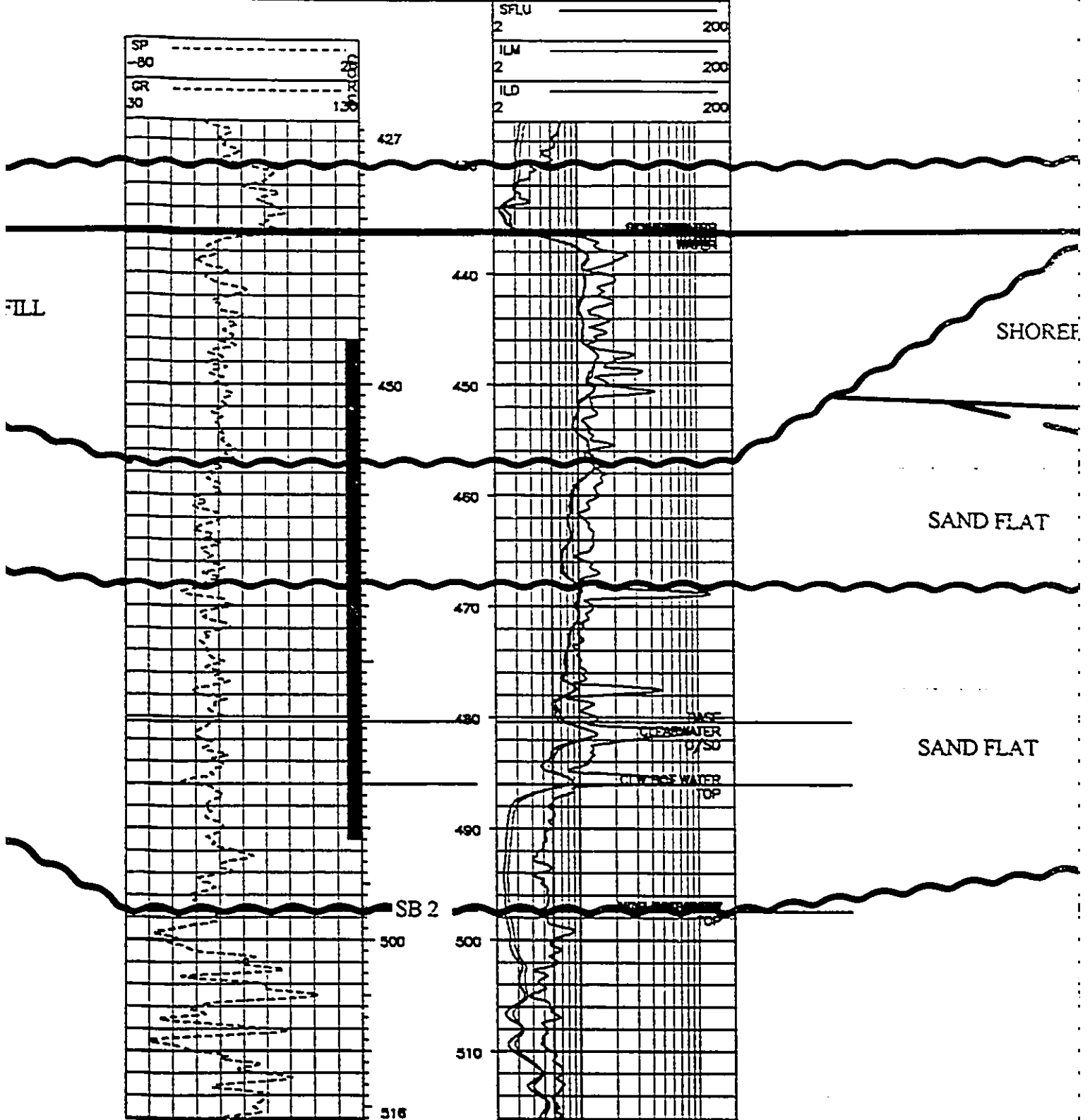


10-33-64-4-AA

AA/10-33-064-04W4

ESSO 86 COLDLK CV 10-33-64-4

ELEVATION:	817	RC REL. DATE:	19/02/1988
WELL STATUS:	ABAND	START DEPTH(METRES):	426
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	516
SCALE (FEET/INCH) :	40.0		

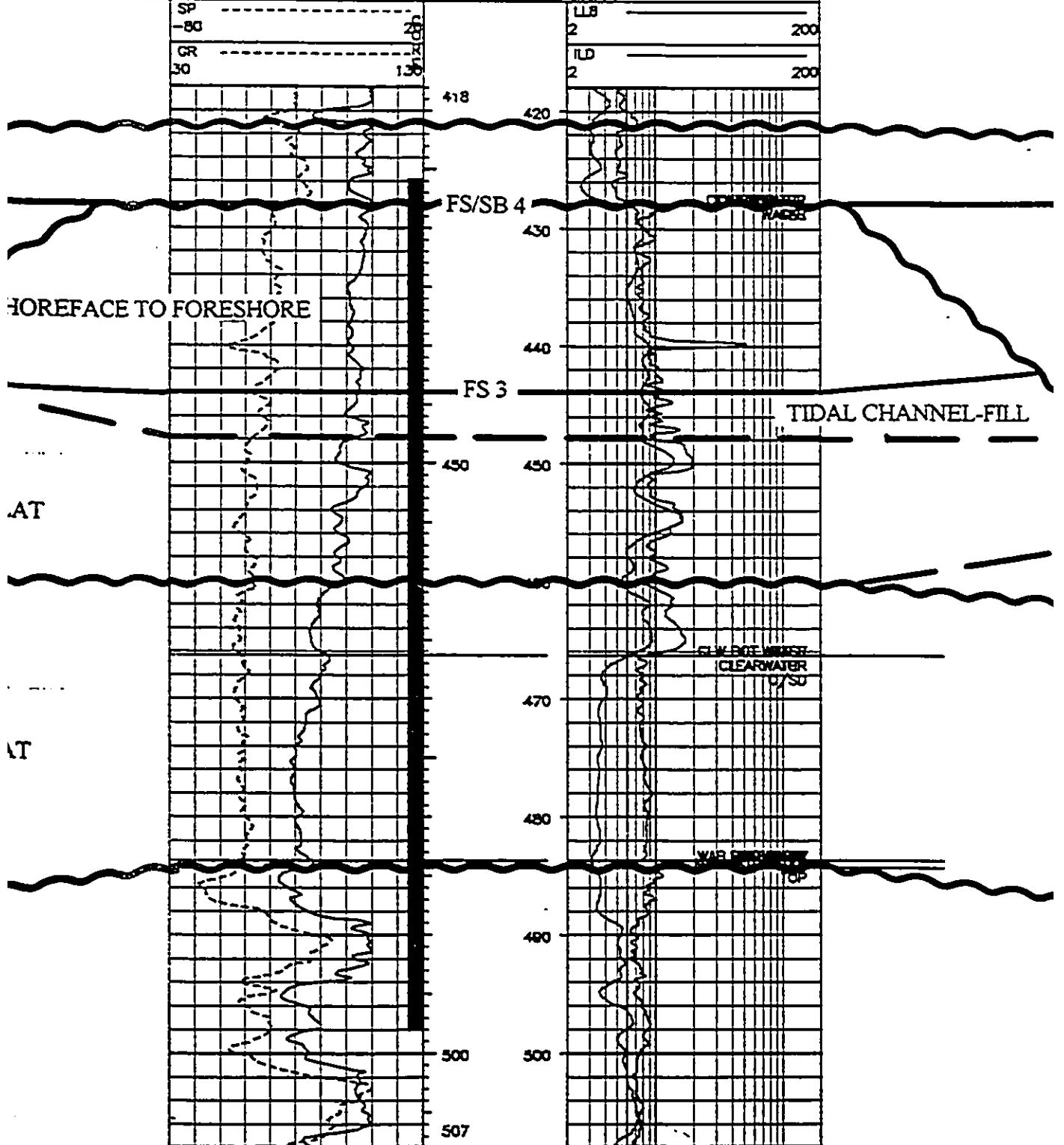


13-26-64-4-AA

AA/13-26-084-04W4

DMP 4 COLDLK OV 13-26-64-4

ELEVATION:	504	ROG REL. DATE:	27/01/1978
WELL STATUS:	ABAND	START DEPTH(METRES):	418
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	508
SCALE (FEET/INCH) :	40.0		

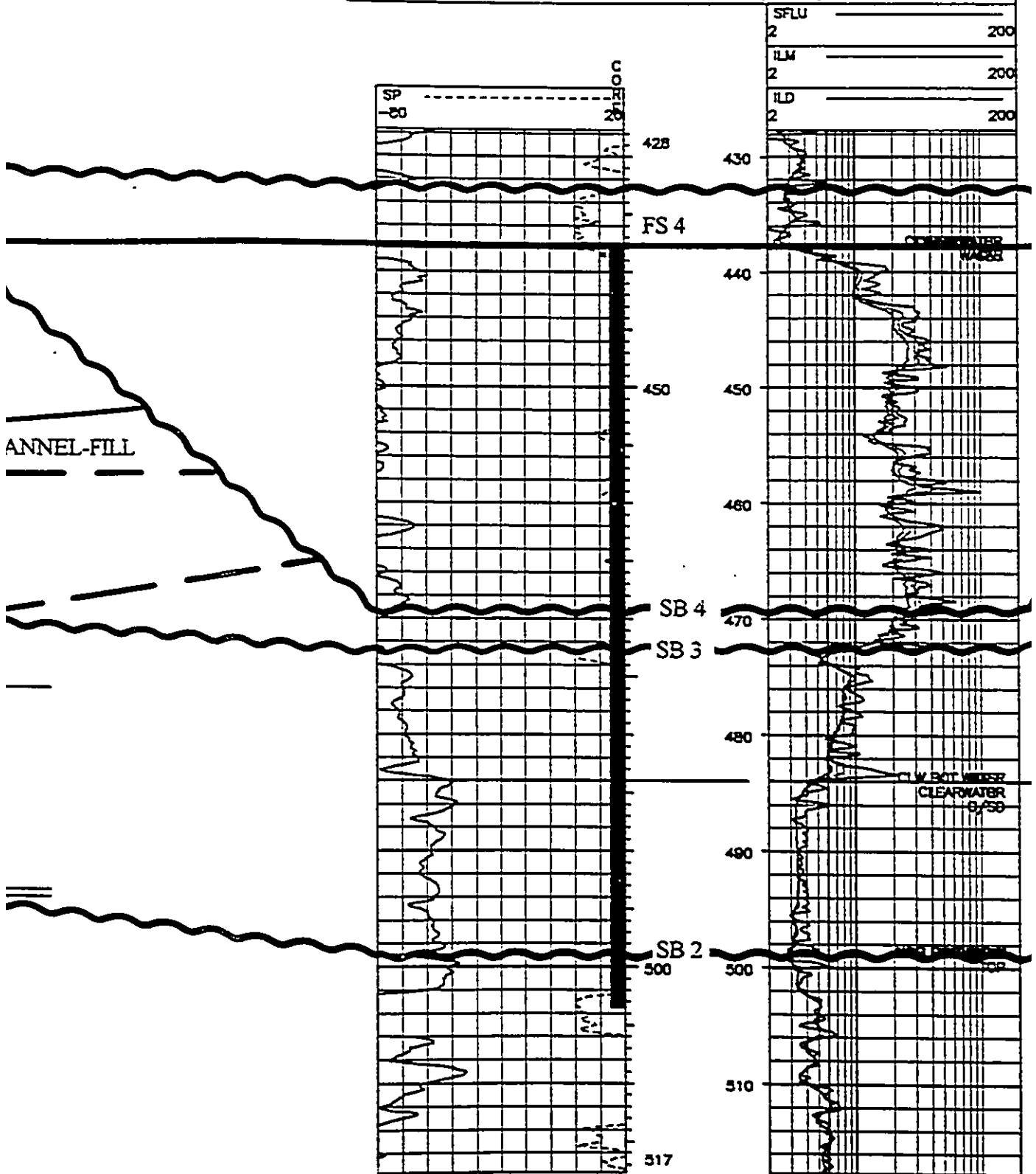


13-25-64-4-AA

AA/13-25-084-04W4

ESSO 88 COLDLX 0V 13-25-64-4

ELEVATION:	813	RIG REL. DATE:	19/07/1988
WELL STATUS:	ABAND	START DEPTH(METRES):	428
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	518
SCALE (FEET/INCH) :	40.0		

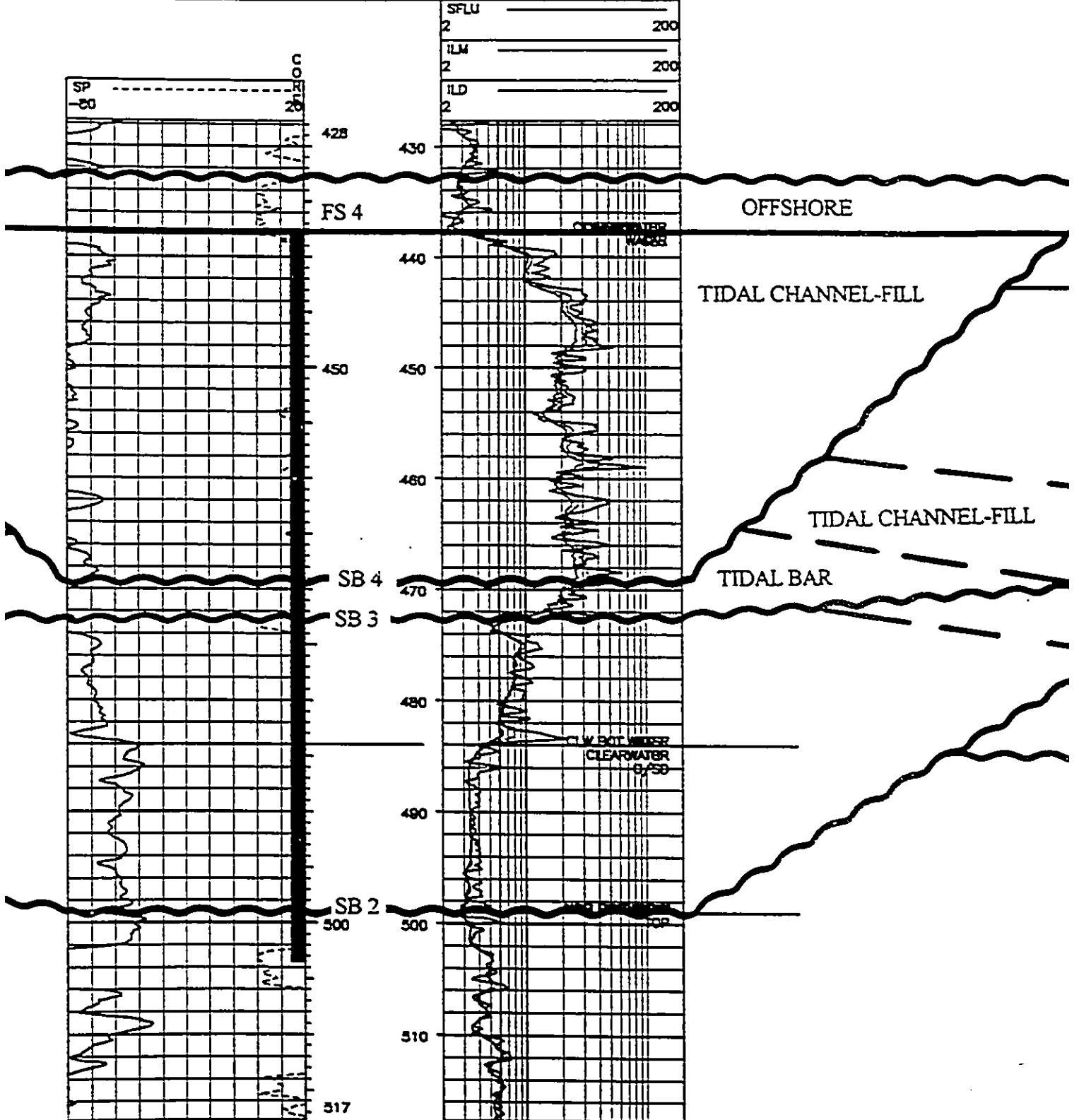


13-25-84-4-AA

AA/13-25-084-04W4

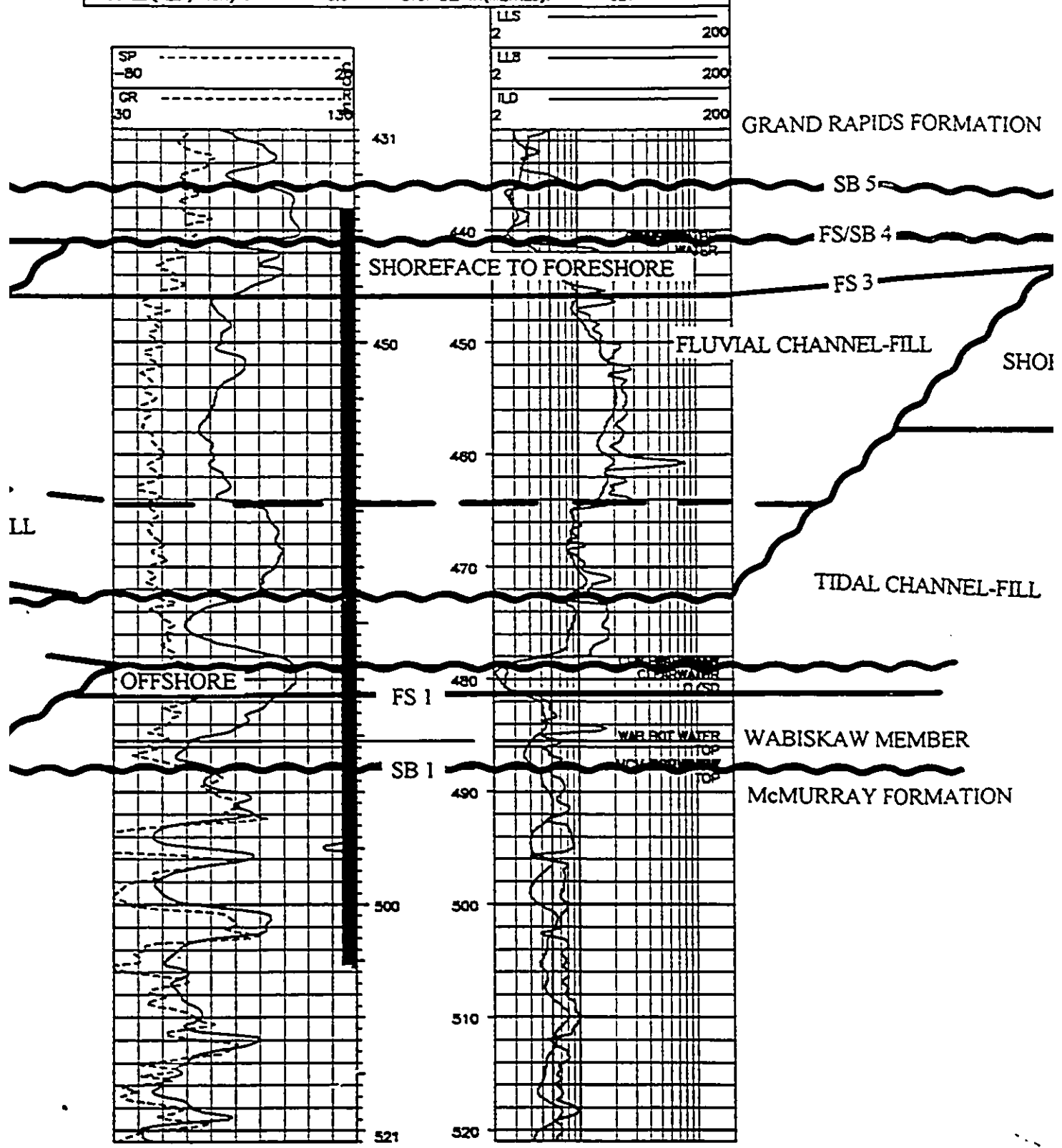
ESSO 88 COLDLX OV 13-25-84-4

ELEVATION:	813	RIG REL. DATE:	19/07/1988
WELL STATUS:	ABAND	START DEPTH(METRES):	428
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	518
SCALE (FEET/INCH) :	40.0		



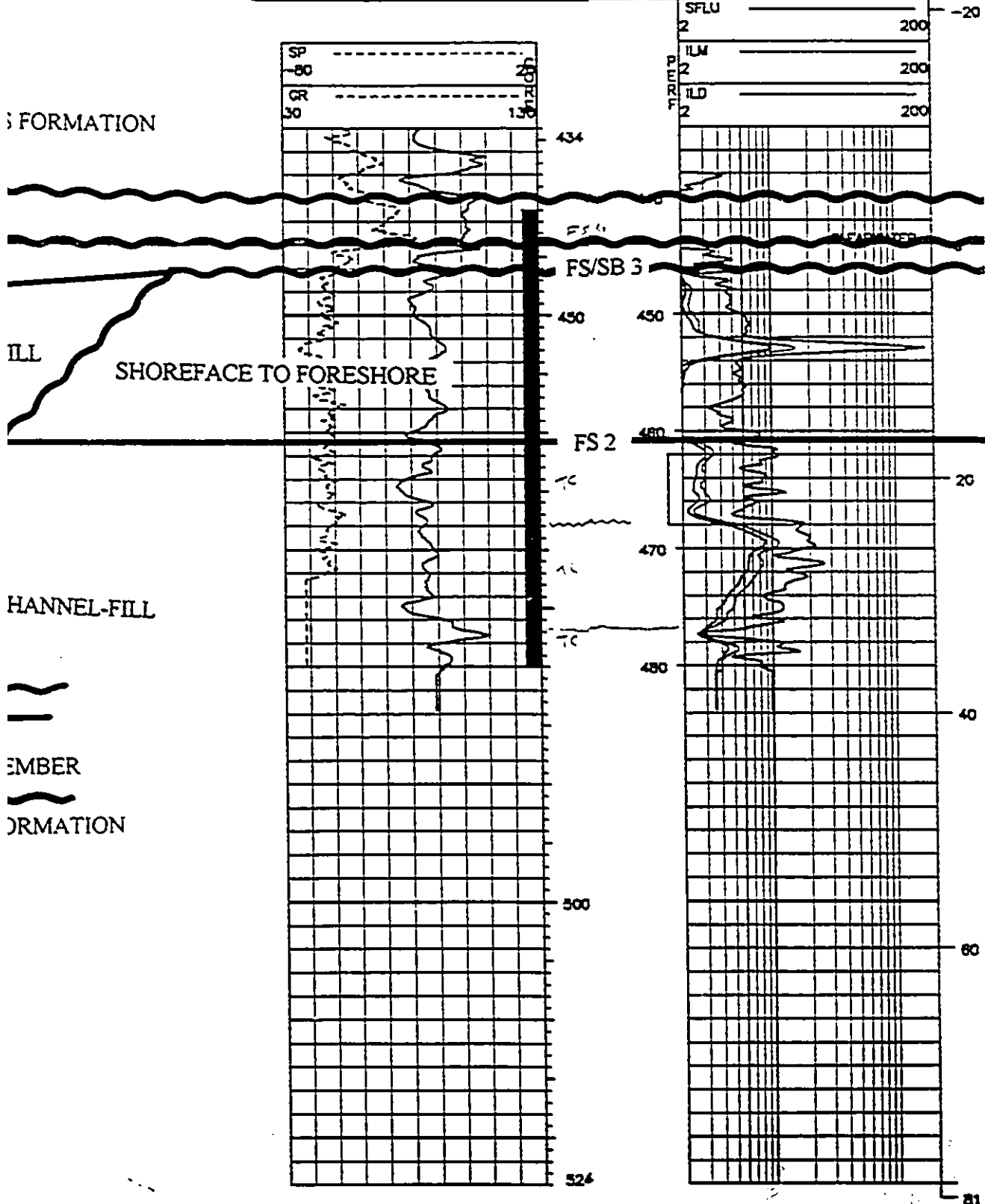
00/03-29-064-03W4
 ESSO 81 STD STRIKK 3-29-64-3

ELEVATION:	814	RIG REL. DATE:	27/03/1981
WELL STATUS:	S-W-D	START DEPTH(METRES):	431
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	521
SCALE (FEET/INCH) :	40.0		



WELL ID
02/03-27-064-03W4
 ESSO 90 MAYBEA COLDEX EX 3-27-64-3

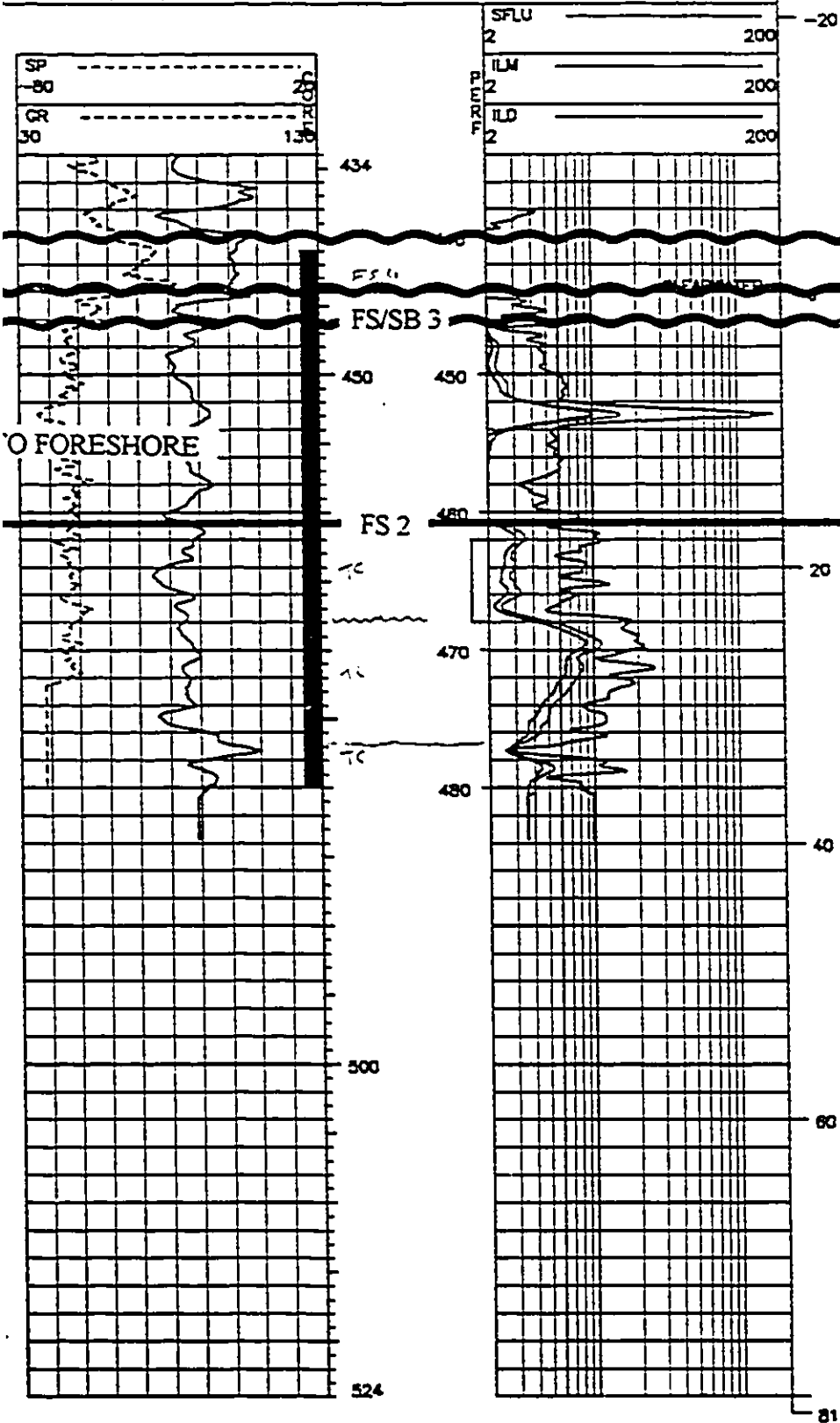
ELEVATION:	813	ROG REL DATE:	01/06/1990
WELL STATUS:	STNDG	START DEPTH(METRES):	434
SCALE (METRES/INCH):	12.2	STOP DEPTH(METRES):	524
SCALE (FEET/INCH) :	40.0		



S
V
H
D
W
S

WELL LOG
 02/03-27-064-03W4
 ESSO 90 MAYBIEA COLDK EX 5-27-64-3

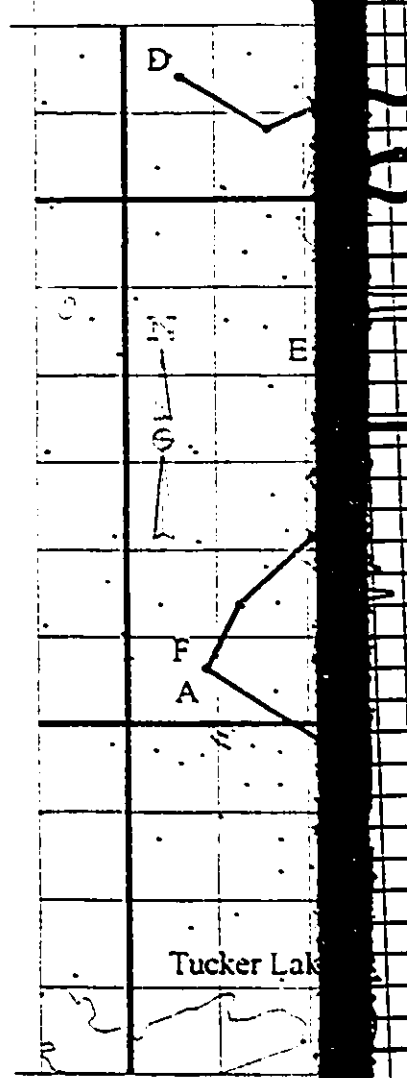
ELEVATION: 513
 WELL STATUS: STRDC RG REL. DATE: 01/05/1990
 SCALE (METRES/INCH): 12.2 START DEPTH(METRES): 434
 SCALE (FEET/INCH) : 40.0 STOP DEPTH(METRES): 524



STRATIGR

VERTICAL SCALE: /05
 HORIZONTAL SCALE: /05
 DATUM:

WELL LOGS COURTESY
 SECTION DRAWN BY: G

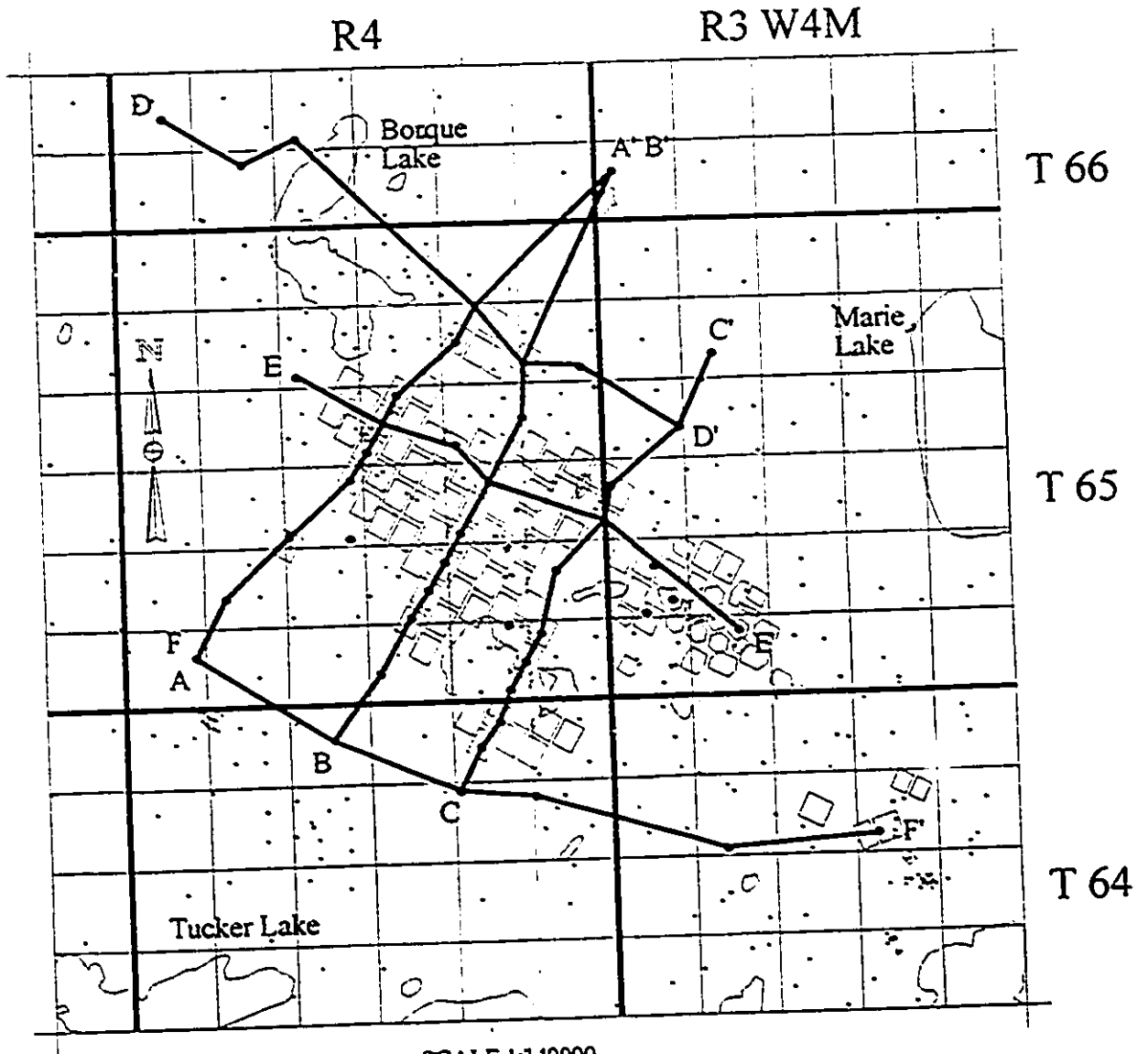


STRATIGRAPHIC CROSS-SECTION F-F'

VERTICAL SCALE: 1:480
HORIZONTAL SCALE: NOT TO SCALE
DATUM: FLOODING SURFACE 4 (FS 4)

WELL LOGS COURTESY IMPERIAL OIL RESOURCES LIMITED, CALGARY

SECTION DRAWN BY: G. Glen McCrimmon August, 1995



SCALE 1:140000

KILOMETRES

