THE UNIVERSITY OF ALBERTA

THE LOWER CRETACEOUS MCMURRAY FORMATION IN THE SUBSURFACE OF SYNCRUDE OIL SANDS LEASE 17, ATHABASCA OIL SANDS, NORTHEASTERN ALBERTA: A PHYSICAL SEDIMENTOLOGICAL STUDY IN AN AREA OF EXCEPTIONAL DRILL CORE CONTROL

by

© ANDREW J. FOX, B.Sc.

A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled THE LOWER CRETACEOUS MCMURRAY FORMATION IN THE SUBSURFACE OF SYNCRUDE OIL SANDS LEASE 17, ATHABASCA OIL SANDS, NORTHEASTERN ALBERTA: A PHYSICAL SEDIMENTOLOGICAL STUDY IN AN AREA OF EXCEPTIONAL DRILL CORE CONTROL submitted by ANDREW J. FOX in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

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Supervisor

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Date June 3/1988 ....

DEDICATION:

To the "Big Wood"

I'll try never to talk about "interbedded sand and mud in the mail" in my sleep again!

ABSTRACT

Previous studies of the McMurray Formation, the main reservoir unit of the Athabasca Oil Sands, have revealed that clean, well sorted sands have the highest bitumen saturation. If the distribution of these sands is known then the character of the reservoir is better understood. By understanding the depositional processes and environments of the sands, known reservoirs can be more effectively developed and the capability to predict new high grade zones is greatly enhanced.

The Lower Cretaceous McMurray Formation occurring in the subsurface of a heavily drilled area within Syncrude Oil Sands Lease 17 was investigated from a physical sedimentological perspective. It was deposited in response to the southward transgression of a northern sea which culminated with the deposition of offshore marine sequences of the Clearwater Formation. The McMurray Formation is informally subdivided into four distinct stratigraphic subdivisions: the lower, middle and upper members and the limy unit. The lower member was deposited in a high sinuosity fluvial environment that developed in valleys on the Devonian-Cretaceous unconformity surface. With the transgression of the boreal sea, the valleys were flooded and estuaries developed resulting in the deposition of the middle member. Sedimentary sequences in the middle member clearly show the effects of tidal currents and the mixing of fresh and saline waters in the estuarine environment. The limy unit fills an incision on the top of the middle member that possibly developed during a down cutting phase associated with a drop in sea level. The limy unit was also deposited in an estuarine environment but is distinctly different from the middle member as it is characterized by fossiliferous sands and calcareous muds. Truncating both the middle member and the limy unit are nearshore bar and interbar

trough sequences of the upper member. These are erosionally overlain by sequences that reflect a gradual deepening to more offshore conditions marking the onset of the deposition of the Clearwater Formation.

ACKNOWLEDGEMENTS

For putting up with the "other woman" for almost three years and providing technical and moral support, as well as making life a lot more interesting and kicking my butt every so often, I thank my wife Teresa.

Technical assistance by Bruce Beynon, Jimbo Magwood and Hugh Stewart is greatly appreciated.

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I thank Dr. Brian Jones who, in the process of roasting me over hot coals, taught me to never discount anything and to appreciate the value of a good presentation. Though your criticism was humbling at the time I feel that I have become a better scientist as a result.

For sparking my interest in sedimentology and showing the confidence in my abilities to encourage me to attend graduate school I thank Dr. Darrel Long of Laurentian University. I hope I did not disappoint you.

Thanks to my sister and my parents for translating critical German and French passages and papers critical to this thesis as well as providing continual support and encouragement throughout the course of this thesis.

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For providing me access to the drill core as well as the use of their facilities in Edmonton I thank Syncrude Canada Limited and their Geological Department; especially Grant Wach (formerly of Syncrude) who introduced me to the drill core and always showed an interest in the study.

Generous financial support provided by Alberta Oil Sands Technology and Research Authority Agreement 474 to Dr. S.G. Pemberton made this research possible. Additional support by a NSERC Postgraduate Scholarship and a University of Alberta Graduate Fellowship is appreciated.

Innumerable thanks to my fellow "Tar Babies", Blair Mattison and Mike Ranger, for providing numerous "separate" discussions (Ha, what a pair!), help with assorted computer applications and a lot of laughs.

Finally I would like to thank my <u>very</u> patient supervisor Dr. George Pemberton for giving me numerous breaks when I needed them most, as well as for providing financial and technical support, encouraging free thinking, and being available to discuss personal and academic problems at any time. I owe you George.

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CHAPTER 1

INTRODUCTION

The oil sands of Western Canada, while dwarfing conventional and tertiary oil reserves (Fig. 1), have had only limited development because of high extraction costs and the need for advanced technology (Procter *et al.* 1983). The bitumen in the oil sands deposits is heavy, having API (American Petroleum Institute) gravities of 8° to 10° compared to values of 25° to 40° API for conventional oil (Mossop 1980a; North 1985). Because this oil is so viscous, it does not flow freely from the reservoir and requires special extraction techniques. At the present time surface mining and *in situ* recovery are the only viable options for exploiting this vast resource. Both of these extraction techniques require a sound knowledge of the extent, geometry and internal structure of the reservoir.

It has become clear that lithology is the major control on bitumen saturation in the McMurray Formation, the stratigraphic unit hosting the bulk of the Athabasca Oil Sands (Kidd 1951; Carrigy 1962; Mossop 1980a). Clean, well sorted sands that have good porosity and permeability have the highest bitumen saturation. The distribution of these sands (and therefore the reservoir) is largely dependent on the depositional environments and processes which were responsible for the sedimentary sequences observed in the McMurray Formation. This knowledge enhances delineation of known oil sands deposits beyond the outcrop or drill core and improves predictive capabilities for undiscovered reservoirs.

The study of physical sedimentary structures and stratification sequences is critical to the understanding of the processes, and the depositional environments responsible for a sedimentary unit. Fluid flow over loose, cohesionless sediments produces predictable

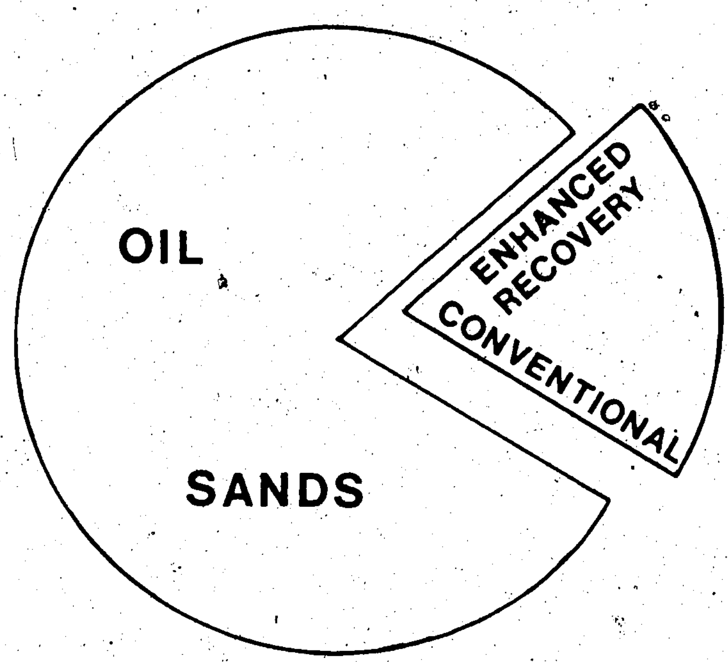


Fig. 1. Canada's oil resources from oil sands, conventional and tertiary (enhanced recovery) sources (modified from Procter *et al.* 1983).

sedimentary bedforms. Therefore the bedforms and the structures and sequences which result are a response to the hydrodynamic conditions that prevailed at the time of deposition (Harms *et al.* 1982). Because a sedimentary environment is a process-response system (Allen 1974) variations in the hydrodynamic conditions should be imparted onto the sedimentary record (Allen 1984).

Sedimentary environments are characterized by a number of interacting processes which vary in space and time. This interaction results in groups of bedforms or bed configurations that may be diagnostic of a particular environment. Individual sedimentary structures produced by specific bedforms reflect specific processes and are therefore non-diagnostic of an environment. Conversely, a series of spatially and temporally related structures produced by a bed configuration are often indicative of a specific depositional environment.

The objective of this study was to determine what processes and depositional environments were responsible for the sedimentary structures and stratification sequences characteristic of the McMurray Formation in an area of exceptional drill core control.

STUDY AREA

Athabasca Oil Sands: facts and figures

The Athabasca Oil Sands, located in northeastern Alberta in the vicinity of the city of Fort McMurray, is the largest of the the four major oil sands deposits in Alberta (Fig. 2) (Govier 1974). The Athabasca deposit is defined as the oil saturated portions of Lower Cretaceous strata (including the McMurray and Clearwater formations) found in the lower Athabasca River area (Carrigy and Zamora 1960). The deposit pinches out against the Canadian Shield in the east and a ridge of resistant carbonates to the west (Stewart 1963).

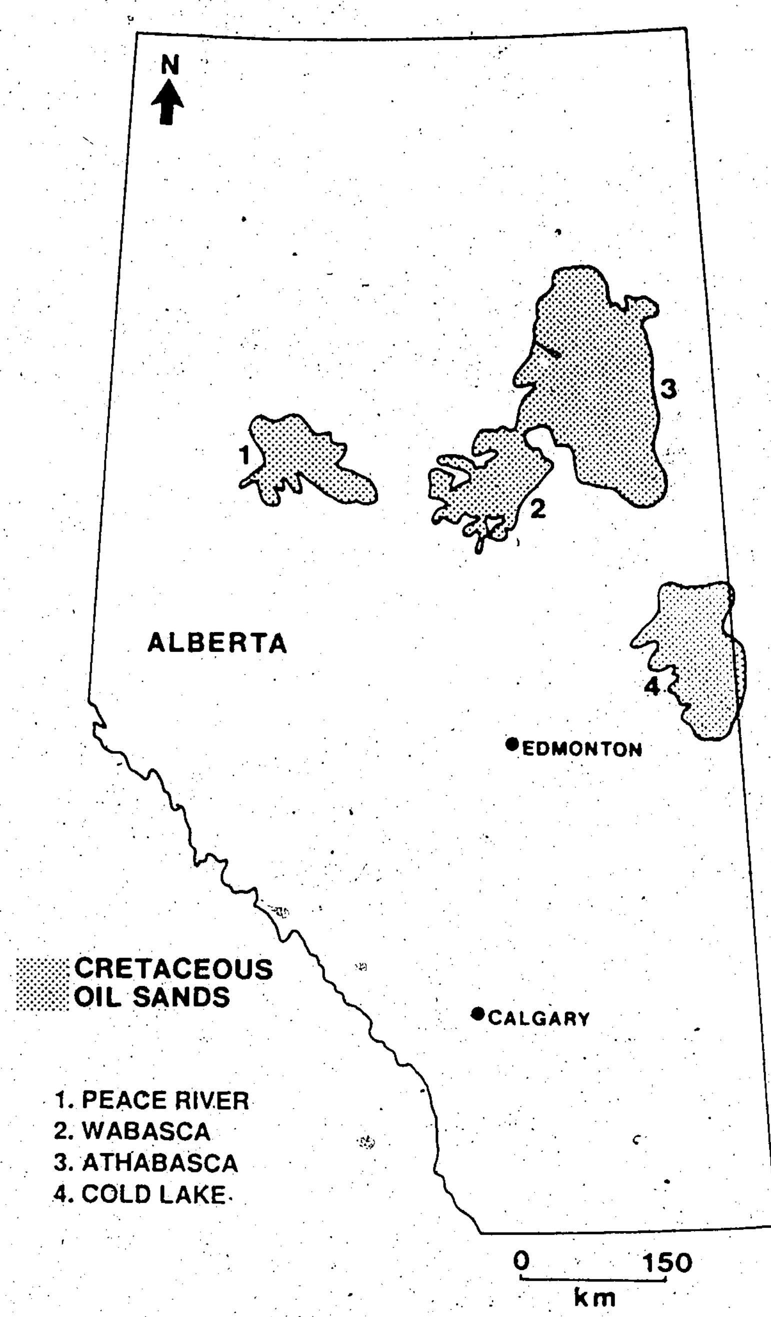


Fig. 2. Cretaceous Oil Sands of Western Canada (modified from Mossop *et al.* 1982).

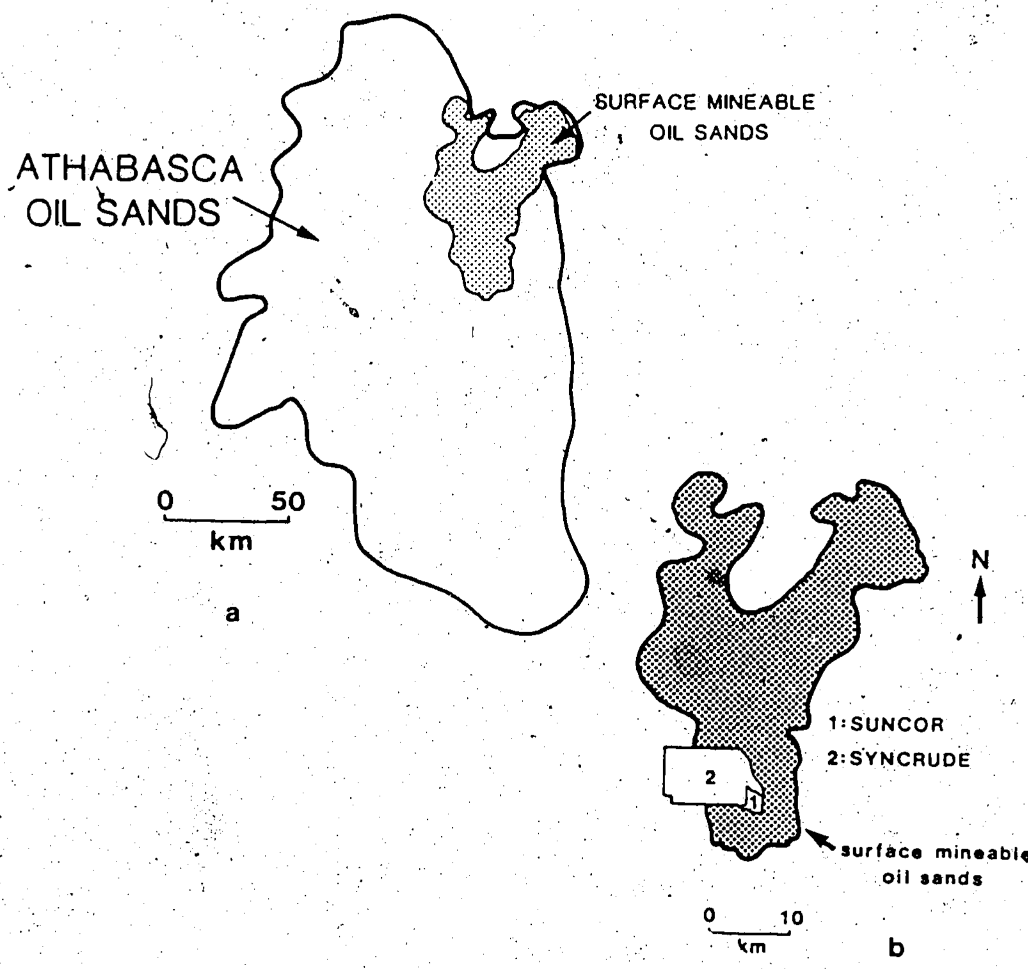
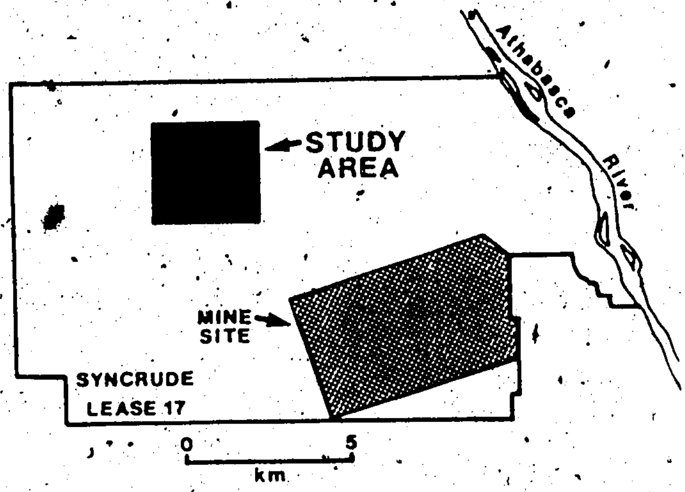
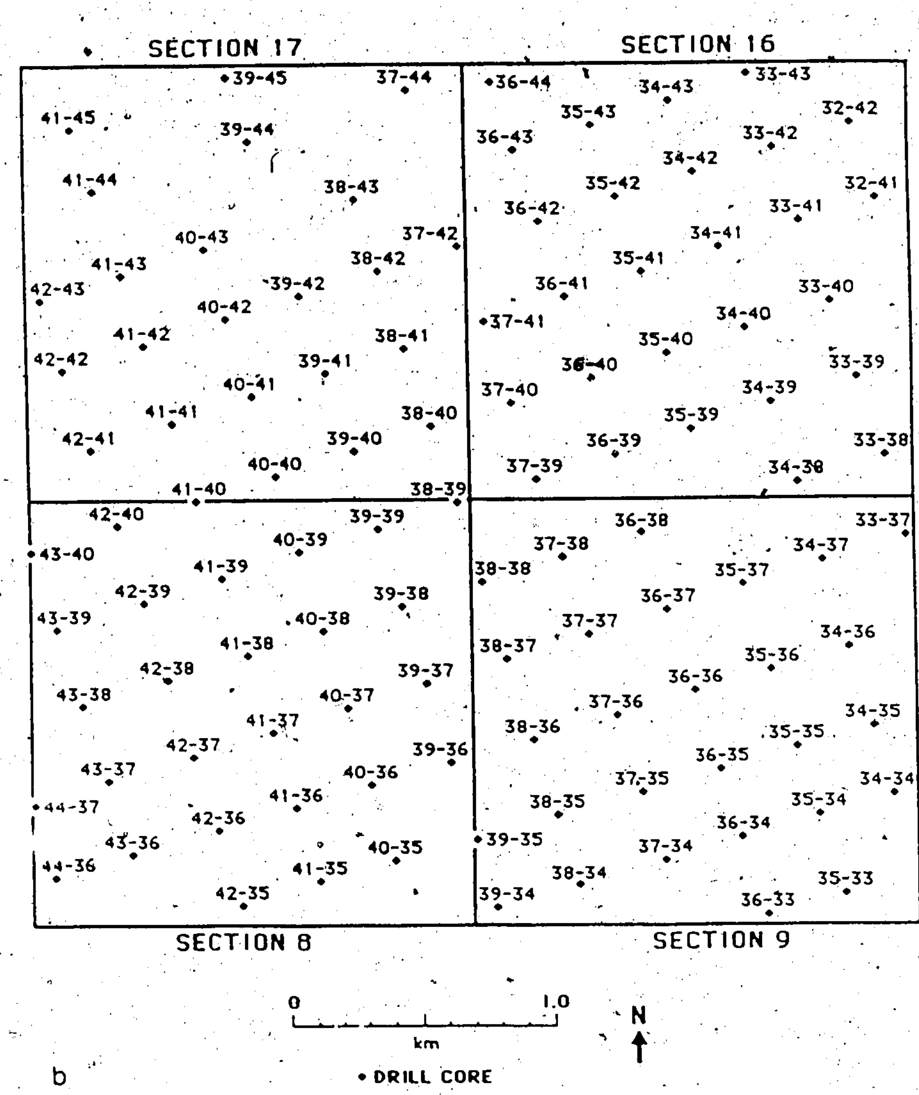


Fig. 3. Athabasca Oil Sands of northeastern Alberta. (a) Extent of the deposit and surface mineable area. (b) Surface mineable area with location of surface mining operations of Suncor(1) and Syncrude(2) (modified from Govier 1974).

Figure 4. (a) Location of current study area and operating mine, Syncrude Oil Sands Lease 17. (b) Current study area (sections 8, 9, 16, 17, Township 93, Range 11, west of 4th Meridian) with core locations and designation numbers.


STUDY
AREA
Athabasca River
MINE
SITE
SYNCRUDE
LEASE 17
0
5
km

a


SECTION 17
SECTION 16
SECTION 8
SECTION 9
0
1.0
km
N
• DRILL CORE

b

The northern edge of the deposit has been truncated by glacial scour while the southern limit is pooly defined (Carrigy 1959). The Athabasca Oil Sands deposit is considered to be the single largest accumulation of hydrocarbon in the world (Demaison 1977), with estimated reserves of 918 billion barrels (145,870 x $10^6 m^3$) of crude bitumen (Energy Resources Conservation Board 1982). It has an areal extent of 23,268 km^2 and a surface mineable area (defined as oil sands with 46m or less of overburden) of 2,023 km^2 (Fig. 3) (Govier 1974). Overburden, consisting of glacial debris and Cretaceous sediments, range in thickness from 0 to 610m (Govier 1974). Currently commercial extraction of crude bitumen is taking place at two surface mining operations. In 1983, Suncor Inc. produced 47,839 barrels (7.6 x 10^3 m^3) of crude bitumen per day while Syncrude Canada Limited produced 112,000 barrels (1.8 x $10^4 m^3$) per day (Gardiner 1984).

Present Study Area

The area on which this study has focused is located in the surface mineable area of the Athabasca Oil Sands, approximately 40km north-northwest of Fort McMurray. According to the Dominion Land Survey System the study area consists of sections 8, 9, 16 and 17, Township 93, Range 11, west of the Fourth Meridian (Alberta-Saskatchewan border). This 10km^2 area is located within Syncrude Oil Sands Lease 17 (now known as Oil Sands Agreement 0979120003) and is approximately 3km northwest of Syncrude's operating mine (Fig. 4a). A total of 108 drill cores from the study area, with spacing of approximately 300m, were examined in detail (Fig. 4b).

Previous work

Regional McMurray Formation

Since the late nineteenth century, the Athabasca Oil Sands and the McMurray Formation have been the subject of intense scrutiny by geologists. Beginning with a reconnaissance study by Bell (1885) and a detailed investigation by McConnell (1893), numerous workers have grappled with various aspects of the McMurray Formation and proposed a wide variety of depositional models for the sequences observed in both outcrop and core (Table 1).

Early studies (McConnell 1893; McLearn 1917, 1932; Russell 1932; Warren 1933) were concerned mainly with local stratigraphy of the Athabasca deposit as well as its correlation to other Lower Cretaceous sequences in the Western Canada Sedimentary Basin. Other studies (e.g. Ells 1914, 1915, 1926; Clark and Blair 1927) focused on the physical and chemical properties of the oil sands, the regional extent and volume of the deposit, and primarily, methods of exploiting this vast resource.

From the 1930's to the 1950's, workers of the Athabasca deposit became preoccupied with the origin of the bitumen in the oil sands (e.g. Hume 1934, 1949, 1951, 1955; Ball 1935; Sproule 1938, 1951; Link 1951, 1954; Corbett 1955a, b). Formulation of a depositional model for the sequences of the McMurray Formation seemed to have been of secondary importance with little or no evidence provided with their proposals.

A new era in the geological study of the McMurray Formation began with a brief paper by Kidd (1951) and reached full force with the work of Carrigy (1959, 1962, 1963a, b, c, 1966, 1967, 1971, 1973b). Detailed stratigraphy, mineralogical studies, paleocurrent analysis and the use of sedimentary structures and stratification sequences helped develop a workable depositional model that was not challenged until the mid

Author	Unit	Subdivisions	Environmental interpretations
McLearn 1932	MCMURRAY FORMATION	upper	marine influenced restricted sea
		lower	alluvial plain
Russell 1932	MCMURRAY FORMATION	upper part of formation; calcareous unit	near-estuarine; estuarine; lacustrine; fluvial
Hume 1934, 1949, 1951, 1955	MCMURRAY FORMATION	upper	marine beds
		lower	delta or alluvial fan; marine shoreline — lagoons, embayments, estuaries
Kidd 1951	MCMURRAY FORMATION		broad flood plain or coastal lowland (no evidence of marine influence)
Falconer 1951	MCMURRAY FORMATION	upper	marine
		middle	deltaic to estuarine
		lower	fluvial
Sproule 1951, 1955	MCMURRAY FORMATION		nearshore sand bar or delta prograding into Clearwater Sea
Link 1954	MCMURRAY FORMATION	barrier island	lagoon — freshwater, brackish water; aeolian sands; nearshore (shoreface)
Corbett 1955a,b	MCMURRAY FORMATION	lagoon; bay	brackish to marine
		fluvial flood deposits	
Carrigy and Zamora 1960; Carrigy 1966, 1967, 1971 (data source: - outcrop, - core, - well logs)	MCMURRAY FORMATION	upper	delta topset beds — lagoonal (estuarine, fresh); lacustrine
		middle	delta foreset beds
		lower	fluvial channel; fluvial floodplain

Table 1. Previous work, McMurray Formation, Athabasca Oil Sands with stratigraphic subdivisions and environmental interpretations.

Author(s)	Data source	Formation	Subdivision	Interpretation
Jardine 1974		MCMURRAY FORMATION	upper	marine; estuarine (bulk of McMurray); fluvial
			lower	fluvial (restricted distribution)
Gallup 1974		MCMURRAY FORMATION	upper member	offshore; shoreface
			middle member	(wave-dominated) delta: lagoon; dunes; bottomset, foreset, topset (delta)
			lower member	brackish lake
James 1977; James and Oliver 1977	core; well logs	MCMURRAY FORMATION	Unit C	interdistributary bay; deltaic (possible tidal influence); nearshore marine
			Unit B	braided stream (channel)
			Unit A	lakes; poorly drained marshes; interdistributary bays; estuaries
Benthin and Orgnero 1977	core; well logs	MCMURRAY FORMATION	upper	coastal swamp
			middle	meandering stream (point bar)
			lower	braided stream
Nelson and Glaister 1978	core; well logs	MCMURRAY FORMATION	Upper Unit	shallow bays and lagoons; distributary channels, crevasse splays, shoreface(?) (minor)
			Middle Unit	distributary channels; interdistributary beaches; offshore shales
			Lower Unit	distributary channels; interdistributary offshore sands and shales
Knight *et al.* 1981	core; well logs	MCMURRAY FORMATION	Unit 2	shoreface/beach; shallow nearshore
			Unit 1	distributary or estuarine channel; off-channel bay
Rennie 1983	core; well logs; outcrop; mine highwalls	MCMURRAY FORMATION	Marine	
			Estuarine	tidal channel; tidal flats; salt marsh; storm spillover; fluvial/estuarine channel
			Delta Marsh	distributary channel; bay/pond; crevasse splay
			Early Fluvial	

Table 1. (continued)

MacCallum 1977
Stewart and MacCallum 1978
Stewart 1981
Wach 1984
Wach *et al.* 1986
Tammam and Wach 1986
Tammam *et al.* 1986

data source:
- core
- well logs
- outcrop
- mine highwall

MCMURRAY FORMATION
- UPPER
  - nearshore marine
    - foreshore
    - shoreface
    - offshore
  - estuarine
    - shoals
    - lagoon
- MIDDLE - estuary
  - channel
  - tidal flat
    - sand flat
    - mixed flat
    - mud flat
  - supratidal marsh
- LOWER - coastal plain
  - channel
  - overbank
  - swamp/marsh
  - lake/pond

Flach 1977
Mossop 1978
Mossop 1980 a, b
Mossop *et al.* 1982
Mossop and Flach 1983
Flach 1984
Flach and Mossop 1985
Pemberton *et al.* 1982

data source:
- outcrop
- core
- well logs

MCMURRAY FORMATION
- upper member
  - coastal complex
    - lakes
    - brackish bays
    - swamps
  - off-channel deposits of middle member channels
- middle member
  - subaqueous floodplain
    - crevasse splay
    - lakes
    - brackish bays
  - lateral accretion deposits (epsilon cross-strata)
  - channel (thalweg)
  - (lateral accretion deposits and channel: periodic marine invasion)
- lower member
  - fluvial channel
    - meandering
    - braided
  - overbank

Smith 1985, 1987

data source:
- outcrop
- core

MCMURRAY FORMATION
- middle member only
  - point bar deposits of meso tidally influenced meandering rivers

Table 1. (continued)

seventies. It is not surprising that Carrigy (1966, 1967, 1971) proposed the deltaic model for the McMurray Formation as it was perhaps the best studied and most published depositional model available to clastic sedimentologists at that time. As an increasing number of different depositional models became available to workers in ancient sediments during the mid sixties to early seventies it became clear that the deltaic depositional model for the McMurray Formation could be put under greater scrutiny.

With the "energy crisis" of the early 1970's, interest in the Athabasca Oil Sands increased substantially. Sedimentological studies focused on small areas of interest (Fig. 5) in the Athabasca deposit were numerous (Flach 1977; James 1977; Benthin and Orgnero 1977; Nelson and Glaister 1978; Mossop 1980a; Knight *et al.* 1981; Wach 1984). Most of these applied the principles of facies analysis to formulate a depositional model of the McMurray Formation. All but one (Flach 1977) were subsurface studies, often utilizing petrophysical well logs. From these two main depositional models developed and gained general acceptance: the estuarine model of Stewart and co-workers (MacCallum 1977; Stewart and MacCallum 1978; Stewart 1981; Wach 1984); and the fluvial model of Mossop and Flach (Flach 1977, 1984; Mossop 1978, 1980a, b; Mossop *et al.* 1982; Mossop and Flach 1983; Flach and Mossop 1985). Recent work by Smith (1985, 1987) proposed a merger of these concepts arguing that both are compatible to the estuarine depositional model.

Present study area McMurray Formation

Wach (1984) included the southeast quarter of the current study area (Section 9, Township 93, Range11 west of the Fourth Meridian) in his examination of the McMurray Formation. The study area has also been the subject of continuous investigation by Syncrude

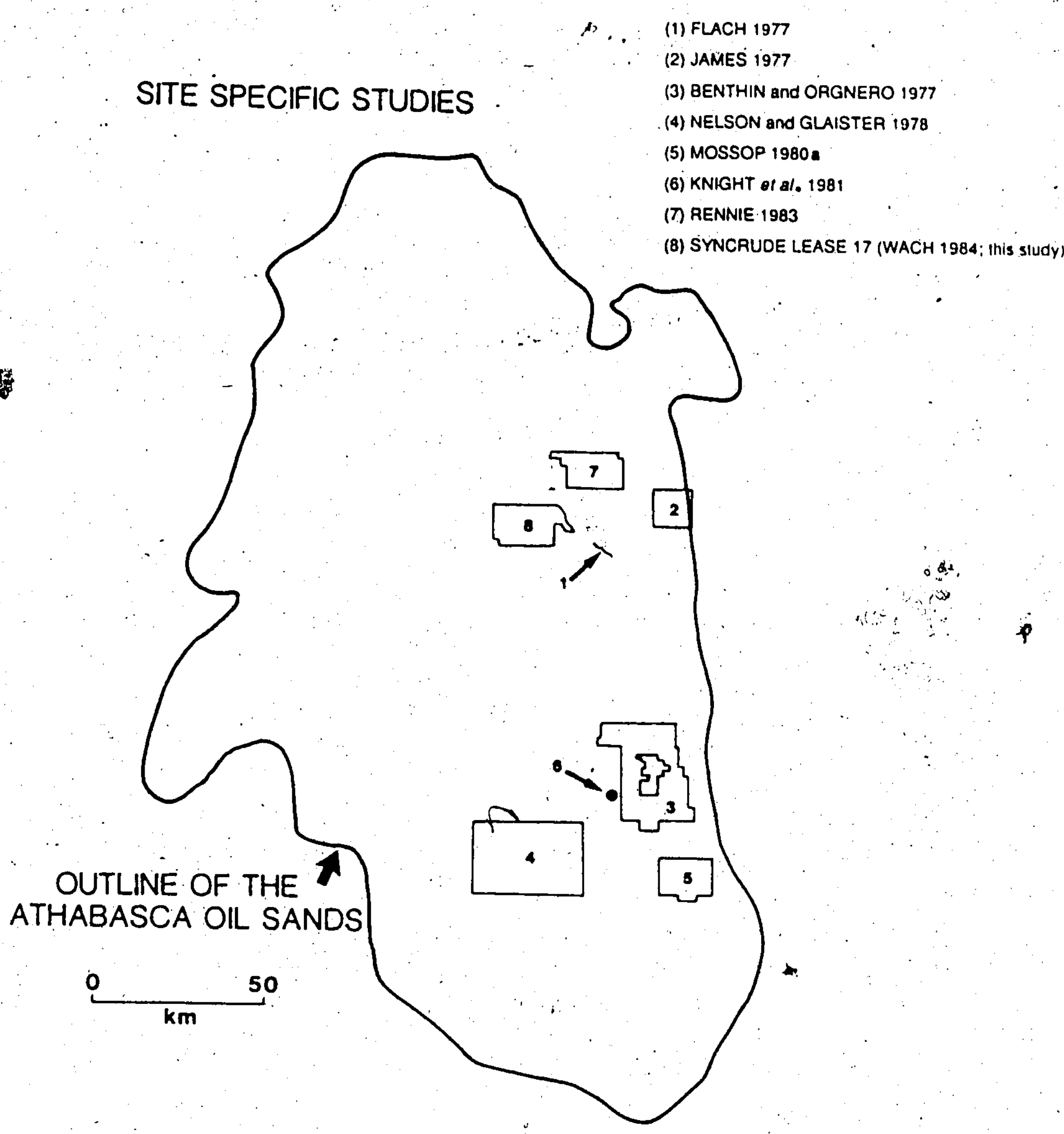


Fig. 5. Location of site specific studies of the McMurray Formation in the Athabasca Oil Sands.

geologists as well as consultants because of its potential as an expansion site for future open pit mining. This work however is confidential and was not made available to the author. Mattison (1987) completed a detailed paleontological examination of the McMurray Formation in the same area of study. The present study was carried out independent from the work of Mattison (1987) and Syncrude and associated geologists.

STRATIGRAPHY

Fort McMurray area

Pre-Cretaceous sequences

In the Athabasca Oil Sands area, Devonian evaporites and carbonates unconformably overlie Precambrian basement (Carrigy 1973a). The Devonian sequence pinches out against the Canadian Shield in the east and thickens westward attaining a thickness of 350m in the Athabasca Oil Sands area (Norris 1973). Strata dip toward the west, with stratigraphic units becoming progressively younger from east to west.

The Devonian sequence (Fig. 6a) consists of: Lower to Middle Devonian dolomite, anhydrite, gypsum and halite of the Elk Point Supergroup; limestone and dolomite of the Middle Devonian Slave Point Formation; and Upper Devonian limestone and dolomite of the Beaverhill Lake and Woodbend groups (Carrigy 1959; Norris 1973). Along the banks of the Athabasca River and many of its tributaries calcareous shale and limestone of the Waterways Formation (Beaverhill Lake Group) can be observed in outcrop (Warren 1933; Norris 1973). The Waterways Formation underlies Lower Cretaceous strata in the current study area, as is indicated by existing maps (Stewart 1963; Norris 1973) of Devonian

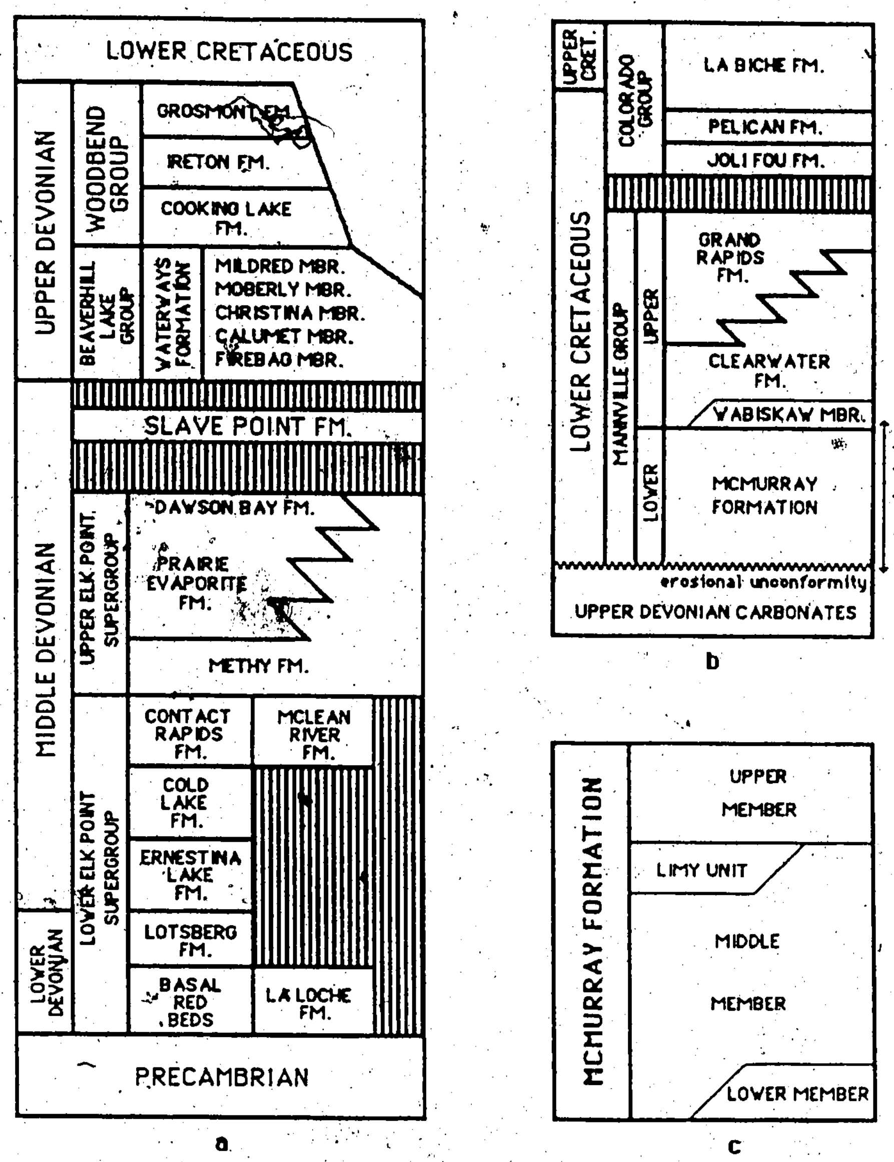


Fig. 6. Stratigraphy of the Athabasca Oil Sands. (a) Pre-Cretaceous (modified from Norris 1973). (b) Lower to Upper Cretaceous (modified from Carrigy 1959, 1973a). (c) Stratigraphic subdivisions of the McMurray Formation in the present study.

strata at the Devonian-Cretaceous boundary (Fig. 7).

Pre-Cretaceous unconformity surface

Lower Cretaceous strata unconformably overlie Upper Devonian carbonates in the McMurray area (Bell 1884; McConnell 1893). This unconformity surface is widespread throughout northeastern and central Alberta (Glaister 1959; Stewart 1963; Park and Jones 1985). There is no evidence of any deposition between the Upper Devonian and the Lower Cretaceous in northeastern Alberta (Carrigy 1959; Stewart 1963; Park and Jones 1985).

Cretaceous sequences

Overlying the unconformity surface in the Athabasca Oil Sands area is a sequence of Lower to Upper Cretaceous sediments. These include (Fig. 6b) the (bottom to top): McMurray; Clearwater; Grand Rapids; Joli Fou; Pelican; and La Biche formations (Carrigy 1959). Only the McMurray and Clearwater formations were encountered during the current study.

The McMurray Formation (McLearn 1917) is defined as the Lower Cretaceous strata in the Athabasca Oil Sands area lying unconformably over Upper Devonian carbonates and whose "top is placed at the base of a green sandstone" (McLearn 1917, p. 147). Typically the McMurray Formation is subdivided into three informal lithologic subdivisions known as the lower, middle and upper members (Carrigy 1959; Flach 1977). These subdivisions were recognized during this examination of the McMurray Formation (Fig. 6c). A fourth subdivision, referred to in this study as the limy unit, was also recognized and is situated between the middle and upper members. Both the lower member and the limy unit have

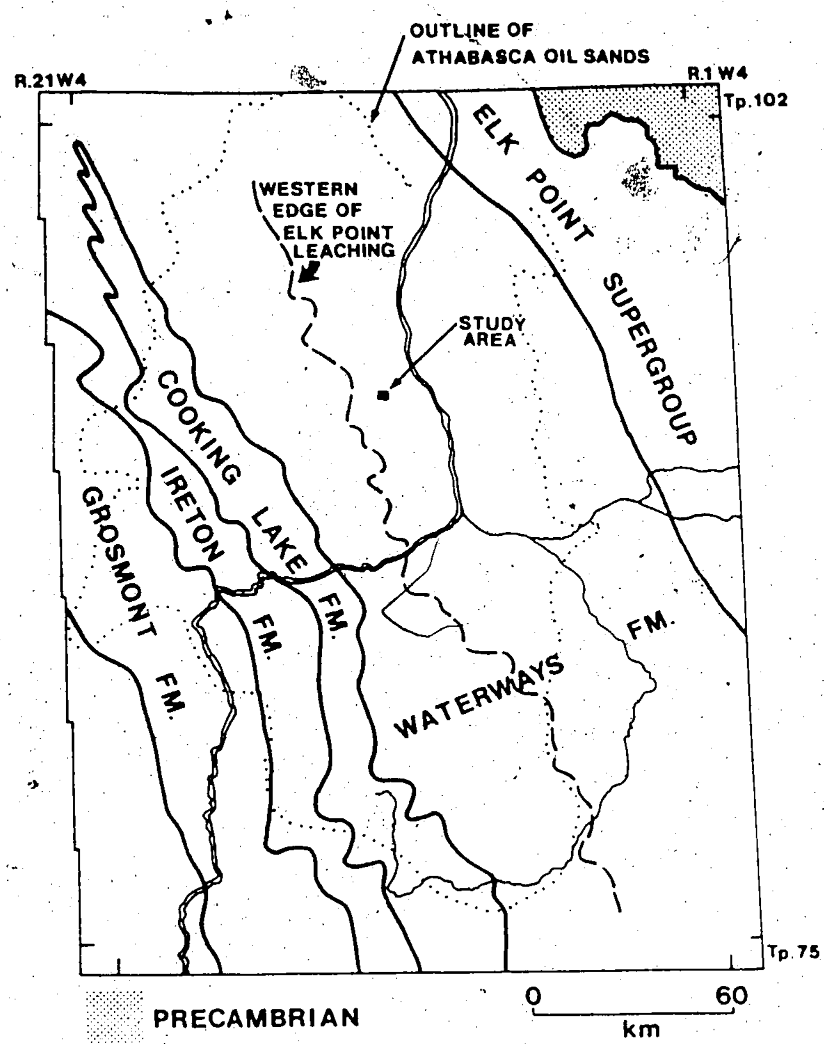


Fig. 7. Stratigraphy of the unconformity surface (pre-McMurray Formation) in the Athabasca Oil Sands area. Western edge of Elk Point Supergroup leaching also indicated (modified from Stewart 1963; Norris 1973).

limited lateral distribution in the present study area whereas the middle and upper members are present in all the drill cores examined. Boundaries of the four subdivisions are typically distinct but there are examples when contacts are vague. A "pre-McMurray" unit (Carrigy 1966) has not been recognized in this study. Because of the lack of body fossils in the McMurray Formation, ages of this stratigraphic unit range from Neocomian to earliest Albian times (Fig. 8).

The Clearwater Formation (McConnell 1893) conformably overlies the McMurray Formation. The base of the Clearwater Formation is defined as the bottom of a well-defined glauconite sand (McLearn 1917; Carrigy 1959). The Clearwater Formation has a gradational upper contact with the Grand Rapids Formation in the Athabasca Oil Sands area (Carrigy 1959). The appearance of glauconite at the base of the Clearwater Formation is the main physical criteria that differentiates it from the underlying McMurray Formation. In the present study the first appearance of glauconite marks the contact between the McMurray and Clearwater formations. This contact has been used as the structural and stratigraphic datum in this study. The glauconitic sands constitute the Wabiskaw Member (Badgley 1952) of the Clearwater Formation which is found at the base of the Clearwater Formation throughout the Athabasca Oil Sands area (Carrigy 1959). The Wabiskaw Member was not differentiated from the rest of the Clearwater Formation during the course of this study because of the incompleteness of the cored stratigraphic record.

Regional Stratigraphy

The Mannville Group (Nauss 1945; Badgley 1952) is defined as the sequence of Lower Cretaceous strata from the base of the Joli Fou Formation to the top of the pre-Cretaceous unconformity surface (Badgley 1952). In the Athabasca Oil Sands area the Mannville Group

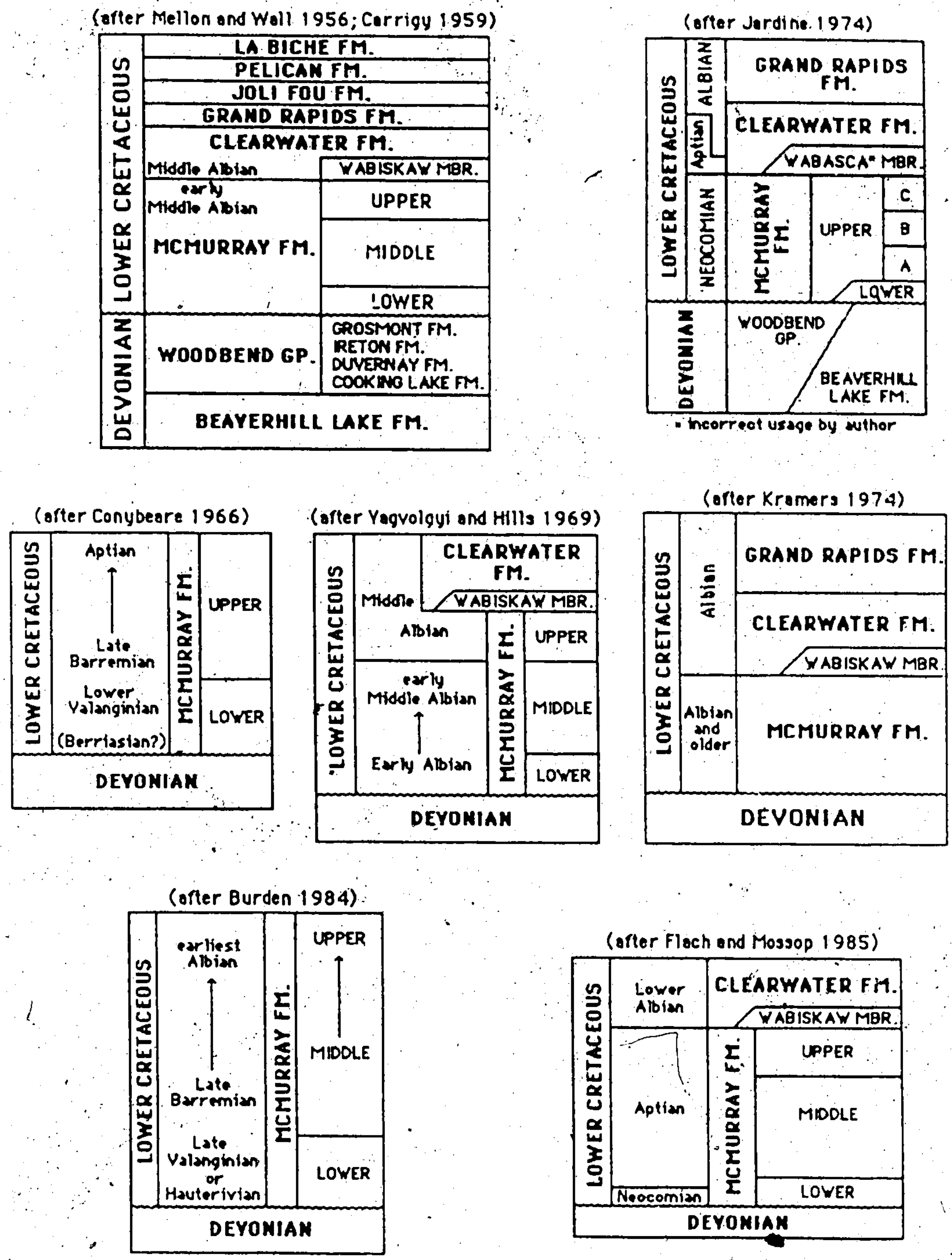


Fig. 8. Proposed ages of the Lower Cretaceous McMurray Formation.

is composed of the McMurray, Clearwater and Grand Rapids formations (Williams 1963). The lower part of the Mannville Group consists of all the strata below the glauconitic sands (Wabiskaw Member of the Clearwater Formation) and above the top of the unconformity surface (Glaister 1959). The McMurray Formation has been equated (Fig. 9) to the lower part of the Mannville Group (Badgley 1952) in central Alberta (Williams 1963), the Dina Formation in the Lloydminster area and southern Saskatchewan (Nauss 1945; Christopher 1980), and the Gething (Bullhead Group) and Gladstone (Blairmore Group) formations in northwest Alberta and the Canadian Rocky Mountain Foothills (McLearn 1945; Mellon 1967).

STRUCTURE

Athabasca Oil Sands

The Precambrian surface underlying the Athabasca Oil Sands area dips toward the west at approximately 4m/km (Carrigy 1959; Norris 1972). Post-Cretaceous tilting is estimated to be approximately 1m/km over most of the McMurray area (Martin and Jamin 1963).

The McMurray Formation was deposited in a broad north-northwest trending basin or syncline bounded by the Canadian Shield in the east and a ridge of resistant Devonian carbonates in the west (Stewart 1963; Vigrass 1965). The McMurray sedimentary basin (Carrigy 1967) developed as the result of the solution of soluble evaporites in the Elk Point Supergroup along the edge of the Canadian Shield (Stewart 1963). Solution of the evaporites caused the collapse and subsidence of the overlying carbonates of the Waterways Formation, forming the basin where sediments accumulated (Carrigy 1959; Stewart 1963; Martin and Jamin 1963). Salt collapse continued during and after deposition of the

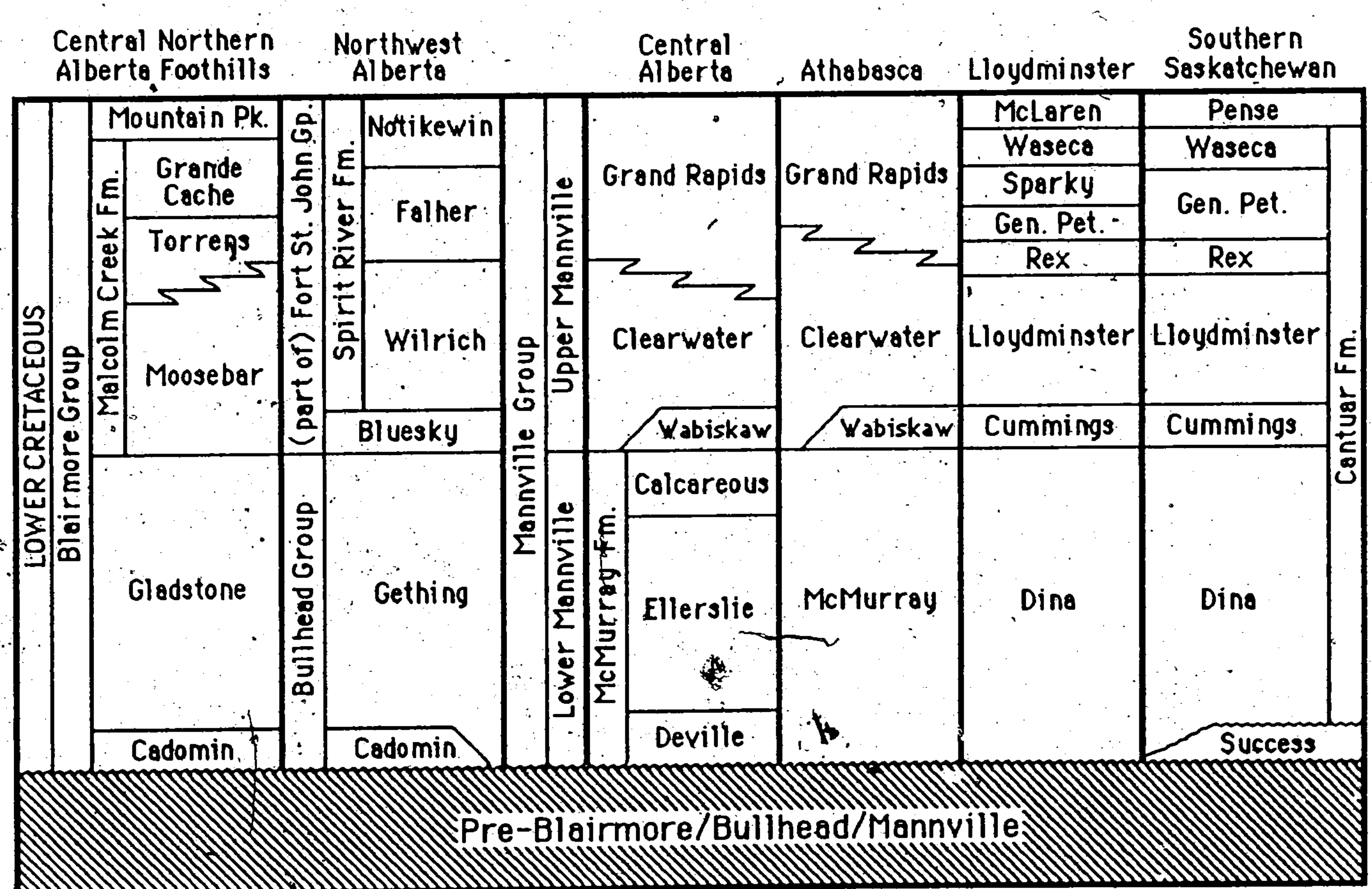


Fig. 9. Regional stratigraphic correlation of part of the Lower Cretaceous of the Canadian Rocky Mountain Foothills, central Alberta, Athabasca Oil Sands, Lloydminster and southern Saskatchewan (modified from McLearn 1945; Nauss 1945; Glaister 1959; Williams 1963; Mellon 1967; Kramers 1974; Christopher 1980; McLean and Wall 1981).

McMurray Formation (Carrigy 1959; Stewart 1963). Solution of these evaporites is still taking place today as is indicated by the presence of numerous saline springs in the Athabasca Oil Sands area (Carrigy 1959).

The structure of the unconformity surface played a major role in controlling deposition of the McMurray Formation. The McMurray Formation tends to be thickest where the unconformity surface has a low elevation and thins in areas of higher elevation (Hume 1947; Stewart 1963). The unconformity surface is irregular and deeply incised with slopes as high as 70m/km (Martin and Jamin 1963). Lithology appears to be the dominant structural control on drainage patterns that developed on the unconformity surface. The westward dip of the Upper Devonian strata resulted in the formation of a surface characterized by north-northwest trending ridges of resistant carbonates separating valleys cut into less resistant lithologies (Martin and Jamin 1963). The most important of the ridges was the Grosmont ridge which served as the western boundary of the Athabasca Oil Sands (Stewart 1963; Stewart and MacCallum 1978). The north-northwest trend of the drainage pattern on the unconformity surface also coincides with the dominant direction of fractures in the Athabasca Oil Sands area, the trend of the western edge of leaching evaporites of the Elk Point Supergroup, and major structural lineaments in the Precambrian underlying the Athabasca Oil Sands (Babcock and Sheldon 1976; Stewart 1963).

Study area

On a map of the unconformity surface (modified from Flach 1984) for the Athabasca Oil Sands north of Township 90, the current study area can be seen located on the western edge of a major northwest trending valley which enters a much broader valley north of

Township 94 (Fig. 10).

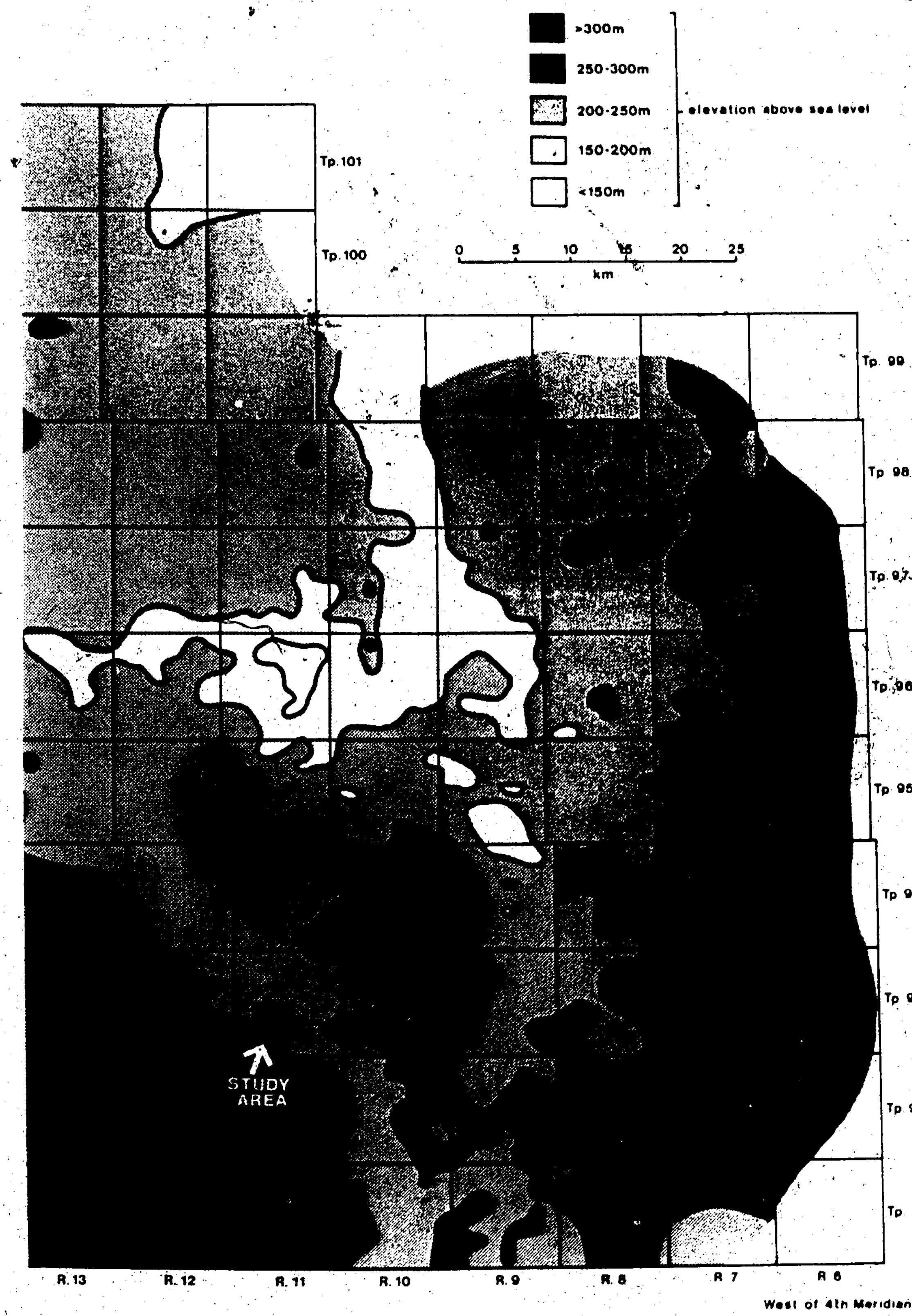
Examination of the map of the unconformity surface (Fig. 11), as well as the isopach of the McMurray Formation (Fig. 12) (which provides a cast of the unconformity surface at the time of deposition), reveals a valley across the south-central part of the study area. The axis of the valley stikes west-northwest. The thickest sequences of the McMurray Formation were deposited in this valley. Possible evidence for syndepositional collapse of underlying carbonates is indicated by the "bull's eye" on both the map of the unconformity surface and the isopach of the McMurray Formation in the northeast part of the study area. Drill core 35-42 reveals the maximum thickness for the McMurray Formation (69.5m) and the lowest elevation on the unconformity surface (216.4m above sea level). The map of the unconformity surface also reveals a low area on the northeast part of the study area but there is no evidence of thickening of the McMurray Formation. This possibly represents a post-McMurray Formation collapse feature.

GEOLOGICAL FRAMEWORK

Alberta Basin: Lower Cretaceous

Situated between a back arc fold and thrust belt and a stable craton (Fig. 13a) is a physiographic feature known as a retroarc or foreland basin (Dickinson 1976). This basin runs parallel to the fold and thrust belt and has a wedge-shaped transverse profile thinning toward the craton and thickening at the edge of or within the fold and thrust belt (Dickinson 1976; Beaumont *et al.* 1982). The Alberta Basin, which prior to the late Jurassic was a passive margin on the western edge of North America, was transformed into a foreland basin during late Jurassic to Paleocene times as the result of collision and accretion of a number of exotic terranes along the continental margin (Porter *et al.* 1982). During the

Figure 10. Map of the unconformity surface (pre-McMurray Formation) in the northern part of the Athabasca Oil Sands (north of Township 90) (modified from Flach 1984) with current study area superimposed on it (sections 8, 9, 16, 17, Township 93, Range 11, west of the 4th Meridian).



>300m
250-300m
200-250m
150-200m
<150m
elevation above sea level
0 5 10 15 20 25
km
Tp.101
Tp.100
Tp. 99
Tp 98
Tp. 97
Tp. 96
Tp 95
Tp 94
Tp 93
Tp 92
Tp 91
STUDY AREA
R.13
R.12
R.11
R.10
R.9
R.8
R 7
R 6
West of 4th Meridian

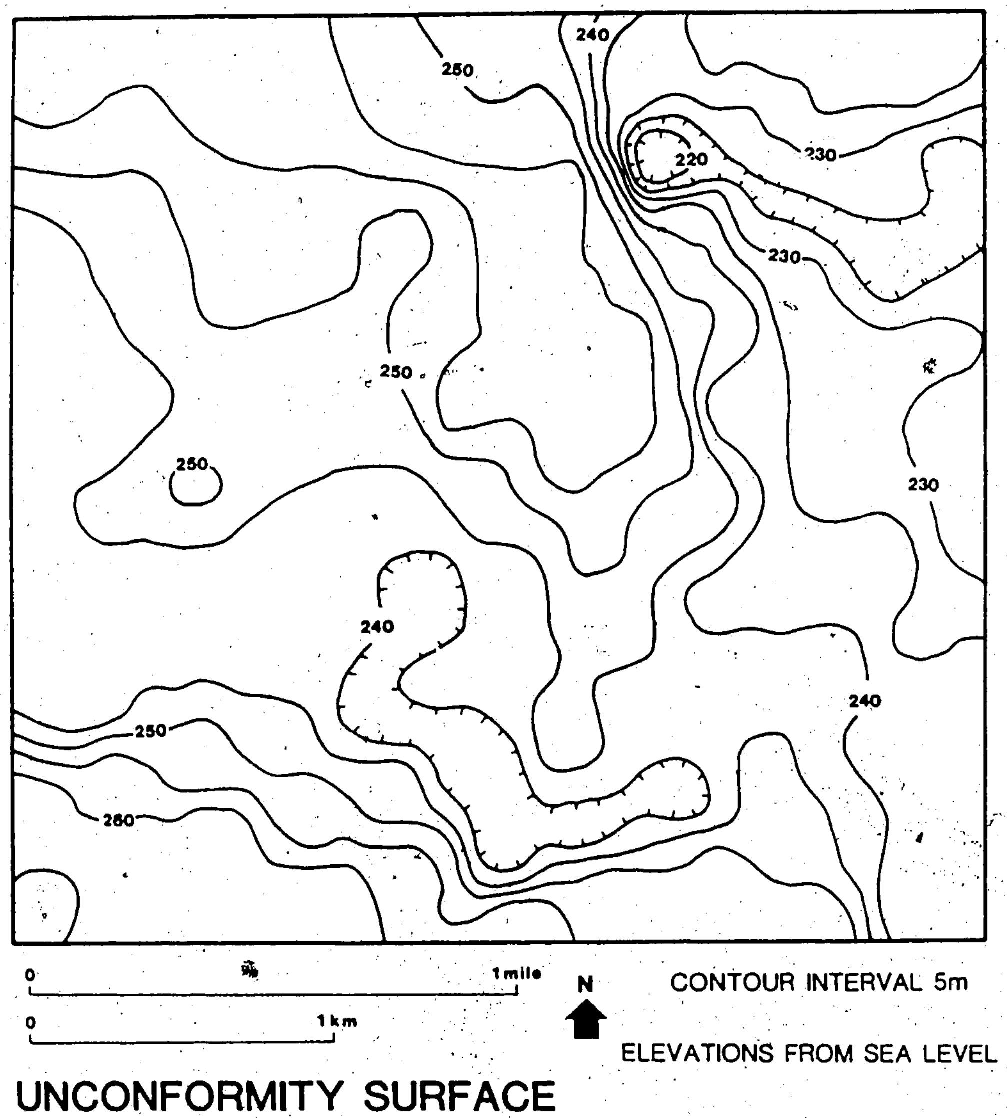


Fig. 11. Map of the unconformity surface (pre-McMurray Formation) for the current study area.

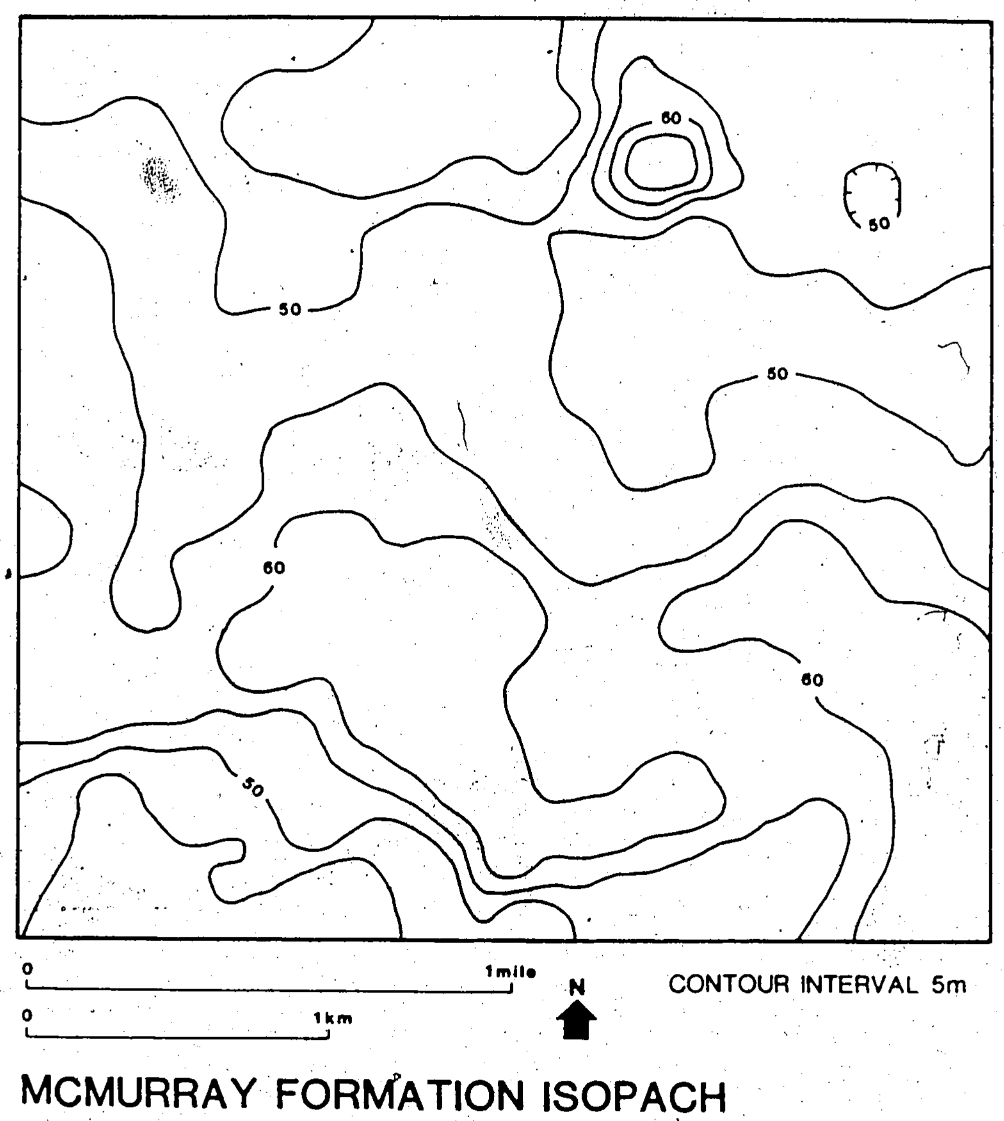


Fig. 12. Isopach of the McMurray Formation for the current study area.

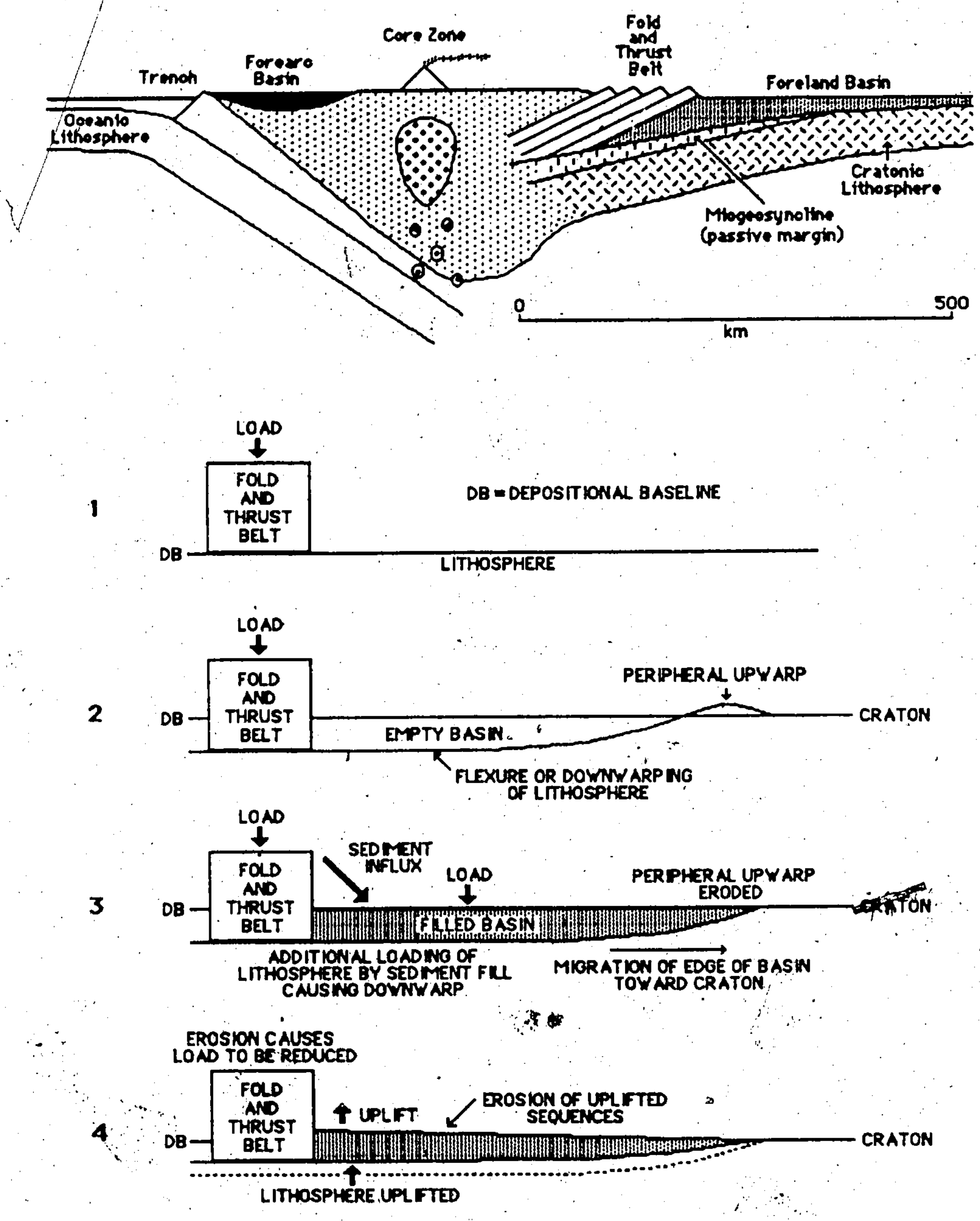
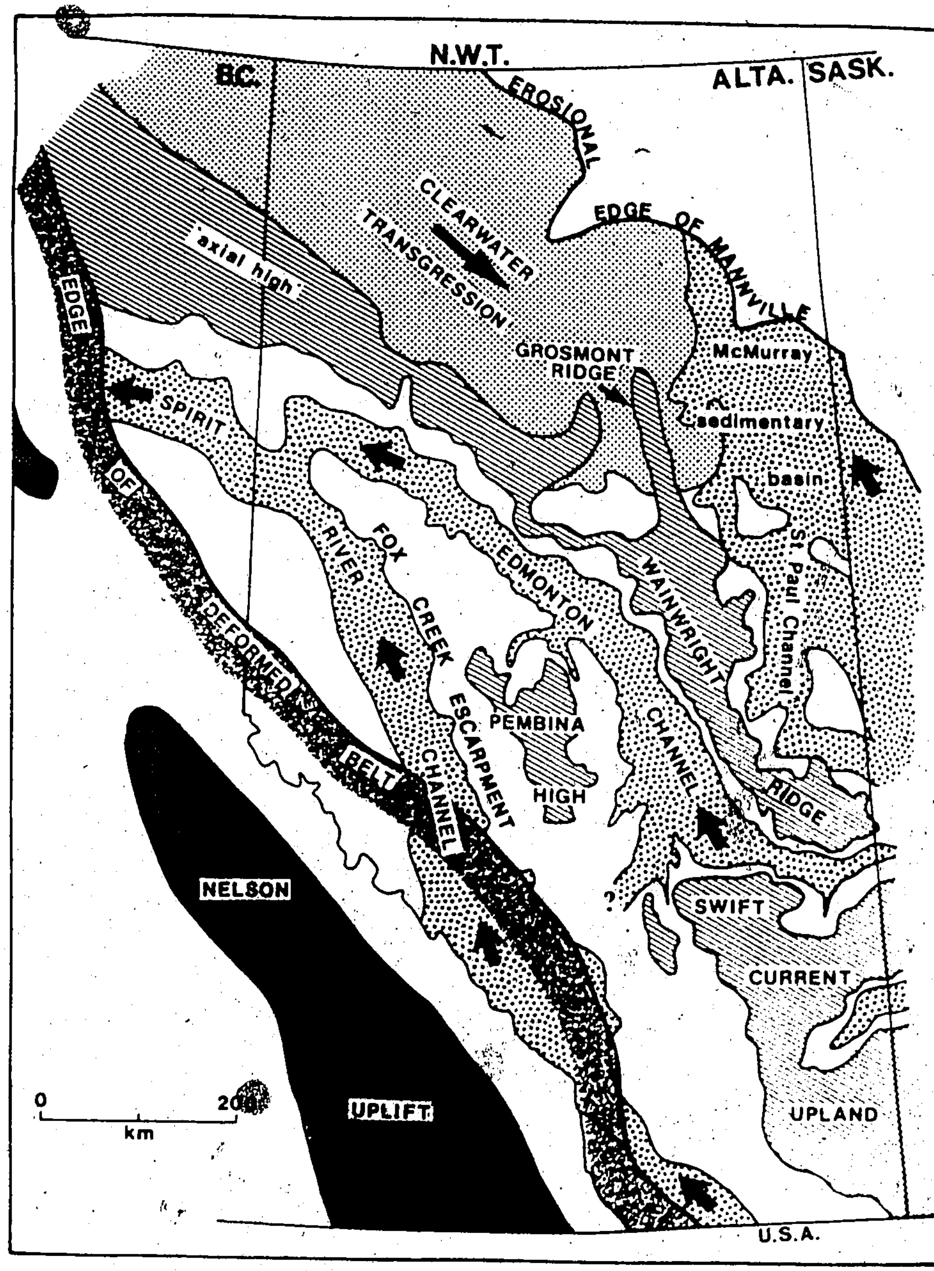


Fig. 13. (a) Destructive plate margin with oceanic crust subducting under continental crust showing development of a fold and thrust belt and adjacent foreland basin (modified from Dickinson 1976; Beaumont 1981). (b) Schematic for the development of a foreland basin as a result of crustal loading in a fold and thrust belt (modified from Price 1973; Beaumont 1981).

Columbian Orogeny (late Jurassic to early Cretaceous), tectonic thickening and eastward thrusting of the continental margin resulted in the development of the foreland basin that greatly influenced sedimentation throughout the Alberta Basin (Porter *et al.* 1982; Jackson 1984). In order to compensate for loading of the lithosphere in the fold and thrust belt, flexure or downwarping occurred producing a basin which was subsequently filled with sediments derived from the erosion of the rising Cordillera in the west and the Canadian Shield in the east (Fig. 13b) (Price 1973; Beaumont 1981). Additional downwarping may have occurred as a result of the weight of the sediment fill (Beaumont 1981). Subsidence could continue as long as the load on the lithosphere was maintained. However if the load was reduced via large-scale erosion in the Cordillera, uplift in the foreland basin would occur resulting in periods of erosion (Beaumont 1981).

The Columbian Orogeny is marked by two clastic wedges in the Canadian Rocky Mountain Foothills (Stott 1984). The first stage of clastic input from the rising Cordillera is marked by the Jurassic to earliest Cretaceous sequences of the Fernie Formation and the Minnes and Kootenay groups (Stott 1984). Sedimentation during this stage was confined to the Foothills with little or no deposition occurring in the eastern part of the Alberta Basin (McLean and Wall 1981). Unconformably overlying these sequences are the Lower Cretaceous Blairmore Group of the Foothills, the Bullhead and Fort St. John groups of northwest Alberta and the Mannville Group in central and northeastern Alberta, and central and southern Saskatchewan (Stott 1984; Williams 1963; Christopher 1980). The unconformity surface that the Blairmore, Bullhead and Mannville groups were deposited on was deeply incised by three large northwest-trending valley systems separated by highland areas (Fig. 14). The Spirit River Channel flowed northward from the United States between the eastern margin of the Cordillera and the Fox Creek Escarpment (McLean 1977). In

Figure 14. Lower Cretaceous paleogeography prior to the deposition of the Mannville, Bullhead and Blairmore groups in Alberta and northeast British Columbia (modified from Williams 1963; Rudkin 1964; Carrigy 1967, McLean 1977; Stewart and MacCallum 1978, McLean and Wall 1981; Jackson 1984).

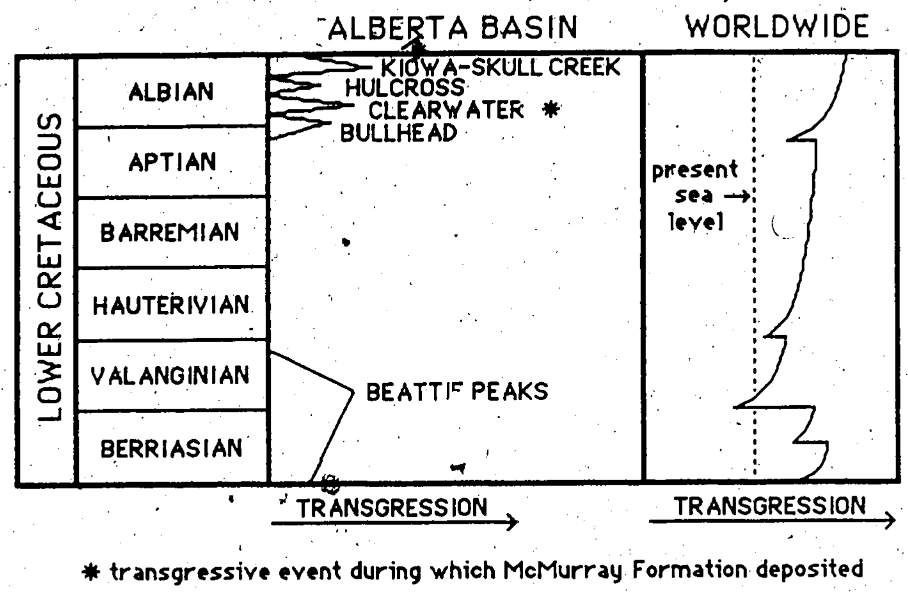

N.W.T.
B.C.
ALTA.
SASK.
EROSIONAL
EDGE OF MANNVILLE
CLEARWATER
TRANSGRESSION
'axial high'
EDGE
OF
DEFORMED
BELT
SPIRIT
RIVER
CHANNEL
FOX
CREEK
ESCARPMENT
EDMONTON
WAINWRIGHT
CHANNEL
RIDGE
GROSMONT
RIDGE
McMurray
sedimentary
basin
St. Paul Channel
PEMBINA
HIGH
SWIFT
CURRENT
UPLAND
NELSON
UPLIFT
0
200
km
U.S.A.

central Alberta, between the Pembina High and the Wainwright Ridge, the Edmonton Channel flowed northward merging with the Spirit River Channel in northwest Alberta and northeast British Columbia (Williams 1963; McLean and Wall 1981; Jackson 1984). The Wainwright Ridge was part of an axial highland that stretched from northeast British Columbia south to the Swift Current Upland in southern Alberta and Saskatchewan (Williams 1963; Rudkin 1964; Christopher 1980). Between the axial ridge and the western margin of the Canadian Shield another valley developed as the result of downwarping due to solution of Middle Devonian evaporites along the eastern edge of the Alberta Basin (Stewart 1963; Vigrass 1965; Christopher 1980). This eastern valley included the McMurray sedimentary basin in northeastern Alberta, and the Meadow Lake and Govan lowlands in central and southern Saskatchewan (Carrigy 1967; Christopher 1980). The St. Paul Channel (Williams 1963) was a tributary entering the southern part of the McMurray sedimentary basin (Carrigy 1967).

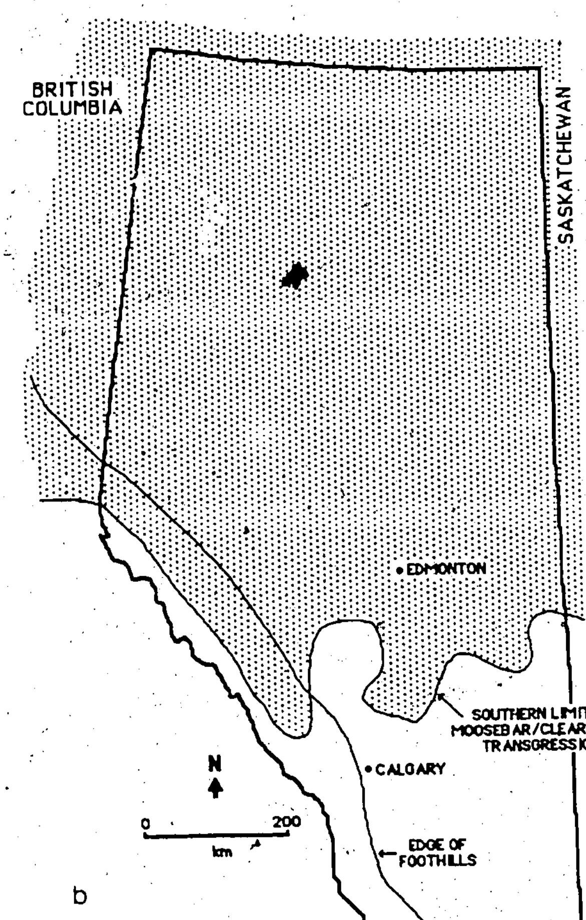
During early Albian times, the Lower Cretaceous boreal sea trangressed southward into Alberta and Saskatchewan (Williams 1963; Christopher 1980). This transgression into the McMurray sedimentary basin was facilitated by three factors. First of all the Alberta Basin was subsiding in response to crustal loading in the Cordillera during the Columbian Orogeny, resulting in the develpment of a foreland basin. Secondly, with the solution of Middle Devonian evaporites along the western edge of the Canadian Shield the McMurray sedimentary basin was subsiding. Finally, a global eustatic sea level rise during the Lower Cretaceous was taking place (Caldwell 1984).

Global sea level curves (Fig. 15a) reveal two transgressive cycles during the Lower Cretaceous (Vail *et al.* 1977). Each of these cycles was characterized by a number of second-order trangressions and regressions which greatly influenced sedimentation in the

Figure 15. Sea level curves showing global transgressions (modified from Vail *et al.* 1977) and transgressive phases in the Western Canada Sedimentary Basin during the Cretaceous (modified from Caldwell 1984). Clearwater transgressive phase during lower Albian is highlighted. (b) Southernmost transgression of Moosebar/Clearwater Sea in Alberta (modified from McLean and Wall 1981).


ALBERTA BASIN
WORLDWIDE
LOWER CRETACEOUS
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
KIOWA-SKULL CREEK
HULCROSS
CLEARWATER *
BULLHEAD
BEATTIE PEAKS
present sea level
TRANSGRESSION
TRANSGRESSION
* transgressive event during which McMurray Formation deposited

a


BRITISH COLUMBIA
SASKATCHEWAN
EDMONTON
SOUTHERN LIMIT OF MOOSEBAR/CLEARWATER TRANSGRESSION
CALGARY
N
0
200
km
EDGE OF FOOTHILLS

b

Alberta Basin (Caldwell 1984). The early Albian trangression which culminated with the deposition of the Clearwater Formation is considered to be part of a long-term rise in sea level that peaked during late Albian times with the deposition of the Joli Fou Formation (Caldwell 1984).

As sea level rose, the major valley systems were flooded and transformed into estuaries and eventually arms of the sea (Williams 1963; McLean and Wall 1981). As the transgression continued the highland areas separating the valleys were inundated and the boreal sea pushed as far south as 52°N in the west (Fig. 15b) and southern Saskatchewan in the eastern part of the Alberta Basin (McLean and Wall 1981; Christopher 1980). It was in this transgressive framework that the McMurray Formation of northeastern Alberta was deposited.

METHODS

Introduction

This study of the McMurray Formation focuses on its occurrence in the subsurface. The subsurface is defined as "the zone below the surface whose geological features, principally stratigraphic and structural, are interpreted on the basis of drill records and various kinds of geophysical evidence" (Bates and Jackson 1980, p.625).

Drill core studies differ significantly from those which utilize data obtained from outcrops (Cant 1984; Miall 1984). The use of drill cores has both advantages and disadvantages. Perhaps the most glaring short-coming of drill core is that it cannot provide the same amount of local data that an outcrop can provide (Cant 1984). Drill core has a narrow width (6cm in this study) and therefore local lateral relationships are virtually unknown. Large-scale sedimentary structures and features are very difficult to recognize whereas small- and medium-scale structures and features are most suitable because of their limited lateral extent (Miall 1984). For example, large-scale structures such as trough and planar tabular cross-stratification can be recognized in core but are difficult (if not impossible) to distinguish from one another. This can have significant environmental implications because these two types of cross-stratification are produced under different flow strengths.

When there is a distinct change in lithology, features such as scours are easy to recognize. However, often the observer is faced with the question of whether this scour is merely a reactivation surface generated by a single migrating bedform or if it is a channel cutting into pre-existing sequences. Regional scour is much easier to recognize in the subsurface because it would be evident in a number of drill cores. Large-scale features such as bars, lateral accretion surfaces and master bedding may also be difficult or impossible to recognize in drill cores because of their wide lateral extent.

Paleocurrents are typically obtained from cross-stratification in outcrops but with drill cores this is virtually impossible. The orientation of a drill core is usually unknown and the use of dipmeter well logs has proved to be both costly and often inconclusive due to the inability of the dipmeter instrument to detect cross-stratification. Paleocurrent data can contribute a great deal to the formulation of the depositional model. Another feature often provided by the outcrop but rarely by drill cores is a view of the bedding suface. Features found on the bedding surface, such as rainprints, mud and synaeresis cracks, rill marks, and ripple patterns, often provide important clues to a depositional setting.

The most notable advantage to subsurface studies over those that rely exclusively on outcrops is that the subsurface is immune to the present-day erosion cycle (Cant 1984; North 1985). In this particular study the stratigraphic sequence of the McMurray

Formation is complete whereas much of the outcrop has been removed by glacial scour, as well as present-day fluvial erosion. Muddy lithologies common in the subsurface, are rare in the outcrops of the McMurray Formation. In outcrop these lithologies are typically recessive and covered by vegetation. A drill core on the other hand provides a fresh unweathered surface of these lithologies. Physical relationships are distinct in drill cores. In the subsurface argillaceous and arenaceous lithologies contribute equally to the development of the depositional model. The outcrop of the McMurray Formation is clearly biased towards the sandy lithologies and the physical relationships which characterize them.

Subsurface studies also provide better regional stratigraphic relationships than do outcrop studies because of the more complete stratigraphic record (Cant 1984). In this particular study, the excellent distribution of drill core and close spacing provides a substantial data base from which stratigraphic cross-sections, as well as structure and isopach(ous) maps could be constructed. As a result lateral stratigraphic trends in the subsurface are well known. Maps were plotted using the SURFACE II graphics system (Sampson 1978) which has been modified by M.J. Ranger of the University of Alberta.

Drill Core Description

A total of 108 drill cores, 80% of which penetrate the entire thickness of the McMurray Formation and parts of the Upper Devonian Waterways Formation and the Lower Cretaceous Clearwater Formation, were described in detail during this sedimentological investigation. From these descriptions vertical profiles were constructed and a lithofacies scheme was devised.

Description focused on the physical sedimentary attributes of the drill cores. Features described include:

a) lithology, which varies from limestone to unconsolidated quartzose and glauconitic sands, as well as siliciclastic and calcareous muds;

b) grain size utilizing the Udden-Wentworth size classification for clastic sediments and sedimentary rocks (Wentworth 1922);

c) bedding thickness including cross-strata set thickness;

d) lower bedding surfaces or contacts;

e) physical sedimentary structures such as cross-stratification, planar and convolute stratification and load structures;

f) other physical sedimentary features such as type and percentage of intraclasts, inclination of stratification, indurated zones and concretions and carbonaceous debris;

g) fossil constituents such as roots, wood, trace fossils, bones, shells and shell debris but identification was not a concern in this study (see Mattison 1987).

Other features described from the drill cores as well include relative bitumen saturation and the relative amount of bioturbation. This data was used to construct vertical lithologs (Appendix) which were drafted at 1cm=1m utilizing a Macintosh computer with a MacPaint graphics programme.

Petrophysical Well Logs

Petrophysical well logs (e.g. gamma ray, resistivity and density logs) were not utilized during the course of this study because of the exceptional quality and distribution of drill cores in the study area. Since well logs only reflect many of the physical features of the drill cores such as lithology, cemented zones, porosity and permeability (Asquith and Gibson 1982), their use would have only corroborated what was provided by the detailed descriptions of drill cores. The use of the well logs for depth correction of the the drill cores was considered initially but was precluded due to the limited amount of time and the fact that a significant number of the well logs were not made available for examination. Therefore the study relied completely on the depths assigned to the drill cores by Syncrude geologists.

Drill core examination of the McMurray Formation

Unique problems arise when examining drill cores from the McMurray Formation. The most troublesome is the high bitumen saturation of some of the sediments. Sands with very uniform and fine to very fine grain sizes typically have an extremely high bitumen saturation making them appear massive. The high bitumen saturation obscures internal sedimentary structures. The use of X-ray radiography has helped considerably in this study, revealing that many of these massive sands are indeed stratified in some way. Cost and time constraints considerably limited the use of this valuable tool. However it was found during the course of this study that with an increasing number of logged (described) drill cores along with limited use of X rays, it was possible to predict with a significant level of confidence what the obscured sedimentary structure was likely to be. Subtle changes in grain size or the orientation of splitting planes often reflect the nature of stratification (Collinson and Thompson 1982). In outcrop studies of the McMurray Formation this problem is less likely to be encountered as the weathered surface of the bituminous sands clearly reveal sedimentary structures.

Although bitumen provides a certain degree of cohesion, the underlying fact is that the McMurray Formation is essentially composed of unconsolidated sediments. Drill cores are typically encased in PVC (polyvinyl chloride plastic) pipe in order to obtain good recovery and provide support for the drill core when handling. These pipes are slabbed in half in order to permit description of the drill cores. The slabbed face is usually the only surface available for observation because the margins of the drill cores (while being encased in the PVC pipe) are typically smeared and distorted during the coring process and are usually heavily encrusted with drilling mud. A drill core is usually damaged if it is removed from the pipe. As a result only a two-dimensional view is available for study. This restriction makes the study of such physical sedimentary structures such as cross-stratification more difficult.

Sands lacking the bitumen "cement" present, major problems as well. The "water sands" (local usage for sands in the McMurray Formation with high water saturation and little or no bitumen) have very poor recovery during drilling and typically crumble as they dry out in the core box destroying any sedimentary structures. Therefore the water sands are "selected against" by their poor recovery and preservation potential and contribute little data for the formulation of the depositional model.

CHAPTER 2

FACIES

Facies, derived from the Latin word *facia* (meaning face, figure, appearance, aspect, look or condition), is a term given to a particular rock or sediment unit that is distinguishable from other units on the basis of lithological, structural and organic aspects (Teichert 1958; de Raaf *et al.* 1965; Middleton 1978; Walker 1984a; Anderton 1985). Facies are therefore descriptive and are indicative of a depositional process rather than a specific sedimentary environment (Teichert 1958; Anderton 1985).

Facies analysis is "the description and classification of any body of sediment followed by the interpretation of its processes and environments of deposition" (Anderton 1985, p. 32). The key to the interpretation of any ancient sequence is to understand the relationships between facies and modern environments (Walther 1893: cited in Middleton 1973). The modern sedimentary environment is characterized by a "facies association" or spatial (both vertical and horizontal) arrangement of facies reflecting the depositional processes of that environment (Walker 1984a; Anderton 1985). A vertical sequence of facies, with no evidence of a depositional hiatus or major erosional event (between facies), can be assumed to have existed adjacent to one another in the sedimentary environment (Walther's Law of Correlation of Facies) (Middleton 1973). This concept is extremely useful when determining environments of deposition from drill cores because only the vertical sequence is available. Extreme caution is required because the vertical sequence does not always reproduce the horizontal relationships of facies that existed at the time of deposition. As was mentioned previously, the lack of lateral facies control limits the interpretive capability in drill core studies.

In this study lithofacies, based on lithology and physical sedimentary structures, were defined and analysed in order to determine processes and environments of deposition that resulted in the sequences that characterize the McMurray Formation (Table 2).

MUD

Description:

Massive to stratified white calcareous mud

Massive to stratified white calcareous muds are only found below the lower member of the McMurray Formation, occurring in 37% of the the drill core examined. This lithofacies directly overlies the Upper Devonian carbonates below the McMurray Formation. Although beds can be up to 40cm thick, they are generally no thicker than 10cm. This lithofacies is absent when the middle member directly overlies Devonian carbonates.

Stratification of the muds is usually flat but can dip up to 10^{o}. The attitude of stratification appears to be dependent on the nature of the unconformity surface. Contorted mud laminae and pseudonodules of sand and non-calcareous mud were commonly observed. In drill core 33-44, rooting is evident in a bed of this lithofacies. Thin lenses and laminae of sand are rarely interbedded in the calcareous muds.

Subrounded calcareous mud intraclasts commonly make up to 50% of a bed of this lithofacies (Plate 1, Fig. a). Intraclasts are up to 3cm in size but average 0.5 to 1cm. Sorting of these intraclasts is moderate to poor and these conglomeratic beds show no evidence of internal stratification. The calcareous mud matrix is commonly bitumen saturated (moderate to high). Voids and spaces between intraclasts are commonly filled with bitumen. Other intraclasts include limestone and coaly fragments. Mud intraclasts

Table 2. Lithofacies of the McMurray Formation, present study, Syncrude Oil Sands Lease 17, Athabasca Oil Sands.

MUD: massive to stratified white calcareous mud
flat to low angle laminated white to grey carbonaceous mud
structureless white to grey carbonaceous mud
flat to low angle laminated light grey to tan mud
flat to low angle laminated dark grey calcareous mud
flat laminated dark grey mud

STRUCTURELESS SAND

FLAT TO LOW ANGLE PLANAR STRATIFIED SAND

SMALL-SCALE CROSS-STRATIFIED SAND

LARGE-SCALE CROSS-STRATIFIED SAND

VERY FINE LARGE-SCALE CROSS-STRATIFIED SAND

MUDDY CARBONACEOUS SAND

INTERBEDDED SAND AND MUD

INTERBEDDED SAND AND CALCAREOUS MUD

HEAVILY BIOTURBATED MUDDY SANDS

PLATE 1

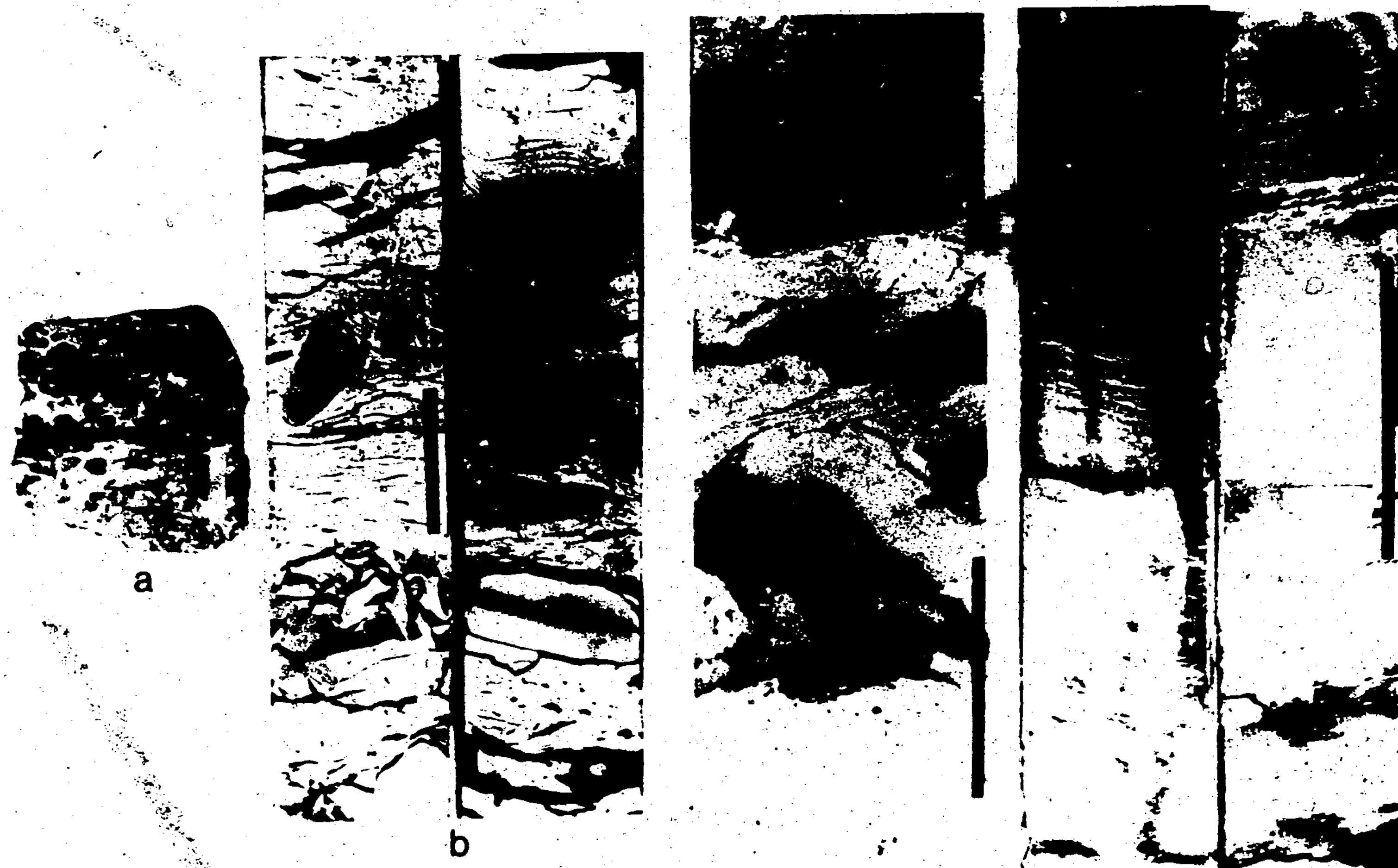
Mud from the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.

Fig. a. Stratified calcareous mud with rounded, bitumen saturated calcareous mud intraclasts, lower member of the McMurray Formation; drill core 39-39, 92.7m (scale 2cm).

Fig. b. Flat to low angle laminated grey carbonaceous mud in the lower member, with carbonaceous clasts and iron concretions; drill core 39-37, 83.6 to 84.2m (scale 5cm).

Fig. c. Structureless to slurried white to grey carbonaceous mud in the lower member, with a sediment aggregate pellet consisting of mud, carbonaceous debris and dispersed sand; drill core 39-40, 88.2m (scale 5cm).

Fig. d. Low angle laminated tan to grey mud (sample is damp) in the middle member, with bioturbated sand lenses; drill core 42-40, 58.6 to 59.2m (scale 10cm).



a b c d

can be iron cemented. Cementation of calcareous mud beds is usually irregular or confined to specific laminae. The contact zone with underlying Devonian carbonates is typically iron cemented.

Basal contacts of this lithofacies with Devonian carbonates are typically sharp but gradational contacts are also common with rubbly limestones often grading upward into cemented calcareous mud with limestone fragments and calcareous mud intraclasts. Upper contacts with non-calcareous mud of the lower member of the McMurray Formation are commonly gradational. Sharp, possibly scoured and loaded upper contacts are apparent with overlying sandy lithofacies.

Flat to low angle laminated white to grey carbonaceous mud

Flat to low angle (0 to 30^{o}, average 10^{o}) laminated white to grey carbonaceous mud is found only in the lower member of the McMurray Formation (Plate 1, Fig. b). Carbonaceous debris is very common in this sublithofacies, occuring in three distinct forms. Macerated, fine grained carbonaceous debris is often found concentrated between mud laminae forming carbonaceous films. Debris can also be dispersed in the muds, apparently partly responsible for the grey colouring. Carbonaceous debris also occurs as coaly laminations and lenses up to 5.0cm thick (drill core 38-34) but average approximately 0.2cm thick. These coaly laminations are commonly observed to pinch-and-swell. Closely associated with this carbonaceous debris are medium to very coarse grained sands, as well as rare angular mud intraclasts (<1.0cm in size), rounded bone fragments and subrounded quartzose and feldspathic pebbles (up to 1.0cm in size). Sand lenses and laminations are rarely interbedded in the muds. These sands are usually deformed, displaying contorted laminae, pseudonodules and faulting (throw 0.1 to 1.0cm).

A relatively common feature are load casts and pseudonodules of sandy mud or sand lenses (often slightly bitumen saturated) in non-sandy muds. Bioturbation, with the exception of rare carbonized roots, is apparently absent in this sublithofacies. Mud intraclasts are often indurated, as are thin beds and lenses of sand and gravel. Concretions in the mud are also common, ranging in size from 0.5 to 10cm thick. Basal contacts with other lithofacies are generally sharp to gradational, but can be loaded or irregular.

Structureless white to grey carbonaceous mud

Massive (no evidence of stratification) white to grey carbonaceous muds are found only in the lower member of the McMurray Formation. Muds have a waxy to granular texture and are commonly broken up into angular or blocky fragments. Broken surfaces of the mud are often characterized by gently undulating slickensides.

Roots (carbonized) are rare, but are usually long (10 to 30cm) and do not branch. Macerated carbonaceous debris is dispersed in the muds and often is responsible for the dark grey coloration which often characterizes this sublithofacies. Fine to very coarse sand grains are often found dispersed in the muds and can be concentrated in irregular sand patches that are commonly slightly bitumen saturated. Aggregate sediment pellets (terminology after Ovenshine 1970) composed of sand, carbonaceous debris, and mud have been recognized (Plate 1, Fig. c). These aggregates occur in irregular patches giving the mud a slurried texture. Mud intraclasts and subrounded quartzose and feldspathic pebbles (up to 1.0cm in diameter) are also dispersed in the muds or are concentrated in thin horizons or patches in otherwise structureless mud. Mud intraclasts, as well as sand and gravel patches are commonly iron-cemented. Iron concretions are abundant in this sublithofacies with size ranging from "pin-heads" (≤1mm in diameter) to those that are

20cm thick. Cementation is highly irregular with both smooth and serrated boundaries between cemented and non-cemented muds recognized. Basal contacts of this sublithofacies are commonly loaded or irregular, but gradational contacts are commonly recognized.

Flat to low angle laminated light grey to tan mud

This sublithofacies is characterized by flat to low angle (0 to 20°) laminated, tan to light grey mud which commonly appears to be massive but infrequently has interbedded lenses and thin laminae of sand (Plate 1, Fig. d). These muds are found only in the middle member of the McMurray Formation.

Deformation of mud beds is relatively rare with infrequent contorted laminae and small-scale faulting (throw 0.5 to 1cm). Bioturbation appears to be highly variable. Most mud units show little or no evidence of burrows or biogenic texture. Where sand is interbedded within the muds, bioturbation is usually intense. Commonly all that is visible is a horizon of irregular sand patches in a matrix of mud. Sand grains (generally very fine to fine grained) are commonly dispersed throughout the muds. Very coarse sand size to pebble size (subangular to subrounded) mud intraclasts are infrequently dispersed in the muds. Mud intraclasts are commonly iron-cemented. In one drill core (42-42), a thick sequence of flat to low angle laminated tan to light grey muds is characterized by 1 to 10cm thick small mud intraclast beds. These mud intraclast beds consist of clast-supported (with little or no matrix), very coarse sand to granule sized mud fragments. These beds appear massive and typically have sharp bottom and top contacts. commonly dispersed in the mud intraclast beds is fine grained macerated carbonaceous debris. In general, however, carbonaceous debris is rare in this sublithofacies occurring as coaly lenses and laminations, or as dispersed material in the muds. Iron-cementation is often associated with the carbonaceous debris. Concretions often develop in muds surrounding lenses of carbonaceous material. Indurated horizons 1 to 2 cm thick, are commonly observed in the muds. Entire mud beds of this sublithofacies can be indurated, especially those closely associated with sandy lithofacies. Basal contacts with other lithofacies tend to be flat and conformable with underlying stratification. Gradational contacts with *interbedded sand and mud* are common whereas loaded and scoured contacts are rare.

Flat to low angle laminated dark grey calcareous mud

This sublithofacies is characterized by calcareous muds which react variably with hydrochloric acid. Muds are flat to low angle (0 to 10°) laminated. Interbedded sand lenses and laminae are rare. Bioturbation is typically low to completely absent but can be moderate when sand is interbedded within the muds. Basal contacts are typically flat to wavy but gradational contacts with *interbedded sand and calcareous mud* are common. This sublithofacies only occurs in the limy unit of the McMurray Formation.

Flat laminated dark grey mud

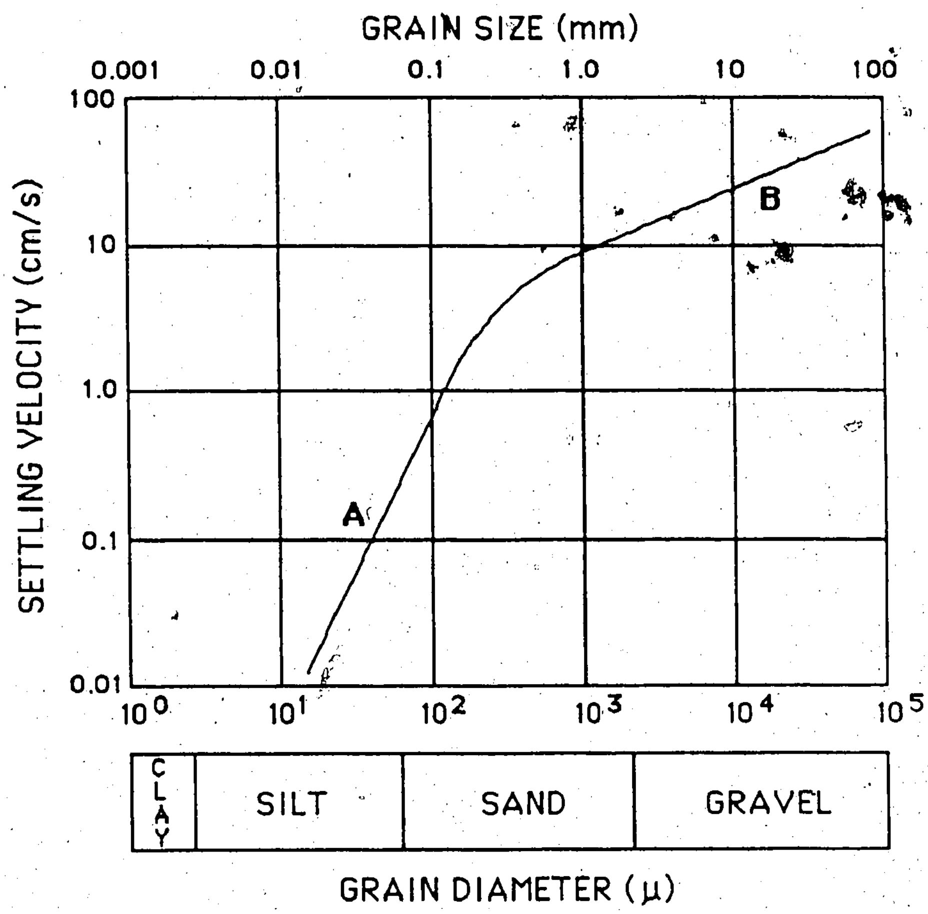
This sublithofacies is characterized by flat to low amplitude wavy laminated dark grey non-calcareous mud. It occurs only in the upper member of the McMurray Formation, as single beds in three different drill cores (41-36, 41-38, 43-40). Bed thicknesses are 10 and 20cm. In one bed, thin lenses of very fine grained sand are interbedded with the muds. Bioturbation is low to absent but sand lenses show slight biogenic disruption. Lower contacts are flat to wavy. This sublithofacies is identical to the mud in mud drapes and composite sand and mud partings in *heavily bioturbated muddy sands.*

Interpretation:

Mud sized particles have very low settling velocities (Fig. 16). Spherical particles with grain diameters of 60μm (silt) require 5 minutes to settle through 1m of water, whereas particles with a grain diameter of 4μm (clay) require 30 hours to settle through the same water depth (Potter *et al.* 1980). Because clay minerals and other mud sized grains are typically non-spherical, their settling velocities are reduced further. Non-spherical particles have lower settling velocities than do equivalent size spherical particles. Sharp edges on a particle can reduce its settling velocity by 8 to 28% (Williams 1966). As a consequence mud particles require bodies of water that are perfectly still for extended periods of time in order to settle (Pryor 1975). This does not occur in many natural environments where even the smallest amount of turbulence can keep most mud particles in suspension.

Pryor (1975) outlines three mechanisms for the deposition of mud. It can be deposited if the body of water, in which it is suspended, evaporates or drains. Individual mud particles can be aggregated into larger particles with greater settling velocities. Aggregation of mud particles can be accomplished by two mechanisms: biogenic pelletization and physico-chemical flocculation.

Suspension feeding and some deposit feeding organisms ingest mud when feeding (Haven and Morales-Alamo 1968; Pryor 1975). Mud-sized particles are injested and aggregated together in the gut of the organism and excreted as aggregate particles that have settling velocities that are much greater than primary mud particles. Some of the fecal pellets produced by organisms can be hydraulically equivalent to fine and medium sand grains (Pryor 1975). As a consequence, some mud aggregates can be transported and deposited in environments where currents would normally be much too strong to allow



* 20°C; still water

calculation of graph:
- **A**: Stokes' Law $W_s = Cd^2$
- **B**: Impact Law $W_s = C_2\sqrt{d}$

W_s = settling velocity
C = constants (e.g. fluid density)
d = particle diameter

Fig. 16. Settling velocity curves for spherical particles in still water (modified from Nichols and Biggs 1985).

individual mud particles to be deposited. Mud deposited as fecal material is difficult to recognize. With compaction and dewatering, fecal pellets loose their identity, amalgamating with other pellets and mud particles to form a deposit with little or no internal structure (Howard and Reineck 1972; Pryor 1975; Howard and Frey 1985). Suspended mud particles can also be fixed or trapped by plants (Van Straaten and Keunen 1957; Coles 1979). Mucus, produced by algae living on and in the substrate, can trap passing suspended mud particles. Vascular plants, such as grasses, act as sediment traps, reducing current velocities so that mud can settle from suspension.

Mud can be aggregated into particles with greater settling velocities by flocculation. Individual clay particles, due to their colloidal nature, are characterized by a net negative charge (Van Olphen 1963; Allen 1985). This negative charge is balanced by positive ions in the solution suspending the clay particles. These positive or "counter" ions surround the clay particle forming an "electric double layer" which acts as a protective sheath repelling other clay particles with similar electric double layers, that come into contact with it. Collisions between individual particles are facilitated by Brownian motion as well as turbulence in the supporting fluid. Because particles repel one another, a dispersion is maintained and little or no deposition occurs. If the number of positive or counter ions (such as Na^+, K^+, Ca^+) in solution is increased through an increase in salinity, the electric double layer is thinned and repulsive forces between clay particles are reduced (Allen 1985). As a consequence, the attractive Van der Waal's forces that exist between any two particles, become more significant and particles that come into contact with one another will adhere, forming an aggregate particle or floccule (Van Olphen 1963). Floccules or flocs have greater settling velocities and therefore settle at a higher rate than individual mud particles. Suspended silt and fine sand sized grains are often trapped within flocs (Migniot 1968). Floc formation is enhanced if the number of interparticle collisions is increased (Migniot 1968). High concentrations of suspended mud, as well as turbulence and differential settling caused by variable floc size, enhance the number of collisions and therefore increases flocculation and the settling of mud (Einstein and Krone 1962; Krone 1962; Van Olphen 1963; Migniot 1968). If concentrations of suspended sediment are high, deposition can occur even if wave and current energy is high (McCave 1971).

In order for settling to occur, interstitial fluids supporting the mud particles, must be expelled (Krone 1962). As the concentration of mud particles increases toward the bed, settling is hindered because it becomes more difficult for interstitial fluids to escape, resulting in the development of a "fluid mud" layer above the bed (Krone 1962; Allen *et al.* 1977). Within the fluid mud layer, the concentration of suspended mud increases downward toward the bed (Einstein and Krone 1962; Allen *et al.* 1980; Kirby and Parker 1983). As a consequence, shear strength increases as mud particles get closer together towards the base of the fluid mud layer (Einstein and Krone 1962). Mud particles are considered settled when they are supported by one another rather than interstitial fluids (Kirby and Parker 1983). With settling, the recognition of flocculated muds is difficult because individual flocs loose their identity through dewatering and compaction (Kranck 1975; Pryor 1975). Therefore, as with biogenically pellitized muds, it is difficult to determine if flocculation was responsible for the deposition of a mud bed.

Mud beds in the McMurray Formation commonly have low levels of bioturbation. Mud substrates are commonly characterized by anaerobic conditions and high levels of toxicity that can be fatal to many organisms (Purdy 1964). Unconsolidated muddy substrates may be too soft for benthic organisms because of high interstitial fluids. Dewatered and highly cohesive mud substrates may exclude many burrowing organisms that can not overcome the strength of the bed (Howard and Frey 1973).

There are a number of possible interpretations for *massive to stratified white calcareous mud*. Finely laminated calcareous muds were most likely deposited from suspension in quiet bodies of water found in low lying areas on the unconformity surface prior to the deposition of the McMurray Formation. Rare interbedded sand lenses are indicative of periodic influxes of coarser sediment or higher current velocities during which time sand transport could occur. The presence of roots suggests the environment of deposition was vegetated to some extent.

The process responsible for generating subrounded calcareous intraclasts supported by a matrix of calcareous mud is enigmatic. Despite their high degree of roundness suggesting extensive transport, the presence of a mud matrix precludes deposition by currents or in sediment dispersions. These units may be thin (or the basal remnants of) debris flow deposits, which are typically characterized by clasts "floating" in a much finer grained matrix (Middleton and Hampton 1973). Debris flow deposits generally have a massive texture. A debris flow develops when water and mud combine to form a highly cohesive fluid that, through buoyancy and strength, can support large clasts (Middleton and Hampton 1973). Debris flows are driven by gravity and will move only when the strength of the flow is exceeded by the shear stress applied on it by gravity (Blatt *et al.* 1980). Debris flows could be expected to develop on the slopes of Upper Devonian hills and accumulate in low lying areas.

An alternative explanation for rounded calcareous mud intraclasts in a matrix of calcareous mud is that these deposits may be a caliche which developed on top of exposed Upper Devonian carbonates. A caliche is the product of subaerial exposure and weathering of carbonate rocks and sediments (Esteban and Klappa 1983). Nodular and chalky caliche are commonly characterized by spherical to subspherical glaebules supported in a matrix of powdery or granular carbonate mud. Glaebules consist of powdery to indurated calcium carbonate concretions (Esteban and Klappa 1983). A detailed petrological and geochemical examination would be required to positively identify this lithofacies as a caliche. It is possible that the constituent grains (mud and mud intraclasts) of this lithofacies are derived from the weathering of Upper Devonian carbonates and subsequently reworked and deposited by other processes.

Flat to low angle laminated white to grey carbonaceous mud was deposited from suspension in a low energy setting. Its stratified character suggests an incremental rather than continuous deposition, each lamina representing a single depositional episode. The attitude of stratification depended on the surface on which the mud was deposited. Dispersed carbonaceous debris and carbonaceous laminae reflect an episodic deposition of carbonaceous material in the environment. Rare roots indicate there was some vegetation at the site of deposition. Sand grains that commonly accompany carbonaceous debris support deposition during relatively high energy events. Sand lenses that are irregularly interbedded in the mud, indicate that currents were, for short periods of time, high enough to transport sand. Loaded sands developed on poorly consolidated muds. Loading occurs when sand deposited on top of a mud with high interstitial water, sinks because of density differences (Collinson and Thompson 1982). Currents were also strong enough to transport gravel and bone fragments, as well as erode consolidated mud forming mud intraclasts. The angularity of many of the mud intraclasts indicates little or no transport from their source. Mud intraclasts deposited in a dynamic aqueous environment have rapid rates of erosion and breakdown (Smith 1972). Erosion due to collisions with other intraclasts, sand grains, the substrate, as well as the shear applied by currents, contribute to their rapid destruction.

Structureless white to grey carbonaceous mud appears to have been modified by secondary processes. The blocky texture of the muds and the occurence of slickensides and roots suggest possible early soil development. Fine roots commonly bind mud particles together forming a blocky texture (FitzPatrick 1983). This texture is also produced by repeated wetting and drying of muddy sediments. Slickensides develop when mud aggregates slide past one another. Movement is generated by the expansion of swelling clays caused by continuous wetting and drying, as well as by the motion of roots penetrating the muds (FitzPatrick 1983; Collinson 1986). Dispersed sand grains, irregular sand patches, aggregate sediment pellets, pebbles and mud intraclasts are the remnants of deposits formed during short episodes of strong current activity in a normally low energy setting. These high energy deposits were modified by loading, rooting and soil development following deposition.

Flat to low angle laminated light grey to tan muds were most likely deposited when current velocities were low enough to allow mud to settle from suspension. Grains of sand dispersed in the mud suggests deposition by flocculation or biogenic pelletization, because sand grains are commonly incorporated in the mud aggregates. Rare interbedded sand lenses indicate that currents were for a short period of time, high enough to transport sand. Bioturbation is greater in the sands as compared to the muds, because benthic organisms would find it much easier to burrow in a less-cohesive substrate. The general lack of sand in this sublithofacies does not necessarily imply that currents were not high enough to transport sand but rather there may have been a lack of sand to be transported.

Subangular to subrounded mud intraclasts dispersed in the muds are indicative of local erosion of consolidated muds. Very coarse sand to granule-sized mud intraclasts that are concentrated between mud beds have most likely been highly reworked. The massive fabric of the intraclasts, as well as sharp bottom and upper contacts, indicate rapid emplacement and burial.

Flat to low angle laminated dark grey calcareous mud and *flat laminated dark grey mud* were deposited when currents were low enough to allow mud to settle from suspension. Thin sand lenses that are rarely interbedded within these muds are indicative of short-lived events when currents were high enough to transport sand and keep mud in suspension.

STRUCTURELESS SAND

Description:

This lithofacies, which is found only in the middle and upper members, is characterized by massive or structureless sand. No physical of biological sedimentary structures are recognized and there is no evidence for grading or stratification. Sands are typically fine grained, but in rare cases can be very coarse sand. Grain size within a single massive bed can be variable but shows a random distribution. Disorganized (lack of preferred clast orientation) mud intraclasts are a common feature of this lithofacies and are usually indicative of the lack of internal structure of the sands. Mud intraclasts have similar lithologies as *flat to low angle laminated light grey to tan mud* and *interbedded sand and mud.* Intraclasts are angular to subrounded, and have an average length of 3cm although intraclasts up to 4cm thick and 5 to 6cm long have been observed. Iron-cementation of mud intraclasts is relatively rare. Less common types of intraclasts include coaly carbonaceous fragments and subrounded quartzose pebbles. Sands usually have moderate to high levels of bitumen saturation. Basal contacts with other lithofacies vary from loaded and sharp (possibly scoured) to highly irregular.

Interpretation:

Structureless or massive sands are produced either by rapid sedimentation from suspension or by deposition from highly concentrated sediment-laden flows (Blatt *et al.* 1980; Collinson and Thompson 1982). Sediment grains in these flows are supported by fluid turbulence and where this turbulence can no longer overcome gravity acting on the sand grains, deposition occurs (Allen 1985). Because they lack any form of stratification, one can assume that primary massive or structureless sands are not the product of bed load transport (Blatt *et al.* 1980; Collinson and Thompson 1982).

Massive sands can also be produced if primary sedimentary structures are destroyed by either biological or physical processes (Blatt *et al.* 1980; Collinson and Thompson 1982). Burrowing organisims commonly rework sediments so completely, destroying primary sedimentary structures, that they impart a massive texture on the sediment. However there is usually evidence of bioturbation in the form of remnant burrows in and around this type of massive bed.

Liquifaction can also destroy primary sedimentary structures producing a massive or structureless bed (Middleton and Hampton 1973; Blatt *et al.* 1980; Collinson and Thompson 1982). Liquifaction occurs when sand grains, which usually support one another, are for an instant supported and dispersed by pore fluid (Allen 1984). This fluid supported sand is easily deformed. Liquifaction occurs when the pressure of pore fluids is sufficent to support the grains of sand (Collinson and Thompson 1982). A shock, induced by an earthquake or very rapid sedimentation, can increase pore pressure (Collinson and

Thompson 1982). Liquifaction can also occur if a partially consolidated (packed) sand which has pore fluid is buried by mud. This restricts the upward escape of pore fluid as compaction and hense volume decrease, occurs with burial. Because pore fluid can not escape, pore pressure builds up, making the sand predisposed to liquifaction (Collinson and Thompson 1982).

Intraclasts that were originally deposited with the sands are also affected by liquifaction. Any preferred orientation that the intraclasts might have had would be destroyed during the liquifaction process, resulting in the development of a disorganized clast fabric. Mud intraclasts in this lithofacies are usually quite angular indicating that they probably underwent little or no transport from their place of origin.

As is indicated by the general lack of abrasion and breakdown of mud intraclasts in this lithofacies, it seems most likely that secondary processes, specifically liquifaction, was responsible for the massive texture of these sands. Primary processes that could produce such a texture are probably too energetic for the survival of angular mud intraclasts. Sharp to scoured basal contacts indicate erosion of underlying lithofacies occurred prior to the emplacement of the unit. Following deposition, liquifaction will impart a massive texture on the sands.

FLAT TO LOW ANGLE PLANAR STRATIFIED SAND

Description:

This lithofacies is found throughout the McMurray Formation. It is characterized by flat to low angle (0-5^{o}) planar stratified sands. Sets of low angle stratified sand commonly show opposing dips and low angle truncations. Stratification varies from finely laminated (laminae 1-2mm thick) to bedded (beds 1cm thick) units. Sands are usually fine to very fine grained whereas coarser sands (medium to very coarse) are less common. Because grain size is very uniform and these sands typically have a very high bitumen saturation, beds of this lithofacies often appear to be massive or nearly so. Limited use of X-ray radiography has revealed that this lithofacies may in fact be much more common than was actually recognized.

Macerated carbonaceous debris is rarely interbedded in flat to low angle planar stratified sands. Continuous to discontinuous carbonaceous laminae may be interbedded in the sands. More commonly recognized are composite units up to 2cm thick, of finely interbedded sand and carbonaceous debris (≤1mm thick laminations) that are typically conformable to underlying strata. Mud intraclasts that have a preferred orientation (suggesting planar stratified sands) are also recognized. Large and small mud intraclasts are most common, often making up 30 to 35% of the unit. Beds with >50% mud intraclasts are rare. Clasts have similar lithologies to *flat to low angle laminated light grey to tan mud* and *interbedded sand and mud*, and are usually subangular to subrounded. Mud clasts are usually small (<1cm in length, 0.5cm thick) but can be as much as 9cm thick. Mud intraclasts are moderate to poorly sorted and are rarely iron-cemented. Other less common clast types include coaly carbonaceous fragments (wood) and subrounded quartzose pebbles. Bioturbation is usually absent to very low in this lithofacies. Lower contacts with other lithofacies are typically sharp and possibly scoured.

Interpretation:

Planar stratified sands are deposited on upper flow regime plane beds (Harms and Fahnestock 1965). During upper flow regime conditions, resistance to flow is weak, turbulence is low and sediment transport is great (Simons *et al.* 1965). Upper flow regime bedforms generally form in very shallow flows (Harms and Fahnestock 1965). Sand grains roll almost continuously under upper flow regime conditions (Simons *et al.* 1965). Plane bed is characterized by a surface topography less than the size of the sand grains. Plane bed develops in finer grained sands at flow strengths that are weaker than those that are required to form plane bed in coarser sands. Stratification is produced by a pulsating flow, with each flow ("burst" or "sweep") producing a discrete lamination (Leeder 1982; Cheel and Middleton 1986). Both unidirectional and oscillatory flows can produce upper flow regime plane bed but it is impossible to determine which type of flow was responsible for the deposit (Collinson and Thompson 1982).

Because plane bed is the first upper flow regime bed form to develop, it is commonly transitional with lower flow regime bed forms (dunes and ripples) and high flow regime bed forms such as antidunes (Fig.17) (Simons *et al.* 1965). Current st[illegible] fluctuate continually between upper and lower flow regimes. Slight turbu[illegible]elop when flow strength diminishes slightly, causing minor scouring and low a[illegible]ned laminations. Antidunes can also produce low angle planar stratification (Harms and Fahnestock 1965) but because antidunes are large bedforms (Reineck and Singh 1975) their deposits would be difficult to recognize in a drill core. For sands coarser that 0.7mm, crude planar stratification can develop just after the initiation of sediment movement (Leeder 1982). Ripples do not form when sand is greater than 0.7mm. Lower flat bed is characterized by a "hummocky micro-relief made up of irregular stream-wise furrows and ridges, no more than a few grain diameters high" (Costello and Southard 1982, p. 855).

It is unlikely that carbonaceous debris that is rarely interbedded in flat to low angle planar stratified sands was deposited during high flow regime conditions. Because

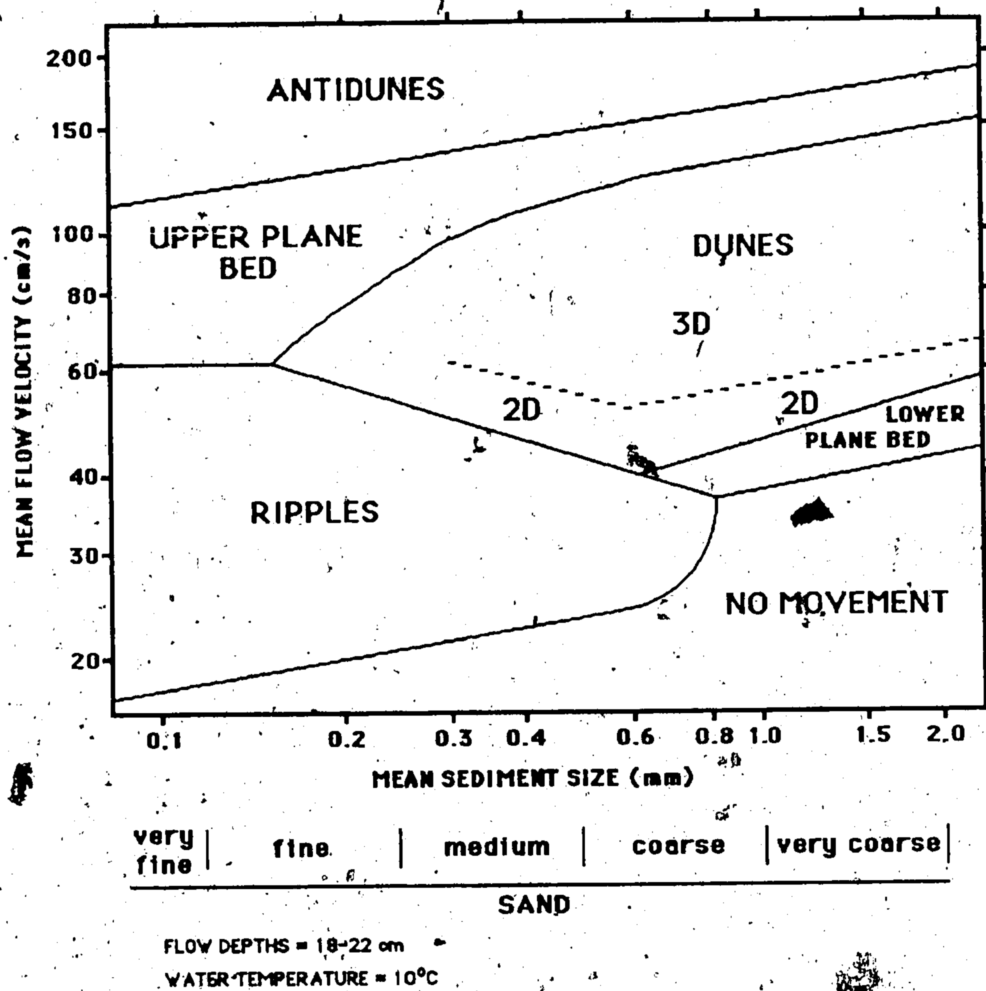


Fig. 17. Size velocity diagram with sand bed form stability fields (modified from Harms *et al.* 1982; Allen 1985).

carbonaceous debris would be expected to have relatively low settling velocities, deposition would probably only occur when current strength was weak. Planar stratified coarse silts and very fine sands can be deposited from suspension (Reineck and Singh 1975; Harms *et al.* 1982). Thus beds of finely intercalated carbonaceous debris and sand are probably the product of sedimentation from suspension when currents were weak. The flat to low angle planar stratification was probably inherited from the surface the sand was deposited on.

Mud intraclasts interbedded in flat to low angle planar stratified sand are typically small. This would be expected in a bed that was deposited under high flow conditions because mud intraclasts would be broken down rapidly. However erosion and breakdown of intraclasts would be reduced as the surface area of the clast exposed to current induced shear was reduced, and the effect of collisions with other clasts and the substrate diminished (Smith 1972). There is, however, a substantial proportion of planar stratified sands with relatively large angular mud intraclasts. These intraclasts show little evidence of attrition indicating little or no transport from their source. These units were probably not deposited under upper flow regime conditions suggesting that perhaps another, less energetic, process was responsible for their deposition. The production of flat to low angle stratified sands with large, angular intraclasts will be further elaborated in the discussion of *large-scale cross-stratified sand* with mud intraclasts.

SMALL-SCALE CROSS-STRATIFIED SAND

Description:

Small-scale cross-stratified sand is found throughout the McMurray Formation and is the most abundant of the stratified sand lithofacies (Plate 2, Fig. a). Cross-stratification

PLATE 2

Cross-stratified sand from the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.

Fig. a. X ray radiograph of small-scale cross-stratified sand in the middle member of the McMurray Formation, exhibiting tabular and trough sets; drill core 35-43, 75.0m (scale 5cm).

Fig. b. Bitumen saturated large-scale cross-stratified sand in the middle member; drill core 43-36, 53.8m (scale 5cm).

Fig. c. Bitumen saturated large-scale cross-stratified sand in the lower member, with bioturbated mud drapes; drill core 39-37, 91.8 to 92.4m (scale 5cm).

Fig. d. Bitumen saturated large-scale cross-stratified sand in the middle member, with large angular to rounded mud intraclasts; drill core 33-40, 97.8 to 98.5m (scale 5cm).

[redacted]

is termed "small-scale" because: (a) set thickness is <10cm (usually 1 to 5cm); (b) the nature of the lower and upper set bounding surfaces is clearer and as a consequence set geometry can be differentiated into tabular or festoon (scoop) shaped sets; and (c) whole cross-strata (from lower to upper bounding surfaces) are recognizable and can generally be differentiated into foresets and toesets.

Tabular sets (upper and lower bounding surfaces are virtually parallel to one another) of small-scale cross-stratified sand are most commonly recognized. Festoon shaped sets (concave lower bounding surface, scoured upper bounding surface) are also common. Sets of cross-stratified sand are usually horizontal but occasionally dip as much as 20°. Cross-strata in these inclined sets usually dip downwards giving the appearance of large-scale cross-stratification with superimposed small-scale cross-stratification. Cross-strata in superimposed tabular sets of small-scale cross-stratified sand usually dip in the same direction. Opposing dips are the norm in festoon shaped sets. Cross-strata in tabular sets dip between 5 and 20° (average 10°). Foresets are always steeper than toesets which flatten tangentially with the lower bounding surface of the set. Cross-strata in tabular sets generally have steeper dips than those in festoon-shaped sets which are usually low angle (0 to 10°).

Sands in this lithofacies are typically fine to very fine grained whereas beds of medium to coarse grained small-scale cross-stratified sand are uncommon. Sands are usually very well sorted and have high bitumen saturation often causing this lithofacies to appear massive. Limited use of X ray radiography has revealed that these "massive" sands are usually small-scale cross-stratified. Splitting planes which develop along set boundaries and interbedded mud drapes help distinguish this lithofacies from true structureless sands.

Mud intraclasts are relatively rare in small-scale cross-stratified sands only constituting 1 to 10% of a bed in this lithofacies. Where they do occur, small mud intraclasts (<1cm long, <0.5cm thick) are most common, though clasts up to 4cm long are observed. In the limy unit, small-scale cross-stratified sand often contains shells and shell debris (gastropods and bivalves, B. Mattison pers. comm.) which are concentrated at the bottom of sets of cross-stratified sand. Sand grain size is much more variable in the limy unit. Often a bed of cross-stratified sand may consist of a sequence of sets which are coarser grained (coarse to medium s[illegible] base and finer grained in upper sets (fine to very fine grained sand) of cross-strati[illegible]nd.

Bioturbation is usually low to absent in small-scale cross-stratified sand in much of the McMurray Formation. In the upper member, beds of this lithofacies often show moderate to high levels of bioturbation. Bioturbation in small-scale cross-stratified sand is often evident in X ray radiographs, as well as disrupted mud drapes and composite sand and mud partings which are often interbedded in the small-scale cross-stratified sand. Mud drapes can be continuous to discontinuous, occuring between individual cross-strata or between sets of small-scale cross-stratified sands. Drapes have an average thickness of 1 to 5mm. Contorted drapes are infrequently observed in small-scale cross-stratified sand in the upper member. Drapes are rarely paired closely together, separated by one or two thin sand cross-strata. "Paired" mud drapes are usually found in the middle member and the limy unit. Composite sand and mud partings can be interbedded between individual cross-strata or between sets of cross-stratification. Partings that are ≥5cm thick are usually designated as part of *interbedded sand and mud.* Partings typically consist of thin lenses and laminae of sand intercalated in laminated mud (mud to sand ratio is high). Partings often have gradational lower contacts with underlying cross-stratified sand.

Sharp, flat contacts are also common. Upper contacts with overlying cross-stratified sand are usually flat or scoured. Gradational upper contacts are less common.

Cementation appears to be mainly restricted to mud drapes and composite sand and mud partings. Basal contacts with other lithofacies are flat, scoured or gradational whereas the upper and lower bounding surfaces of individual sets of small-scale cross-stratified sand are usually scoured.

Interpretation:

Small-scale cross-stratification is produced by the migration of ripples (Harms *et al.* 1963) which are triangular shaped lower flow regime bedforms, transverse to flow direction (Simons *et al.* 1965; Leeder 1982). During low flow regime conditions resistance to flow is large while sediment transport is small. Individual sand grains move by intermittent skipping or rolling (Harms 1969). Ripples are characterized by gentle upstream-dipping (stoss) slopes and steep downtream-dipping (lee) slopes. Lee slopes of ripples may dip as much as 35° (Reineck and Singh 1975; Leeder 1982). Ripples are usually less than 30cm in length and 3cm in height. Ripples can either be straight-crested (two-dimensional) or linguoid (three-dimensional) (Harms *et al.* 1982). Ripples become more linguoid with increasing current strengths (Simons *et al.* 1965)

Ripples form almost immediately when movement of sand (<0.8mm mean diameter) is initiated (Leeder 1982). Deceleration of flow over an irregularity on a bed (either pre-existing or current induced) causes an increase in turbulence downstream of the irregularity (Fig.18) (Allen 1984). If the irregularity has enough relief above the bed, flow separation will occur as the boundary layer between the bed and the flowing current detaches from the bed. Downstream of the irregularity, the boundary layer will reattach itself to the bed where shear stress on the bed will be high and scouring occurs, resulting in the development of a scour pit downstream of the irregularity (Leeder 1982; Allen 1984). Between the points of separation and reattachment, deposition of sediment grains occurs.

Small-scale cross-stratification is produced on the lee slope of the irregularity which can become a ripple (Leeder 1982). Sand grains are transported as bed load up the stoss side of the ripple (or irregularity) until they reach the point of separation where they are deposited at the top of the lee slope and/or are suspended by fluid turbulence for a short period of time and deposited on the lower part of the lee slope (Jopling 1964; Allen 1968). Grains of sand accumulating on the upper part of the lee slope can become unstable when the angle of accumulation exceeds the angle of repose, resulting in an avalanche of grains down the lee slope (Leeder 1982). Sand grains may also be transported as bedload upstream toward the lee slope by backflow currents generated in the separation eddy (Reineck and Singh 1975). As a result of deposition from avalanching, suspension and backflow, a lamina is formed on the lee slope (Leeder 1982). This addition of material causes the separation part to shift slightly downstream as does the point of reattachment. This process repeats itself with deposition in the lee forming cross-strata and the migration of the ripple and its associated downstream scour (created at the point of reattachment). "Older" scours are filled with cross-strata.

A series or configuration of ripples migrating across a bed can produce a sequence of stacked sets of small-scale cross-stratification (Harms *et al.* 1982) with each set produced by a single migrating ripple. Preservation of a set will occur only if successive upstream ripples do not erode too deeply. Ripples themselves are usually not preserved but rather the cross-laminae deposited on the lower parts of the lee slope and in the scour pit downstream of each migrating ripple. If migration of ripples is accompanied by sedimentation from suspension, bedforms will begin to vertically accrete or "climb" (Harms *et al.* 1982). Large angles of climb are not evident in small-scale cross-stratified sands in the McMurray Formation. These cross-stratified sands were probably formed by migrating ripples with little deposition from suspension. When climb is zero, thin discontinuous lenticular sets of cross-stratification are produced (Harms *et al.* 1982). A small angle of climb (minor suspended sediment contribution) results in more laterally continuous sets of cross-strata. Vertical sections parallel to flow reveal tabular sets of cross-strata. Vertical sections transverse to flow exhibit festoon to broad lenticular shaped sets. Cross-strata in flow tranverse sections may even appear to be low amplitude wavy stratified. Downward-dipping small-scale cross-stratification develops when ripples migrate down the lee slope of a larger flow transverse bedform such as a dune (Banks 1973).

Mud drapes and composite sand and mud partings interbedded between individual cross-strata or between sets of cross-stratification are indicative of momentary pauses or reductions in bedload transport of sand associated with reduction of current velocities. During periods of reduced current velocity, mud deposition from suspension can occur. Composite sand and mud partings indicate that while currents were reduced they were also fluctuating between those under which minor sand transport could occur and those under which only mud deposition would occur. The numerous causes of current unsteadiness in an aqueous environment will be discussed in greater detail in the interpretation of interbedded sand and mud .

Water waves, generated by the action of winds on the surface of bodies of water, also produce ripples (Allen 1985). The motion of a water wave causes fluid particles in the water column below, to have a circular motion (Reineck and Singh 1975). At the bed this circular motion becomes flattened, causing fluid particles to oscillate back and forth. At a critical velocity (Fig. 19) this oscillatory motion is capable of initiating sediment movement. Ripples form as sediment transport is increased, in much the same way that unidirectional currents form ripples, with the exception that flow separation occurs on both sides of the ripple with oscillating flow. Ripple height increases with increasing wave energy and near bed orbital velocity. Plane or undulatory bed is produced as velocity is further increased (Allen 1985). At very high velocities sediment grains are no longer transported only as bedload but also in suspension just above the bed (Reineck and Singh 1975). An ideal oscillatory flow created by water waves would create a perfectly symmetrical ripple that was characterized by symmetrical chevron-like internal cross-stratification (Harms *et al.* 1982). Although examination of wave ripples in actual sedimentary environments reveals that they may be symmetrical in profile, the small-scale cross-stratification they produce is often asymmetrical, closely resembling cross-stratification produced by unidirectional or current ripples (e.g. Newton 1968). Asymmetrical cross-stratification is indicative of a net translation or migration of the wave ripple, which can be produced if one component of the oscillation is stronger than the other (Reineck and Singh 1975). Translation of a wave ripple can also occur if a unidirectional current is superimposed onto oscillatory motion caused by waves Harms *et al.* 1982). Waves are very effective mobilizers of sediment grains so as a consequence they greatly enhance the ability of a weak unidirectional flow to transport sediment (Swift *et al.* 1986; R.W. Arnott pers. comm.). This attribute makes the differentiation of small-scale cross-stratification produced by pure unidirectional currents, from those

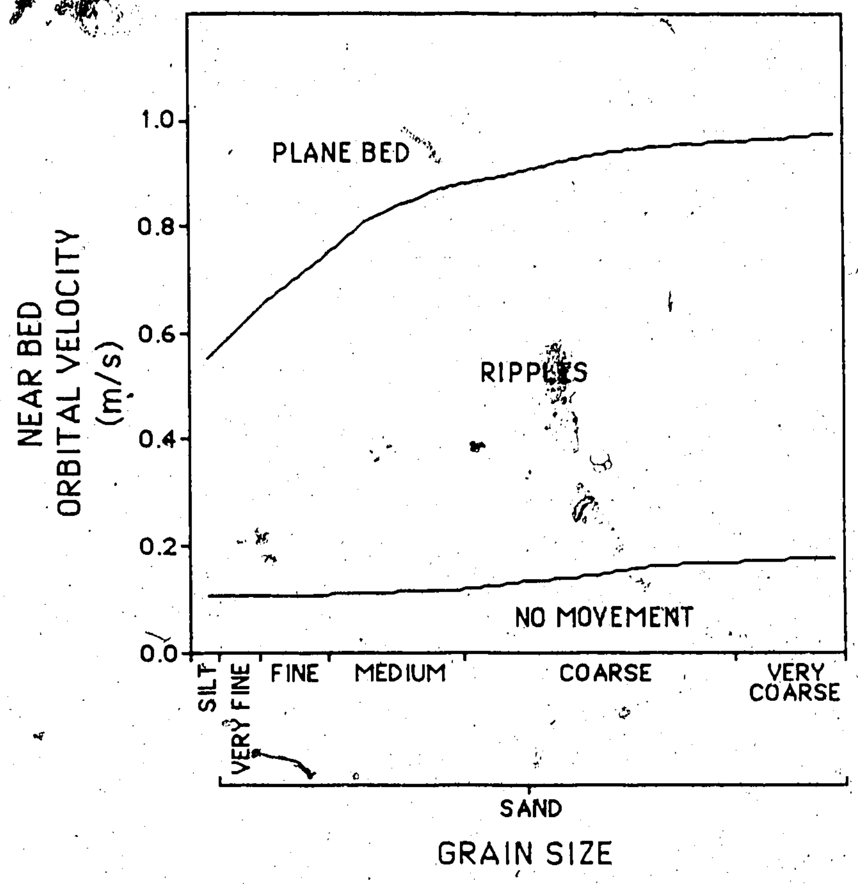


Fig. 19. Size velocity diagram for oscillatory motion generated by water waves acting on a bed, showing stability fields of bed phases (modified from Allen 1985).

produced by "combined" (terminology from Harms 1969) oscillatory and unidirectional flows, very difficult.

LARGE-SCALE CROSS-STRATIFIED SAND

Description:

This lithofacies, which is commonly found in the lower and middle members and the limy unit, is characterized by large-scale cross-stratified sand. Because each inclined strata extends across the entire width of the drill core this cross-stratification is termed "large-scale" (Plate 2, Fig. b). Individual cross-strata have an average thickness of 1cm (range from 0.5 to 3cm) and dip between 5 and 25°, averaging approximately 10°. Within a single set of cross-strata dips can vary with no evidence of a depositional break and adjacent sets often show opposing dips. Set thickness is estimated to range between 5 to 150cm because the drill core are cut up into short lengths (for easier transport, storage and observation) and set thickness is difficult to measure accurately.

The relationship between the lower bounding surface of a set of large-scale cross-stratified sand and individual cross-strata (within that set) is variable. Cross-strata usually have the same attitude as the lower bounding surface but asymptotic or tangential intersections of the cross-strata and the lower bounding surface are also common (Fig.20). Cross-strata intersecting the lower bounding surface at an angle are rare.

Sands in this lithofacies are typically fine grained whereas medium to very coarse grained sands are less common and are usually found in the lower member. Sorting of cross-stratified sands is usually very high in the middle member, but moderate to poor in the lower member and limy unit. Grain size within a single cross-stratum is usually uniform, but normal (fining upward) grading is also observed. Graded cross-strata can

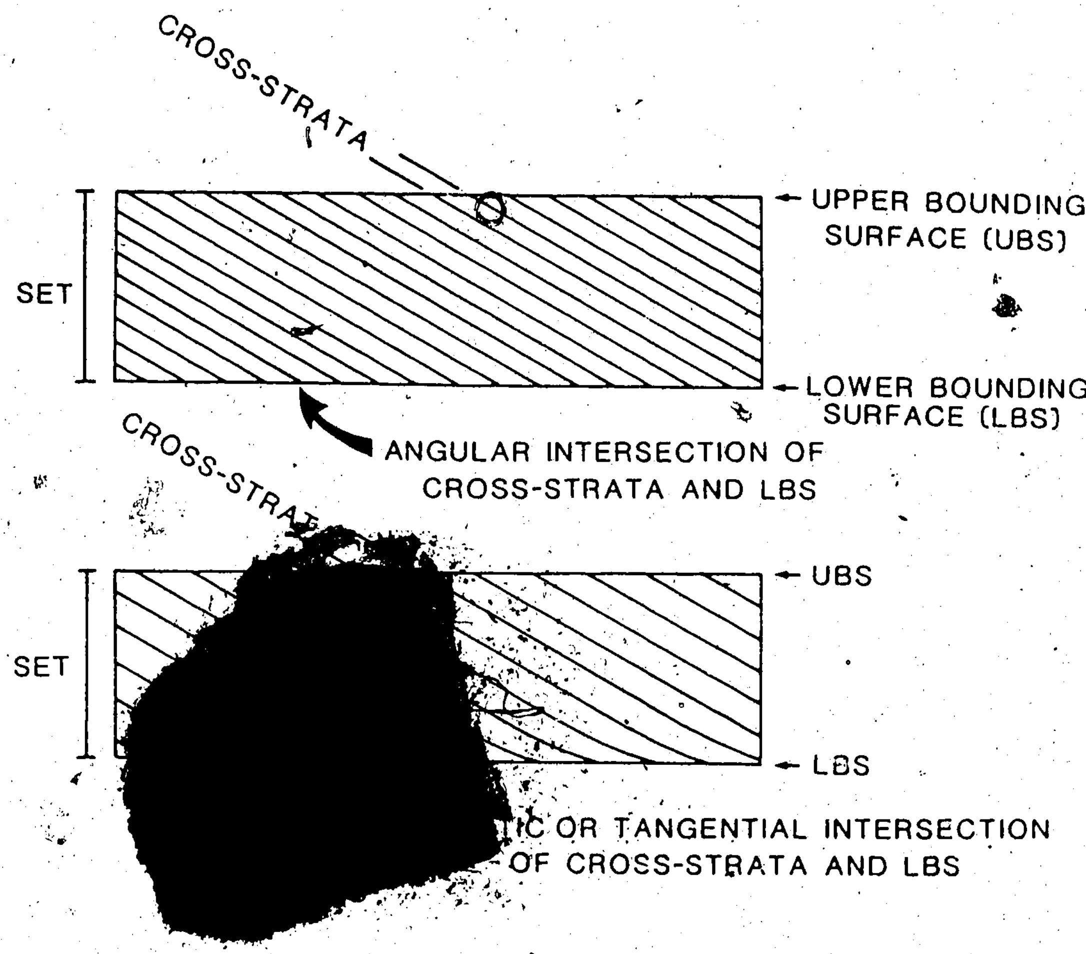


Fig. 20. Cross-stratification in sands exhibiting two types of intersections, angular and asymptotic, of cross-strata with the lower bounding surface of the set (modified from Collinson and Thompson 1982).

consist of a medium or coarse grained sand grading upward into a fine sand. A single set of large-scale cross-stratified sand usually consists of a sequence of cross-strata with the same grain size. Less common are sets characterized by cross-strata with differing grain sizes. Large-scale cross-stratified sands in the lower member are commonly muddy and as a consequence often have lower levels of bitumen saturation.

Thin mud drapes and composite sand and mud partings are often interbedded within large-scale cross-stratified sand (Plate 2, Fig. c). Mud drapes consist of continuous to discontinuous mud laminae up to 1cm thick and are often deformed and contorted. Bioturbation in the mud drapes is usually low to absent but in rare examples can be intense. Mud drapes are typically conformable to the cross-strata that they are intercalated with. Drapes are rarely unconformable with overlying cross-stratified sand. Thin composite sand and mud partings interbedded in large-scale cross-stratified sand are also recognized in this lithofacies. Partings greater than 5cm are usually designated as units of *interbedded sand and mud*. Partings, which are usually characterized by the intercalation of thin sand lenses or laminae with mud forming a composite interbed, often have variable but typically low levels of bioturbation. Partings are usually conformable to underlying cross-strata but cross-strata overlying the parting can be conformable or disconformable.

In the limy unit, mud drapes and composite sand and mud partings often have a thin enveloping film of carbonaceous debris. Carbonaceous debris is common in large-scale cross-stratified sands in the lower and middle members, as well as the limy unit. Subrounded to angular coaly fragments up to 6cm long and 2.5cm thick are commonly found interbedded in large-scale cross-stratified sand. These fragments often have relic textures that resemble growth rings of woody vascular plants. Carbonaceous debris is also found in the form of coaly laminae that are usually ≤ 1cm thick with thicker units (e.g. 8cm, drill core 38-39) being much more rare. Coaly units appear to lack any type of roots. Macerated carbonaceous debris is often finely interlaminated with sand forming composite units that have an average thickness of 1cm and are usually conformable to the large-scale cross-stratified sand that they are intercalated with. Dispersed carbonaceous fragments and slivers are common in large-scale cross-stratifed sands in the lower member.

Large-scale cross-stratified sand in the lower member, as well as the lower portion of the middle member, can be gravelly. Gravelly sands typically contain subrounded feldspathic (lower member only) and quartzose granules and pebbles. In the lower member subrounded fragments of bones (drill core 40-39) and limestone (similar lithologically to underlying Devonian carbonates) are found in large-scale cross-stratified sands whereas in the limy unit, this lithofacies often contains shells and shell debris. Shells are often found at the base of individual cross-strata or they are dispersed throughout an entire set. Cross-strata of shells and shell debris (with a sand matrix) are often interbedded with cross-strata of sand with few or no shells (drill core 35-43).

Large-scale cross-stratified sands in the middle member often contain angular to subrounded mud intraclasts which are usually aligned parallel to the attitude of the cross-strata (Plate 2, Fig. d). Mud intraclasts appear to have the same lithology as *flat to low angle laminated light grey to tan mud* and *interbedded sand and mud*. In the lower member, mud intraclasts resemble *structureless white to grey carbonaceous mud*. Intraclasts usually comprise 30 to 35% of a set of large-scale cross-stratified sand with sets with greater than 50% intraclasts more rare. Intraclasts are more likely to be sand matrix supported rather than clast-supported. Mud intraclasts have an average length of 3cm and thickness of 2cm but larger intraclasts up to 16cm thick have also been recognized. Because one is examining a 6cm wide drill core, very large mud intraclasts can be easily mistaken for beds of *flat to low angle laminated light grey to tan mud* and/or *interbedded sand and mud.* Mud intraclasts are usually moderately to well sorted with bimodal clast size distributions (two dominant clast sizes) infrequently recognized. Large-scale cross-stratified sands with mud intraclasts can form units up to 6.9m thick (drill core 35-41) but are usually 0.5 to 1m thick units interbedded with units of large-scale cross-stratified sand with no or few mud intraclasts.

Iron-cementation of large-scale cross-stratified sand is generally rare but mud intraclasts can be indurated. Contacts between superimposed sets of large-scale cross-stratified sand are often scoured and less commonly conformable. Conformable sets of cross-stratification can be separated by a mud drape, by a horizon of bioturbated sand or a horizon of clay-filled burrows. Basal contacts with other lithofacies are usually scoured but apparent gradational, wavy, loaded and flat contacts are also common. Large-scale cross-stratified sand with mud intraclasts often gradationally overlies *flat to low angle planar stratified sand* with mud intraclasts.

Interpretation:

Large-scale cross-stratification is the result of bedload transport of sand in migrating subaqueous dunes (Harms and Fahnestock 1965; Harms *et al.* 1982; Allen 1985). Dunes are flow tranverse lower flow regime bed forms (Simons *et al.* 1965) and form in a similar way to ripples, except that they develop in coarser grained sands and at higher flow velocities (Fig. 17). Dunes have wavelengths ranging between 60cm and hundreds of meters whereas height varies between 0.05 to 10m (Leeder 1982). At lower current velocities dunes are straight-crested (two-dimensional) in plan view, but become more sinuous-crested or linguoid (three-dimensional) at higher flow velocities (Simons *et al.* 1965). Straight-crested or two dimensional dunes produce planar tabular cross-stratification (Harms and Fahnestock 1965; Harms *et al.* 1982). In vertical sections parallel to flow, sets are tabular and laterally continuous (Fig.21) and cross-strata intersect the lower bounding surface of the set at an angle (Harms *et al.* 1982). In vertical sections transverse to flow, sets of cross-strata are also tabular and laterally continuous. Cross-strata, which appear in this section to be almost flat and undulating, are generally not conformable to lower set boundaries. Planar tabular cross-stratification develops on the steep (30^{o} or more) avalanche slope on the lee of a migratory straight-crested dune. There is no development of distinct scour pits at the toe of the dune, but rather a laterally extensive zone of erosion. Deposition is confined to the avalanche slope of straight-crested dunes, with little or none taking place in the lee scour. In order for cross-strata to be preserved, successive dunes cannot erode too deeply and there must be some element of climb. A vertical sequence of sets of planar tabular cross-stratification indicates deposition from a "train" of migrating straight-crested dunes (Harms *et al.* 1982). Set thickness of planar tabular cross-stratification can range from a few decimeters to a meter or more. Planar tabular cross-stratification can also develop by the migration of bars or the progradation of small deltas (Harms *et al.* 1963, 1982; Reineck and Singh 1975; Dalrymple 1984a).

Linguoid dunes produce trough cross-stratification (Harms *et al.* 1982). In vertical sections parallel to flow, sets of cross-stratification are tabular with set boundaries virtually parallel to one another. However sets thicken or wedge laterally. In vertical

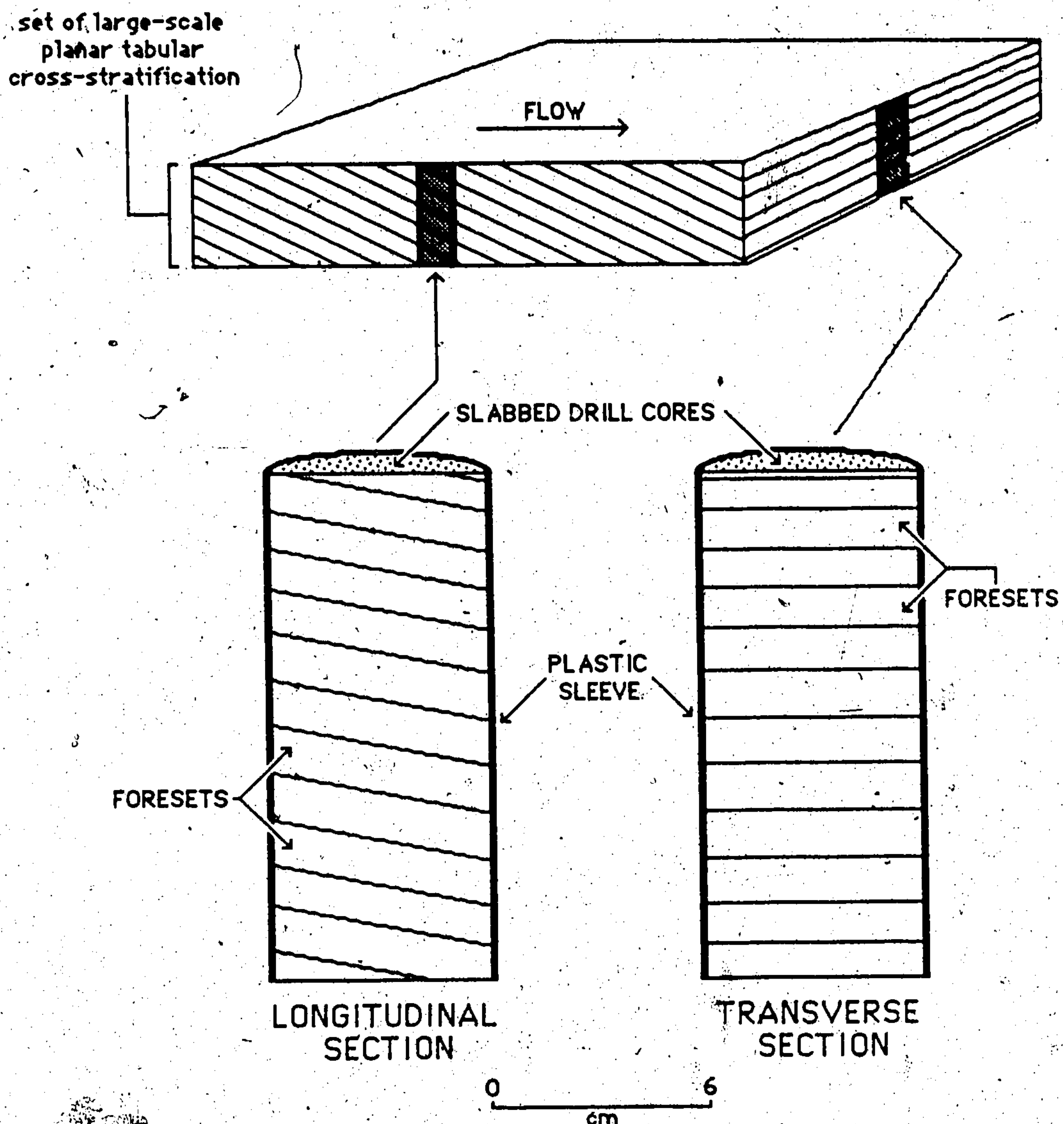


Fig. 21. Block diagram of a set of planar tabular cross-stratification showing potential stratification from transverse and longitudinal vertical sections.

sections transverse to flow, sets of large-scale cross-stratification are festoon-shaped. Lower set boundaries are concave upward with overlying cross-strata more or less parallel with the lower bounding surface. Trough cross-stratification develops in elongate scours, parallel to flow, that develop downstream of a migrating linguoid dune (Harms *et al.* 1982). Scours are filled from the upstream end, with low angle curved laminae as the dune migrates downstream. These laminae are deposited from suspension and/or by avalanche on the lee slope of the dune which results in a gradational transition from the foresets (avalanche deposits) to the toesets (suspension and possible back flow induced bedload deposits) producing an asymptotic or tangential relationship between cross-strata and the lower bounding surface. In order to preserve a portion of the cross-strata deposited as the dune migrates downstream, there must be a small amount of climb, or erosion by successive migrating dunes will occur (Harms *et al.* 1982). Because climb is usually quite low, only the toesets and the lower foresets filling the deepest part of the "lee-scour" will be preserved. Large-scale trough cross-stratification has a maximum set thickness of a few decimeters (Harms *et al.* 1982).

Large-scale cross-stratification is also produced by migrating sand waves. Sand waves are flow tranverse bedforms which are large enough to have dunes superimposed on them (Dalrymple 1984b). Sand waves are often thought to be exclusively shallow marine tidal bedforms but they also occur on non-tidal shallow marine settings (e.g. Flemming 1978), as well as fluvial environments (e.g. Coleman 1969). Sand wave foresets, where most of the cross-stratification develops, have dips which range from a few degrees to 30^{o} (Dalrymple 1984b).

Shells, shell debris, mud intraclasts and wood fragments can be deposited on the avalanche slopes of both straight-crested and linguoid dunes and become incorporated into foreset deposits. These larger grains can also accumulate in the lee scours of linguoid dunes and be incorporated in toeset deposits. Mud intraclasts deposited in the lee-scour would be expected to have a near horizontal orientation giving the impression, especially in a 6cm wide drill core, that these deposits were *flat to low angle planar stratified sand* with mud intraclasts.

Because both planar tabular and trough cross-stratification, as well as the cross-stratification produced by sand waves and bars are laterally extensive, it is difficult to differentiate between them because of the restricted width provided by the drill core. However, specific features may provide clues to one or the other type of cross-stratiification. Features such as rare angular intersections of cross-strata with lower bounding surfaces and set thickness of up to 1.5m support planar tabular cross-stratification produced by the migration of straight-crested dunes. Other features such as: multiple cross-strata dip reversals within a coset of large-scale cross-stratification; abundant parallel and tangential contacts of cross-strata with lower bounding surfaces of sets; the shallow dip of cross-strata suggesting deposition on the lower part of the lee slope, as well as in the lee scour; and the common occurence of *planar stratified sand* with angular mud intraclasts in association with large-scale cross-stratification suggesting depostion in a lee scour, all suggest trough cross-stratification formed by the migration of linguoid dunes. The latter interpretation seems most likely in the case of this lithofacies because these features are most abundant.

Mud drapes and composite sand and mud partings interbedded between cross-strata indicate that there was a pause in bed form migration during which time sand transport was enough to allow mud to settle from suspension on the avalanche slopes and in the lee-scours. Composite sand and mud partings indicate that currents, though substantially, weakened, fluctuated between those capable of transporting minor amounts of sand, and those under which mud could be deposited.

VERY FINE LARGE-SCALE CROSS-STRATIFIED SAND

Description:

This lithofacies is rare in the McMurray Formation, occurring only in the middle member and the limy unit. It differs from the previously described *large-scale cross-stratified sand* in that it is usually characterized by finer cross-stratification. Cross-strata usually have thicknesses between 1 and 3mm. Cross-strata dips range between 5 and 15° and are often variable within a single set of cross-stratification, with no evidence of depositional breaks. Set thickness ranges from 1 to 10cm, averaging 5cm. Often a bed of this lithofacies consists of a single set of cross-stratification whereas thicker beds are composed of multiple sets of large-scale cross-stratification. Cross-strata in these stacked sets all have the same dip direction and are usually parallel to the lower bounding surface of the set, but angular intersections are also recognized. Set boundaries are typically erosional.

Sands in this lithofacies are usually fine grained but can range from very fine to medium sands. Bitumen saturation is usually moderate to low, increasing the ability to recognize structures in this lithofacies. Bioturbation is generally absent in this lithofacies but is often evident in mud drapes interbedded in the cross-stratified sands. Continuous to discontinuous mud drapes (1-2mm thick) are rare and macerated carbonaceous debris is often finely interbedded within the cross-stratified sands forming composite units, 1-2cm thick. Small (≤0.5cm thick, ≤1cm long) mud intraclasts aligned parallel to the cross-stratification are infrequently interbedded in these cross-stratified sands. Basal contacts with other lithofacies are typically scoured or flat but rare gradational contacts are also recognized.

Interpretation:

This lithofacies was probably deposited by processes similar to those that were responsible for the more common *large-scale cross-stratified sands*. Migrating dunes and bars, as well as prograding small deltas, produce large-scale cross-stratification (Reineck and Singh 1975; Harms *et al.* 1982; Dalrymple 1984a). Thin cross-strata suggest a decrease in the rate of deposition, probably reflecting diminished current velocities, and as a result, slower migration or progradation. Deposition was probably confined to avalanche down the lee slope of a dune, bar or delta, each avalanche producing a single cross-stratum. Carbonaceous debris, often finely interbedded between cross-strata, was likely deposited from suspension onto the avalanche slope. If current velocities were sufficiently low to allow mud to settle from suspension, mud drapes could develop on the lee slope.

Dunes generally do not form in very fine grained sands (Harms *et al.* 1982), therefore it is questionable whether very fine grained sand beds of this lithofacies were in fact the result of migrating dunes. It is possible that some of these units were deposited from suspension and inherited their attitude of stratification from the surface on which they accumulated. The limited lateral exposure provided by the drill core restricts the interpretation of this lithofacies.

MUDDY CARBONACEOUS SAND

Description:

This lithofacies is characterized by muddy carbonaceous sands which typically lack any recognizable sedimentary structures. There is vague evidence of ambiguous convolute lamination and small-scale cross-stratification in some beds. This lithofacies is only found in the lower member where it is abundant. Sands are usually poorly sorted, with grain size ranging from very fine to very coarse sand (not necessarily in the same bed). Sands have a high mud content (hence the term muddy sand) and as a consequence levels of bitumen saturation are [illegible]gular patches of relatively clean sand (therefore higher bitumen saturation) occur sporadically in muddy sands. Fine slivers of carbonaceous material are usually dispersed in the sands of this lithofacies. Subrounded quartzose and feldspathic granules and pebbles, as well as subangular to angular mud intraclasts, are infrequently found scattered in the sands but are more frequently concentrated at the bottom of beds of this lithofacies. Iron-cementation of either all or part of beds in this lithofacies is common and may contribute to the massive texture of the sands. Simple and deeply penetrating carbonized roots are commonly recognized. Basal contacts with other lithofacies are typically flat to scoured but gradational and loaded contacts are also common.

Interpretation:

Relict sedimentary structures such as small-scale cross-stratification and convoluted stratification indicate that these structureless sands probably underwent secondary modifications. It is likely that primary sedimentary structures were completely or partially disrupted by liquifaction. Certain features observed in this lithofacies provide some clues as to what primary processes were responsible for their deposition. Physical reworking by currents was low as indicated by the poor sorting of the sediments of this lithofacies, which range from mud to gravel. The relatively high angularity of many mud intraclasts found in the sands indicate little or no transport from their source. The poor sorting of sediments and the angularity of mud intraclasts suggests that current energy levels were much too low to form a primary massive sand bed. Vague small-scale cross-stratification in some beds of this lithofacies are indicative that some bed load transport of sand in ripples occurred. Generally, stratification in sands is indicative of some type of transport in bed forms (Harms and Fahnestock 1965).

The high mud content of the sands in this lithofacies may be primary (deposited at the same time as the sand) or the result of the alternation of feldspathic and lithic grains into clay. Feldspars can be chemically broken down, through hydrolysis, into clay minerals such as illite and kaolinite (Blatt *et al.* 1980; Leeder 1982). A detailed petrological examination of these clays would be required to accurately determine the source of the mud in the sands of this lithofacies.

INTERBEDDED SAND AND MUD

Description:

This lithofacies is characterized by composite sets of interbedded sand and mud. The sand to mud ratio (within a given set of this lithofacies) can vary such that: sand is more abundant than mud; mud and sand have approximately equal abundance; and mud is more abundant than sand. This lithofacies is commonly found in the middle member of the McMurray Formation but also occurs less frequently in the lower and upper members.

Interbedded sand and mud are commonly flat to low angle stratified with stratification attitude varying between 0 to 10° (Plate 3, Fig. a). Steeper dips (up to 20°) are infrequent (Plate 3, Fig. b). Dip reversals within a single set of interbedded sand and mud are relatively uncommon. Stratification appears to "fan" from one dip direction to an opposing dip with no evidence of a depositional break. Deformation of interbedded sand and mud is generally low. Load structures, small-scale faults (throw 1 to 2cm) and flame structures are scarce. Intense distortion or convolution (in sets up to 40cm thick) of interbedded sand and mud is also uncommon. Sand-filled vertical cracks, which are often highly convoluted, are rare in this lithofacies.

Sand and mud are usually coarsely interbedded with one another (Plate 3, Fig. c). Interbeds of 2 to 5 cm thick sands with or without interbedded mud drapes and flasers are usually interbedded with 1 to 5cm thick muds which typically contain intercalated sand lenses and laminae. Finely interbedded sand and mud (sand and mud beds <1cm thick) are less common. Contacts between the sand and mud interbeds are usually flat or scoured but sand beds overlying mud rarely contain mud interclasts. Gradational and irregular contacts are less common. Sands are typically fine to very fine grained with medium and coarse sands much more scarce. Sand interbeds are usually small-scale cross-stratified but tabular and festoon shaped sets are also frequently recognized. Less commonly, sands are flat to low amplitude wavy stratified or massive. Individual sand interbeds can consist of a single or multiple sets of cross-stratified sands. Mud drapes and flasers in the sands are usually intercalated between individual cross-strata or are found on set boundaries. Sands usually have moderate to high levels of bitumen saturation but overall bitumen saturation is relatively low due to the intercalations of mud. Mud interbeds are usually finely laminated and have intercalated sand lenses and laminae often showing hints of cross-stratification. These sands have variable bitumen saturations. Carbonaceous debris

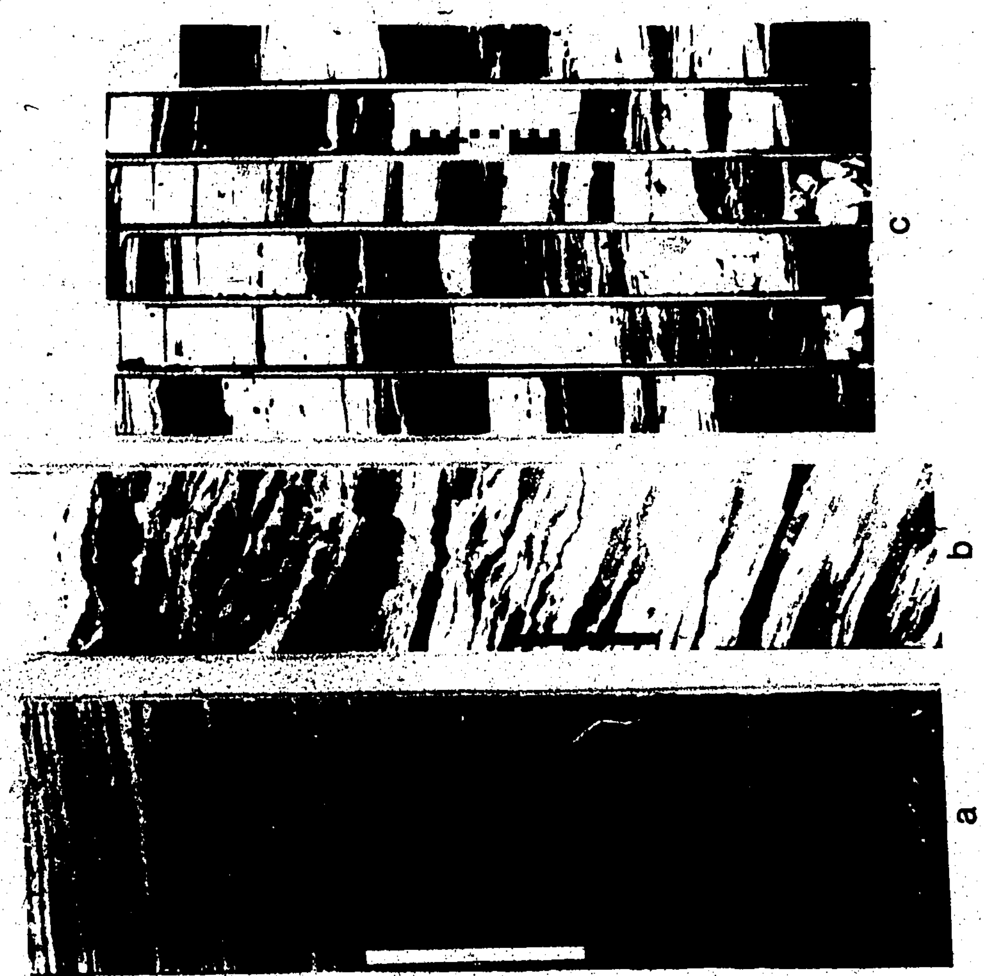
PLATE 3

Interbedded sand and mud from the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.

Fig. a. Low angle dipping, finely stratified interbedded sand and mud in the middle member of the McMurray Formation; drill core 41-35, 58.4m (scale 5cm).

Fig. b. Steeply dipping interbedded sand and mud in the middle member, exhibiting small-scale faulting and convoluting; drill core 40-35, 52.1 to 52.4m (scale 5cm

Fig. c. Sequence of interbedded sand and mud in the middle member, consisting of small-scale cross-stratified sand intercalated between mud with sand laminae and lenses; drill core 42-41, 72.8 to 76.8m (scale 15cm).


a
b
c

in this lithofacies is generally rare. Elongate carbonaceous fragments (0.5mm thick, 1 to 3 mm long) interbedded in the muds, are typically aligned parallel to the stratification. Associated with the carbonaceous debris are dispersed sand grains (fine to medium sand). On bedding planes, carbonaceous debris does not appear to have a preferred orientation. Carbonaceous debris is usually rare in sand interbeds. In the lower member, sands in this lithofacies are often carbonaceous, and are typically muddy resulting in diminished levels of bitumen saturation. Bioturbation is highly variable with sand interbeds having few biogenic structures. Bioturbation in the mud beds is generally higher, especially those with intercalated sand lenses and laminae. Sets of interbedded sand and mud can be so intensely bioturbated that only a crude stratification remains. Homogenized muddy sand beds, which usually lack any distinctive physical sedimentary structures, are often interbedded between sets of heavily bioturbated interbedded sand and mud beds. Mud interbeds tend to be iron-cemented more commonly than sand interbeds. Basal contacts with other lithofacies are typically flat to gradational whereas scoured, loaded and irrregular contacts are less common. Contacts between sublithofacies of interbedded sand and mud are generally gradational.

Interpretation:

Interbedded sand and mud has commonly been classified as flaser, wavy and lenticular bedding (Fig. 22a) (terminology after Reineck and Wunderlich 1968). Flaser bedding, from the German word "flaser" meaning streak or vein, consists of sand with thin wavy lenses of mud (Reineck 1960). Wavy bedding is characterized by laterally continuous interbedded sand and mud in approximately equal abundance (Reineck and Wunderlich 1968). Lenticular bedding consists of mud with interbedded lenses of sand (Reineck

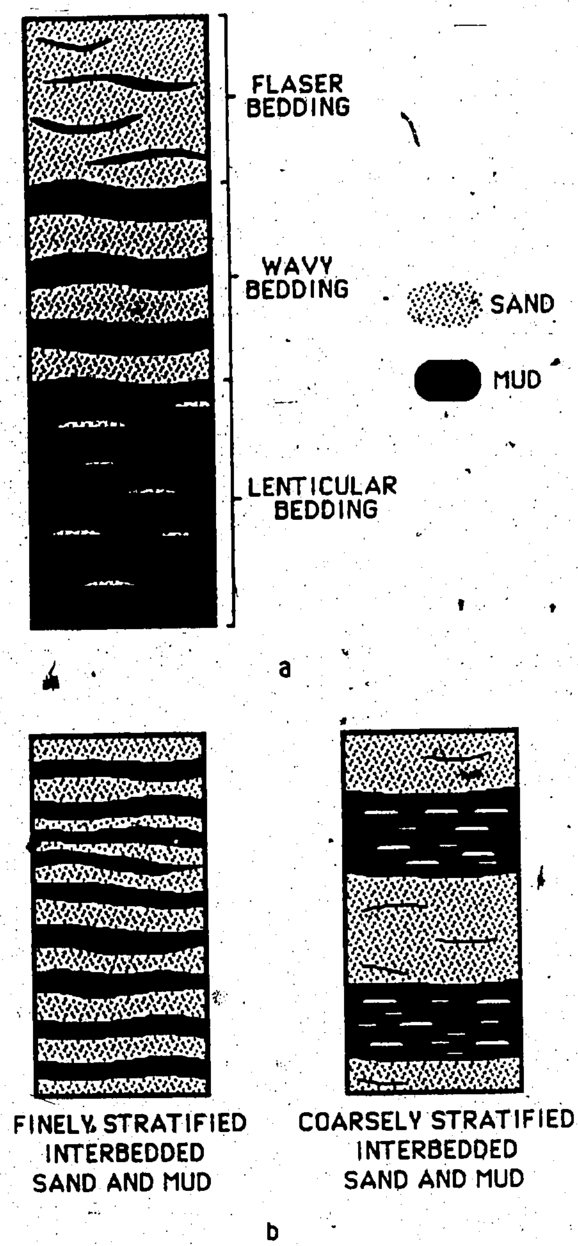


Fig. 22. (a) Interbedded sand and mud as classified by Reineck and Wunderlich (1968) showing flaser, lenticular and wavy bedding (modified from Hawley 1981a). (b) Finely- and coarsely-stratified interbedded sand and mud.

1960). Because interbedded sand and mud was often coarsely interbedded, this classification scheme was not used (Fig 22b). Interbedded sand and mud usually indicates that: (a) sand and mud are abundant in the environment; and (b) that there is a mechanism which allows for the alternative deposition of sand and mud (Hawley 1981a). Generally sand is deposited when current velocities are such that sand can be transported either in suspension or as bed load. Mud is kept in suspension while sand transport is taking place. Mud can be deposited only when current velocities are such that mud particles can settle from suspension. Sand transport stops prior to the settling of mud.

Interbedded sand and mud has often been referred to as "tidal bedding" (e.g. Reineck and Wunderlich 1968) because it is typically found in nearshore environments where tides are the most important mechanism of sediment transport and deposition. Interbedded sand and mud is commonly deposited in both intertidal (e.g. Häntzschel 1936; Van Straaten 1954; Reineck 1960) and subtidal environments (e.g. Oomkens and Terwindt 1960). The nearshore tidal environment, comprised of tidal flats and estuaries, is often characterized by abundant sand and mud, and by currents that fluctuate between those capable of transporting sand and those under which mud can be deposited. Interbedded sand and mud is not however ubiquitous to the nearshore tidal environment. Interbedded sand and mud can also be deposited in offshore marine environments (e.g. Aigner and Reineck 1982; Howard and Nelson 1982). It is also deposited in shoreface environments (e.g. Howard and Reineck 1972), deltaic settings (e.g. Coleman and Prior 1982); subaqueous fans,(e.g. Howell and Normark 1982) and fluvial environments (e.g. Jackson 1981; Taylor and Woodyer 1978; Parkash *et al.* 1983; Calverly 1984).

Interbedded sand and mud found in the middle member of the McMurray Formation, appears to have been deposited under regular occurring fluctuations in current velocities.

Tides are the best mechanism of regular current unsteadiness in a sedimentary environment (Hawley 1981a). The other depositional environments where interbedded sand and mud can be produced, are characterized by a less regular or random current unsteadiness. Regular and random current unsteadiness should be imprinted on the sedimentary record (de Mowbray and Visser 1984).

Tides are defined as the rhythmic or periodic rise and fall of sea level resulting from the interaction of the Sun and the Moon on the Earth (Defant 1958; Dietrich *et al.* 1980). Associated with this rise and fall of sea level is a lateral translation of water producing tidal currents. The rise in water level is known as the "flood" whereas a fall is referred to as the "ebb". A single rise and fall of the water level is a single tidal cycle. The distance between the peak of the flood (high water) and the bottom of the ebb (low water) is known as the tidal range. Tidal range is primarily dependent on the position of the Moon and the Sun about the Earth. According to Newton's Laws of Gravitation, masses are attracted to one another. Thus a mass such as the Earth is attracted to the Moon as well as the Sun, but they do not collide with each other because they are in orbit about one another. This orbit creates a centrifugal force which is equal but opposite to the attractive forces, resulting in an equilibrium. Although the Earth itself is in equilibrium with the Moon and the Sun, particles on the surface of the Earth are not. Centrifugal forces are constant in magnitude and direction all over the Earth, whereas attractive forces are variable. On the surface of the Earth closest to (for example) the Moon (i.e. the zenith), attractive forces are greatest. At the point on the Earth furthest from the Moon (i.e. the nadir), attractive forces are weakest. Different positions on the surface of the Earth have variable (magnitude and direction) attractive forces acting on them. As a result, the difference between attractive and centrifugal forces is variable, depending on the location on the

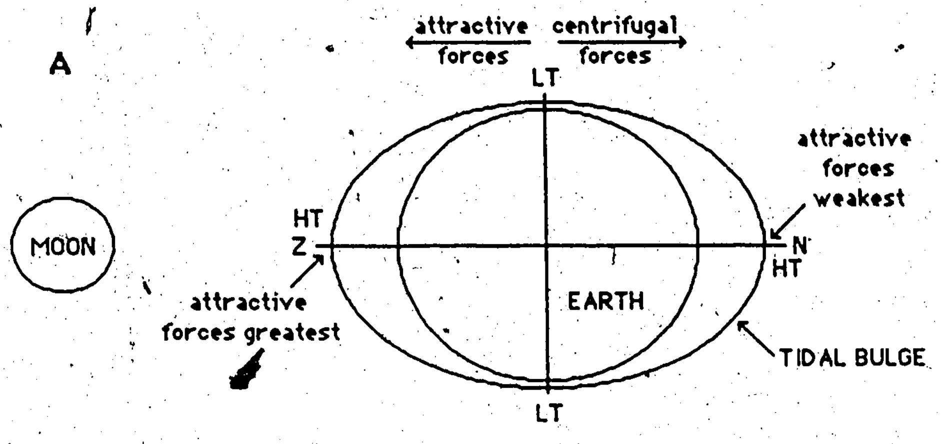
Earth's surface. The difference between the attractive and centrifugal force, known as the residual force, is what generates tides. At the zenith, attractive forces are greater than the centrifugal forces. Therefore a residual force is directed away from the surface of the Earth. At the nadir, attractive forces are weaker than the centifugal forces so a residual force is also directed away from the surface of the Earth. Along the meridian half way between the nadir and the zenith, a downward (toward the centre of the Earth) directed residual force occurs.

Newton successfully explained oceanic tides by proposing a model consisting of an ideal ocean with equal depth covering the entire earth (Fig. 23a). Because residual forces at the zenith and the nadir were directed away from the Earth's surface, water in the ocean would be pulled outward resulting in the development of a tidal "bulge" or "mountain" on either side of the Earth. Along the meridian half way between the nadir and zenith, residual force would push the water downward and toward the tidal bulges. With the rotation of the Earth about its axis and the fact that there are tidal bulges on either side of the Earth, most points on the Earth have two high tides (tidal buldge) and two low tides daily resulting in a semi-diurnal tide. If the Moon is directly in line with the celestial equator of the Earth, the two high tides will be of equal magnitude (Fig 23b.). However, if the Moon is not in line with the celestial equator, the two high tides will not have equal magnitude resulting in an inequality of tides (Fig. 23c). Inequality can be so great that there may only be one high tide per day.

Both the Sun and the Moon "contribute" attractive forces on the Earth, though the tidal bulge produced by the Sun is only 46% of that produced by the Moon (Ross 1982). The position of the Moon and the Sun relative to the Earth figure greatly in tides. Besides the daily cycle of ebb and flood (either semidiurnal or diurnal), a 2 week neap/spring cycle

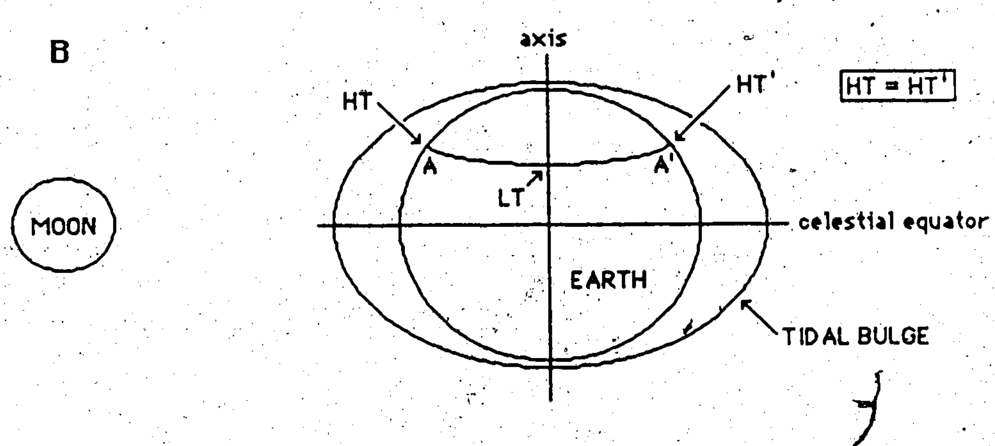
Fig. 23. (a) The Earth covered by an ocean of uniform depth with no intervening continents showing the development of tidal bulges in response to the gravitational attractions of the Moon as well as the centrifugal forces generated by the orbit of the Earth and Moon (modified after Defant 1958; Deitrich *et al.* 1980). (b) When the orbit of the Moon is directly in line with the celestial equator of the Earth, a point in the northern hemisphere (A) will experience 2 high tides of equal magnitude in 12 hours, producing a diurnal tide. (c) When there is a large declination in the orbit of the Moon about the Earth (with regard to the celestial equator), a point in the northern hemisphere (A) will experience 2 high tides of unequal magnitude producing a diurnal inequality.

A



Z : zenith (point on the surface of the Earth closest to the Moon)
N : nadir (point on the surface on the Earth furthest from the Moon)
A : point on the Earth's surface
A' : same point after 12 hours
LT : low tide
HT : high tide
HT' : high tide after 12 hours

B



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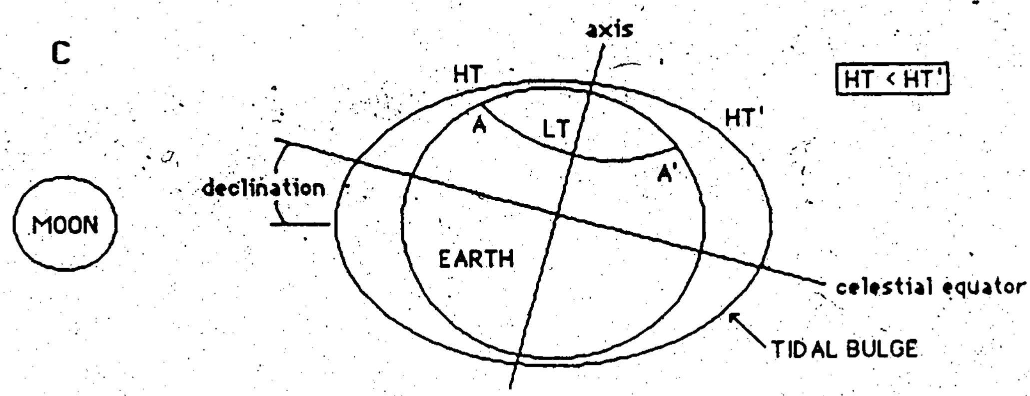


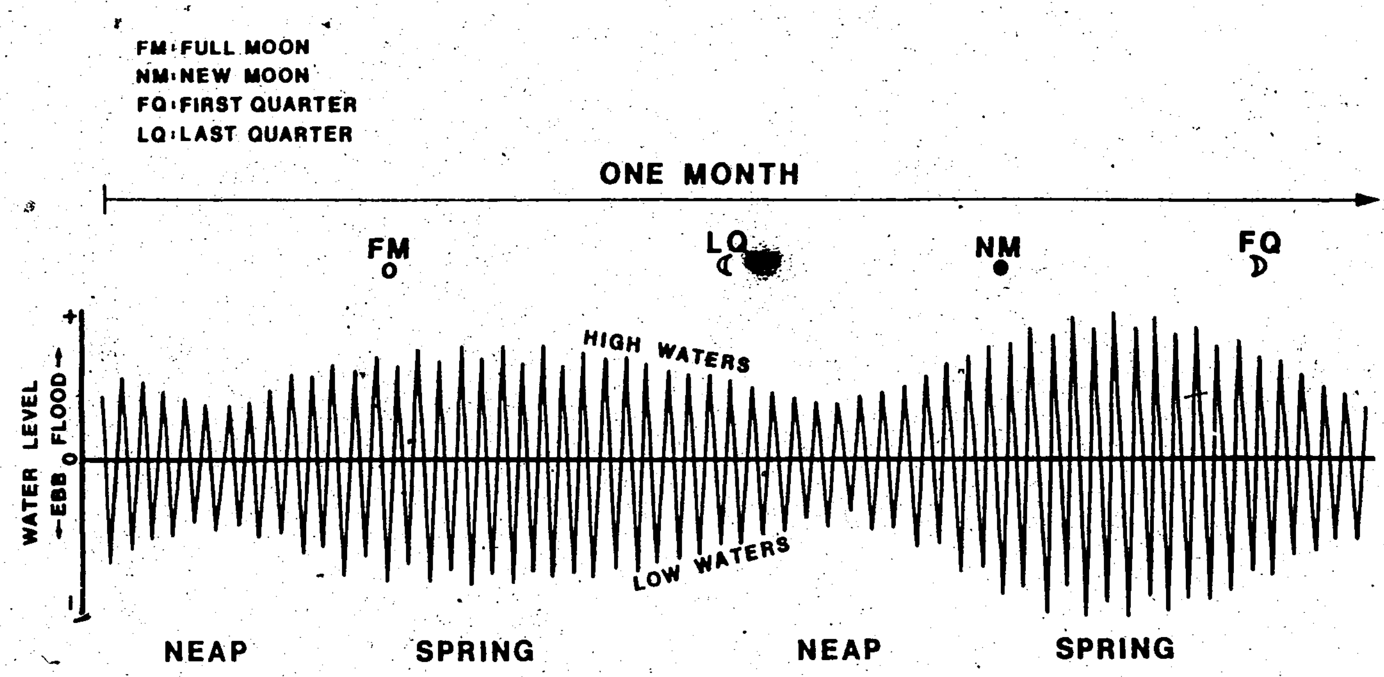


Fig. 24. Variations in tidal range over 2 neap/spring tidal cycles (modified from Defant 1958).

Table 3. Other sources of tidal cyclicity (from Defant 1958; Dronkers 1964; Dietrich *et al.* 1980; Beer 1983; Forrester 1983; Allen 1985).

(a) Changes in the distance between the Moon and the Earth during the month long orbit of the Moon about the Earth. When the Moon is closest to the Earth (perigee) tidal range is greater. When the Moon is furthest from the Earth (apogee) tidal range is reduced. Perigean tides ar 20% greater than apogean tides.

(b) Changes in the distance between the Sun and the Earth during the year long orbit of the Earth about the Sun. When the Earth is closest to the Sun (perihelion) the pull of the Sun is greatest and therefore tidal range increases. When the Earth is furthest from the Sun (aphelion) tidal range is reduced.

(c) Changes in the declination of the Moon and the Sun relative to the celestial equator of the Earth. When the Moon or the Sun are at their maximum declination, tidal range is small. When the Moon or the Sun are in line with the celestial equator of the Earth tidal range is greater. Thus during the solar equinox tidal range is higher whereas at the solstice, tidal range is diminished.

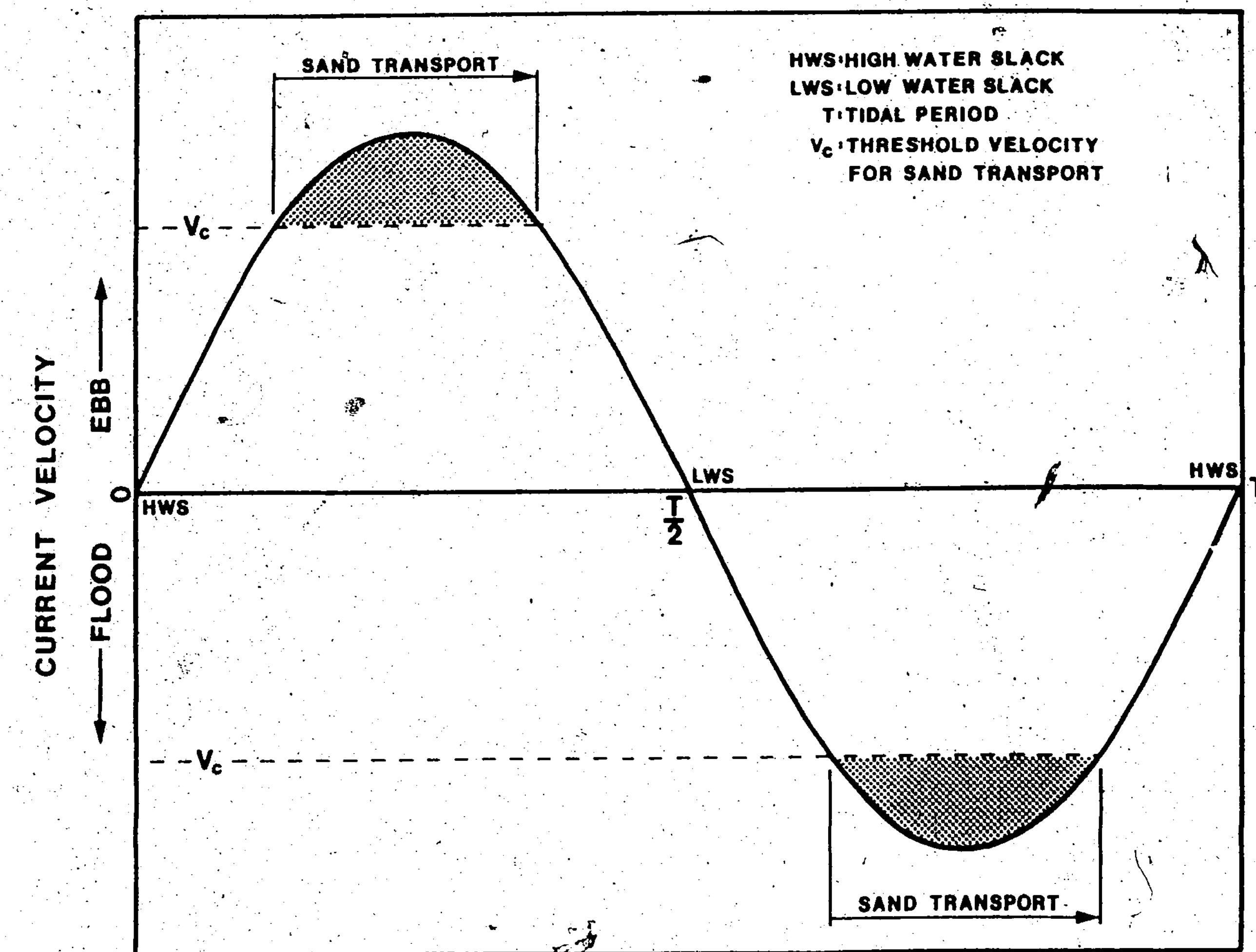


Fig. 25. Variations in sand transport over a single tidal cycle (modified from Allen 1985).

is important as well. Twice in the monthly orbit of the Moon about the Earth it is in line with the Sun (i.e. full moon and new moon). At this time attractive forces from both the Moon and Sun reinforce one another resulting in the greatest tidal range known as the spring tide (Fig. 24). At the quarters, attractive forces of the Moon act at right angles to those of the Sun resulting in diminished tidal range (neap tides). Tidal range at the spring tide is usually 50 to 100% greater than at the neap (Allen 1984). Other long term tidal periodicities affecting tidal ranges also exist (Table 3).

Of course the ideal ocean of uniform depth does not exist. Tides and tidal currents are modified by continents, the morphology of oceanic basins, the rotation of the Earth (Coriolis Force)and friction on the sea bed (Defant 1958; Dietrich *et al.* 1980). Tidal range can be enhanced by "resonance" caused by the synchronization of an embayment (such as the Bay of Fundy) with oceanic tides (Defant 1958) as well as a reduction in cross-sectional area (Castaing and Allen 1981).

It has been shown experimentally (Terwindt and Breusers 1972; Little-Gadow and Reineck 1974; Hawley 1981a, b) and in the field (Reineck 1960; Reineck and Wunderlich 1968; Little-Gadow and Reineck 1974) that interbedded sand and mud can be produced by current unsteadiness associated with a single tidal cycle. Sand transport and deposition occur during the ebb and/or flood stages whereas mud is deposited during intervening slack water stages.

The contact between individual sand and mud interbeds is typically sharp with little evidence of size grading between the mud and the sand. This feature is due to the difference in settling velocity of sand and mud particles (Little-Gadow and Reineck 1974). When currents are high, sand is transported, either in suspension or as bed load in a variety of bed forms such as ripples (Fig. 25). Mud however, remains in suspension. As current

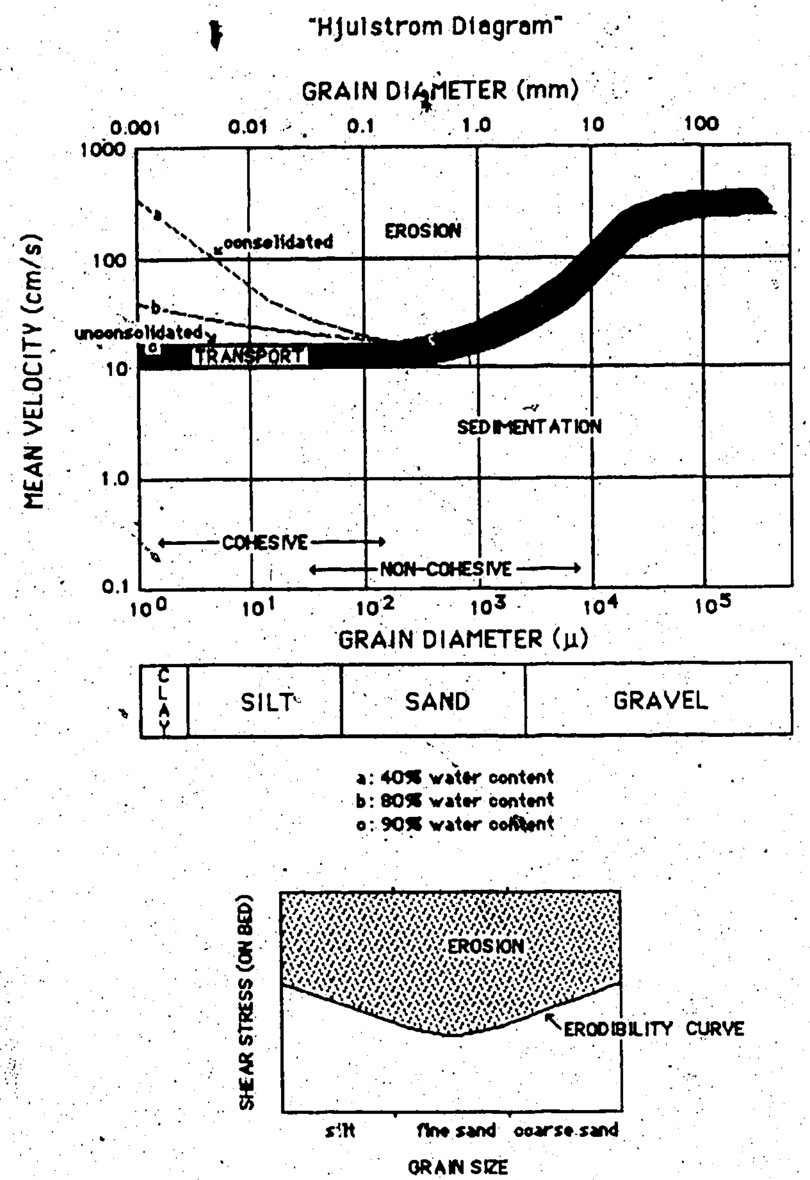


Fig. 26. "Hjulstrom Diagram" velocity versus grain size showing fields of erosion transport and sedimentation. Erosion of muds requires increasing current velocities as the consolidation of a mud bed increases (modified from Nichols and Biggs 1985). Bottom diagram shows similar relationship for shear stress versus grain size.

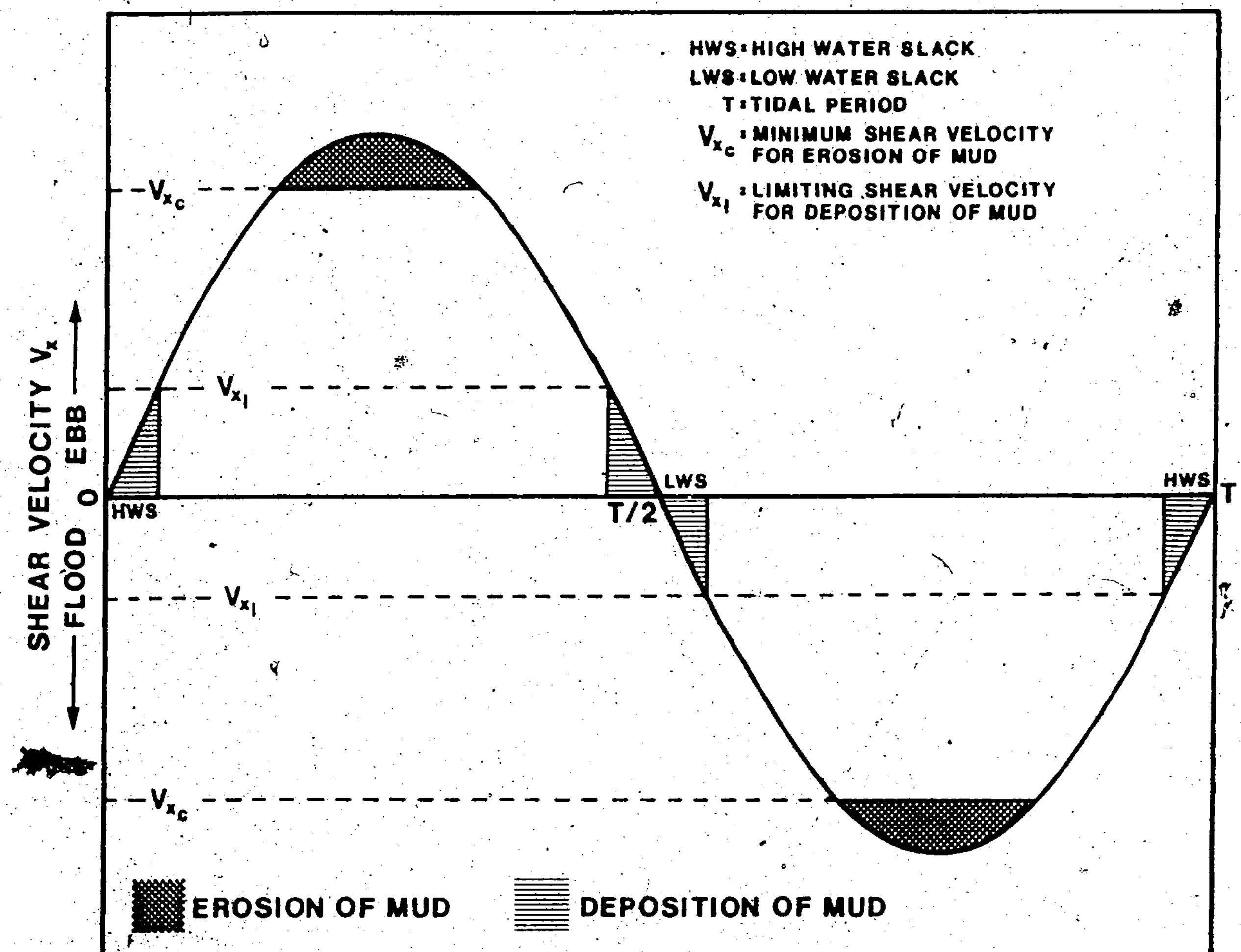


Fig. 27. Deposition and erosion of a mud during a single tidal cycle (modified after Harrison and Owen 1971).

Table 4. Factors which increase or decrease the shear strength of a deposited mud as it resists erosion by currents.

INCREASE SHEAR STRENGTH

1: cohesion of settled mud particles (Krone 1962)

2: greater consolidation (decreasing water content) with time (Van Straaten 1954; Postma 1967; Terwindt and Breusers 1972) which can be enhanced by interbedded sand laminae and interstitial sand (Migniot 1968; Terwindt and Breusers 1972)

3: deposited sediments create an overburden to underlying sediments resulting in further consolidation and greater shear strength (Migniot 1968)

4: algal coatings and organic binding (Van Straaten 1954; Rhoads *et al.* 1978; Young and Southard 1978)

5: coatings of iron oxide (longer time period) (Parthenaides 1965)

DECREASE SHEAR STRENGTH

1: erosion of interlaminated sand laminae and lenses weaken structure of the mud bed (Terwindt *et al.* 1968)

2: burrowing fluffs up sediment decreasing strength and increasing bed roughness causing greater near-bed turbulence (Rhoads *et al.* 1978; Young and Southard 1978)

3: removal of binding organic material and algae by feeding organisms (Young and Southard 1978)

4: ionic imbalances (i.e. salinity differences) between the pore fluid and eroding fluid can result in swelling, therefore weakening interparticle bonds and increasing bed roughness (Arulanandan 1975)

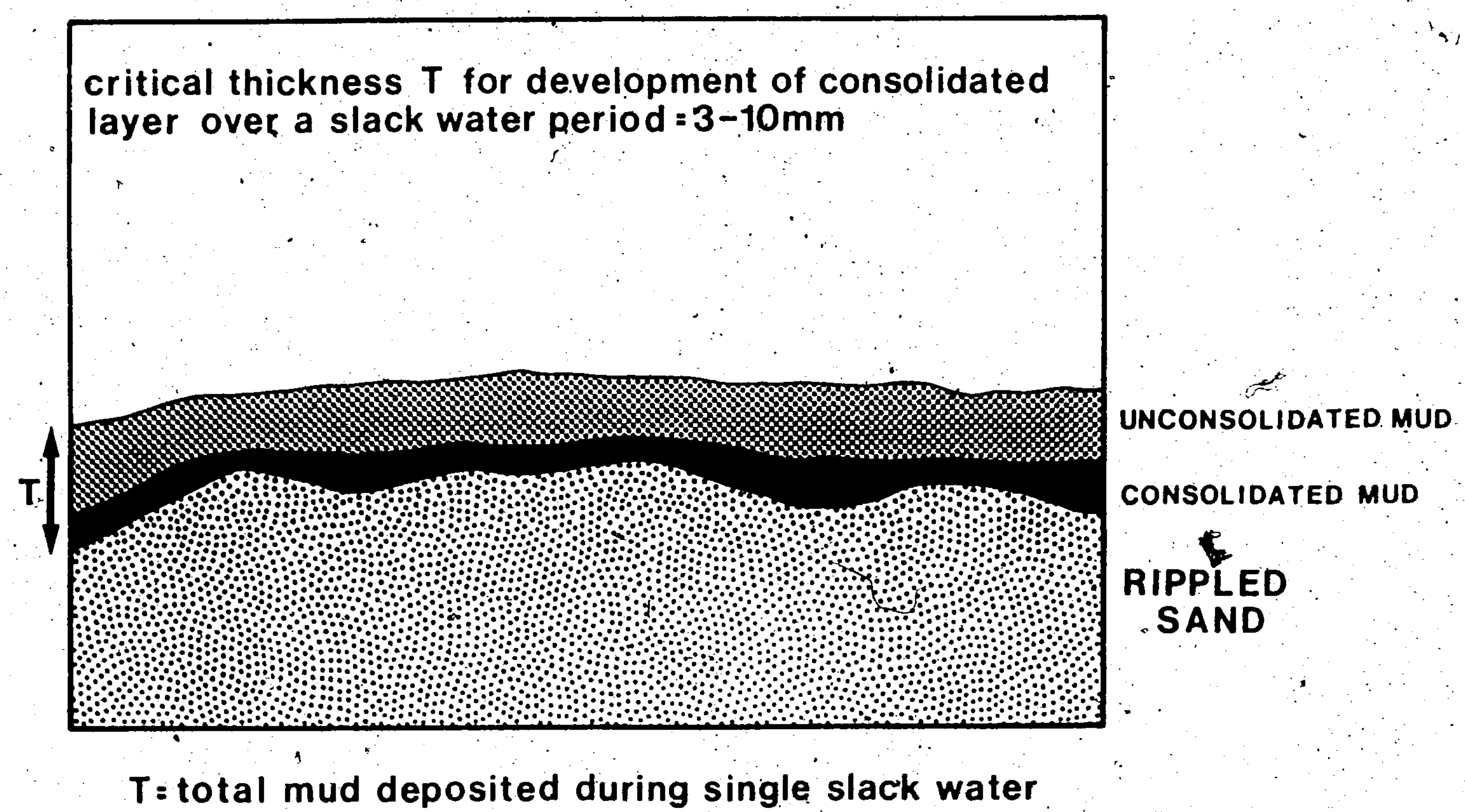


Fig. 28. Mud settled onto a rippled sand during a 1.25 hour slackwater stage showing development of basal layer resistant to erosion and upper layer that is easily eroded and resuspended by subsequent current activity (modified from Hawley 1981b).

velocity drops, sand transport diminishes until there comes a point when it ceases completely but muds are still kept in suspension because current velocities are too high. At some point, when currents become weak enough, mud particles begin to settle out. Thus there is lag between the time when sand transport stops and mud deposition begins resulting in the development of a sharp contact between sand and mud (Little-Gadow and Reineck 1974).

Because interbedded sand and mud is produced and preserved in the stratigraphic record, the mud that is deposited during slack water stages survives erosion by currents responsible for depositing overlying sand interbeds. Erosion of a deposited mud requires a current-induced shear that is considerably higher than the shear under which it was initially deposited (Fig. 26, 27) (Postma 1967). A number of factors influence the strength of a bed, either weakening it or making it more resistant to erosion by currents (Table 4). Deposited muds can often withstand erosion by currents that are capable of transporting sand and gravel (Terwindt *et al.* 1968; Drake 1976).

Although only a thin mud layer is usually deposited during a single slack water stage, a thicker bed can develop as the result of the amalgamation of several mud layers deposited over a succession of slack water stages (Owen 1970; Terwindt and Breusers 1972; Hawley 1981b). Mud that is deposited during a slack water stage and preserved in the stratigraphic record likely represents the basal remnant of a thicker unit that accumulated during a slack water stage. This remnant layer would be all that could withstand erosion by subsequent flood and /or ebb current activity. Experimental work (Hawley 1981b) simulating the deposition of mud from suspension onto a sand bed during a 1.25 hour slack water stage revealed that deposited mud consisted of two layers (Fig. 28). The basal layer could withstand erosion by relatively strong currents whereas the upper layer was eroded by much weaker currents. In order to form a resistant basal layer, an initial thickness of 3 to 10mm of mud had to be deposited (Hawley 1981b). If this critical thickness of mud was not attained, mud that settled to the bed would not survive erosion by subsequent current activity. In order to deposit appreciable amounts of mud over a short period of time, such as a slack water stage, high concentrations of suspended sediment are required (McCave 1970; Hawley 1981b). Nearshore environments are characterized by high levels of suspended mud (Van Staaten and Keunen 1957; Postma 1961). Estuaries are often characterized by very high suspended sediment with concentration ranging from a few mg to hundreds of mg/L (e.g. Kirby and Parker 1983).

Interbedded sand and mud that is produced by daily tidal current unsteadiness is usually thinly stratified because of the relatively small volumes of sediment deposited during each current or slack water stage. Interbedded sand and mud in the middle member of the McMurray Formation is generally coarsely stratified. Sand and mud interbeds are much thicker and often reflect two temporal levels of current unsteadiness. The thicker interbeds probably were deposited in response to larger term variations in current velocities, possibly the neap/spring cycle, whereas thin intercalations of mud in the sand beds and sand lenses in the mud bed reflect a more short term current unsteadiness possibly associated with the daily tidal cycle. Tidal currents during a spring tide are greater than those during a neap tide. At the mouth of the Haringvliet Estuary in southwest Netherlands, tidal currents at the spring are on average 25% stronger than at the neap (Terwindt and Breusers 1972). With stronger current velocities sand transport would be expected to be greater during ebb and flood stages during the spring whereas the preservation of mud deposited during intervening slack water stages would be low

(Oomkens and Terwindt 1960; Terwindt and Breusers 1972; Hawley 1981a). During the neap, sand transport would be diminished and mud deposited during slack water stages would have a greater likelihood of preservation. Daily current fluctuations are recorded by mud laminae in the sand beds and sand lenses in the mud beds. Owen (1971) observed that the settling of mud from suspension was greater during the neap tidal phase than the spring and concluded that turbulence was one of the major controlling factors for mud deposition. During the spring tidal phase increased turbulence resulted in the mechanical breakup of large flocs, reducing their settling velocities, whereas during the neap tidal phase turbulence was lower but sufficient to cause numerous particle collisions without breaking up larger flocs. As a consequence of these higher settling velocities mud deposition would be expected to be greater during the neap tidal phase.

Coarsely stratified interbedded sand and mud is also produced in response to seasonal current energy fluctuations that occur in many tidal environments (Van den Berg 1981). During the summer months current energy levels are reduced resulting in little or no sand being deposited. Current energy levels are much higher during the winter months because of increased storm activity resulting in greater sand transport with mud deposited during daily slack water stages.

The attitude of stratification of interbedded sand and mud is dependent on the surface that they were deposited on. The odd "fanning" of dip direction may be the result of the coring process. Although there is no direct evidence for it, twisting of the drill core along glide planes that develop in the mud interbeds may cause this feature.

Low levels of bioturbation in this lithofacies suggest either rapid rates of accumulation or an impoverished benthic fauna. Heavily reworked and biogenically homogenized units of interbedded sand and mud indicate a slow rate of deposition and an abundance of burrowing organisms.

Rare sand-filled cracks in mud intercalations are possible desiccation or synaeresis cracks. These cracks form in response to tension created by a reduction in the volume of the mud (Plummer and Gostin 1981). Desiccation cracks form subaerially, developing in response to a loss of water through evaporation. Synaeresis cracks form subaqueously forming in response to pore water loss that occurs with compaction, or because of salinity changes which cause swelling clays to contract. Both types of cracks are commonly filled with sand after formation. These sand-filled cracks are typically deformed during compaction (Collinson and Thompson 1982). Whether the cracks observed in the McMurray Formation are formed by synaeresis or desiccation is not known, but because of their restricted occurrence they contribute little to the final interpretation of the sequences observed.

INTERBEDDED SAND AND CALCAREOUS MUD

Description:

This lithofacies is characterized by compositely interbedded sand and calcareous muds (Plate 4, Fig. a, b). The sand to mud ratio within a given bed is variable such that: sand is more abundant than mud; sand and mud have equal abundance; and mud is more abundant than sand. Interbedded sand and calcareous mud occurs only in the limy unit of the McMurray Formation.

Interbedded sand and mud are typically flat to low angle stratified with strata dipping 5 to 10^{o} (maximum 15^{o}). Sands and calcareous muds are typically coarsely interbedded with one another. Beds of 2 to 5cm thick sands (with rare mud drapes and flasers) are interbedded with 0.5 to 4cm thick mud beds (which often have thin sand lenses and

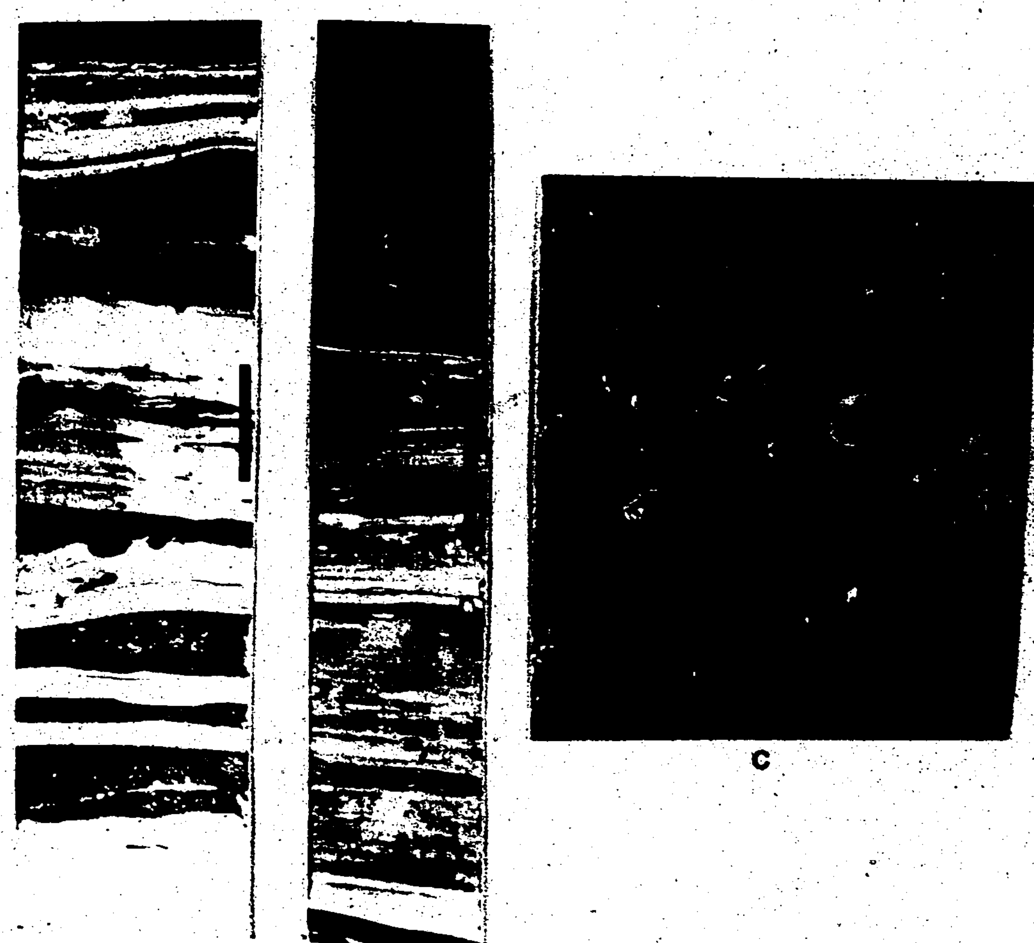
PLATE 4

Interbedded sand and calcareous mud from the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.

Fig. a. Interbedded sand and calcareous mud in the limy unit of the McMurray Formation, showing coarse fossiliferous sands and low bioturbation; drill core 34-43, 58.9m (scale 3cm).

Fig. b. Flat to low angle dipping interbedded sand and calcareous mud in the limy unit, with mud being much more abundant than sand; drill core 34-41, 68.0m (scale 5cm).

Fig. c. Fossiliferous sands with intact gastropod shells in the limy unit; drill core 35-43, depth unknown (scale 2cm) (photo courtesy of B. Mattison).


a
b
c

laminae). Finely interbedded sand and calcareous sands are less common, with 1-2 cm thick sands intercalated with 0.5 to 2cm thick mud beds. Sands interbedded with the calcareous muds are predominantly small-scale cross-stratified. Tabular sets are most commonly observed, with set thickness varying from 0.5 to 5cm. Superimposed sets of cross-stratification often show opposing dips but are generally unimodal. Interbedded mud laminae are not common in these sands. Low amplitude wavy to planar laminated sands have a limited occurrence. Two different types of normally graded sand beds are recognized. One is characterized by a bed of planar or cross-stratified sands with grain size becoming progressively finer from basal laminae (or cross-sets) to upper laminae (or cross-sets). Other graded sands show evidence of stratification, fining upward from a coarse or medium sand at the base to a fine or very fine sand at the top of the bed. Graded sand beds are typically 1 to 2 cm thick.

Fine to very fine sands are most common in this lithofacies whereas medium to coarse grained sands are less common, typically occurring only at the base of graded units. Sand beds can contain very coarse sand to granule sized subangular mud fragments. Shells (mostly gastropods) and shell debris are also common in the sands. Shells (<1.0cm in size) are mainly intact and are typically found dispersed (1 to 10%) in medium to coarse grained sands. They are also found at the base of graded sand beds. Shell beds (>50% shells) up to 5cm thick are also observed (Plate 4, Fig. c). These "shell-supported" beds have a matrix of sand and sand sized shell fragments. Shell beds, which are typically poorly sorted and show no evidence of internal stratification, often consist of a horizon only a shell or two thick.

Mud in this lithofacies is calcareous, reacting variably in intensity with 10% hydrochloric acid. Mud beds range in thickness from 0.5 to 4.0cm, averaging 1.0cm. Muds in this lithofacies appear to be segregated into clay (<0.0039mm) and silt (<0.0624mm, >0.0030mm) with single mud beds often consisting of silt with a "core" of clay. Deformation of mud beds, as indicated by contorted or curved laminae, is relatively rare.

Interbedded sand and calcareous mud are typically characterized by low rates of bioturbation with only one occurrence of heavily bioturbated interbedded sand and calcareous mud observed (drill core 35-35). Sands are usually more bioturbated than muds which are rarely disrupted by bioturbation. Carbonaceous material occurs in this lithofacies as dispersed coaly clasts and as coaly laminae and lenses intebedded with the sands and muds. Indurated zones and concretions are infrequent. Bitumen saturation of the sands is usually high to moderate but overall levels of saturation are low due to the intercalations of mud. Basal contacts with other lithofacies are typically flat to scoured, with gradational contacts mainly confined to the three sublithofacies of interbedded sand and calcareous mud. The upper and lower contacts within the intercalations of sand and mud themselves are typically sharp to scoured.

Interpretation:

Interbedded sand and calcareous muds were formed by processes similar to those that were responsible for *interbedded sand and mud* found in the middle member of the McMurray Formation. Deposition as a result of current unsteadiness associated with the neap/spring tidal cycle is supported by the regular pattern of stratification, reflecting a regular fluctuation in current velocity, as well as the predominance of coarsely stratified interbedded sand and calcareous mud. The occurrence of sand lenses in mud beds and mud laminae in sand beds possibly indicates daily current fluctuations.

With the exception of the occurrence of calcareous muds, there are three features which differentiate this lithofacies from interbedded sand and mud. These are: low levels of bioturbation; normally graded sand interbeds; and shells dispersed in sands or concentrated in distinct beds. Levels of bioturbation are low in most cases indicating either high rates of sedimentation or that there was an impoverished infauna. Shells found dispersed in sands or concentrated into distinct beds, appear to have undergone little or no transport as is indicated by a lack of abrasion and fragmentation, despite the fact that they appear to be very delicate. Shell preservation requires rapid burial by sediment because the longer skeletal material remains at or near the sediment - water interface the greater the likelihood that chemical, biological and physical reworking will occur (Weidemann 1972). Laterally extensive concentrations of living gastropods and bivalves are often found on intertidal flats as well as the subtidal margins of tidal channels (Weidemann 1972; Mayou and Howard 1975; Reineck and Singh 1975).

Normally graded sand beds are deposited when a sand-laden current looses its ability to keep grains in suspension (Reineck and Singh 1975; Collinson and Thompson 1982). In order for normal grading to develop, grain concentrations in sand-laden flow need to be relatively low (Leeder 1982). Flows with high concentrations of sand grains are characterized by high dispersive pressures which result in the development of reverse grading. The graded sand beds observed in interbedded sand and calcareous mud were likely deposited from suspension by low concentration sand dispersions that were probably generated by high energy conditions. These high energy deposits are randomly intercalated within the more regular tidal deposits.

HEAVILY BIOTURBATED MUDDY SAND

Description:

Heavily bioturbated muddy sand is often the dominant lithofacies in the upper member of the McMurray Formation. Sands are typically fine to very fine grained and are rarely medium to coarse grained. Physical sedimentary structures are absent in this lithofacies, obscured by a pervasive bioturbate texture. Abundant interbedded dark grey mud drapes and composite sand and mud partings often constitute up to 30% of the entire lithofacies (Plate 5, Fig. a, b). Mud drapes have thicknesses between 0.5 to 1cm whereas composite sand and mud units, characterized mainly by laminated mud with interbedded thin lenses and laminations of massive sand, can be up to 5cm thick. The drapes and partings give this lithofacies a sense of stratification. Dips of the drapes and partings can vary considerably (0-30°) but are typically flat to very low angle (0-10°) with adjacent sets often dipping in opposing directions. Drapes and partings are typically highly bioturbated, especially the interbedded lenses and laminations of sand in the composite units. Deformations of the partings and drapes are also common as is indicated by contorted laminations. Drapes and partings appear to be continuous to discontinuous across the width of the drill core with the main cause of discontinuity appearing to be bioturbation. Commonly bioturbation is so intense that all that remains of a parting or drape is a horizon of irregular mud patches in a matrix of bioturbated sand (Plate 5, Fig. c). Mud intraclasts (0.5 to 2cm in size), with lithologies similar to the drapes and partings, and coaly carbonaceous clasts are dispersed in the sands in less than 1% of the beds. Drapes and partings, as well as the horizons of mud patches are often indurated, especially when they are overlain by relatively clean sands. The bioturbated sands themselves can also be indurated but this is not common. Bitumen saturation is dependent on the mud content of the lithofacies. Because mud is

PLATE 5

Heavily bioturbated muddy sand from the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.

Fig. a. Heavily bioturbated muddy sand in the upper member of the McMurray Formation, exhibiting disrupted muddy intercalations; drill core 40-38, 42.7 to 43.0m (scale 5cm).

Fig. b. Heavily bioturbated muddy sand in the upper member, with disrupted muddy interbeds; drill core 39-39, 44.2 to 44.8m (scale 5cm).

Fig. c. Heavily bioturbated muddy sand in the upper member, scattered muddy interbeds; drill core 36-41, 32.6 to 34.2m (scale 5cm).

a b c

mixed with the sands, bitumen saturation is low. Interbedded drapes and partings also result in a decrease in the overall bitumen saturation of a specific unit. This lithofacies is usually characterized by gradational basal contacts but sharp and possibly scoured basal contacts with other lithofacies were also observed. Internal truncations, possibly scours were recognized but are generally rare.

Interpretation:

With the exception of the crude stratification provided by the interbedded mud drapes and composite sand and mud partings, this lithofacies lacks primary physical sedimentary structures. These physical sedimentary structures appear to have been completely obliterated by the burrowing activity of benthic organisms. In order for this to have occurred, sedimentation rates must have been quite low whereas rapid sediment accumulation would result in the preservation of primary structures before the organisms would have a opportunity to rework them. Physical reworking of the substrate by waves and/or currents would also have had to have been low in order for biogenic structures to predominate. Because this lithofacies is mostly sand, there would have been a need for sand to have been transported into the environment but this was low to allow extensive reworking by burrowing organisms. Such a highly bioturbated lithofacies would also require a large population of benthic organisms that could extensively and quickly burrow the substrate, destroying any physical sedimentary structures (Howard and Reineck 1972).

The muddiness of much of the bioturbated sands (indicated by a substantial decrease in bitumen saturation), as well as the common occurrence of mud drapes and composite sand and mud partings indicate that mud was an important component of the environment. Mud could be deposited when and where current velocities were low enough to allow settling from suspension. Thick mud accumulations would require extended periods of low current activity. An alternative explanation for the occurrence of drapes and partings in this lithofacies is that deposition of mud occurred during times of high suspended mud concentrations. If suspended mud concentration are high enough, deposition by flocculation will occur even if current and/or wave activity is strong (McCave 1971). The occurrence of interbedded sand lenses and laminae in the partings indicates that although there was a period of high suspended mud and hence mud deposition, currents were also fluctuating between those under which sand transport could occur, and those which were low enough to allow mud to be deposited. The mechanism of current or wave unsteadiness is not known but could be tidally influenced. Low levels of bioturbation in the mud reflect the potential difficulties benthic organisms have with this sediment grain size.

CHAPTER 3

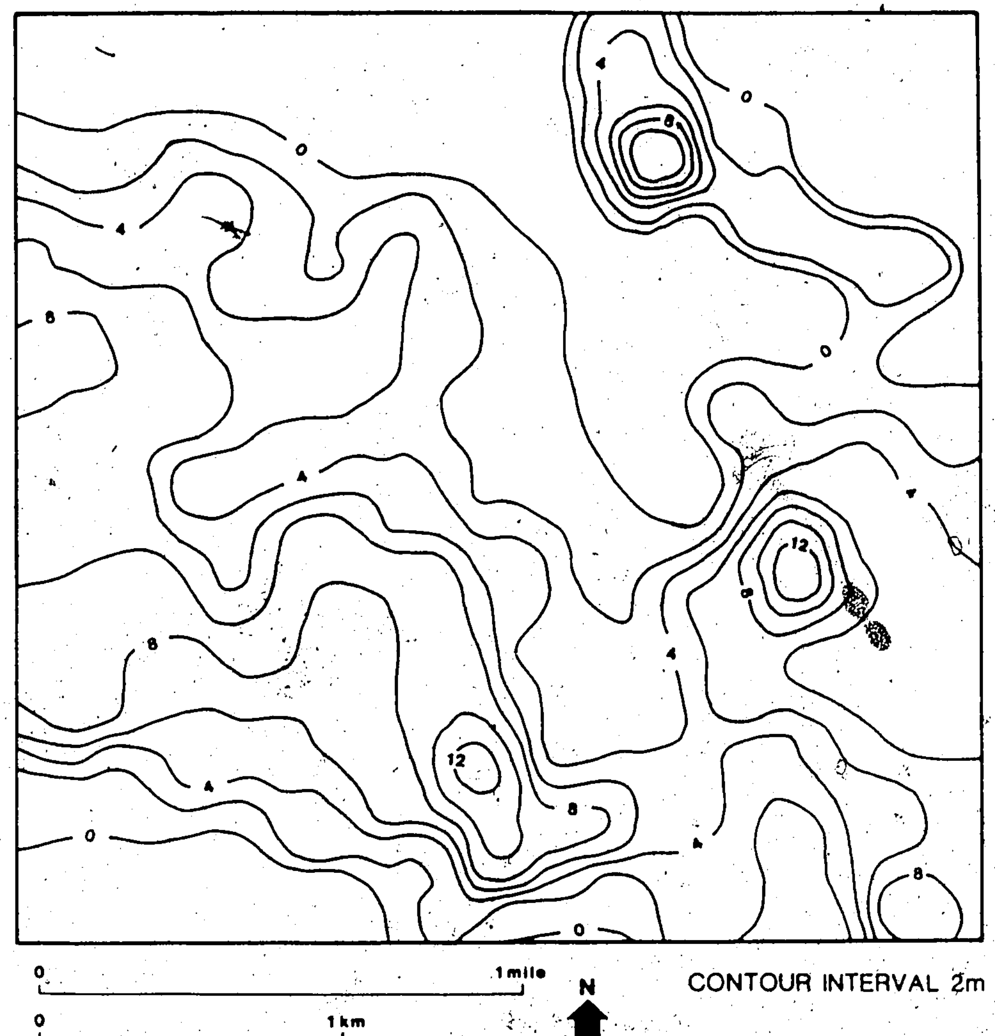
LOWER MEMBER

Description:

The lower member, the lowest informal stratigraphic subdivision of the McMurray Formation is present in 75% of the drill cores examined in this study. It has a maximum thickness of 12.8m in the east-central part of the study area (drill core 35-37). Examination of the isopach map of the lower member (Fig. 29) shows that the topography of the Devonian-Cretaceous unconformity surface played a major role in controlling deposition. Lower member sequences are confined to the east-west trending valley on the unconformity surface that is evident on both the map of the unconformity surface (Fig. 11) and the isopach of the McMurray Formation (Fig. 12). The net sand isopach of the lower member (Fig. 30) also shows a similar depositional trend, with the bulk of sand deposition occurring along the axis of the east-west trending valley. Lower member sequences and sand accumulations are also present in a topographically low area on the unconformity surface in the northeast part of the study area.

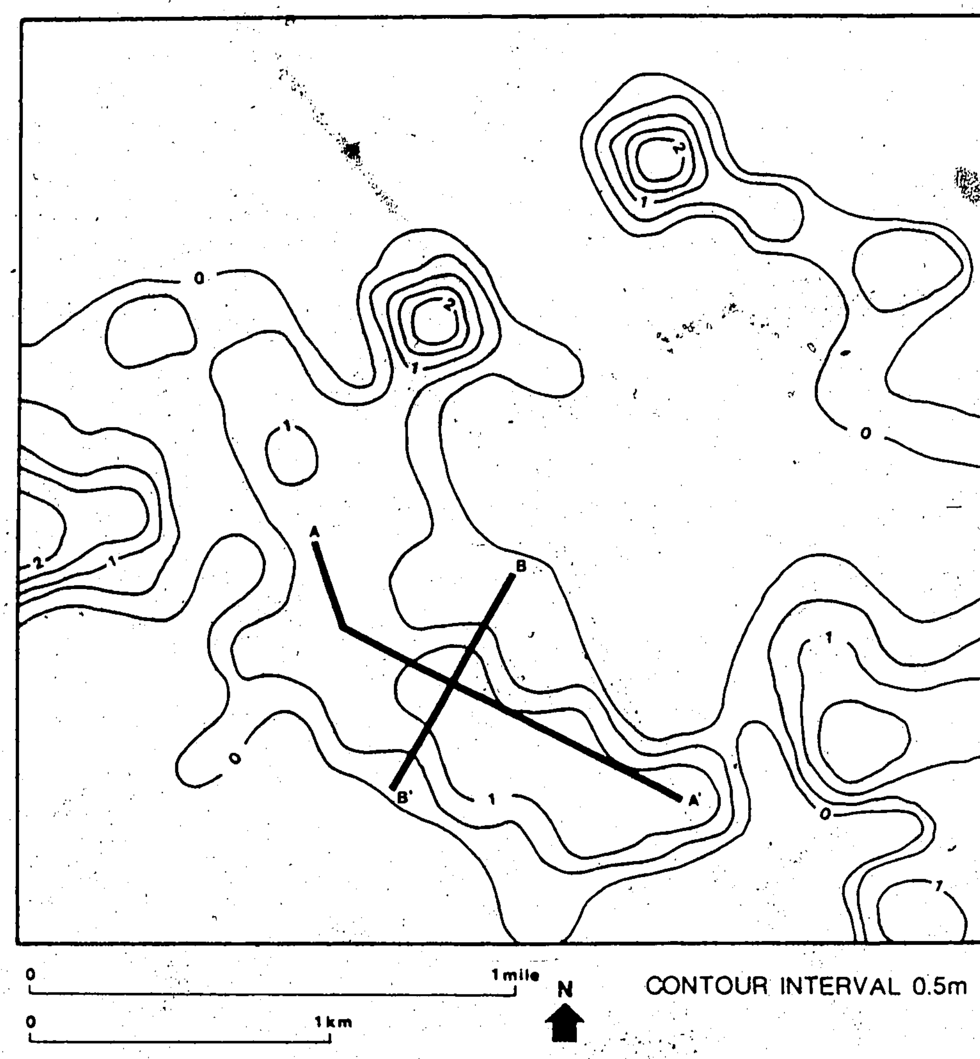
Lithofacies association and interpretation:

Stratigraphic cross-sections through a lower member sand accumulation (Fig. 32) reveal important vertical and lateral lithofacies relationships that help determine the depositional environment responsible for the sequences observed. A single lithofacies association is recognized in the lower member, consisting of basal beds of structureless or stratified sand which are gradationally overlain by a thick sequence of structureless to laminated carbonaceous muds with thin sand and gravel interbeds (e.g. Plate 6, Fig. a).



LOWER MEMBER ISOPACH

Fig. 29. Isopach map of the lower member of the McMurray Formation in the present study area, Syncrude Oil Sands Lease 17, Athabasca Oil Sands.



LOWER MEMBER NET SAND ISOPACH

Fig. 30. Net sand isopach map of the lower member of the McMurray Formation in the study area, Syncrude Oil Sands Lease 17, Athabasca Oil Sands, showing locations of stratigraphic cross-sections (A-A' and B-B') through sand accumulations.

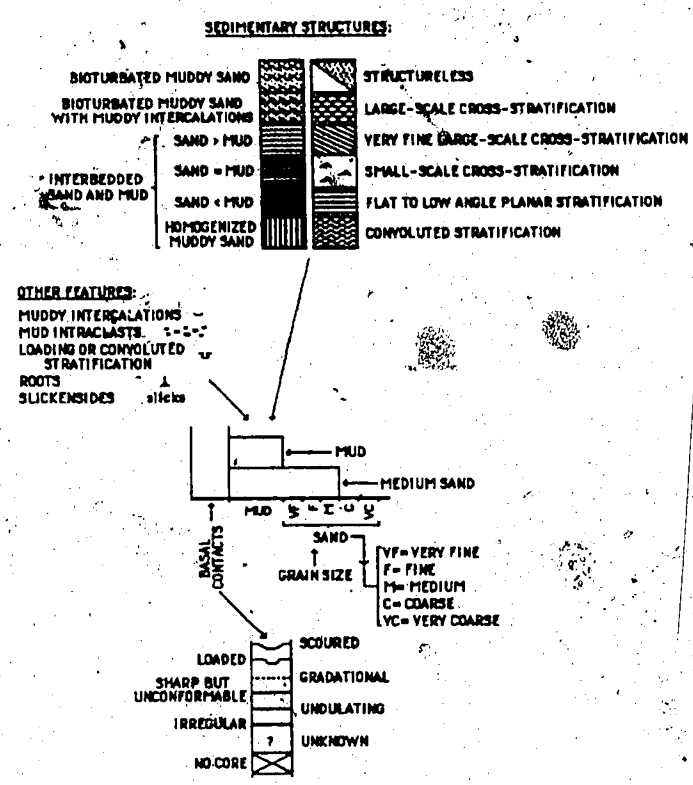


Fig. 31. Legend for stratigraphic cross-section used in the present discussion of the McMurray Formation.

Fig. 32. Longitudinal (A-A') and transverse (B-B') stratigraphic cross-sections through a lower member (of the McMurray Formation) sand accumulation.

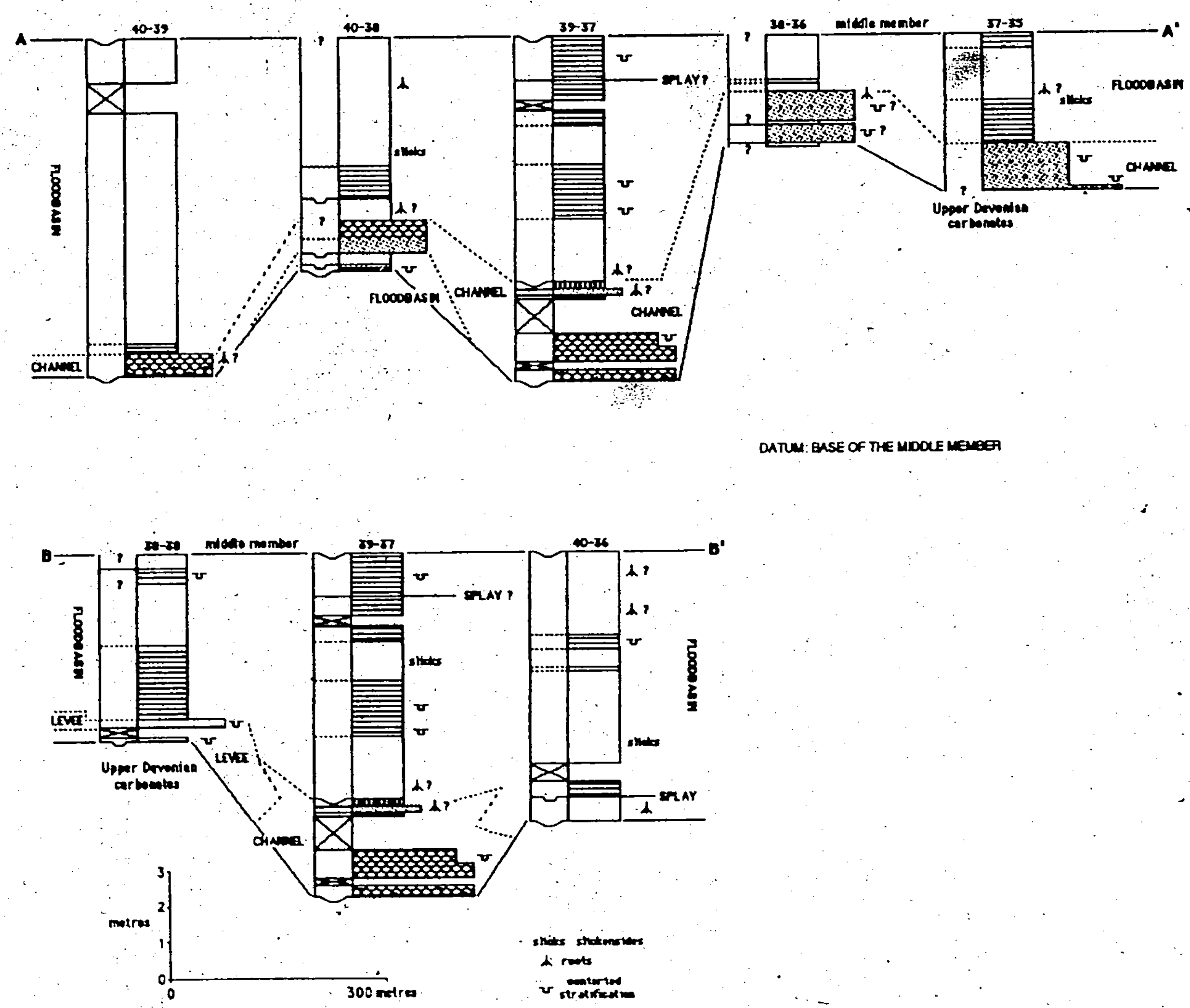
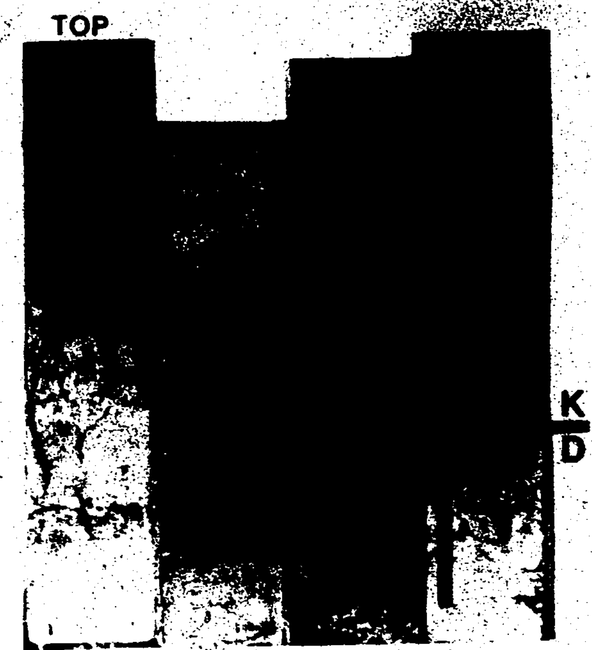

A
A'
40-39
40-38
39-37
38-36
middle member
37-35
FLOODBASIN
CHANNEL
SPLAY ?
Upper Devonian carbonates
DATUM: BASE OF THE MIDDLE MEMBER
B
B'
38-38
39-37
40-36
LEVEE
SPLAY
metres
300 metres
slicks slickensides
roots
contorted stratification

PLATE 6

Lithofacies sequences from the lower member of the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.

Fig. a. Fining upward sequence in the lower member of the McMurray Formation, overlying the Devonian (D) - Cretaceous (K) unconformity surface. Sequence consists of large-scale cross-stratified sand overlain by rooted structureless carbonaceous muds and an *in situ* coal. Drill core 40-40, 87.8 to 89.1m (scale 5cm).

Fig. b. Highly disrupted sand in deformed carbonaceous mud in the lower member; drill core 39-40, 89.8 to 90.1m (scale 5cm).



a

b

The basal sequences of sand beds usually have sharp or scoured bottom contacts with the underlying unconformity surface or thin beds of calcareous and non-calcareous muds which overlie Upper Devonian carbonates. Just above this scour contact, sandy lithofacies often contain lithic pebbles and mud intraclasts. Grain size typically decreases in overlying sand beds. Thin beds of mud and interbedded sand and mud are often intercalated between sand beds. Cross-stratified sands infrequently have interbedded mud drapes and composite sand and mud partings. These muddy intercalations are indieative of temporary reductions of current velocity causing sand transport to stop or be significantly reduced. Currents were then weak enough to allow mud to settle from suspension. Muddy intercalations in the sands appear to have an irregular distribution indicating that current velocity unsteadiness was probably random. The vertical sequence of lithofacies in the basal sand beds is variable from one drill core to another. The sequence is further complicated by possible disruption of primary structures by liquifaction resulting in the development of structureless sands. Most basal sand sequences exhibit an upward decrease in the sand to mud ratio, as well as a decrease in the grain size of sand, reflecting an upward reduction of current strength. Lithofacies sequences in the basal sand beds also reflect upward diminishing current strength. These lithofacies sequences include: structureless or massive sand overlain by large-scale cross-stratification (e.g. drill core 40-38); and an upward change from large-scale to small-scale cross-stratification (e.g. drill core 38-35).

The topmost beds of the basal sand sequences are typically muddy structureless sands which are often rooted. Relic structures visible in these sands indicate that primary physical sedimetary structures were destroyed, possibly by liquifaction and/or by plant roots. These structureless sands grade upward into structureless or laminated muds. These Muds are rich in carbonaceous debris which is dispersed in the mud or concentrated in laminae. Muds are often characterized by slickensides, roots and by a blocky or waxy texture. Interbedded within the mud sequences are thin massive to small-scale cross-stratified sands, as well as concentrations of lithic pebbles and angular mud intraclasts. These interbeds, which are often deformed (Plate 6, Fig. b) typically have sharp to loaded basal contacts, suggesting that underlying muds were not well consolidated allowing loading of the sand and gravel beds to occur. Muds were likely deposited from suspension in a low energy setting and were often disrupted by plant roots, as well as soil forming processes. Sand and gravel interbeds were deposited by randomly occurring periods of strong current activity.

Bioturbation, with the exception of disruption caused by roots, is rare in the lower member. Thin mud interbeds in cross-stratified sands are infrequently extensively bioturbated. Rarely, units of heavily bioturbated interbedded sand and mud are intercalated between thick sequences of non-bioturbated mud. The general lack of bioturbation in lower member sequences suggests that burrowing organisms were probably absent in the environment of deposition. Thin bioturbated units interbedded in non-bioturbated sequences indicate that ecological conditions were such that burrowing organisms did inhabit the environment for a relatively brief period of time.

The lithofacies association found in the lower member of the McMurray Formation was deposited in a high sinuosity fluvial floodplain environment. Four major depositional sites characterize this environment: channel; levee; crevasse splay; and floodbasin (Hughes and Lewin 1982). The scour based, fining upward sequences of sand, reflecting an upward decrease in current velocity, are interpreted to be the deposits formed as a consequence of a laterally migrating meandering channel. The sinuous geometry of the lower member sand accumulations also supports deposition in a meandering channel.

Channels meander because a sinuous path offers the least resistance to fluid flow over a near horizontal surface (Leopold and Langbein 1966). Meandering occurs when: slope is low; the flow is characterized by high suspended sediment; and the confining banks are composed of cohesive material (Collinson 1986). Deposition is dependent on the nature of fluid flow in the channel. Fluid flowing around a meander bend (Fig. 33a) is piled up against the concave or outer bank by centrifugal forces (Leeder 1982; Allen 1984). Coincident with this rise in water level along the concave bank is a drop along the inner or convex bank of the meander bend. The imbalance of water level creates a helical flow that is tranverse to the main direction of fluid flow. Fluid at the surface of the flow is pushed toward the concave bank while fluid at the base of the flow (or channel) moves toward the convex bank of the meander bend. The helical flow drives sediment grains toward the convex bank where they can be deposited on a point bar (Leeder 1982; Collinson 1986). Strength of the flow varies in the channel at the meander bend, with the strongest currents occurring along the concave bank and diminishing toward the convex bank or point bar (Leeder 1982). The deepest part of the channel or thalweg develops along the concave bank of the meander bend where current strength is greatest (Collinson 1986). Mud intraclasts, derived from erosion and collapse of the convex bank, and lithic pebbles are often concentrated in the thalweg, whereas finer grained sediments are winnowed out by the strong currents. Sand bed forms develop on the point bar and reflect the weakening of currents from the bottom to the top of the bar. Dunes develop on the lower part of the point bar whereas current ripples form on the upper part of the bar. With erosion of the concave bank and deposition on the convex bank point bar, the channel migrates laterally, producing a fining upward cycle or sequences (Allen 1965). The fining upward sequence, which develops as the point bar migrates laterally, is characterized by an upward decrease in

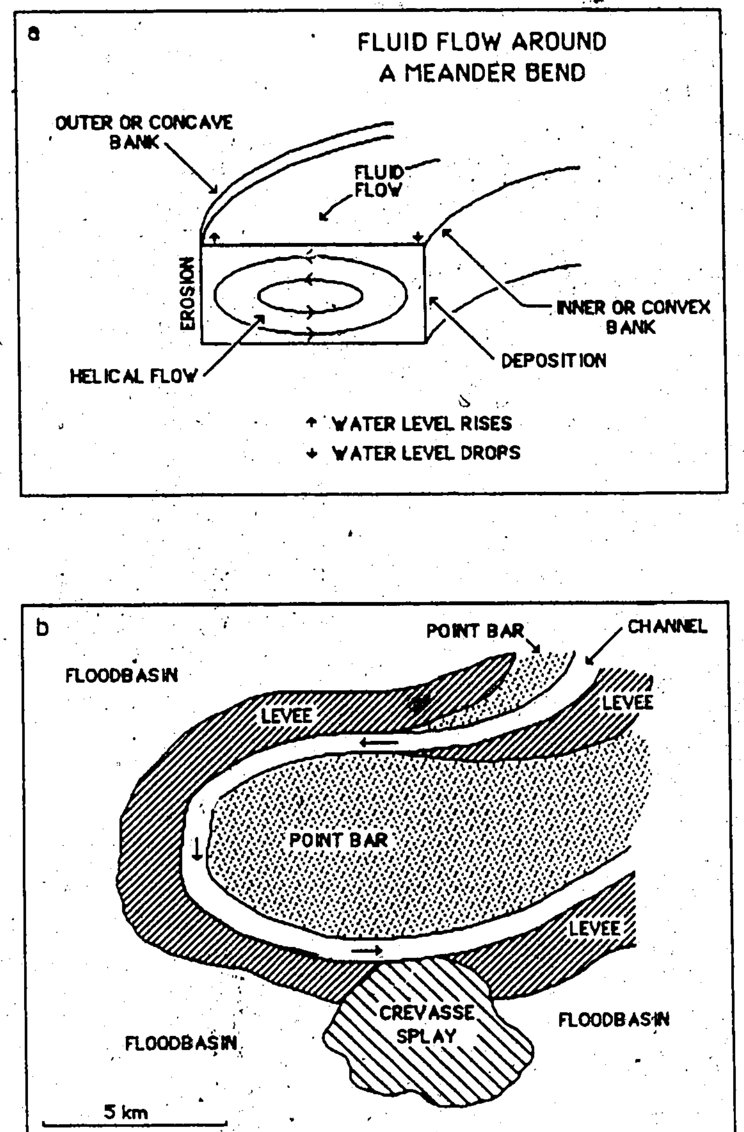


Fig. 33. (a) Schematic diagram of fluid flow through a hypothetical channel curve or meander bend showing development of transverse helical flow and potential sediment transport path (modified from Allen 1984). (b) Schematic diagram of an actual fluvial meander bend showing spatial distribution of subenvironments that include point bars, levees, crevasse splays and floodbasins (modified from Farrell 1987).

grain size and scale of cross-stratification (Allen 1970). These two features reflect diminishing current strengths up the surface of the point bar.

Levee, crevasse splay and floodbasin deposits (Fig. 33b) form as a consequence of a channel breaching or overtopping its banks and flooding the surrounding floodplain (Hughes and Lewin 1982; Galloway and Hobday 1983). Overbank deposits become progressively finer as distance from the channel increases, reflecting a gradual diminishing of current strength away from the channel (Kesel *et al.* 1974; Hughes and Lewin 1982). Floodwaters quickly loose their ability to keep coarse sediment (sand and silt) in suspension resulting in rapid sedimentation along the margins of the channel and the formation of levees and crevasse splays (Galloway and Hobday 1983; Collinson 1986). Levees are wedge-shaped ridges that develop along the edge of the channel due to rapid sediment fall-out and the building up of crevasse splay deposits (Collinson 1986). Stratification in levees reflect fast and shallow flows that quickly decelerate causing rapid sedimentation (Galloway and Hobday 1983). Small-scale cross-stratification, climbing ripple lamination and upper flow regime planar stratification are common in levee deposits. As the flood wanes, current strength weakens allowing mud to settle from suspension on top of the strong current deposits (Lattman 1960; Farrell 1987). Physical sedimentary structures in levee deposits are often destroyed by plant roots and soil forming processes (Galloway and Hobday 1983; Farrell 1987). Levee deposits are also disrupted by brecciation, folding, faulting and liquifaction (Coleman 1969). Because levees are best developed on the concave bank of a meandering channel (Collinson 1986) they would be subject to erosion as lateral migration of the channel occurred. Small channels commonly lack levees completely (Reineck and Singh 1975).

Crevasse splays are formed when floodwaters pass through a small channel or crevasse in the channel bank forming a sheet of sediment, with variable width, that progrades onto the floodbasin away from the channel (Reineck and Singh 1975). Sediment is transported by strong and shallow flows which quickly decelerate away from the channel causing rapid sedimentation (Reineck and Singh 1975; Galloway and Hobday 1983). Small-scale cross-stratification, climbing ripple lamination and upper flow regime planar stratification are commonly produced in crevasse splays (Reineck and Singh 1975). Muddy sediments deposited during the last stages of the flood, typically overly these sand beds. Carbonaceous debris is often incorporated in crevasse splay deposits. Physical sedimentary structures in crevasse splay deposits are often disrupted by plant roots and soil forming processes (Galloway and Hobday 1983; Farrell 1987).

The floodbasin or backswamp is characterized by low energy levels with mud settling from suspension (Hughes and Lewin 1982). Vegetation in a floodbasin can act as a baffle, dampening currents and enhancing the deposition of mud. During a flood, the floodbasin is often submerged, with quiet water deposition occurring in marshes, ponds and lakes that subsequently dry up after the flood ends. Floodbasin deposits are dominated by laminated muds which commonly have interbedded carbonaceous debris (Lattman 1960; Hughes and Lewin 1982; Farrell 1987). Thin sand beds derived from crevasse splays can be interbedded in the floodbasin muds (Reineck and Singh 1975). Crevasse splay switching can cause variations in grain size of floodbasin deposits (Hughes and Lewin 1982). Because of the slow rates of sedimentation, floodbasin deposits are often reworked by organisms, plant roots and soil development (Galloway and Hobday 1983). Thick floodbasin deposits suggest slow deposition over a long period of time (Kesel *et al.* 1974).

Levee and crevasse splay deposits are probabably present in the lower member of the McMurray Formation. Thin beds of structureless and often rooted muddy sands adjacent to the channel deposits are possibly levee or proximal crevasse splay deposits that were subsequently modified by secondary processes such as liquifaction, pedogenesis and the action of plant roots. More distal crevasse splay deposits, composed of thin beds of sand and gravel sized material, are interbedded in muds deposited in a floodbasin. Laminated carbonaceous muds were probably deposited in a quiet water setting, possibly in ponds and lakes which developed on the floodbasin during fluvial floods. Structureless carbonaceous muds having roots, as well as features suggesting some soil development, were probably deposited in marshes that were inundated by floodwaters.

Environmental summary:

The lower member of the McMurray Formation was deposited in a high sinuosity fluvial floodplain that developed between low hills of Devonian carbonates (Fig. 34). Major depositional sites included channel and overbank areas. Channel deposits formed as a result of laterally migrating meandering streams. Deposition occurred mainly on point bars which developed on the convex banks of meander bends. Sand was transported when currents were strong, probably during floods. Muddy interbeds were deposited when current strength was substantially weakened probably during the waning stages of floods. Overbank deposits developed in levees, crevasse splays and floodbasins during floods when channel waters breached or overtopped their confining banks. With rapid deceleration of flow as floodwaters left the channel levee and crevasse splays were formed adjacent to the channel. Floodbasin deposits formed in marshes and ponds which were submerged or filled during floods. Following flood deposition, overbank deposits were disrupted by plant roots and soil development.

CHAPTER 4

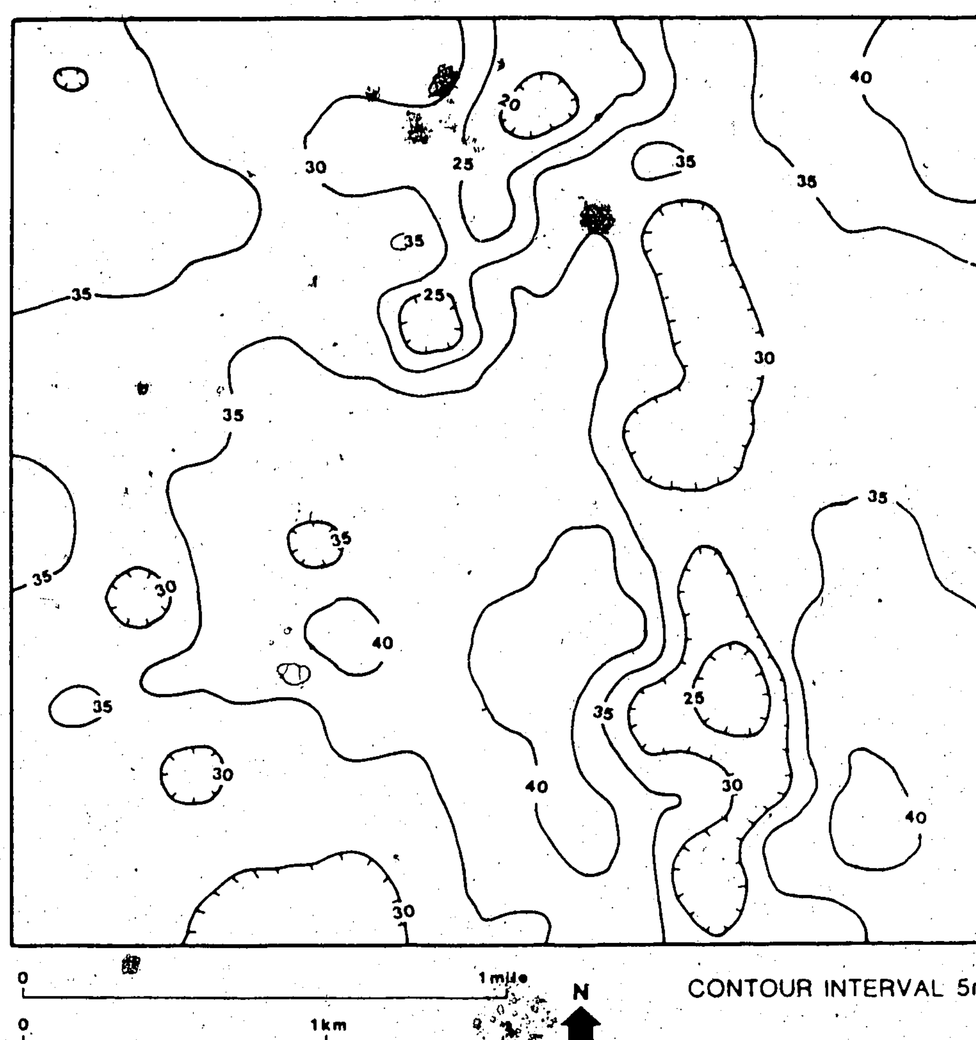
MIDDLE MEMBER

Description:

The middle member is the thickest informal stratigraphic subdivision of the McMurray Formation and host of the richest oil sand accumulations in the study area. It either sharply overlies sequences of the lower member or lies directly on top of Upper Devonian carbonates. The isopach map of the middle member (Fig. 35) reveals that it has a highly irregular thickness reaching a maximum thickness of 44.3m in the central part of the study area (drill core 38-37) but is only 17m in the north (drill core 36-43). Examination of the net sand isopach of the middle member (Fig. 36) shows northeast - southwest trending accumulations of sand. Neither maps of the middle member mirror any patterns of deposition that might indicate control by the underlying Devonian - Cretaceous unconformity surface. Stratigraphic cross-sections through the McMurray Formation (Fig. 37, 38, 39, 40) reveal that the limy unit, which sharply overlies the middle member in the eastern half of the study area, has filled an incision or trough cut into the top of the middle member. The effect of this incision is evident in both maps of the middle member where sequences and sand accumulations are noticeably thinned in much of the eastern half of the study area.

Lithofacies associations:

The middle member is characterized by complex vertical and lateral sequences of lithofacies. Drill cores that are adjacent to one another often show distinctly different sequences. Lateral lithofacies variability is best exhibited in a stratigraphic cross-section



MIDDLE MEMBER ISOPACH

Fig. 35. Isopach map of the middle member of the McMurray Formation in the present study area, Syncrude Oil Sands Lease 17, Athabasca Oil Sands.

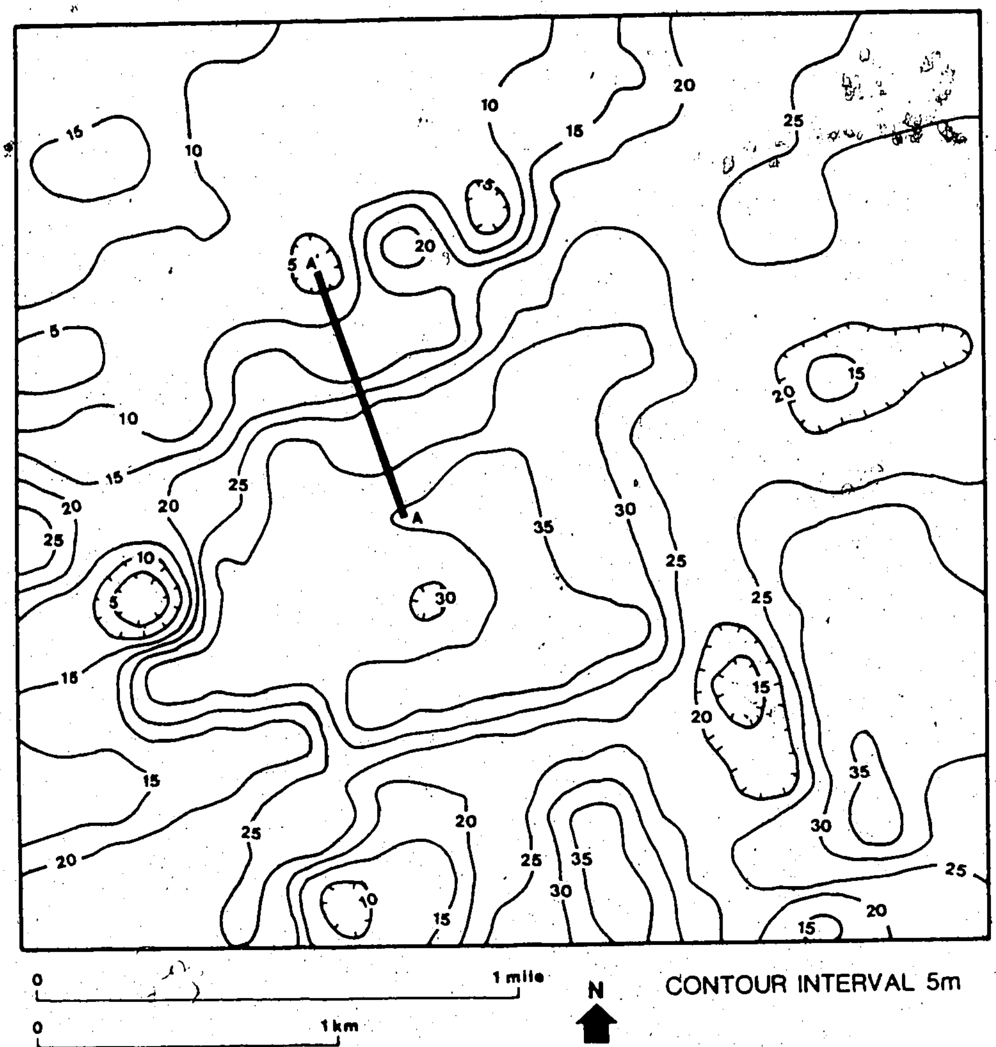


Fig. 36. Net sand isopach map of the middle member of the McMurray Formation in the present study area, Syncrude Oil Sands Lease 17, Athabasca Oil Sands showing location of stratigraphic cross-section (A-A').

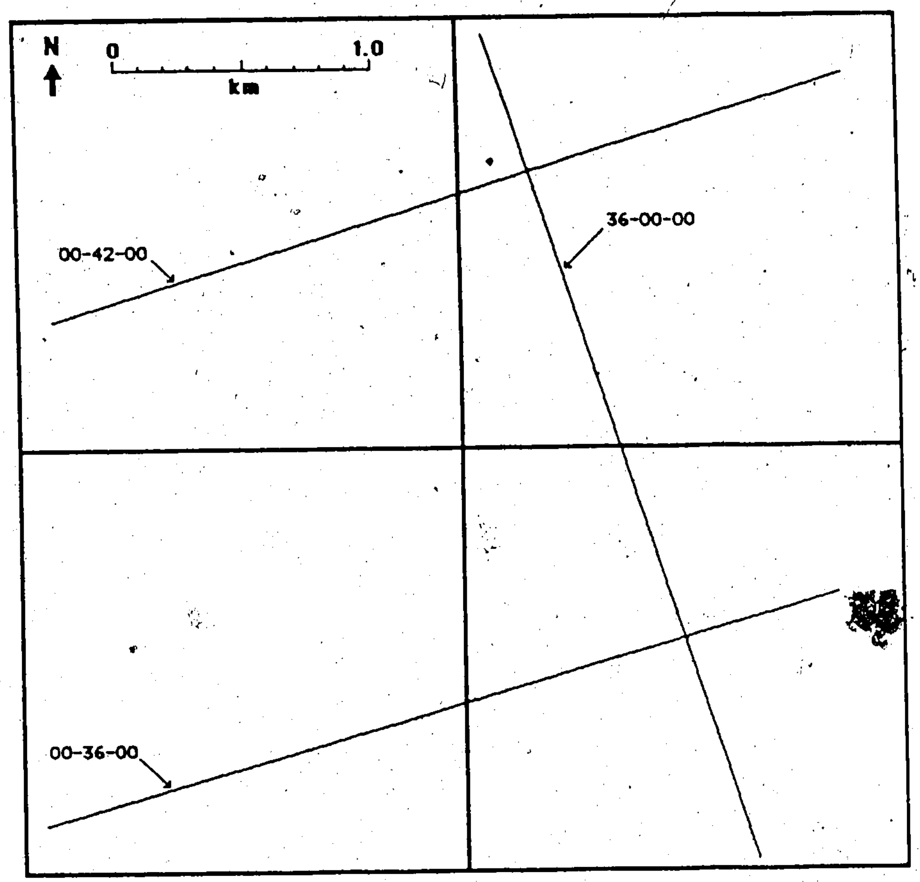


Fig. 37. Location of stratigraphic cross-sections (36-00-00, 00-36-00, 00-42-00) through the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.

through the middle member (Fig. 41) extending from an area of thick sand accumulation to one where arenaceous lithofacies have not been extensively developed. Two major associations are recognized in this cross-section: a sandy association; and a muddy association. Sandy lithofacies sequences are overlain by sequences of the muddy assocciation and often have sharp basal contacts and gradational upper contacts.

The sandy association is dominated by large- and small-scale cross-stratified sand whereas other arenaceous lithofacies such as massive, planar stratified and very fine grained large-scale cross- stratified sand are less common. Argillaceous lithofacies such as mud and interbedded sand and mud are found in the sandy association but occur only in minor amounts. As evident from the drill core descriptions (see Appendix) lithofacies sequences in the sandy association are complex and variable from one drill core to another. Many sequences are characterized by a general trend from large-scale to small-scale cross-stratified sand going up through the middle member. Thick sequences of large-scale cross-stratified sand commonly have 5 to 20cm thick interbeds of other arenaceous lithofacies such as small-scale cross-stratified sand or very fine large-scale cross-stratified sand, which have gradational basal and scoured upper contacts. Large-scale cross-stratified sands at the bottom of sequences are commonly medium to very coarse grained with grain size becoming finer in overlying beds. Gravelly large-scale cross-stratified sands are restricted to the basal portions of the middle member. Angular mud intraclasts commonly observed in large-scale cross-stratified sand, as well as massive and planar stratified sand, do not appear to be confined to any specific position in the sequences. Beds of stratified or massive sands with mud intraclasts are typically interbedded with those that lack mud intraclasts.

Another distinctive feature of lithofacies sequences in the sandy association is the

Fig. 38. Stratigraphic cross-section 36-00-00 through the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.

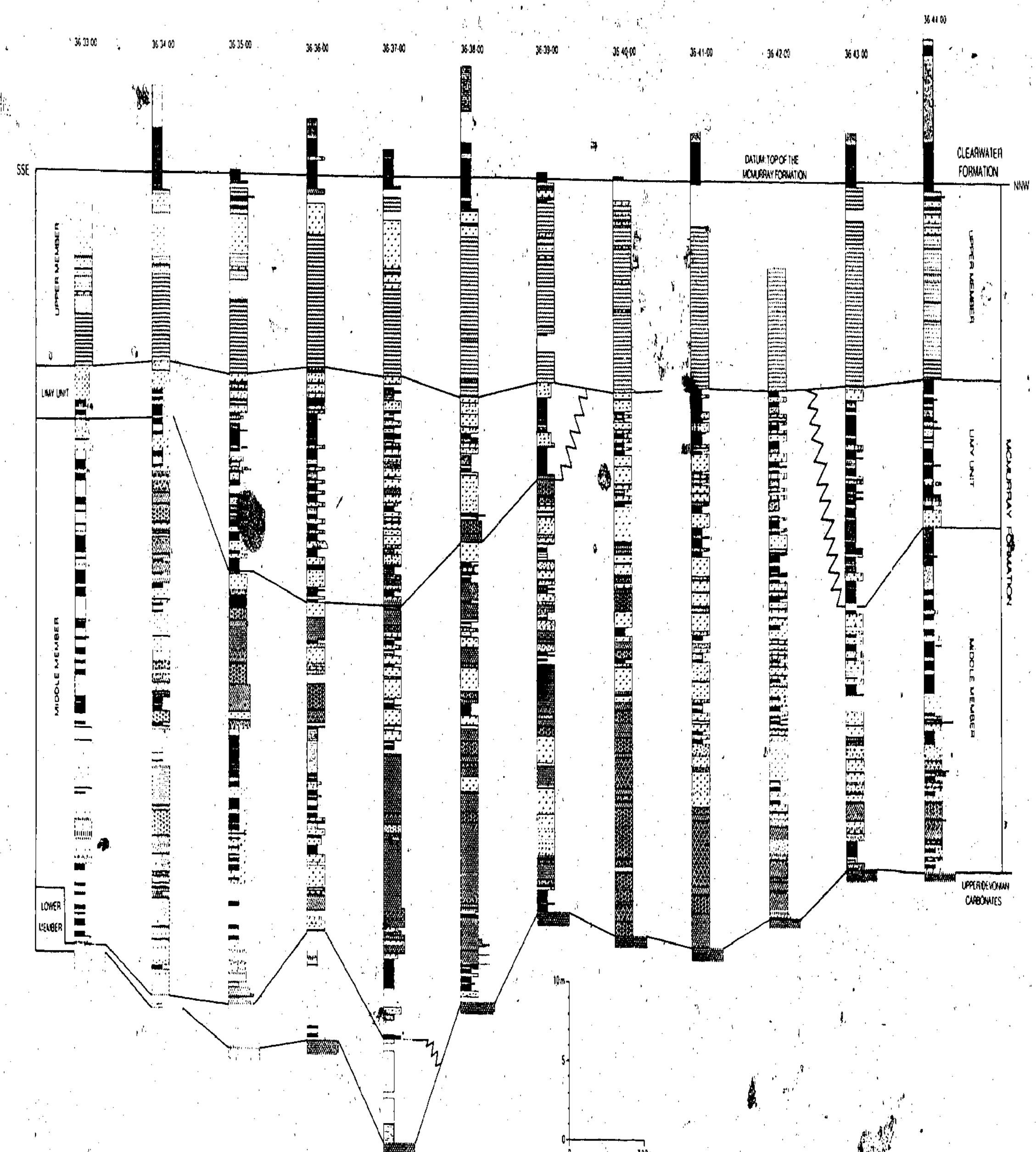
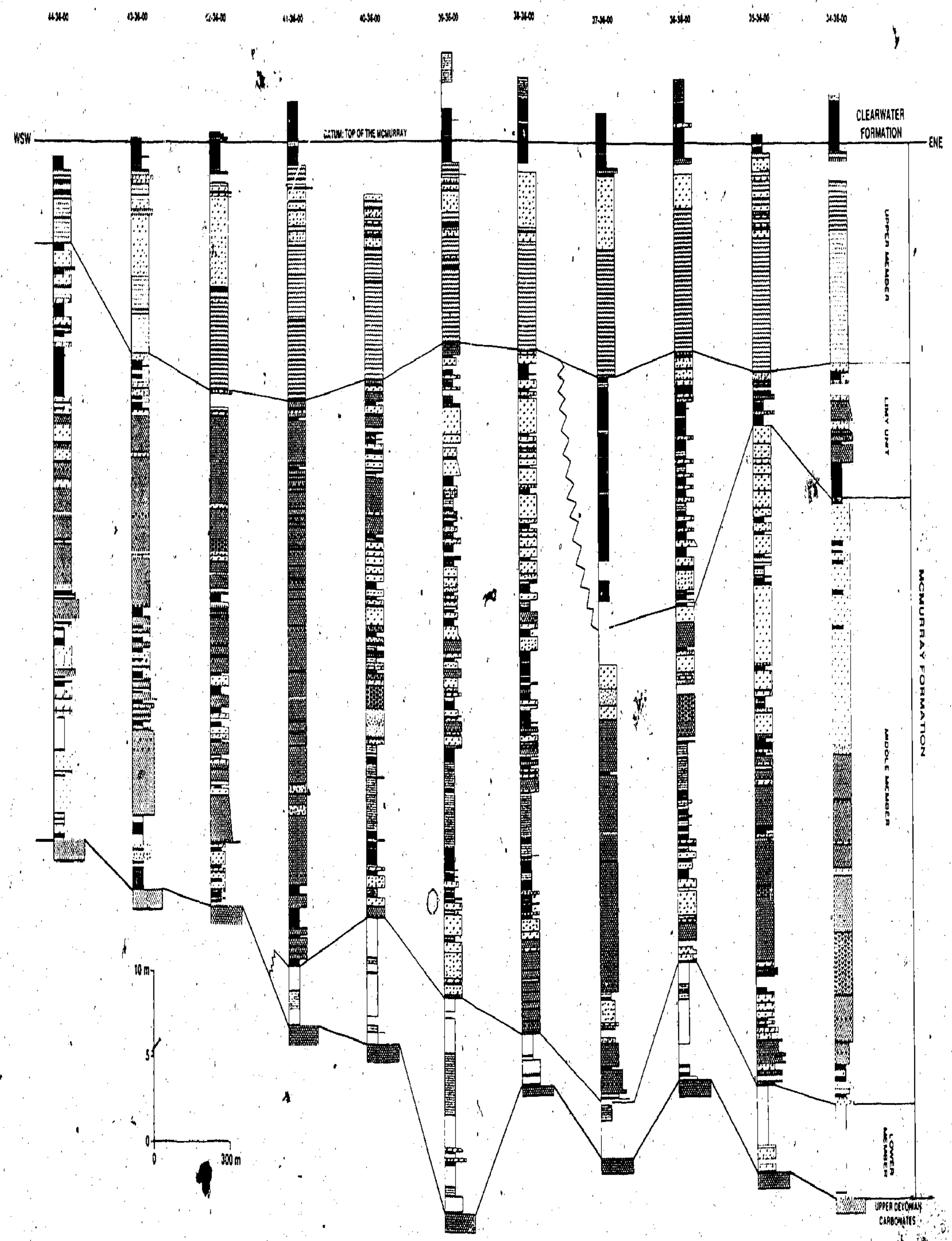

SSE
NNW
CLEARWATER FORMATION
DATUM TOP OF THE McMURRAY FORMATION
UPPER MEMBER
LIMY UNIT
MIDDLE MEMBER
LOWER MEMBER
McMURRAY FORMATION
UPPER DEVONIAN CARBONATES
10m
5
0
300m

Fig. 39. Stratigraphic cross-section 00-36-00 through the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.



44-36-00
43-36-00
42-36-00
41-36-00
40-36-00
39-36-00
38-36-00
37-36-00
36-36-00
35-36-00
34-36-00
WSW
DATUM: TOP OF THE MCMURRAY
ENE
CLEARWATER FORMATION
UPPER MEMBER
LIMY UNIT
MCMURRAY FORMATION
MIDDLE MEMBER
LOWER MEMBER
UPPER DEVONIAN CARBONATES
10 m
5
0
0
300 m

Fig. 40. Stratigraphic cross-section 00-42-00 through the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.

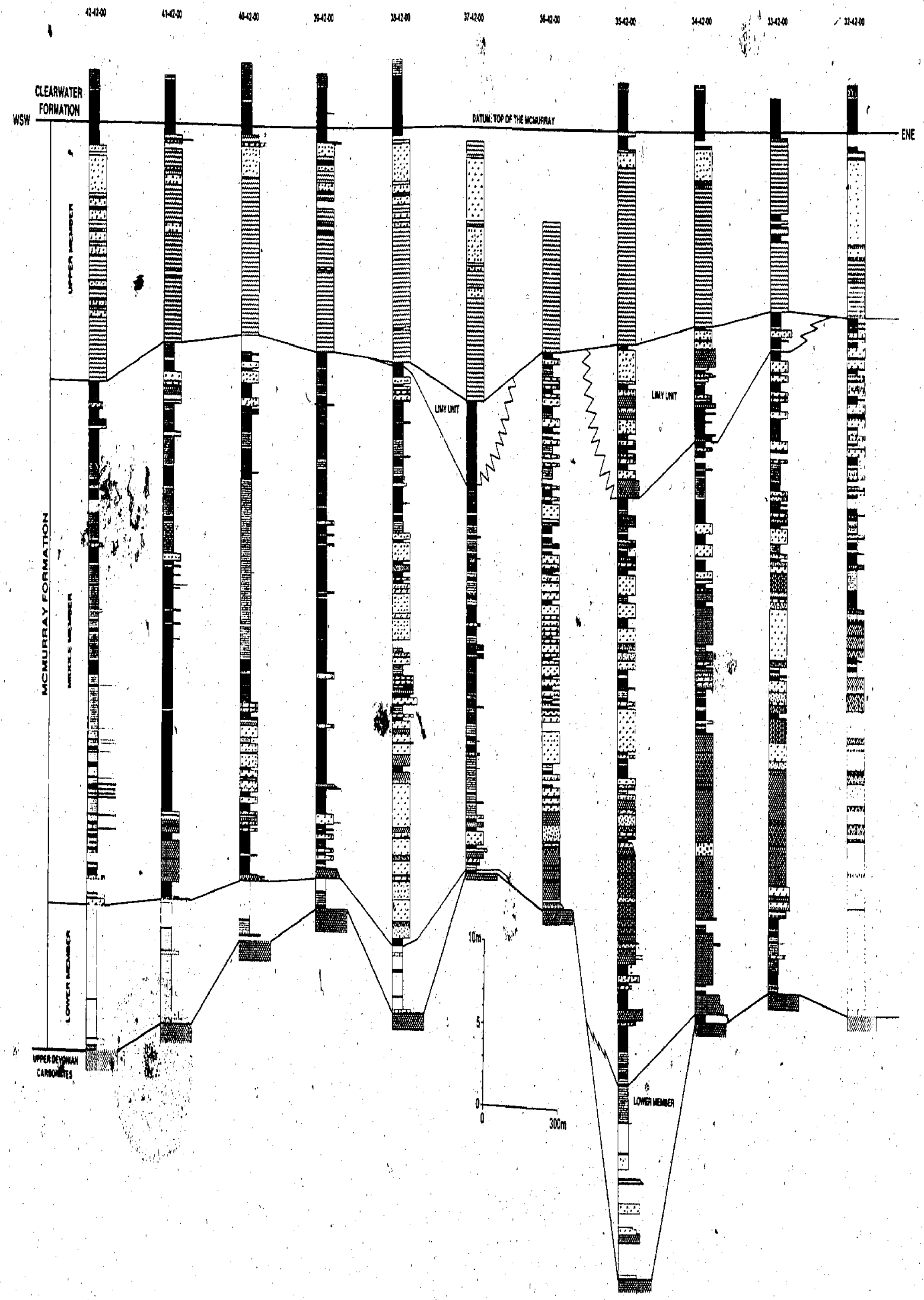
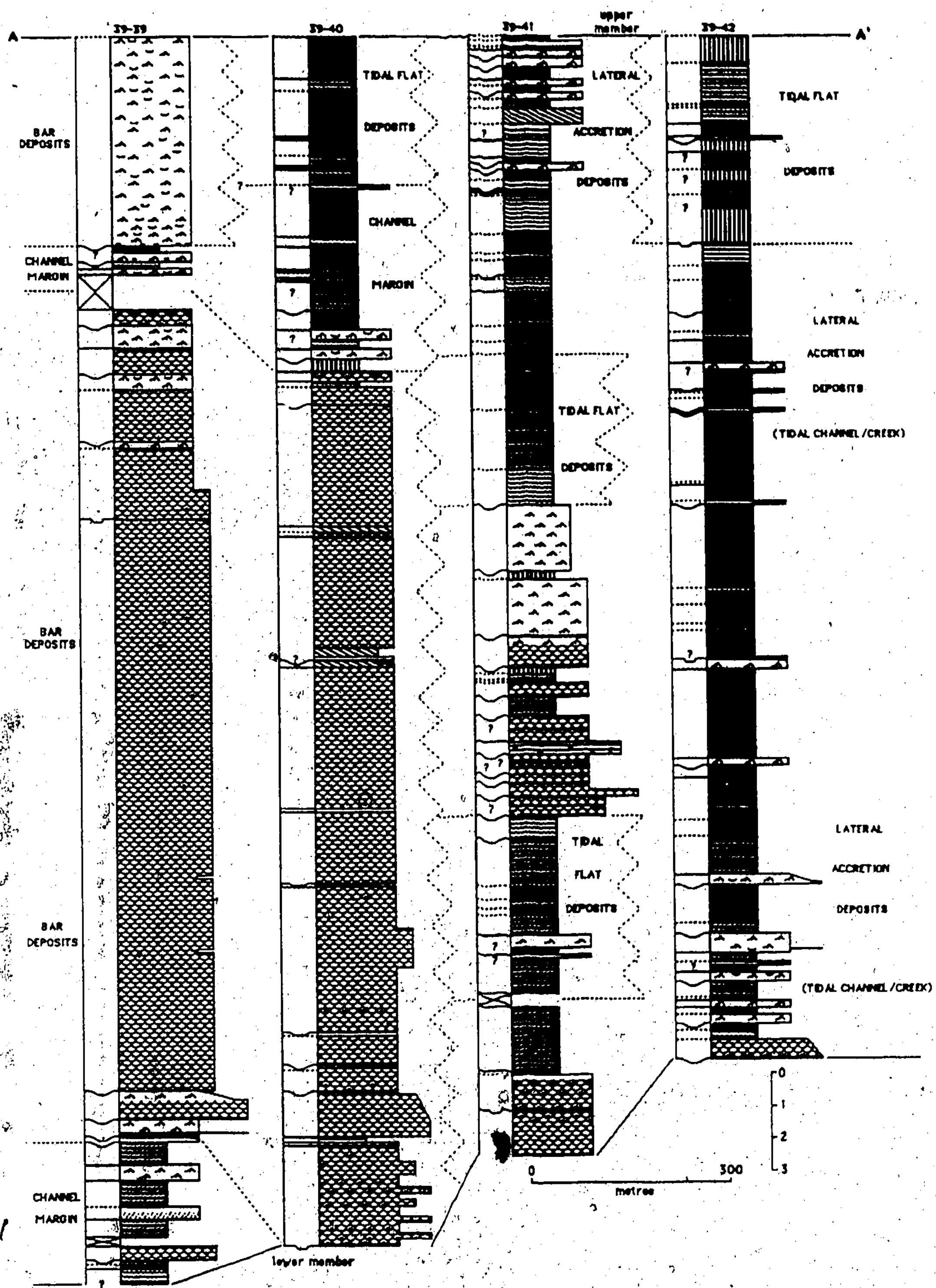

42-42-00
41-42-00
40-42-00
39-42-00
38-42-00
37-42-00
36-42-00
35-42-00
34-42-00
33-42-00
32-42-00
CLEARWATER FORMATION
WSW
DATUM: TOP OF THE MCMURRAY
ENE
MCMURRAY FORMATION
UPPER MEMBER
MIDDLE MEMBER
LOWER MEMBER
LIMY UNIT
LIMY UNIT
UPPER DEVONIAN CARBONATES
10m
5
0
0
300m
LOWER MEMBER

Fig. 41. Stratigraphic cross-section (A-A') from an area of thick sand accumulation to one where arenaceous lithofacies are not extensively developed, middle member of the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.



A
39-39
39-40
39-41
upper member
39-42
A'
BAR DEPOSITS
CHANNEL MARGIN
BAR DEPOSITS
BAR DEPOSITS
CHANNEL MARGIN
TIDAL FLAT
DEPOSITS
CHANNEL
MARGIN
lower member
LATERAL
ACCRETION
DEPOSITS
TIDAL FLAT
DEPOSITS
TIDAL
FLAT
DEPOSITS
TIDAL FLAT
DEPOSITS
LATERAL
ACCRETION
DEPOSITS
(TIDAL CHANNEL/CREEK)
LATERAL
ACCRETION
DEPOSITS
(TIDAL CHANNEL/CREEK)
0
300
metres
0
1
2
3

PLATE 7

Muddy intercalations in cross-stratified sand from the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.

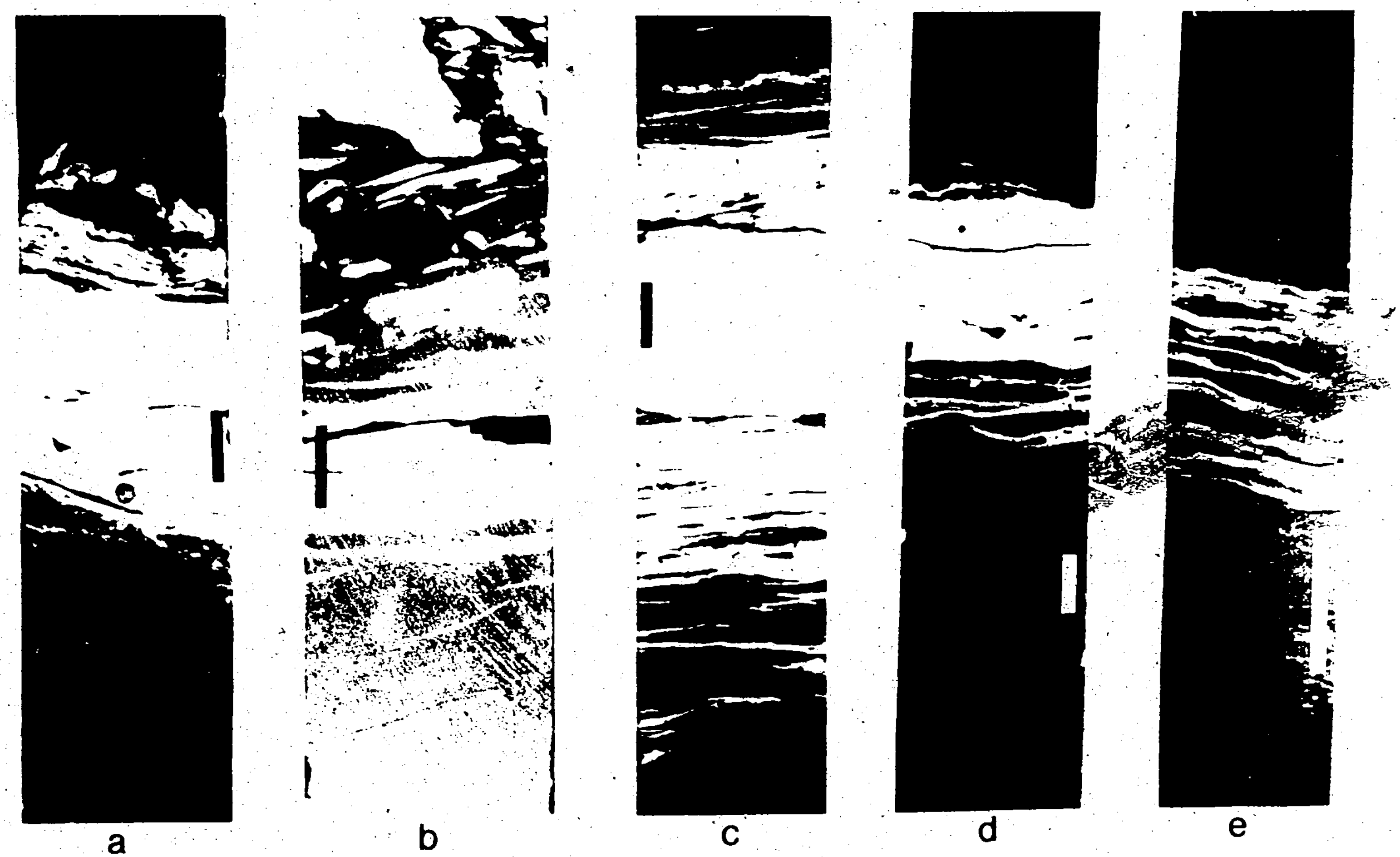
Fig. a. Large-scale cross-stratified sand with a composite sand and mud parting in the middle member of the McMurray Formation; drill core 37-38, 73.1 to 73.4m (scale 2cm).

Fig. b. A composite sand and mud parting interbedded in small-scale cross-stratified sand (overlying large-scale cross-stratified sand which is not shown) and large-scale cross-stratified sand with angular mud intraclasts; drill core 35-36, 79.9 to 80.2m (scale 2cm).

Fig. c. A composite sand and mud parting in small-scale cross-stratified sand in the middle member; drill core 33-39, 72.5m (scale 2cm).

Fig. d. A composite sand and mud parting in small-scale cross-stratified sand in the middle member; drill core 37-34, 61.2m (scale 2cm).

Fig. e. A composite sand and mud parting in small-scale cross-stratified sand in the middle member, showing paired sand/mud couplets; drill core 38-37, 52.0m (scale 5cm).


a
b
c
d
e

regular occurrence of muddy interbeds in large- and small-scale cross-stratified sand (Plate 7). These muddy intercalations, which consist of thin beds of mud and/or interbedded sand and mud, exhibit a wide degree of variability. A complete sequence (Fig. 42a) of large-scale cross-stratified sand with a muddy interbed, showing a gradual change from one lithofacies to another, consists of (in ascending order): (i) large-scale cross-stratified sand; (ii) interbedded sand and mud (wavy to lenticular bedding); (iii) mud; (iv) interbedded sand and mud (wavy to lenticular bedding); and (v) large-scale cross-stratified sand. Commonly only an upward fining sequence (Fig. 42b) is present consisting of: (i) large-scale cross-stratified sand; (ii) interbedded sand and mud; and (iii) mud, overlain by large-scale cross-stratified sand. Some sequences consist only of a mud drape conformably interbedded between the sand foresets (Fig. 42c). Sequences consisting of large-scale cross-stratified sand overlain by (in ascending order) small-scale cross-stratified sand and interbedded sand and mud (Fig. 42d) are infrequently observed. Overlying the interbedded sand and mud are large-scale cross-stratified sands. Small-scale cross-stratified sands often contain mud laminae and flasers. In even rarer examples a thin bed of small-scale cross-stratified sand is recognized above the mud or interbedded sand and mud, and is sharply overlain by large-scale cross-stratified sand. This latter example exhibits a fining upward followed by a coarsening upward sequence, as well as an upward reduction followed by an increase in the scale of cross-stratification.

Large-scale cross-stratified sand overlying a mud or interbedded sand and mud bed often contains angular mud intraclasts (Plate 7, Fig. b). The upper contact of the mud or interbedded sand and mud beds intercalated within the large-scale cross-stratified sand, is usually sharp, often appearing scoured as is indicated by bedding and burrow truncations

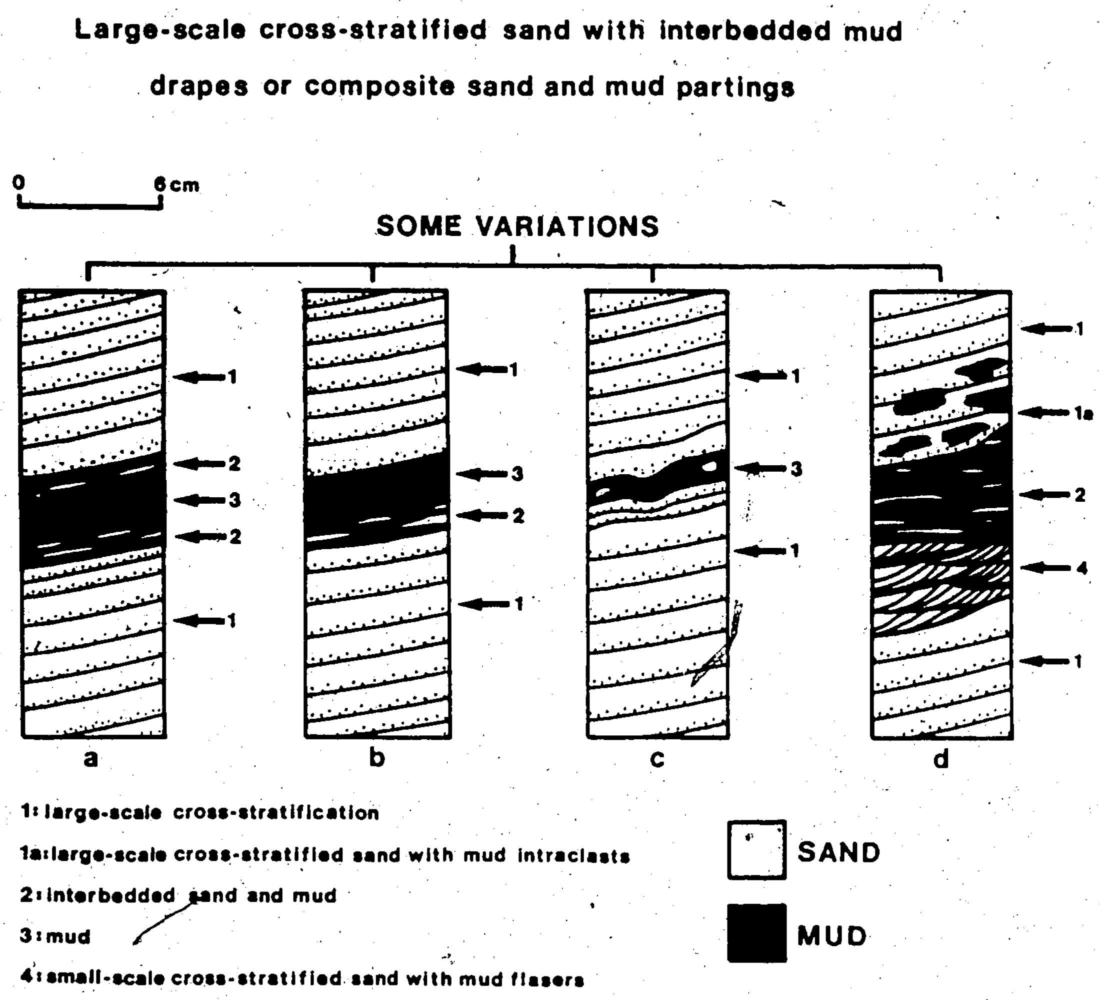


Fig. 42. Diagramatic representation of drapes and partings in large-scale cross-stratified sand.

or by deformed mud laminae or flasers. The lower contact is often gradational but is most commonly sharp and conformable. Mud interbeds have thicknesses ranging from 0.5 to 5cm, whereas intercalations of interbedded sand and mud are thicker, ranging from 2 to 10cm. Deformation of muddy interbeds is usually low as is bioturbation. In rare examples, bioturbation is intense, even affecting underlying cross-stratified sands.

Muddy interbeds appear to be more common in small-scale cross-stratified sand. Complete sequences (Fig. 43a), showing a gradual transition from small-scale cross-stratified sand to muddy interbeds and back to cross-stratified sand consist of (in ascending order): (i) small-scale cross-stratified sand; (ii) small-scale cross-stratified sand with mud laminae and/or flasers; (iii) interbedded sand and mud; (iv) mud; (v) interbedded sand and mud; (vi) small-scale cross-stratified sand with mud laminae and/or flasers; and (vii) small-scale cross-stratified sand. This sequence is characterized by a decrease followed by an increase in the sand to mud ratio. Another commonly occurring sequence (Fig. 43b) consists of: (i) small-scale cross-stratified sand; (ii) small-scale cross-stratified sand with mud laminae and/or flasers; (iii) interbedded sand and mud; (iv) mud; and (v) small-scale cross-stratified sand. In this example the contact of the muddy interbed and the overlying small-scale cross-stratified sand is sharp and appears to be scoured, as indicated by burrow and bedding truncations. Angular mud intraclasts may also be interbedded within the overlying small-scale cross-stratified sand. Sequences such as: small-scale cross-stratified sand; interbedded sand and mud; and small-scale cross-stratified sand, are characterized by sharp upper and lower contacts of the muddy intercalation (Fig. 43c). Other common sequences include small-scale cross-stratified sand overlain by interbedded sand and mud, small-scale cross-stratified sand with mud laminae and/or flasers, and small-scale cross-stratified sand (Fig. 43d). Thin mud

Composite sand and mud partings in small-scale cross-stratified or ripple laminated sand

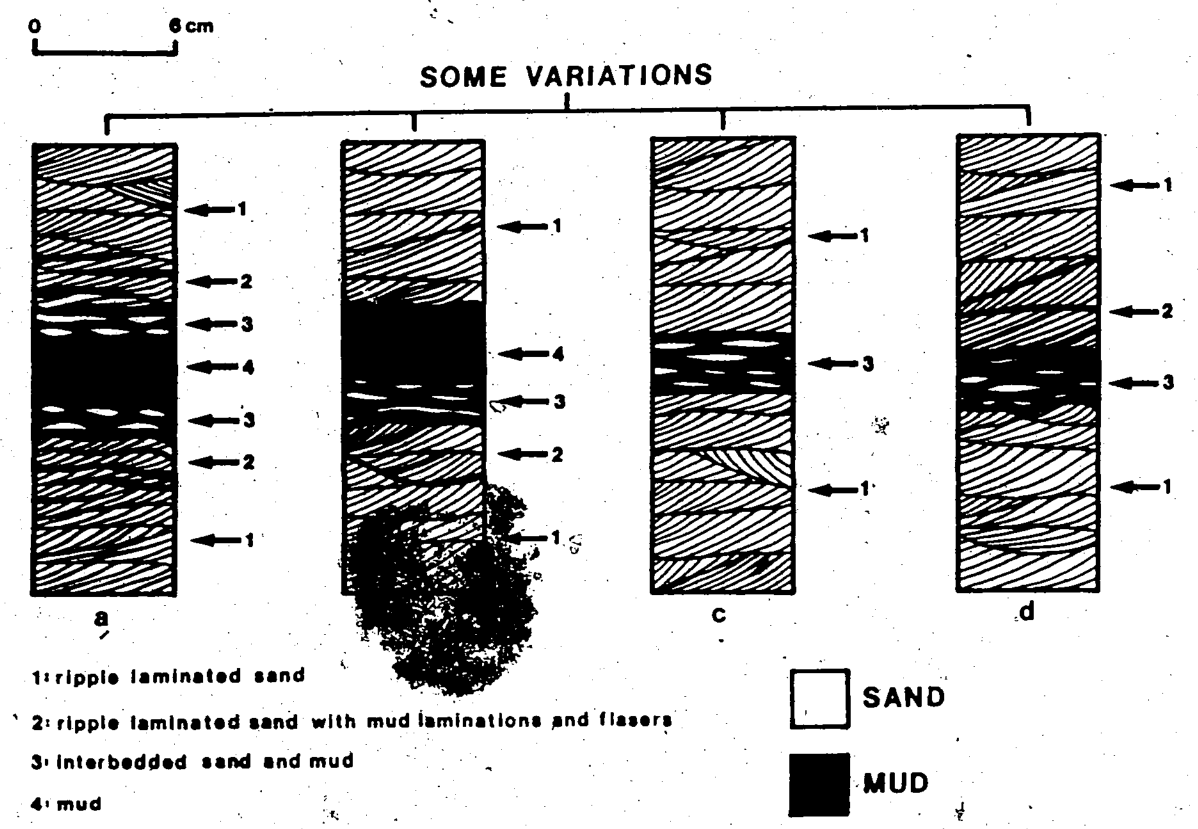


Fig. 43. Diagramatic representation of composite sand and mud partings interbedded in small-scale cross-stratified sand.

laminae and flasers are also common in small-scale cross-stratified sand. Thicknesses of muddy intercalations in small-scale cross-stratified sand range from 0.5 to 20cm. Deformation of these intercalations is rare, whereas bioturbation can range from slight to intense and is usually present in both the muddy interbeds and underlying small-scale cross-stratified sand.

Muddy intercalations appear to increase both in abundance and thickness upward often becoming so common as to mark a gradational contact with sequences that characterize the muddy association. This overall decrease in the sand to mud ratio appears to be very common in the sandy association (Fig.44). Fining upward sequences have variable thickness, ranging from a few meters to tens of meters, some appearing to make up almost the entire middle member (e.g. drill core 34-37). Another type of sequence recognized in the sandy association consists of a repetitive alternation of sandy lithofacies, most commonly large- and small-scale cross-stratification. Thin muddy interbeds are common and regularly intercalated between beds of cross-stratified sand in this type of sequence which are typically thick and in some examples (e.g. drill core 38-39) appear to make up the entire middle member. Whether these sequences represent single genetic units or a series of amalgamated sequences is not clear. The narrow width of the drill core makes it difficult to clearly differentiate temporally related sequences of lithofacies.

The muddy association of the middle member is dominated by beds of flat to low angle stratified mud and coarsely stratified interbedded sand and mud. Arenaceous lithofacies, most commonly small-scale cross-stratified sand, are minor constituents of this assemblage, occurring as thin (10 to 20cm thick), sharp based beds. These small-scale cross-stratified sands often have thin interbedded mud laminae and/or flasers and low levels of bioturbation. Sequences of the muddy association can directly overlie the Devonian

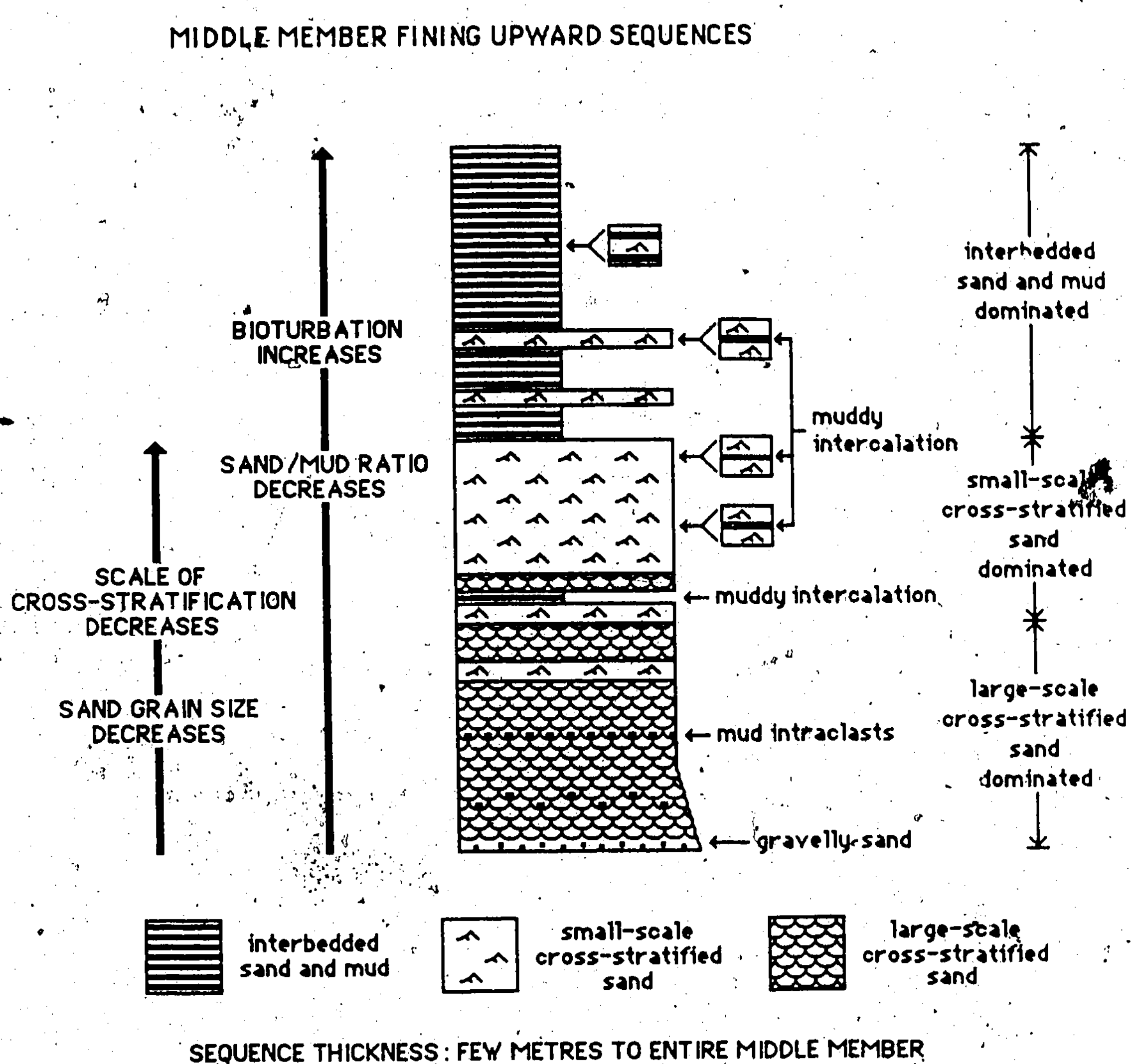


Fig. 44. Schematic of large-scale fining upward sequences in the middle member of the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.

- Cretaceous unconformity surface or the lower member, but more commonly gradationally overlie fining upward sequences of the sandy association. Individual lithofacies sequences within the muddy association are usually less than 1m thick. The muddy association is thin in many drill cores but in the northwest part of the study area it is well developed, often constituting most of the middle member. In drill core 38-43 more than 80% of the middle member is made up of argillaceous lithofacies.

Lithofacies sequences in the muddy association appear to be highly complex though fining upward sequences are most common. Lithofacies boundaries are usually gradational within a single sequence whereas scoured contacts are more prevalent when lithofacies are overlain by a bed that is significantly sandier. Perhaps the most common sequence involves a gradational change from one sublithofacies of interbedded sand and mud to another.

Bioturbation is highly variable in the muddy association but clearly greater than in the sandy association. Beds of homogenized mud and sand are often closely associated with beds of interbedded sand and mud that have lower levels of bioturbation. Interbedded sand and mud appears to have higher levels of bioturbation than muds with few or no sand interbeds. Intensely bioturbated argillaceous lithofacies appear to occur most commonly in the upper part of the middle member as well as at the top of fining upward arenaceous sequences. Thick sequences of flat to low angle stratified argillaceous lithofacies with low to moderate bioturbation are commonly recognized where the muddy association is well developed.

Interpretation:

Both small- and large-scale sequences of lithofacies provide important clues to the processes and environments of deposition that produced the middle member. Muddy interbeds in large- and small-scale cross-stratified sands are indicators of periodic current velocity reductions during which time sand transport is halted or substantially reduced. Currents which were capable of transporting sand in bedforms such as current ripples, dunes, and sand waves, were interrupted or diminished during which time mud deposition and subordinate sand transport took place. This reduction of current velocity was only temporary as is indicated by the cross-stratified sand overlying the muddy interbed. This feature is repeated throughout vertical sequences of cross-stratified sand in the middle member indicating a repetitive and regular pattern of sedimentation. Bioturbation in many of these interbeds indicates that the interruption of flow was of sufficient duration to allow substrate colonization by organisms.

Within the sequence that reflects a temporary weakening of flow there is an internal cyclicity which is best exhibited in the composite sand and mud partings where laminations of mud alternate with lenses and laminations of sand. This indicates that although currents were weak enough to allow for the development of the muddy interbed, they were also fluctuating from those capable of transporting sand (though weaker and of shorter duration) to conditions during which deposition of mud could take place. This internal cyclicity is also found in the cross-stratified sands that bound the muddy intercalations. Thin mud laminations and/or flasers are often interbedded within the cross-stratified sand just above and below the muddy interbed.

Lithofacies boundaries in these small-scale sequences have important hydrodynamic implications. Sequences which gradationally fine-upward, then coarsen-upward, reflect a gradual reduction or deceleration, followed by an increase or acceleration of current velocities. A decrease in the scale of the cross-stratification reflects a reduction of current strength as well. Other sequences show distinct scouring on the upper surface of the muddy intercalation implying that erosion occurred with the re-establishment of stronger currents. Mud intraclasts in the overlying cross-stratified sand could be the remnants of eroded muddy intercalations. Examples where the muddy interbed has sharp upper and lower contacts with the cross-stratified sand may indicate that there was a lag between the time when the sand bedform stopped moving and the time when mud deposition occurred. With the restoration of currents capable of transporting sand, the bedform would become reactivated resulting in renewed deposition of cross-stratified sand. Thin beds of very fine large-scale and small-scale cross-stratification intercalated between cosets of large-scale cross-stratified sand also appear to mirror short term reductions of current velocity.

The muddy interbeds in cross-stratified sands in the middle member, especially composite sand and mud partings, appear to reflect the regular unsteadiness of currents characteristic of tidal environments. More specifically, these small-scale sequences reflect current velocity fluctuations associated with the fortnightly (neap to spring) tidal cycle. During the spring tide phase, currents are strong whereas during the neap tide phase, currents are weaker. The alternation of sand and mud within the partings as well as in some of the cross-stratified sands reflect shorter duration current velocity fluctuations possibly associated with daily ebb and flood tides. During a single tidal cycle bedload transport of sand only occurs when ebb and/or flood currents are at or above the threshold velocity for sand transport. During slack water stages sand transport is negligible and currents are sufficiently weak to allow for the deposition of mud from suspension over and between bedforms (Clifton and Phillips 1980; Allen 1982). Cross-stratified sands are deposited during the spring tide and intermediate phases of the two week tidal cycle. During the spring tide phase, current velocities are sufficient to transport sand in a variety of bedforms ranging from current ripples to dunes and sand waves. During the neap tide phase, sand transport can be significantly reduced or halted altogether. Both large- and small-scale sandy bedforms can be immobile or have restricted movement in both subtidal (Clifton and Phillips 1980; Langhorne1982; Pickrill 1986) and intertidal (Allen *et al.* 1969; Allen and Friend 1976; Boersma and Terwindt 1981; Langhorne and Read 1986) settings during the neap tide phase. Large-scale bedforms such as dunes and sand waves tend to be active only when the strongest currents prevail, but are virtually inactive for most of the neap to spring tidal cycle (Allen and Friend 1976; Clifton and Phillips 1980). Current ripples are active over a broader range of current velocities but can also be inactive for a significant number of tides per neap to spring cycle (Allen and Friend 1976).

Estuaries are nears[illegible]al environments characterized by large amounts of suspended and deposited mud (Postma 1967; Allen *et al.* 1977; Kirby and Parker 1983). This muddiness is due to the physical (tidal currents) and chemical (mixing o[illegible] and salt water) conditions that characterize the estuarine environment (Krone 19[illegible]ostma 1967). Strong tidal current activity also results in the extensive erosion and resuspension of existing mud deposits further increasing the amount of suspended mud (Allen *et al.* 1977). The amount of suspended sediment in the estuary appears to be mostly controlled by tidal current strength (Allen *et al.* 1977, 1980; Castaing and Allen 1981; Kirby and Parker 1983). During the maxima of currents of the daily tidal cycle (Fig. 45a), as well as during the spring tidal phase, estuarine waters are turbulent and erosion and resuspension of existing mud deposits are great resulting in high suspended sediment concentrations (Postma 1967; Avoine *et al.* 1981; Allen *et al.* 1977; Castaing and Allen 1981; Kirby and Parker 1983). During slack water stages of the daily tidal cycle when currents are negligible (Fig. 45b) and during the neap tidal phase when currents are sluggish, suspended sediment concentrations become high near the bed as mud settles from

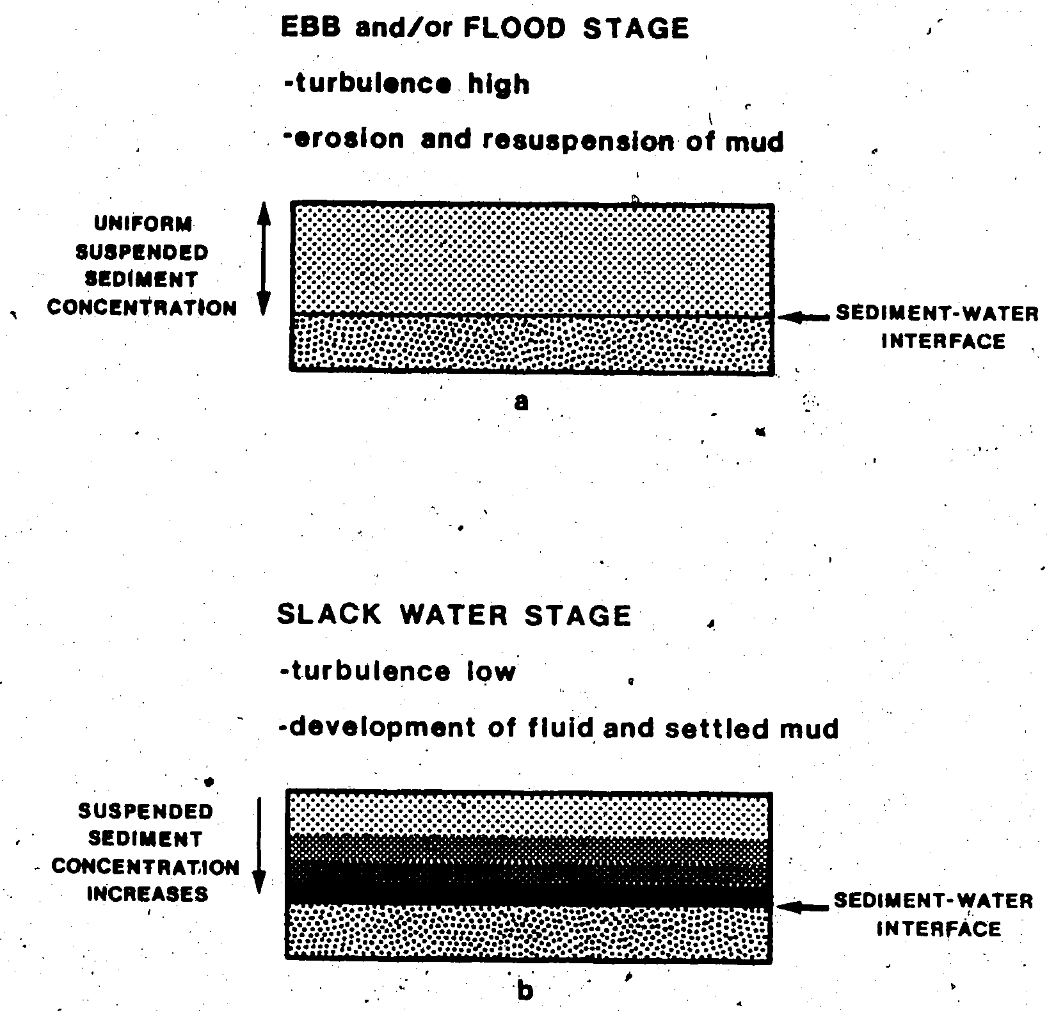


Fig. 45. Schematic of variations in the vertical distribution of suspended sediment during a single tidal cycle. (a) Suspended sediment distribution during an ebb and/or flood current stage. (b) Suspended sediment distibution during a slack water stage (adapted from various authors).

suspension (Allen *et al.* 1977, 1980). Mud that settles during a spring tidal phase slack water stage is usually eroded and resuspended by subsequent ebb and/or flood currents (Allen *et al.* 1980; Kirby and Parker 1983). As the two week tidal cycle switches from the sping to the neap tidal phase, ebb and/or flood currents weaken with decreasing tidal range and subsequently the ability to erode and resuspend mud deposited during a previous slack water stage is diminished. The length of the slack water stages increases towards the neap tidal phase resulting in increased mud deposition. Weaker ebb and/or flood currents may still be capable of some erosion and resuspension of a settled mud but often there is a remnant deposit left behind. During the neap tidal phase, mud deposition is at a maximum with little erosion and resuspension by subsequent ebb and/or flood currents occurring. As the two week tidal cycle progresses toward the next spring, currents strengthen and the result is a decrease in overall mud deposition as erosion and resuspension increases. The record of the neap is preserved in a mud deposit that has, to some degree, been able to withstand erosion by subsequent ebb and/or flood currents (Allen *et al.* 1980). It is proposed that the muddy intercalations between cosets of cross-stratified sand in the middle member were deposited during a neap tidal phase whereas cross-stratified sand bounding the muddy intercalations are spring tidal phase deposits.

During the spring phase (Fig. 46), sand transport in current ripples, dunes and sand waves is facilitated by high current velocities. Mud is deposited during slack water stages but is easily eroded and resuspended by subsequent ebb and/or flood currents. The result is the deposition of cross-stratified sand with few or no mud intercalations. As the fortnightly tidal cycle progresses from the spring towards the neap tidal phase (Fig. 47), sand transport in large-scale bedforms ceases, but can continue in small-scale bedforms. As sand transport diminishes, physical reworking of the sediments diminishes while

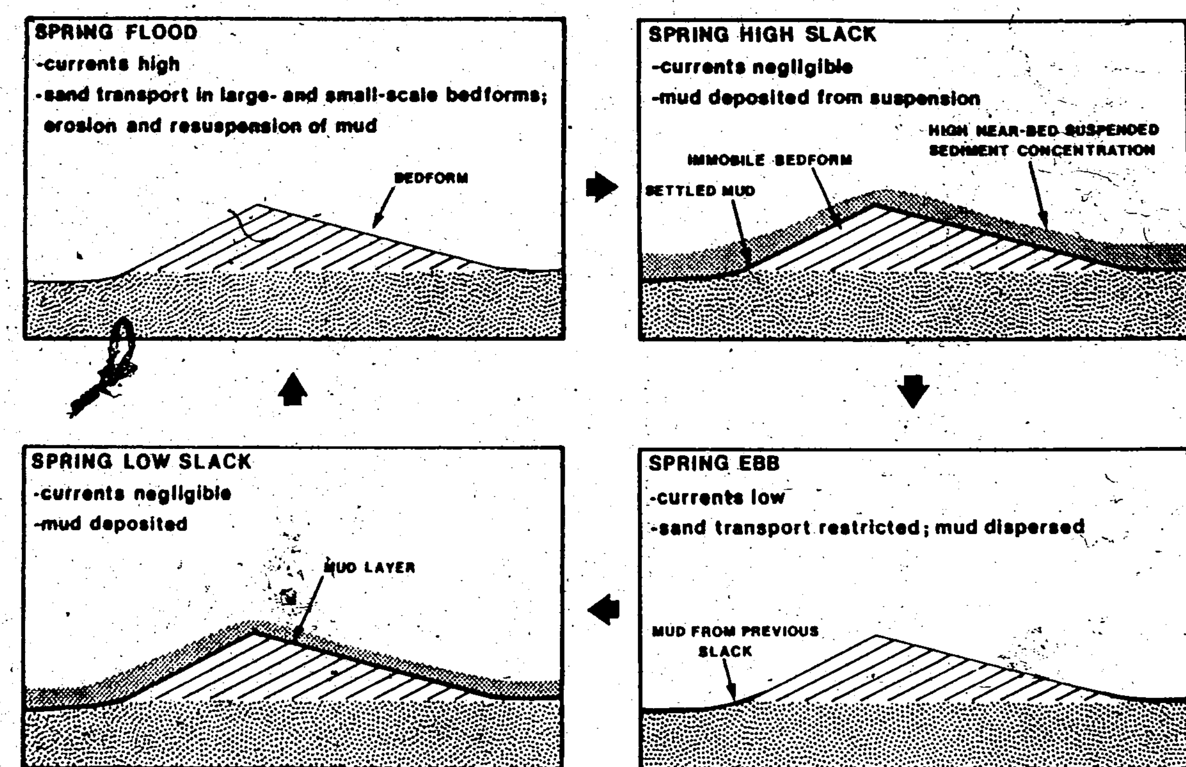


Fig. 46. Proposed model for the deposition of predominantly sand with little or no mud during a single spring tidal cycle.

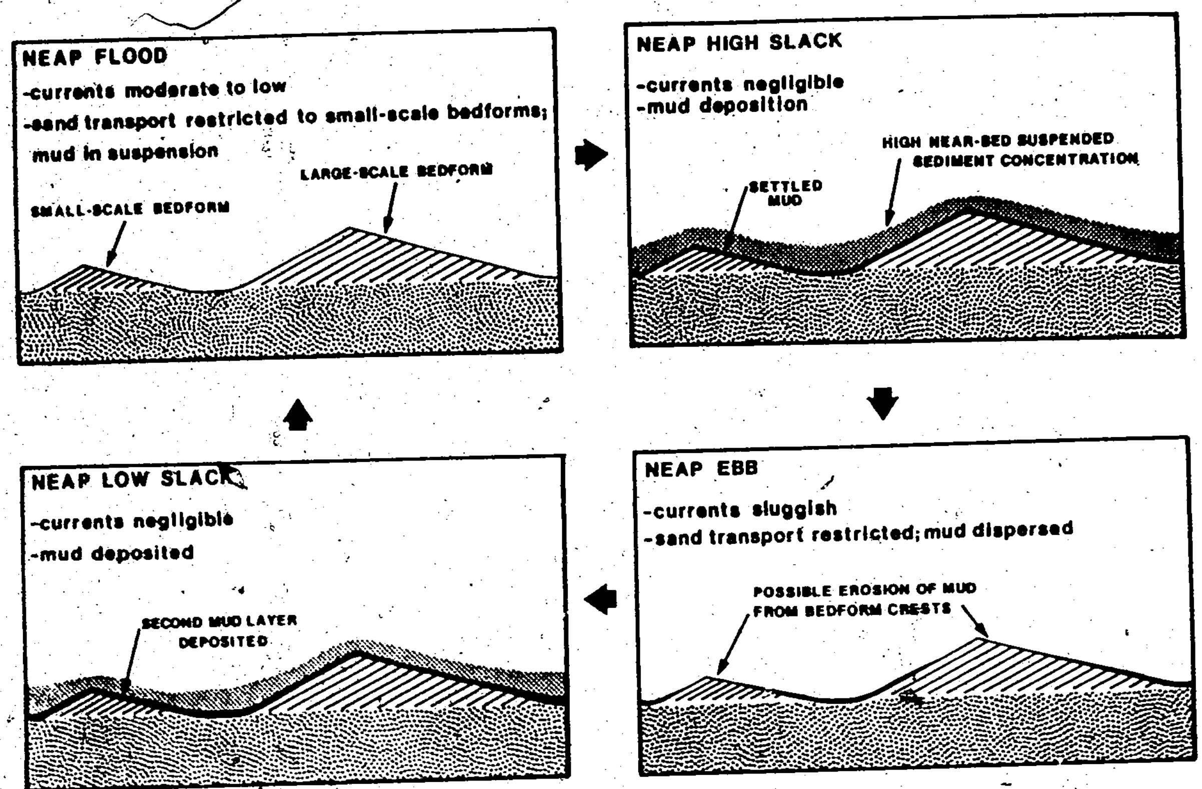


Fig. 47. Proposed model for the deposition of predominantly mud with little or no sand during a single neap tidal cycle.

biological reworking increases and consequently these sediments are more bioturbated. Mud can still be eroded and resuspended during the ebb and/or flood current stages, but this is minimal because of weakened currents. Sand transport decreases volumetrically due to weaker currents and shorter transport times. The result is the deposition of interbedded sand and mud, with mud deposition increasing and sand deposition decreasing toward the neap tidal phase. At the neap, sand transport may cease completely and erosion and resuspension of deposited mud is at a minimum. As the cycle shifts from the neap to the spring tidal phase, sand transport increases until even large-scale bedforms are mobile, and mud deposition and (most importantly) preservation decreases. The resultant deposit from the single spring to neap to spring cycle is a mud drape or composite sand and mud parting interbedded in cross-stratified sand. The extent to which the muddy intercalation develops is dependant on two factors: the amount of mud deposited; and the amount of mud eroded and resuspended by subsequent ebb and/or flood currents (Allen 1982). Variations in these factors result in different types of sequences. For example, strong storm-induced waves and currents can hinder the settling of suspended sediment resulting in a thinner mud deposit (McCave 1971; Allen 1982; Wells 1983; Eisma and Kalf 1987). On the other hand where suspended sediment concentrations are high, waves and currents may have little or no effect on the deposition of mud (McCave 1971; Wells and Coleman 1981). Erosion and resuspension of existing mud deposits by storms may in fact result in thicker mud beds by increasing suspended sediment concentrations (McCave 1970; Hawley 1981a). Variable current strength related to the annual maximum and minimum spring tides affects the rate of erosion of deposits formed during previous neap tides. These deposits, formed prior to the maximum spring tide, will be subjected to significantly stronger currents. As a result erosion of neap tidal deposits will be greater during the maximum spring tide compared to the minimum spring tide.

Other cycles are evident in the middle member besides those resulting from neap/spring current unsteadiness. Daily tidal cyclicity is possibly indicated by the occurrence of paired sand/mud couplets (cf. Reineck and Wunderlich 1967; Boersma 1969; Visser 1980). During a single tidal cycle (flood - slack water - ebb - slack water) a pair of sand and mud laminae can be deposited. It is apparent from this study that the preservation of such features would be very low during the spring tidal phase but should be higher during the neap tidal phase. Close examination of the muddy intercalations in the cross-stratified sands of the middle member has revealed a number of these small-scale sequences deposited during a single tidal cycle. Seasonal cycles are also evident in the middle member. Smith (1985) has suggested that each "sand/mud couplet" (cross-stratified sand with a muddy intercalation) in the middle member of the McMurray Formation is the result of a single seasonal flood event in a tidally influenced river. The cross-stratified sand is deposited during the fluvial flood whereas the muddy interbed represents deposition for the rest of the year when fluvial discharge is low and tidal processes predominate. The present study has revealed that this may be the case only for muddy intercalations, as well as cross-stratified sands, that exhibit high levels of bioturbation and the presence of well developed domiciles. The degree and development of the bioturbation is indicative of a prolonged period of low sedimentation and it is most likely that these features represent longer-term cyclicity. Periods of high fluvial discharge into the estuarine environment may in fact have occurred throughout deposition of the middle member, but these deposits would likely be difficult to recognize in drill cores.

Despite evidence of various temporal levels of current unsteadiness in sequences in the middle member, the neap to spring tidal cycle appears to predominate. The muddy intercalations in cross-stratified sand, as well as the coarsely stratified character of interbedded sand and mud in the muddy association (see lithofacies discussion) seem to reflect a tidal source of current velocity unsteadiness.

Tidally influenced sand bedforms are not confined to estuaries. Houbolt (1968) reported muddy intercalations (cf. Houbolt 1968, p.255: fig.13) formed during slack water stages interbedded within sandy foreset bedding of subtidal sand ridges in the Southern Bight of the North Sea. Muddy interbeds appear to have limited occurrence in these offshore tidal sand ridges because they are likely to be eroded by subsequent strong tidal currents and intense wave activity. Low suspended sediment concentrations on the offshore shelf also results in the limited occurrence of muddy interbeds in the sand ridges (McCave 1970, 1971). Wunderlich (1978) described mud drapes up to 2cm thick in subtidal "giant ripples" in the Inner Jade of the German Bight. These drapes were deposited during single slack-water stages with thicker and more numerous drapes developing in the troughs of the large-scale sand bedforms. Mud drapes appeared to be most common in large-scale bedforms in the Inner Jade reflecting high concentrations of suspended sediment whereas large-scale sand bedforms in the Outer Jade, which is characterized by much lower suspended sediment concentrations, appeared to lack mud drapes. It is apparent from these examples that muddy interbeds in cross-stratified sand are unlikely to be common in an offshore setting because of the significantly lower levels of suspended sediment as compared with the nearshore or estuarine environment.

Muddy intercalations in cross-stratified sand are by no means restricted to the tidal environment. They also can be produced in rivers with high suspended load and variable discharge (e.g. Taylor and Woodyer 1978; Parkash *et al.* 1983; Calverley 1984; Bristow

1987). Often just a simple layer of mud is draped overtop cross-stratified sand (e.g. Cossey 1981). Small-scale fining upward sequences are also deposited, with cross-stratified sand grading upward into a mud drape with intermediate deposits such as flaser and wavy bedding (Parkash *et al.* 1983; Calverley 1984). Sequences produced on middle to upper point benches in the Barwon River of eastern Australia (Taylor and Woodyer 1978, p. 267; Fig. 9) seem similar to those present in the McMurray Formation. These bench deposits of interbedded sand and mud commonly exhibit reverse grading (coarsening upward sequences of mud to sand) and rarely "waning and waxing grading" (sand to mud to sand sequences) (Taylor and Woodyer 1978, p. 265). Sands in the middle and upper bench deposits are typically wavy-laminated, rarely cross-stratified (Taylor and Woodyer 1978). This feature is a notable difference from the sequences recognized in the McMurray Formation, indicating possible suspension rather than bedload transport of sand. Other features which may help distinguish these types of fluvial deposits from those of marine or marginal marine settings include the apparent lack of invertebrate burrows and [illegible] for pedogenesis and plant roots to destroy or disrupt primary [illegible]es (e.g. Taylor and Woodyer 1978; Jackson 1981).

[illegible]n estuary is are variable (Table 5) but most seem to stress the [illegible]: (a) the mixing of fresh and salt water; (b) that tides are the [illegible] sediment transport; and (c) a semi-enclosed or embayed coastal g[illegible]phology. These three criteria are critical when recognizing an ancient estuarine sequence. Geomorphologically an estuary consists of tidal channels that incise broad low lying tidal flats (Clifton 1982). Channels may be wide and deep, serving as major conduits for tidal currents in the estuary, or they may be smaller drainage or run-off channels on the tidal flats. Flach (1977) first recognized that most of the outcrop of the middle

Table 5. Definitions of an estuary from modern studies, and applications of these definitions to ancient estuarine deposits.

ESTUARY: derived from the Latin *aestus*, meaning the tide, and *aesto*, meaning to boil, as well as *aestuarium*, meaning tidal (Fairbridge 1968, 1980).

Definitions: "a semi-enclosed coastal body of water which has free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage" (Pritchard 1967, p. 3)

"an inlet of the sea, reaching into a river valley as far the upper limit of tidal rise" (Fairbridge 1980, p. 7)

"a complex of intertidal and shallow subtidal intercoastal facies dominated by tidal proceses" (Howard and Frey 1980, p. 221).

"something like pornography - hard to define exactly, but we know one we see one" (Beer 1983, p. 169)

Recognition of an estuary in the <u>ancient record</u>:

(a) indications that there was **mixing** of fresh and sea water
- (i) paleontological evidence of brackish water
- (ii) physical evidence for deposition of large volumes of mud via flocculation

(b) dominant mechanism of sediment transport were **tides**
- (i) lithofacies sequences indicative of regular occurring current unsteadiness

(c) semi-enclosed or embayed coastal geomorphology member of the McMurray Formation was deposited in channels on the accretionary banks of large migrating high sinuosity channels. Mossop (1980a) suggested that it was very likely that much of the middle member in the subsurface was also made up of these lateral accretion deposits. In the present study large-scale vertical lithofacies sequences (Fig. 44) that reflect an upward decrease in current strength (ie. upward decrease in: sand grain size; scale of cross-stratification; and the sand to mud ratio) are interpreted to be the result of lateral accretion in channels. Physical evidence for tidal activity in cyclic small-scale lithofacies sequences in the middle member suggests that these lateral accretion deposits formed in tidal channels. Recent examples of "fining upward" sequences produced by laterally migrating tidal channels are numerous (e.g. Oomkens and Terwindt 1960; Land and Hoyt 1966; Howard *et al* 1975; Meckel 1975; Barwis 1978; Clifton and Phillips 1980). Although the overall vertical sequence of lithofacies produced by a migrating tidal channel appears to fine up, it is also highly complex because of substantial short- and long-term variations in current strength (de Raaf and Boersma 1971; Terwindt 1971, 1975; Howard and Frey 1980). Short-term fluctuations of current strength could be attributed to the daily and neap to spring tidal cycles whereas long-term fluctuations might be associated with storms, fluvial floods and the shifting of channels. The character of the tidal channel deposit appears to depend heavily on the strength of the currents as well as the supply of sediment (Terwindt 1971; Howard and Frey 1975; Clifton 1982; Nichols and Biggs 1985). In channels where currents are strong and the supply of sand is high, cross-stratified sand is the dominant deposit. Where currents are weaker and suspended sediment concentrations are high, muddy lithofacies will most likely predominate.

Estuaries tend to be sandier at their mouths because mud is winnowed away by waves and strong tidal currents whereas muddier lithofacies are more common in the middle to upper parts of estuaries where mixing of fresh and salt water enhances the deposition of suspended sediment (Clifton 1982; Nichols and Biggs 1985). Because the present study area is so localized, no attempt has been made to place the middle member in any specific geographic location within the estuary, however the abundance of argillaceous lithofacies seems to favour a middle or upper estuary setting. Studies of modern estuaries (e.g. Gironde Estuary of France, Fig. 48; Ogeechee River - Ossabaw Sound estuary of Georgia, Fig. 49; and Willapa Bay estuary of Washington, Fig. 50) have revealed that there is a general depositional trend of lithofacies in this environment. Cross-stratified sand is commonly produced in bars within channels or the accretionary banks of channels which are covered with migrating ripples and dunes. Where tidal currents are strong, dunes and sand waves cover the channel bottom resulting in the deposition of cross-stratified sand. Interbedded sand and mud is deposited on the channel bottom, as well as on channel accretionary banks, where currents are weaker but still capable of transporting sand, and concentrations of suspended sediment are high resulting in mud deposition during slack water stages. Mud is also deposited in channels where currents are very weak, perhaps in protected areas or where abandonment has occurred.

Inclined sets of interbedded sand and mud may represent lateral accretion deposits of migrating tidal channels in which both sand and mud are abundant. Though not exclusively tidal, this sedimentary feature, which has been recently classified as "inclined heterolithic stratification" (Thomas *et al.* 1987), is best documented as the product of deposition on point bars of tidal channels (Fig. 51) (e.g. Van Straaten 1954; Reineck 1958; Bridges and Leeder 1976; Clifton and Phillips 1980; deMowbray 1983). Interbedded sand and mud deposited on the accretionary banks of tidal channels commonly have gentle dips (e.g. 5 to 15^{o}, deMowbray 1983). Bioturbation in these lateral accretion deposits is typically low

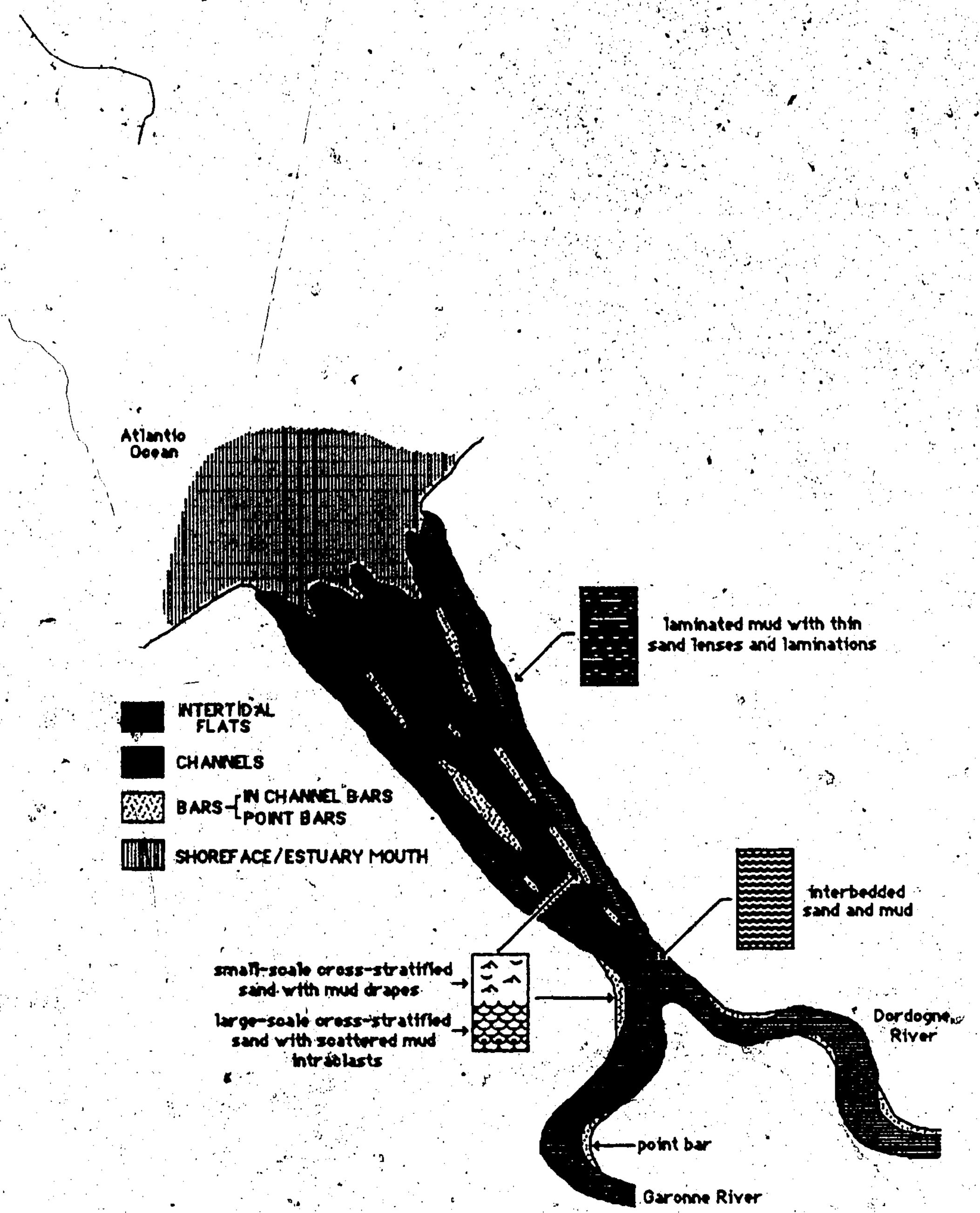


Fig. 48. Schematic representation of the Gironde Estuary of southwest France, showing the distribution of estuarine subenvironments with dominant lithofacies (modified after Allen 1972, cited in Jouanneau and Latouche 1981; Allen *et al.* 1983, cited in Nichols and Biggs 1985).

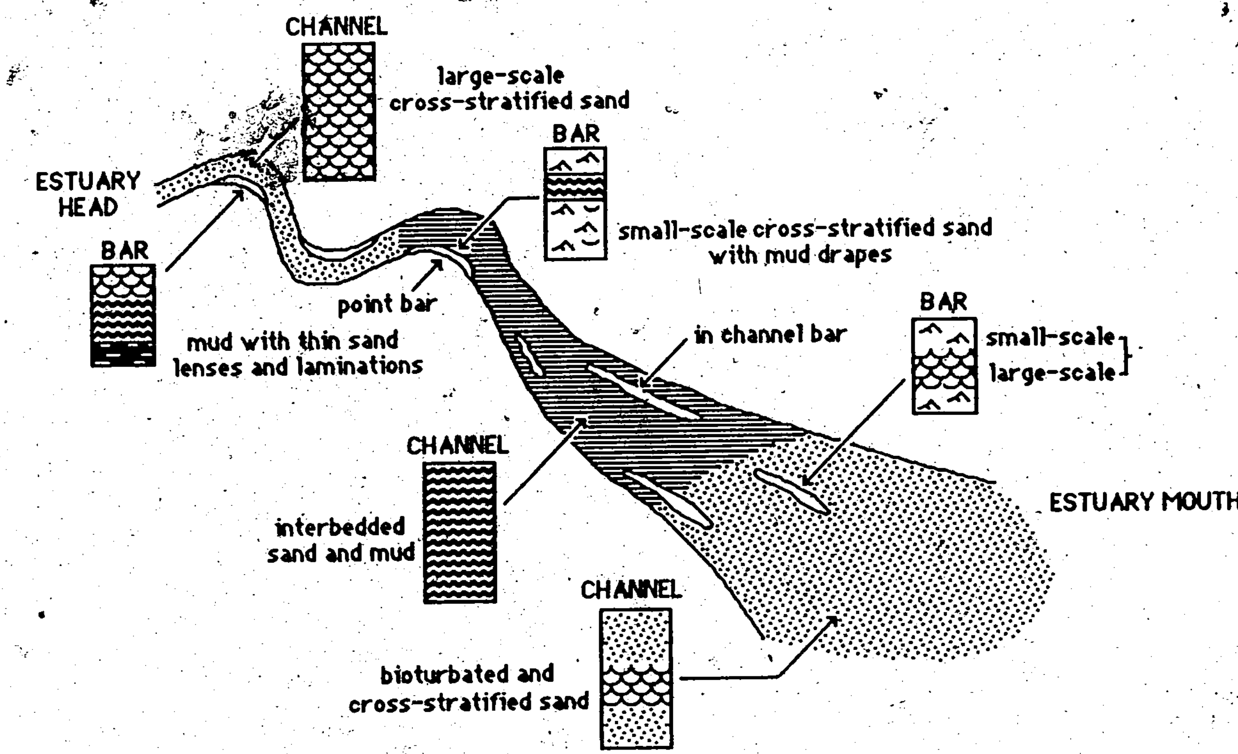


Fig. 49. Schematic representation of the Ogeechee River - Ossabaw Sound estuary of Georgia, showing lithofacies distribution (modified from Dörjes and Howard 1975; Howard *et al.* 1975).

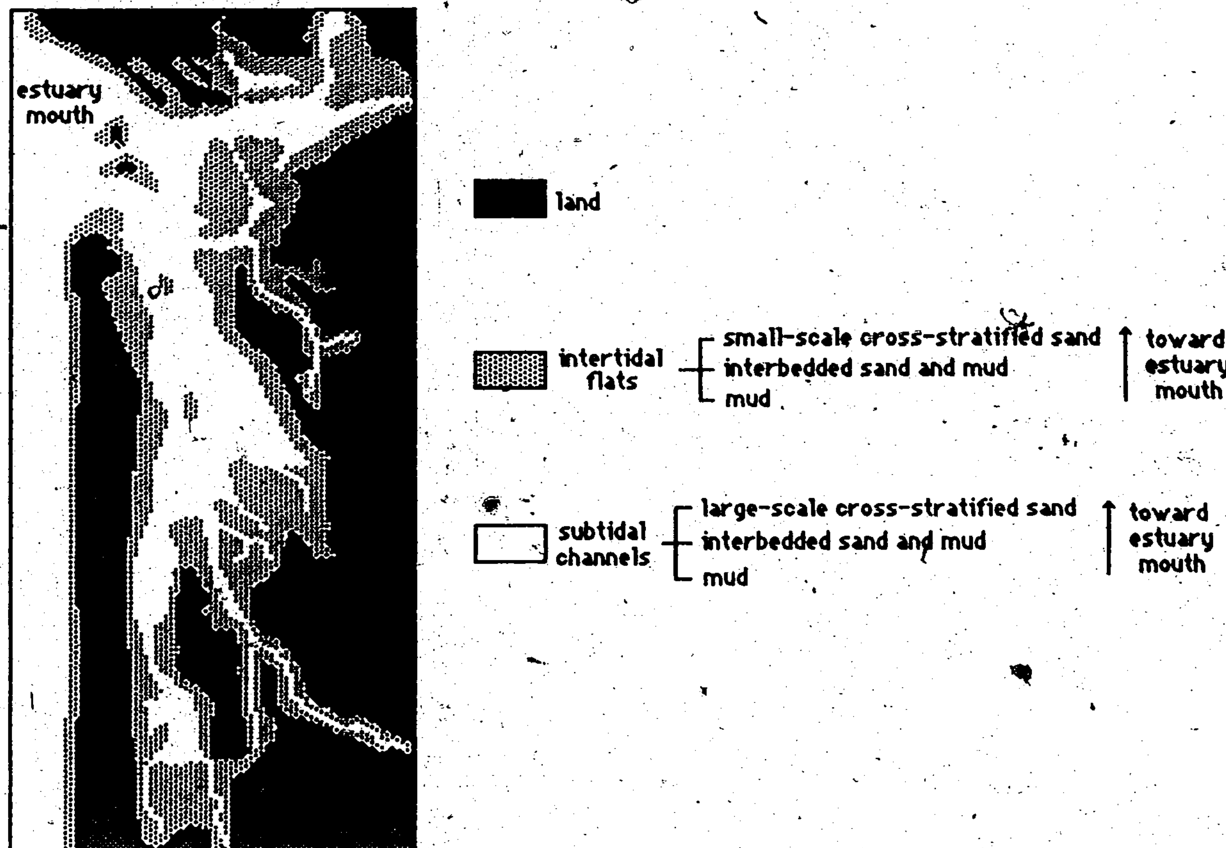


Fig. 50. Schematic representation of Willapa Bay estuary of Washington, showing estuarine subenvironments and lithofacies distribution (modified from Clifton and Phillips 1980).

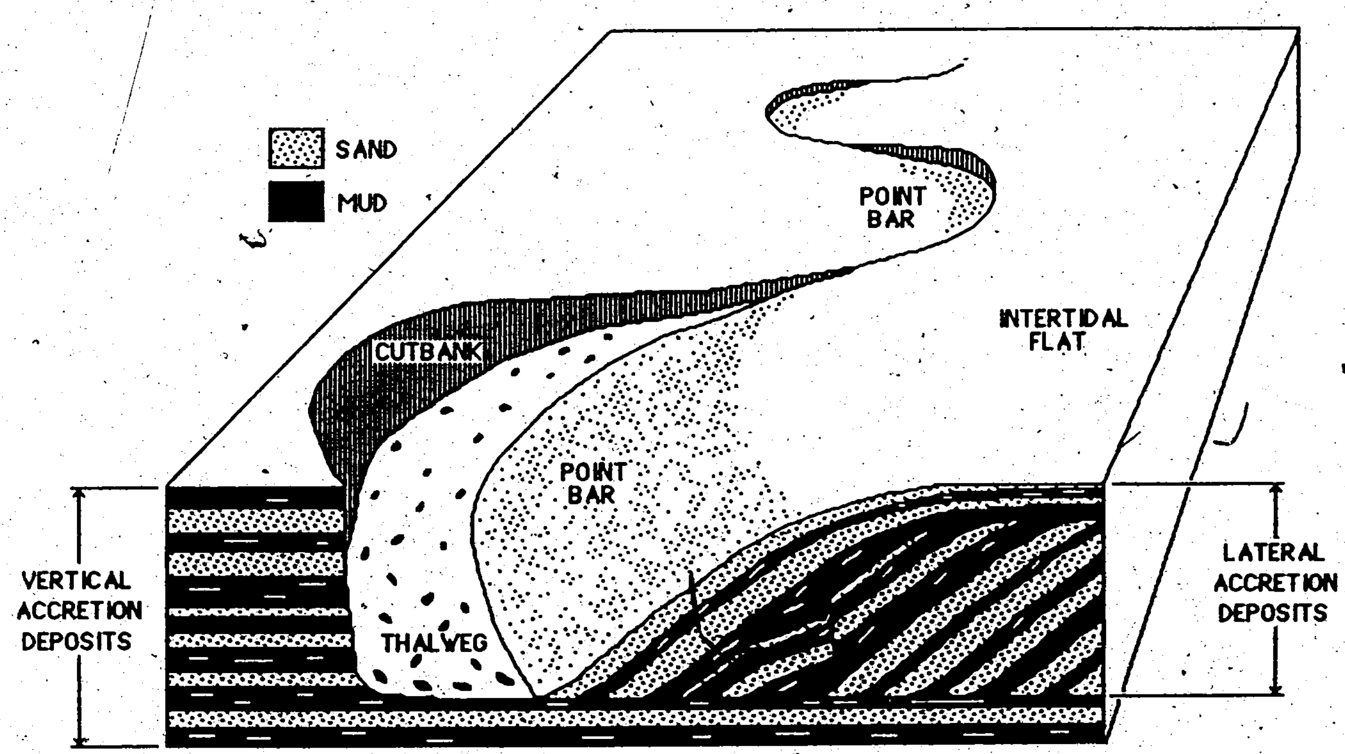


Fig. 51. Development of lateral accretion deposits (gently inclined interbedded sand and mud) on the accretionary bank of a meandering tidal channel or creek (modified from Reineck 1958; Bridges and Leeder 1976; deMowbray 1984).

because of relatively high rates of sedimentation. DeMowbray (1983) reported that point bars in intertidal creeks in Solway Firth of southwest Scotland, laterally accrete several centimetres per year. In contrast, the adjacent intertidal flats are characterized by very low sedimentation rates, with vertical accretion in the order of only 3 to 4cm per month. As a consequence of these low sedimentation rates, intertidal flat deposits are often heavily reworked by burrowing organisms (e.g. Van Straaten 1954; Reineck 1967). Where waves and tidal currents are stronger, physical reworking of the substrate is greater and bioturbation would be expected to be low. However Clifton (1982) reports that physical sedimentary structures beneath wave ripples and large-scale intertidal dunes and sand waves are often highly disrupted or obliterated by extensive biogenic reworking. Therefore heavily bioturbated lithofacies found at the top of possible channel sequences in the middle member may be interpreted to be intertidal flat deposits. These lithofacies may also represent channel margin deposits where sedimentation rates are low and biogenic reworking can be extensive.

Because intertidal deposits typically develop at the top of estuarine sequences they are more susceptible to removal by subsequent erosion whereas subtidal channel deposits are low in the stratigraphic sequence and are less likely to be affected by susequent erosive events (Meckel 1975; Visser 1980). Tidal flat deposits are especially prone to erosion by waves and currents (Allen 1987). Because intertidal flat sediments are dominated by clay minerals and are subject to drying out with regular subaerial exposure, shrinkage and fracturing of deposits is common. Weakening by fracturing greatly increases the ability of waves and tidal currents to rework intertidal flat deposits. Another characteristic of intertidal flat deposits making them predisposed to erosion is the predominance of interbedded sand and mud (e.g. Reineck 1967). Mud beds may resist erosion but sand laminations are easily washed out, undermining the mud beds which in time collapse and breakup (Allen 1987).

Estuaries are best developed during a rise in sea level when river valleys are flooded and the coastline is embayed (Nichols and Biggs 1985). As previously discussed (see Structure), the present study area lies along the margin of a major northwest trending paleo-valley that widens toward the north. This valley was most likely flooded with the transgression of the boreal sea, turning it and its tributary valleys into estuaries. As sea level continued to rise these estuaries were filled with a series of superimposed sequences. This is recognized in the present study by the stacking or superposition of apparent channel sequences and associated overlying channel margin and/or intertidal flat deposits. Thick accumulations of cross-stratified sand, some apparently single genetic units, were probably deposited in channels that deeply incised pre-existing sediments whereas smaller channels only eroded the uppermost portions of underlying estuarine sequences that were deposited when sea level was lower. Evidence that middle member tidal channels eroded into existing estuarine deposits is often indicated by sharp, often scoured basal contacts of fining upward sequences, as well as the abundant large angular mud intraclasts that were probably derived from erosion of existing muddy deposits by the migrating channel. Migration rates of modern tidal channels are typically high. Van den Berg (1982) reports that tidal channels near the mouth of the Oosterschelde (Scheldt Estuary of southwest Holland) migrated 2km laterally in 35 years. Because of this rapid migration, lateral accretion deposits tend to dominate estuarine sequences despite the fact that the channels have a limited areal distribution at a given time in the estuary (Clifton 1982; Frey and Howard 1980). Tidal flats may cover a wide area in the estuary but their deposits form only a thin veneer overtop the predominant channel deposits (Frey and Howard 1980).

Environmental summary:

The middle member of the McMurray Formation was most likely deposited in an aggrading estuarine setting (Fig. 52) that developed in response to rising sea levels. Most of the sequences observed in the middle member are lateral accretion deposits formed in migrating large- and small-scale tidal channels. The type of lithofacies that was deposited in the channel depended mainly on the strength of tidal currents and the concentration of suspended sediment. Where currents were strong and physical reworking extensive, cross-stratified sand was likely to be deposited. Interbedded sand and mud would accumulate where currents were weaker and concentrations of suspended sediment were high. Channel margin and intertidal flat sequences accumulated on top of the lateral accretion deposits. These sequences, which are typically heavily bioturbated, reflect weak currents, slow rates of sedimentation and extensive biogenic reworking. Because these sequences often develop at the top of estuarine sequences, they are vulnerable to removal by subsequent erosive events.

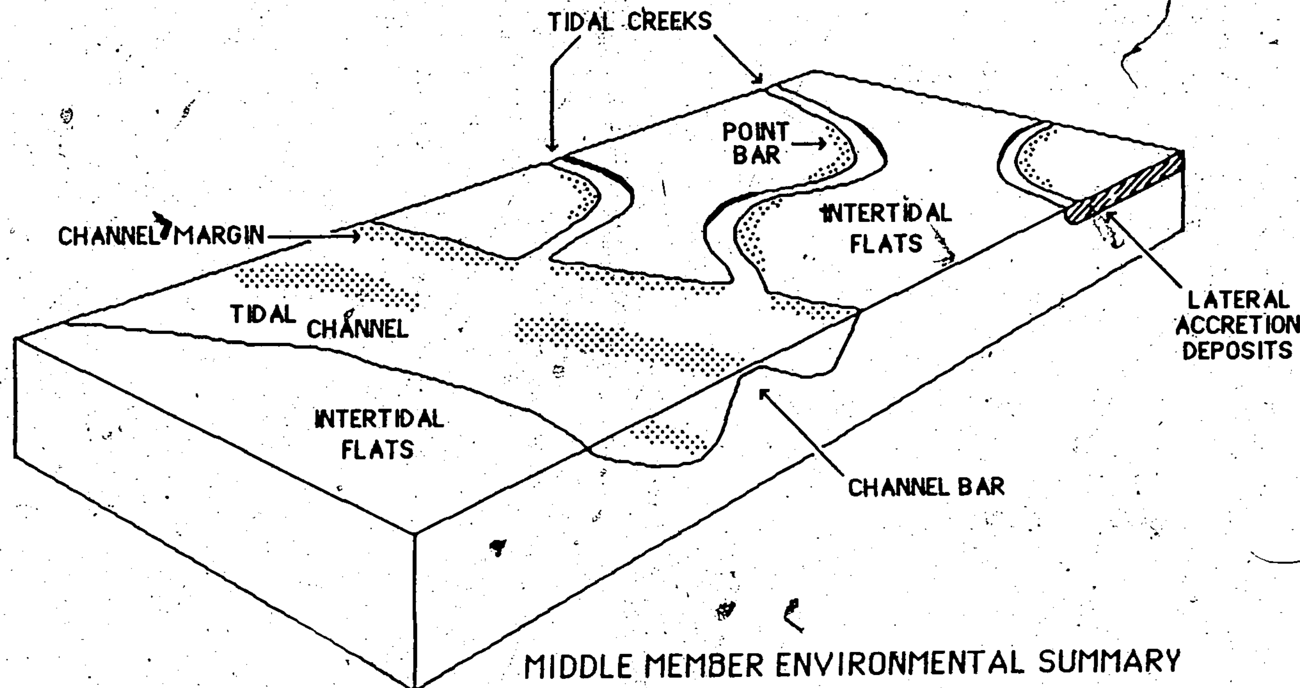


Fig. 52. Environmental summary of the middle member of the McMurray Formation, Syncrude Oil Sands Lease 17 study, showing estuarine depositional setting.

CHAPTER 5

LIMY UNIT

Description:

In 40% of the drill cores examined, the middle member is unconformably overlain by the limy unit which is distinguished from the rest of the McMurray Formation by muds that are slightly calcareous and sands that often contain shells and scattered shell fragments. This informal stratigraphic unit fills an incision on the top of the middle member in the eastern half of the study area and attains a maximum thickness of 15.1m (drill core 36-36). The isopach map of the limy unit (Fig. 53) indicates that it is a north-south trending stratigraphic body with a north-northeast trending arm or branch in the north central part of the study area and a 30cm thick outlier (drill core 33-39) 300m west of the main body. The net sand isopach of the limy unit (Fig. 54) reveals elongate sand accumulations parallel to the trend of the limy unit. The limy unit extends southward into 4-93-11W4 as is indicated by "facies slice maps" of Wach (1984) who classified sequences characteristic of the limy unit as "estuarine fill". The north-south trend of the limy unit differs from depositional trends in the lower and middle members and there is no evidence for control on sedimentation by the Devonian - Cretaceous unconformity surface. The limy unit may be equivalent to fossiliferous beds (see discussions by Ells 1926; Russell 1932; Carrigy 1966) situated between the middle and upper members of the McMurray Formation in outcrops along the Hangingstone River in southern Fort McMurray.

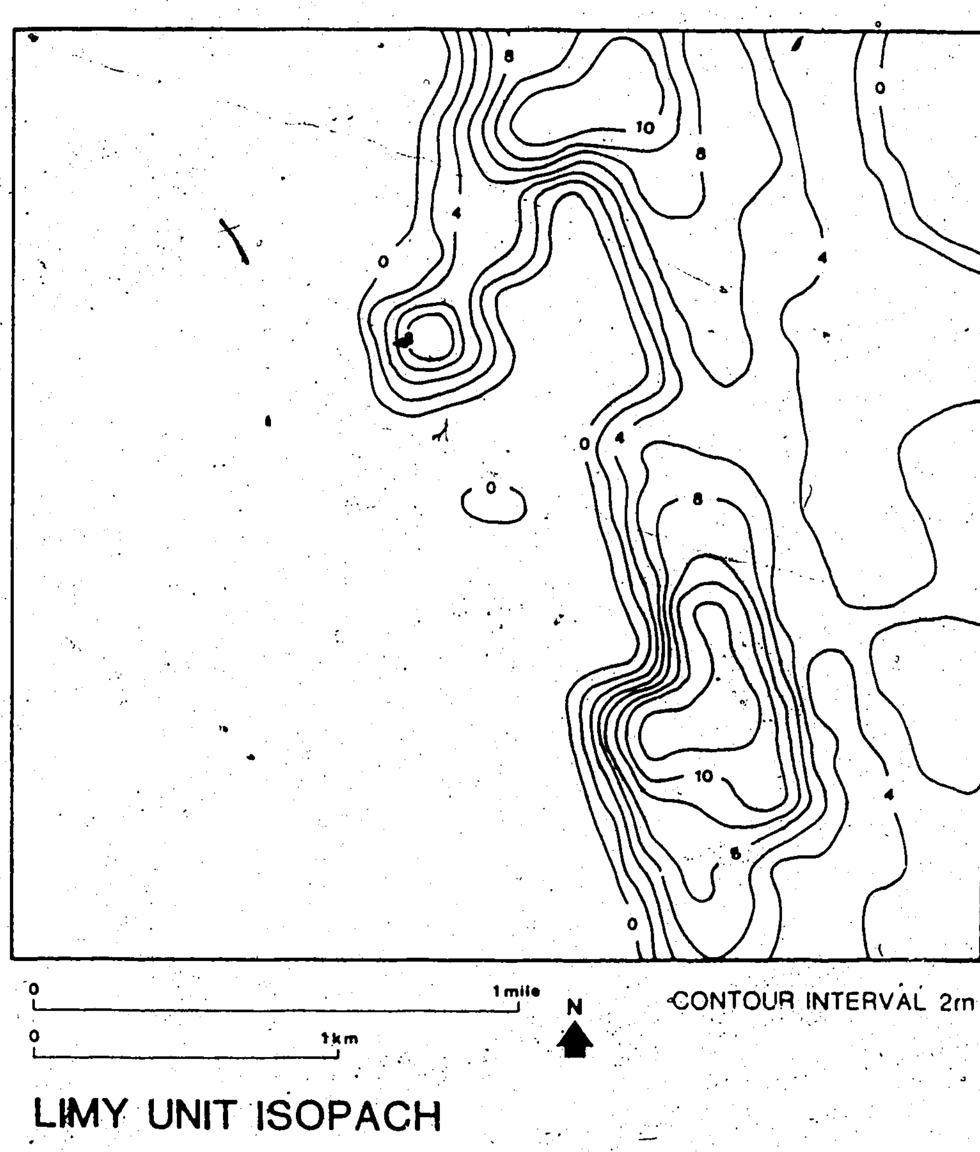
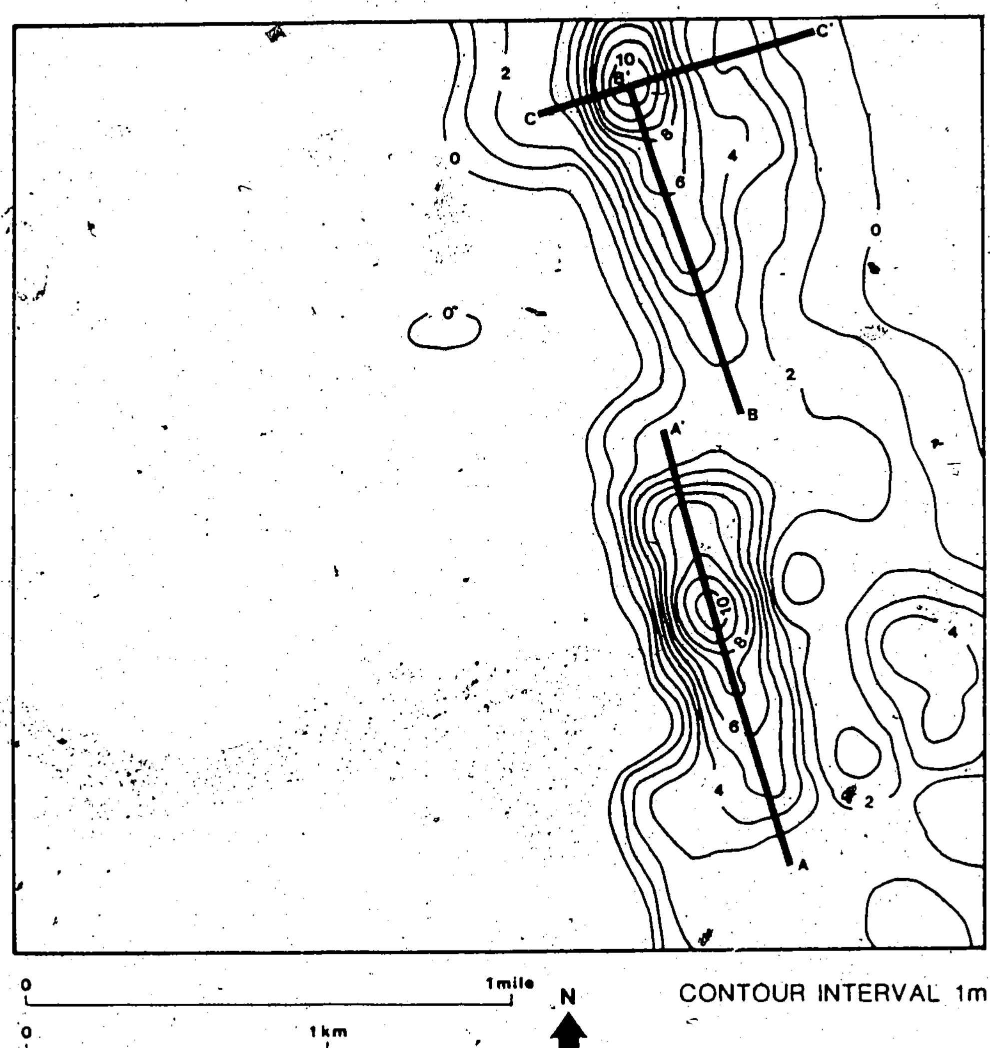


Fig. 53. Isopach map of the limy unit of the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.



LIMY UNIT NET SAND ISOPACH

Fig. 54. Net sand isopach map of the limy unit of the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands, showing locations of stratigraphic cross-sections (A-A', B-B' and C-C') through linear sand accumulations.

Lithofacies associations:

As with the middle member of the McMurray Formation, the limy unit is characterized by complex vertical and lateral lithofacies sequences. Stratigraphic cross-sections (Fig. 55, 56, 57) through sand accumulations in the limy unit reveal two distinct lithofacies associations, one superimposed on the other. The basal association, which makes up 50 to 100% of the limy unit, is characterized by sequences of cross-stratified sand that are overlain by interbedded sand and calcareous mud. Small-scale cross-stratified sands predominate in this association but large-scale cross-stratified sands are often found in the basal portions of sequences. Flat to low angle planar stratified sands are infrequently interbedded with the cross-stratified sands. Arenaceous lithofacies, especially small-scale cross-stratified sands, often have intercalated calcareous mud drapes and composite sand and calcareous mud partings (Plate 8, Fig. a). Intact shells and scattered shell fragments are commonly found in these arenaceous lithofacies. Cross-stratified sands typically have sharp, often scoured basal contacts and grade upward into more argillaceous lithofacies. The general sequence in the basal association (Fig. 58) is characterized by an upward decrease in the sand to mud ratio, as well as sand grain size, scale of cross-stratification and thickness of sand beds. These fining upward sequences are commonly stacked on top of one another, each averaging 1 to 2m in thickness. Interbedded sands and calcareous muds, which are typically inclined at low angles (5^{o} to 10^{o}), also exhibit small-scale fining upward sequences whereas coarsening upward sequences are more rare. In a few examples (e.g. drill core 36-39) a series of stacked fining upward sequences of cross-stratified sand and interbedded sand and calcareous mud dip consistently at low angles. Where sand accumulations are thick, sequences in the basal association consist of a repetitive alternation of small-scale cross-stratified sand with large-scale cross-stratified and/or

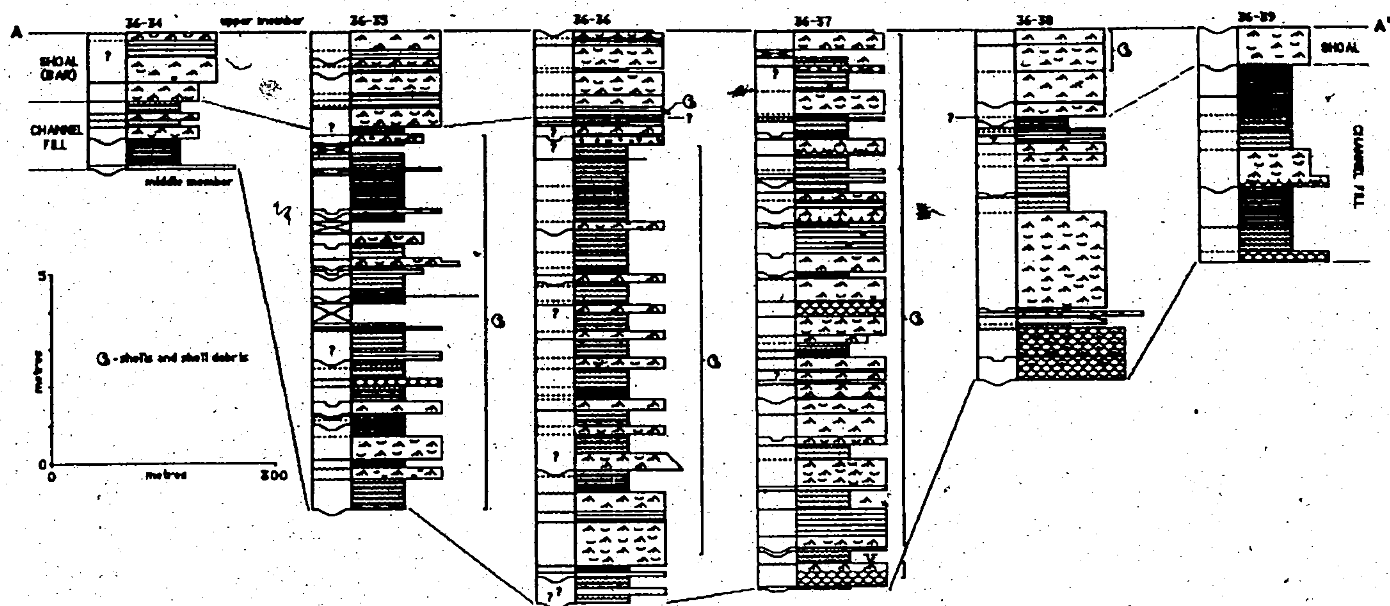


Fig. 55. Longitudinal stratigraphic cross-section (A-A') through the southern linear sand accumulation in the limy unit of the McMurray Formation.

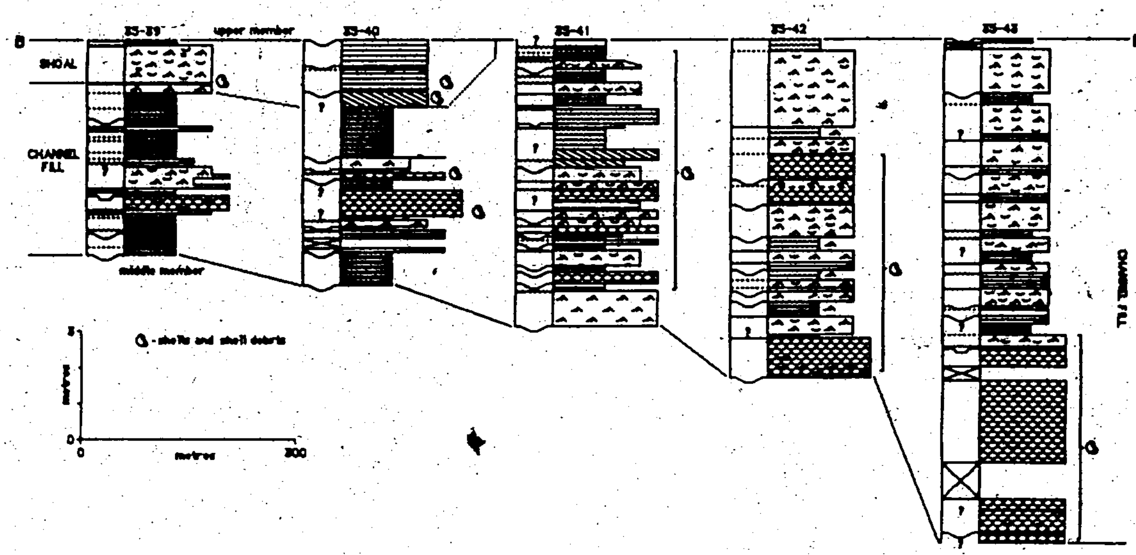


Fig. 56. Longitudinal stratigraphic cross-section (B-B') through the northern linear sand accumulation in the limy unit of the McMurray Formation.

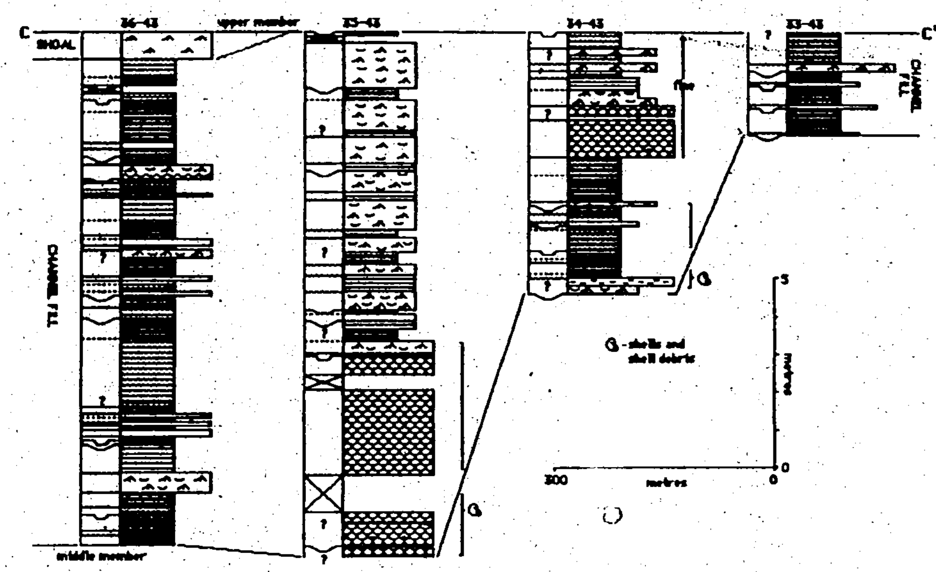


Fig. 57. Transverse stratigraphic cross-section (C-C') through the northern linear sand accumulation in the limy unit of the McMurray Formation.

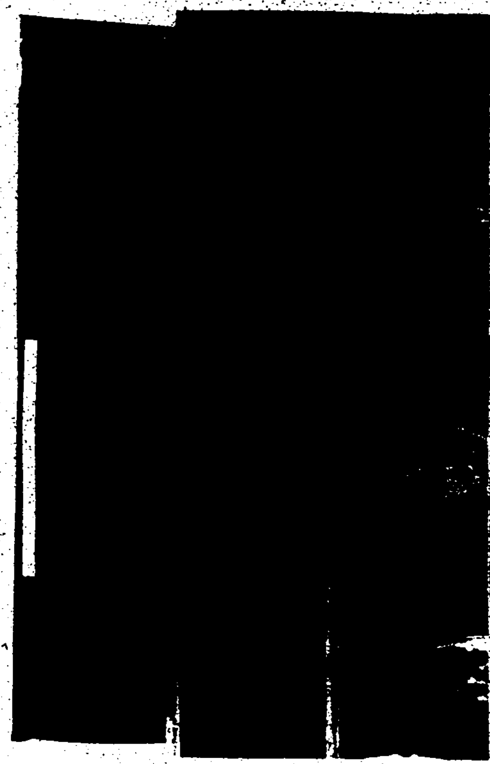
PLATE 8

Lithofacies sequences from the limy unit of the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.

Fig. a. A composite sand and calcareous mud parting in small-scale cross-stratified sand in the limy unit of the McMurray Formation, exhibiting paired sand/mud couplets and possible neap/spring cyclicity; drill core 36-44, 51.5m (scale 5cm).

Fig. b. Small-scale cross-stratified sand with muddy intercalations and fossiliferous interbeds, overlain by heavily bioturbated planar stratified sand, in the limy unit; drill core 35-40, 51.2 to 52.2m (scale 10cm).

a



b

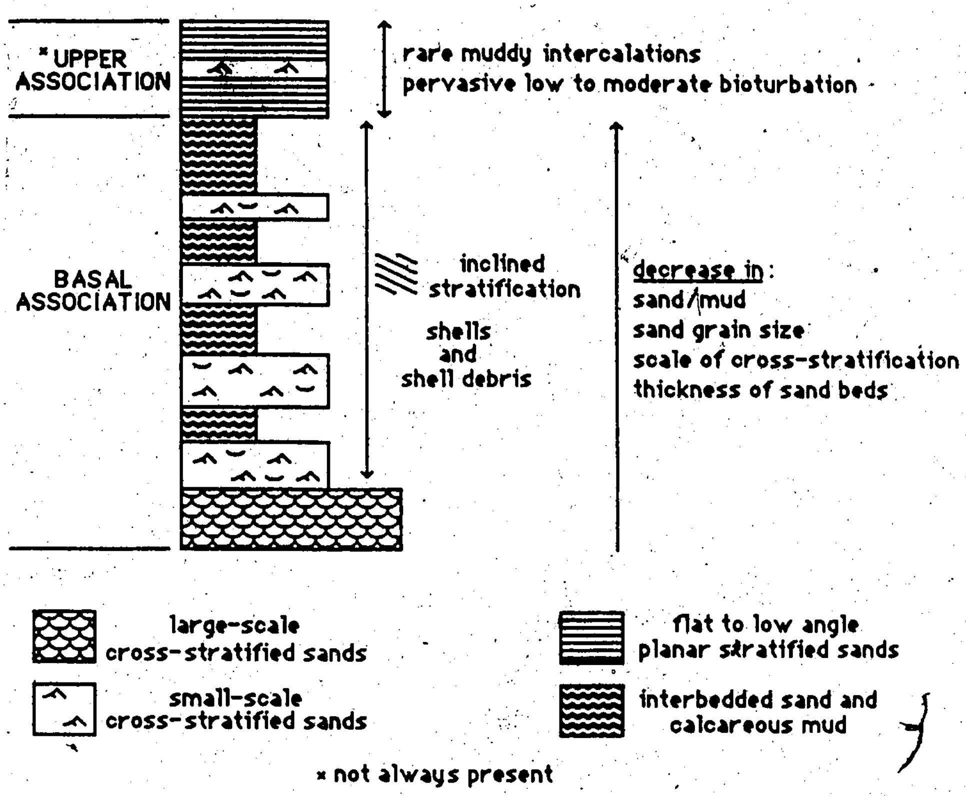


Fig. 58. Schematic summary of the vertical sequence of lithofacies in the limy unit of the McMurray Formation, showing the basal and upper associations of lithofacies.

planar stratified sand, with only thin (10 to 20cm thick) intercalations of interbedded sand and calcareous mud. Shells appear to be concentrated where sand accumulations are thickest, whereas in areas along the edge of the limy unit where argillaceous lithofacies appear to predominate, shells are virtually absent. Bioturbation is substantially lower in the basal association of the limy unit as compared with the underlying middle member.

In approximately 20% of the drill core that penetrate limy unit sequences, the basal association is sharply overlain by an assemblage of flat to low angle planar stratified and small-scale cross-stratified sand which typically lack muddy intercalations (Plate 8, Fig. b). Argillaceous lithofacies such as interbedded sand and calcareous mud appear to be rare in the association. Shells are sparse, occurring mainly in sands at the bottom of sequences. Sands in the upper association differ from those in the basal association in that they are characterized by pervasive low to moderate bioturbation.

Interpretation:

The fining upward sequences of cross-stratified sand and interbedded sand and calcareous mud reflect an upward reduction of current strength. The regular alternation of sand and mud in these lithofacies indicates a regular fluctuation of current strength within the overall fining upward sequence. Currents fluctuated between those capable of transporting sand and those that were weak enough to allow mud to settle from suspension. The repetitive stacking of these small fining upward sequences might suggest separate depositional events, but the consistent dip of stratification points to a single genetic unit. Rare and irregularly distributed thin intercalations of normally graded sands in interbedded sand and calcareous mud (see discussion in Lithofacies) are most likely the consequence of short lived periods of higher energy when sand was suspended and subsequently deposited. The abundance of argillaceous lithofacies and muddy intercalations in cross-stratified sand suggests high suspended sediment concentrations in the environment of deposition. The low intensity of bioturbation in the basal association possibly reflects the difficulty that organisms had coping with a muddy substrate. The general lack of abrasion or fragmentation of shells in the limy unit suggests they underwent little or no transport from their source.

The predominance of planar stratified and small-scale cross-stratified sands in the upper association and the general lack of argillaceous lithofacies or muddy intercalations suggests a relatively high energy setting. Any mud deposited during a reduction of energy levels was probably resuspended by subsequent high energy conditions. The paucity of shells and shell debris also suggests a depositional setting where currents and/or waves were strong and continually reworking the substrate. However, the pervasive bioturbation of arenaceous lithofacies in the upper association indicates that extensive biological reworking of the substrate occurred despite the high energy conditions of the depositional setting.

At first glance the limy unit consists of sequences that fill a linear and relatively steep-sided incision on top of the middle member. Fining upward sequences and possible inclined heterolithic stratification suggest that the basal association, which forms the bulk of the limy unit, is made up of lateral accretion deposits that developed in a channel setting. Linear accumulations of cross-stratified sand that are parallel to the axis of the limy unit may represent the deposits of migrating bars or ridges. Interbedded sand and mud was deposited in the channel between the bars and on the accretionary banks of migrating channels. The regular alternation of sand and mud in interbedded sand and calcareous mud, as well as muddy interbeds in cross-stratified sand suggests deposition in tidal channels.

Small-scale lithofacies sequences similar to those in the middle member that possibly reflect daily and neap to spring tidal cyclicity are evident in the limy unit. The abundance of interbedded sand and calcareous mud as well as mud intercalated in arenaceous lithofacies, indicating high suspended sediment concentrations, suggests deposition in an estuary where mixing of fresh and saline waters enhances the deposition of mud. On shoals and along the margins of tidal channels the substrate is affected by locally derived waves in addition to tidal currents. With decreasing depth along the channel margins and shoals, wave effectiveness on the substrate is enhanced, resulting in greater physical reworking. Any mud deposited when tidal currents are weak is winnowed away by wave activity. As a result planar stratified and small-scale cross-stratified sand with little or no calcareous mud predominate. Waves would have little influence on deeper parts of the channels except during storms when wave base would extend to greater depths possibly resulting in the emplacement of thin normally graded sand beds within channel deposits.

Planar stratified and small-scale cross-stratified sand are the dominant lithofacies to be deposited in the intertidal channel margins of Ossabaw Sound of Georgia (Greer 1975). Strong wave and tidal current activity limits the deposition of mud on the channel margin whereas the adjacent channel is characterized by lithofacies that typically have a significant argillaceous component (Oertel 1973; Greer 1975). Despite the high energy conditions of the channel margin setting, biological reworking of the substrate is extensive resulting in the disruption of primary stratification (Greer 1975).

Source of the calcareous mud:

Carbonate in calcareous muds can either be derived from direct chemical precipitation (calcareous algae, planktonic micro-organisms or direct precipitation from sea water) or from the breakdown of pre-existing carbonate (Blatt *et al.* 1972; Wilson 1975). Pre-existing carbonate, such as shell material, can be broken down into mud-sized particles by boring and grinding activities of predators, as well as mechanical breakdown by waves and currents (Blatt *et al.* 1972; Bathhurst 1975; Wilson 1975). Fixing of calcium carbonate from solution by various organisms usually requires clear, shallow and warm waters, and is severely inhibited in environments where clastic input is very high and suspended sediment concentrations are high (Wilson 1975). Lithofacies that characterizes the limy unit of the McMurray Formation strongly indicate that sedimentation rates were most likely high and suspended sediment concentrations were great. As a consequence, direct precipitation of carbonate seems unlikely. The carbonate in the calcareous muds was probably derived from either the breakdown of the shells that are present in many of the sands of the limy unit, or that it was derived from a locality of carbonate production and transported by wave and current activity to the present area of study. The latter source is more likely because the shells in the limy unit show little or no evidence of wearing or breakdown. Van Straaten (1954) reported that the bulk of the carbonate sediment found in the estuaries of northwest Holland was derived from the remains of calcareous organisms living in tidal channels and on the intertidal flats, as well as fine grained calcareous sediment from the North Sea. Detailed paleontological, mineralogical and geochemical analysis would be required in order to determine more accurately the source of the carbonate in the calcareous muds of the limy unit.

Environmental summary:

Sequences which characterize the limy unit of the McMurray Formation mainly consist of tidal channel deposits that filled an incision that developed on top of the middle member (Fig. 59). Fining upward sequences of cross-stratified sand and interbedded sand and calcareous mud, as well as inclined heterolithic stratification, probably represent lateral accretion deposits which formed as a result of migrating tidal channels. Linear accumulations of cross-stratified sand that are parallel to the axis of the limy unit are believed to be channel bar deposits. The abundance of argillaceous lithofacies and muddy intercalations in stratified sands suggests deposition in an estuarine environment. Capping the tidal channel sequences are bioturbated stratified sands interpreted to have been deposited on shoals or channel margins where waves as well as tidal currents winnowed out any mud.

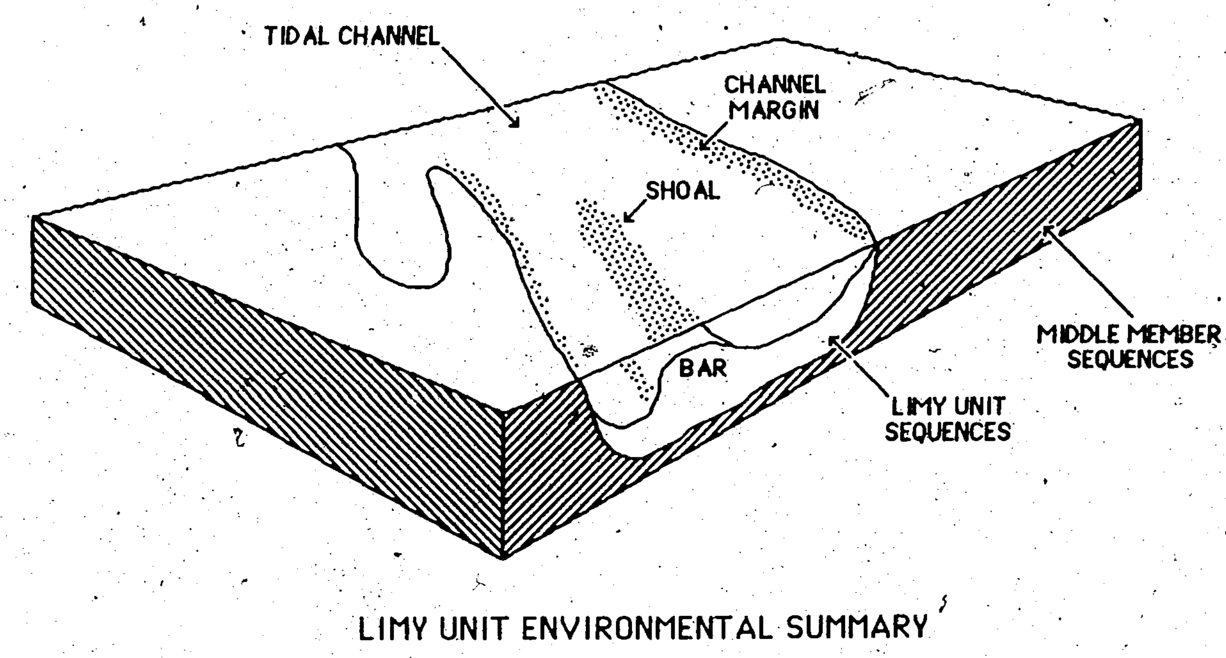


Fig. 59. Environmental summary of the limy unit of the McMurray Formation in the present study area, exhibiting an estuarine environment that developed in an incision on the top of the middle member.

CHAPTER 6

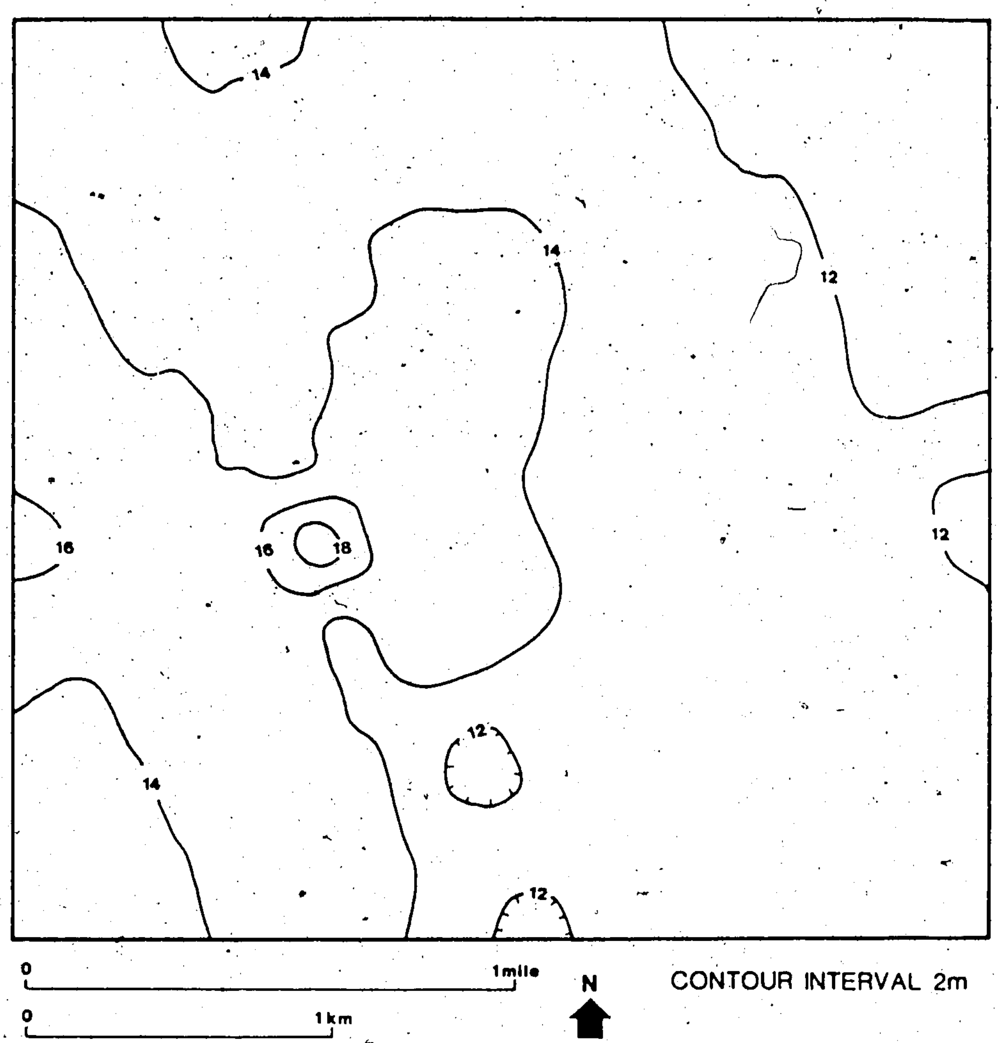
UPPER MEMBER

Description:

The upper member, the uppermost informal stratigraphic subdivision of the McMurray Formation erosively overlies both the middle member and the limy unit. The isopach map of the upper member (Fig. 60) indicates that the upper member has a relatively uniform thickness throughout the study area suggesting that there was little or no structural control on its accumulation. It has a maximum thickness of 18.4m in the west central part of the study area (drill core 40-39) and a minimum thickness of 10.7m in the northeast part of the study area (drill core 32-42). Examination of the isopach of cross-stratified sand in the upper member (Fig. 61) reveals a series of north-northwest trending linear accumulations of cross-stratified sand. Cross-stratified sand accumulations in the central part of the study area are approximately 0.5km wide and have a discontinuous sinuous or meandering pattern.

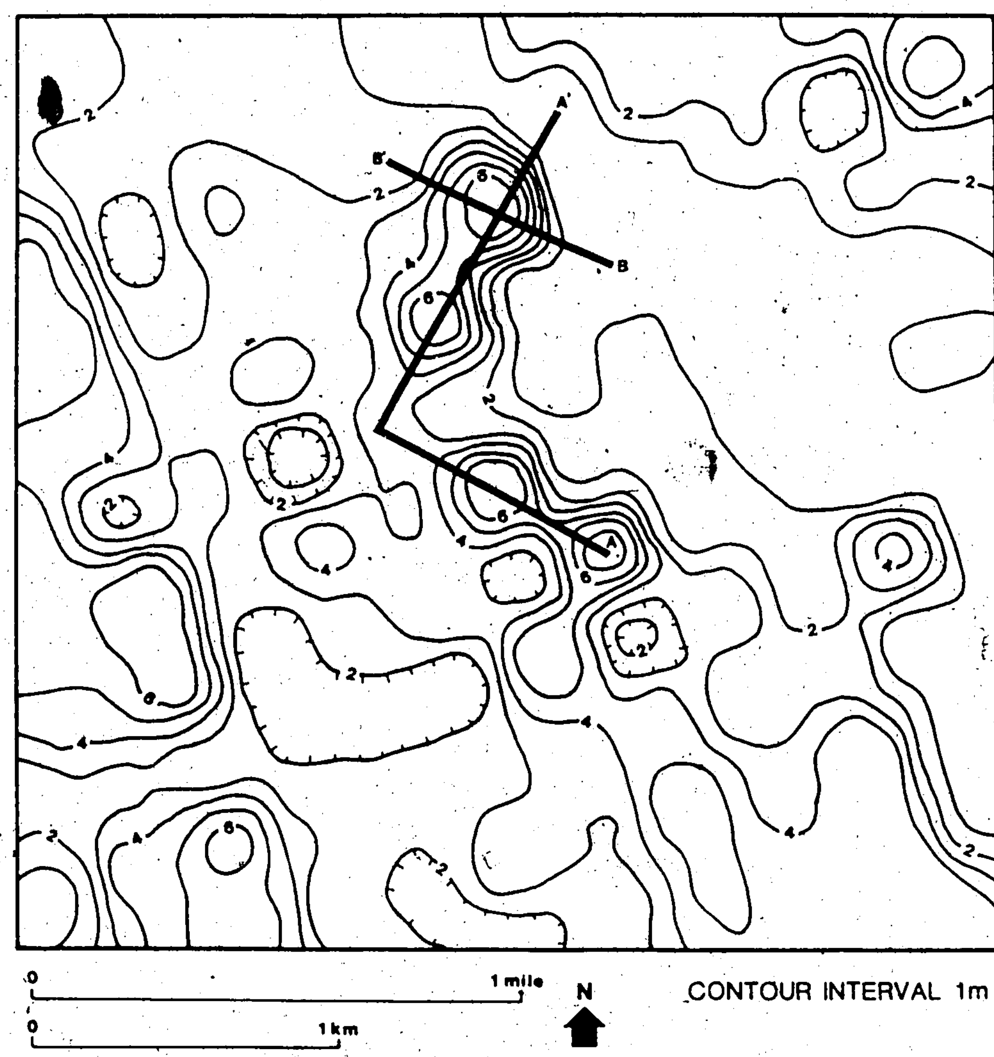
Lithofacies associations and interpretation:

Stratigraphic cross-sections through an upper member cross-statified sand accumulation (Fig 62, 63) reveal important vertical and lateral lithofacies relationships that help to determine which depostional environments were responsible for sequences that characterize the upper member. Two lithofacies associations are recognized in the upper member. Between 75 and 85% of the upper member is characterized by sequences of heavily bioturbated muddy sands that are overlain by small-scale cross-stratified sands.. The heavily bioturbated muddy sands, which can make up 30 to 100% of the total



UPPER MEMBER ISOPACH

Fig. 60. Isopach map of the upper member of the McMurray Formation in the present study area, Syncrude Oil Sands Lease 17, Athabasca Oil Sands.



UPPER MEMBER CROSS-STRATIFIED SAND ISOPACH

Fig. 61. Cross-stratified sand isopach of the upper member of the McMurray Formation in the present study area, Syncrude Oil Sands Lease 17, Athabasca Oil Sands showing locations of stratigraphic cross-sections (A-A', B-B') through cross-stratified sand accumulations.

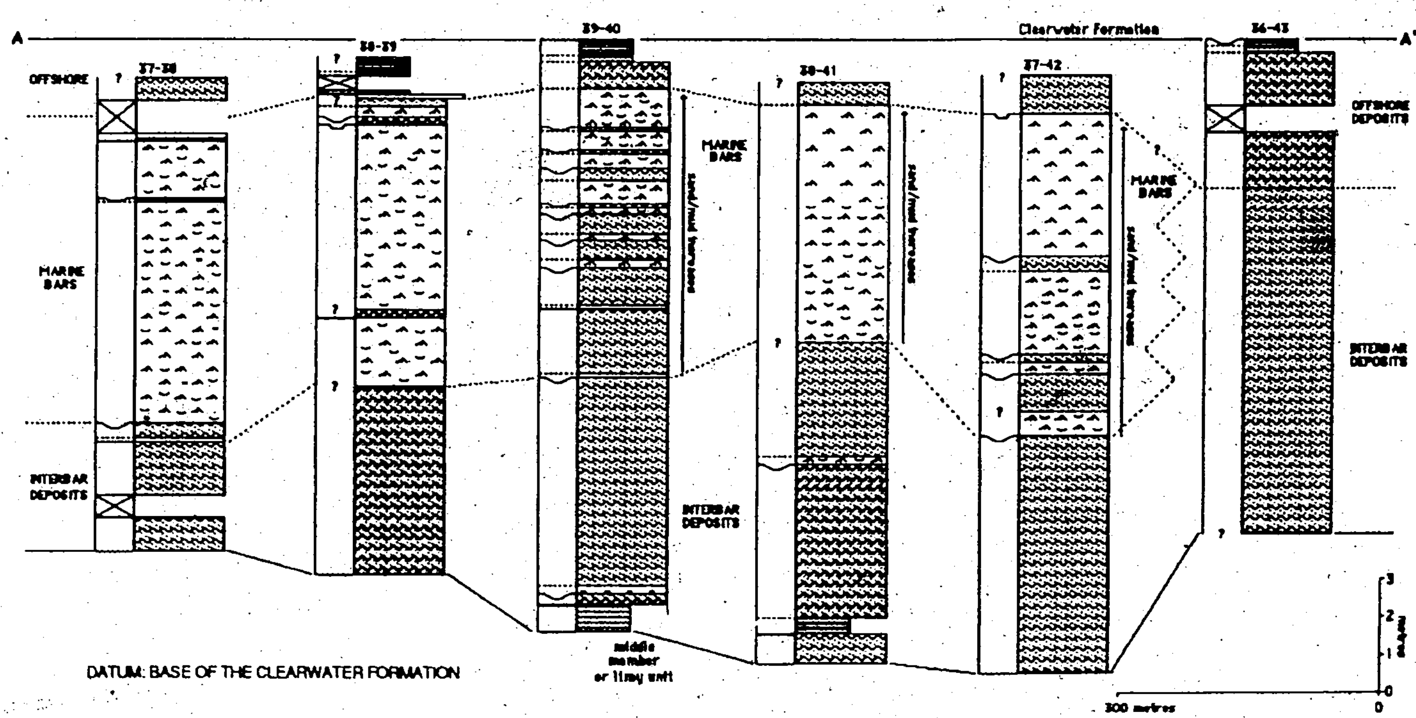


Fig. 62. Longitudinal stratigraphic cross-section (A-A') through an upper member cross-stratified sand accumulation.

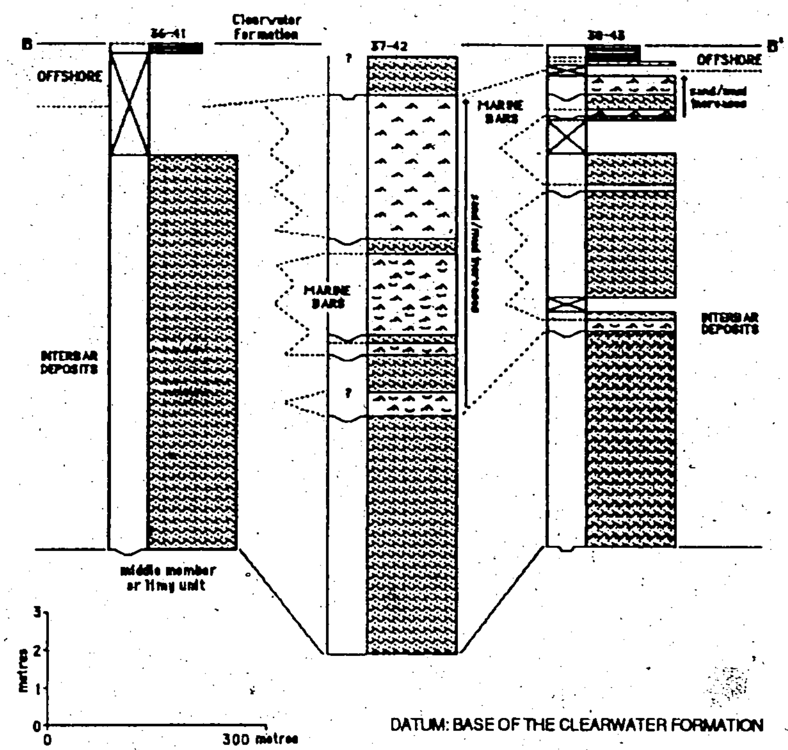


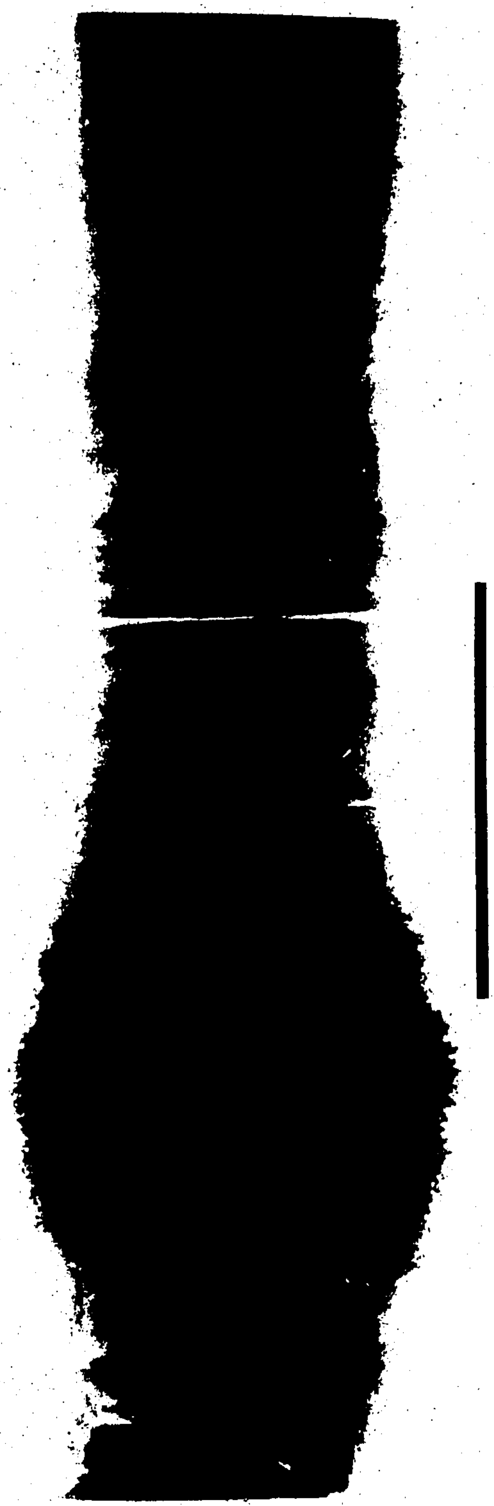
Fig. 63. Transverse stratigraphic cross-section (B-B') through an upper member cross-stratified sand accumulation.

sequences, often have interbedded mud drapes and/or composite sand and mud partings. Drapes and partings that exceed 5cm in thickness are classified as beds of dark grey mud and interbedded sand and mud. Thin sharp to scour based beds of small-scale cross-stratified sand or flat planar stratified sand are infrequently interbedded within the bioturbated muddy sands (Plate 9). Cross-stratified sands are often characterized by thin mud drapes interbedded between cross-strata set boundaries. Stratified sand interbeds range in thickness from 5 to 20cm, and typically have gradational upper contacts with overlying beds of bioturbated muddy sand. Less commonly, the upper contact is sharp, marked by a thin undulating mud drape. Stratified sand beds often become thicker and more numerous, grading into overlying thick accumulations of small-scale cross-stratified sand found at the top of the sequence. Usually the bioturbated muddy sands are abruptly overlain by a thick accumulation of small-scale cross-stratified sand. Because of the high bitumen saturation which masks physical sedimentary structures in these sands, beds of planar stratified sands may be intercalated between the cross-stratified sands. These small-scale cross-stratified sands are usually characterized by thick sets, ranging from 5 to 10cm in thickness. Cross-stratified sands often have thin interbedded dark grey mud drapes. Drapes typically become less abundant further up the sequence. Composite sand and mud partings intercalated between cross-stratified sands are rare. The thick accumulations of cross-stratified sand are usually characterized by low to moderate levels of bioturbation. Thin beds of bioturbated muddy sand are infrequently interbedded between beds of cross-stratified sand, and their abundance also decreases upward through the sequence. Thick accumulations of cross-stratified sand are often absent in many drill cores in the study area. As indicated by the isopach of cross-stratified sand in the upper member beds of this lithofacies are concentrated in a series of north-northwest trending linear

PLATE 9

Lithofacies sequence from the upper member of the McMurray Formation, Syncrude Oil Sands Lease 17 study area, Athabasca Oil Sands.

X ray radiograph of a sharp based bed of planar stratified sand intercalated between heavily bioturbated muddy sands of the upper member of the McMurray Formation; drill core 40-39, 37.0m (scale 5cm).



accumulations. Areas adjacent to these linear accumulations are dominated by heavily bioturbated muddy sand.

The sequence of heavily bioturbated muddy sands overlain by small-scale cross-stratified sands is characterized by an upward decrease in the amount of mud resulting in an increase in bitumen saturation. There is also an upward decrease in bioturbation as physical sedimentary structures become more predominant. This vertical sequence of lithofacies is indicative of an upward increase of energy levels. The basal heavily bioturbated muddy sands are indicative of slow sand deposition such that extensive reworking by burrowing organisms could take place. The muddiness of this lithofacies indicates that suspended sediment (mud sized grains) concentrations were relatively high resulting in enhanced deposition. Slow deposition resulting in bioturbated muddy sands was punctuated by possibly short lived high energy events that rapidly emplaced thin beds of planar stratified and cross-stratified sand. The tops of these beds were probably reworked by burrowing organisms when lower energy levels were restored. During these high energy events, suspended sediment concentrations were most likely elevated probably due to erosion and resuspension of existing mud deposits which would enhance flocculation and deposition of mud. An upward decrease in bioturbation and the predominance of cross-stratification indicates that the ability of burrowing organisms to rework these deposits was reduced due to continuous reworking of the substrate by stronger currents. Mud drapes interbedded between cosets of small-scale cross-stratification indicate that either ripple migration was momentarily stopped because of reduced currents allowing mud to settle from suspension, or these were periods of enhanced flocculation and deposition of mud as a consequence of elevated suspended sediment concentration. The gradual upward decrease in the number of intebedded mud drapes in the cross-stratification suggests that any mud that settled when current strength was reduced would have been almost immediately resuspended by subsequent strong current activity.

Overlying the basal association of the upper member of the McMurray Formation is an association characterized by sequences of lithofacies which grade upward into glauconitic sediments of the Clearwater Formation. The relationship between the lower and upper associations is often vague due to high levels of bioturbation in lithofacies on either side of the contact. Scoured to gradational contacts are recognized but usually there is distinctive change from small-scale cross-stratified sand to heavily bioturbated muddy sand. The upper association is typically characterized by a vertical sequence of bioturbated muddy sand overlain by highly bioturbated interbedded sand and mud. Beds of dark grey mud rarely overlie the interbedded sand and mud. In 28% of the drill cores examined during this study, a bed or sequences of beds of medium to coarse grained sand sharply or erosively overlie the basal lithofacies association of the upper member. These sand beds are small-scale cross-stratified, structureless or heavily bioturbated muddy sand. Individual beds range in thickness from 1 to 30cm, averaging 10cm. Sequences of medium to coarse grained sand beds can be up to 70cm thick. Cross-stratified beds often have interbedded dark grey mud drapes. Medium to coarse grained sand beds are gradationally overlain by beds of fine grained bioturbated muddy sands and/or highly bioturbated interbedded sand and mud. The coarse to medium grained sand beds appear to be unrelated to cross-strafied sand of the basal association that they commonly overlie. This is indicated by the differences in the distribution of these beds in the study area (Fig. 64) as compared to the pattern of cross-stratified sand accumulations.

The lithofacies sequences that chatacterize the upper association of the upper member typically exhibit an upward decrease in sand grain size whereas mud and the intensity of

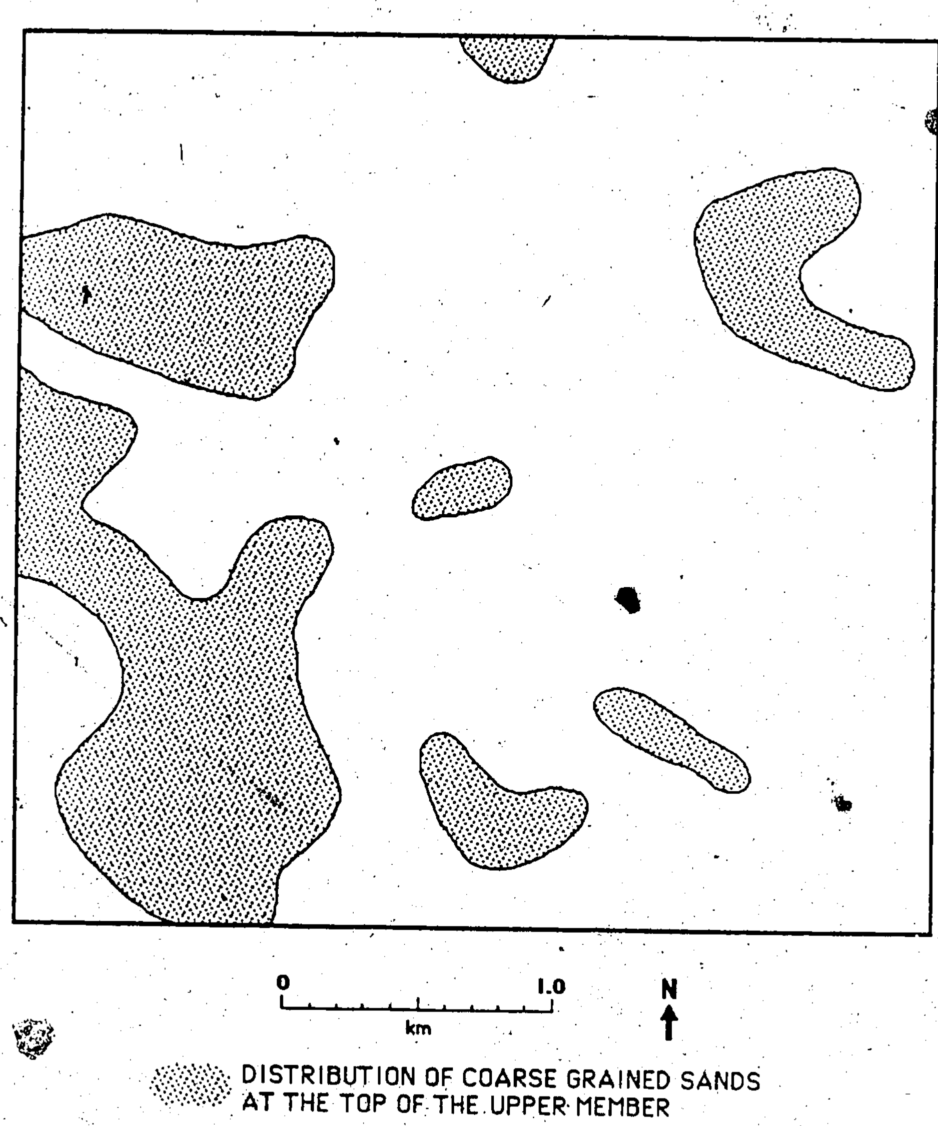


Fig. 64. Spatial distribution of medium to coarse grained sand beds found at the base of the upper lithofacies association of the upper member of the McMurray Formation.

bioturbation increase. In general, these sequences reflect an upward weakening of currents. The intensity of bioturbation is indicative of slow rates of deposition which allowed burrowing organisms to thoroughly rework the substrate. The abundance of mud reflects weak currents and/or high concentrations of suspended sediment. The structureless and cross-stratified sand beds found at the base of some sequences were emplaced by stronger currents that were capable of transporting sand in suspension or else in migrating ripples. Mud drapes in the cross-stratified sands indicate that sand transport ceased temporarily and mud settled from suspension because of weaker currents or increased suspended sediment concentrations. The apparent sharp, often scoured contact between the upper and lower lithofacies associations of the upper member suggests a laterally extensive erosional event, that possibly truncated upper sequences of the basal association. This erosional event of which the medium to coarse grained sand beds may represent a lag deposit, was followed by a gradual reduction of current strengths resulting in the deposition of progressively muddier lithofacies.

The vertical sequence of lithofacies observed in the basal association of the upper member closely resemble sequences produced in part by a beach face prograding over an upper offshore environment. A beach face is a shallow nearshore environment dominated by waves and the currents associated with them (Elliott 1986). Subenvironments of a beach face include the backshore, foreshore and shoreface (Fig. 65). The most seaward subenvironment, the shoreface, is defined as the nearshore zone between the low tide mark and the depth at which currents generated by fairweather waves first influence the bottom (Reinson 1984). The shoreface is subdivided, on the basis of energy levels, into the upper and lower shoreface (Elliott 1986). The upper shoreface is within the highly energetic surf zone where rip and longshore currents interact (Reinson 1984). Because of these

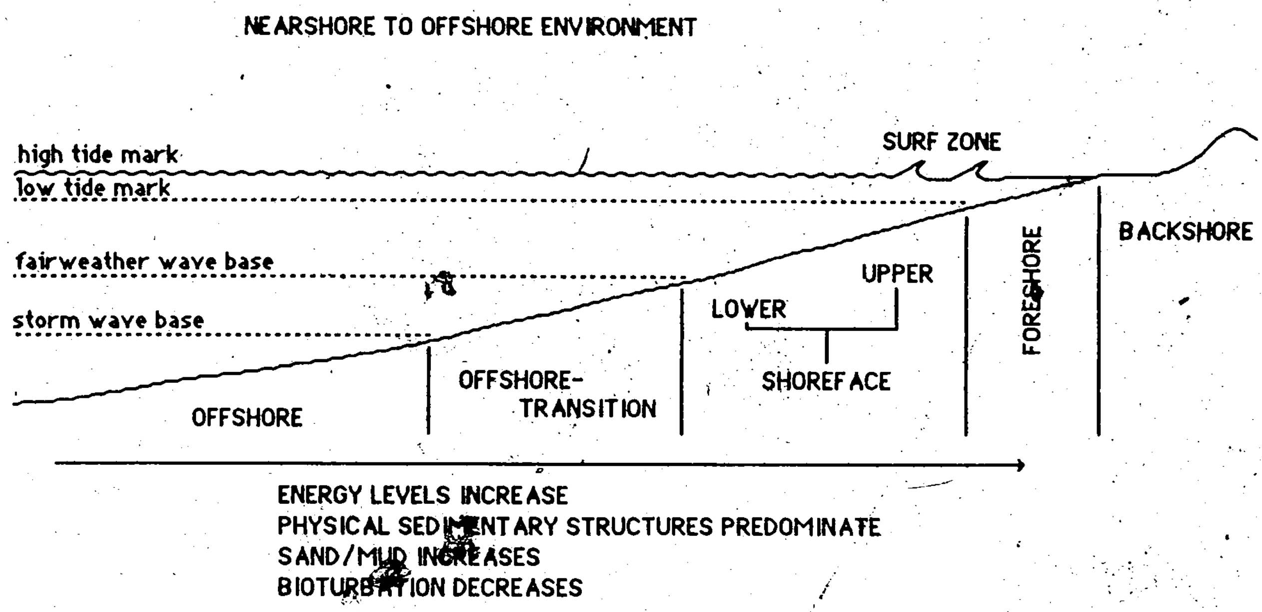


Fig. 65. Longitudinal schematic section through a nearshore to offshore environment (modified from Reineck and Singh 1975; Elliott 1986).

highly energetic conditions sedimentary deposits are dominated by large-scale cross-stratified and planar stratified sand. Bioturbation is usually low due to extensive physical reworking of the substrate by current activity. The lower shoreface is seaward of the surf zone and is characterized by much lower energy levels (Elliott 1986). Sedimentation is slow and biogenic reworking of the substrate can be high. On the Georgia coast lower shoreface deposits are characterized by small-scale cross-stratified sand with low levels of bioturbation due to continuous physical reworking of the substrate (Howard and Reineck 1972). Seaward of the lower shoreface is the offshore environment which is only influenced by storm wave activity (Elliott 1986). During fairweather conditions only mud is deposited, settling from suspension. These deposits are extensively reworked by burrowing organisms. During storms, wave generated currents influence the bottom, transporting and depositing sand. Storm deposits typically have sharp bases and are characterized by physical sedimentary structures, such as planar stratification, that reflect strong currents. These storm deposits can be partially or totally reworked by burrowing organisms during subsequent fairweather conditions. Upper offshore deposits along the Georgia coast are characterized by bioturbated muddy sands with interbeds of parallel laminated sand (Howard and Reineck 1972). Further offshore, deposits consist exclusively of bioturbated muddy sand. The vertical sequence of upper offshore deposits overlain by lower shoreface deposits from the Georgia coast would be very similar to some of the vertical sequences of lithofacies observed in the basal association of the upper member.

On the other hand, lateral lithofacies relationships in the basal association of the upper member indicate a series of linear accumulations of cross-stratified sand overlying and separated by zones of bioturbated muddy sand. This pattern suggests a series of elongate sand bars, where currents were strong enough to continuously transport sand in ripples, and interbar troughs, where currents were weak for much of the time and sedimentation was low allowing for the extensive biogenic reworking of the substrate. Short lived periods of stronger current activity, which even affected the interbar troughs, resulted in the deposition of high energy sequences such as planar stratification. These short lived periods of stronger than normal current activity could be attributed to storms or to spring tides. The linear bars and interbar troughs evident in the basal association of the upper member are interpreted to have developed in a nearshore to offshore shelf environment influenced by longshore currents. Tidal, storm and oceanic currents are capable of transporting sand in a variety of bedforms in nearshore and offshore environments (Walker 1984b).

Lithofacies sequences similar to those observed in the basal association of the upper member of the McMurray Formation, are evident in sand shoals erosionally overlying Holocene deltaic and backbarrier deposits on the Louisiana offshore shelf (Fig. 66). These landward migrating, inner shelf shore parallel sand bodies are believed to have been derived from shoreface erosion of a transgressed barrier shoreline (Penland *et al.* 1986). These sand shoals are of a much larger scale than those that are proposed for the upper member, having lengths of up to 50km and widths of 8 to 12km. Relief of the shoals above the surrounding shelf ranges from 3 to 7m. Shoals are characterized by three major subenvironments: shoal crest; shoal front; and shoal base. The shoal crest is characterized by the highest energy levels on the shoal, being subjected to both fairweather and storm wave processes. Sedimentary structures found in the shoal crest include graded beds, planar stratification, medium-scale trough cross-stratification and wave ripple cross-stratification. Bioturbation is low in shoal crest deposits. The shoal crest sharply overlies deposits formed on the shoal front where energy levels are significantly reduced,

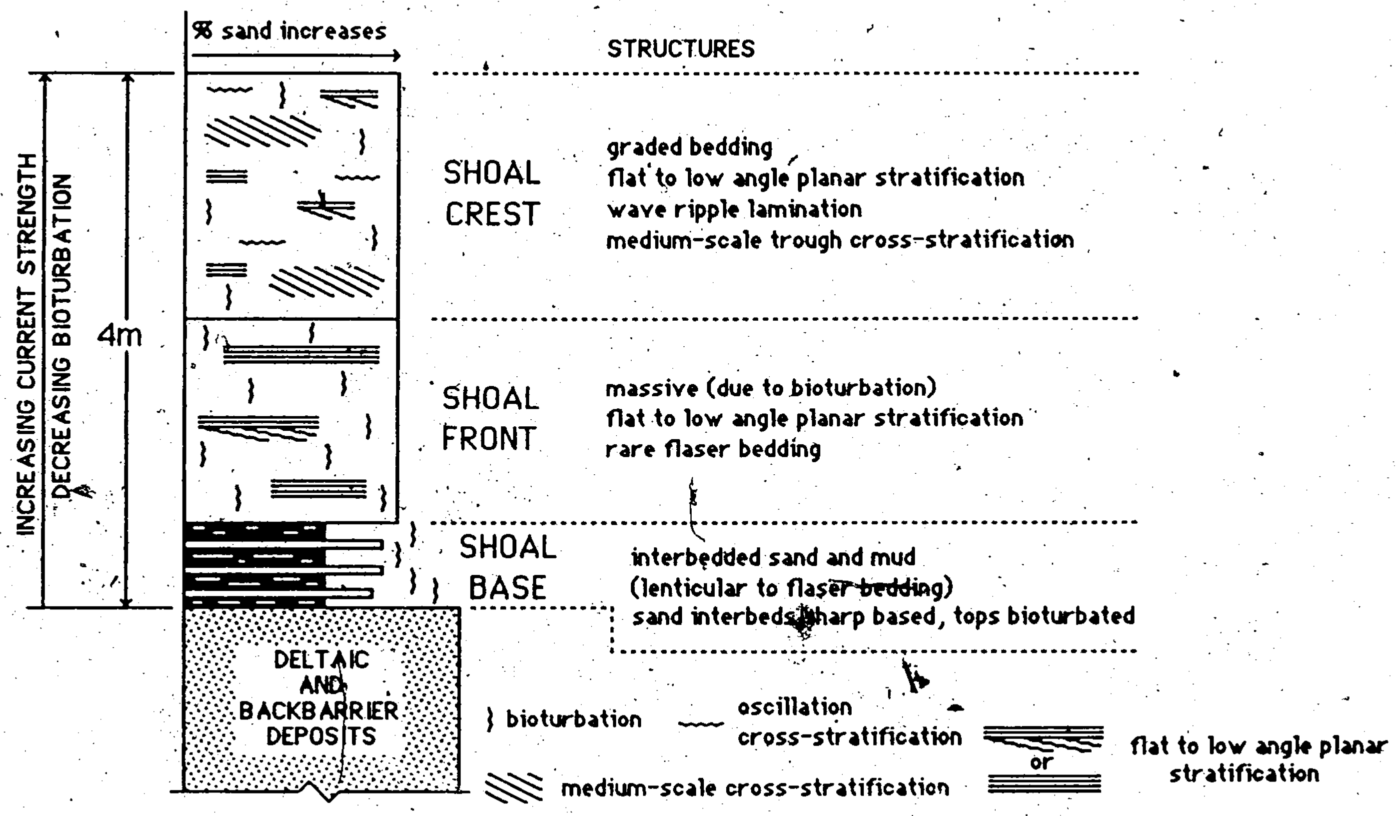


Fig. 66. Vertical sequence of a shore parallel sand shoal on the Louisiana offshore unconformably overlying deltaic and backbarrier deposits, showing subenvironments and their respective sedimentary features (modified from Penland *et al.* 1986).

The shoal front is at or below fairweather wave base and as a consequence there is more extensive biogenic reworking of the substrate. Deposits formed on the shoal front are dominated by massive, probably highly bioturbated sand, as well as some horizontal to subhorizontal stratified sands. Shoal front sands gradationally overlie shoal base deposits. The shoal base is well below fairweather wave base and deposits are subject to extensive biogenic reworking. Deposits include mud and lenticular to wavy interbedded sand and mud, as well as some planar stratified sands. Sand beds are typically sharp based and have bioturbated tops. Sedimentary sequences produced by these shelf sand bodies are characterized by an upward decrease in bioturbation, increasing grain size and an upward predominance of physical sedimentary structures, reflecting an upward increase in current energy.

Meckel (1975) describes marine sand bars with intervening troughs that extend 40km from the mouth of the Colorado River estuary, of northwestern Mexico, into the offshore of the Gulf of California. Strong tidal currents are believed to be responsible for the formation of these bars (though offshore currents may also be responsible for their formation). Bars have a maximum relief of 9m and have spacings of several kilometers, far greater than those proposed for the upper member of the McMurray Formation. Bars migrate laterally in the estuary mouth and the offshore in response to estuary mouth migration, as well as shoreline progradation (Meckel 1975). Shallow, more nearshore bars are sandy on both crests and troughs of the bars, whereas bars further offshore are characterized by sandy crests and mixed sand and mud troughs. Bar deposits have thicknesses of 3 to 6m and are gradationally underlain by offshore muds. The vertical sequences of the bars (Fig. 67) are characterized by an upward coarsening of grain size and an upward decrease in bioturbation and mud. Flat to low angle stratification is abundant and

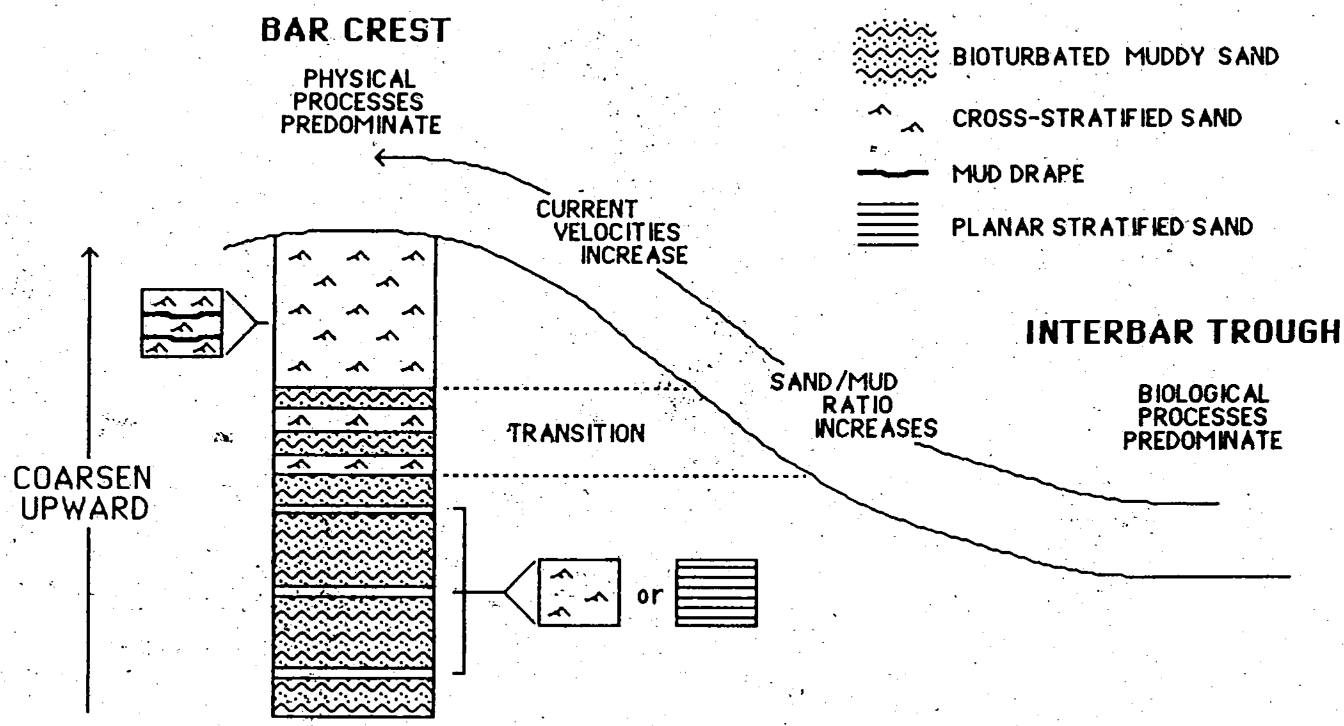


Fig: 67. Transverse section trough a laterally migrating offshore tidal bar and adjacent interbar trough from the Colorado River estuary, showing possible vertical sequence of lithofacies (modified from Meckel 1975).

cross-stratification changes from small- to medium scale upward in the sequence. Thin and irregular mud drapes are common throughout bar deposits. The vertical sequence of the bar deposits are interpreted by Meckel (1975) to be the result of the lateral migration of offshore bars. As the bar migrates, bar crest deposits, which reflect stronger currents, are superimposed on lower energy bar trough deposits.

The bar deposits observed in the upper member of the McMurray Formation appear to lack the high energy bar crest deposits seen in both the sand shoals of the Louisiana offshore (Penland *et al.* 1986) or the deep water tidal bars of the Colorado River estuary (Meckel 1975). It is quite probable that these bar crest deposits were truncated by the erosional event responsible for the sharp and often scoured lower contact of the upper lithofacies association of the upper member.

The abundance of muddy sands, mud drapes and composite sand and mud partings in upper member lithofacies suggests high suspended sediment concentrations in the environment of deposition. Suspended sediment concentrations tend to increase toward nearshore areas from the offshore (Postma 1961). The muddiness of the upper member sediments suggests an environment close to shore. Mud deposition occurs in nearshore environments despite strong current activity because of high suspended sediment concentrations (McCave 1971; Wells and Coleman 1981). High concentrations of suspended sediment can actually dampen wave activity. On the Georgia coast, mud layers are common in shoreface deposits closely situated near estuaries (Howard and Reineck 1972). Nearshore areas adjacent to estuaries are often characterized by high concentrations of suspended sediment, which enhances the deposition of mud despite relatively strong current energies (Howard and Reineck 1972; Oertel and Dunstan 1981). The amount of suspended sediment transported out of the estuary into the adjacent shelf environment is often dependent on river flow and/or the neap /spring tidal cycle. During spring tides when flushing of the estuary by tidal currents is high, large volumes of suspended sediment are transported from the Gironde Estuary seaward into the shelf environment (Castaing and Allen 1981). A similar phenomenon occurs when fluvial run off is high during seasonal floods. Suspended sediment transported out of the Gironde Estuary by either spring tides or by increased river flow is then transported northward by longshore currents in the shelf environment. Suspended sediment concentrations in nearshore and offshore waters can also be enhanced by storms, which erode and resuspend existing mud deposits (McCave 1970). Storms may be marked in the sedimentary record by an accumulation of mud deposited as currents waned (McCave 1970; Hawley 1981a). This feature may explain the occurrence of mud drapes overlying possible storm deposits in the basal association of the upper member of the McMurray Formation. The muddiness of the upper member lithofacies suggests deposition close to shore and/or an estuary (Fig. 68).

The upper lithofacies association of the upper member, characterized by a vertical sequence of lithofacies that reflects a gradual upward reduction of current strength, is interpreted to represent deposits formed in a deepening shoreface to offshore environment. Muddy lithofacies predominate and bioturbation is typically extensive indicating slow rates of sedimentation. These sequences are sharply to gradationally overlain by glauconitic lithofacies of the Clearwater Formation. Glauconite develops mainly in marine environments as a result of the alteration of mica and some clay minerals, as well as organic material such as fecal pellets, close to the sediment water interface (Blatt *et al.* 1980; Leeder 1982). Glauconite formation requires some turbulence, low rates of sedimentation and some organic material (Reineck and Singh 1975; Leeder 1982). The vertical sequence of lithofacies sequences reflect a continuing reduction in current

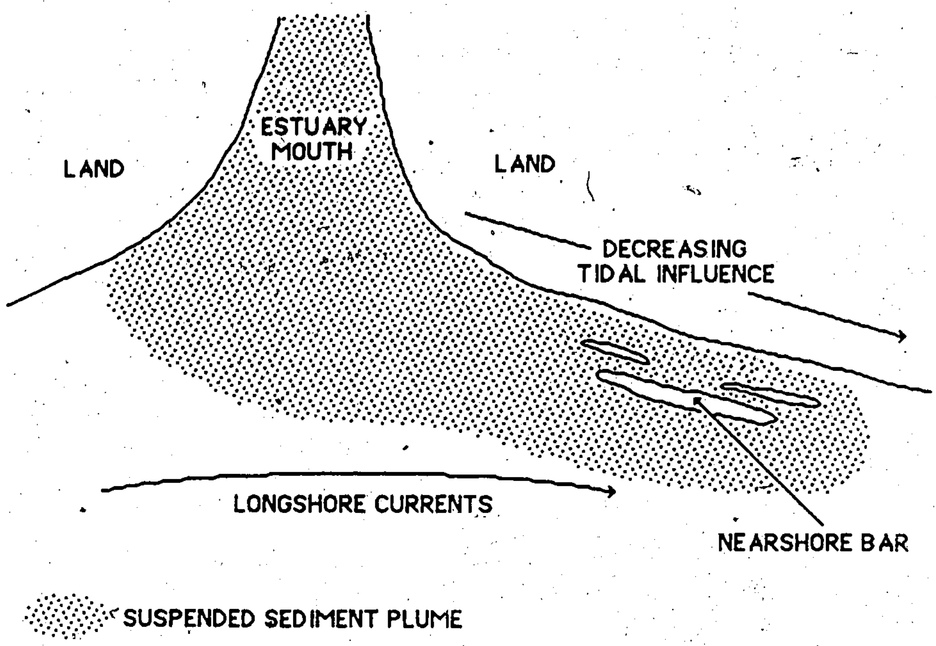
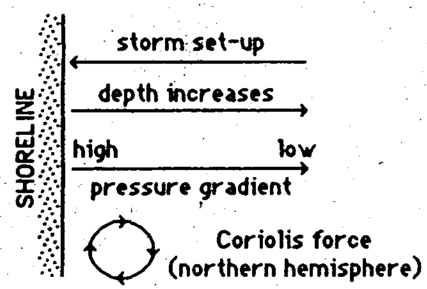


Fig. 68. Possible relationship of upper member sand bars to a retreating estuary from which suspended sediment is being transported into nearshore and offshore areas, and dispersed by longshore currents.

strengths as interbedded glauconitic sand and mud grades upward into grey mud with rare sand lenses and sand-filled burrows. Infrequently sands interbedded with muds appear to be small-scale cross-stratified, indicating sand transport in ripples. Rare 1 to 20cm thick beds of small-scale cross-stratified and planar stratified sands are intercalated between beds of mud or interbedded sand and mud. These stratified sand beds are typically sharp to scour based, and usually have burrowed upper contacts. These beds, as well as many of the thin bioturbated sands interbedded with muds, were deposited during periods of strong current activity which punctuated the normally low energy environment. It is possible that these sand beds are deposits formed during storms when wave activity was attenuated and geostrophic currents (Fig.69), generated by a seaward directed pressure gradient caused by storm setup on the shoreline (Walker 1984b), acted on nearshore and offshore environments. It is also possible that these sand beds may be the result of stronger current activity during spring tides whereas muds represent mean and neap tide deposits (Bouma *et al.* 1982).

Environmental summary:

Sedimentary sequences of both the middle member and the limy unit were erosionally overlain by the upper member of the McMurray Formation, which was deposited in a nearshore to offshore environment. The bulk of the upper member was deposited in a series of linear bars and interbar troughs (Fig. 70). As bars migrated, low energy deposits formed in the interbar troughs would be overlain by higher energy deposits of the bars. High concentrations of suspended sediment, probably derived from a nearby estuary, resulted in the deposition of abundant mud despite relatively strong current activity. The upper parts of the bar and interbar trough sequences were truncated by an erosional event.



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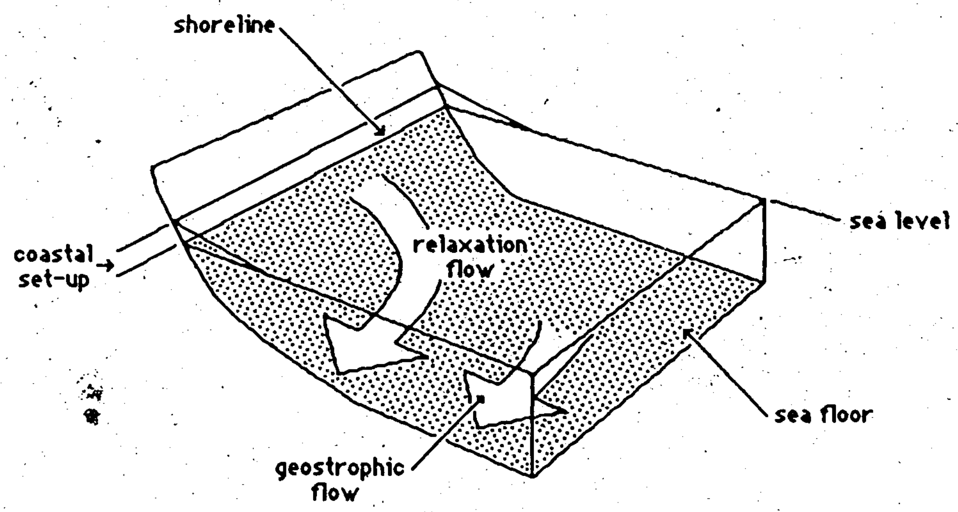


b

Fig. 69. Geostrophic flow generation due to storm set-up. (a) Plan view schematic of storm set-up on coast creating a seaward directed pressure gradient that pushes water offshore (modified from Walker 1984b). (b) Seaward directed bottom currents, produced by pressure gradient, are deflected along the coast by the Coriolis force (modified from Walker 1984b).

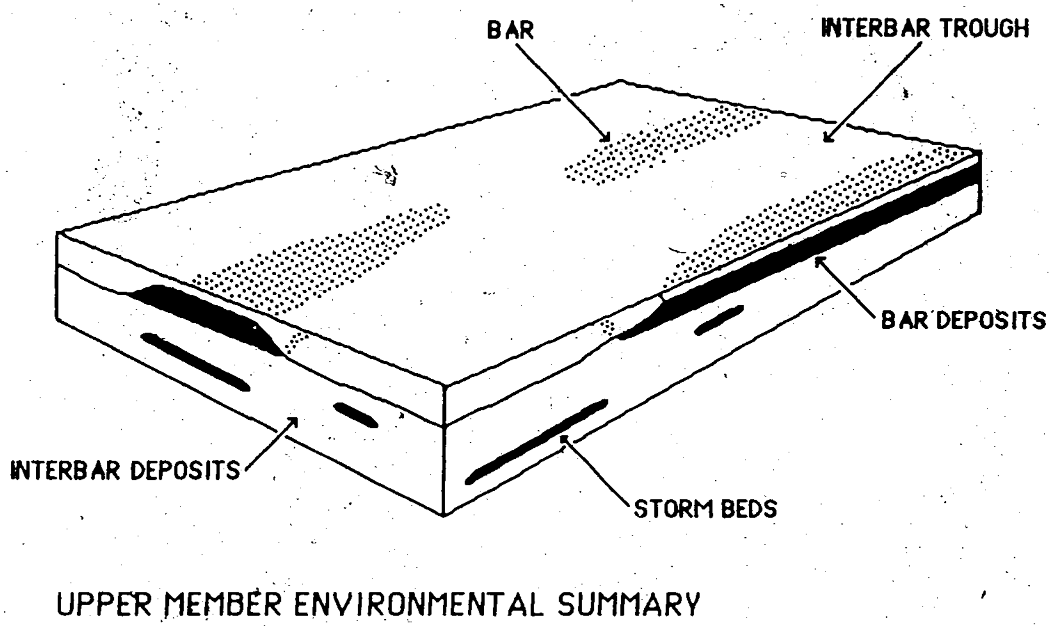


Fig. 70. Environmental summary of the basal lithofacies association of the upper member of the McMurray Formation, showing nearshore to offshore linear sand bars and interbar troughs.

Overlying this erosional contact is a possible erosional lag and sequences of lithofacies that reflect a gradual decrease in current strength caused by a deepening to more offshore environments. Glauconitic lithofacies of the Clearwater Formation are indicative of slow rates of sedimentation. Lithofacies sequences in the Clearwater Formation also reflect a gradual deepening of the offshore environment. Quiet water deposits, which dominate the Clearwater Formation, have infrequent interbedded high energy deposits, possibly attributed to storms or spring tides.

CHAPTER 7

SUMMARY AND CONCLUSIONS

At the beginning of the Lower Cretaceous, the present study area was situated on the western edge of a major northwest trending valley that had developed on the pre-Cretaceous unconformity surface in the Fort McMurray area. This valley widens toward the north and possibly had its head waters to the southeast. An east-west trending valley on the unconformity surface, possibly a tributary of the main valley, is apparent in the present study area. Within this valley the bulk of the lower member of the McMurray Formation accumulated in a high sinuosity fluvial environment, with deposition occurring in channels and adjacent overbank areas (Fig. 71). Channel deposits are characterized by fining upward sequences that developed on the accretionary banks of migrating streams. Overbank deposits accumulated on levees, crevasse splays and floodbasins when the channels overtopped or breached their banks. These deposits typically become more argillaceous further from the channel reflecting a decrease in energy levels in more distal portions of the flood plain.

During the Lower Cretaceous, the boreal sea trangressed southward in response to global sea level rise and subsidence associated with salt solution and collapse of Devonian strata along the western edge of the Canadian Shield, as well as the development of a foreland basin in western Canada during the Columbian Orogeny. With this transgression the major valley and its tributaries were flooded and transformed into estuaries. It is in this depositional setting that the middle member developed. Evidence for an estuarine depositional setting includes an embayed coastline, small-scale lithofacies sequences indicating that tides were the dominant mechanism of sediment transport, and the

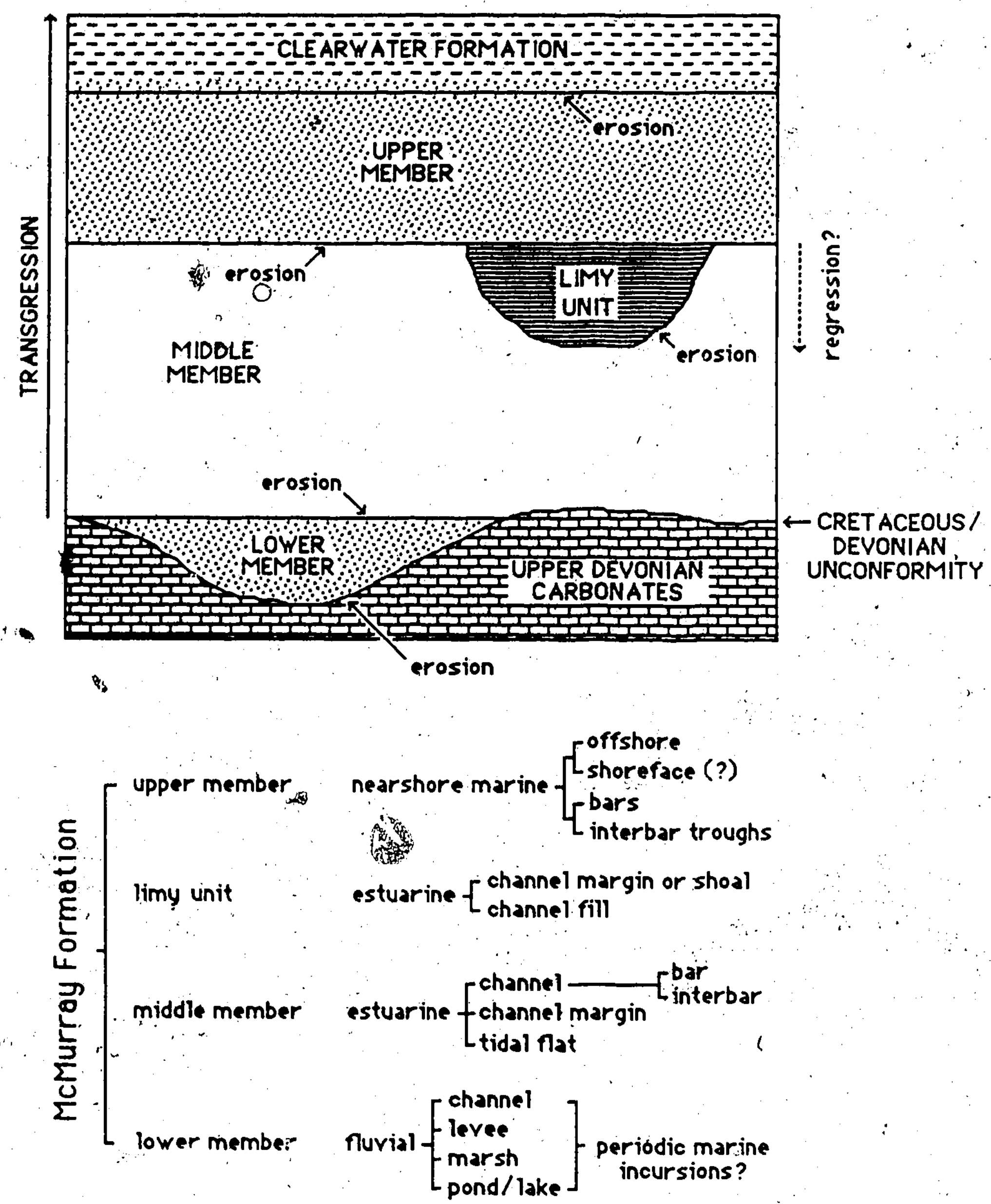


Fig. 71. Stratigraphic and environmental summary of the McMurray Formation, Syncrude Oil Sands Lease 17 study, Athabasca Oil Sands.

abundance of mud in middle member sequences suggesting enhanced deposition of mud as a consequence of fresh and saline water mixing. Middle member sequences accumulated mainly in tidal channels with deposition on bars or accretionary banks. Overlying channel sequences are heavily bioturbated intertidal flat deposits. These deposits have limited distribution in the middle member reflecting their vulnerability to subsequent erosive events because of their position at the top of estuarine sequences. Tidal channel deposits are lower in the stratigraphic sequence and are therefore less susceptible to erosion.

Filling an incision on the top of the middle member are sequences that characterize the limy unit. The cause of this incision is unknowh and could possibly be the result of a down cutting event associated with a drop in sea level. The limy unit is distinct from the underlying middle member due to its characteristic fossiliferous sand and slightly calcareous muds. Lithofacies sequences and associations are however, indicative of an estuarine setting with the bulk of deposition in the limy unit occurring in bars and on the accretionary banks of tidal channels. Capping these channel deposits are sequences that accumulated on wave influenced tidal channel margins or shoals. Increased wave activity during storms resulted in the deposition of thin, normally graded sand beds in deeper parts of the channel.

With continued sea level rise the middle member and the limy unit were sharply truncated and overlain by sequences of the upper member that were deposited in a nearshore to offshore environment. Lateral and vertical lithofacies sequences are indicative of deposition in a series of linear nearshore bars and interbar troughs. Abundant muddy intercalations in the bar and trough deposits indicates high suspended sediment concentrations possibly reflecting the influence of a nearby estuary. The upper part of the bar and trough sequence is truncated by an erosion surface. On top of this surface is a possible transgressive lag, which in turn is overlain by fining upward lithofacies sequences that reflect a gradual deepening to a more offshore environment. These sequences mark the onset of the deposition of marine muds and glauconitic sands of the Clearwater Formation which represent the peak of the Lower Cretaceous transgression.

REFERENCES

Aigner, T. and Reineck, H.E. 1982. Proximality trends in modern storm sands from the Helgoland Bight (North Sea) and their implications for basin analysis. Senckenbergiana maritima, 14, pp. 183-215.

Allen, G. P., Deresseguiers, A. and Klingebiel, A. 1969. Evolution des structures sédimentaires sur un banc sableux d'estuaire en fonction de l'amplitude des marées. Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences, Série D, pp. 2167-2169.

--------, Salomon, J.C., Bassoullet, P., Du Penhoat, Y. and De Grandpré, C. 1980. Effects of tides on mixing and suspended sediment transport in macrotidal estuaries. Sedimentary Geology, 26, pp. 69-90.

--------, Sauzay, G., Castaing, P. and Jouanneau, J.M. 1977. Transport and deposition of suspended sediment in the Gironde Estuary, France. In Estuarine Processes. Volume II. Circulation, sediments, and transfer of material in the estuary. Edited by M. Wiley, Academic Press, New York, pp. 63-81.

Allen, J.R.L. 1968. The diffusion of grains in the lee of ripples, dunes, and sand deltas. Journal of Sedimentary Petrology, 38, pp. 621-633.

-------- 1974. Reaction, relaxation and lag in natural sedimentary systems: general principles, examples and lessons. Earth-Science Reviews, 10, pp. 263-343.

-------- 1982. Mud drapes in sand-wave deposits: a physical model with applications to the Folkstone Beds (early Cretaceous, southeast England). Philosophical Transactions of the Royal Society of London, A 306, pp. 291-345.

-------- 1984. Sedimentary structures, their character and physical basis (unabridged one-volume edition). Elsevier Science Publishers, Amsterdam, 1256p.

-------- 1985. Principles of physical sedimentology. Allen and Unwin Ltd., London, 272p.

-------- 1987. Reworking of muddy intertidal sediments in the Severn Estuary, southwestern U.K. - a preliminary survey. Sedimentary Geology, 50, pp. 1-23.

-------- and Friend, P.F. 1976. Changes in intertidal dunes during two spring-neap cycles, Lifeboat Station Bank, Wells-next-the-Sea, Norfolk (England). Sedimentology, 23, pp. 329-346.

Anderton, R. 1985. Clastic facies models and facies analysis. In Sedimentology: recent developments and applied aspects. Edited by P.J. Brenchley and B.P.J. Williams. Geological Society Special Publication, Number 18, pp. 31-47.

Arulanandan, K. 1975. Fundamental aspects of erosion of cohesive soils. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, 101, pp. 635-639.

Asquith, G.B. and Gibson, C.R. 1982. Basic well log analysis for geologists. American Association of Petroleum Geologists, Tulsa, 216p.

Avoine, J., Allen, G.P., Nichols, M., Salomon, J.C. and Larsonneur, C. 1981. Suspended-sediment transport in the Seine Estuary, France: effect of man-made modifications on estuary-shelf sedimentology. Marine Geology, 40, pp. 119-137.

Babcock, E.A. and Sheldon, L.G. 1976. Structural significance of lineaments on aerial photos of the Athabasca Oil Sands area near Fort MacKay, Alberta. Bulletin of Canadian Petroleum Geology, 24, pp. 457-470.

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, 12p.

Ball, M.W. 1935. Athabaska Oil Sands: apparent example of local origin of oil. American Association of Petroleum Geologists, Bulletin, 19, pp. 153-171.

Banks, N.L. 1973. The origin and significance of some down current-dipping cross-stratified sets. Journal of Sedimentary Petrology, 43, pp. 423-7.

Barwis, J.H. 1978. Sedimentology of some South Carolina tidal-creek point bars, and a comparison with their fluvial counterparts. In Fluvial Sedimentology. Edited by A.D. Miall. Canadian Society of Petroleum Geologists, Memoir 5, pp. 129-160.

Bates, R.L. and Jackson, J.A. 1980. (Editors) Glossary of geology (second edition). American Geological Institute, Falls Church, Virginia, 751p.

Bathhurst, R.G.C. 1975. Carbonate sediments and their diagenesis (second enlarged edition). Developments in Sedimentology, 12, Elsevier Scientific Publishing Company, New York, 658p.

Beer, T. 1983. Environmental oceanography. Pergamon Press Ltd., Oxford, United Kingdom, 262p.

Bell, R. 1885. Report on the part of the basin of the Athabasca River, North-west Territory. Geological Survey of Canada, Report of Progress, 1882-83-84, Part CC, V, 37p.

Benthin, H.L. and Orgnero, U.J. 1977. Geology and heavy-oil reserves of the Gregoire Lake area. Bulletin of Canadian Petroleum Geology, 25, pp. 367-377.

Beaumont. C. 1981. Foreland basins. Geophysical Journal of the Royal Astronomical Society, 65, pp. 291-329.

-------, Keen, C.E. and Boutilier, R. 1982. A comparison of foreland and rift margin sedimentary basins. Philosophical Transactions of the Royal Society of London, Series A, 305, pp. 295-317.

Blatt, H., Middleton, G.V. and Murray, R.C. 1980. Origin of sedimentary rocks (second edition). Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 782p.

Boersma, J.R. 1969. Internal structure of some tidal mega-ripples on a shoal in the Westerschelde Estuary, the Netherlands. Report of a preliminary investigation. Geologie en Mijnbouw, 48, pp. 409-414.

-------- and Terwindt, J.H.J. 1981. Neap-spring tide sequences of intertidal shoal deposits in a mesotidal estuary. Sedimentology, 28, pp. 151-170.

Bouma, A.H., Berryhill, H.L., Brenner, R.L. and Knebel, H.J. 1982. Continental shelf and epicontinental seaways. In Sandstone depositional environments. Edited by P.A. Scholle and D. Spearing. American Association of Petroleum Geologists, Memoir 31, pp. 281-327.

Bridges, P.H. and Leeder, M.R. 1976. Sedimentary model for intertidal mudflat channels, with examples from the Solway Firth, Scotland. Sedimentology, 23, pp. 533-552.

Bristow, C.S. 1987. Brahmaputra River: channel migration and deposition. In Recent developments in fluvial sedimentology. Edited by F.G. Ethridge, R.M. Flores and M.D. Harvey. Society of Economic Paleontologists and Mineralogists, Special Publication No. 39, pp. 63-74.

Burden, E.T. 1984. Terrestrial palynomorph biostratigraphy of the Mannville Group (Lower Cretaceous), Alberta and Montana. In The Mesozoic of Middle North America. Edited by D.F. Stott and D.J. Glass. Canadian Society of Petroleum Geologists, Memoir 9, pp. 249-269.

Caldwell, W.G.E. 1984. Early Cretaceous transgressions and regressions in the southern interior plains. In The Mesozoic of Middle North America. Edited by D.F. Stott and D.J. Glass. Canadian Society of Petroleum Geologists, Memoir 9, pp. 173-203.

Calverley, A. 1984. Sedimentology and geomorphology of the modern epsilon cross-stratified point bar deposits in the Athabasca upper delta plain. M.Sc. Thesis, University of Calgary, 116p.

Cant, D.J. 1984. Subsurface facies models. In Facies models (second edition). Edited by R.G. Walker. Geoscience Canada, Reprint Series 1, pp. 297-310.

Carrigy, M.A. 1959. Geology of the McMurray Formation (Part III: general geology of the McMurray area). Research Council of Alberta, Memoir 1, 130p.

--------- 1962. Effect of texture on the distribution of oil in the Athabasca Oil Sands, Alberta, Canada. Journal of Sedimentary Petrology, 32, pp. 312-325.

--------- 1963a. Criteria for differentiating the McMurray and Clearwater formations in the Athabasca Oil Sands. Research Council of Alberta, Bulletin 14, 32p.

--------- 1963b. Paleocurrent directions from the McMurray Formation. Bulletin of Canadian Petroleum Geology, 11, pp. 389-395.

--------- 1963c. Petrology of coarse-grained sands in the lower part of the McMurray Formation. In The K.A. Clark Volume. Edited by M.A. Carrigy. Research Council of Alberta, Information Series, Number 45, pp. 43-54.

--------- 1966. Lithology of the Athabasca Oil Sands. Research Council of Alberta, Bulletin 18, 48p.

--------- 1967. Some sedimentary features of the Athabasca Oil Sands. Sedimentary Geology, 1, pp. 327-352.

--------- 1971. Deltaic sedimentation in Athabasca Tar Sands. American Association of Petroleum Geologists, Bulletin, 55, pp. 1155-1169.

--------- 1973a. Introduction and general geology. In Guide to the Athabasca Oil Sands area. Edited by M.A. Carrigy and J.W. Kramers. Alberta Research Council, Information Series, 65, pp. 3-13.

--------- 1973b. Mesozoic geology of the Fort McMurray area. In Guide to the Athabasca Oil Sands area. Edited by M.A. Carrigy and J.W. Kramers. Alberta Research Council, Information Series, 65, pp. 77-101.

--------- and Zamora, W.J. 1960. The Athabasca Oil Sands. In Oil fields of Alberta. Edited by R.J. White. Alberta Society of Petroleum Geologists, Calgary, pp. 38-49.

Castaing, P. and Allen, G.P. 1981. Mechanisms controlling seaward escape of suspended sediment from the Gironde: a macrotidal estuary in France. Marine Geology, 40, pp. 101-118.

Cheel, R.J. and Middleton, G.V. 1986. Horizontal laminae formed under upper flow regime plane bed conditions. Journal of Geology, 94, 489-504.

Christopher, J.E. 1980. The Lower Cretaceous Mannville Group of Saskatchewan - a tectonic over-view. In Lloydminster and beyond: geology of Mannville hydrocarbon reservoirs. Edited by L.S Beck, J.E. Christopher and D.M. Kent. Saskatchewan Geological Society, Special Publication Number 5, pp. 3-32.

Clark, K.A. and Blair, S.M. 1927. The bituminous sands of Alberta. Part 1. Occurrence. Scientific and Industrial Research Council of Alberta, Report Number 18, 74p.

Clifton, H.E. 1982. Estuarine deposits. In Sandstone depositional environments. Edited by

P.A. Scholle and D. Spearing. American Association of Petroleum Geologists, Memoir 31, pp.179-189.

------- and Phillips, R.L. 1980. Lateral trends and vertical sequences in estuarine sediments, Willapa Bay, Washington. In Quaternary depositional environments of the Pacific coast. Edited by M.E. Field, A.H. Bouma, I.P. Colburn, R.G. Douglas and J.C. Ingle. Pacific Section of the Society of Economic Paleontologists and Mineralogists, Pacific coast paleogeography Symposium 4, pp. 55-71.

Coles, S.M. 1979. Benthic microalgal populations on intertidal sediments and their role as precursors to salt marsh development. In Ecological processes in coastal environments Edited by R.L. Jefferies and A.J. Davy. Blackwell Scientific Publications,London, pp. 25-42.

Coleman, J.M. 1969. Brahmaputra River: channel processes and sedimentation. Sedimentary Geology, 3, pp. 129-239.

-------- and Prior, D.B. 1982. Deltaic environments of deposition. In Sandstone depositional environments. Edited by P.A. Scholle and D. Spearing, American Association of Petroleum Geologists, Memoir 31, pp. 139-178.

Collinson, J.D. 1986. Alluvial sediments. In Sedimentary environments and facies (second edition). Edited by H. G. Reading. Blackwell Scientific Publications, London, pp. 29-62.

--------- and Thompson, D.B. 1982. Sedimentary structures. George Allen and Unwin (Publishers) Ltd., London, 194p.

Conybeare, C.E.B. 1966. Origin of Athabasca Oil Sands: a review. Bulletin of Canadian Petroleum Geology, 14, pp. 145-163.

Corbett, C.S. 1955a. *In situ* origin of McMurray oil of northeastern Alberta and its relevance to general problems of origin of oil. American Association of Petroleum Geologists, Bulletin, 39, pp. 1601-1649.

-------- 1955b. Reply to discussion of "*In situ* origin of McMurray oil". American Association of Petroleum Geologists, Bulletin, 39, pp.1636-1649.

Cossey, S.P.J. 1981. Sedimentology photo. Journal of Sedimentary Petrology, 51, p.81.

Costello, W.R. and Southard, J.B. 1981. Flume experiments on lower-flow-regime bed forms in coarse sand. Journal of Sedimentary Petrology, 51, pp. 849-864.

Dalrymple, R.W. 1984a. Morphology and internal structure of sandwaves in the Bay of Fundy. Sedimentology, 31, pp. 365-382.

---------- 1984b. Runoff microdeltas: a potential emergence indicator in cross-stratified sandstone. Journal of Sedimentary Petrology, 54, pp. 825-830.

Defant, A. 1958. Ebb and flow. The tides of Earth, air, and water. University of Michigan Press, Ann Arbour, 121p.

Demaison, G.J. 1977. Tar sands and supergiant oil fields. American Association of Petroleum Geologists, Bulletin, 61, pp. 1950-1961.

deMowbray, T. 1983. The genesis of lateral accretion deposits in recent intertidal mudflat channels, Solway Firth, Scotland. Sedimentology, 30, pp. 425-435.

-------- and Visser, M.J. 1984. Reactivation surfaces in subtidal channel deposits, Oosterschelde, southwest Netherlands. Journal of Sedimentary Petrology, 54, pp. 811-824.

de Raaf, J.F.M. and Boersma, J.R. 1971. Tidal deposits and their sedimentary structures (seven examples from Western Europe). Geologie en Mijnbouw, 50, pp. 479-504.

--------, Reading, H.G. and Walker, R.G. 1965. Cyclic sedimentation in the lower Westphalian of north Devon. Sedimentology, 4, pp. 1-52.

Dickinson, W.R. 1976. Sedimentary basins developed during the evolution of Mesozoic-Cenozoic arc-trench system in western North America. Canadian Journal of Earth Sciences, 13, pp. 1268-1287.

Dietrich, G., Kalle, K., Krauss, W. and Siedler, G. 1980. General oceanography (second edition). John Wiley and Sons, New York, 626p.

Dörjes, J. and Howard, J.D. 1975. Estuaries of the Georgia coast, U.S.A.: sedimentology and biology. IV. Fluvial-marine transition indicators in an estuarine environment, Ogeechee River - Ossabaw Sound. Senckenbergiana maritima, 7, pp. 137-179.

Drake, D.E. 1976. Suspended sediment transport and mud deposition on continental shelves. In Marine sediment transport and environmental management. Edited by D.J. Stanley and D.J.P. Swift. John Wiley and Sons, New York, pp. 127-158.

Dronkers, J.J. 1964. Tidal computations in rivers and coastal waters. North-Holland Publishing Co., Amsterdam, 518p.

Einstein, H.A. and Krone, R.B. 1962. Experiments to determine modes of cohesive sediment transport in salt water. Journal of Geophysical Research, 67, pp. 1451-1461.

Eisma, D. and Kalf, J. 1987. Dispersal, concentration and deposition of suspended matter in the North Sea. Journal of the Geological Society, London, 144, pp. 161-178.

Elliott, T. 1986. Siliciclastic shorelines. In Sedimentary environments and facies (second edition). Edited by H.G. Reading. Blackwell Scientific Publications, London, pp. 155-188.

Ells, S.C. 1914. Preliminary report on the bituminous sands of northern Alberta. Canada

Department of Mines, Mines Branch, Number 281, 92p.

------ 1915. Bituminous sands of northern Alberta. Canada Department of Mines, Mines Branch, Summary Report for the Calender Year ending December 31 1914, Number 346, pp. 60-73.

------ 1926. Bituminous sands of northern Alberta. Canada Department of Mines, Mines Branch, Report on investigations to the end of 1924, Number 632, 244p.

Energy Resources Conservation Board 1982. Atlas of Alberta's crude bitumen reserves at 31 December, 1981. Energy Resources Conservation Board, Report 82-38, 39p.

Esteban, M. and Klappa, C.F. 1983. Subaerial exposure environment. In Carbonate depositional environments. Edited by P.A. Scholle, D.G. Bebout and C.H. Moore. American Association of Petroleum Geologists, Memoir 33, pp. 1-54.

Falconer, W.L. 1951. Stratigraphy of the McMurray Formation. In Proceedings Athabasca Oil Sands Conference, September 1951, Board of Trustees Oil Sands Project, Government of Alberta, pp. 26-29.

Fairbridge, R.W. 1968. Estuary. In The encyclopedia of geomorphology. Edited by R.W. Fairbridge. Reinhold Book Corporation, New York, pp. 325-330.

--------- 1980. The estuary: its definition and geodynamic cycle. In Chemistry and biogeochemistry of estuaries. Edited by E. Olausson and I. Cato. John Wiley and Sons, Inc., Toronto, pp. 1-35.

Farrell, K.M. 1987. Sedimentology and facies architecture of overbank deposits of the Mississippi River, False River region, Louisiana. In Recent developments in fluvial sedimentology. Edited by F.G. Ethridge, R.M. Flores and M.D. Harvey. Society of Economic Paleontologists and Mineralogists, Special Publication No. 39., pp. 111-120.

FitzPatrick, E.A. 1983. Soils, their formation, classification, and distribution (second edition). Longman Inc., New York, 353p.

Flach, P.D. 1977. A lithofacies analysis of the McMurray Formation, lower Steepbank River, Alberta. M.Sc. Thesis, University of Alberta, 139p.

------- 1984. Oil sands geology - Athabasca deposit north. Alberta Research Council Natural Resources Division, Alberta Geological Survey, Bulletin 46, 31p.

------- and Mossop, G.D. 1985. Depositional environments of the Lower Cretaceous McMurray Formation, Athabasca Oil Sands, Alberta. American Association of Petroleum Geologists, Bulletin, 69, pp. 1195-1207.

Flemming, B.W. 1978. Underwater sand dunes along the southeast African continental margin - observations and implications. Marine Geology, 26, pp. 177-198.

Forrester, W.D. 1983. Canadian tidal manual. Department of Fisheries and Oceans, Canadian Hydrographic Service, Ottawa, 138p.

Frey, R.W. and Howard, J.D. 1980. Physical and biogenic processes in Georgia estuaries. II. Intertidal facies. In Sedimentary processes and animal-sediment relationships in tidal environments. Edited by S.B. McCann. Geological Association of Canada, Short Course Notes, 1, pp. 183-220.

Gallup, W.B. 1974. The geological history of McMurray-Clearwater deposition in the Athabasca Oil Sands area. In Oil sands fuel of the future. Edited by L.V. Hills. Canadian Society of Petroleum Geologists, Memoir 3, pp. 100-114.

Galloway, W.E. and Hobday, D.K. 1983. Terrigenous clastic depositional systems. Springer-Verlag, New York, 423p.

Gardiner, C.D. 1984. (Editor) Canadian oil and gas handbook 1984-85. North Miner Press Limited, Toronto, 312p.

Glaister, R.P. 1959. Lower Cretaceous of southern Alberta and adjoining areas. American Association of Petroleum Geologists, Bulletin, 43, pp. 590-640.

Govier, G.W. 1974. Alberta's oil sands in the energy supply picture. In Oil sands fuel of the future. Edited by L.V. Hills. Canadian Society of Petroleum Geologists, Memoir 3, pp. 35-49.

Greer, S.A. 1975. Estuaries of the Georgia coast, U.S.A.: sedimentology and biology. III. Sandbody geometry and sedimentary facies at the estuary - marine transition zone, Ossabaw Sound, Georgia: a stratigraphic model. Senckenbergiana maritima, 7, pp. 105-135.

Häntzschel, W. 1936. Die schichtungs-formen rezenter Flachmeer-Ablagerungen im Jade-Gebiet. Senckenbergiana, 18, pp. 316-356.

Harms, J.C. 1969. Hydraulic significance of some sand ripples. Geological Society of America, Bulletin, 80, pp. 363-396.

-------- and Fahnestock, R.K. 1965. Stratification, bed forms, and flow phenomena (with an example from the Rio Grande). In Primary sedimentary structures and their hydrodynamic interpretation. Edited by G.V. Middleton. Society of Economic Paleontologists and Mineralogists, Special Publication, No. 12, pp. 84-115.

--------, MacKenzie, D.B. and McCubbin, D.G. 1963. Stratification in modern sands of the Red River, Louisiana. Journal of Geology, 71, pp. 566-580.

--------, Southard, J.B. and Walker, R.G. 1982. Structures and sequences in clastic rocks. Society of Economic Paleontologists and Mineralogists, Short Course Notes, No. 9, 249p.

Harrison, A.J.M. and Owen, M.W. 1971. Siltation of fine sediments in estuaries. In Hydraulic research and its impact on the environment. Fourteenth Congress of the International Association for Hydraulic Research, 29 August - 3 September 1971, 4, Part D, pp. 1.1-1.8.

Haven, D.S. and Morales-Alamo, R. 1968. Occurrence and transport of faecal pellets. Sedimentary Geology, 2, pp. 141-151.

Hawley, N. 1981a. Flume experiments on the origin of flasar bedding. Sedimentology, 28, pp. 699-712.

------ 1981b. Mud consolidation during a short time interval. Geo-Marine Letters, 1, pp. 7-10.

Houbolt, J.J.H.C. 1968. Recent sediments in the Southern Bight of the North Sea. Geologie en Mijnbouw, 47, pp. 245-273.

Howard, J.D., Elders, C.A. and Heinbokel, J.F. 1975. Estuaries of the Georgia coast, U.S.A.: sedimentology and biology. V. Animal-sediment relationships in estuarine point bar deposits; Ogeechee River - Ossabaw Sound, Georgia. Senckenbergiana maritima, 7, pp. 181-203.

------ and Frey, R.W. 1973. Characteristic physical and biogenic sedimentary structures in Georgia estuaries. American Association of Petroleum Geologists Bulletin, 57, pp. 1169-1184.

------ and ----- 1975. Estuaries of the Georgia coast, U.S.A.: sedimentology and biology. II. Regional animal-sediment characteristics of Georgia estuaries. Senckenbergiana maritima, 7, pp. 33-103.

------ and ----- 1985. Physical and biological aspects of back barrier sedimentary sequences, Georgia Coast. Marine Geology, 63, pp, 77-127.

-------- and Nelson, C.H. 1982. Sedimentary structures on a delta-influenced shallow shelf, Norton Sound, Alaska. Geologie en Mijnbouw, 61, pp. 29-36.

-------- and Reineck, H.E. 1972. Georgia coastal region, Sapelo Island, U.S.A.: sedimentology and biology. IV. Physical and biogenic sedimentary structures of the nearshore shelf. Senckenbergiana maritima, 4, pp. 81-123.

Howarth, M.J. 1982. Tidal currents of the continental shelf. In Offshore tidal sands. Edited by A.H. Stride. Chapman and Hall, New York, pp. 10-26.

Howell, D.G. and Normark, W.R. 1982. Sedimentology of submarine fans. In Sandstone depositional environments Edited by P.A. Scholle and D. Spearing. American Association of Petroleum Geologists, Memoir 31, pp. 139-178.

Hughes, D.A. and Lewin, J. 1982. A small-scale flood plain. Sedimentology, 29, pp. 891-895.

Hume, G.S. 1934. Distribution of probable source rocks in relation to natural gas and petroleum production in Alberta, Canada. In Proceedings of the World Petroleum Congress. Edited by A.E. Dunstan and G. Sell. Volume 1, Geological and production sections, pp. 62-65.

------- 1947. Results and significance of drilling operations in the Athabaska Bituminous Sands. Transactions of the Canadian Institute of Mining and Metallurgy, L, pp. 298-324.

------- 1949. Geology of the bituminous sands area. In Drilling and sampling of bituminous sands of northern Alberta. Volume 1. Results of investigations 1942-1947. Canada Department of Mines and Resources, Mines, Forests and Scientific Services Branch, pp. 7-13.

------- 1951. Possible Lower Cretaceous origin of bitumen in bituminous sands of Alberta. In Proceedings Athabasca Oil Sands Conference, September 1951, Board of Trustees Oil Sands Project, Government of Alberta, pp. 66-75.

------- 1955. Discussion of "*In situ* origin of McMurray oil". American Association of Petroleum Geologists, Bulletin, 39, pp. 1621-1624.

Jackson, P.C. 1984. Paleogeography of the Lower Cretaceous Mannville Group of Western Canada. In Elmworth, case study of a deep-basin gas field. Edited by J.A. Masters. American Association of Petroleum Geologists, Memoir 38, pp. 49-77.

Jackson, R.G. 1981. Sedimentology of muddy fine-grained channel deposits in meandering streams of the American Middle West. Journal of Sedimentary Petrology, 51, pp. 1169-1192.

James, D.P. 1977. The sedimentology of the McMurray Formation, east Athabasca. M.Sc. thesis, University of Calgary, 198p.

---- and Oliver, T.A. 1977. The sedimentology of the McMurray Formation, east Athabasca. In The oilsands of Canada-Venezuela. Edited by D.A. Redford and A.G. Winestock. Canadian Institute of Mining and Metallurgy, Special Volume 17, pp. 17-26.

Jardine, D. 1974. Cretaceous oil sands of Western Canada. In Oil sands fuel of the future. Edited by L.V. Hills. Canadian Society of Petroleum Geologists, Memoir 3, pp. 50-67.

Jopling, A.V. 1964. Laboratory study of sorting processes related to flow separation. Journal of Geophysical Research, 69, pp. 3403-3418.

Jouanneau, J.M. and Latouche, C. 1981. The Gironde Estuary. Contributions to Sedimentology, 10, E. Schwaeizerbart'sche Verlagsbuchhandlung, Stuttgart, F.R.G., 115p.

Kesel, R.H., Dunne, K.C., McDonald, R.C., Allison, K.R. and Spicer, B.E. 1974. Lateral erosion and overbank deposition on the Mississippi River in Louisiana caused by 1973 flooding. Geology, 2, pp. 461-464.

Kidd, F.A. 1951. Geology of the bituminous sand deposits of the Fort McMurray area, Alberta. In Proceedings Athabasca Oil Sands Conference, September 1951, Board of Trustees Oil Sands Project, Government of Alberta, pp. 30-38.

Kirby, R. and Parker, W.R. 1983. Distribution and behaviour of fine sediment in the Severn Estuary and inner Bristol Channel, U.K. Canadian Journal of Fisheries and Aquatic Sciences, 40 (Supplement 1), pp. 83-95.

Knight, R.J., Dekker, F.G.C. and McIntyre, D.J. 1981. Sedimentary facies from McMurray-Wabiskaw Oilsands (Lower Cretaceous) northeastern Alberta: 8-26-85-9W4. In Environmental analysis from core and field sample studies. Compiled by F.A. Stoakes. Canadian Society of Petroleum Geologists, Annual Core Conference, pp. 32-37.

Kramers, J.W. 1974. Geology of the Wabasca A Oil Sand deposit (Grand Rapids Formation). In Oil sands fuel of the future. Edited by L.V. Hills. Canadian Society of Petroleum Geologists, Memoir 3, pp. 68-83.

Kranck, K. 1975. Sediment deposition from flocculated suspensions. Sedimentology, 22, pp. 111-123.

Krone, R.B. 1962. Flume studies of the transport of sediment in estuarial shoaling processes. Hydraulic Engineering Laboratory and Sanitary Engineering Research Laboratory, University of California, Berkeley, 110 p.

Land, L.S. and Hoyt, J.H. 1966. Sedimentation in a meandering estuary. Sedimentology, 6, pp. 191-207.

Langhorne, D.N. 1982. A study of the dynamics of a marine sandwave. Sedimentology, 29, pp. 571-594.

---------- and Read, A.A. 1986. The evolution and mechanics of modern intertidal and subtidal bedforms: their relevance to geological structures. Journal of the Geological Society, London, 143, pp. 957-962.

Lattman, L.H. 1960. Cross section of a floodplain in a moist region of moderate relief. Journal of Sedimentary Petrology, 30, pp. 275-282.

Leeder, M.R. 1982. Sedimentology: process and product. George Allen and Unwin (Publishers) Ltd., London, 344p.

Leopold, L.B. and Langbein, W.B. 1966. River meanders. Scientific American, 214 (6), pp.

60-70.

Link, T.A. 1951. Source of oil in "tar sand" of Athabaska River, Alberta, Canada. American Association of Petroleum Geologists, Bulletin, 35, pp. 854-864.

------ 1954. Source of oil in "tar sands" of Athabaska River, Alberta, Canada. In Western Canada Sedimentary Basin. Edited by L.M. Clark. American Association of Petroleum Geologists, Ralph Leslie Rutherford Memorial Volume, pp. 464-473.

Little-Gadow, S. and Reineck, H.E. 1974. Diskontinuierliche sedimentation von sand und schlick in Wattensedimenten. Senckenbergiana maritima, 6, pp. 149-159.

MacCallum, G.T. 1977. Emerging geology of the heavy-oil sands. Bulletin of Canadian Petroleum Geology, 25, pp. 305-313.

Martin, R. and Jamin, F.G.S. 1963. Paleogeomorphology of the buried Devonian landscape in northeastern Alberta. In The K.A. Clark Volume. Edited by M.A. Carrigy. Research Council of Alberta, Information Series, Number 45, pp. 31-42.

Mattison, B.W. 1987. Ichnology, paleontology, and depositional history of the Lower Cretaceous McMurray Formation, Athabasca Oil Sands area, northeastern Alberta. M.Sc. Thesis, University of Alberta. 437p.

Mayou, T.V. and Howard, J.D. 1975. Estuaries of the Georgia coast, U.S.A.: sedimentology and biology. VI. Animal-sediment relationships of a salt marsh estuary Doboy Sound. Senckenbergiana maritima, 7, pp. 205-236.

McCave, I.N. 1970. Deposition of fine-grained suspended sediment from tidal currents. Journal of Geophysical Research, 75, pp. 4151-4159.

------- 1971. Wave effectiveness at the sea bed and its relationship to bed-forms and the deposition of mud. Journal of Sedimentary Petrology, 41, pp. 89-96.

McConnell, R.G. 1893. On a portion of the District of Athabasca, comprising of the country between Peace River and Athabasca River north of Lesser Slave Lake. Geological Survey of Canada , Annual Report 1890-1891, 5, Report D, pp. 5-67.

McLean, J.R. 1977. The Cadomin Formation: stratigraphy, sedimentology, and tectonic implications. Bulletin of Canadian Petroleum Geology, 25, pp. 792-827.

-------- and Wall, J.H. 1981. The early Cretaceous Moosebar Sea in Alberta. Bulletin of Canadian Petroleum Geology, 29, pp. 334-377.

McLearn, F.H. 1917. Athabasca River section, Alberta. Geological Survey of Canada, Summary Report 1916, pp. 145-151.

-------- 1932. Problems of the Lower Cretaceous of the Canadian Interior. Transactions of the Royal Society of Canada, Section IV, pp. 157-175.

--------- 1945. Revision of the Lower Cretaceous of the Western Interior of Canada. Geological Survey of Canada, Paper 44-17. 6p.

Meckel, L.D. 1975. Holocene sand bodies in the Colorado Delta area, northern Gulf of California. In Deltas: models for exploration. Edited by M.L. Broussard. Houston Geological Society, pp. 239-265.

Mellon, G.B. 1967. Stratigraphy and petrology of the Lower Cretaceous Blairmore and Mannville groups, Alberta Foothills and Plains. Research Council of Alberta, Bulletin 21, 270p.

-------- and Wall, J.H. 1956. Geology of tne McMurray Formation. Part 1. Foraminifera of the upper McMurray and basal Clearwater formations. Research Council of Alberta, Report Number 72, 29p.

Miall, A.D. 1984. Principles of sedimentary basin analysis. Springer-Verlag New York Inc., New York, 490p.

Middleton, G.V. 1973. Johannes Walther's Law of the correlation of facies. Geological Society of America, Bulletin, 84, pp. 979-988.

--------- 1978. Facies. In The Encyclopedia of sedimentology. Edited by R.W. Fairbridge and J. Bourgeois. Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pennsylvannia, pp. 323-325.

-------- and Hampton, M.A. 1973. Sediment gravity flows: mechanics of flow and deposition. In Turbidites and deep-water sedimentation. Society of Economic Paleontologists and Mineralogists, Pacific Section, Short Course, Anaheim, pp. 1-38.

Migniot, C. 1968. Etude des propriétés physiques de différents sédiments trés fins et de leur comportement sous des actions hydrodynamiques. La Houille Blanche, 23, pp. 591-620.

Mossop, G.D. 1978. Epsilon cross-strata in the Athabasca Oil Sands. (Abstract) In Fluvial sedimentology. Edited by A.D. Miall. Canadian Society of Petroleum Geologists, Memoir 5, pp. 854-855.

------ 1980a. Facies control on bitumen saturation in the Athabasca Oil Sands. In Facts and principles of world oil occurrence. Edited by A.D. Miall. Canadian Society of Petroleum Geologists, Memoir 6, pp. 609-632.

------- 1980b. Geology of the Athabasca Oil Sands. Science, 207, pp. 145-152.

------- and Flach, P.D. 1983. Deep channel sedimentation in the Lower Cretaceous McMurray Formation, Athabasca Oil Sands, Alberta. Sedimentology, 30, pp. 493-509.

-------, -------, Pemberton, S.G. and Hopkins, J.C. 1982. Field excursion 22:

Athabasca Oil Sands, sedimentology and development technology. International Association of Sedimentologists, 11th International Congress, Field excursion guide book, Hamilton, 59p.

Nauss, A.W. 1945. Cretaceous stratigraphy of Vermillion area, Alberta, Canada. American Association of Petroleum Geologists, Bulletin, 29, pp. 1605-1629.

Nelson, H.W. and Glaister, R.P. 1978. Subsurface environmental relationships of the McMurray Oil Sands, northeastern Alberta. Bulletin of Canadian Petroleum Geology, 26, pp. 177-207.

Newton, R.S. 1968. Internal structure of wave-formed ripple marks in the nearshore zone. Sedimentology, 11, pp. 275-292.

Nichols, M.M. and Biggs, R.B. 1985. Estuaries. In Coastal sedimentary environments. Edited by R.A. Davis. Springer-Verlag New York Inc., New York., pp. 77-186.

Norris, A.W. 1973. Paleozoic (Devonian) geology of northeastern Alberta and northwestern Saskatchewan. In Guide to the Athabasca Oil Sands area. Edited by M.A. Carrigy and J.W. Kramers. Alberta Research Council, Information Series, Number 65, pp. 15-61.

North, F.K. 1985. Petroleum geology. Allen and Unwin Inc., Boston, 607p.

Oertel, G.F. 1973. A sedimentary framework of the substrates adjacent to Georgia tidal inlets. In The Neogene of the Georgia coast. Edited by R.W. Frey. Georgia Geological Society, Guidebook 8, pp. 59-66.

------- and Dunstan, W.M. 1981. Suspended - sediment distribution and certain aspects of phytoplankton production off Georgia, U.S.A. Marine Geology, 40, pp. 171-197.

Oomkens, E. and Terwindt, J.H.J. 1960. Inshore estuarine sediments in the Haringvliet (Netherlands). Geologie en Mijnbouw, 39, pp. 701-710.

Ovenshine, A.T. 1970. Observations of iceberg rafting in Glacier Bay, Alaska and the identification of ancient ice-rafted deposits. Geological Society of America, Bulletin, 81, pp. 891-894.

Owen, M.W. 1970. Properties of a consolidating mud. Hydraulics Research Station, Walingford, Report No. INT 83, 95p.

------- 1971. The effect of turbulence on the settling velocities of silt flocs. Hydraulic research and its impact on the environment. Fourteenth Congress of the International Association for Hydraulic Research, 29 August - 3 September 1971, Volume 4, Part D, pp. 4.1-4.6.

Park, D.G. and Jones, B. 1985. Nature and genesis of breccia bodies in Devonian strata, Peace Point area, Wood Buffalo Park, northeast Alberta. Bulletin of Canadian

Petroleum Geology, 33, pp. 275-294.

Parkash, B., Awasthi, A.K. and Gohain, K. 1983. Lithofacies of the Markanda terminal fan, Kurukshetra, Haryana, India. In Modern and ancient fluvial systems. Edited by J.D. Collinson and J. Lewin. International Association of Sedimentologists, Special Publication Number 6, pp. 337-344.

Parthenaides, E. 1965. Erosion and deposition of cohesive soils. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, 91, pp. 105-139.

Pemberton, S.G., Flach, P.D. and Mossop, G.D. 1982. Trace fossils from the Athabasca Oil Sands, Alberta, Canada. Science, 217, pp. 825-827.

Penland, S., Suter, J.R. and Moslow, T.F. 1986. Inner-shelf shoal sedimentary facies and sequences: Ship Shoal, northern Gulf of Mexico. In Modern and ancient shelf clastics: a core workshop. Edited by T.F. Moslow and E. G. Rhodes. Society of Economic Paleontologists and Mineralogists, Core workshop No. 9, pp. 73-123.

Pickrill, R.A. 1986. Sediment pathways and transport rates through a tide-dominated entrance, Rangaunu Harbour, New Zealand. Sedimentology, 33, pp. 887-898.

Plummer, P.S. and Gostin, V.A. 1981. Shrinkage cracks: dessication or synaeresis? Journal of Sedimentary Petrology, 51, pp. 1147-1156.

Porter, J.W., Price, R.A. and McCrossan, R.G. 1982. The Western Canada Sedimentary Basin. Philosophical Transactions of the Royal Society of London, Series A, 305, pp. 169-192.

Postma, H. 1961. Transport and accumulation of suspended matter in the Dutch Wadden Sea. Netherlands Journal of Sea Research, 1, pp. 148-190.

------- 1967. Sediment transport and sedimentation in the estuarine environment. In Estuaries. Edited by G.H. Lauff. American Association for the Advancement of Science, Publication Number 83, pp. 158-179.

Potter, P.E., Maynard, J.B. and Pryor, W.A. 1980. Sedimentology of shale. Springer-Verlag, New York, 306p.

Price, R.A. 1973. Large-scale gravitational flow of supra-crustal rocks, southern Canadian Rockies. In Gravity and tectonics. Edited by K.A. De Jong and R.A. Scholten. John Wiley and Sons, New York, pp. 491-502.

Pritchard, D.W. 1967. What is an estuary: a physical viewpoint. In Estuaries. Edited by G.H. Lauff. American Association for the Advancement of Science, Publication Number 83, pp. 3-5.

Procter, R.M., Taylor, G.C. and Wade, J.A. 1983. Oil and natural gas resources of Canada. Geological Survey of Canada, Open File 966, 57p.

Pryor, W.A. 1975. Biogenic sedimentation and alternation of argillaceous sediments in shallow marine environments. Geological Society of America, Bulletin, pp. 1244-1254.

Purdy, E.G. 1964. Sediments as substrates. In Approaches to paleoecology. Edited by J. Imbrie and N. Newell. John Wiley and Sons, Inc., New York, pp. 238-271.

Reineck, H.E. 1958. Longitudinale schräschicht im Watt. Geologische Rundschau, 47, pp. 73-82.

-------- 1960. Über die entstehung von linsen- und flaser-schichten. Abhandlung der Deutschen Akademie der Wissenschaften zu Berlin, 1, pp. 369-374.

-------- 1967. Layered sediments of tidal flats, beaches, and shelf bottoms of the North Sea. In Estuaries. Edited by G.H. Lauff. American Association for the Advancement of Science, Publication Number 83, pp. 191-206.

-------- and Singh, I.B. 1975. Depositional sedimentary environments, with reference to terrigenous clastics. Springer-Verlag, New York, 439 p.

-------- and Wunderlich, F. 1967. Zeitmessungen an Gezeitenschichten. Natur und Museum, 97, pp. 193-197.

-------- and -------- 1968. Classification and origin of flaser and lenticular bedding. Sedimentology, 11, pp. 99-104.

Reinson, G.E. 1984. Barrier-island and associated strand-plain systems. In Facies models (second edition). Edited by R.G. Walker. Geoscience Canada, Reprint Series 1, pp. 119-140.

Rennie, J.A. 1983. Applied geology: key to mining the Athabasca Oil Sands. Canadian Institute of Mining and Metallurgy, First District 5 Meeting, Calgary, 38p.

Rhoads, D.C., Yingst, J.Y. and Ullman, W.J. 1978. Seafloor stability in central Long Island Sound: part I. Temporal changes in the erodibility of fine-grained sediment. In Estuarine interactions. Edited by M.J. Wiley. Academic Press, New York, pp. 221-244.

Ross, D.A. 1982. Introduction to oceanography (third edition). Prentice-Hall Inc., Englewood Cliffs, New Jersey, 544p.

Rudkin, R.A. 1964. Lower Cretaceous. In Geological history of Western Canada. Edited by R.G. McCrossan and R.P. Glaister. Alberta Society of Petroleum Geologists, Calgary, pp. 156-168.

Russell, L.S. 1932. Mollusca from the McMurray Formation of northern Alberta. Transactions of the Royal Society of Canada, Section IV, pp. 37-44.

Sampson, R.J. 1978. Surface II graphics system (revised edition). Kansas Geological Survey, Series on spatial analysis, Number 1, 240p.

Simons, D.B., Richardson, E.V. and Nordin, C.F. 1965. Sedimentary structures generated by flow in alluvial channels. In Primary sedimentary structures and their hydrodynamic interpretation. Edited by G.V. Middleton. Society of Economic Paleontologists and Mineralogists, Special Publication, No. 12, pp. 34-52.

Smith, D.G. 1985. Modern analogues of the McMurray Formation channel deposits, sedimentology of meso tidal-influenced meandering river point bars with inclined beds of alternating sand and mud. Final Report for AOSTRA Research Project Number 391, 78p.

------- 1987. Meandering river point bar lithofacies models: modern and ancient examples compared. In Recent developments in fluvial sedimentology. Edited by F.G. Ethridge, R.M. Flores and M.D. Harvey. Society of Economic Paleontologists and Mineralogists, Special Publication Number 39, pp. 83-91.

Smith, N.D. 1972. Flume experiments on the durability of mud clasts. Journal of Sedimentary Petrology, 42, pp. 378-383.

Sproule, J.C. 1938. Origin of McMurray Oil Sands, Alberta. American Association of Petroleum Geologists, Bulletin, 22, pp. 1133-1152.

-------- 1951. The McMurray Formation in its relation to oil occurrence. In Proceedings Athabasca Oil Sands Conference, September 1951, Board of Trustees Oil Sands Project, Government of Alberta, pp. 6-25.

-------- 1955. Discussion of "*In situ* origin of McMurray oil". American Association of Petroleum Geologists, Bulletin, 39, pp. 1632-1636.

Stewart, G.A. 1963. Geological controls on the distribution of Athabasca Oil Sand reserves. In The K.A. Clark Volume on the Athabasca Oil Sands. Edited by M.A. Carrigy. Research Council of Alberta, pp.15-26.

-------- 1981. Athabasca Oil Sands. In The future of heavy crude oils and tar sands. Edited by R.F. Meyer, C.T. Steele and J.C. Olson. United Nations Institute for Training and Research, McGraw-Hill, New York, pp. 208-222.

-------- and MacCallum, G.T. 1978. Athabasca Oil Sands Guide Book. Canadian Society of Petroleum Geologists, Facts and Principles of World Oil Occurrence Conference, Calgary, 33p.

Stott, D.F. 1984. Cretaceous sequences of the Foothills of the Canadian Rocky Mountains. In The Mesozoic of Middle North America. Edited by D.F. Stott and D.J. Glass. Canadian Society of Petroleum Geologists, Memoir 9, pp. 85-107.

Swift, D.J.P., Han, G. and Vincent, C.E. 1986. Fluid processes and sea-floor response on a modern storm-dominated shelf: middle Atlantic shelf of North America. Part 1: the storm-current regime. In Shelf sand and sandstones. Edited by R.J. Knight and J.R. McLean. Canadian Society of Petroleum Geologists, Memoir 11, pp. 99-119.

Tammam, A.O. and Wach, G.D. 1986. Geology of Syncrude oil-sand leases. (Abstract) American Association of Petroleum Geologists, Bulletin, 70, p. 654.

-------, Stewart, G.A. and MacCallum, G.T. 1986. Sediment distribution, McMurray Formation, Syncrude oil-sand leases, Alberta, Canada. (Abstract) American Association of Petroleum Geologists, Bulletin, 70, p.654.

Taylor, G. and Woodyer, K.D. 1978. Bank deposition in suspended-load streams. In Fluvial sedimentology. Edited by A.D. Miall. Canadian Society of Petroleum Geologists, Memoir 5, pp. 257-275.

Teichert, C. 1958. Concepts of facies. American Association of Petroleum Geologists, Bulletin, 42, pp. 2718-2744.

Terwindt, J.H.J. 1971. Litho-facies of inshore estuarine and tidal-inlet deposits. Geologie èn Mijnbouw, 50, pp. 515-526.

------- 1975. Sequences in inshore subtidal deposits. In Tidal deposits. Edited by R.N. Ginsberg. Springer-Verlag New York, Inc., pp. 85-89.

-------, Breusers, H.N.C. and Svasek, J.N. 1968. Experimental investigation on the erosion-sensitivity of a sand-clay lamination. Sedimentology, 11, pp. 105-114.

-------- and -------- 1972. Experiments on the origin of flaser, lenticular and sand-clay alternating bedding. Sedimentology, 19, pp. 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, 53, pp. 123-179.

Vagvolgyi, A. and Hills, L.V. 1969. Microflora of the Lower Cretaceous McMurray Formation, northeast Alberta. Bulletin of Canadian Petroleum Geology, 17, pp.155-181.

Vail, P.R., Mitchum, R.M. and Thompson, S. 1977. Seismic stratigraphy and global changes of sea level, part 4: global cycles of relative changes of sea level. In Seismic stratigraphy - applications to hydrocarbon exploration. Edited by C.E. Payton. American Association of Petroleum Geologists, Memoir 26, pp. 83-97.

Van den Berg, J.H. 1981. Rhythmic seasonal layering in a mesotidal channel fill sequence, Oosterschelde Mouth, the Netherlands. In Holocene marine sedimentation in the North Sea Basin. Edited by S.D. Nio, R.T.E. Shüttenheim and T.C.E. Van Weering. International Association of Sedimentologists, Special Publication Number 5, pp. 147-159.

--------- 1982. Migration of large-scale bedforms and preservation of cross-bedded sets in highly accreted parts of tidal channels in the Oosterschelde, SW Netherlands. Geologie en Mijnbouw, 61, pp. 253-263.

Van Olphen, H. 1963. An introduction to clay colloid chemistry. Interscience Publishers, New York, 301p.

Van Straaten, L.M.J.U. 1954. Composition and structure of recent marine sediments in the Netherlands. Leidse Geologische Mededelingen, 19, pp. 1-110.

------- and Kuenen, P.H. 1957. Accumulation of fine-grained sediments in the Dutch Wadden Sea. Geologie en Mijnbouw, 19, pp. 329-354.

Vigrass, L.W. 1965. General geology of Lower Cretaceous heavy oil accumulations in Western Canada. Journal of Canadian Petroleum Technology, 4, pp. 168-176.

Visser, M.J. 1980. Neap-spring cycles reflected in Holocene subtidal large-scale bedform deposits: a preliminary note. Geology, 8, pp. 543-546.

Wach, G.D. 1984. The depositional history of the McMurray Formation: Section 3, 4, 9 and 10, Township 93, R11. M.Sc. Thesis, University of South Carolina, 173p.

------, Hayes, M.O., Tammam, A.O. and Stewart, G.A. 1986. Tidal-dominated estuarine sequence in Lower Cretaceous Athabasca Basin, northeast Alberta. (Abstract) American Association of Petroleum Geologists, Bulletin, 70, pp. 659-660.

Walker, R.G. 1984a. General introduction: facies, facies sequences and facies models. In Facies models (second edition). Edited by R.G. Walker. Geoscience Canada, Reprint Series 1, pp. 1-9.

-------- 1984b. Shelf and shallow marine sands. In Facies models (second edition). Edited by R.G. Walker. Geoscience Canada, Reprint Series 1, pp. 141-170.

Warren, P.S. 1933. Age of Devonian limestone at McMurray, Alberta. Canadian Field-Naturalist, 47, pp. 148-149.

Wells, J.T. 1983. Dynamics of coastal fluid muds in low-, moderate-, and high-tide-range environments. Canadian Journal of Fisheries and Aquatic Sciences, 40 (Supplement 1), pp. 130-142.

------ and Coleman, J.M. 1981. Physical processes and fine-grained sediment dynamics, coast of Surinam, South America. Journal of Sedimentary Petrology, 51, pp. 1053-1068.

Wentworth, C. K. 1922. A scale of grade and class terms for clastic sediments. Journal of Geology, 30, pp. 377-392.

Wiedemann, H.U. 1972. Shell deposits and shell preservation in Quarternary and Tertiary estuarine sediments in Georgia, U.S.A.. Sedimentary Geology, 7, pp. 103-125.

Williams, G.D. 1963. The Mannville Group (Lower Cretaceous) of central Alberta. Bulletin of Canadian Petroleum Geology, 11, pp. 350-368.

Williams, G.P. 1966. Particle roundness and surface texture effects on fall velocity. Journal of Sedimentary Petrology, 36, pp. 255-259.

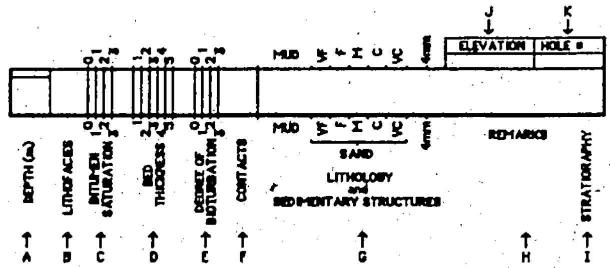
Wilson, J.L. 1975. Carbonate facies in geological history. Springer-Verlag, New York, 471p.

Wunderlich, F. 1978. Deposition of mud in the giant ripples of Inner Jade, German Bight, North Sea. Senckenbergiana maritima, 10, pp. 257-267.

Young, R.N. and Southard, J.B. 1978. Erosion of fine-grained marine sediments: sea-floor and laboratory experiments. Geological Society of America, Bulletin, 89, pp. 663-672.

APPENDIX

- legend for drill core lithologs and lithofacies distribution
- drill core lithologs



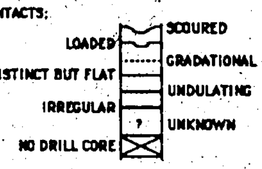
A. DEPTH: METRES FROM SURFACE
B. LITHOFACIES (SEE LITHOFACIES CODES)
C. BITUMEN SATURATION: 0 = NONE
1 = LOW
2 = MODERATE
3 = HIGH

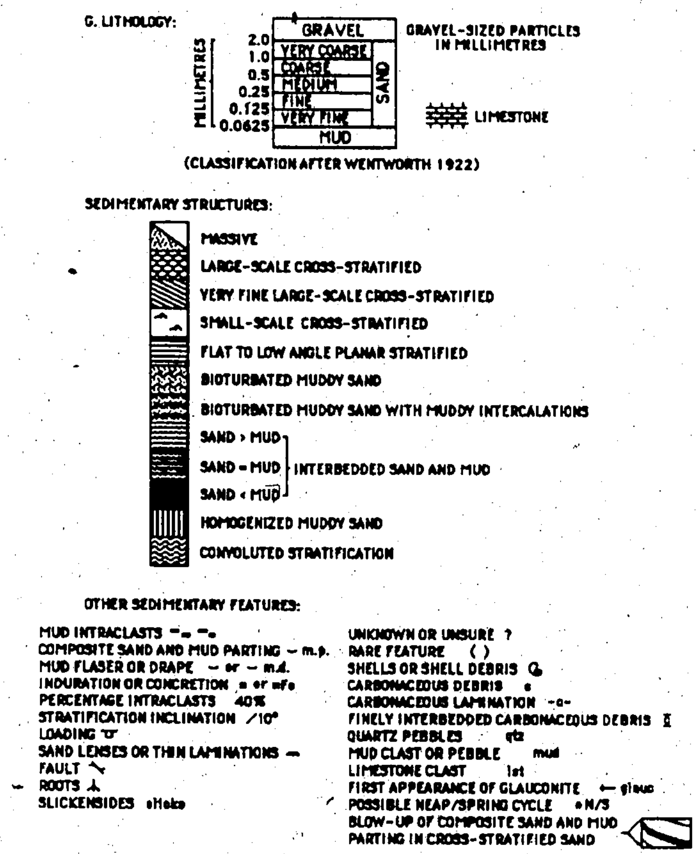
* BITUMEN SATURATION CAN BE REDUCED BY MUDDY INTERCALATIONS AND MUD INTRACLASTS

D. BED THICKNESS: 1 = LAMINATED (≤1cm)
2 = THIN BEDDED (>1cm, <10cm)
3 =, 4 =, 5 = } BED THICKNESS >10cm

E. DEGREE OF BIOTURBATION: 0=NONE
1=SLIGHT
2=MODERATE
3=HIGH

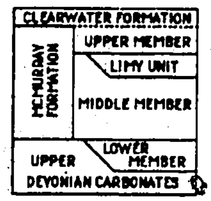
F. BASAL CONTACTS:




G. LITHOLOGY:
MILLIMETRES
2.0
1.0
0.5
0.25
0.125
0.0625
GRAVEL
VERY COARSE
COARSE
MEDIUM
FINE
VERY FINE
MUD
SAND
GRAVEL-SIZED PARTICLES IN MILLIMETRES
LIMESTONE
(CLASSIFICATION AFTER WENTWORTH 1922)
SEDIMENTARY STRUCTURES:
MASSIVE
LARGE-SCALE CROSS-STRATIFIED
VERY FINE LARGE-SCALE CROSS-STRATIFIED
SMALL-SCALE CROSS-STRATIFIED
FLAT TO LOW ANGLE PLANAR STRATIFIED
BIOTURBATED MUDDY SAND
BIOTURBATED MUDDY SAND WITH MUDDY INTERCALATIONS
SAND > MUD
SAND = MUD
SAND < MUD
INTERBEDDED SAND AND MUD
HOMOGENIZED MUDDY SAND
CONVOLUTED STRATIFICATION
OTHER SEDIMENTARY FEATURES:
MUD INTRACLASTS
COMPOSITE SAND AND MUD PARTING — m.p.
MUD FLASER OR DRAPE — or — m.d.
INDURATION OR CONCRETION or Fe
PERCENTAGE INTRACLASTS 40%
STRATIFICATION INCLINATION /10°
LOADING
SAND LENSES OR THIN LAMINATIONS
FAULT
ROOTS
SLICKENSIDES
UNKNOWN OR UNSURE ?
RARE FEATURE ( )
SHELLS OR SHELL DEBRIS
CARBONACEOUS DEBRIS
CARBONACEOUS LAMINATION
FINELY INTERBEDDED CARBONACEOUS DEBRIS
QUARTZ PEBBLES qtz
MUD CLAST OR PEBBLE mud
LIMESTONE CLAST lst
FIRST APPEARANCE OF GLAUCONITE ← glauc
POSSIBLE NEAP/SPRING CYCLE N/S
BLOW-UP OF COMPOSITE SAND AND MUD PARTING IN CROSS-STRATIFIED SAND

H. REMARKS: ANY FEATURES THAT ARE NOT ADEQUATELY DESCRIBED BY LITHOLOGY AND SEDIMENTARY STRUCTURES.

I. STRATIGRAPHY:



J. ELEVATION: SURFACE ELEVATION (FROM SEA LEVEL)

K. HOLE #: CORE DESIGNATION NUMBER (AFTER SYNCRUDE) WITH PAGE NUMBER
e.g. 35-35-2 = HOLE NUMBER 35-35-00, PAGE 2

LITHOFACIES CODES FOR DRILL CORE DESCRIPTIONS

LITHOFACIES 1. mud
1A: flat to low angle laminated grey to tan mud
1B: flat laminated dark grey mud
1C: flat to low angle laminated dark grey calcareous mud
1D: structureless white to grey carbonaceous mud
1E: flat to low angle laminated white to grey carbonaceous mud

LITHOFACIES 2. massive to stratified white calcareous mud
2A: with mud intraclasts

LITHOFACIES 3. structureless sand
3A: with disorganized mud intraclasts

LITHOFACIES 4. flat to low angle planar stratified sand
4A: with interbedded or dispersed carbonaceous debris
4B: with mud intraclasts

LITHOFACIES 5. very fine large-scale cross-stratified sand
5A: with mud laminae and/or flasers
5B: with mud intraclasts

LITHOFACIES 6. muddy carbonaceous sand

LITHOFACIES 7. large-scale cross-stratified sand
7A: with mud drapes and/or composite sand and mud partings
7B: with mud intraclasts

LITHOFACIES 8. small-scale cross-stratified sand
8A: with mud drapes, flasers, and/or composite sand and mud partings

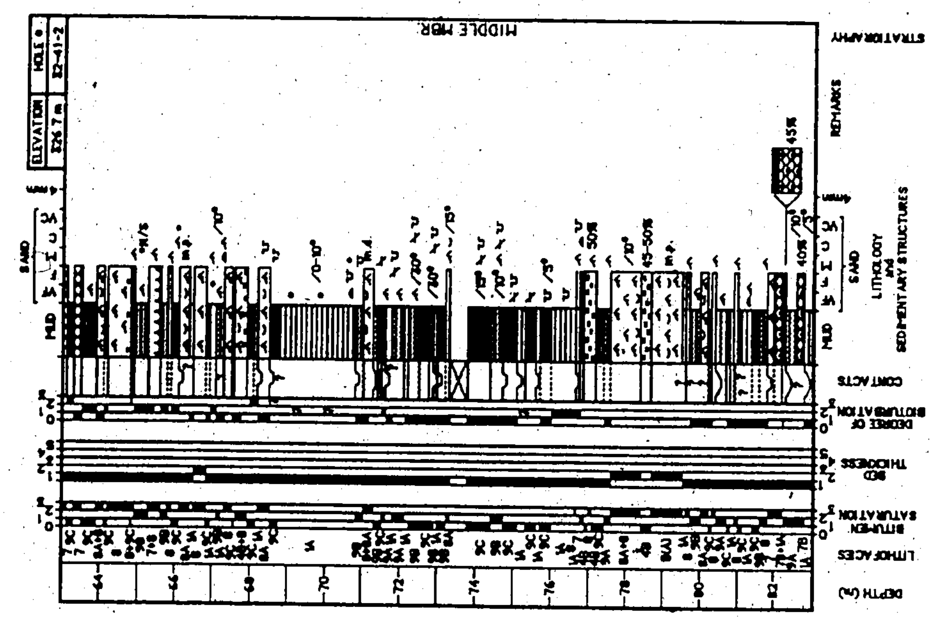
LITHOFACIES 9. interbedded sand and mud
9A: sand >> mud
9B: sand = mud
9C: sand << mud
9D: homogenized sand and mud

LITHOFACIES 10. heavily bioturbated muddy sand
10A: with mud drapes and/or composite sand and mud partings

LITHOFACIES 11. interbedded sand and calcareous mud
11A: sand >> mud
11B: sand = mud
11C: sand << mud

		LITHOFACIES DISTRIBUTION	
		common	rare
McMurray Formation	upper member	8A,10,10A	1B,3*,4,8,9A,9B,9C
	limy unit	4,7,8,8A,11A,11B,11C	1C,5,5A
	middle member	1A,7,7A,8,8A,9A,9B,9C,9D	3*,3A,4,4A,4B,5,5A,5B,7A
	lower member	1D,1E,2,2A,6,7	4,8,9B,9C,9D

* high bitumen saturation enhances occurrence.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REMARKS
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
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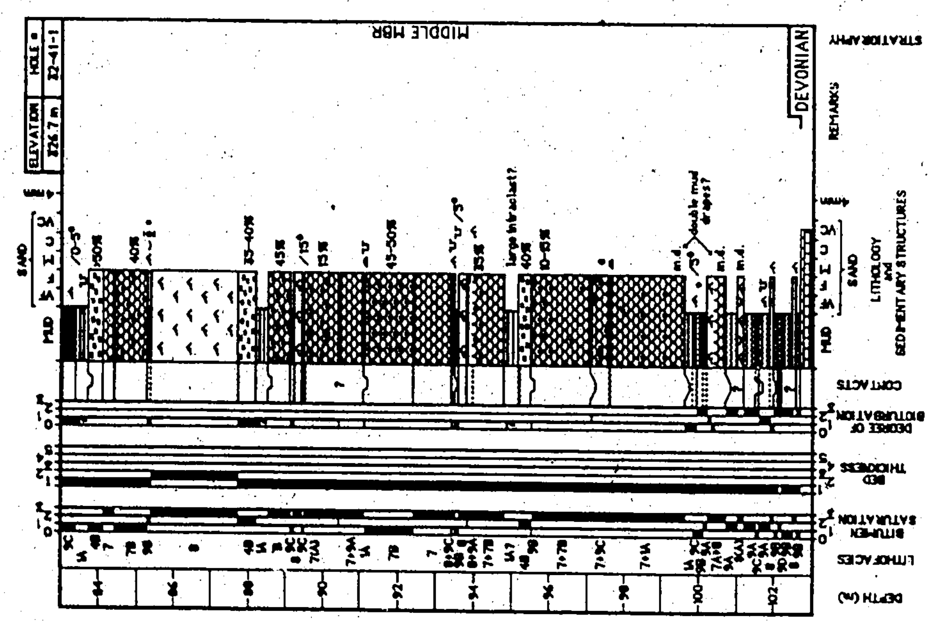
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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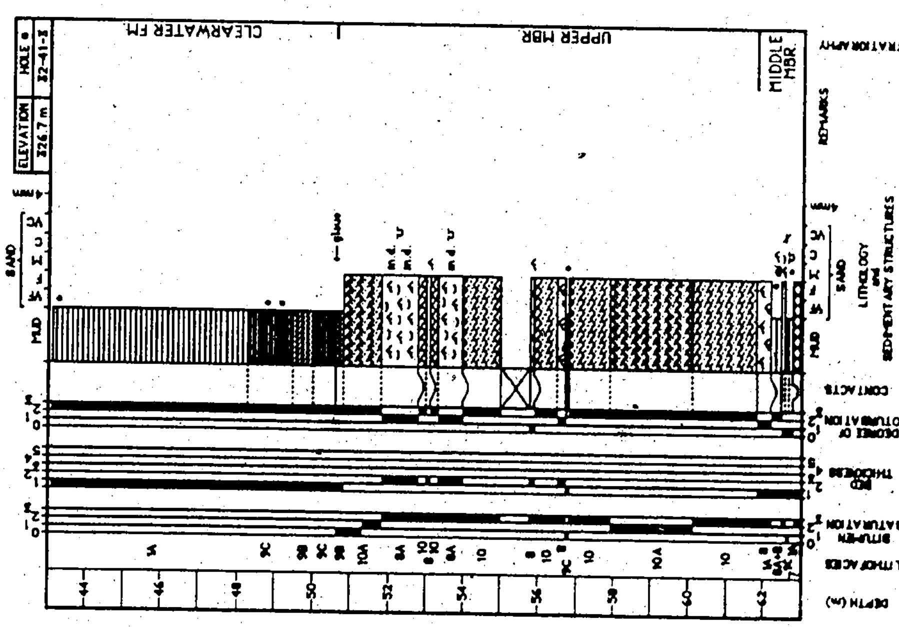
LITHOFACIES
DEPTH (m)



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ELEVATION
326.7 m
STRATIGRAPHY
REMARKS
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CONTACTS
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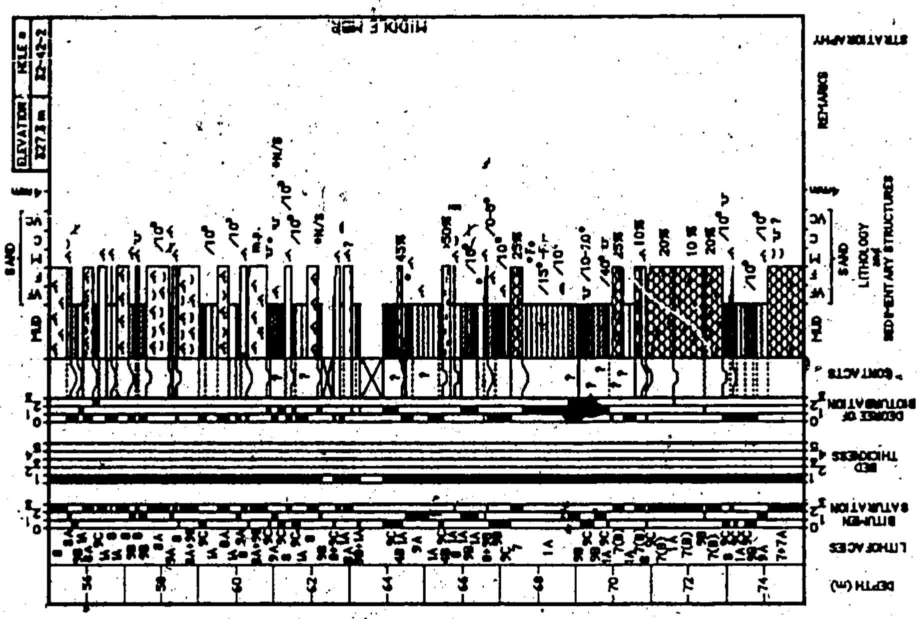
LITHOFACIES
DEPTH (m)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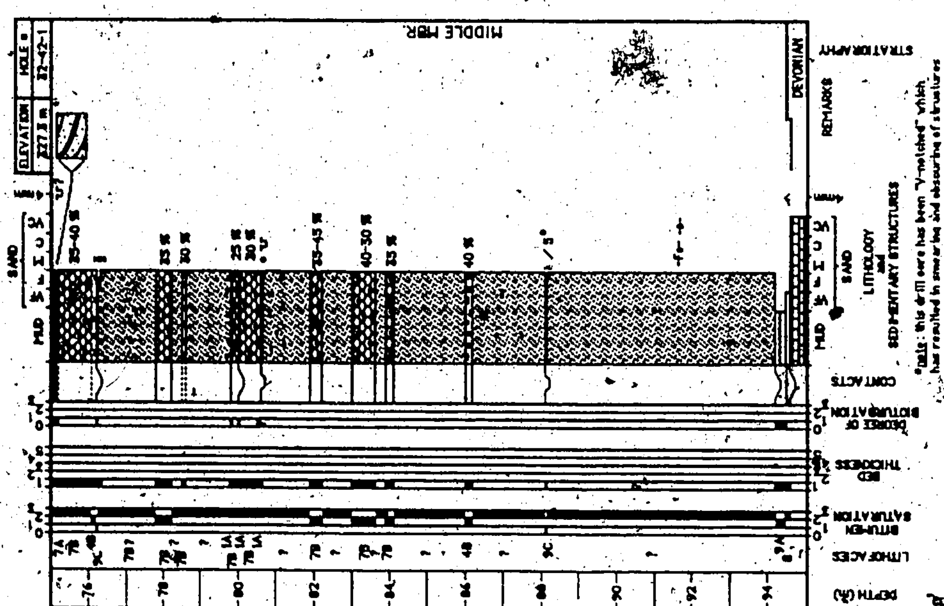
LITHOFACIES
DEPTH (m)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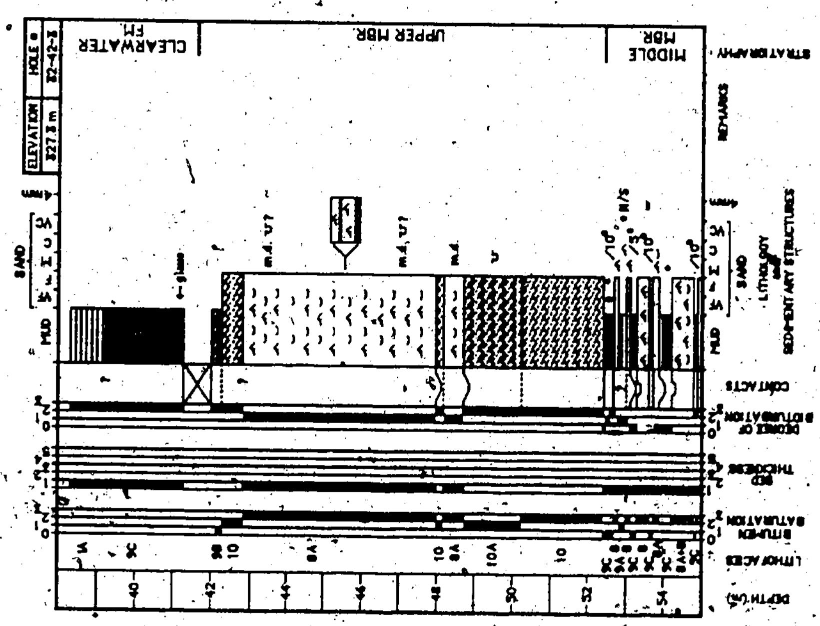
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CONTACTS
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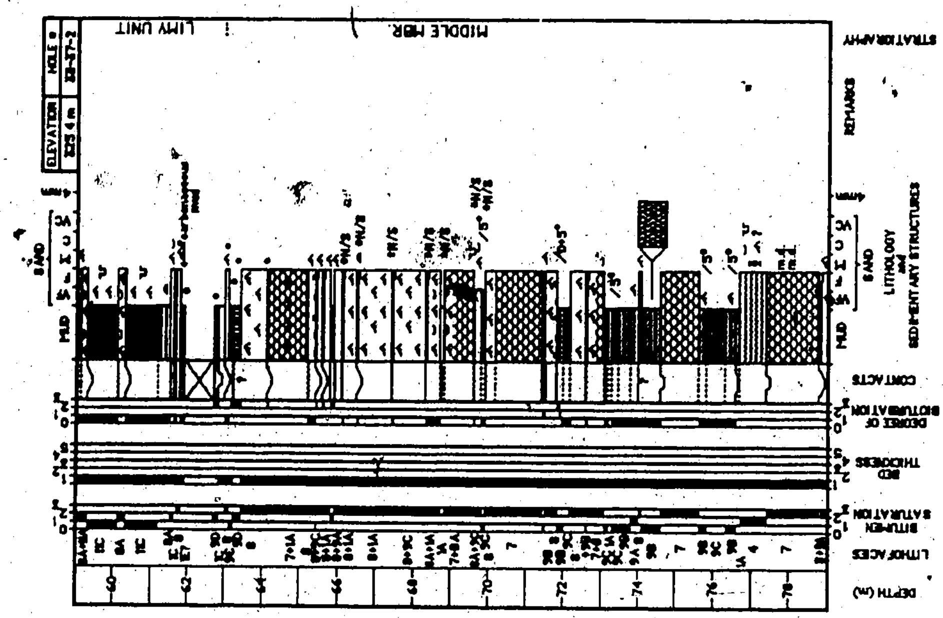

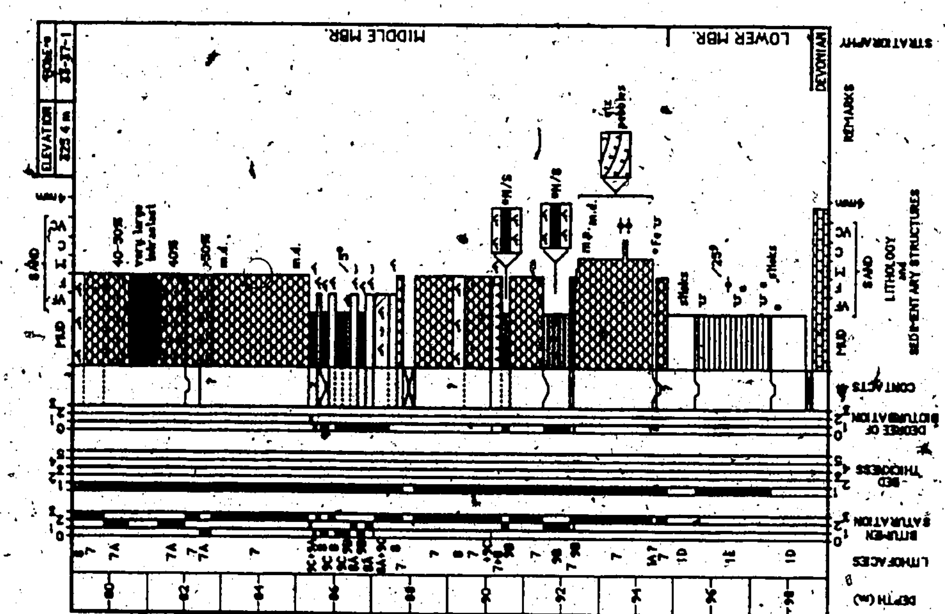

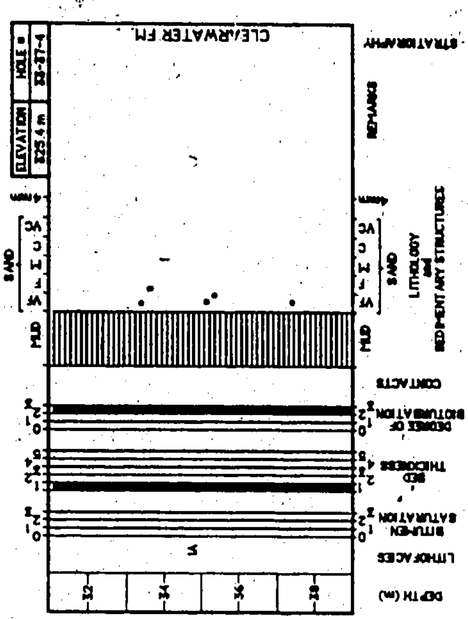
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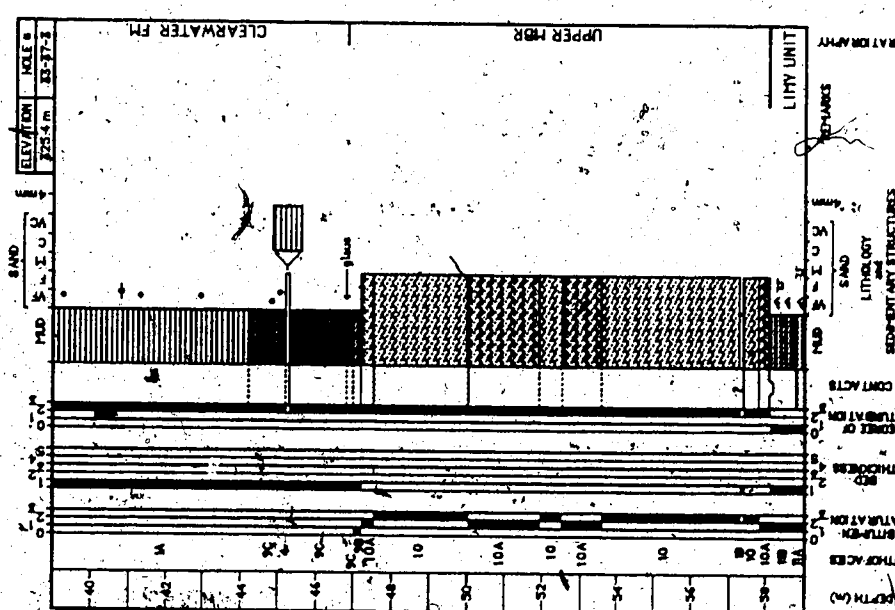
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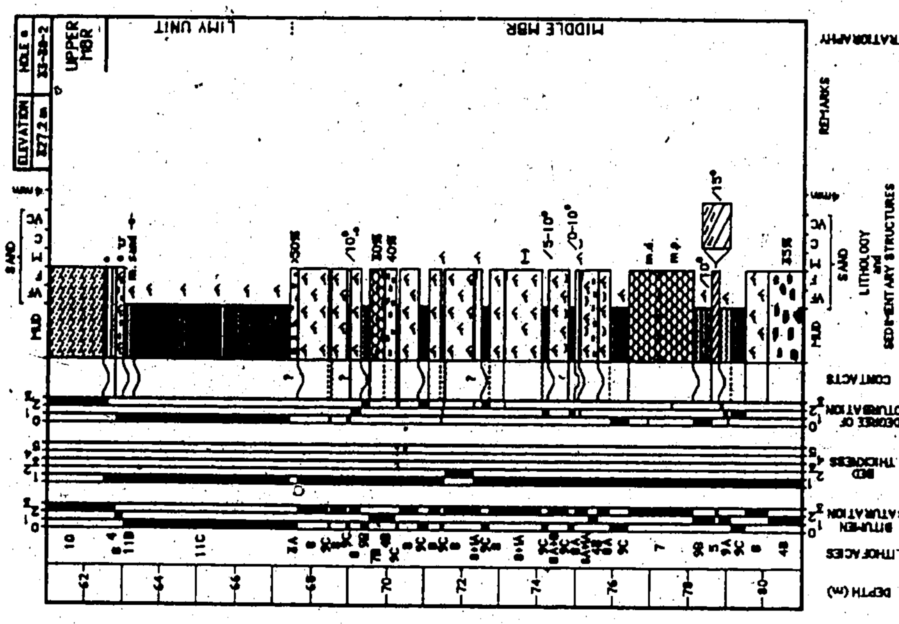

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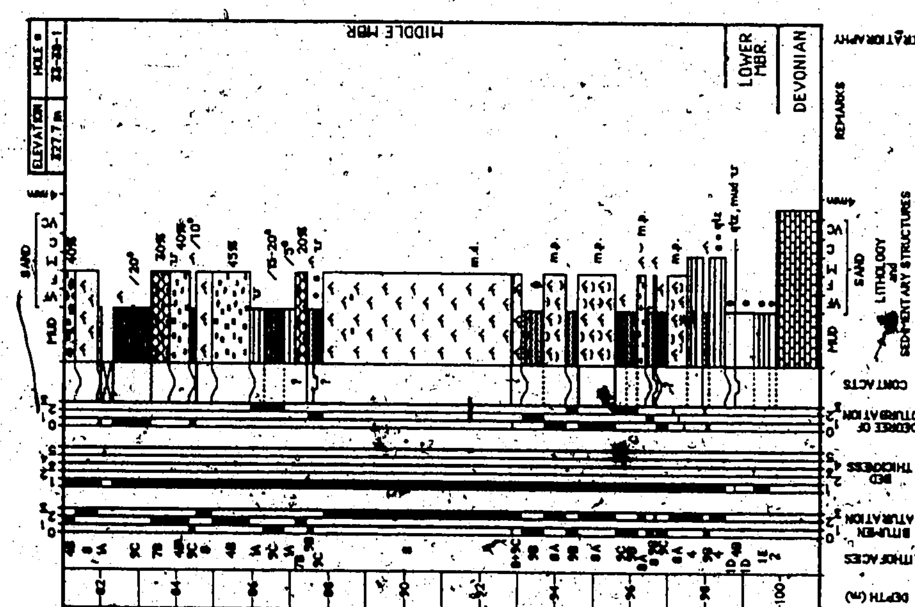

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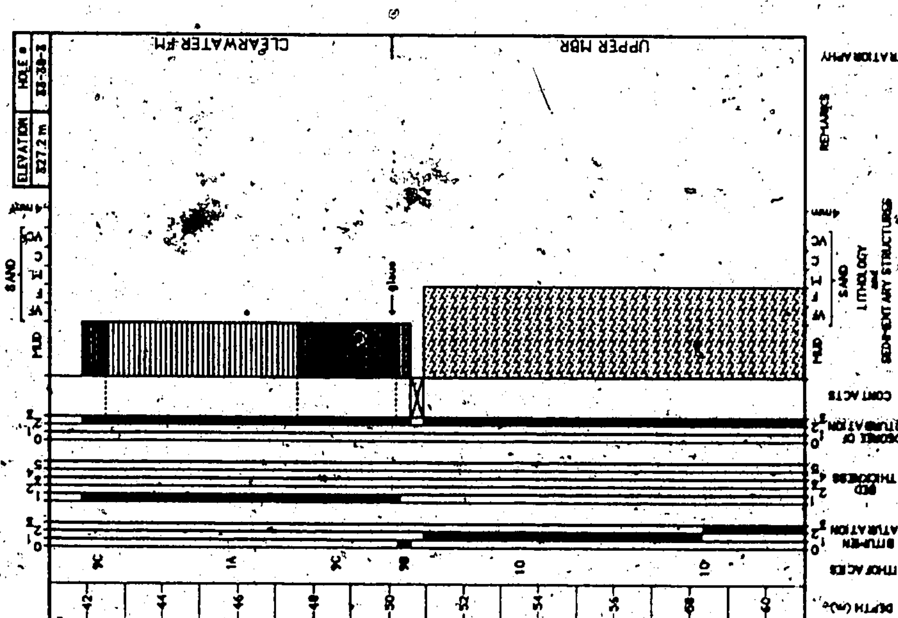
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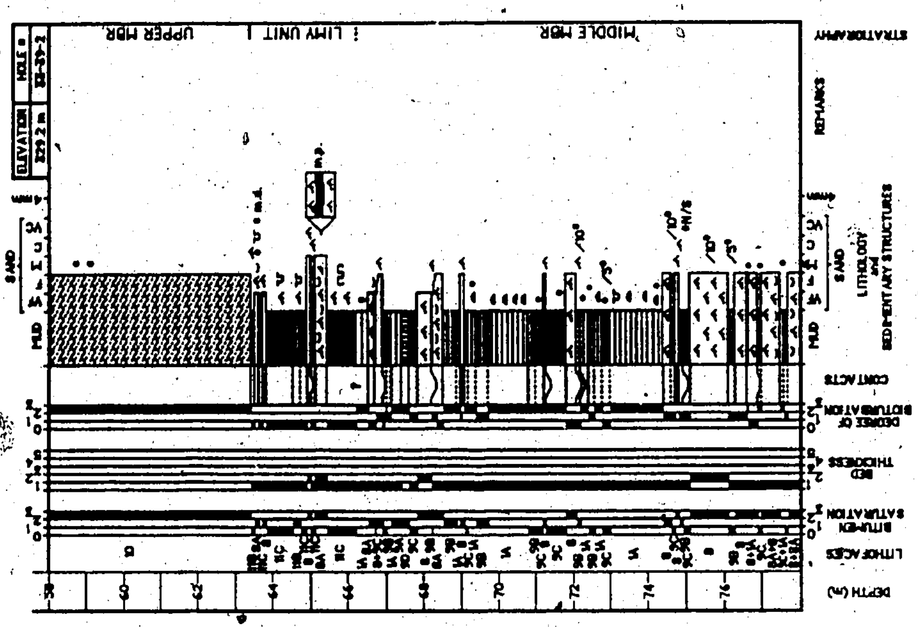
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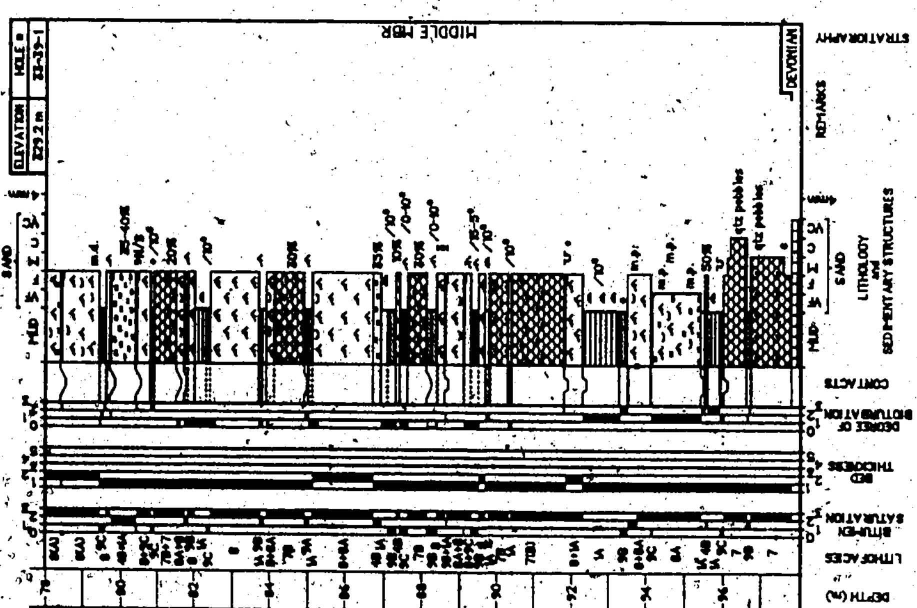
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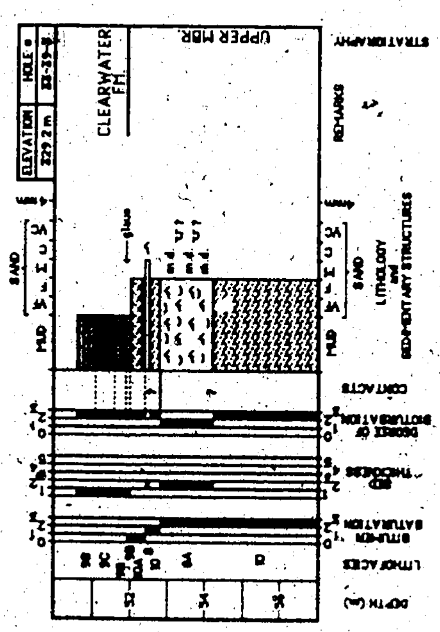
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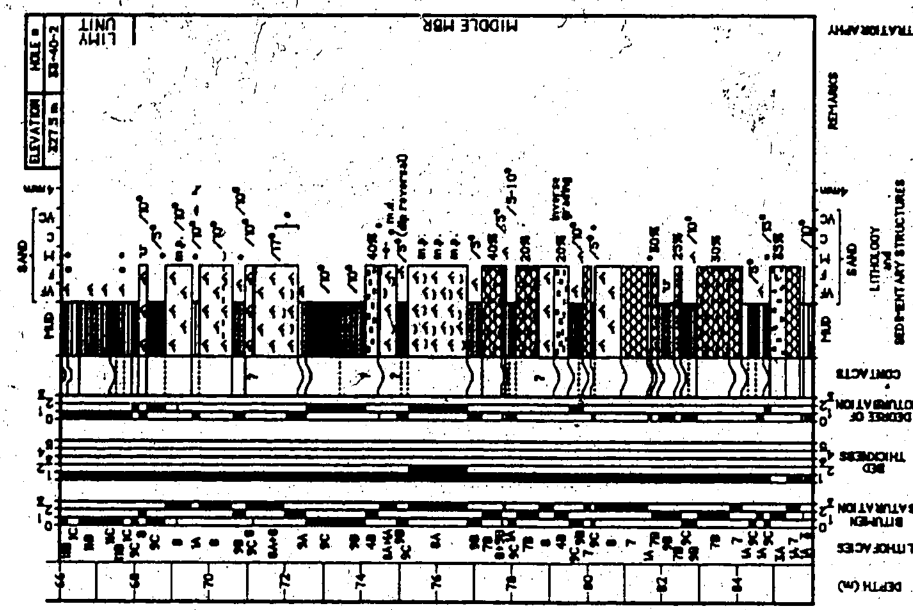
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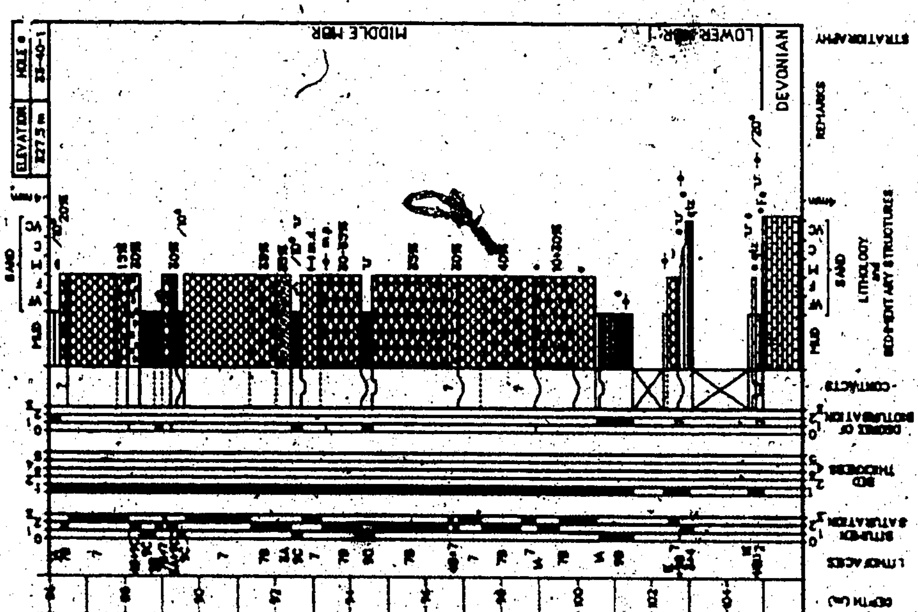
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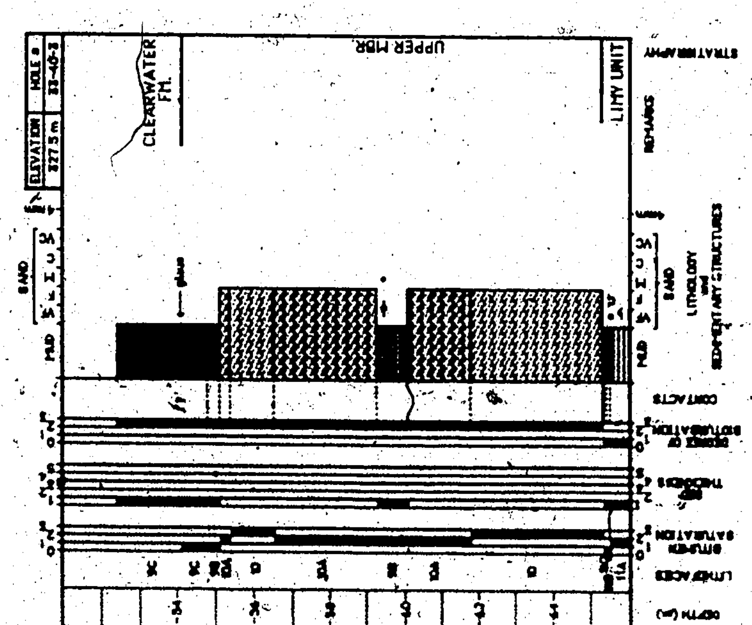
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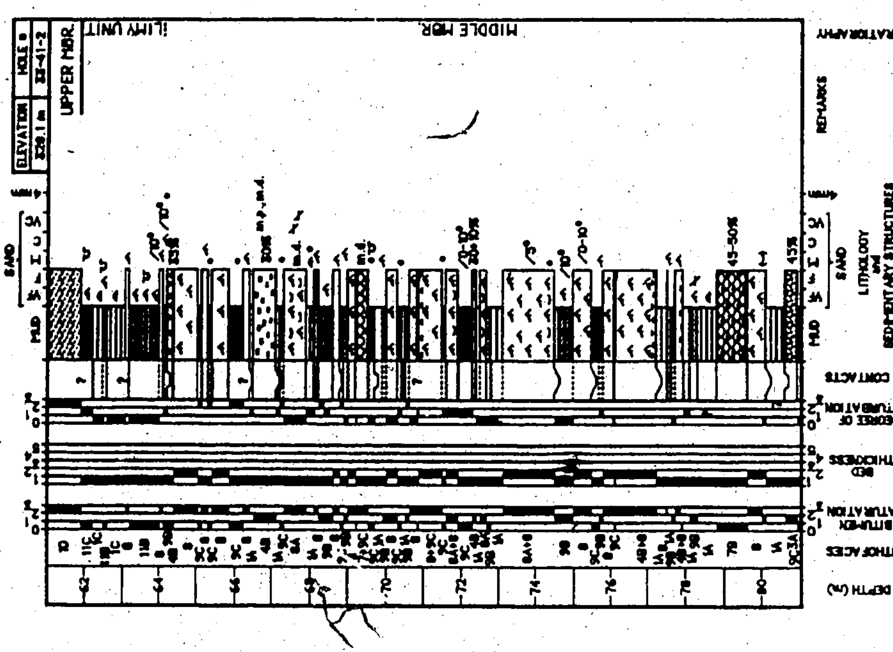
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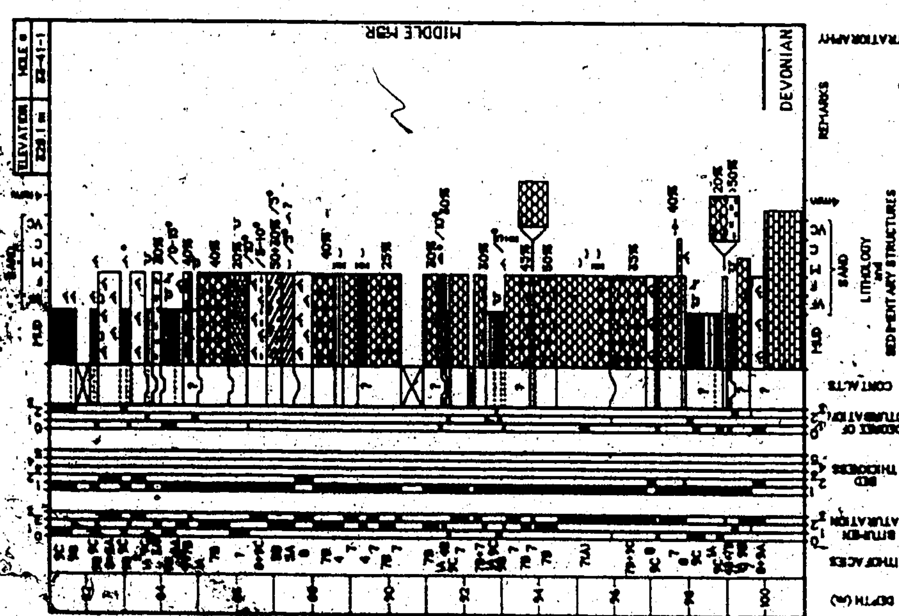
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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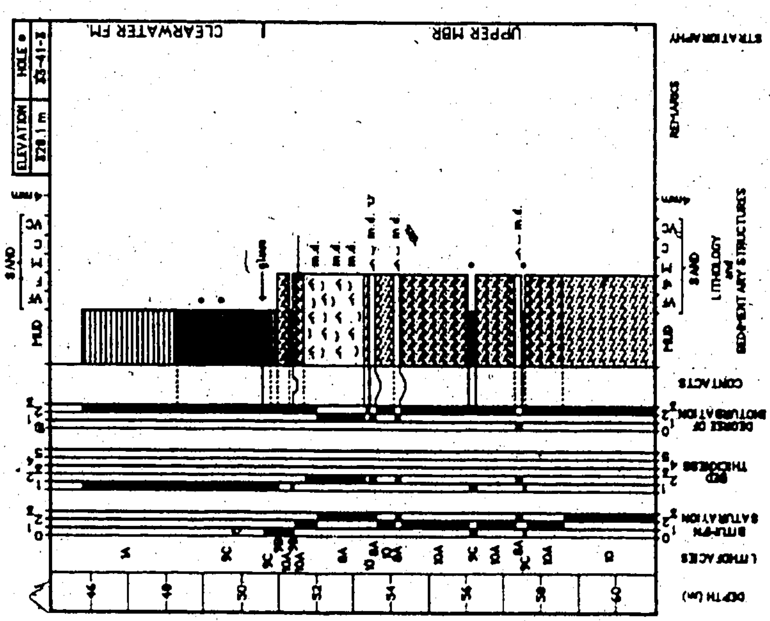
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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DEGREE OF BIOTURBATION
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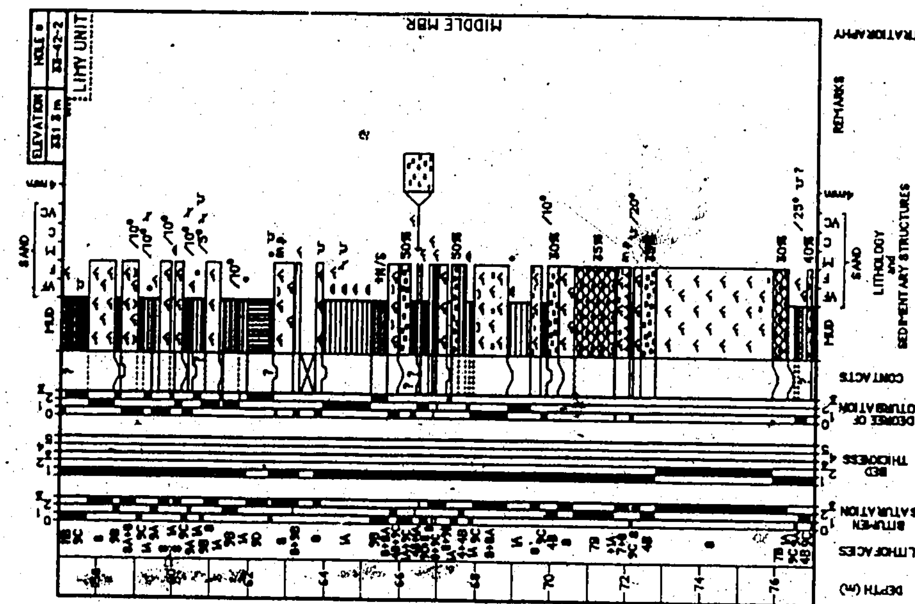
CLEARWATER FM.
ELEVATION
HOLE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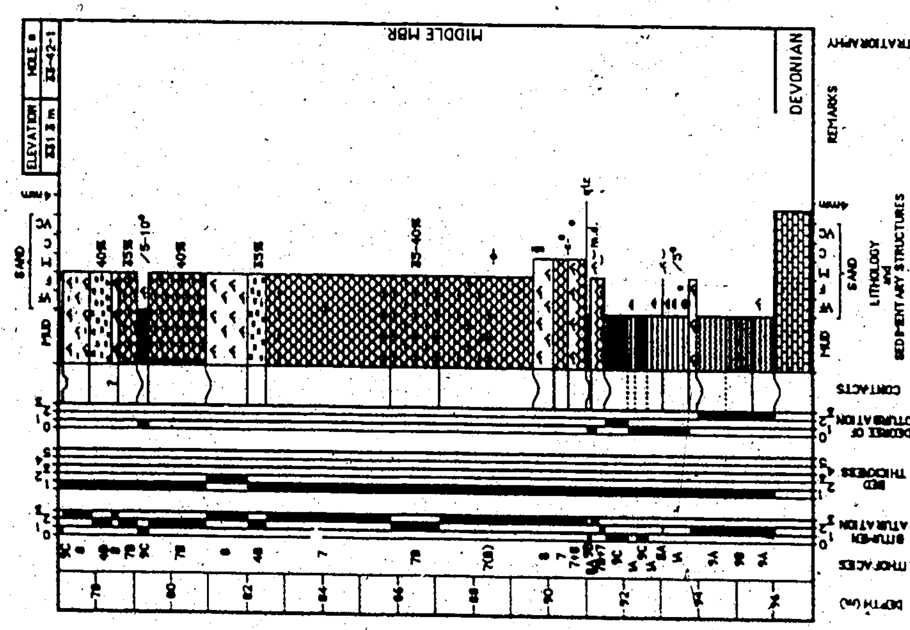
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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BITUMEN SATURATION
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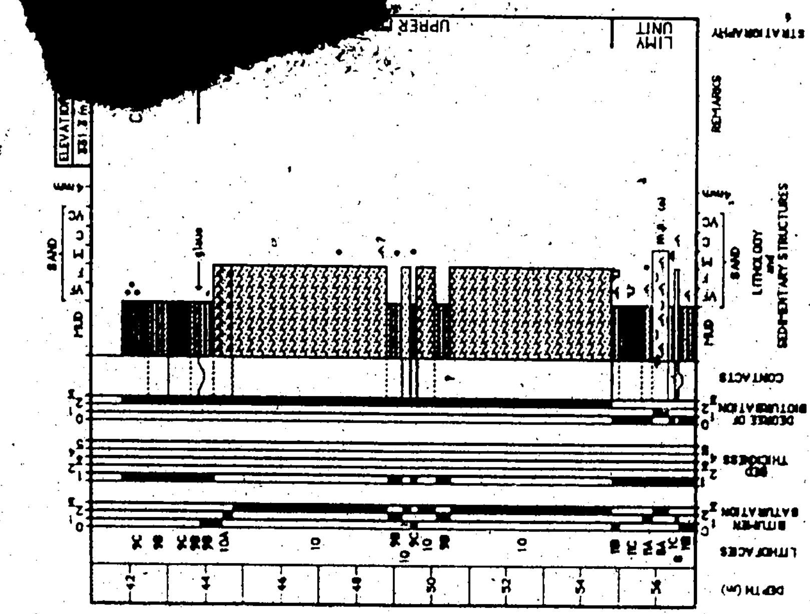

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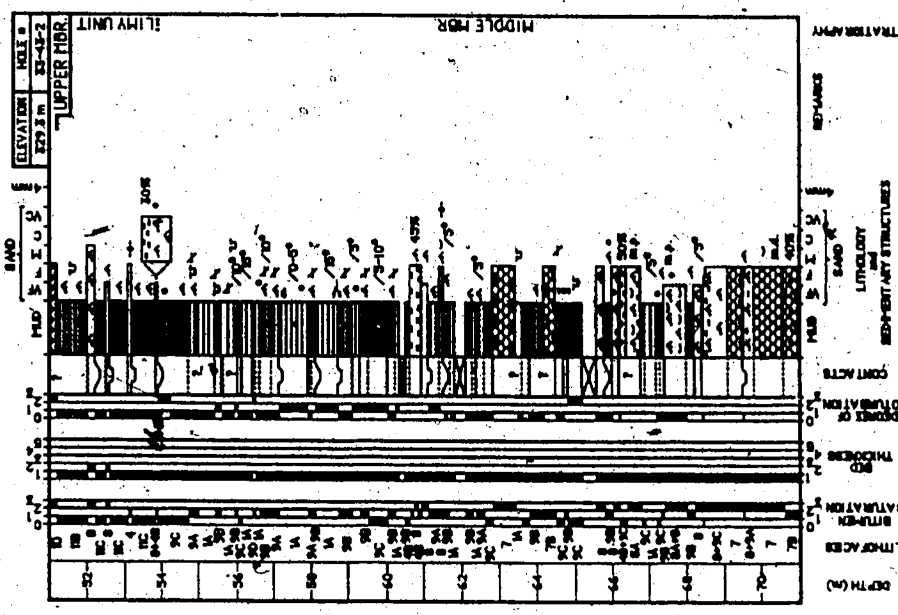
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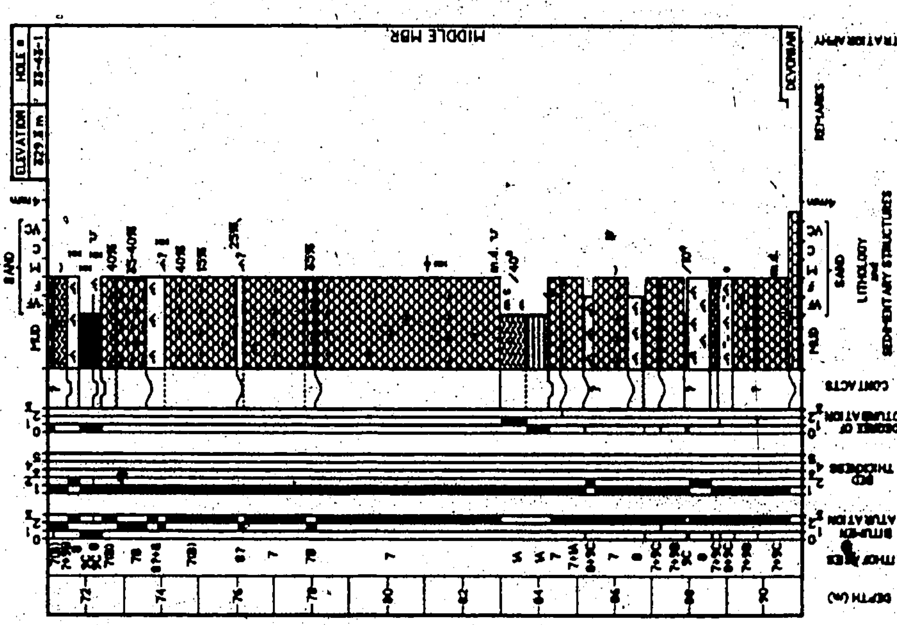
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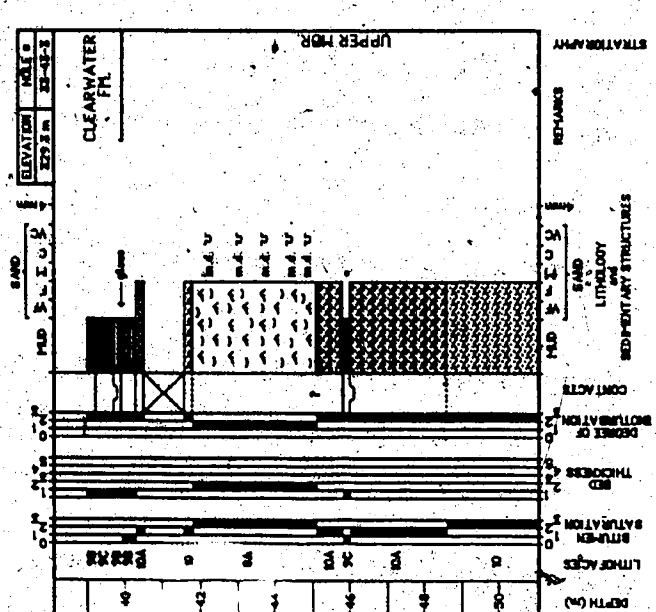
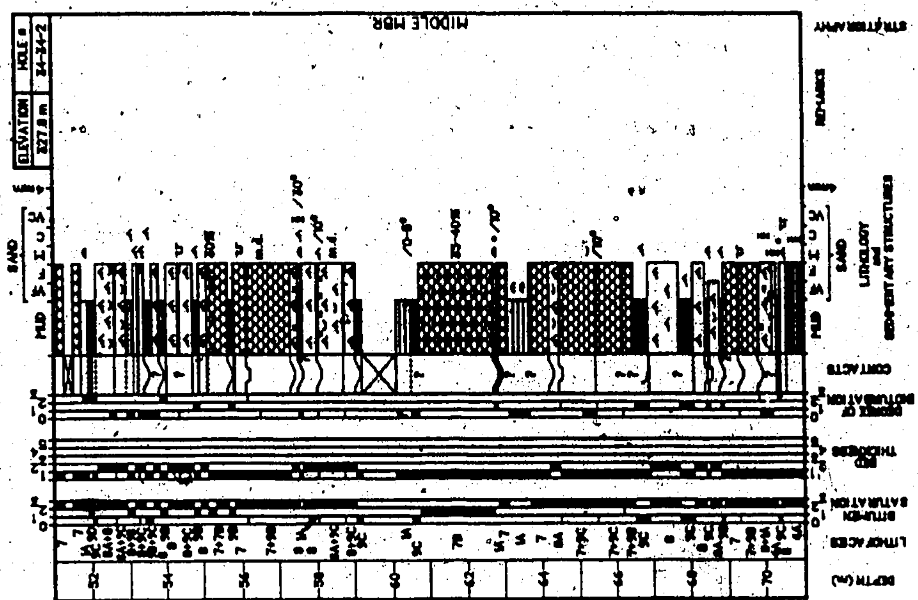
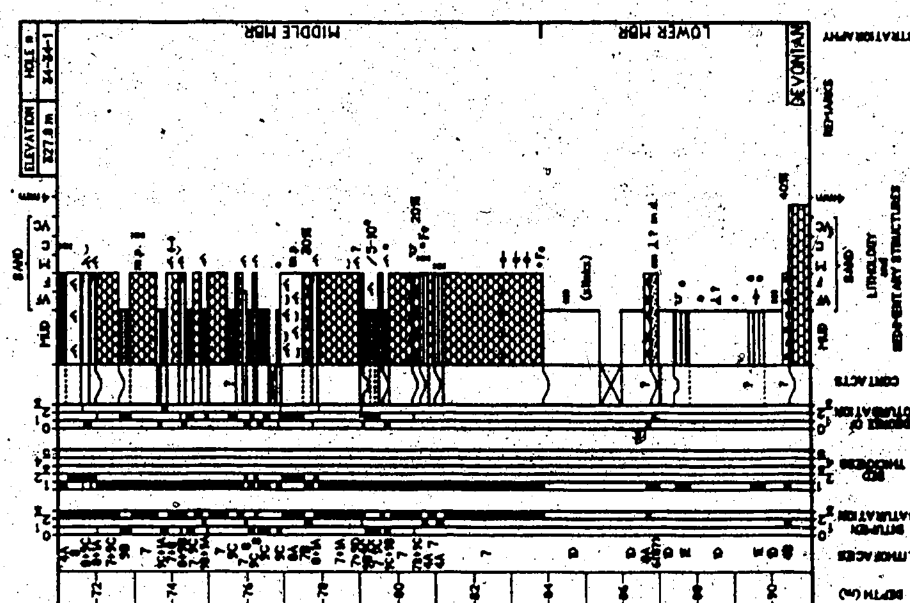
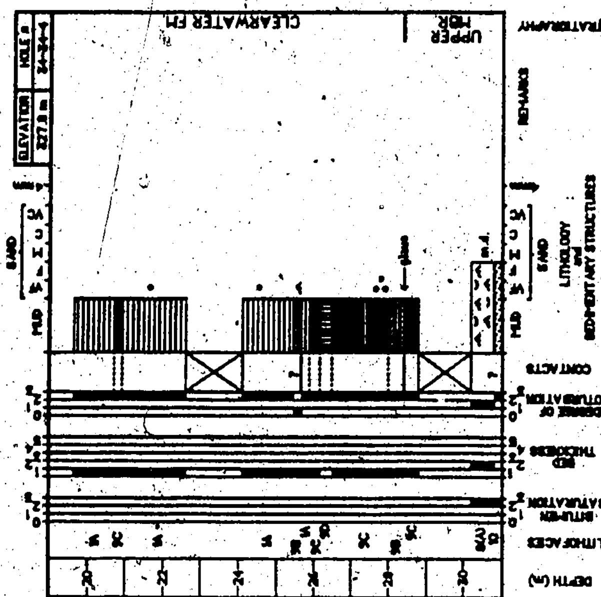
DEPTH (m)





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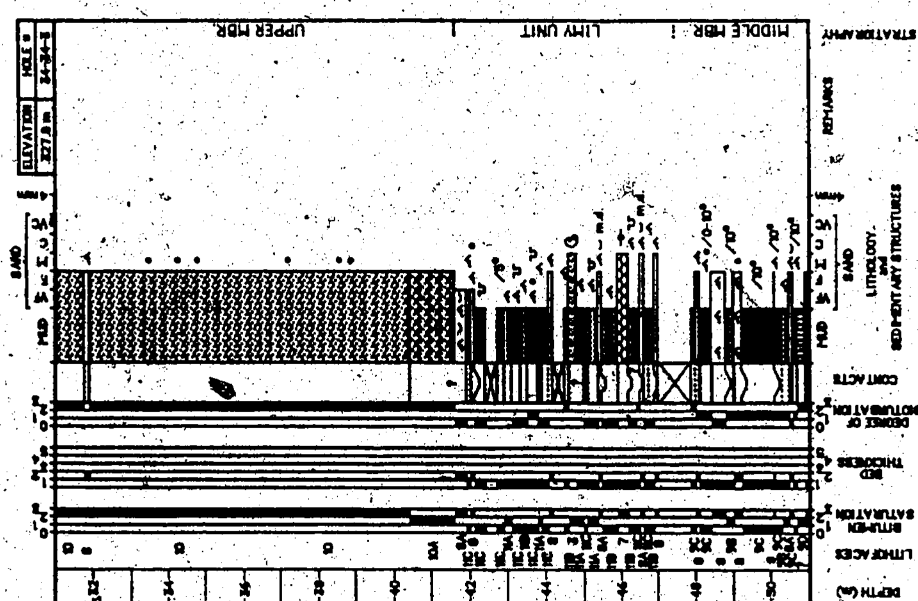
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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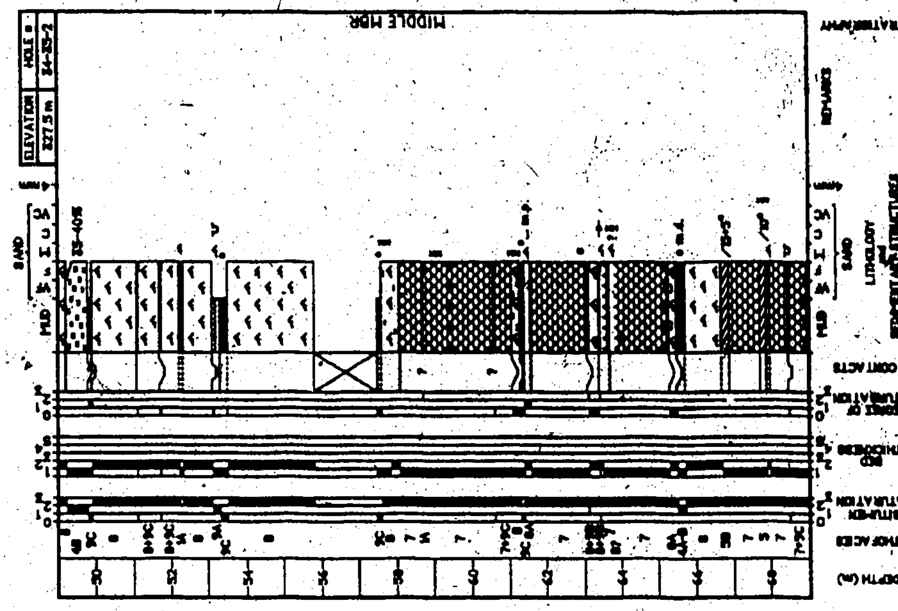
LITHOFACIES
DEPTH (m)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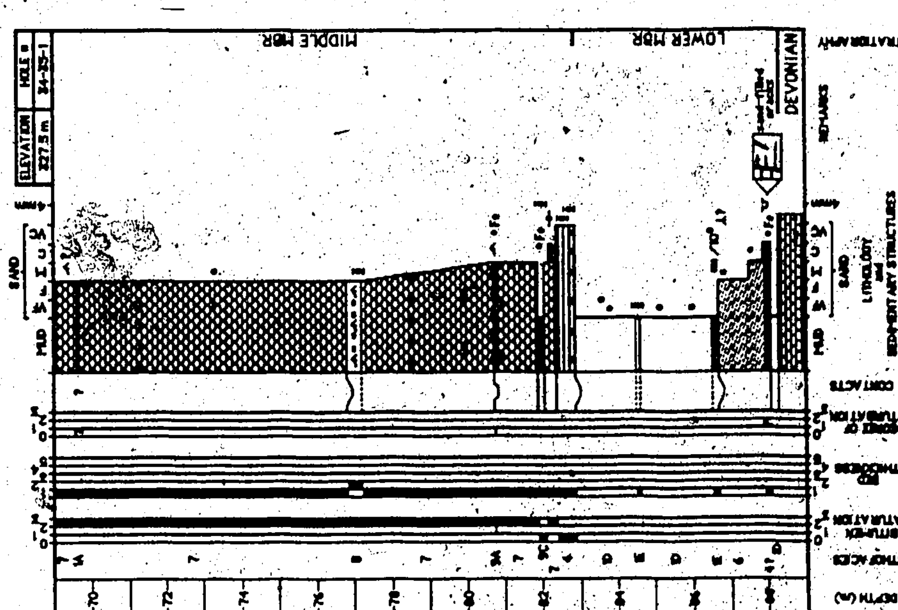
MIDDLE MBR
LOWER MBR
DEVONIAN
ELEVATION
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STRATIGRAPHY
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CONTACTS
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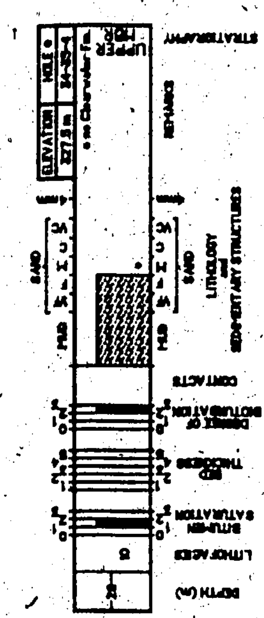
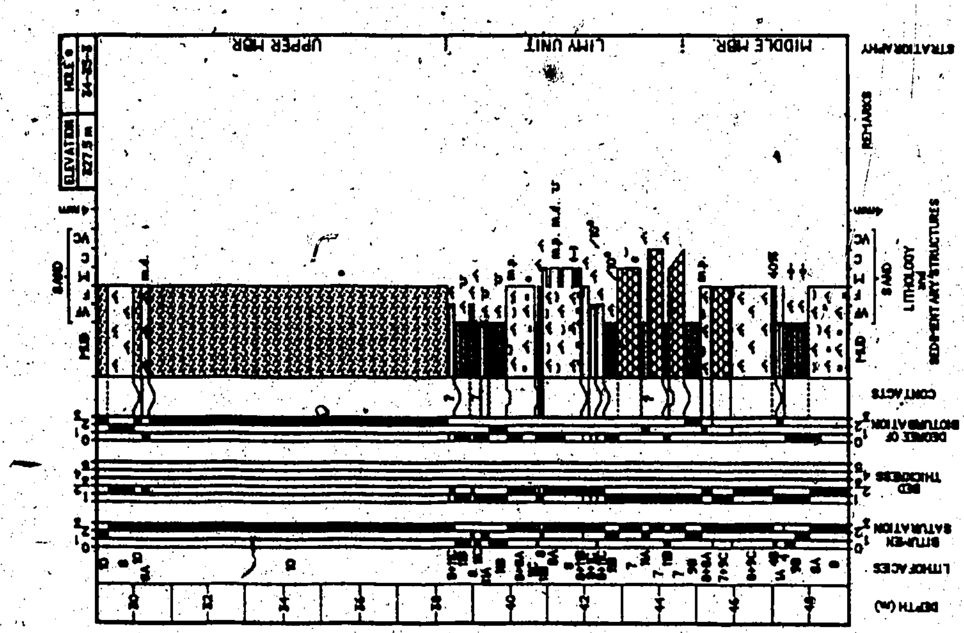
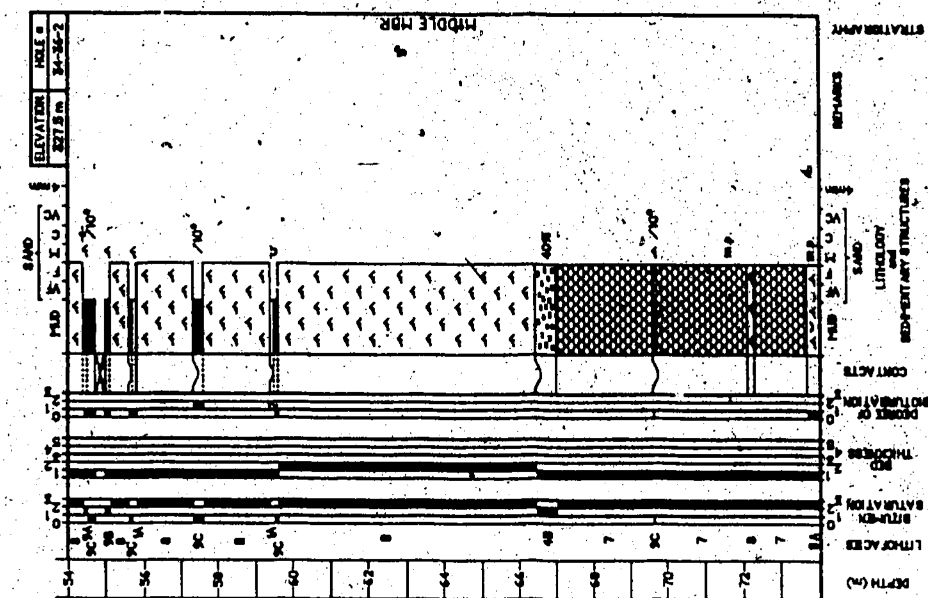
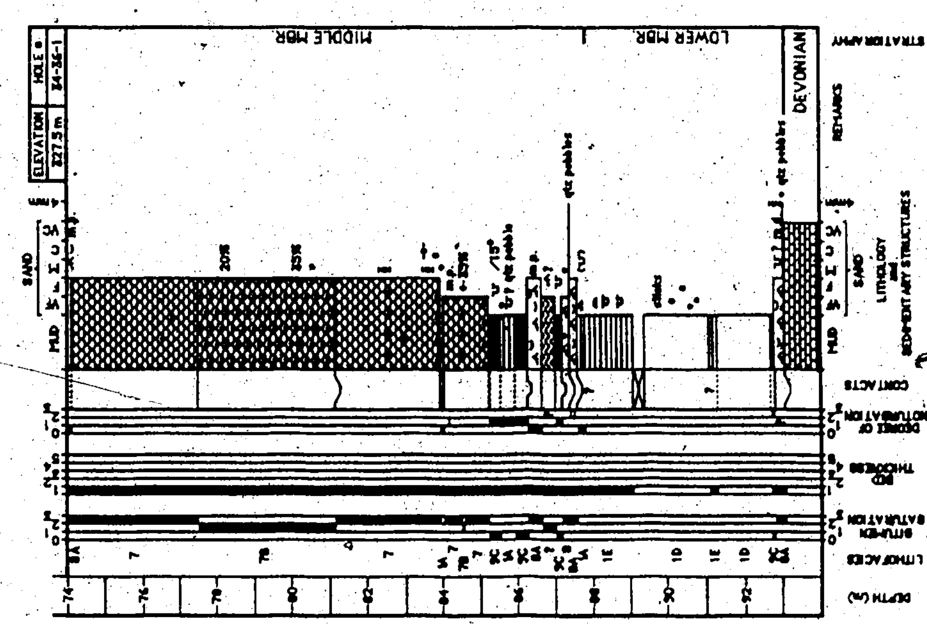
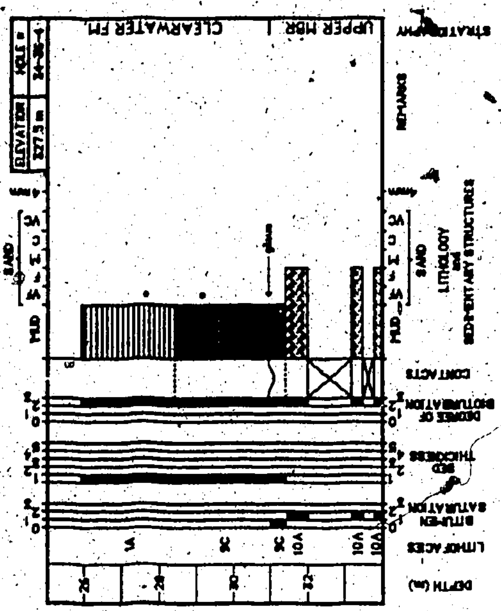
DEPTH (m)

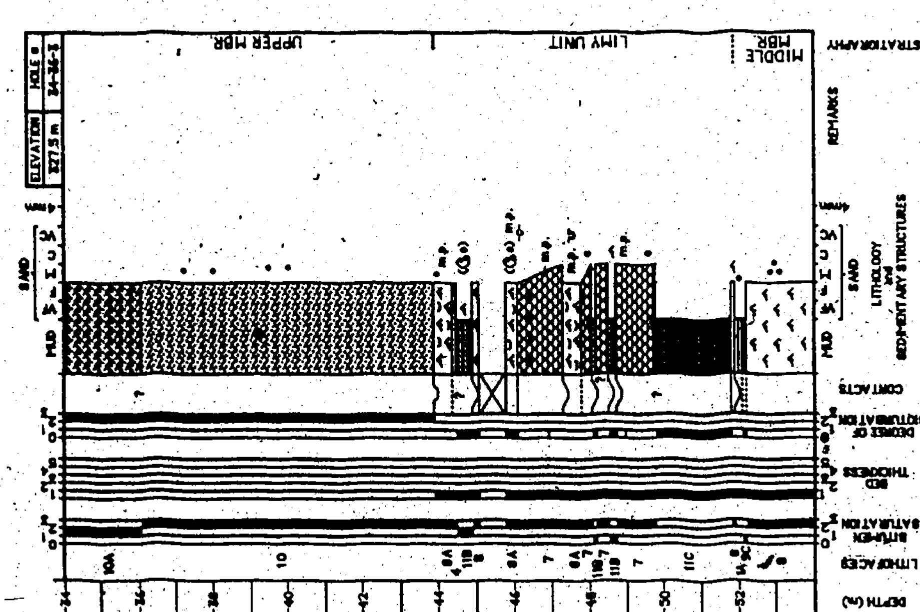


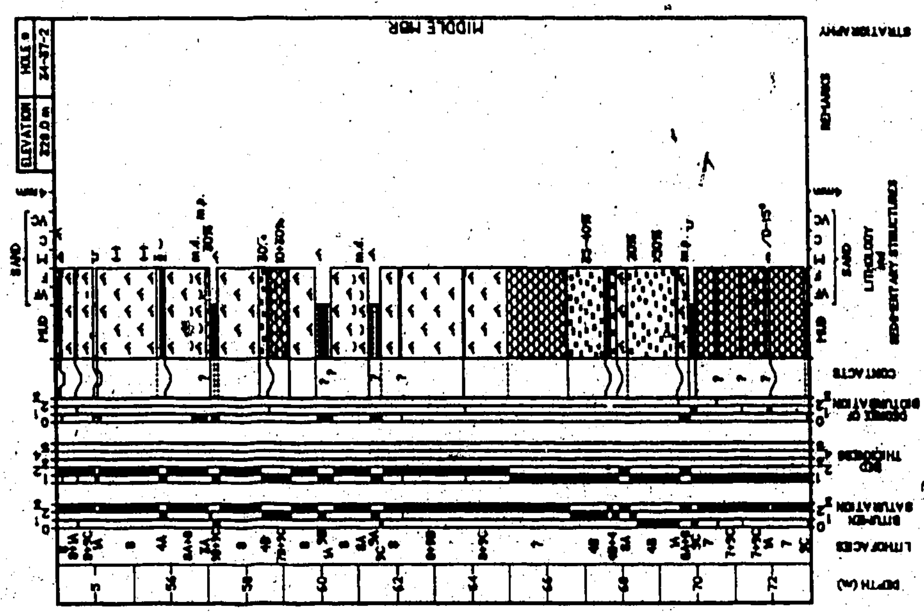


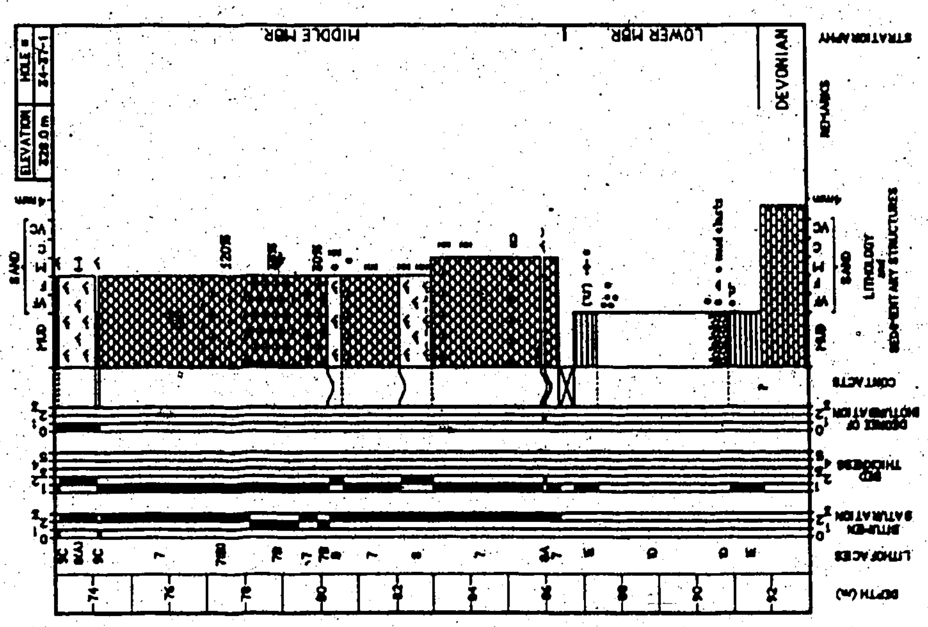


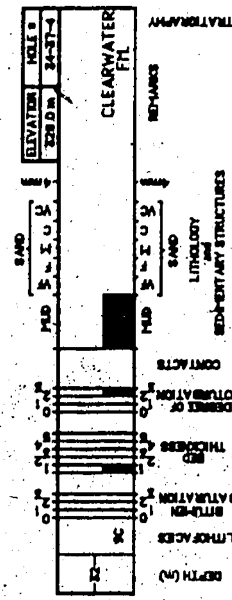








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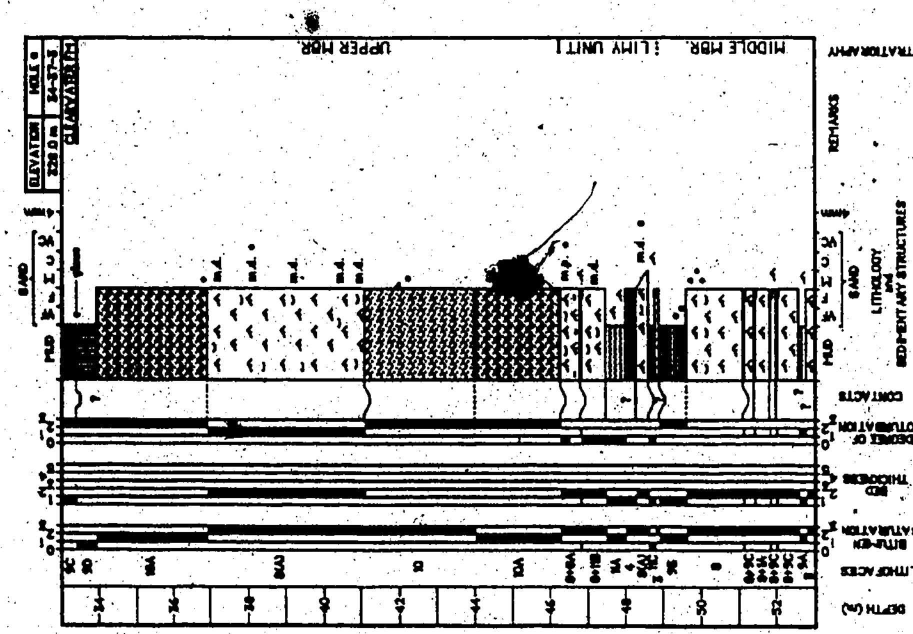
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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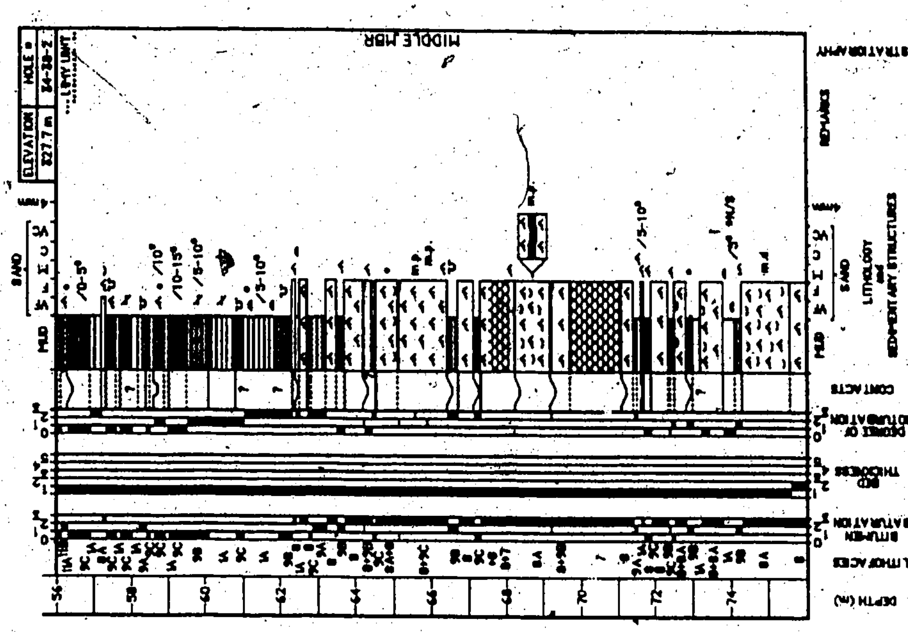

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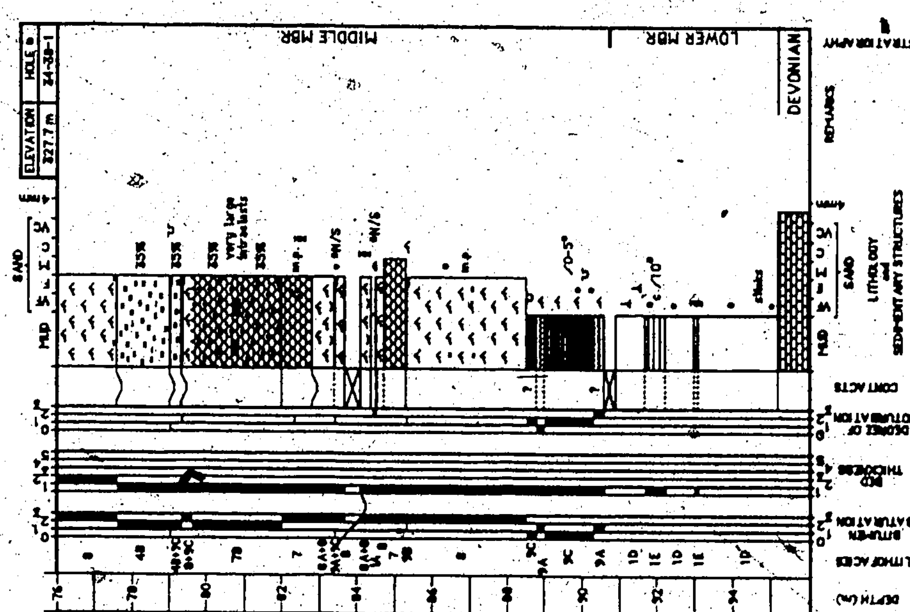

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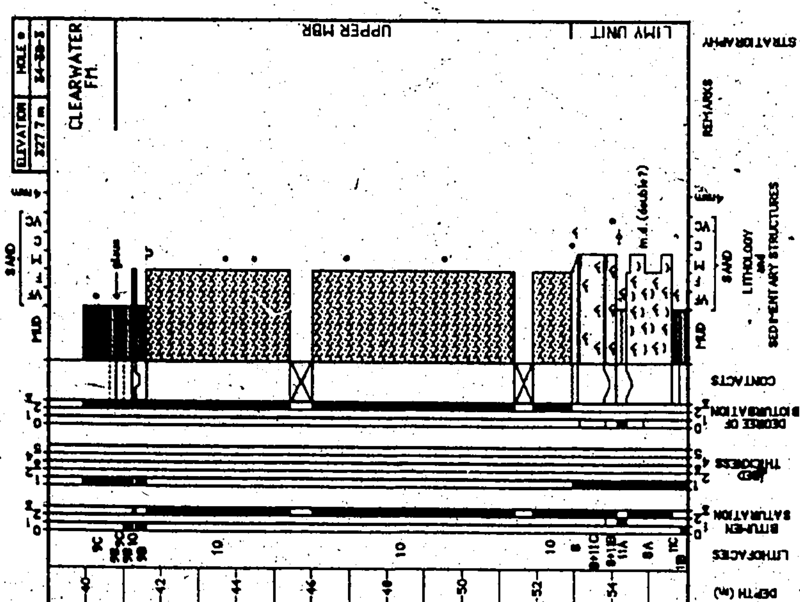

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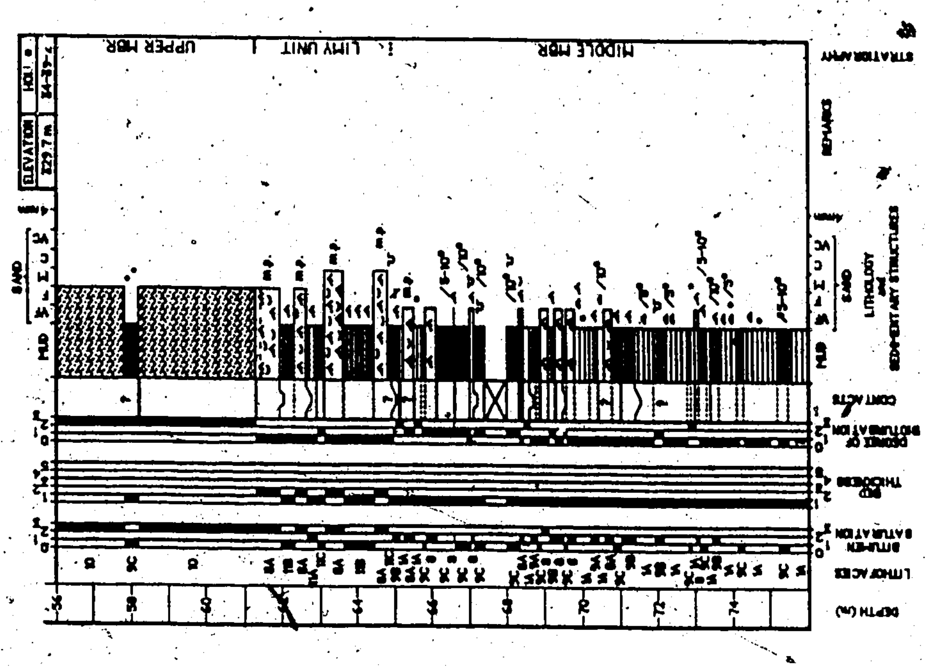
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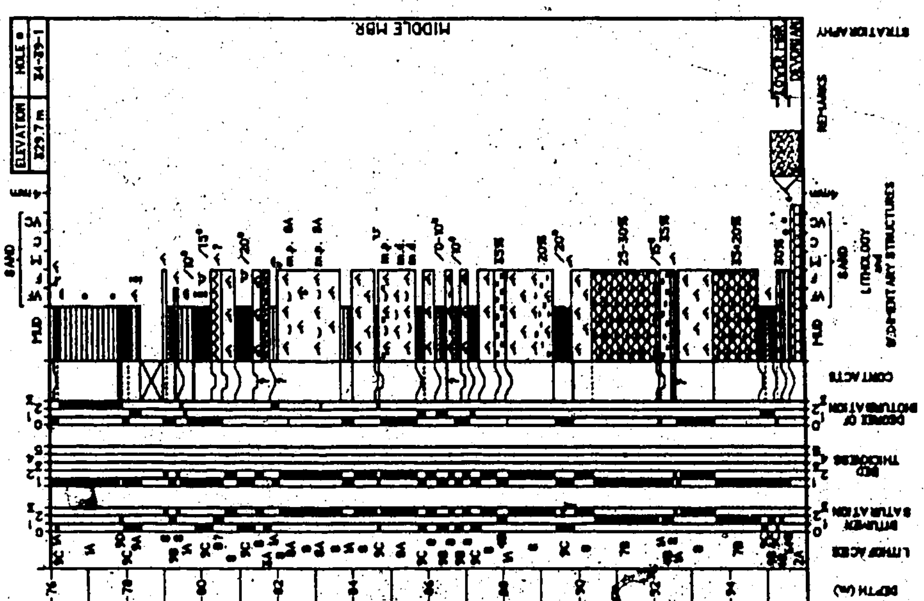
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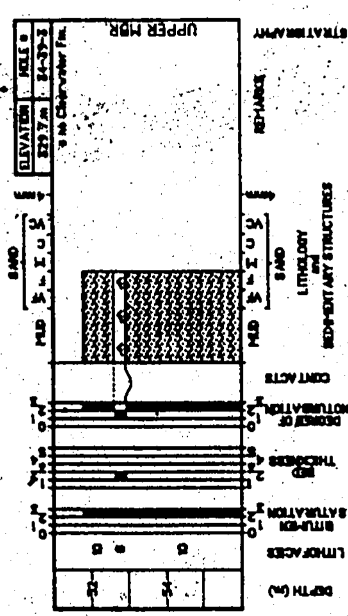
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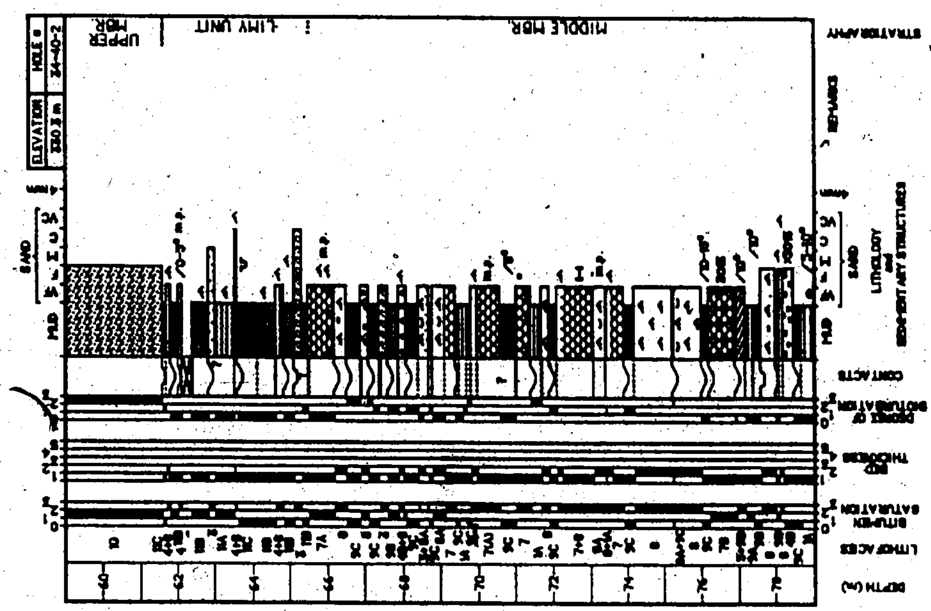
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LIMY UNIT
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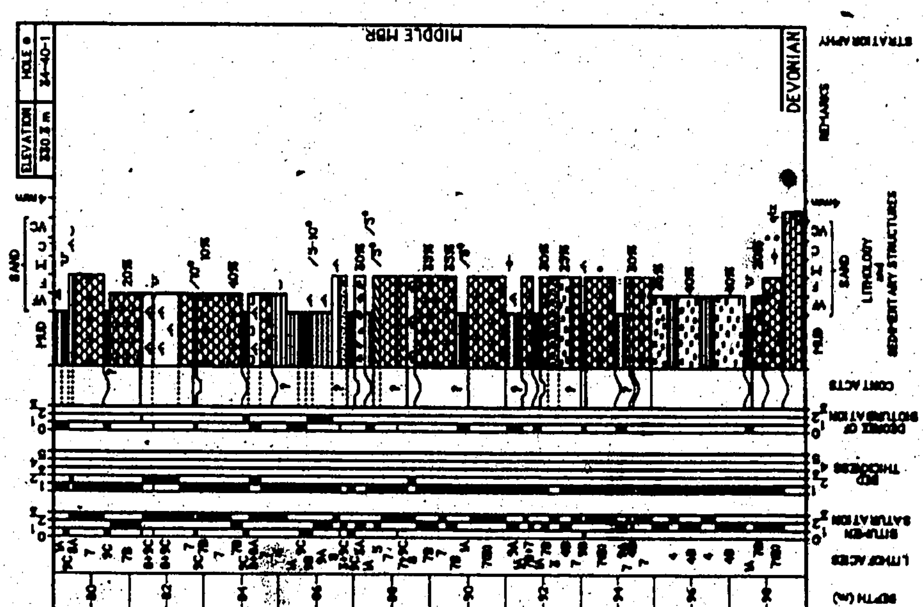
LITHOFACIES
DEPTH (m)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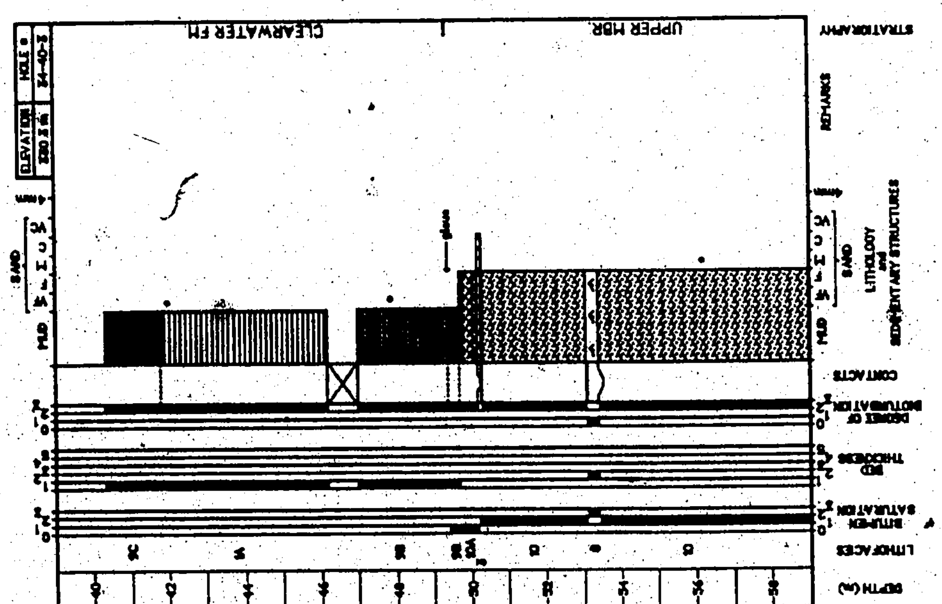
DEPTH (m)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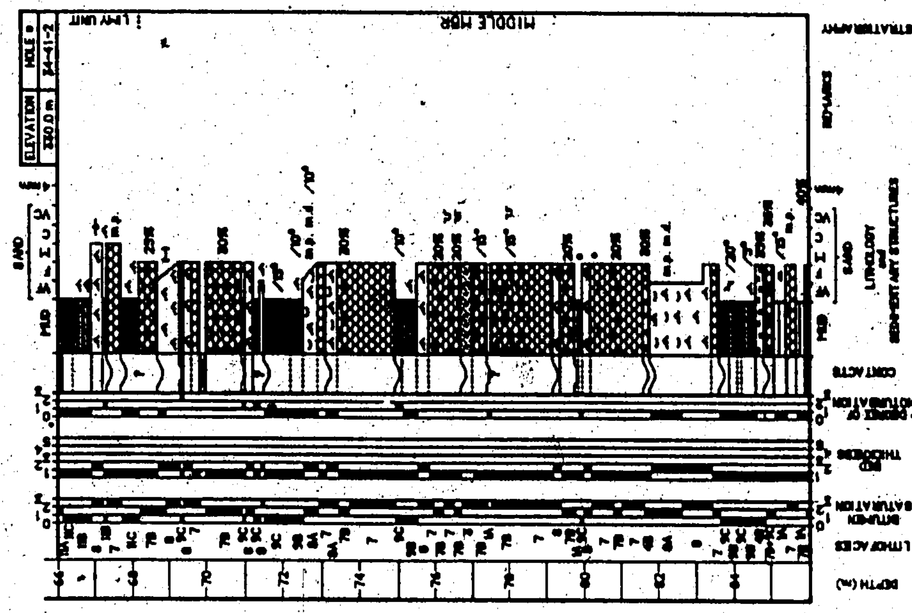
ELEVATION
HOLE #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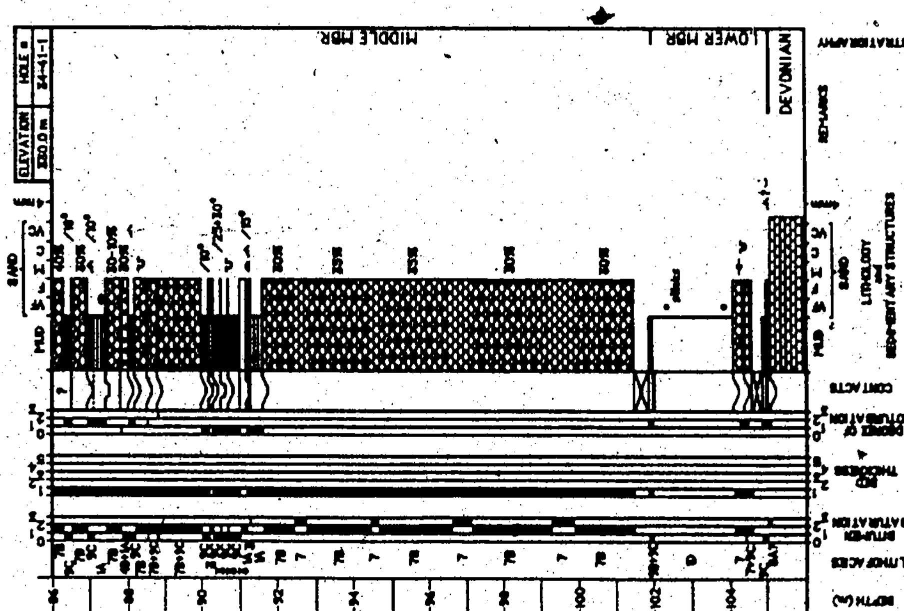
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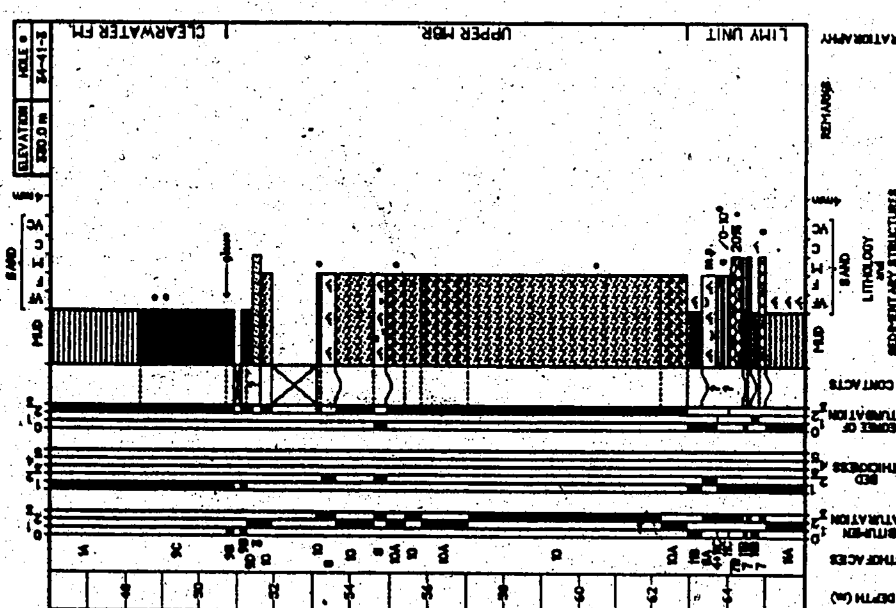
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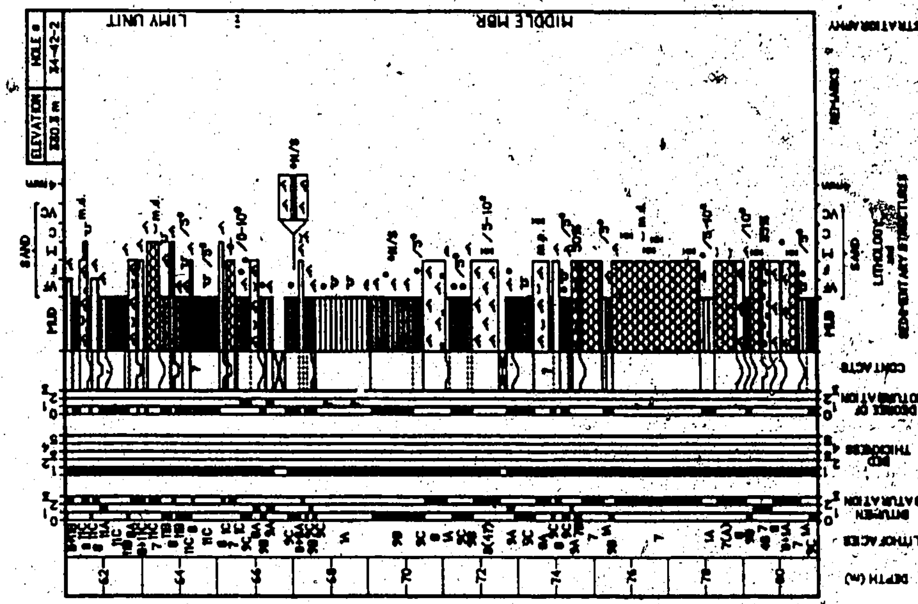
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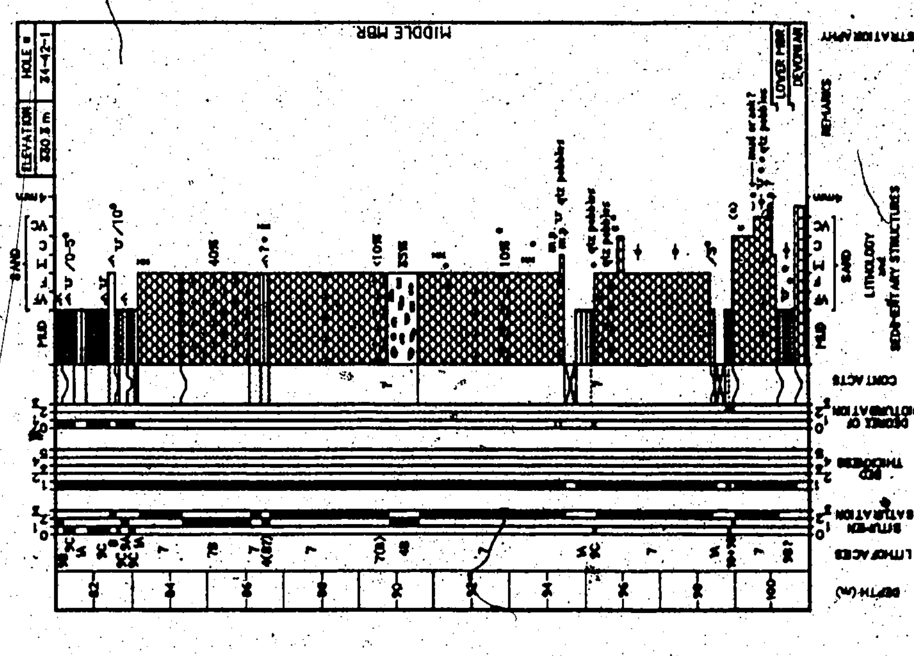
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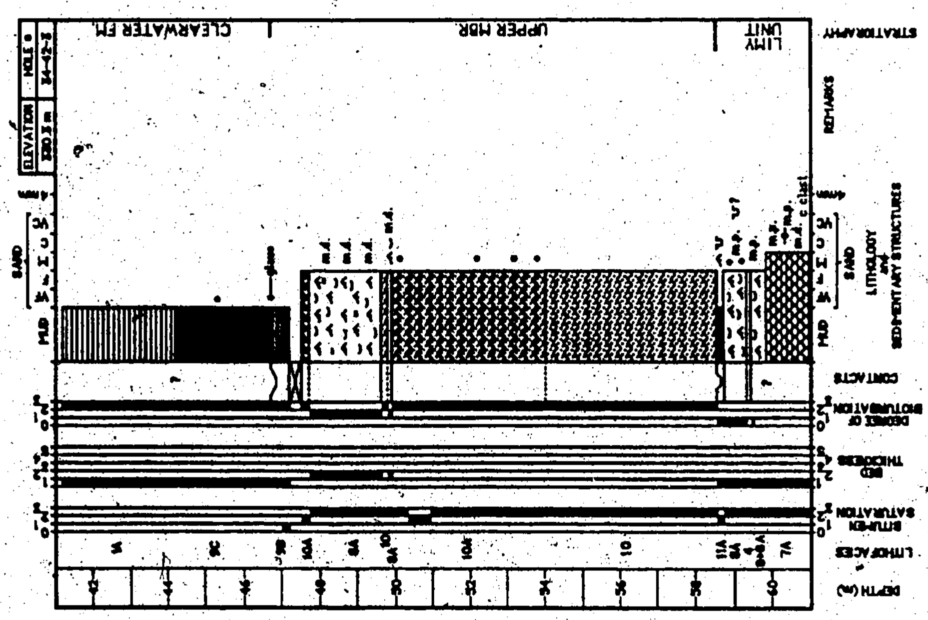
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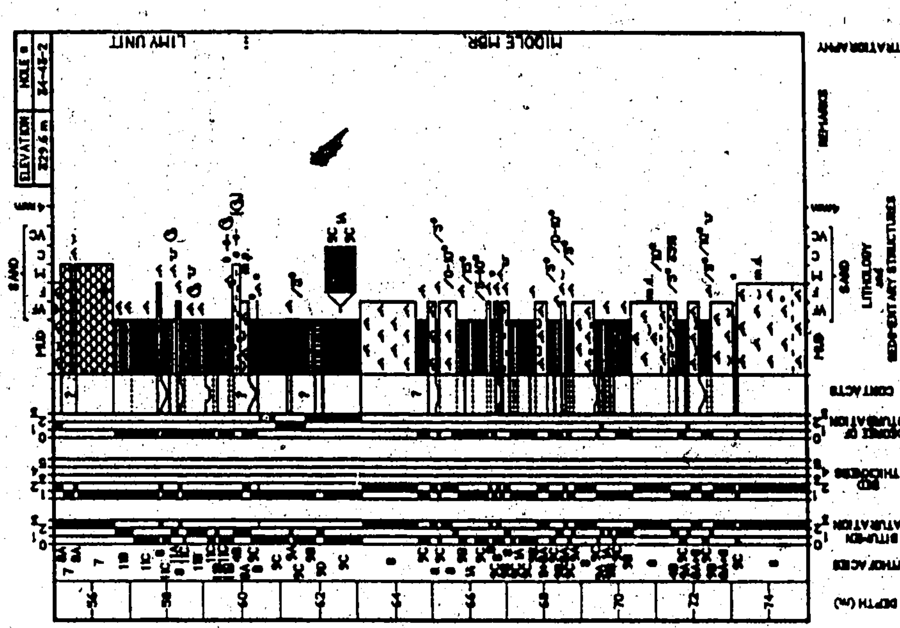

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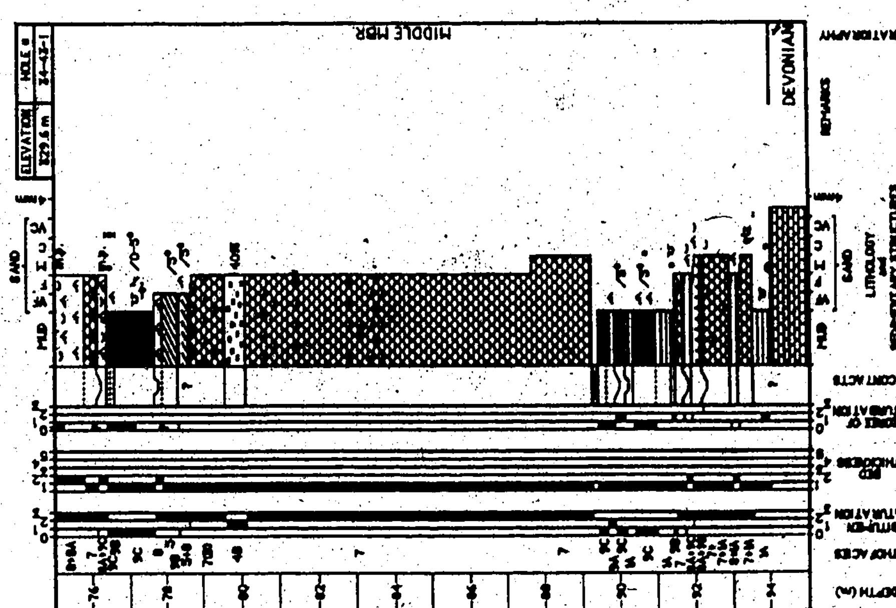

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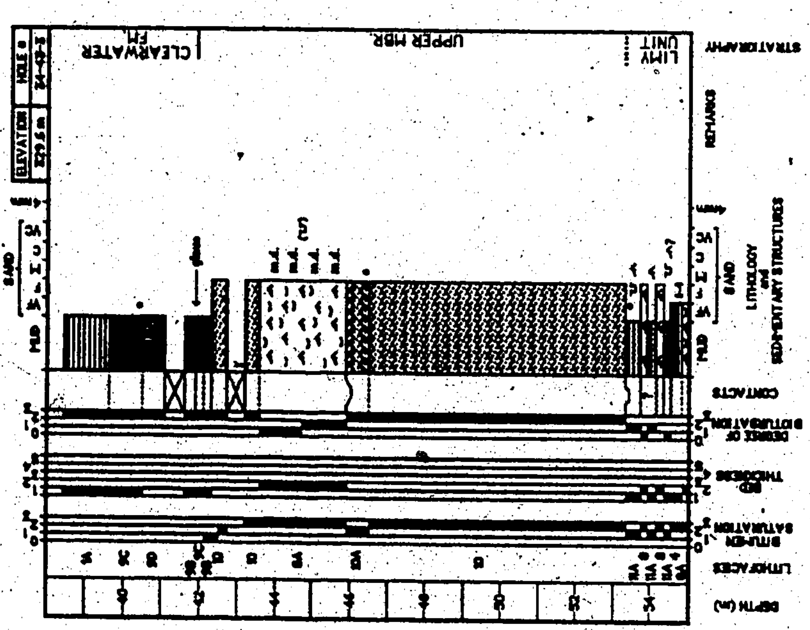
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LIMY UNIT
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HOLE #
MUD
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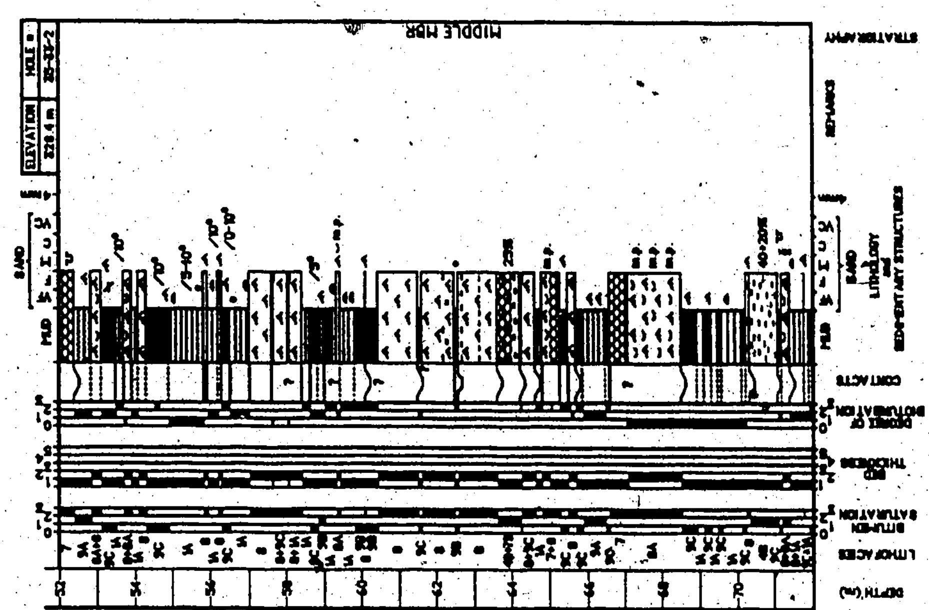

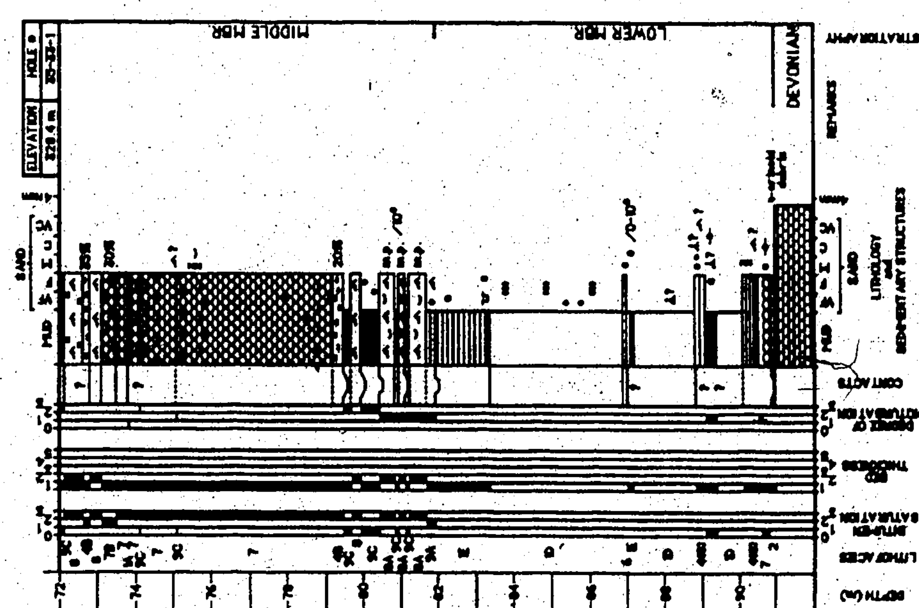

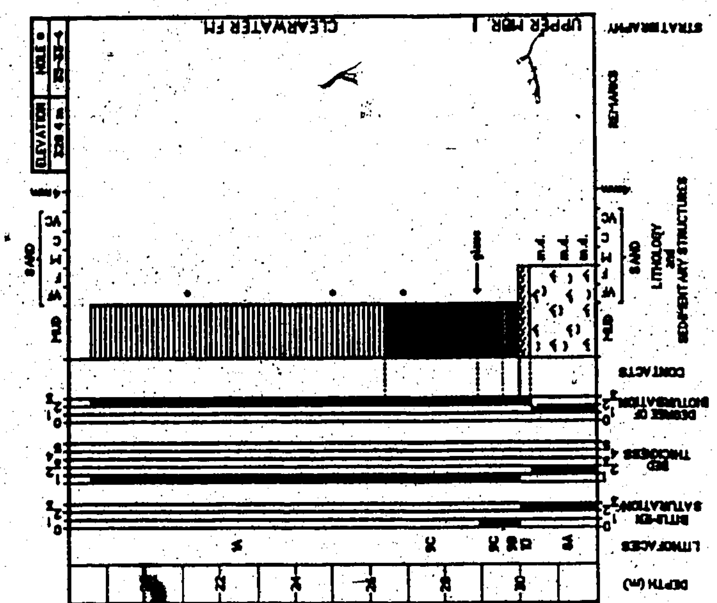
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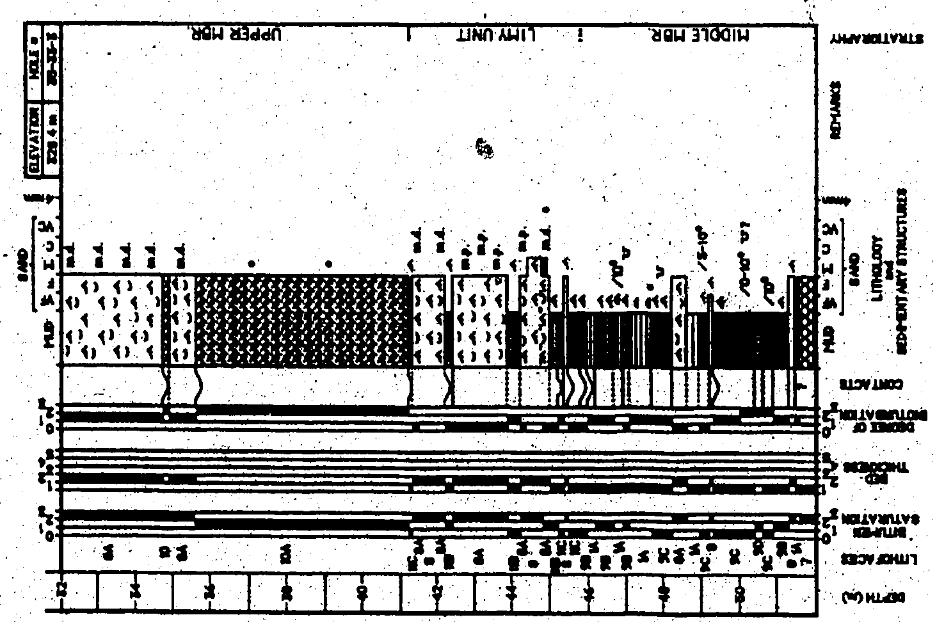
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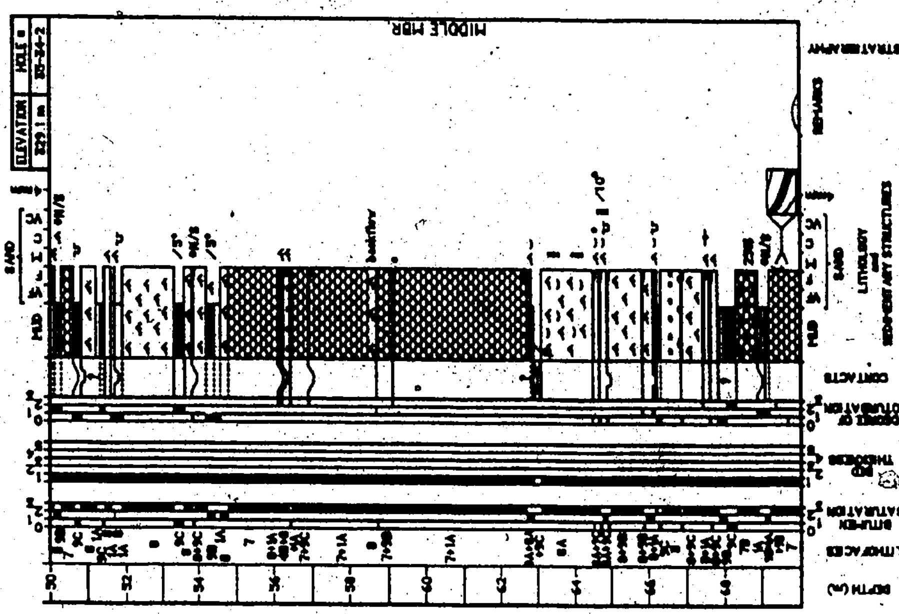
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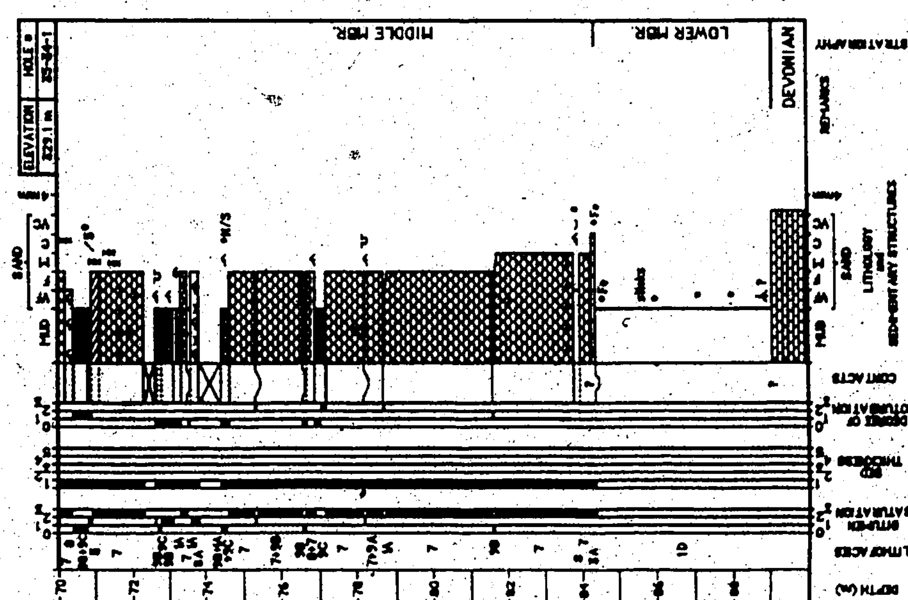
LITHOFACIES
DEPTH (m)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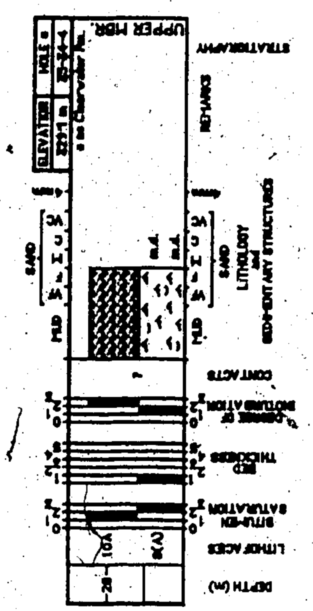
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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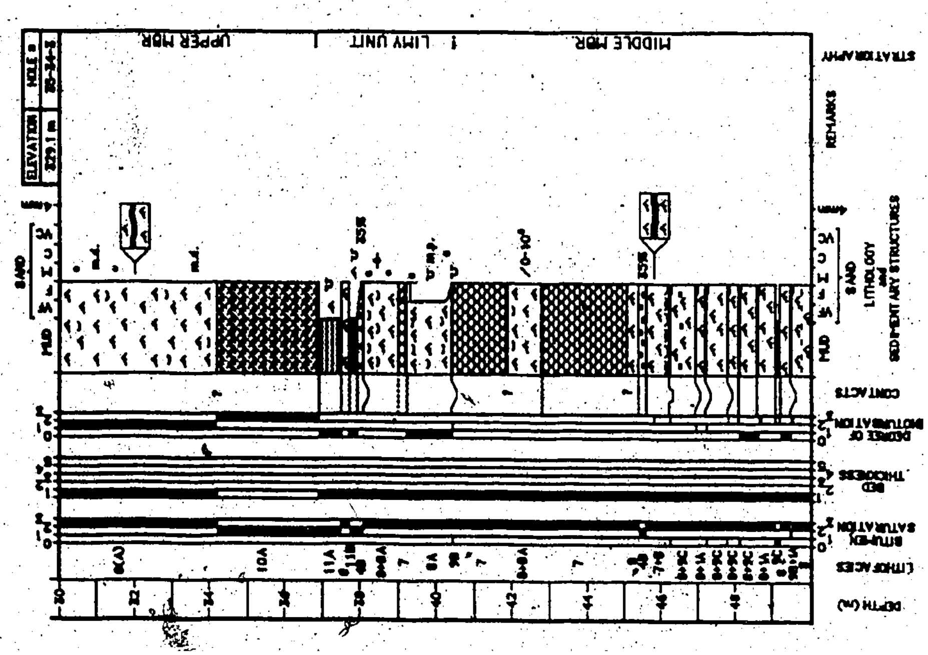
DEPTH (m)
LITHOFACIES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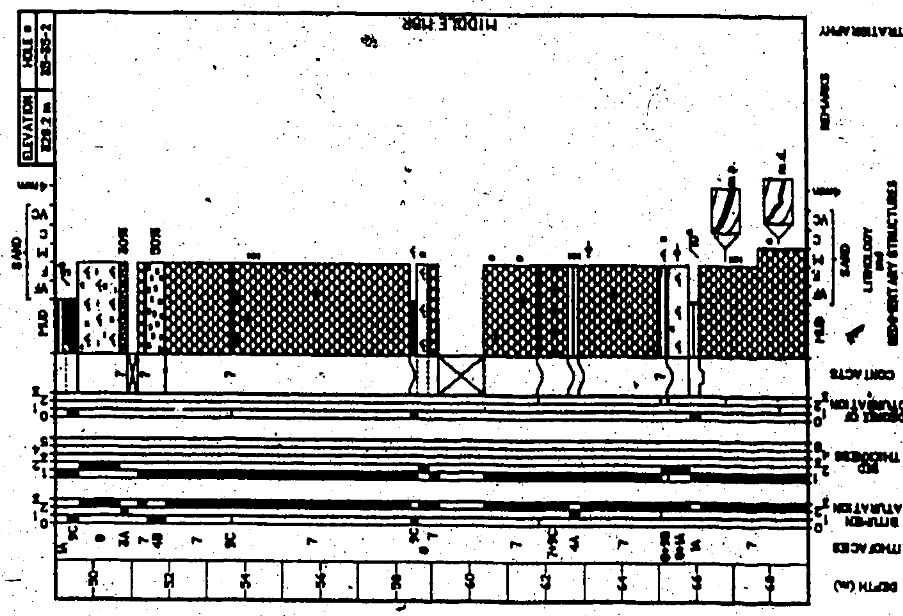
CONTACTS
DEPTH (m)
LITHOFACIES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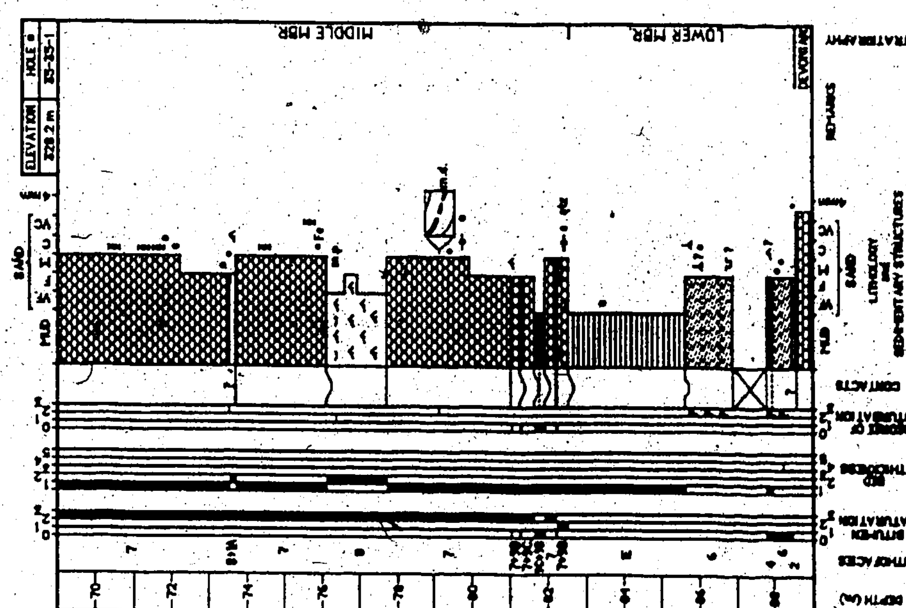
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BITUMEN SATURATION
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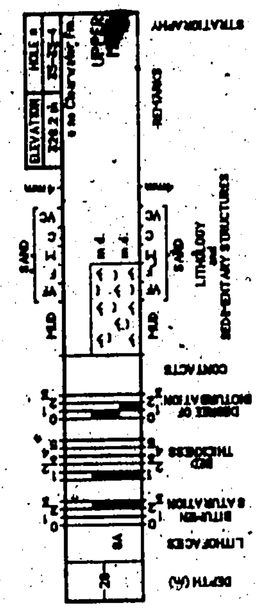
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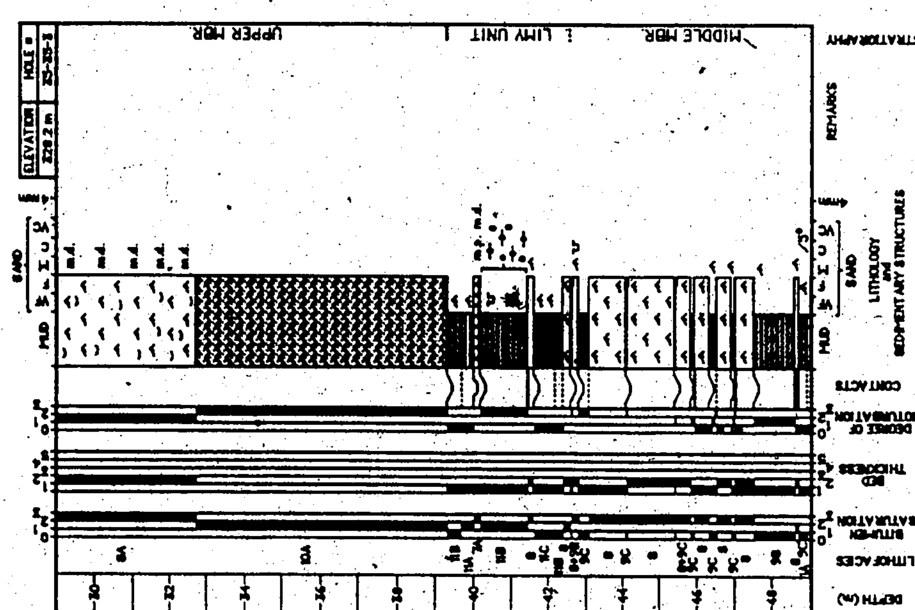
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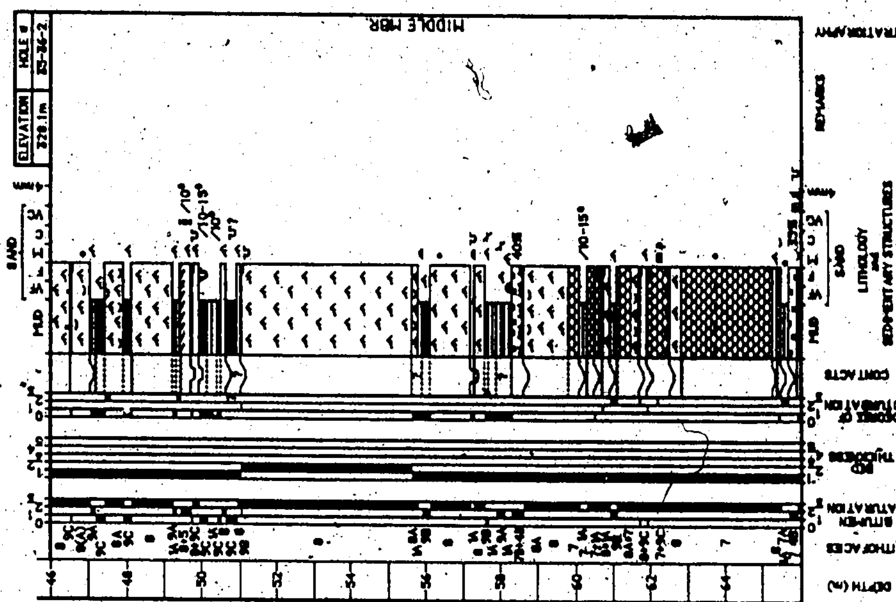

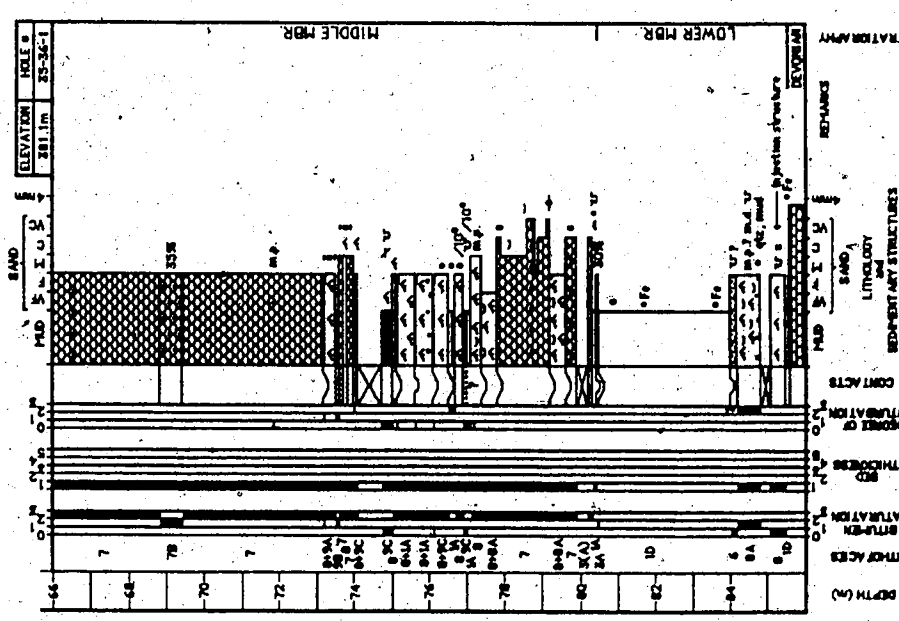

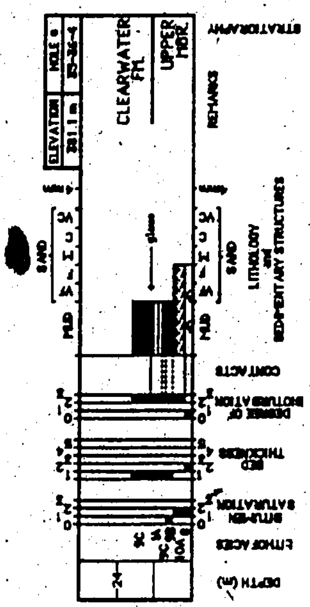
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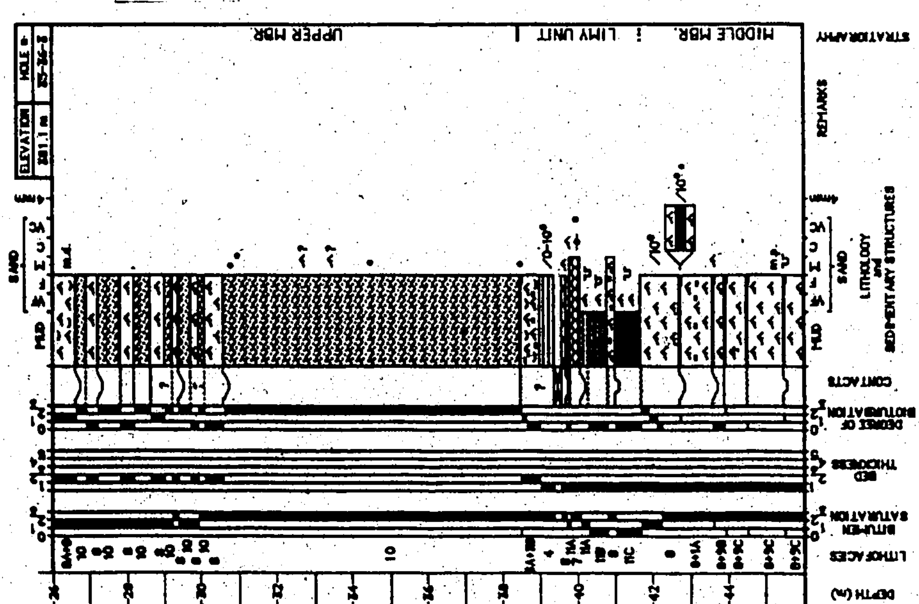
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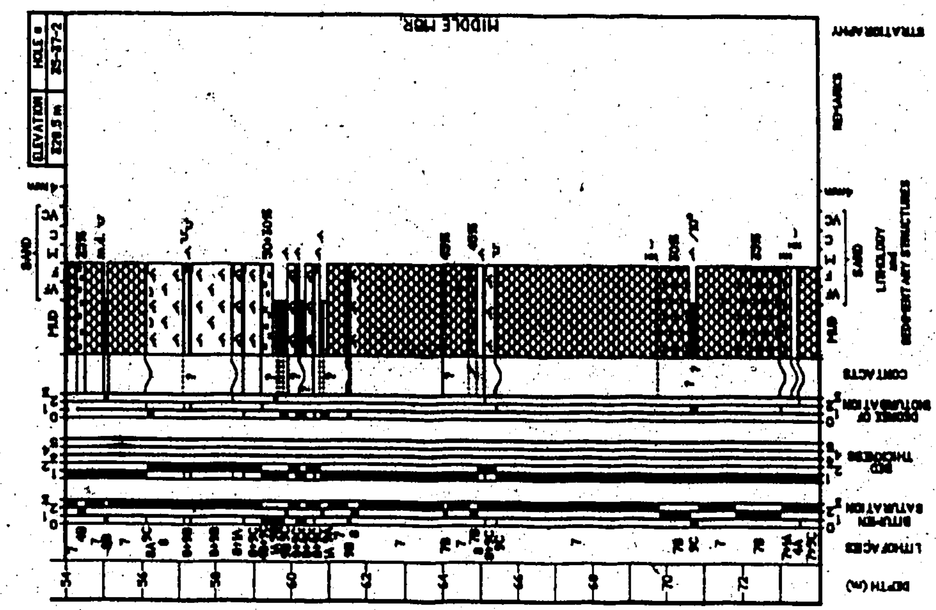
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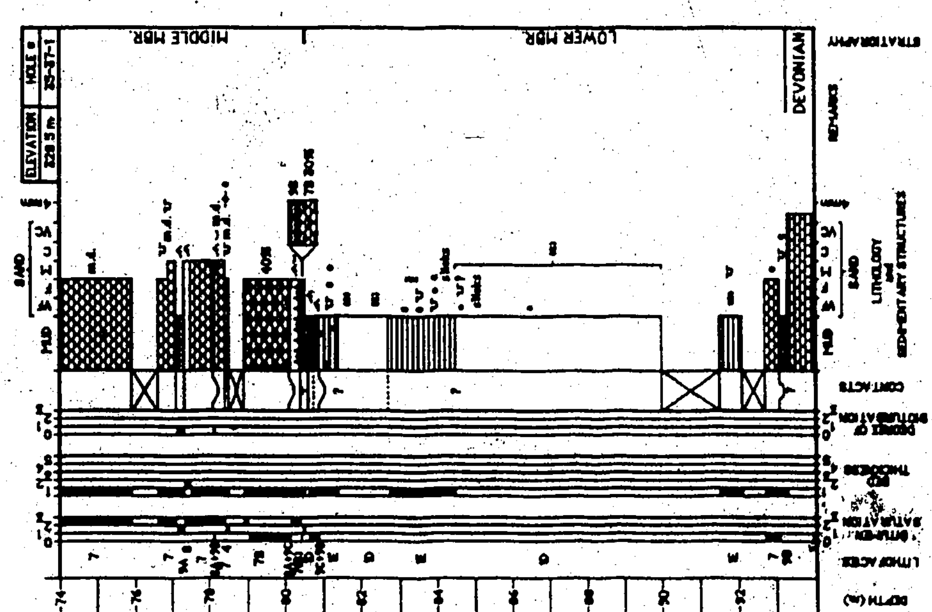
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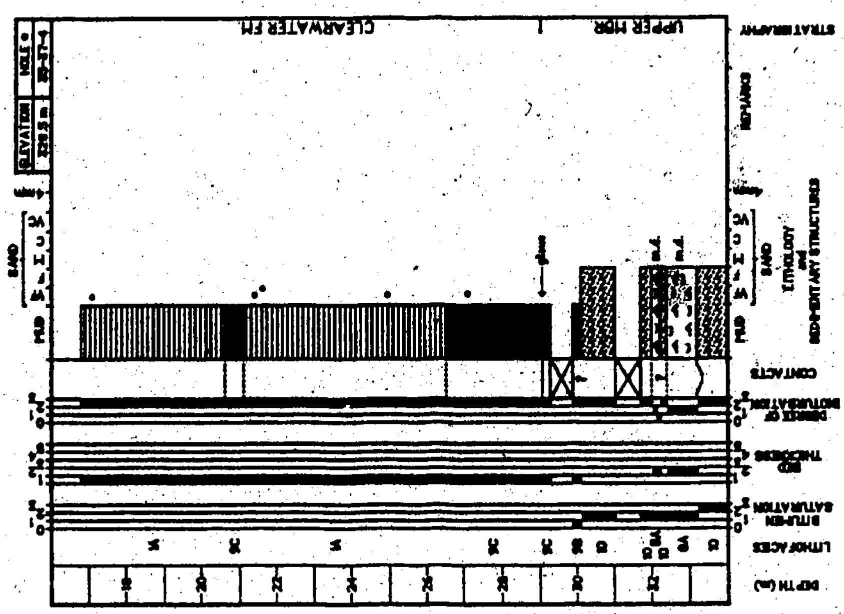
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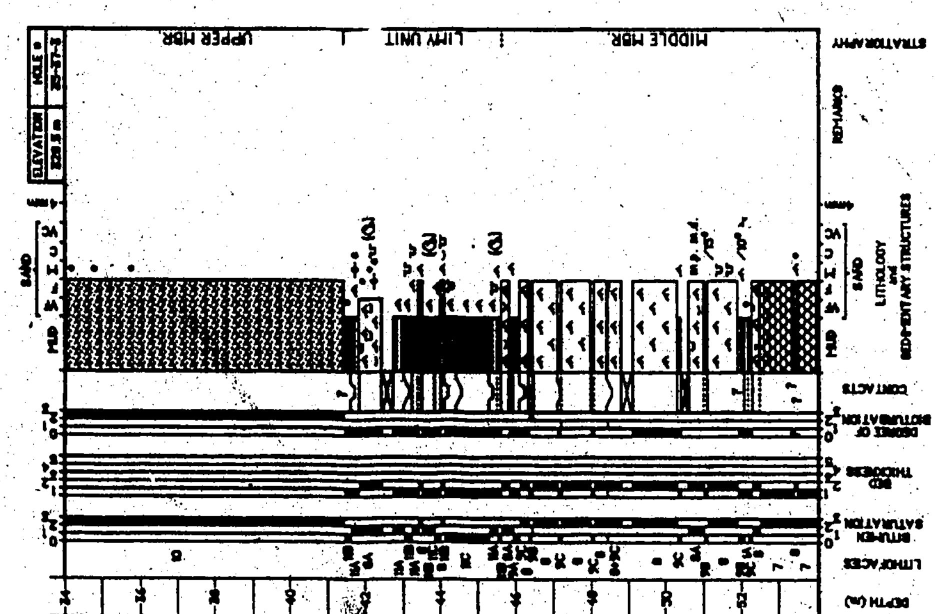
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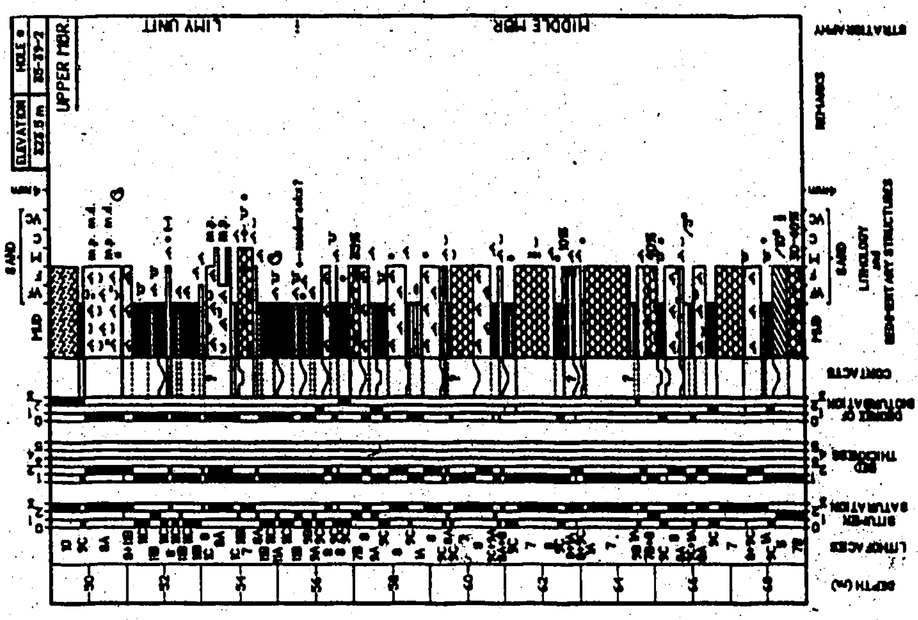
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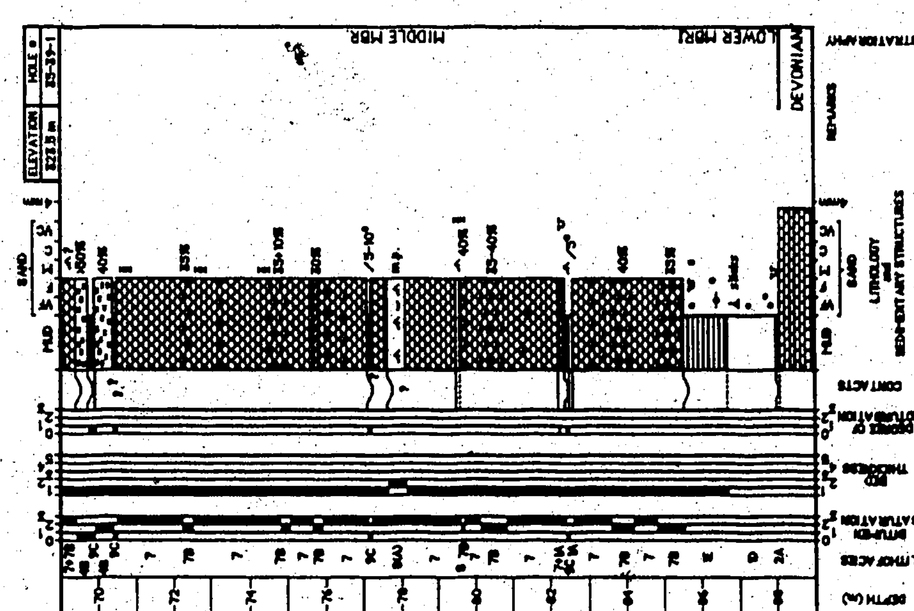
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MUD
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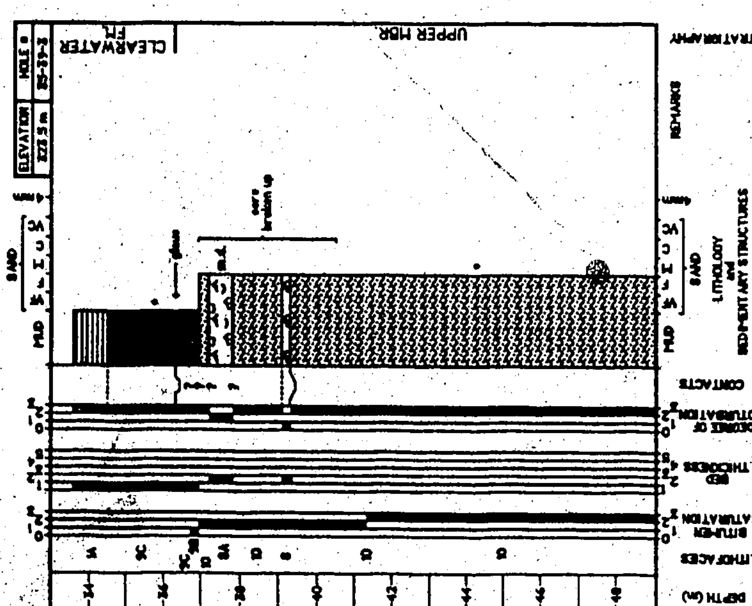
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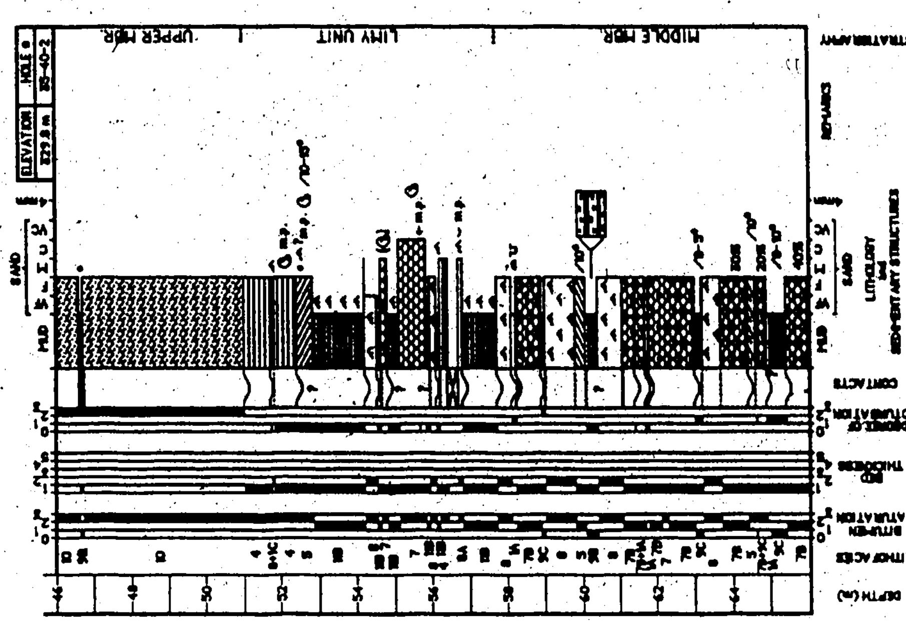
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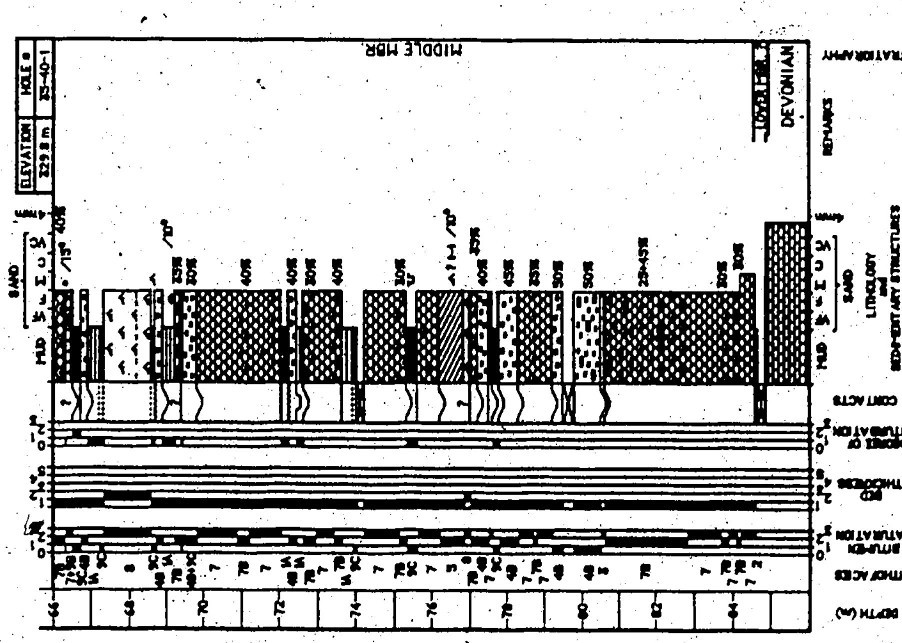
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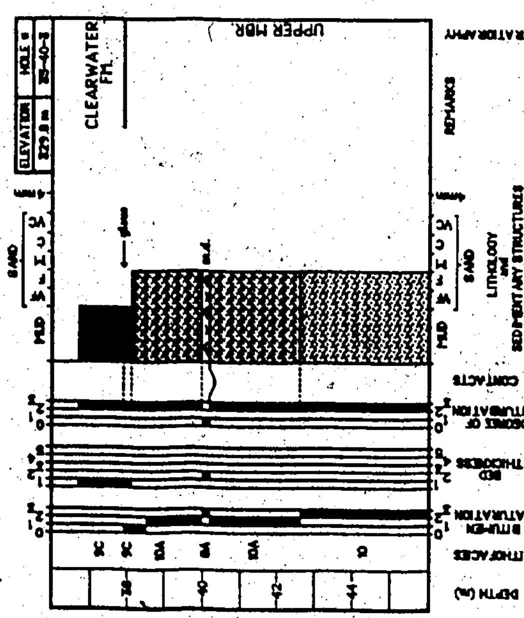
DEPTH (m)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25-40-8
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UPPER MBR.
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CONTACTS
DEGREE OF BIOTURBATION
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BITUMEN SATURATION
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8A
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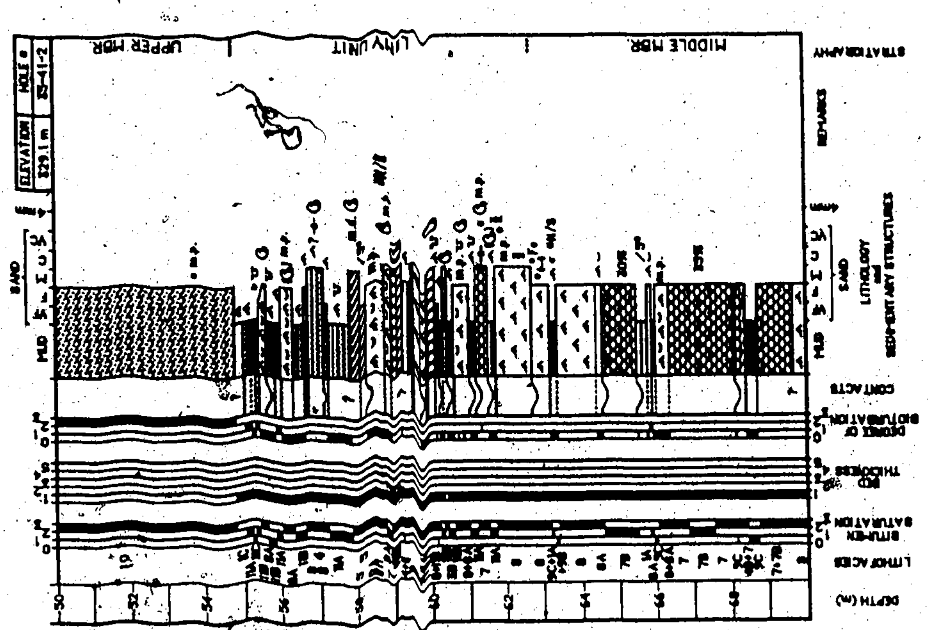
38
40
42
44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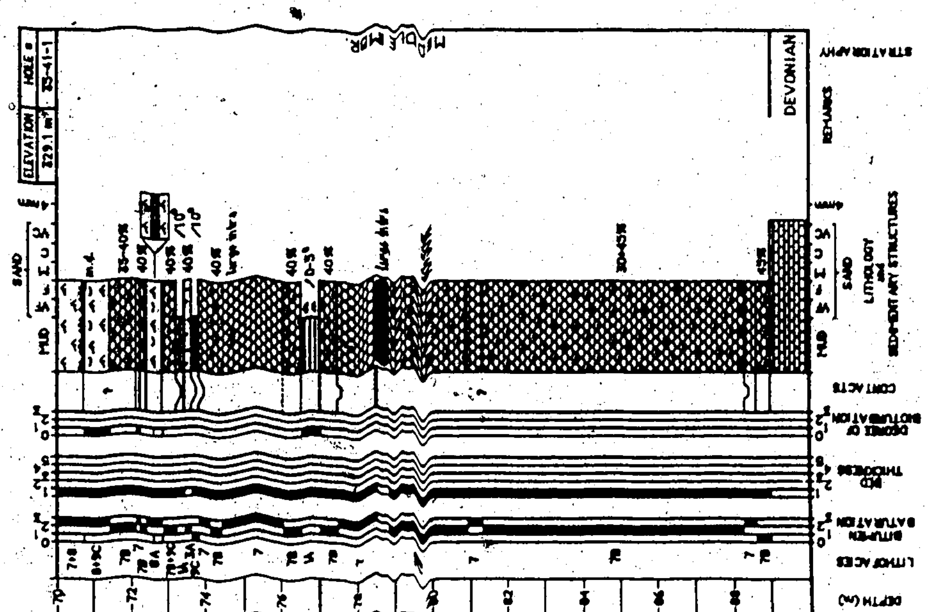
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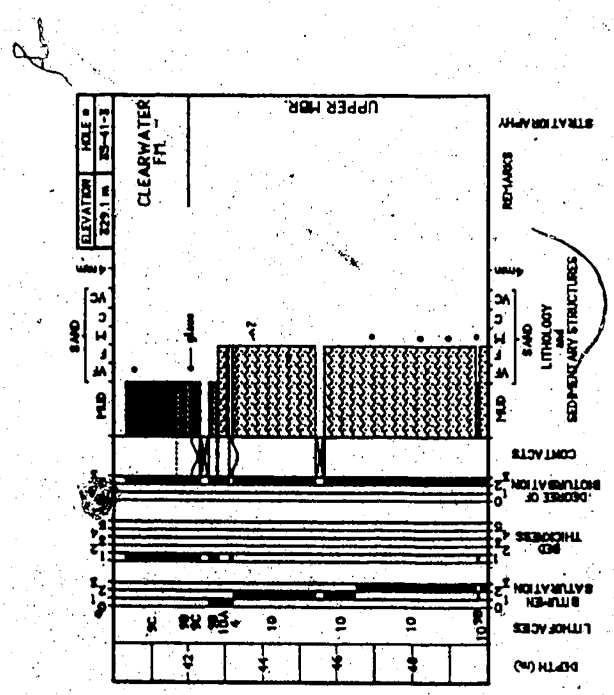

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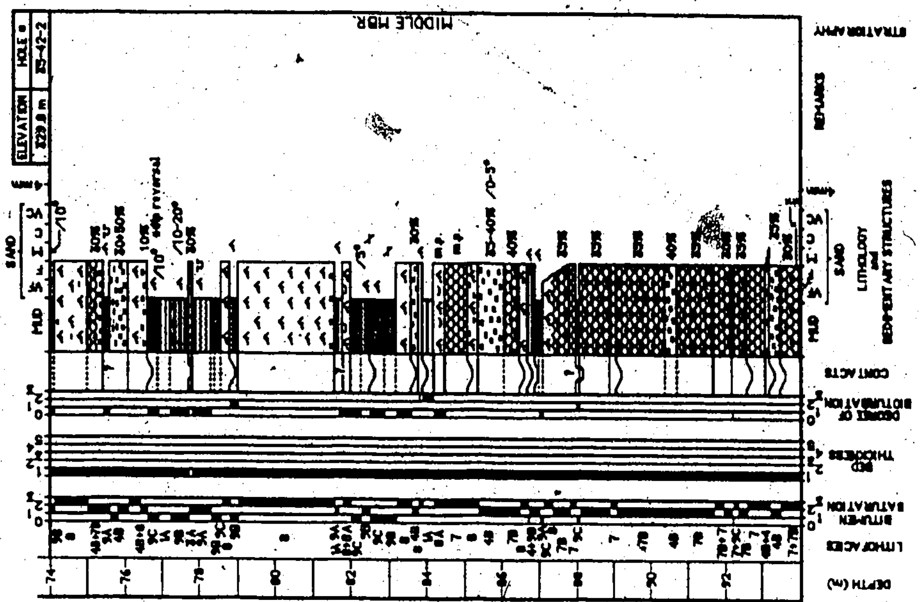
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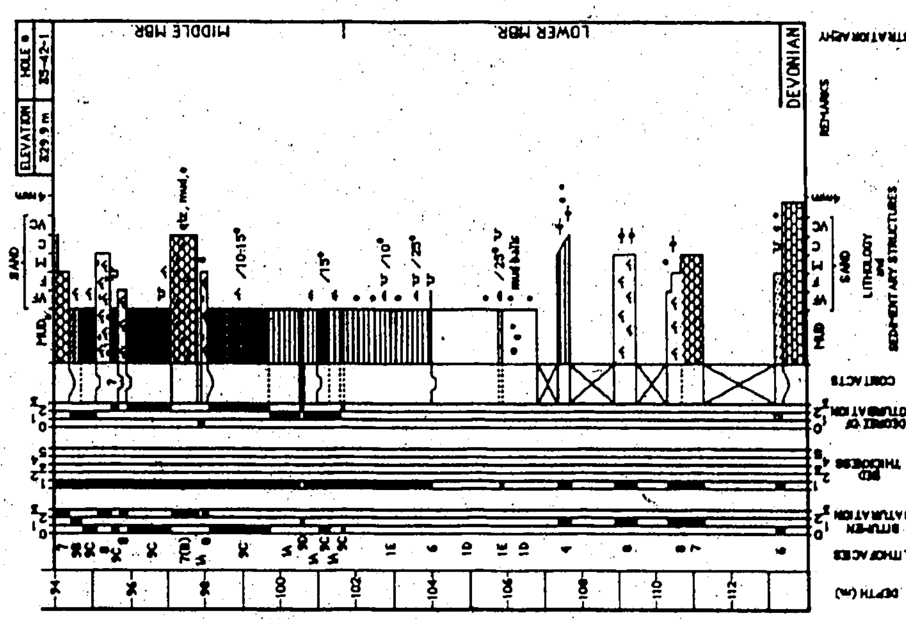
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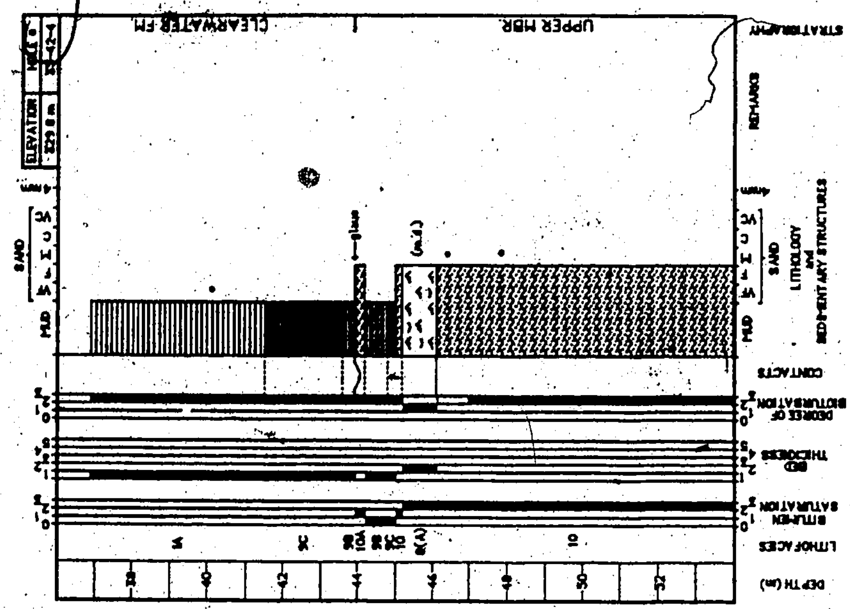
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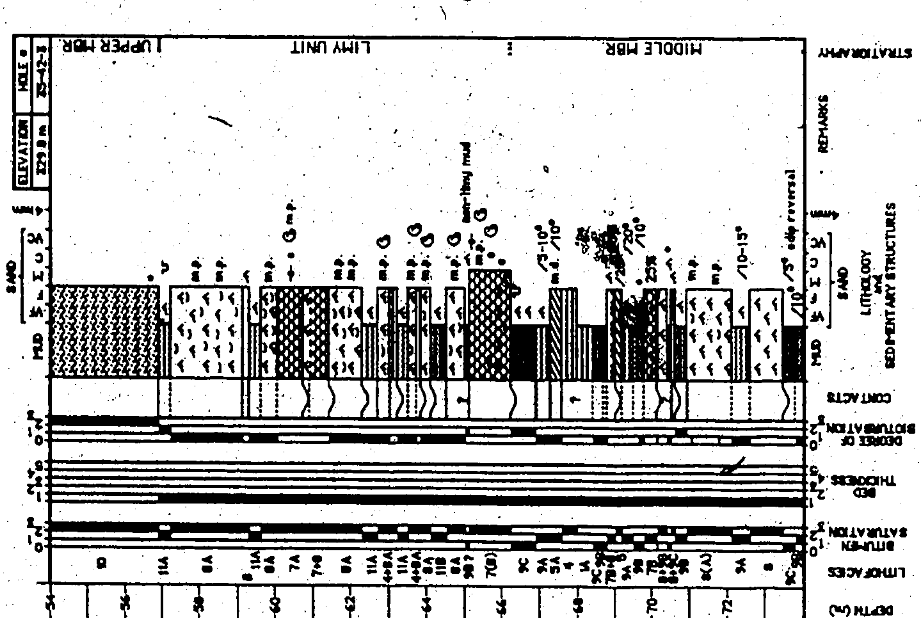
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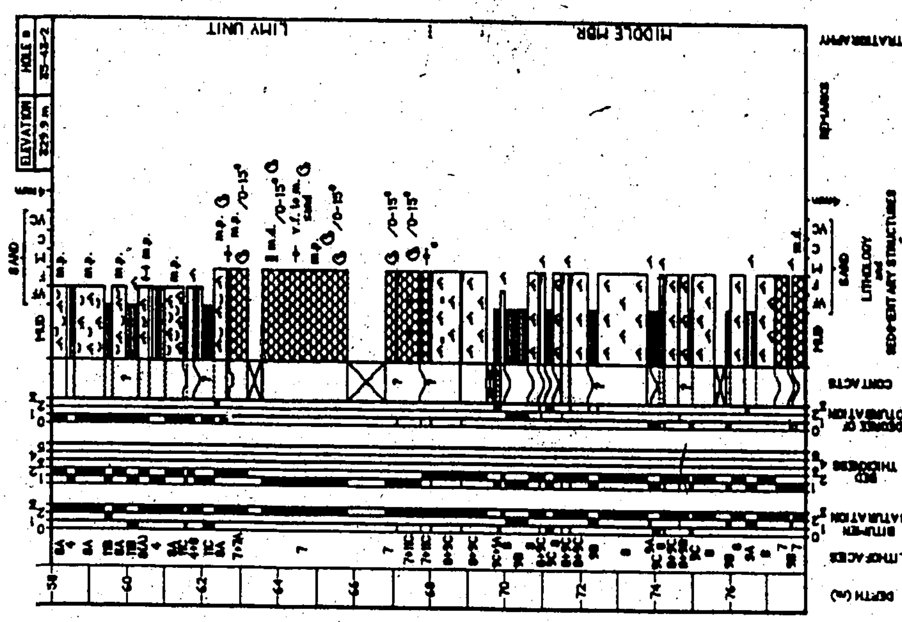
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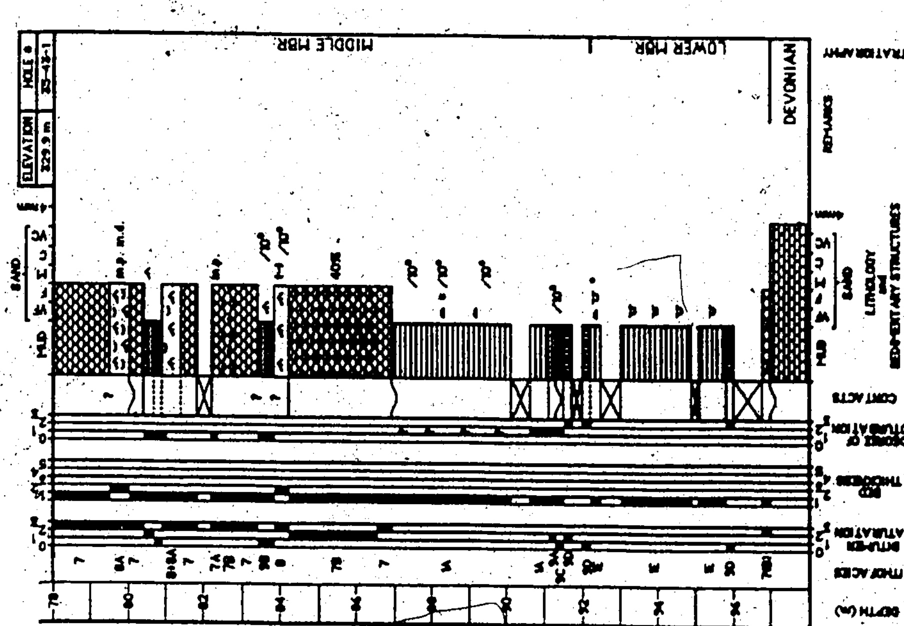
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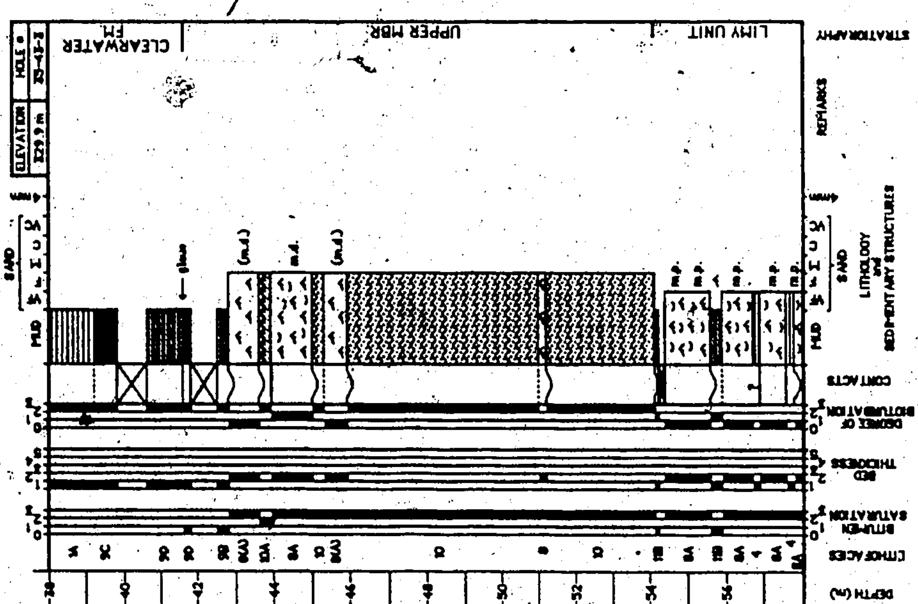
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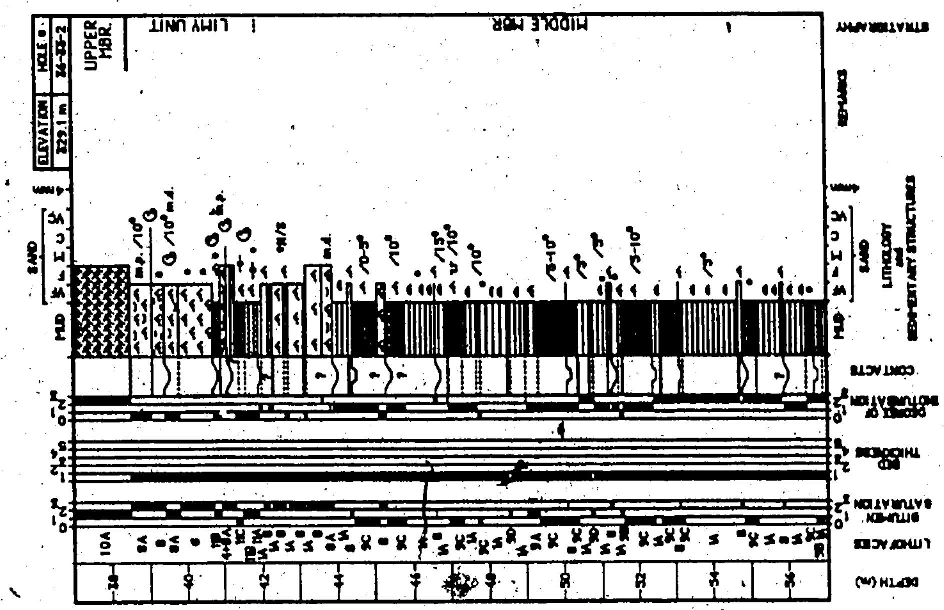

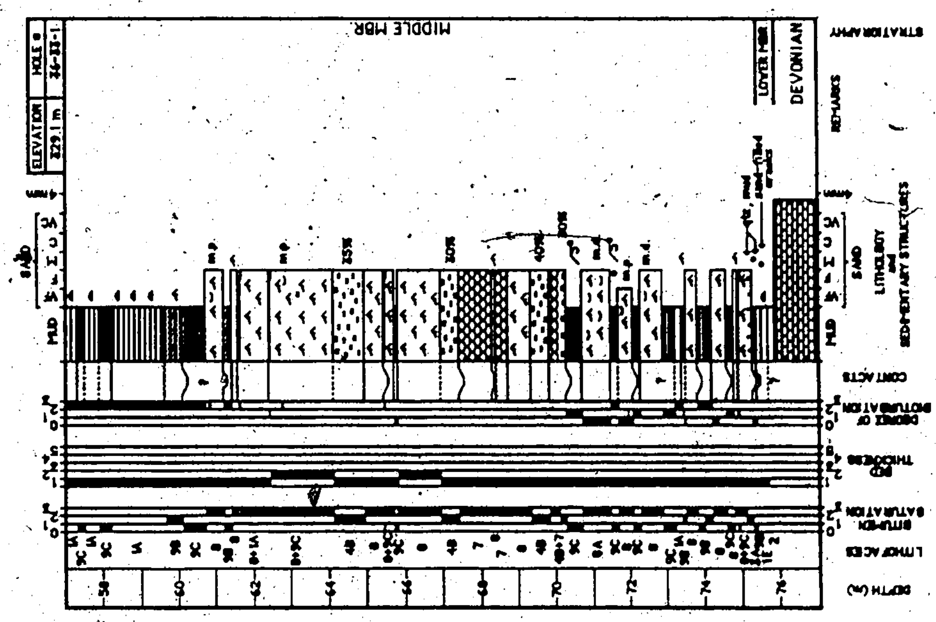

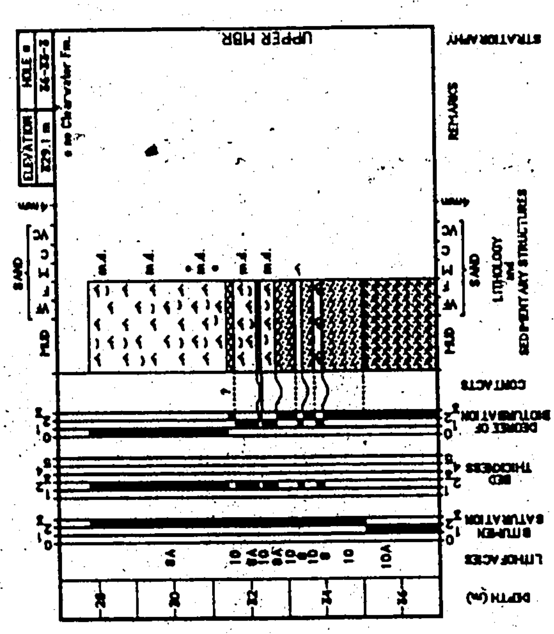
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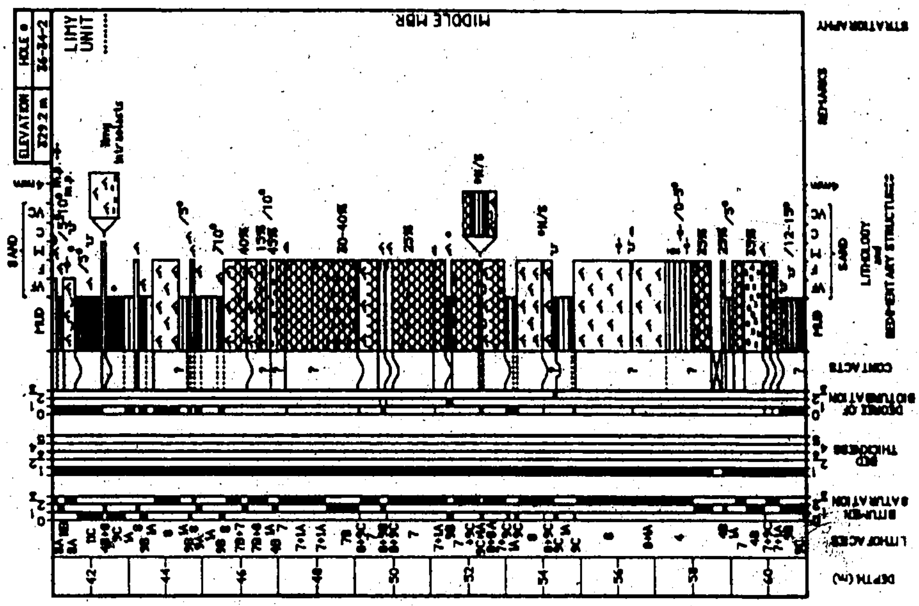
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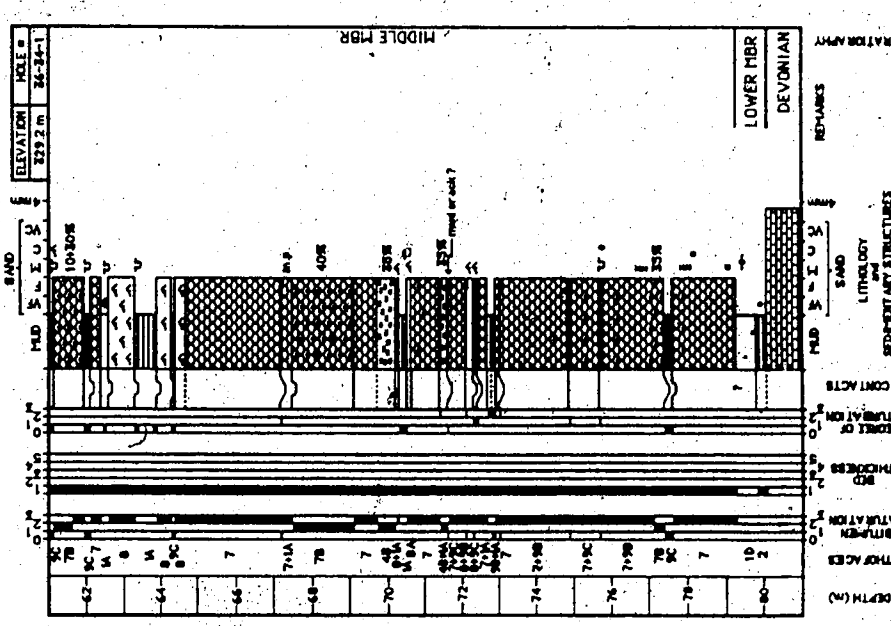
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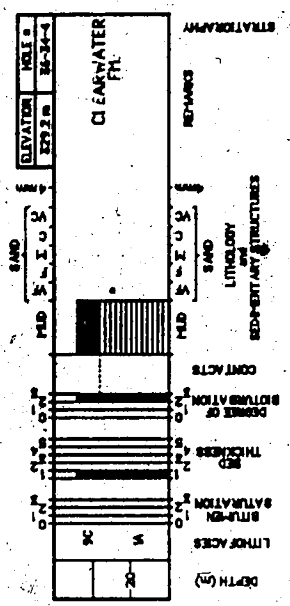
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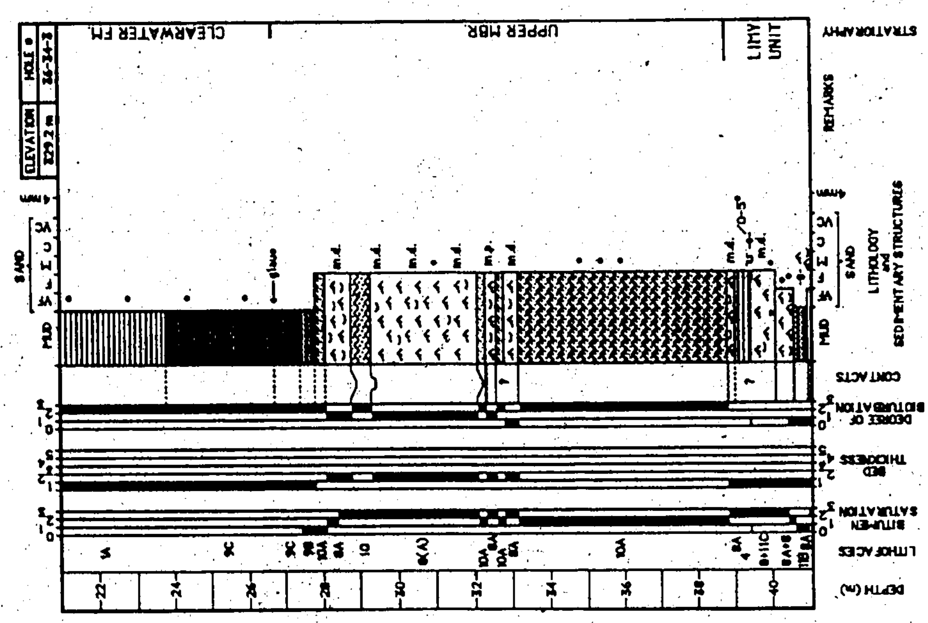
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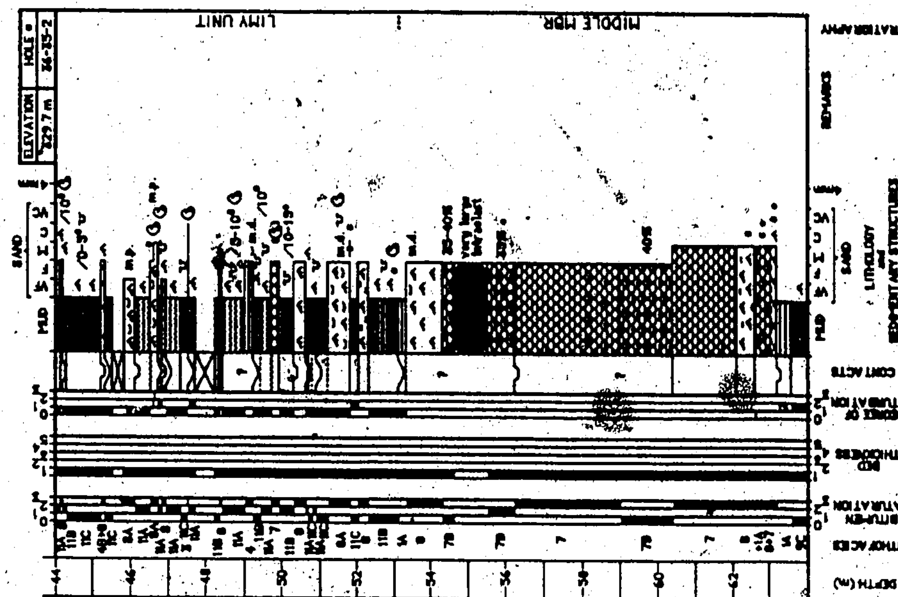

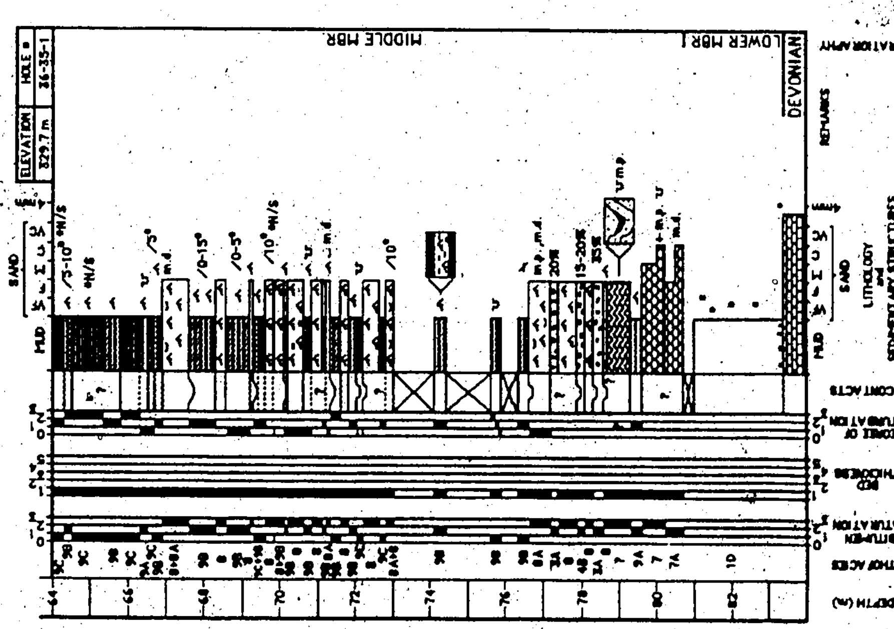

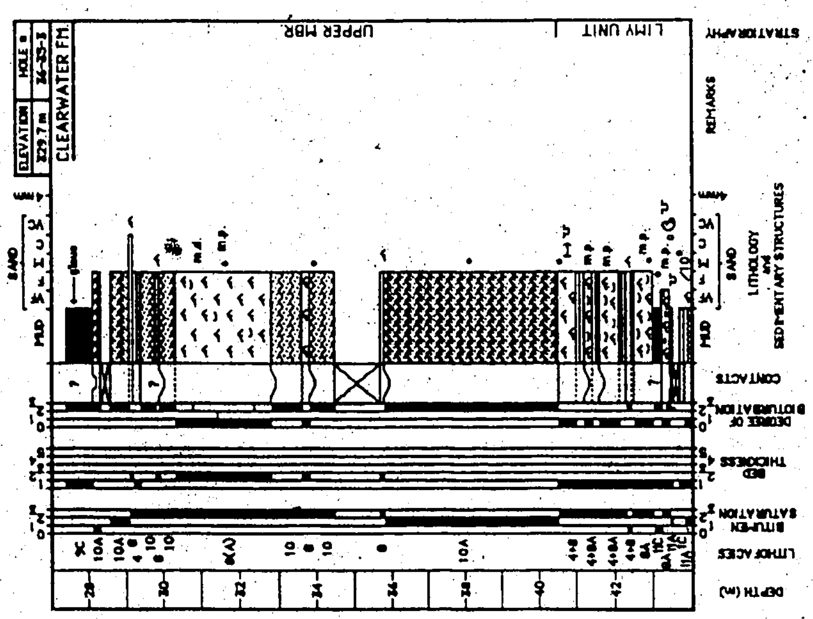
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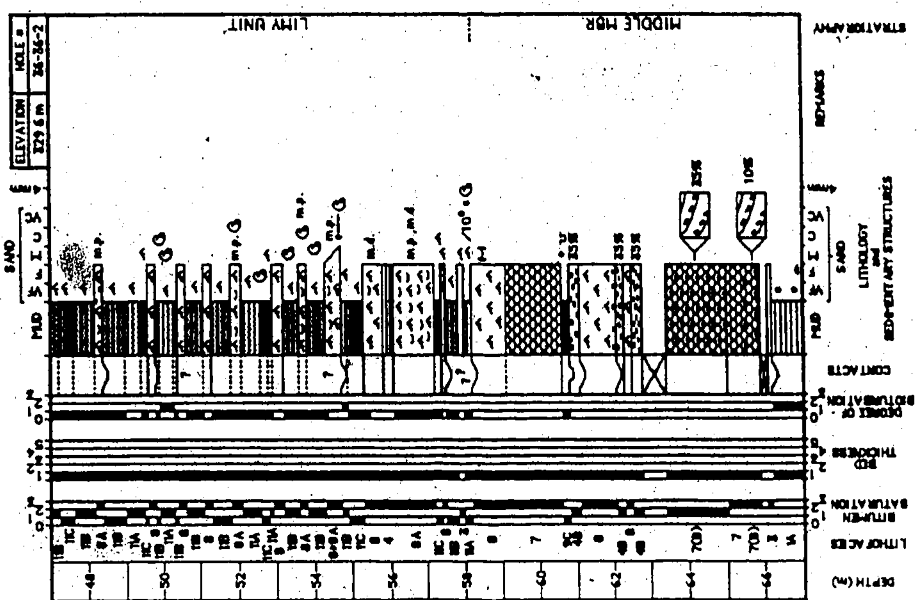
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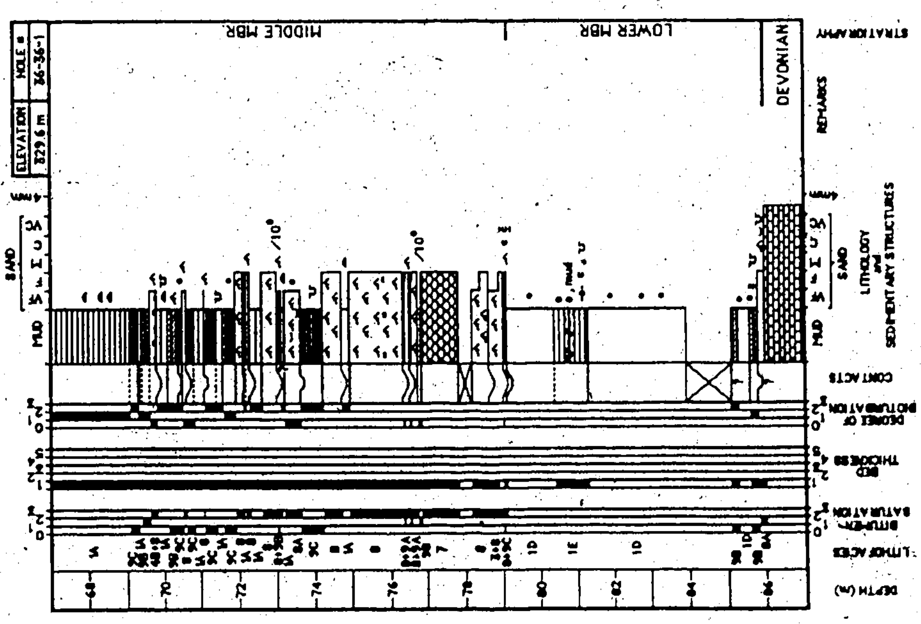
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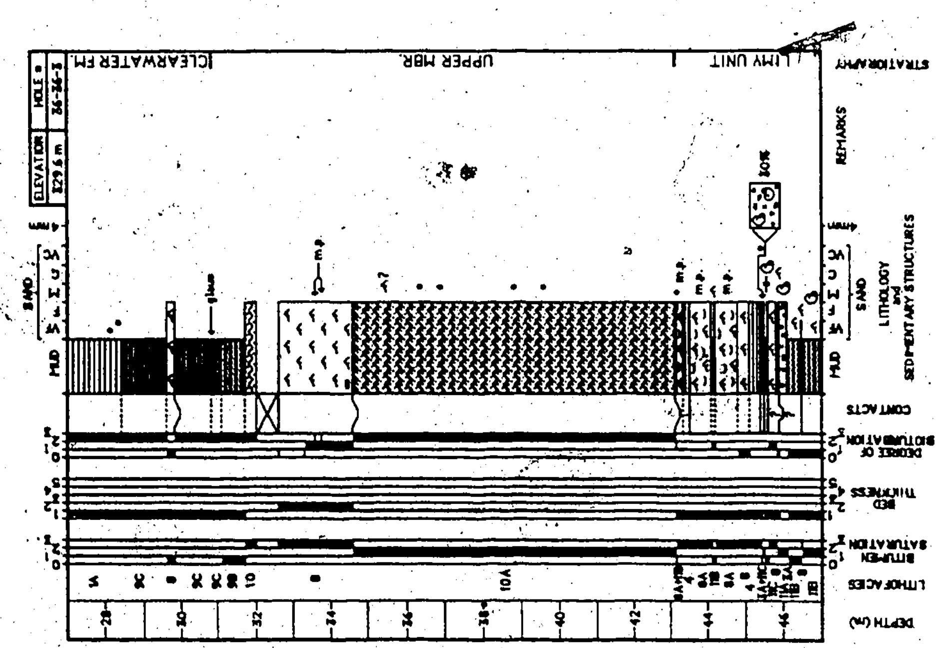
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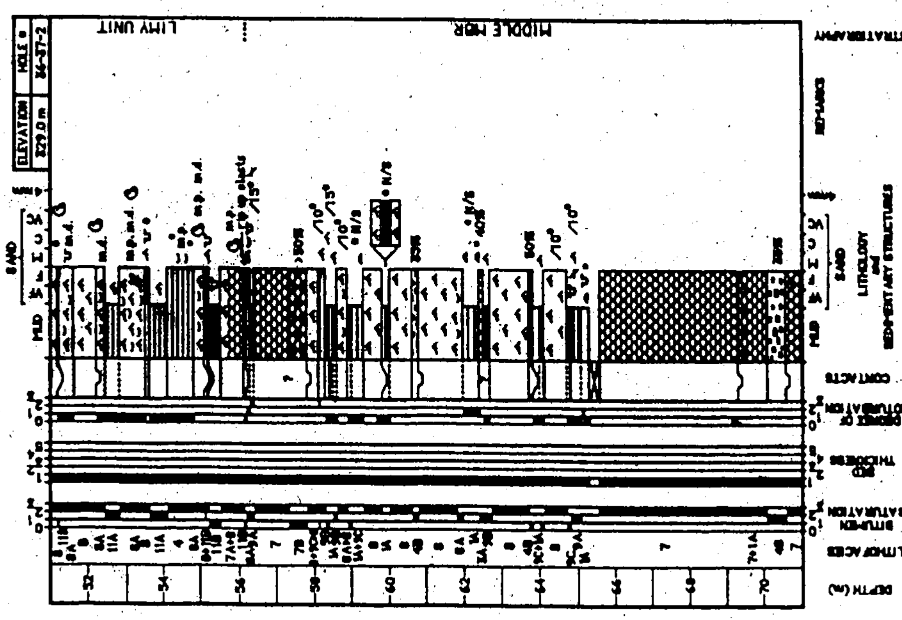
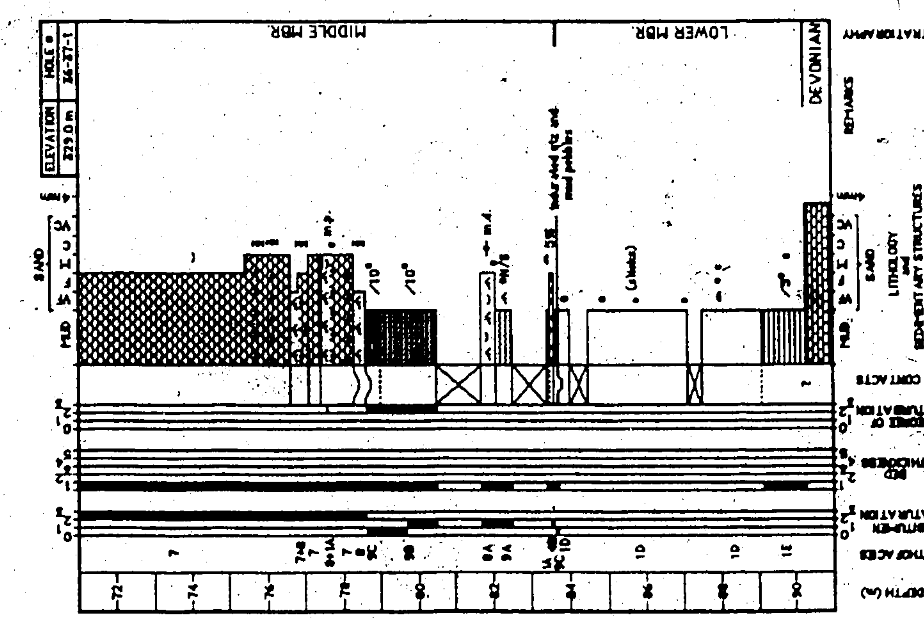
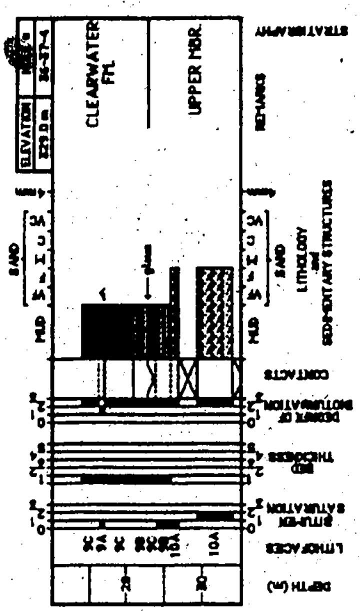
DEPTH (m)



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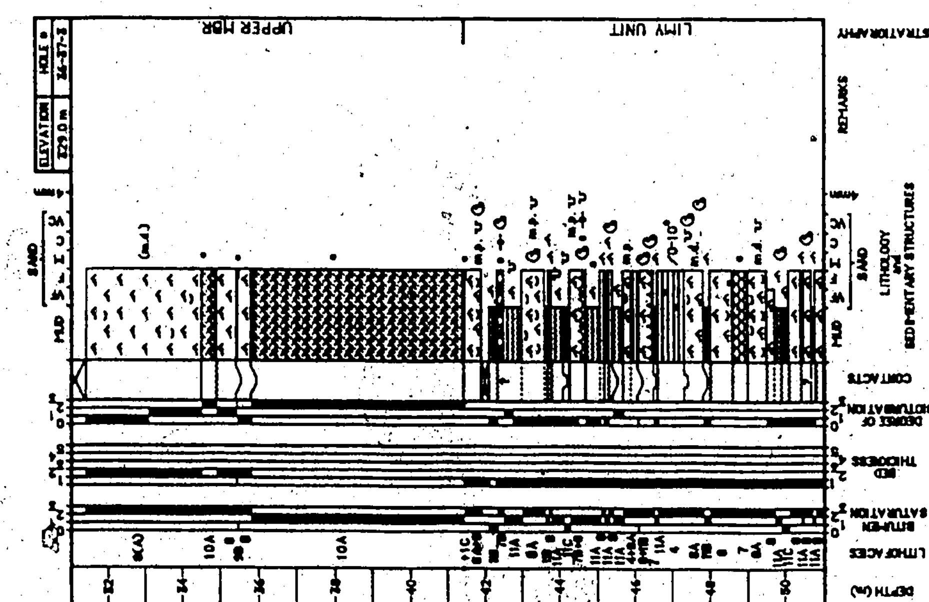
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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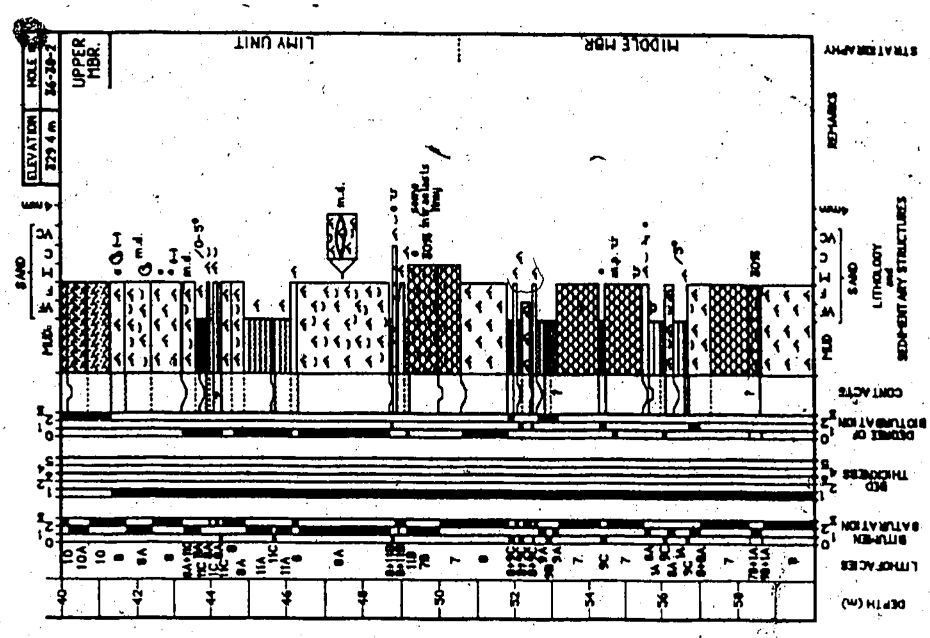
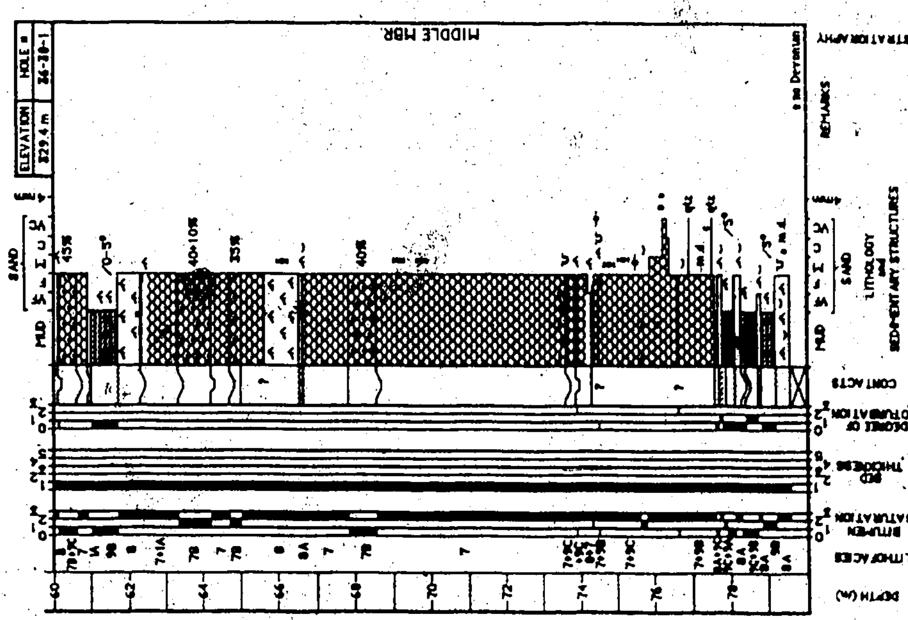
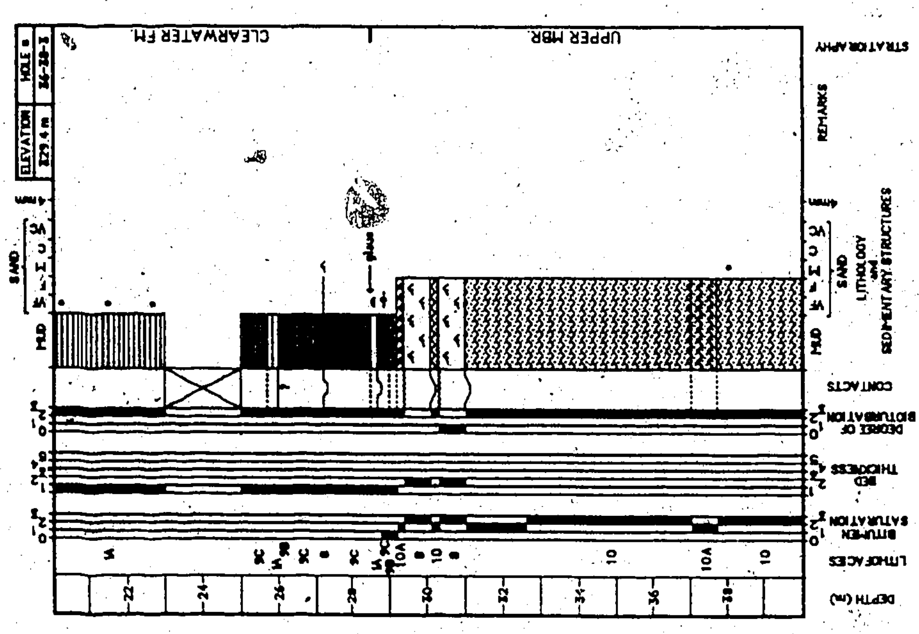
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)



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LITHOFACIES
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BED THICKNESS
DEGREE OF BIOTURBATION
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STRATIGRAPHY
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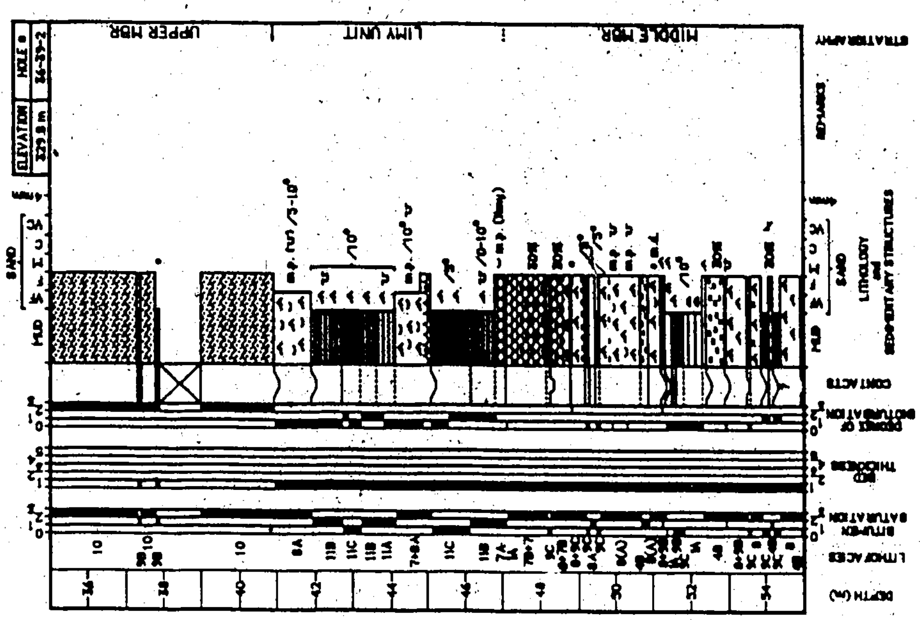
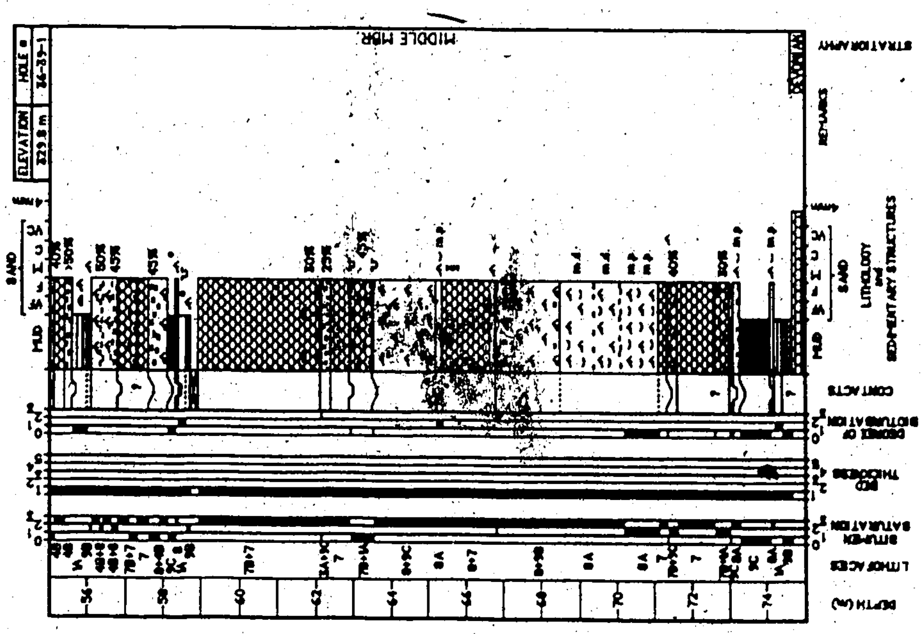
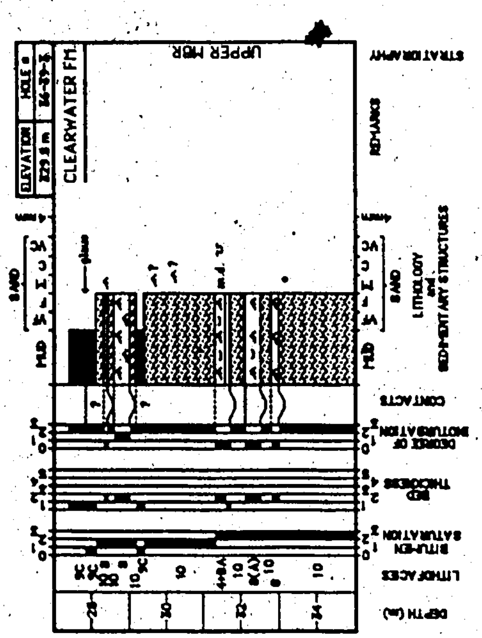
CLEARWATER FM.
ELEVATION
HOLE #



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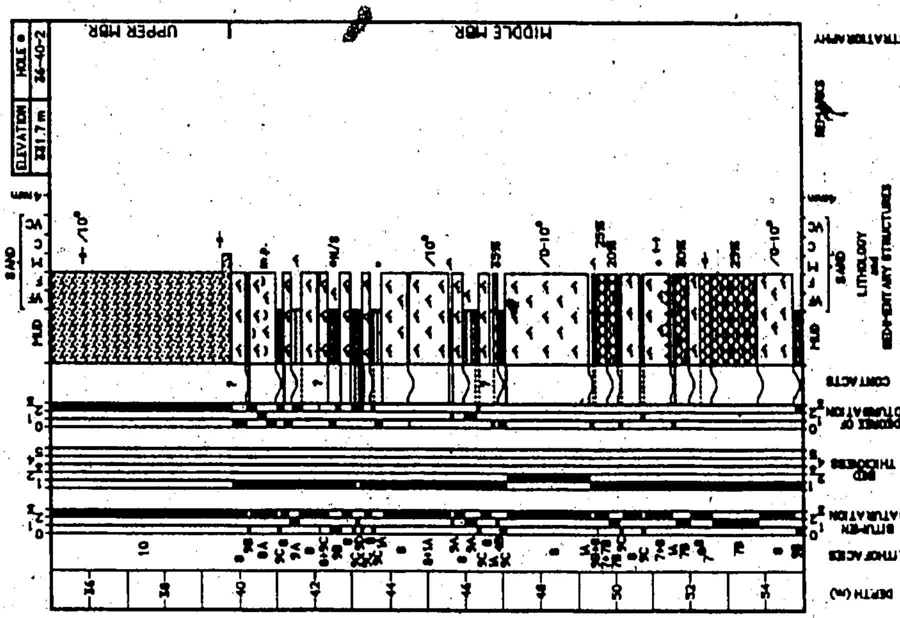
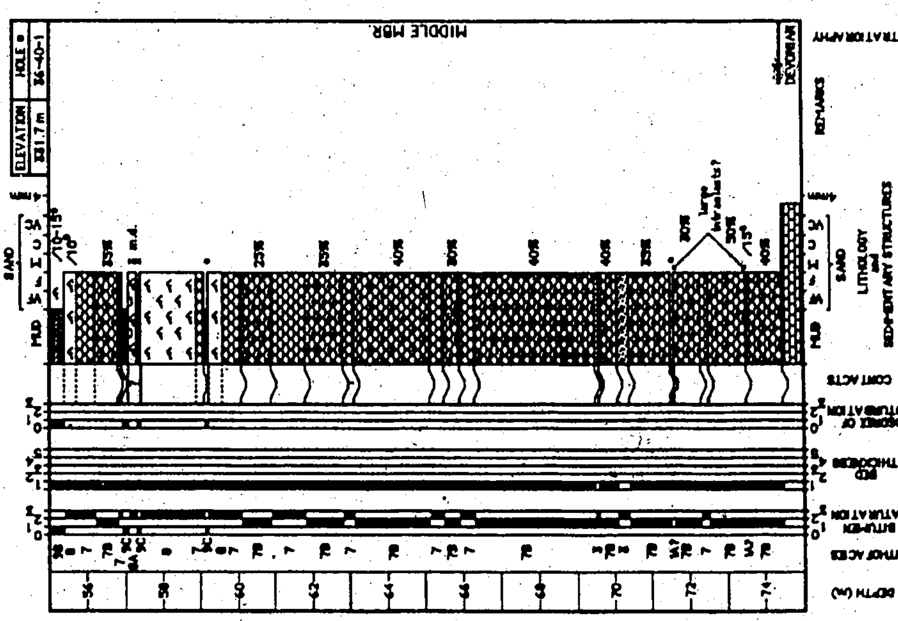
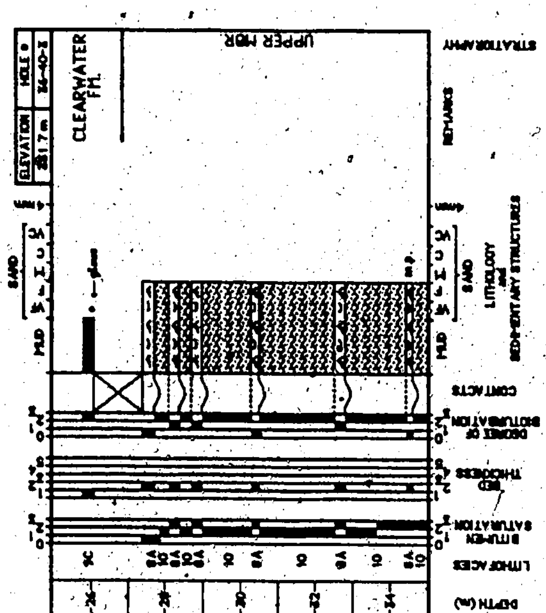
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)







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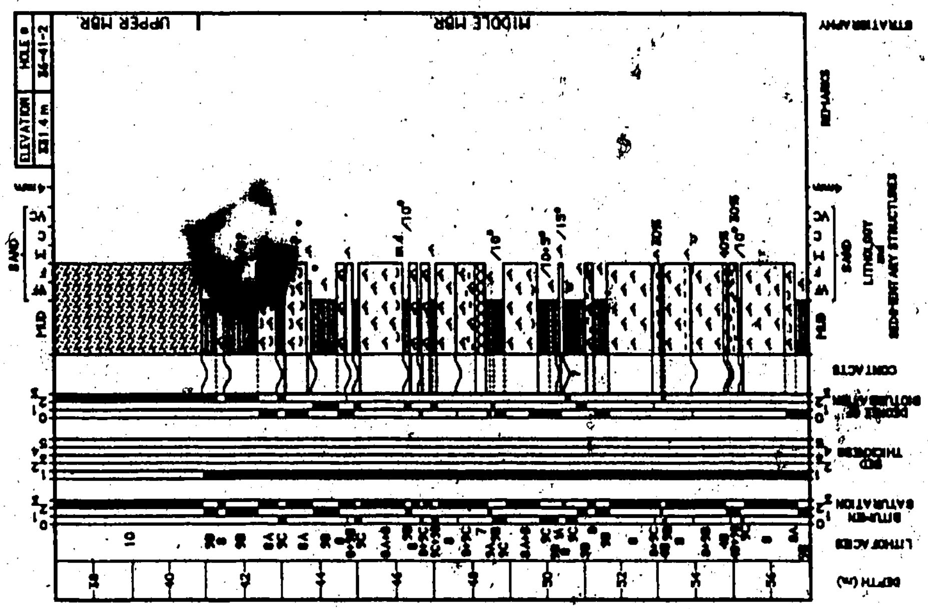
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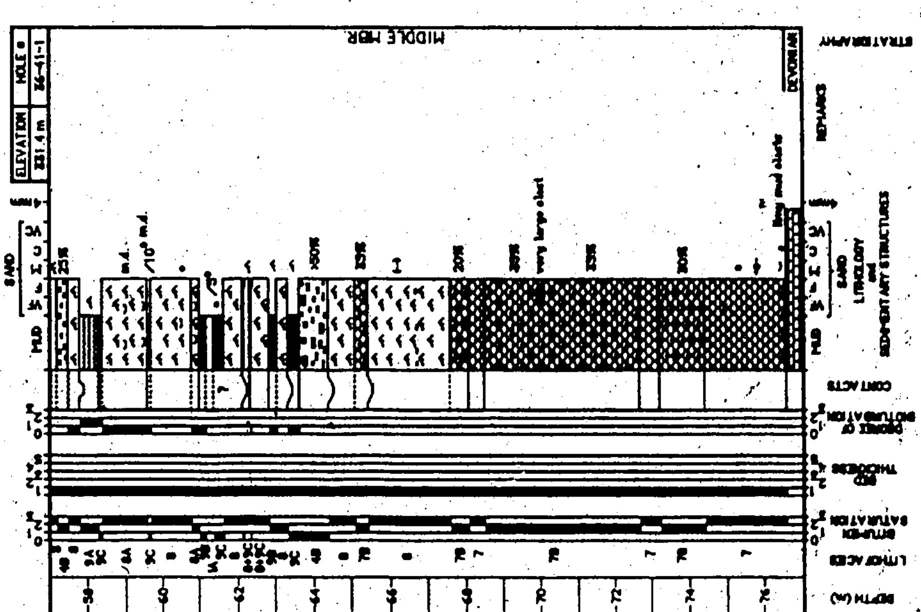
LITHOFACIES
DEPTH (m)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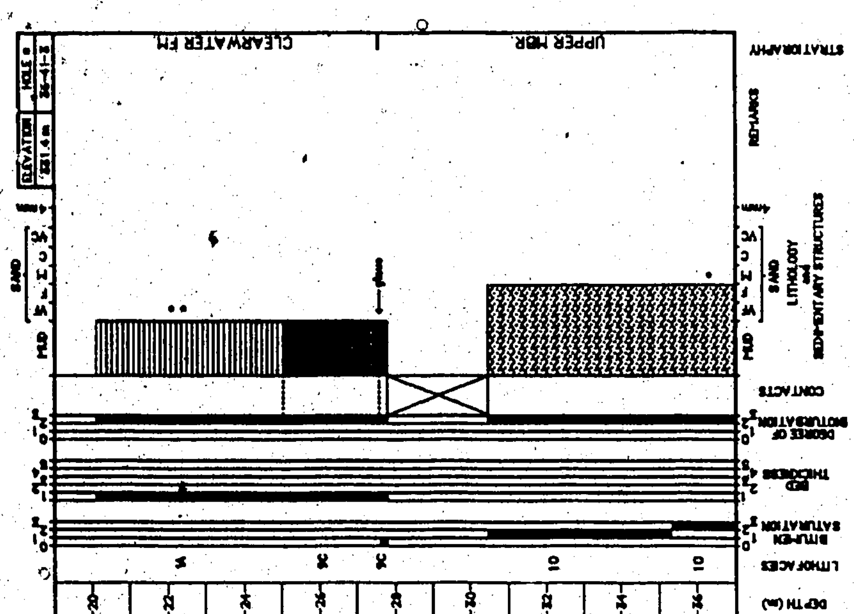
6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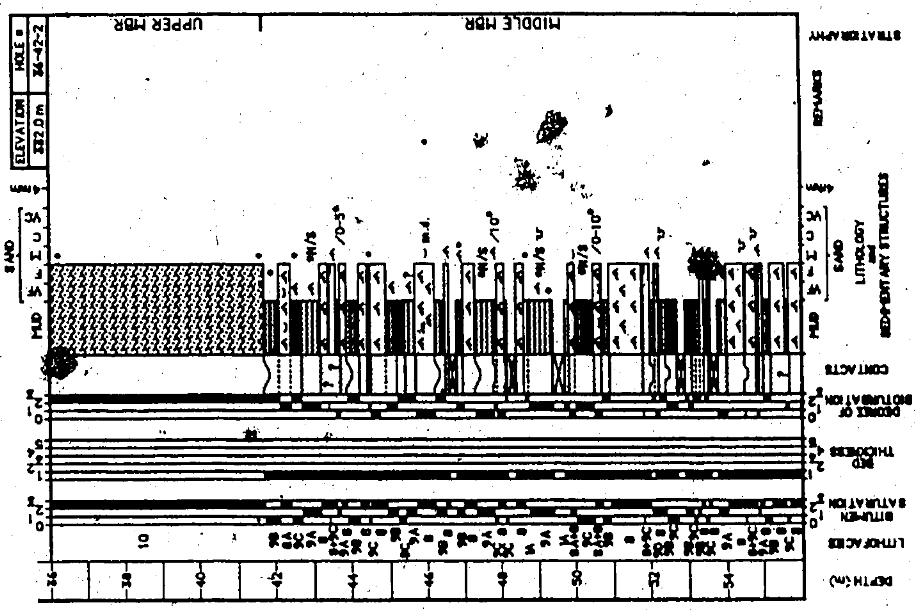
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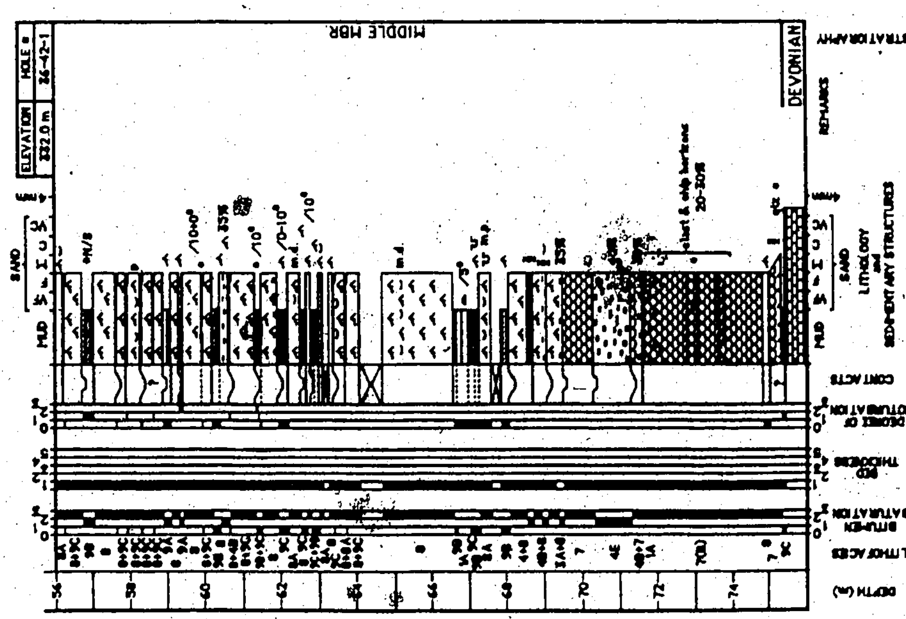
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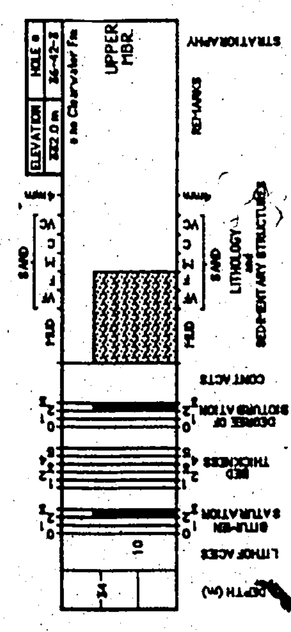
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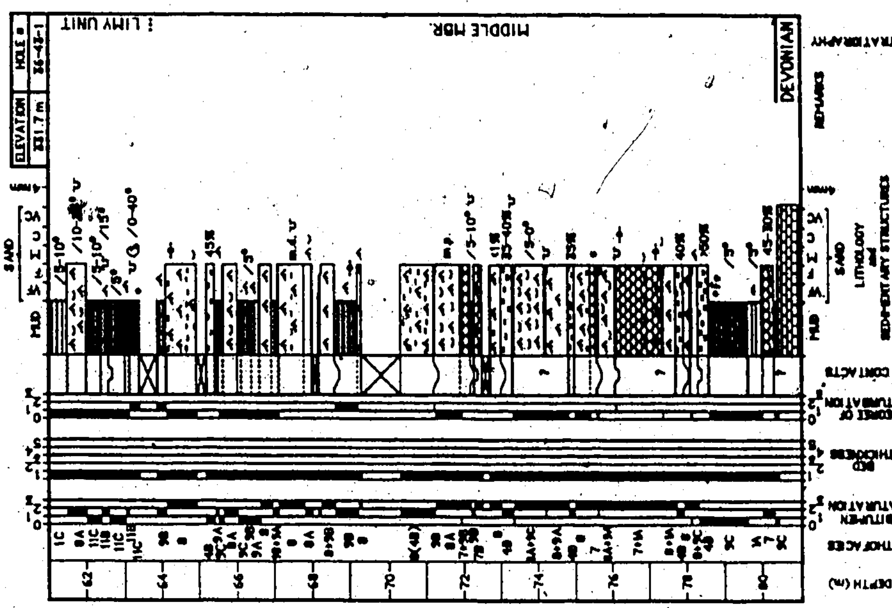
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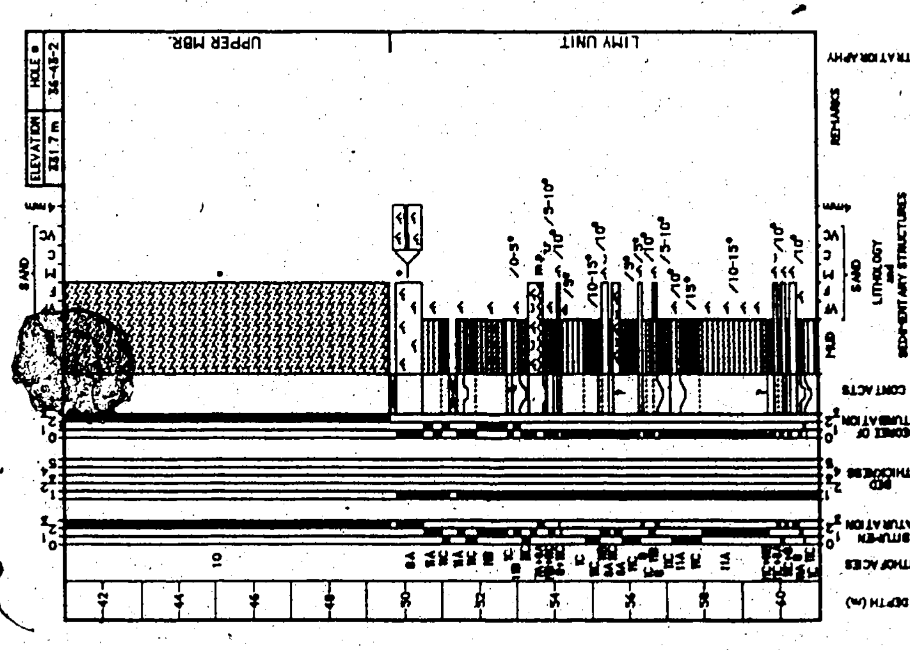
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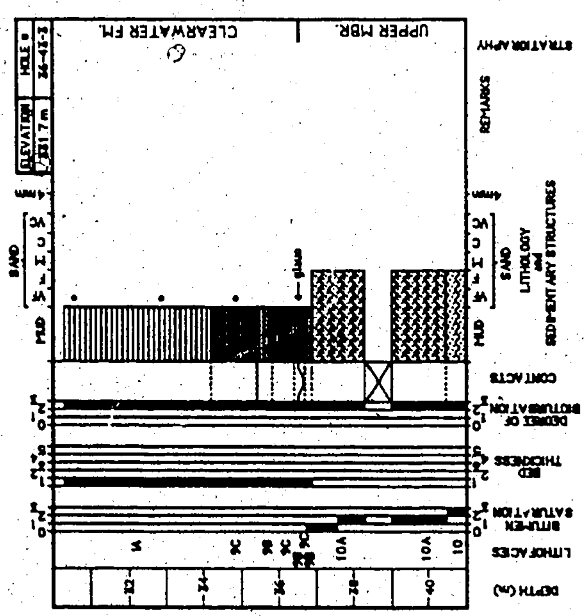
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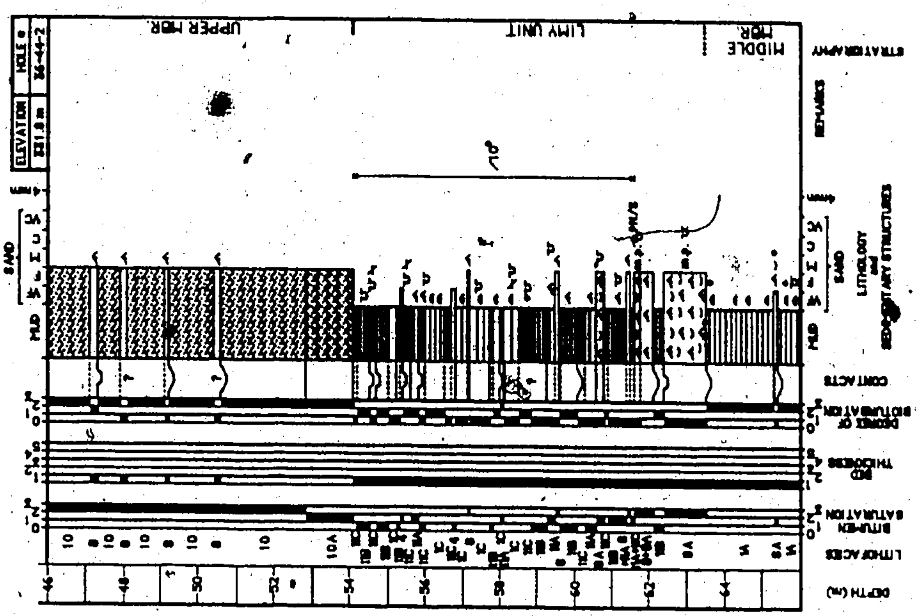
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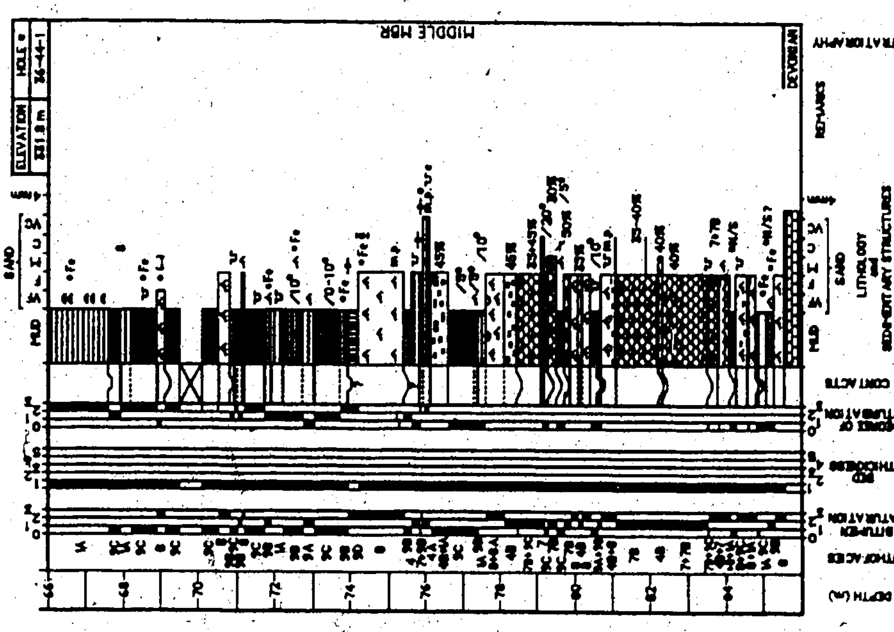
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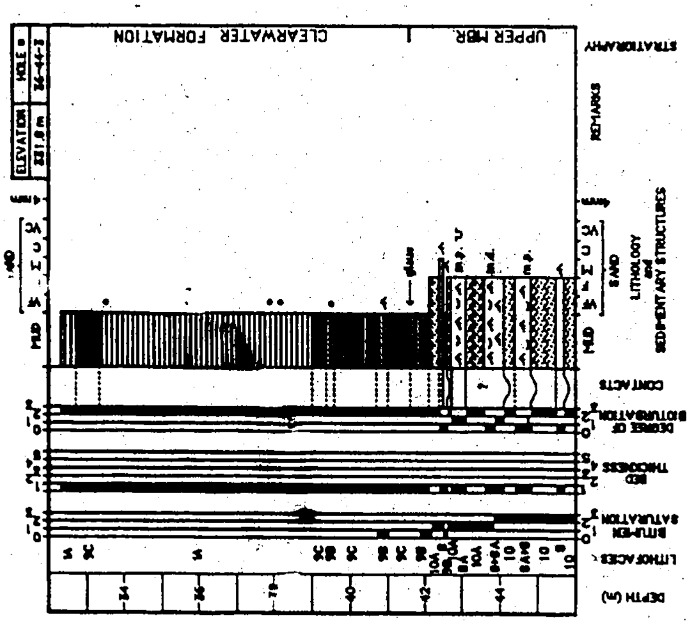
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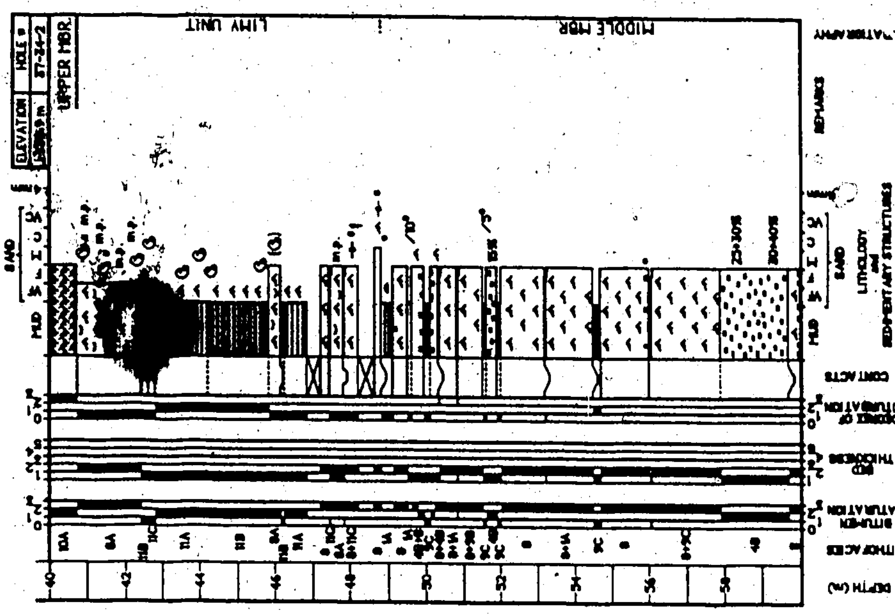

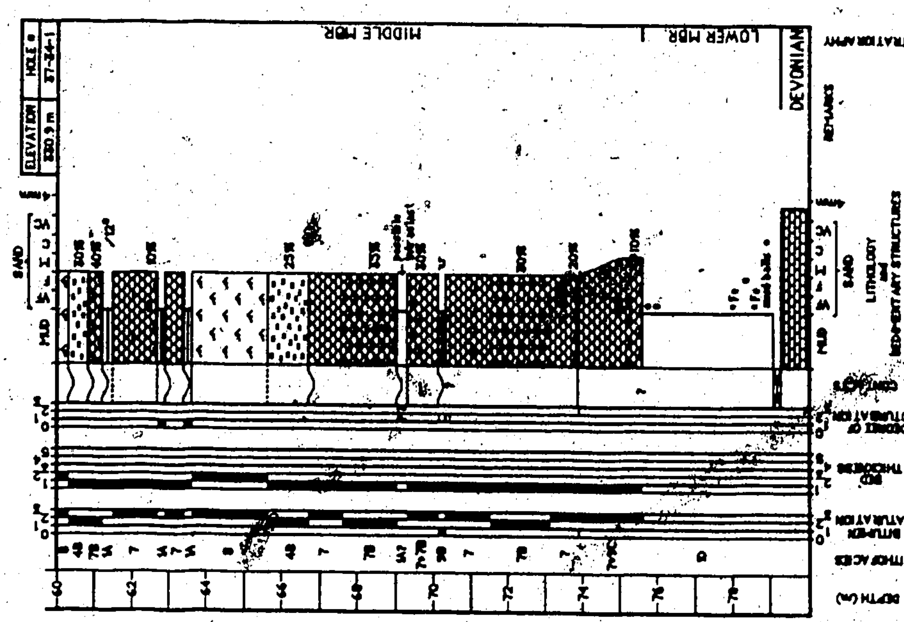

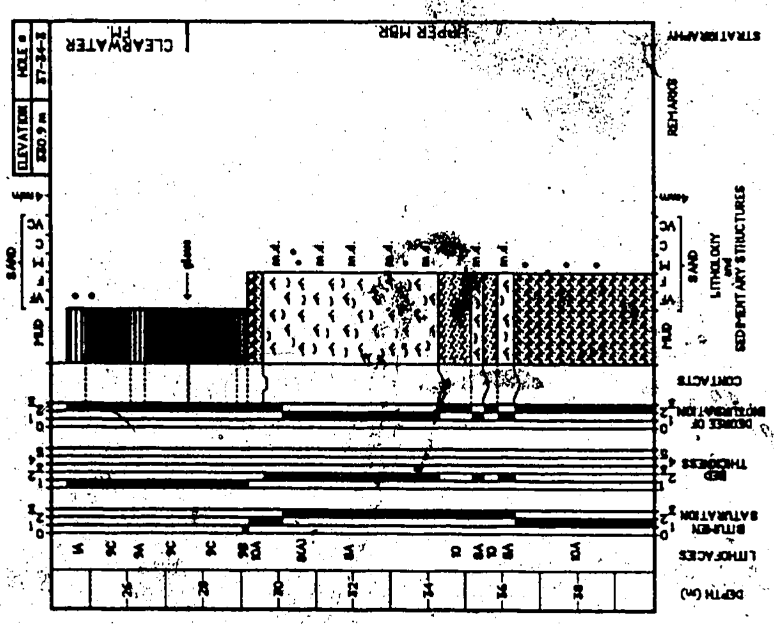
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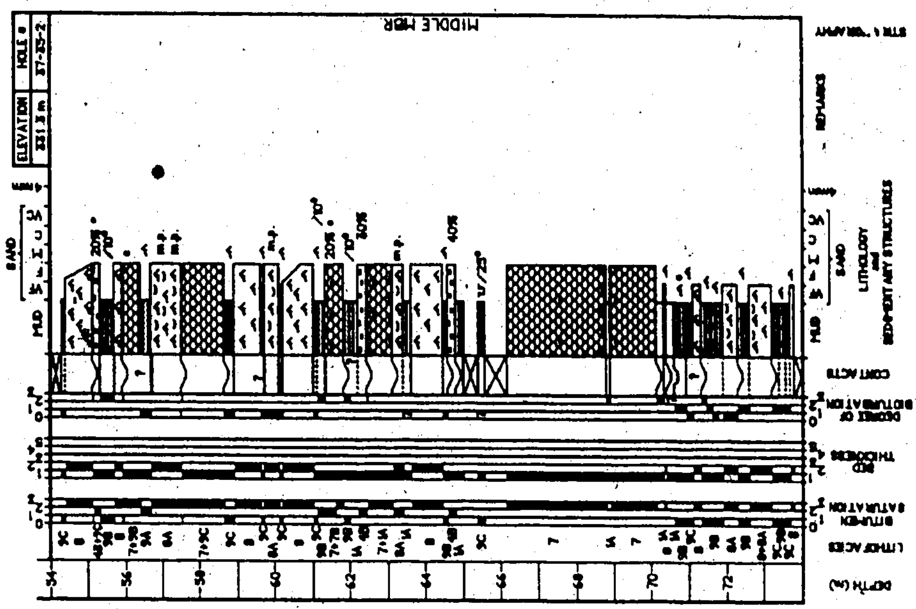
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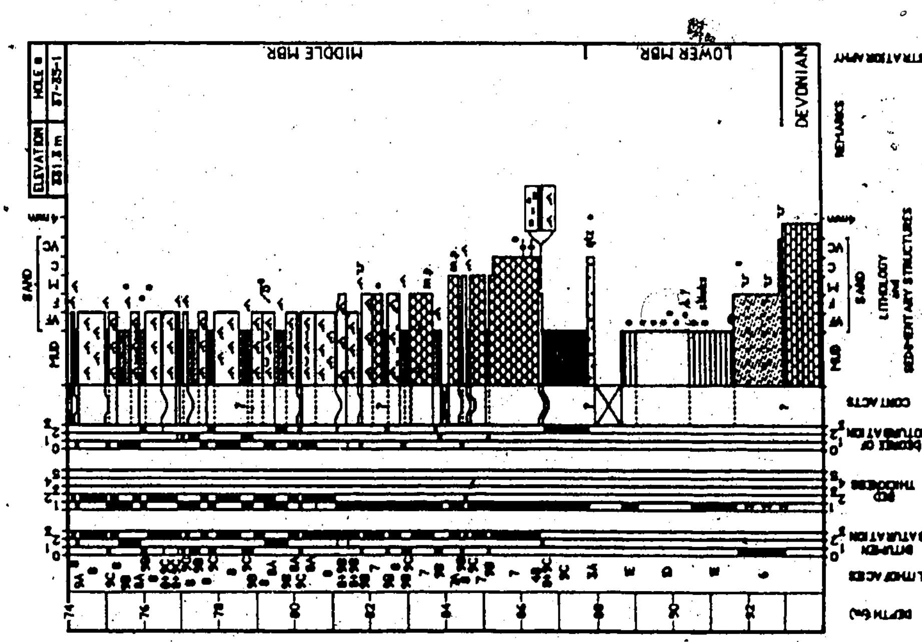
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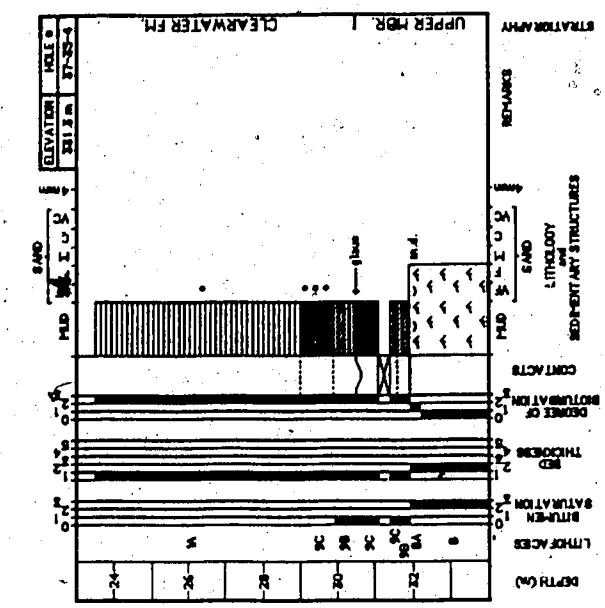
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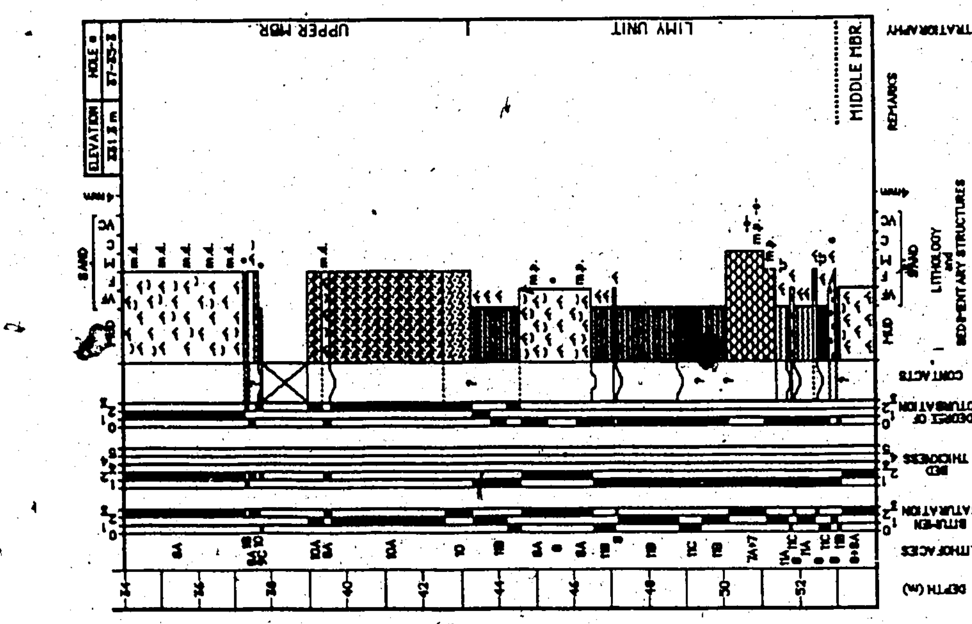
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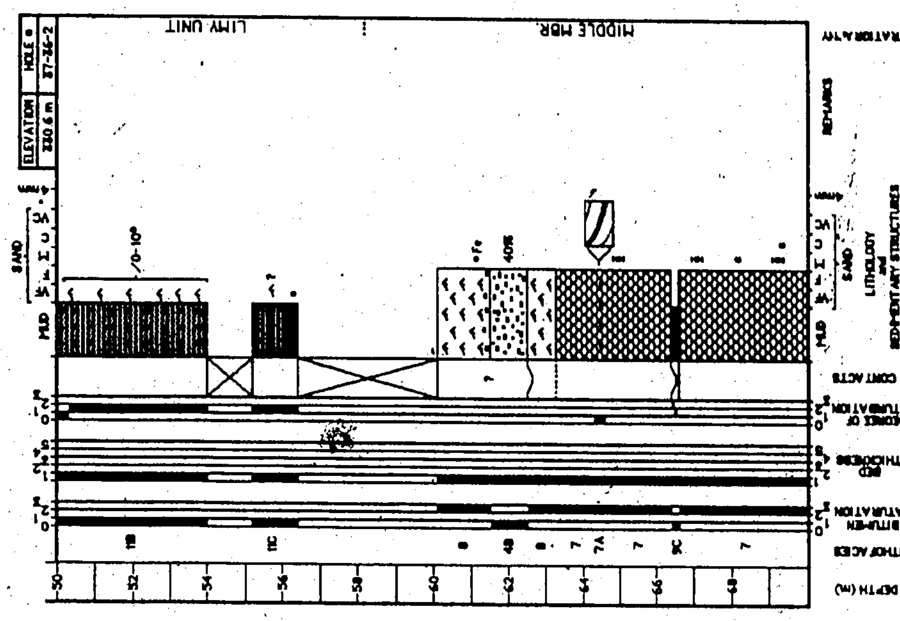
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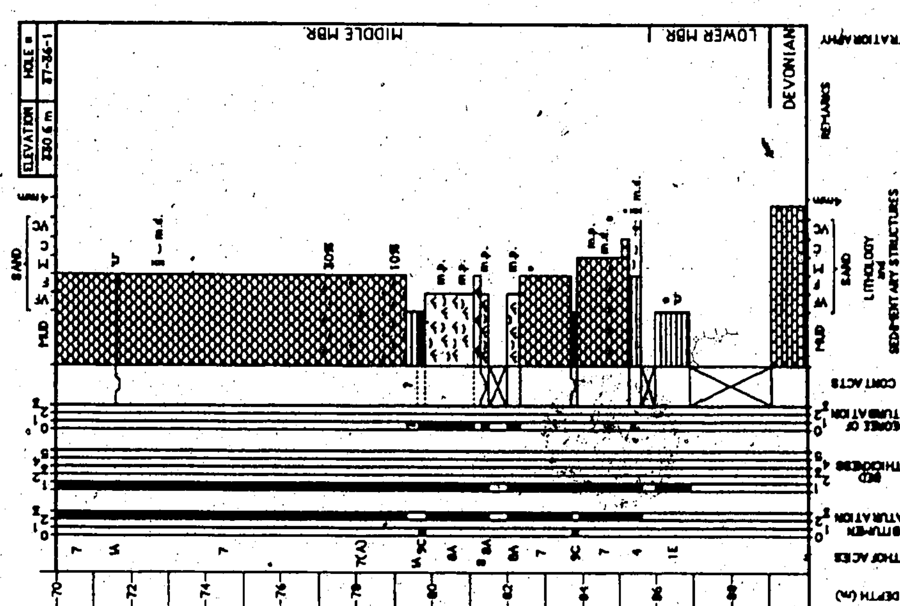
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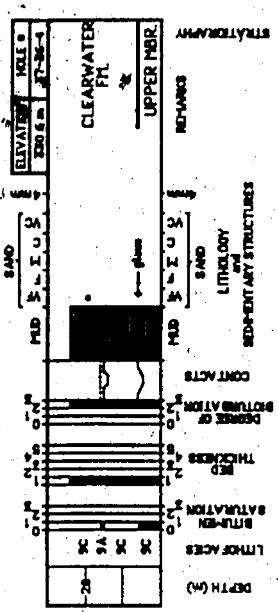
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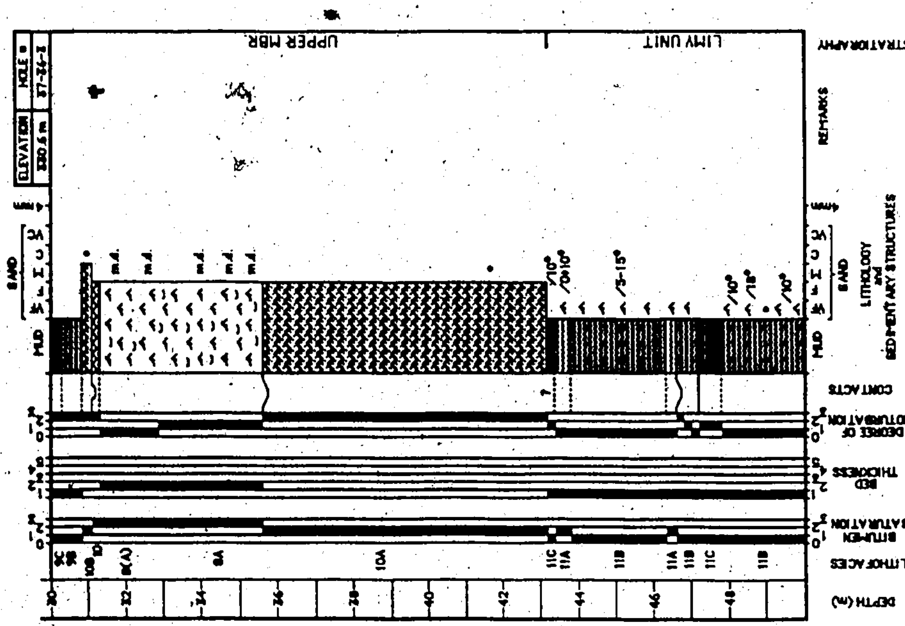
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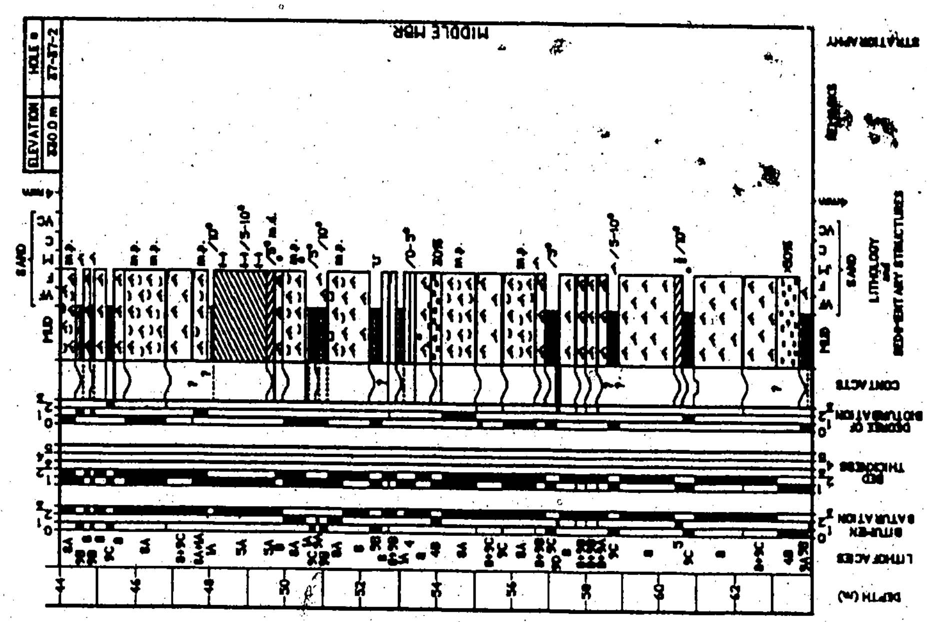

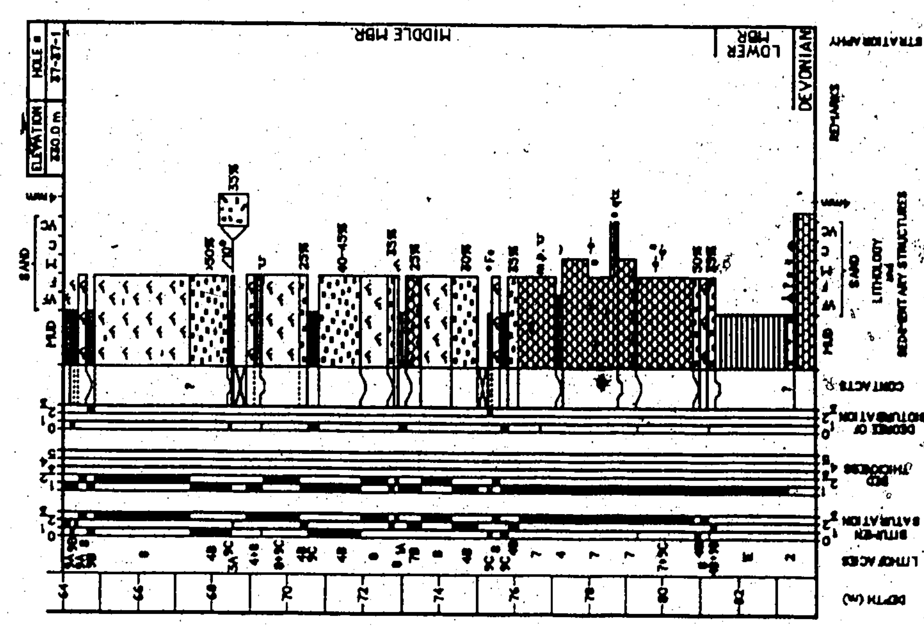

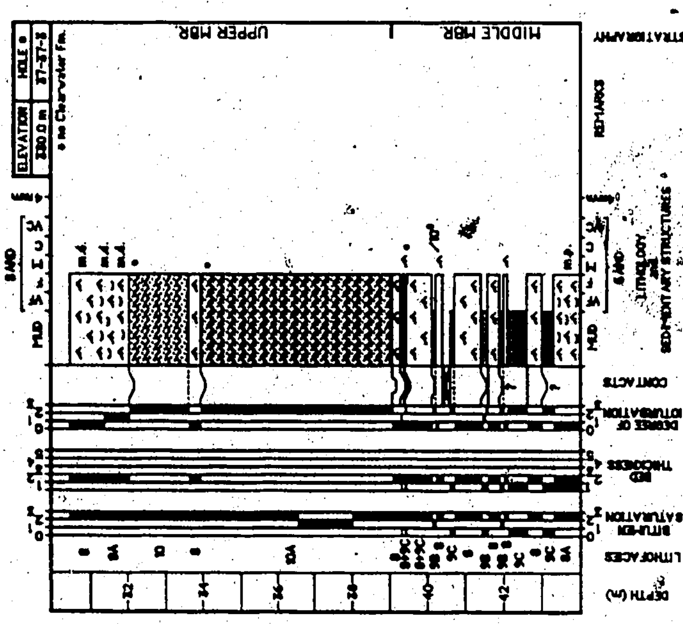
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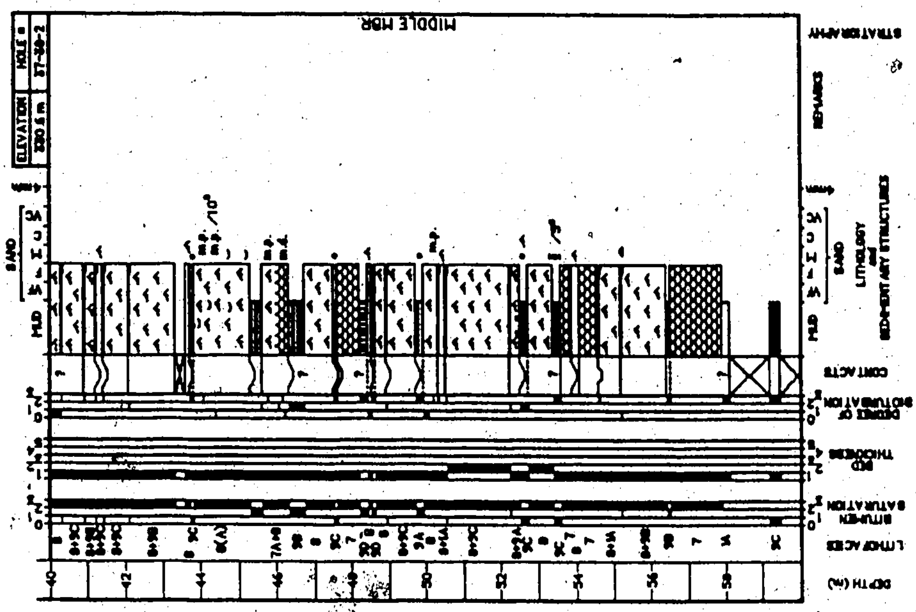
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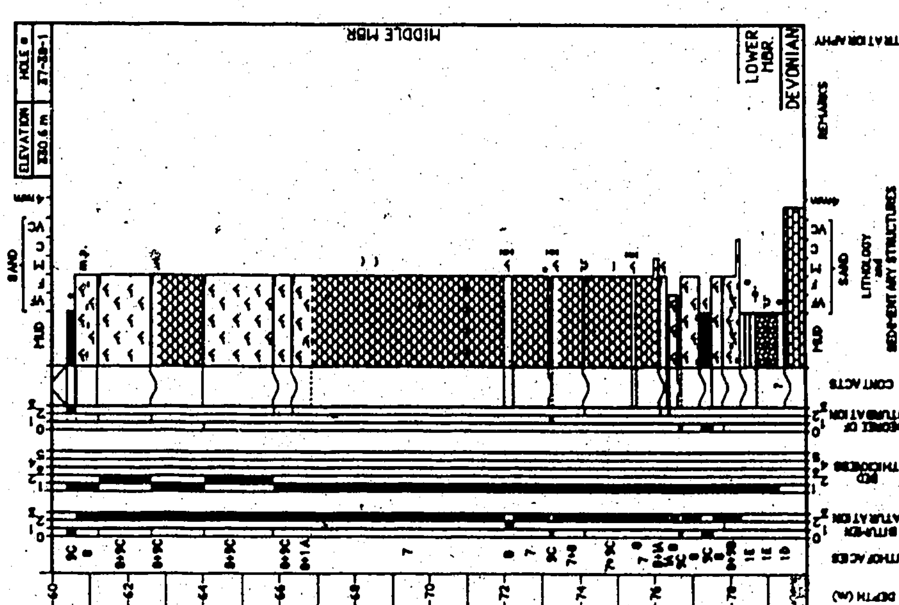
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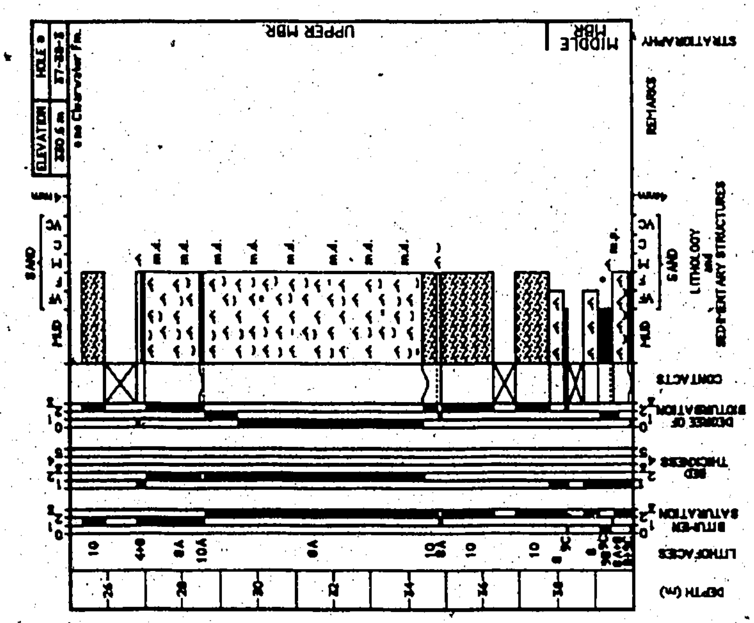
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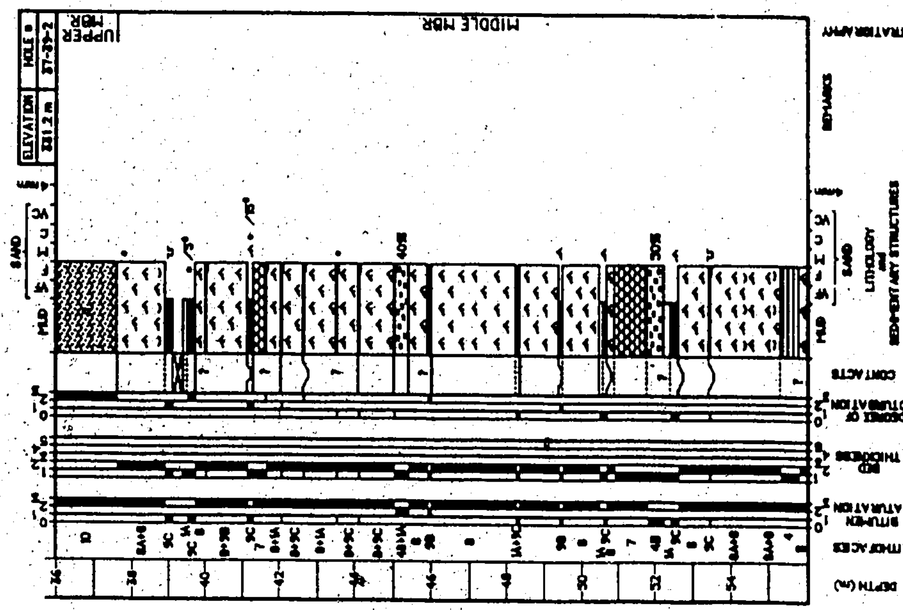
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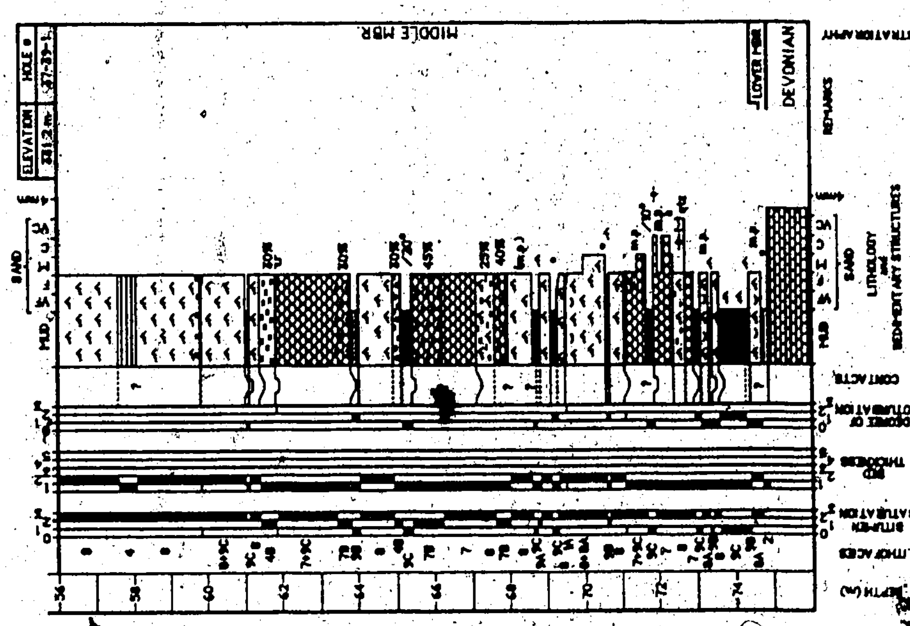
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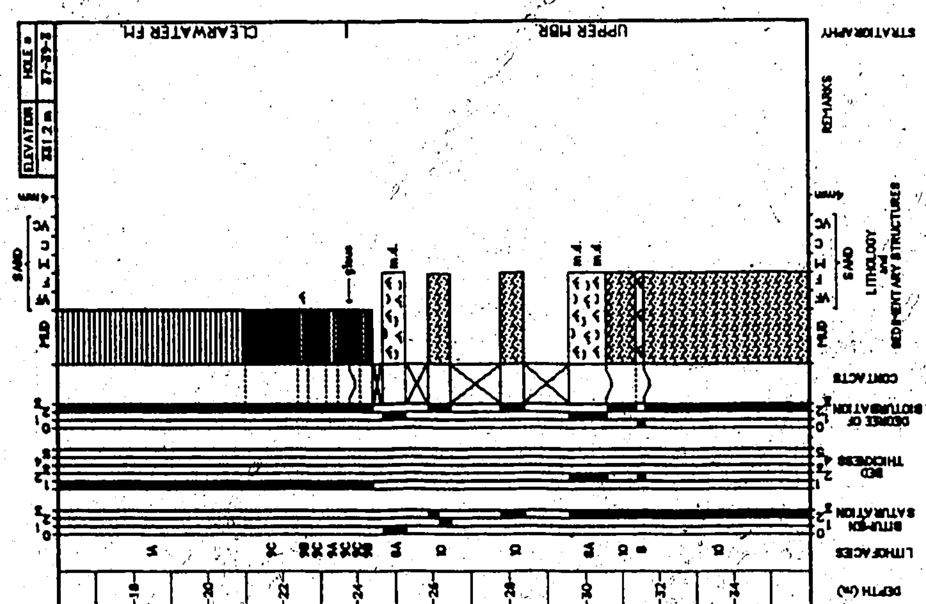
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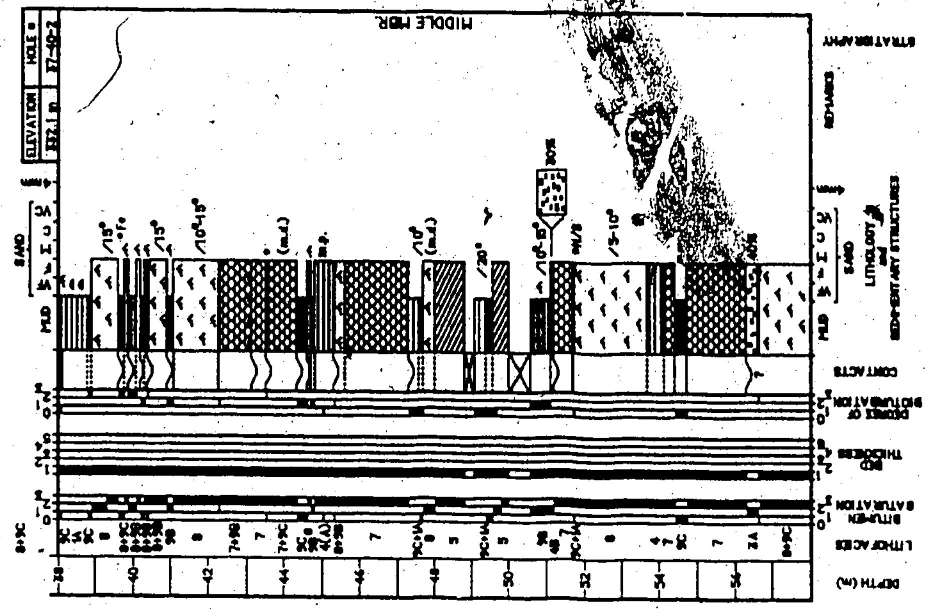
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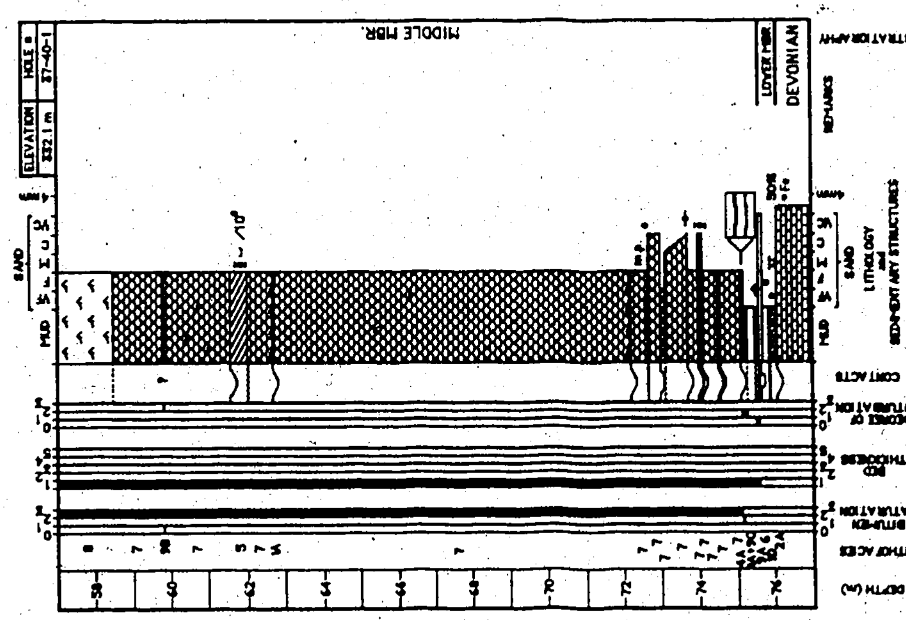
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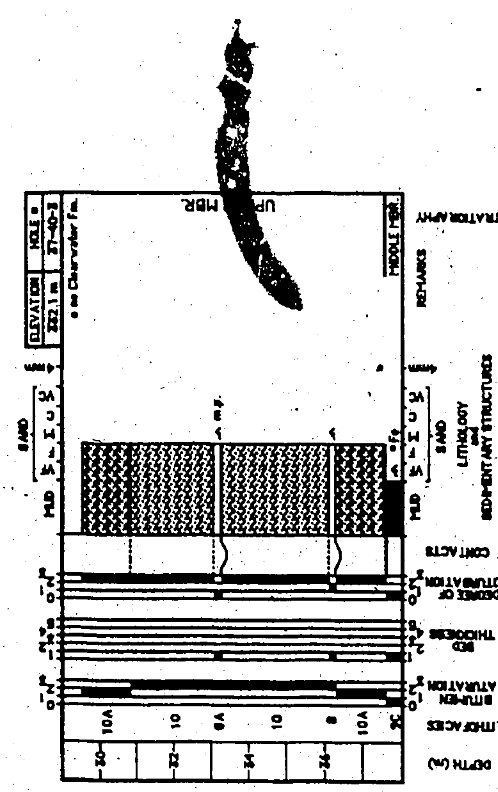
LOWER MBR.
DEVONIAN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HOLE #
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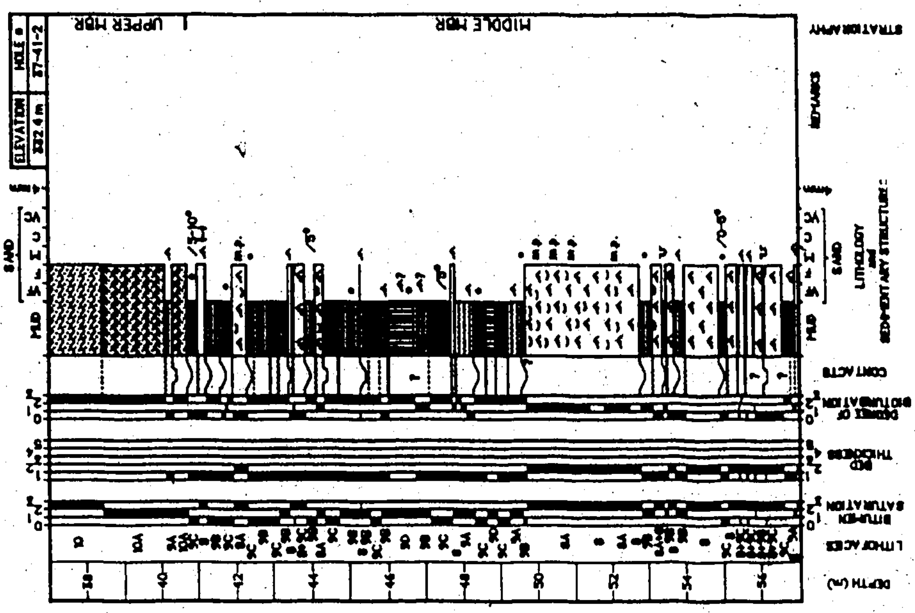
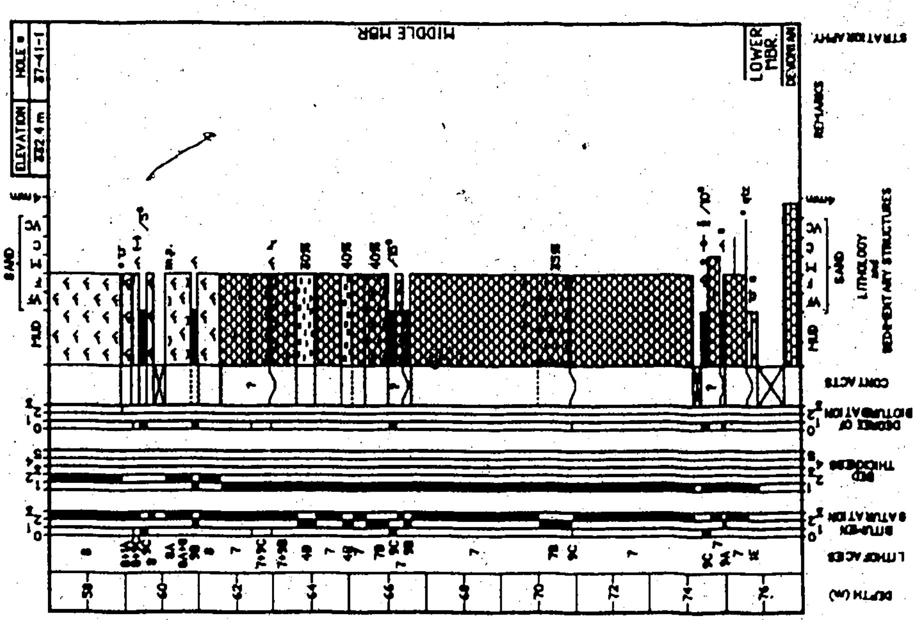
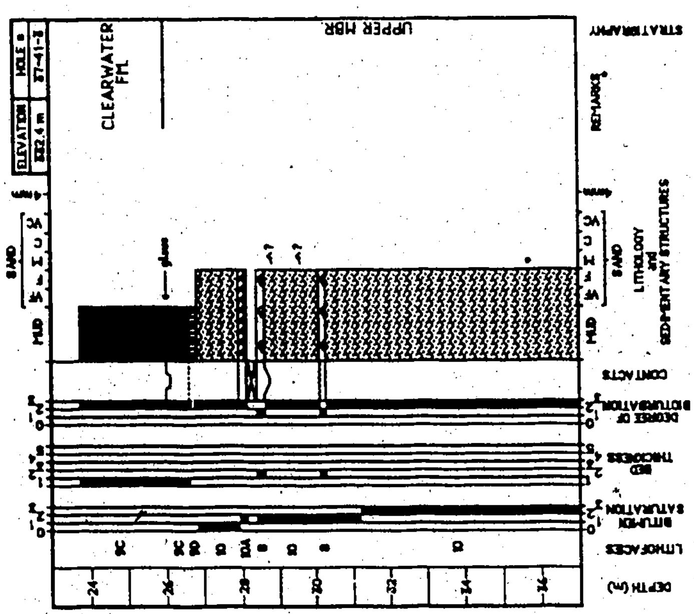
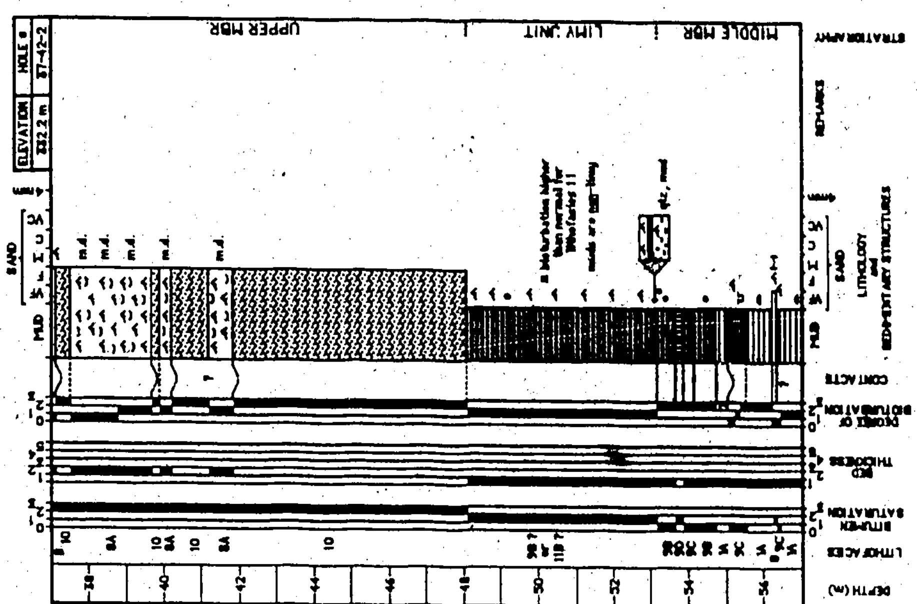
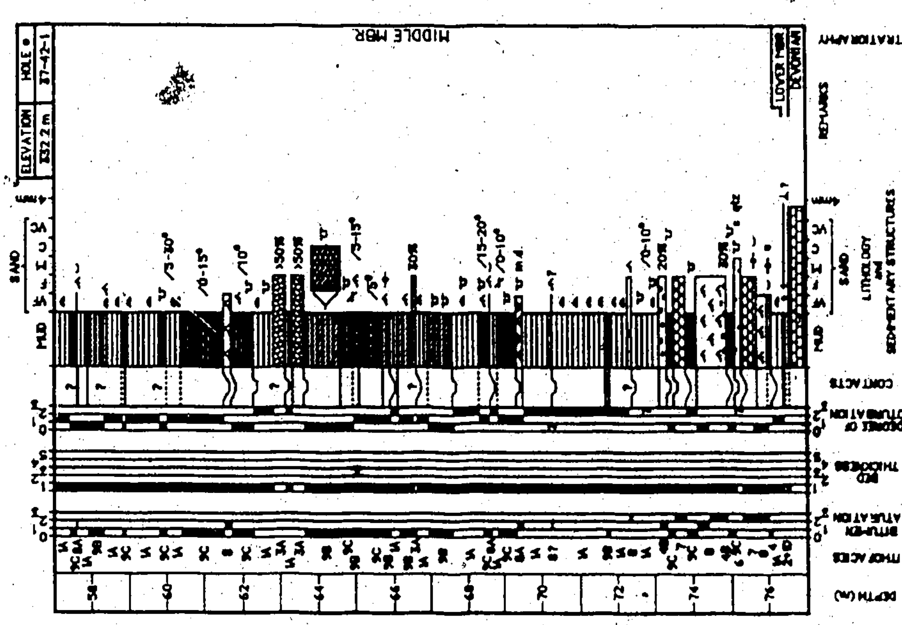
UPPER MBR.
MIDDLE MBR.
REMARKS
SAND
MUD
VF
F
M
C
VC
4mm
LITHOLOGY
and
SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF
BIOTURBATION
BED
THICKNESS
BITUMEN
SATURATION
LITHOFACIES
10A
10
8A
8
3C
DEPTH (m)
30
32
34
36

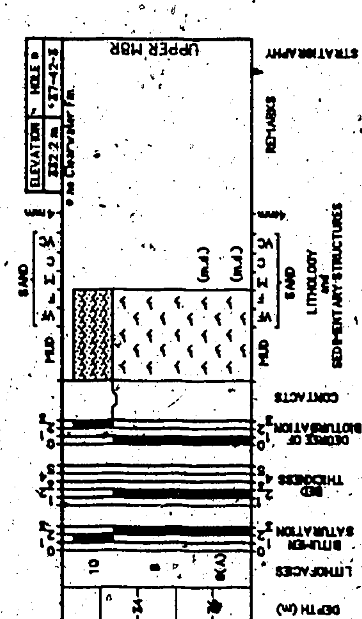





ELEVATION
HOLE #
CLEARWATER FM.
UPPER MBR
STRATIGRAPHY
REMARKS
MUD
SAND
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION 332.2 m
HOLE # 87-42-2
UPPER MBR
LIMY UNIT
MIDDLE MBR
STRATIGRAPHY
REMARKS
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION 332.2 m
HOLE # 87-42-1
MIDDLE MBR
LOWER MBR
DEVONIAN
STRATIGRAPHY
REMARKS
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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CONTACTS
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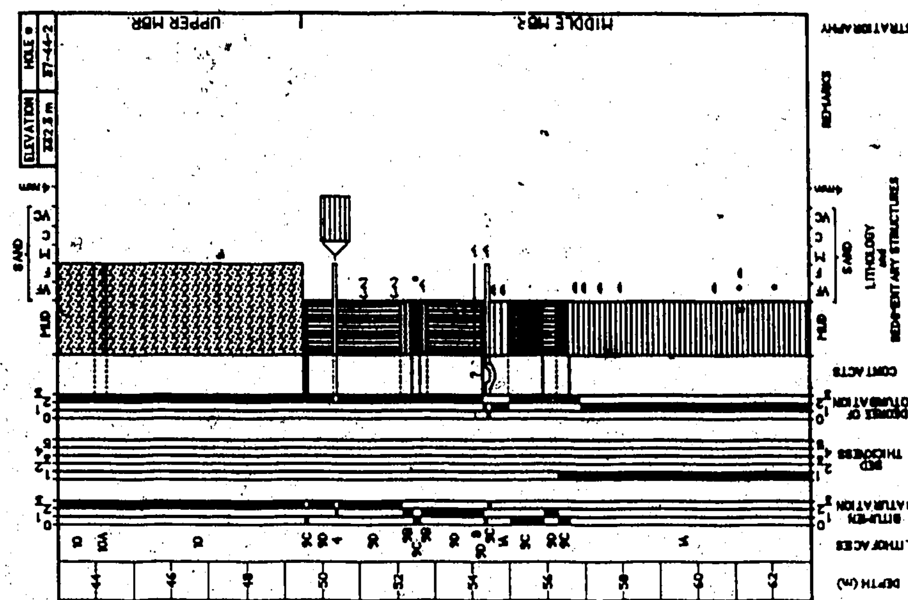
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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MIDDLE MBR.
ELEVATION
332.5 m
HOLE #
87-44-2
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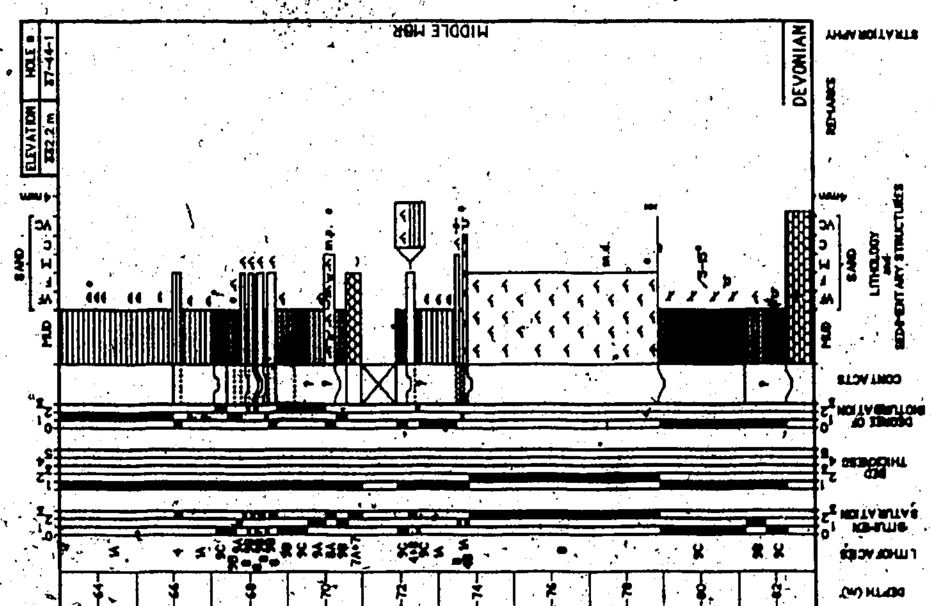
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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DEVONIAN
ELEVATION
332.2 m
HOLE #
87-44-1
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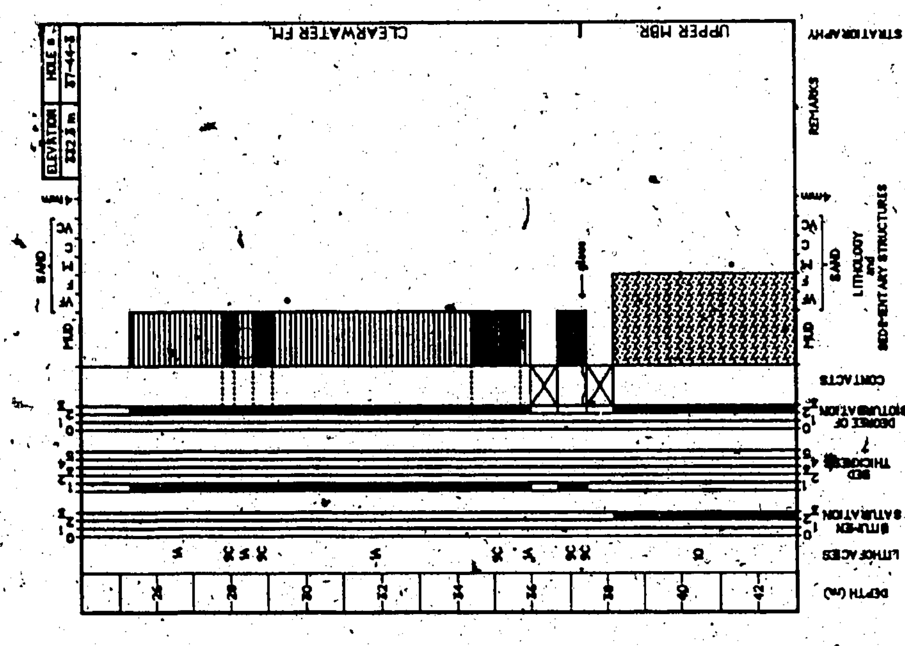
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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CONTACTS
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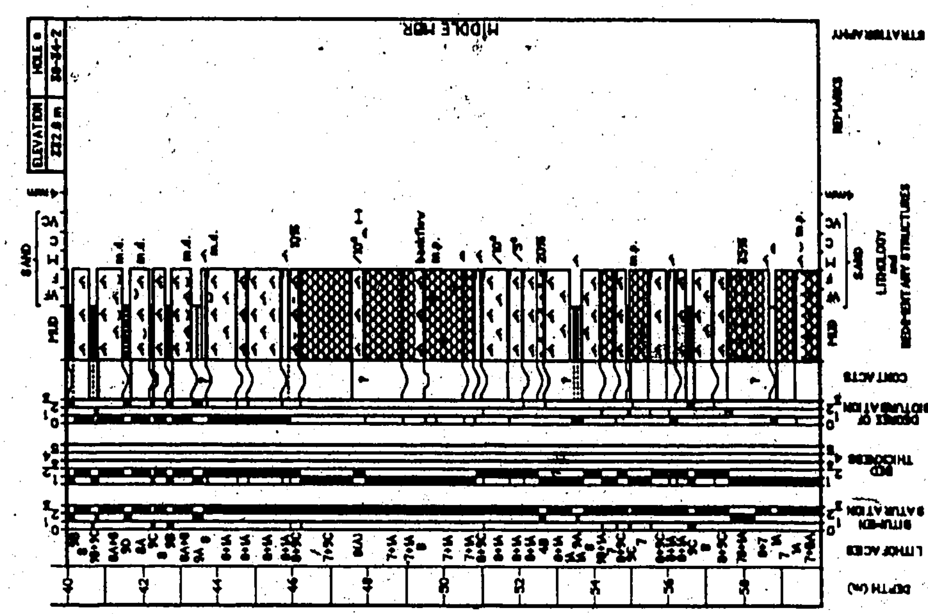
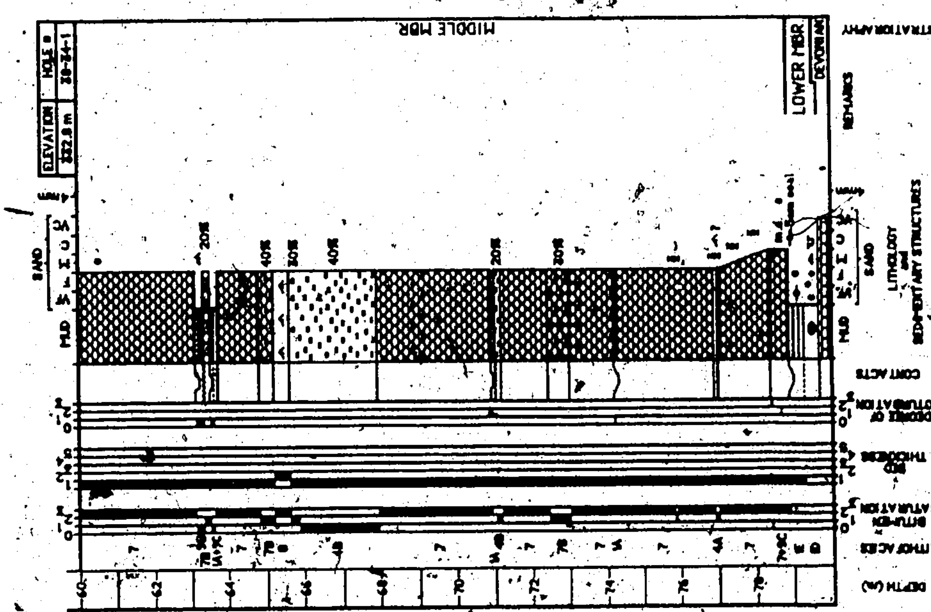
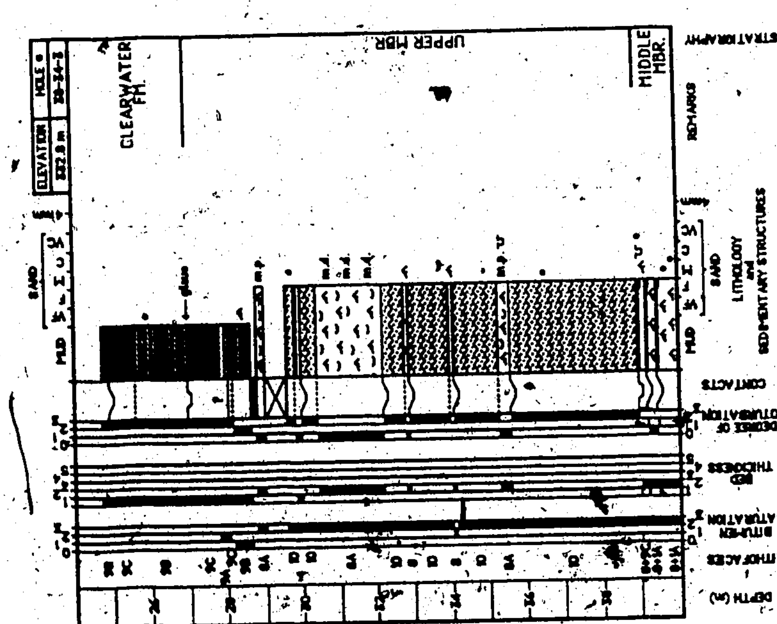
LITHOFACIES
DEPTH (m)






ELEVATION
HOLE #
CLEARWATER FM.
UPPER MBR
MIDDLE MBR.
STRATIGRAPHY
REMARKS
MUD
SAND
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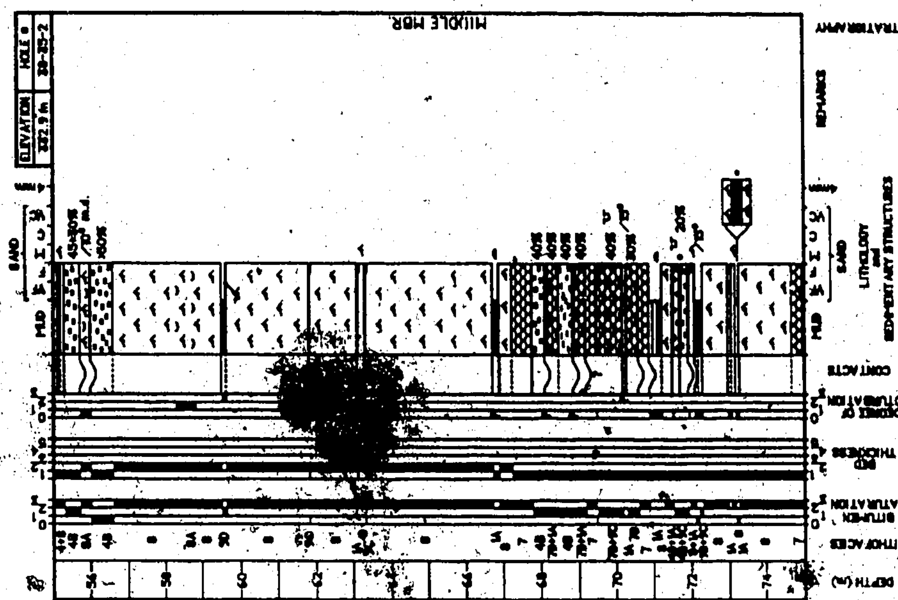
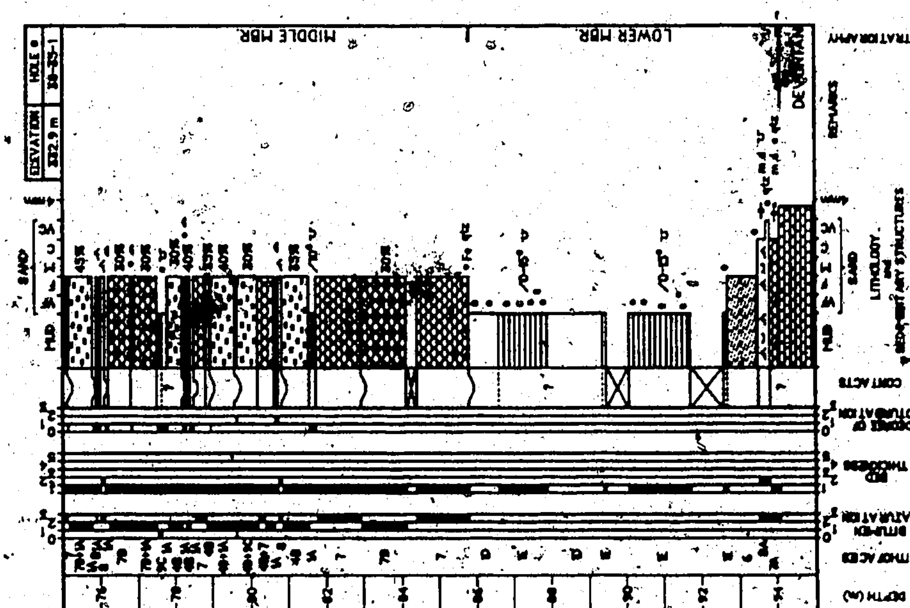
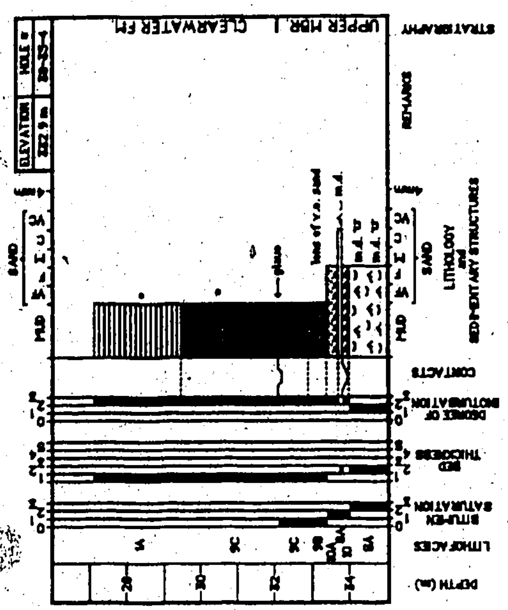
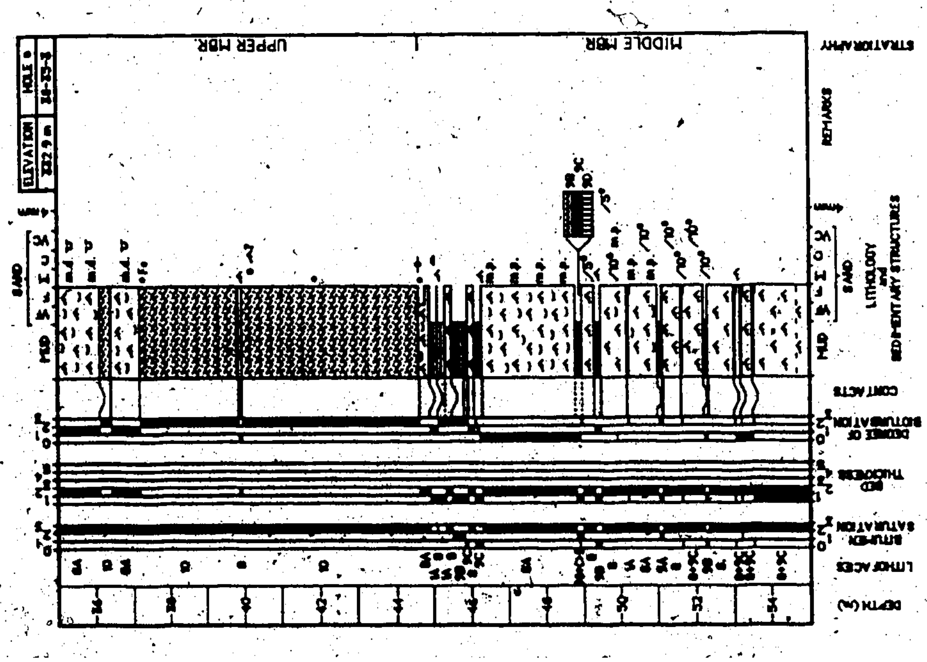
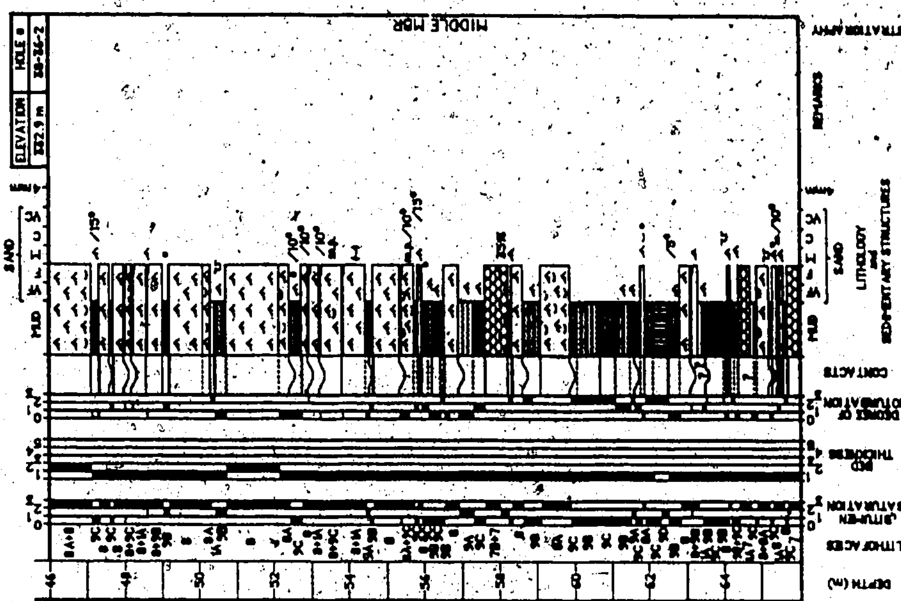
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)







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332.9 m
HOLE #
MIDDLE MBR
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REMARKS
SAND
MUD
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CONTACTS
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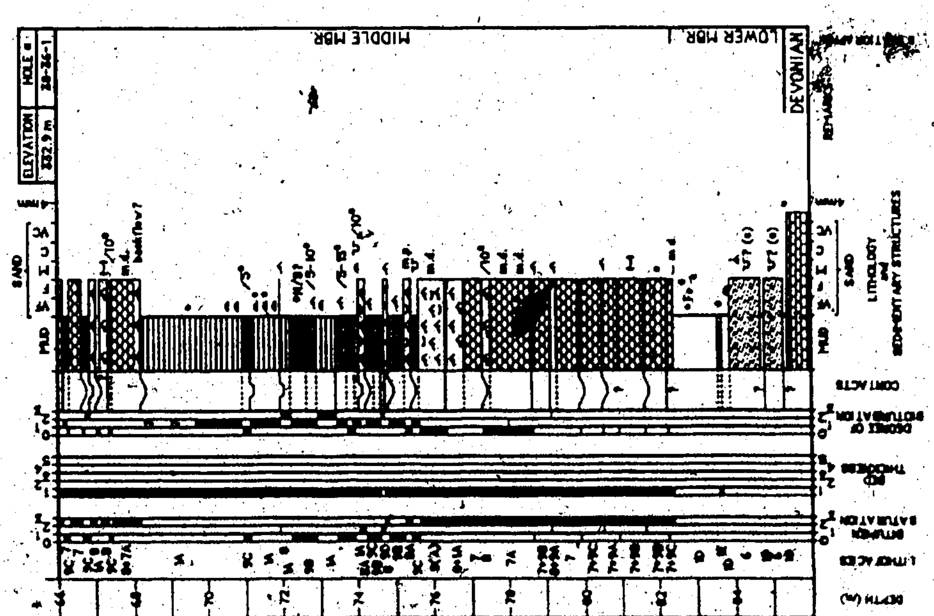
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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332.9 m
HOLE #
MIDDLE MBR
LOWER MBR
DEVONIAN
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REMARKS
SAND
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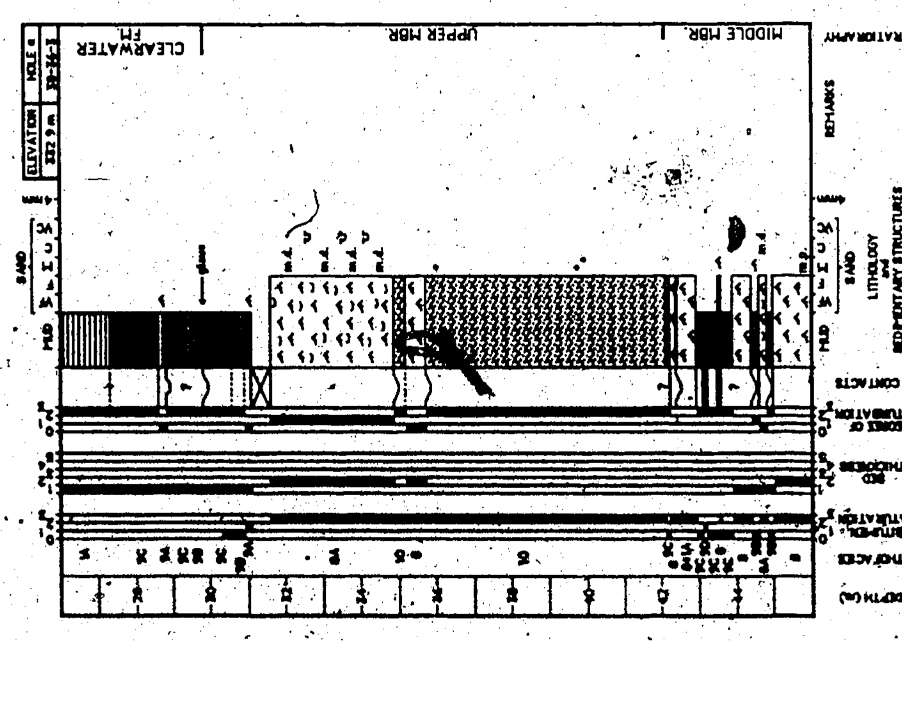
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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MIDDLE MBR.
UPPER MBR.
CLEARWATER FM.
ELEVATION
HOLE #
REMARKS
SAND
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BITUMEN SATURATION
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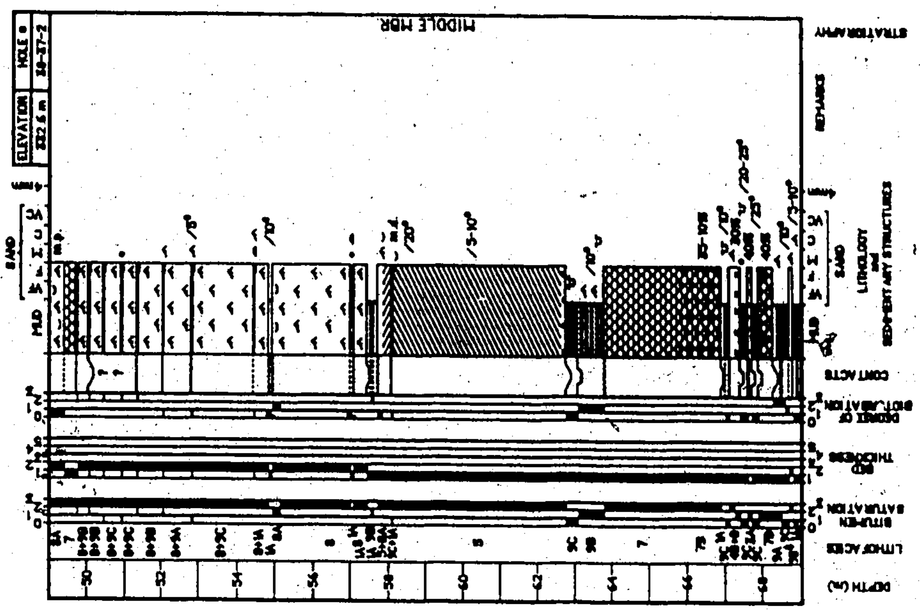
DEPTH (m)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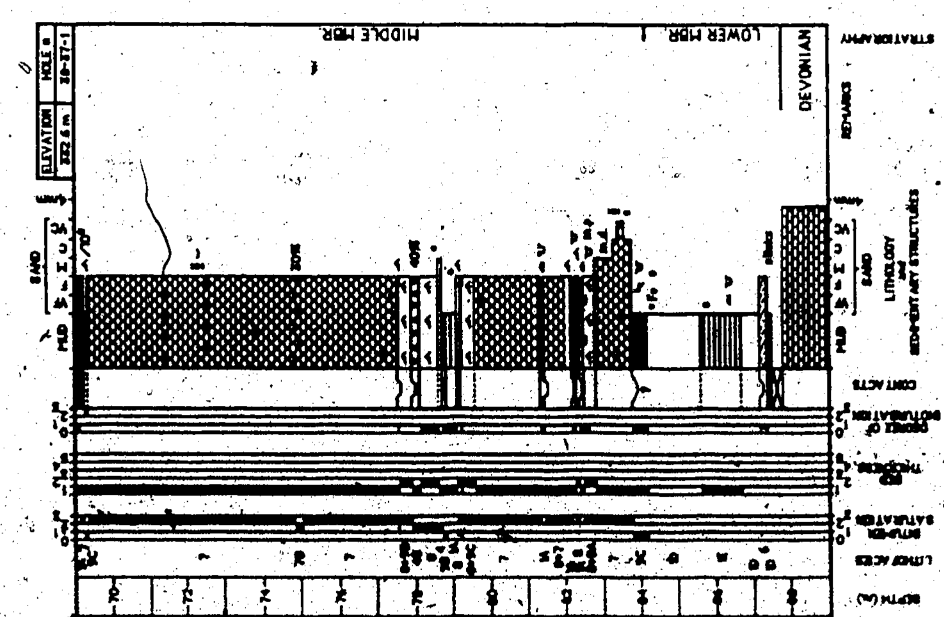
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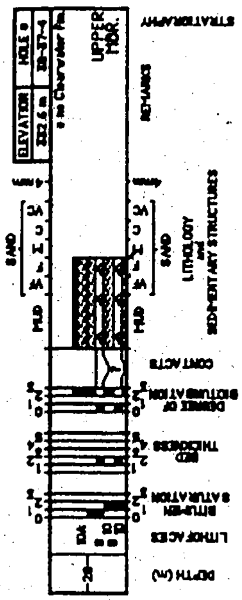
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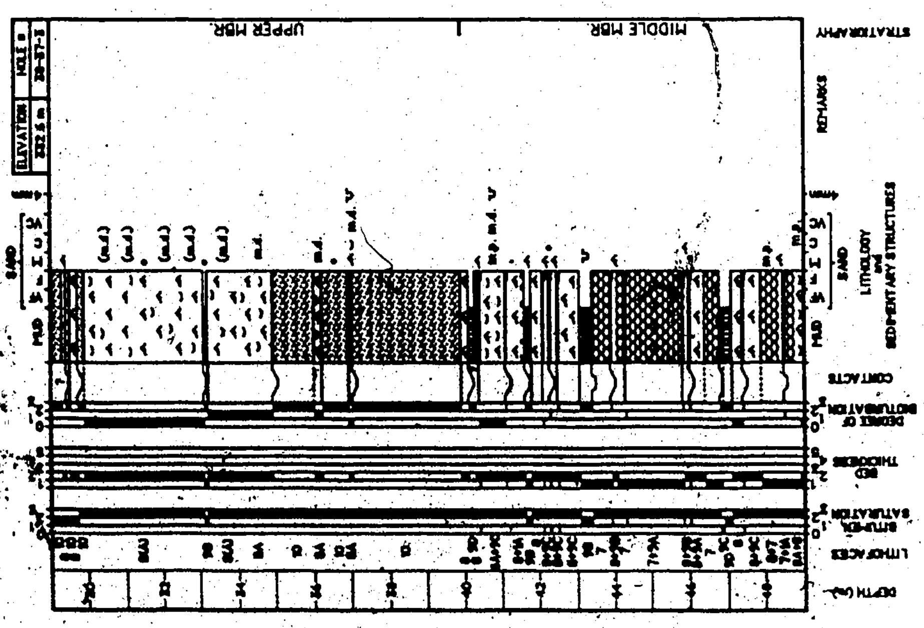
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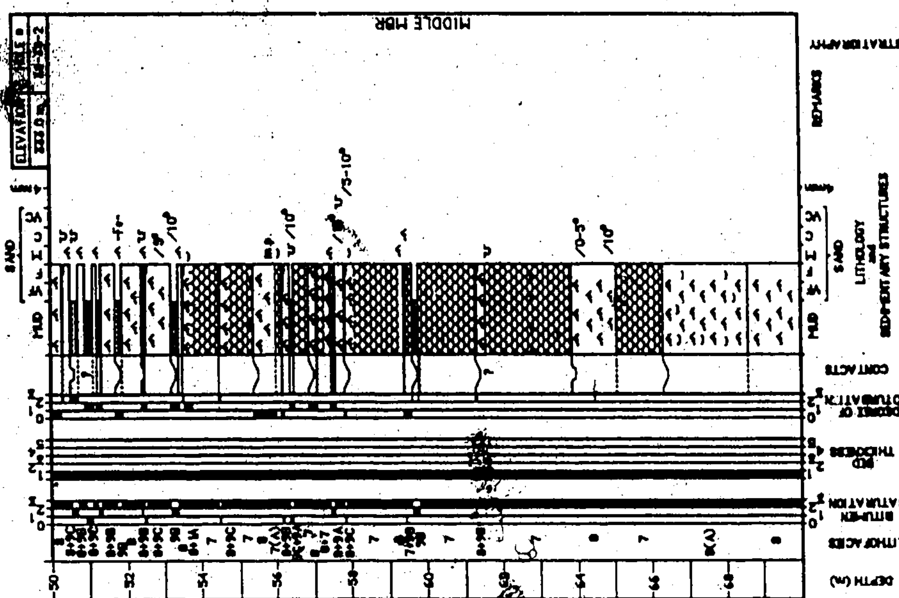
DEPTH (m)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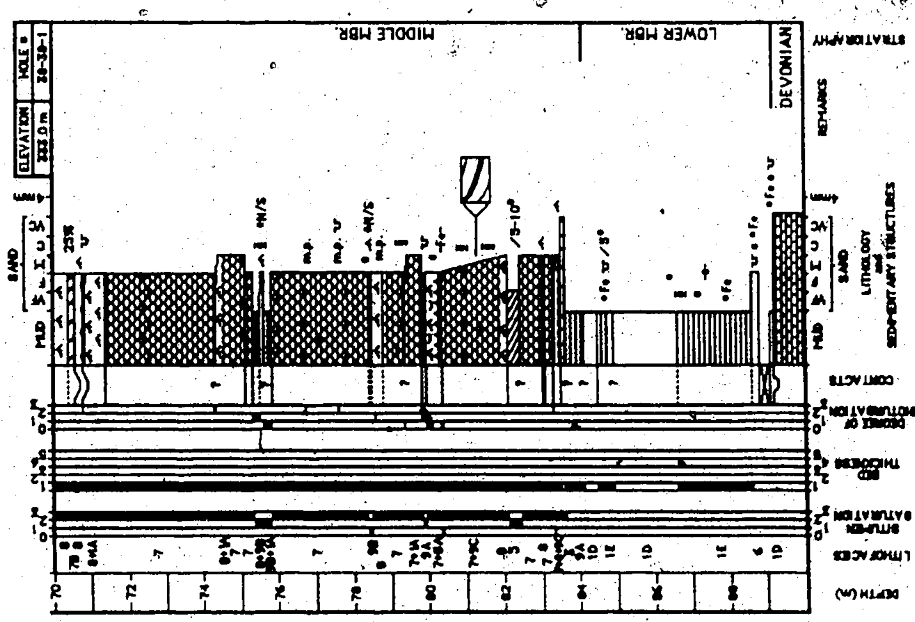
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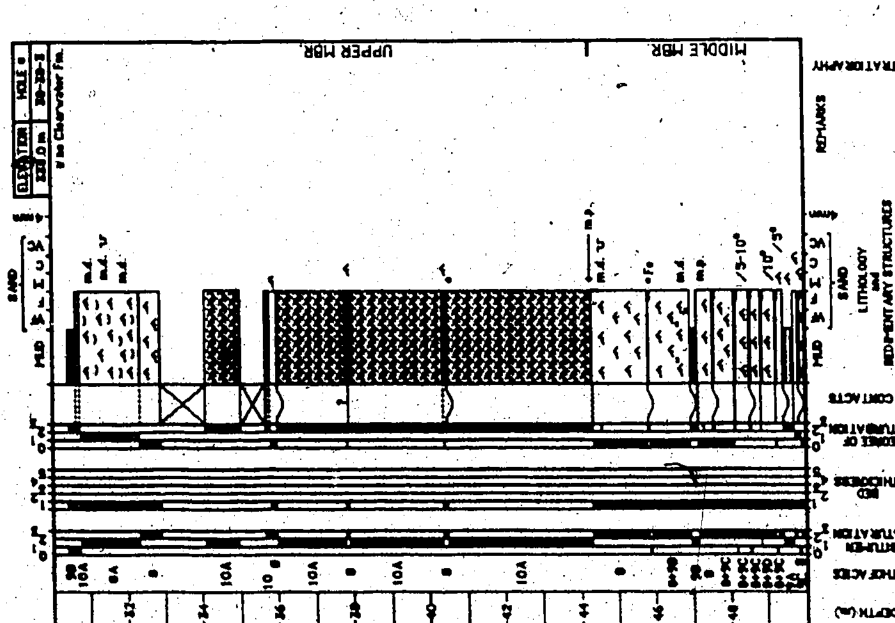
DEPTH (m)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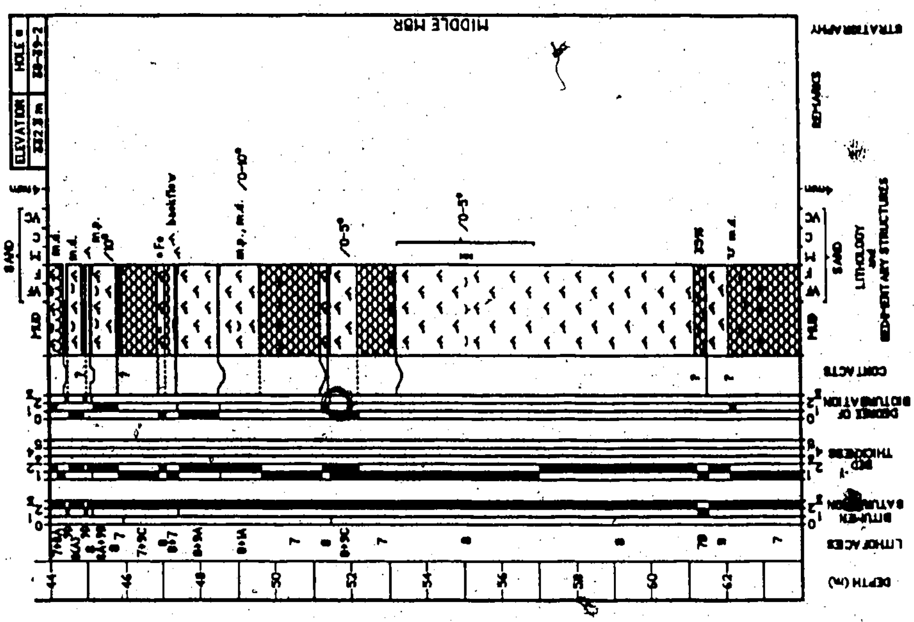

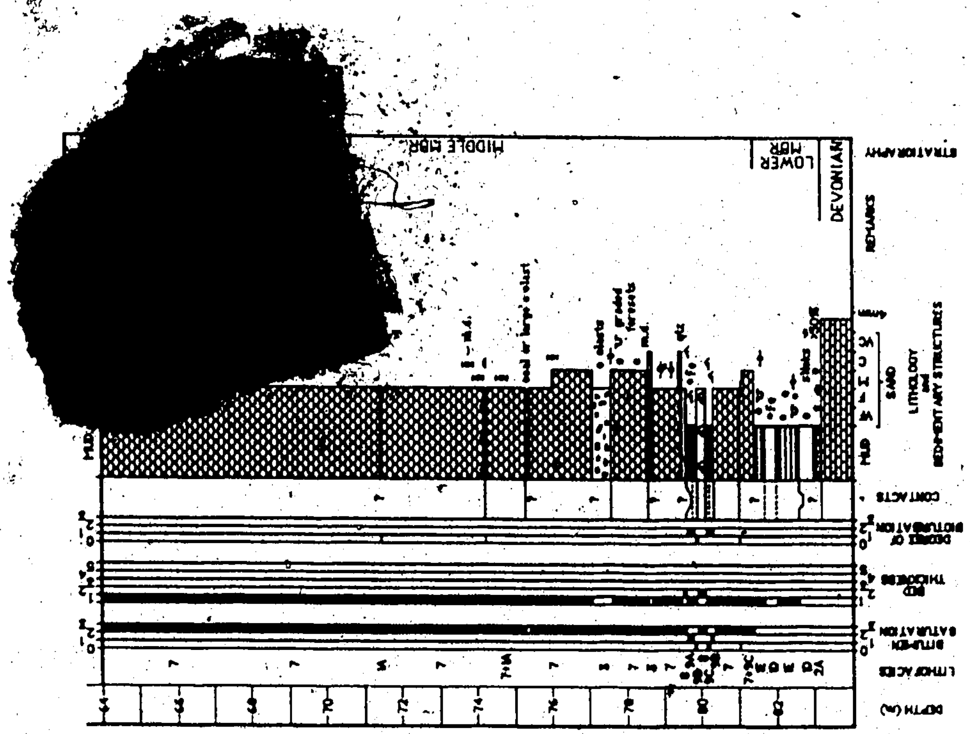

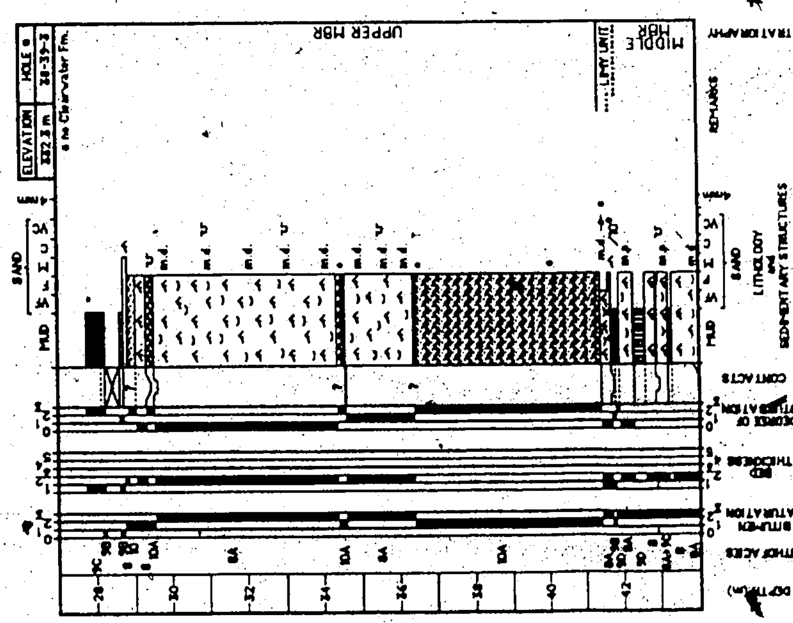

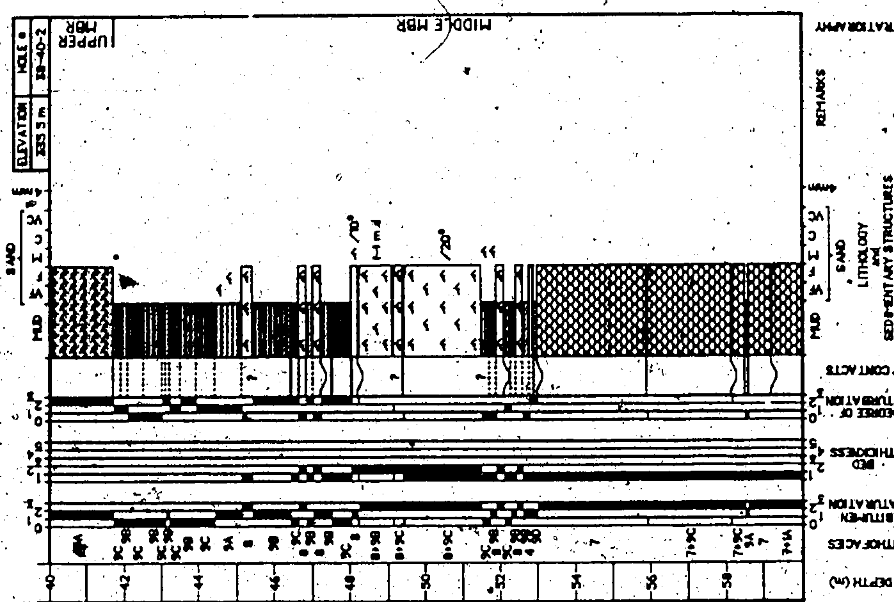
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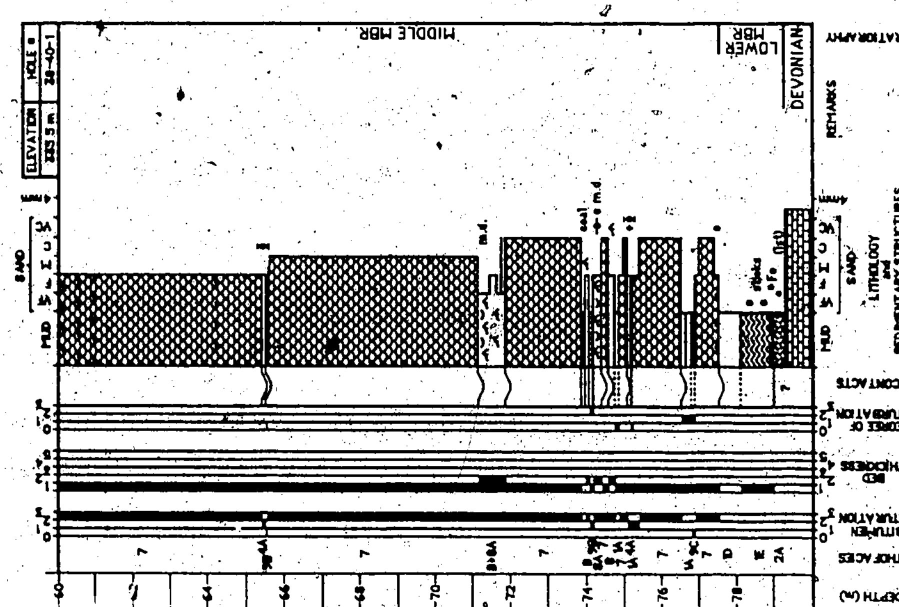
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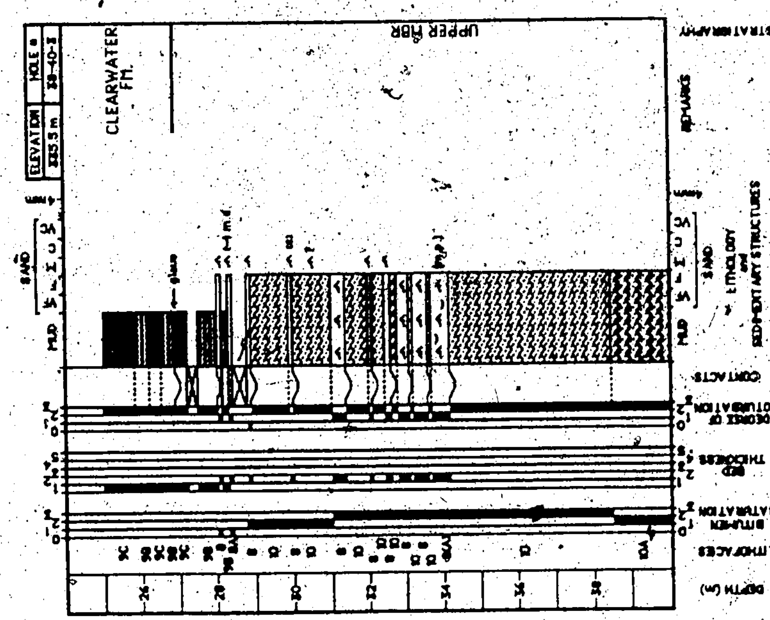
DEVONIAN
ELEVATION
HOLE #
MUD
SAND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HOLE
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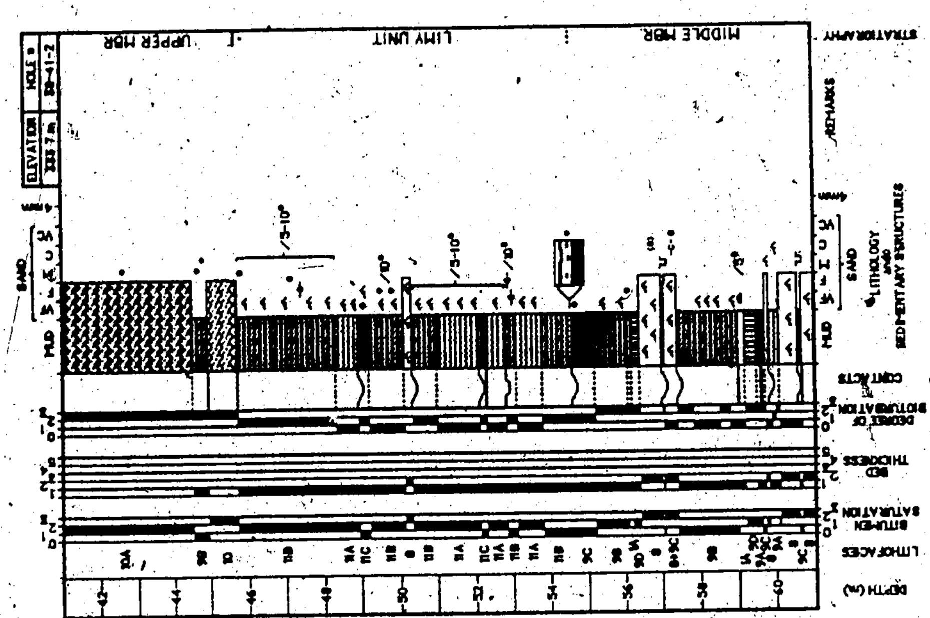
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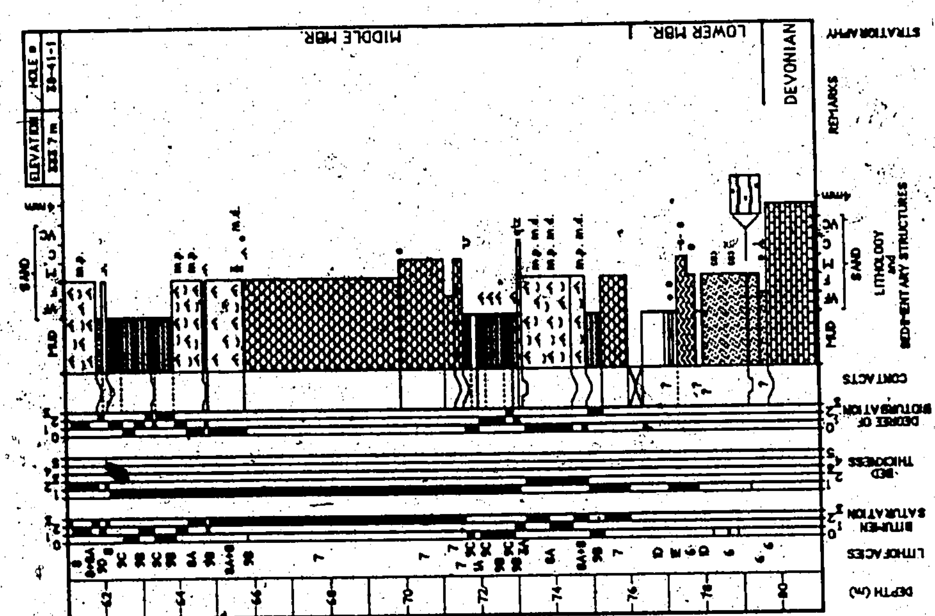
ELEVATION
HOLE #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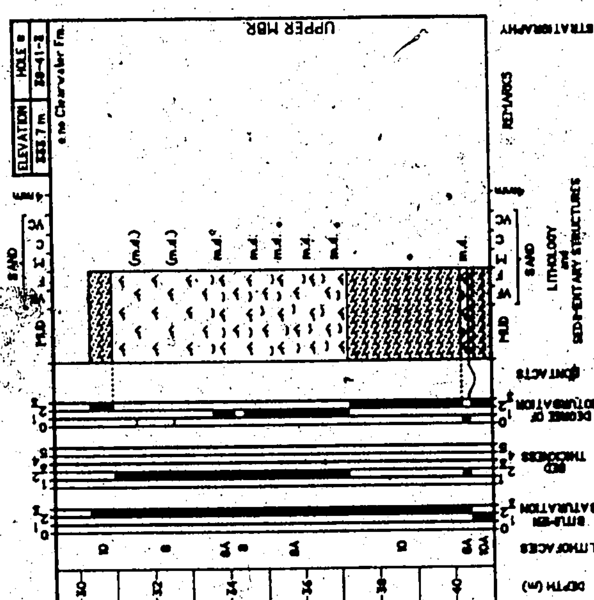
ELEVATION
HOLE #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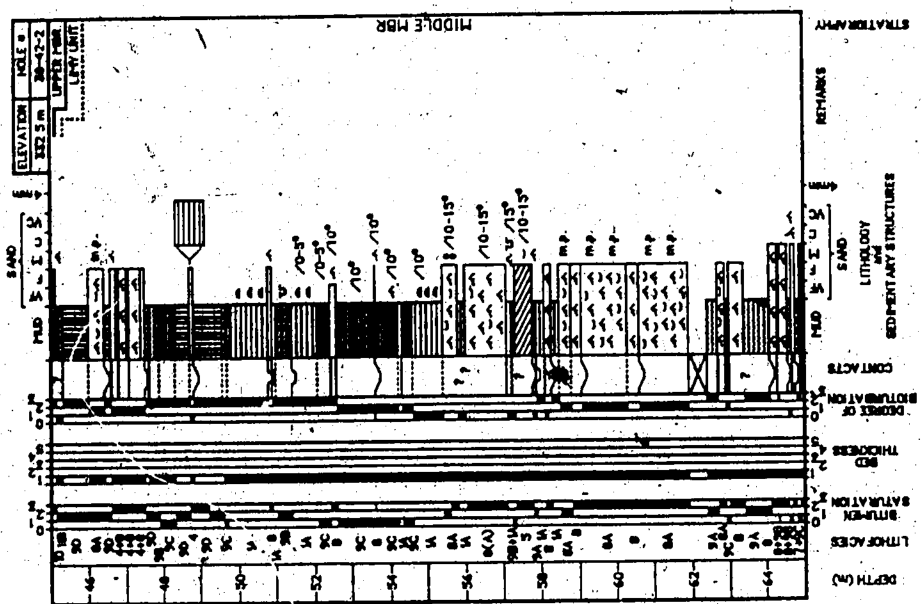
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332.5 m
HOLE #
30-42-2
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LIMY UNIT
MIDDLE MBR
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BITUMEN SATURATION
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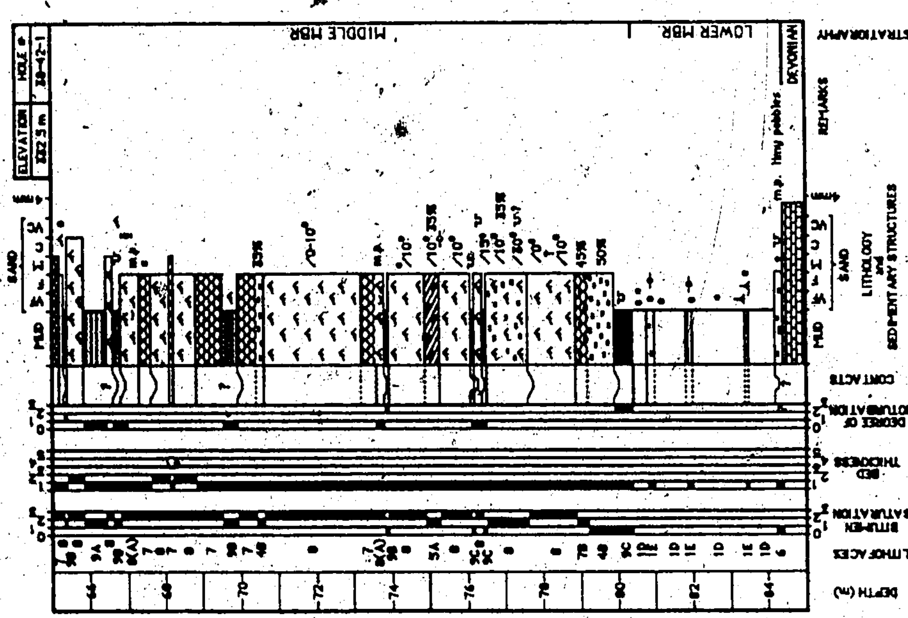
DEPTH (m)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332.5 m
HOLE #
30-42-1
MIDDLE MBR
LOWER MBR
DEVONIAN
limy pebbles
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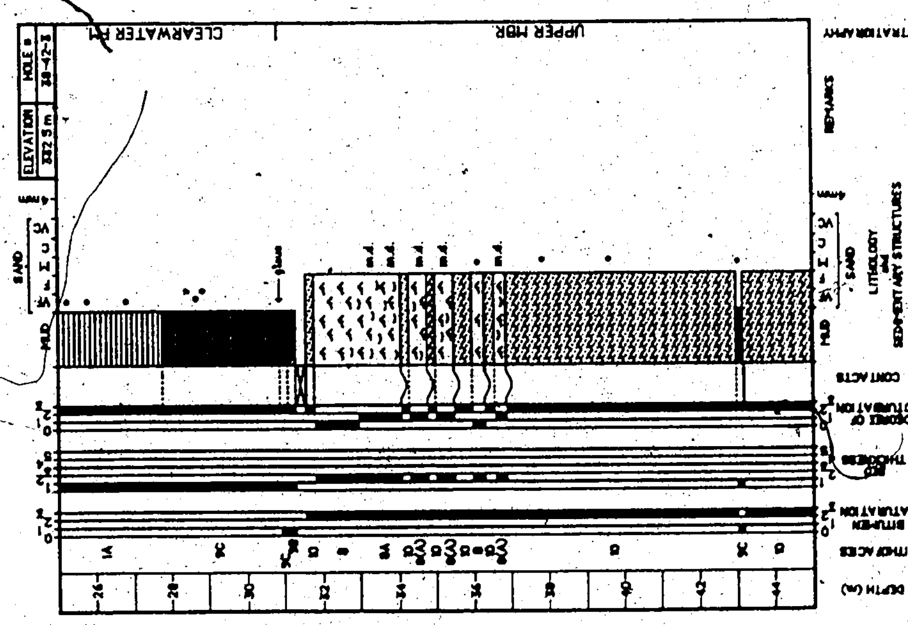
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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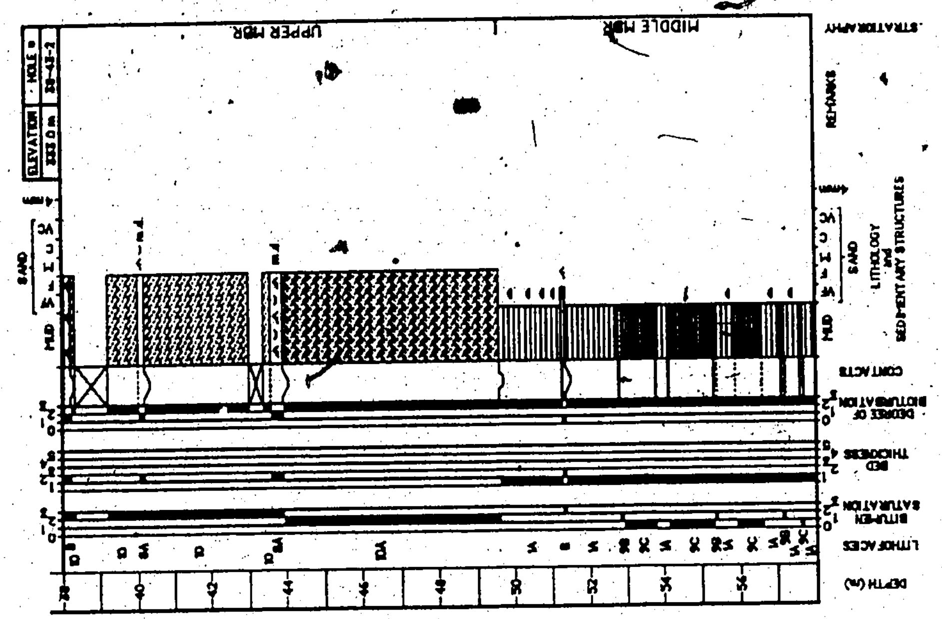

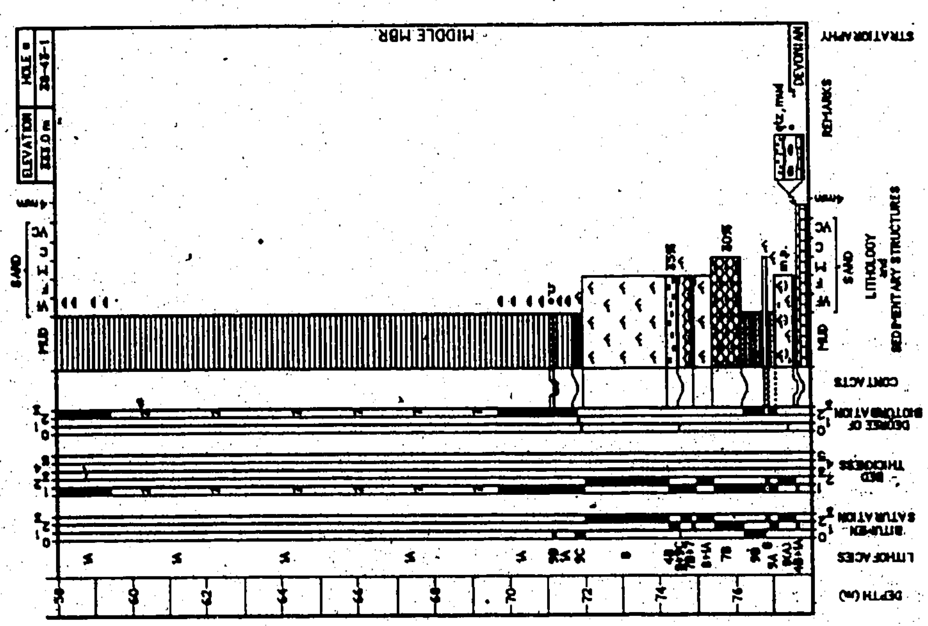

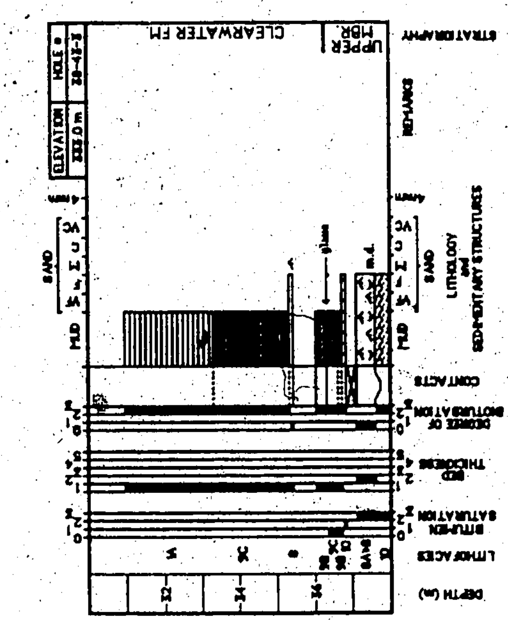
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CLEARWATER FM.
UPPER MBR.
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REMARKS
MUD
SAND
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CONTACTS
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BITUMEN SATURATION
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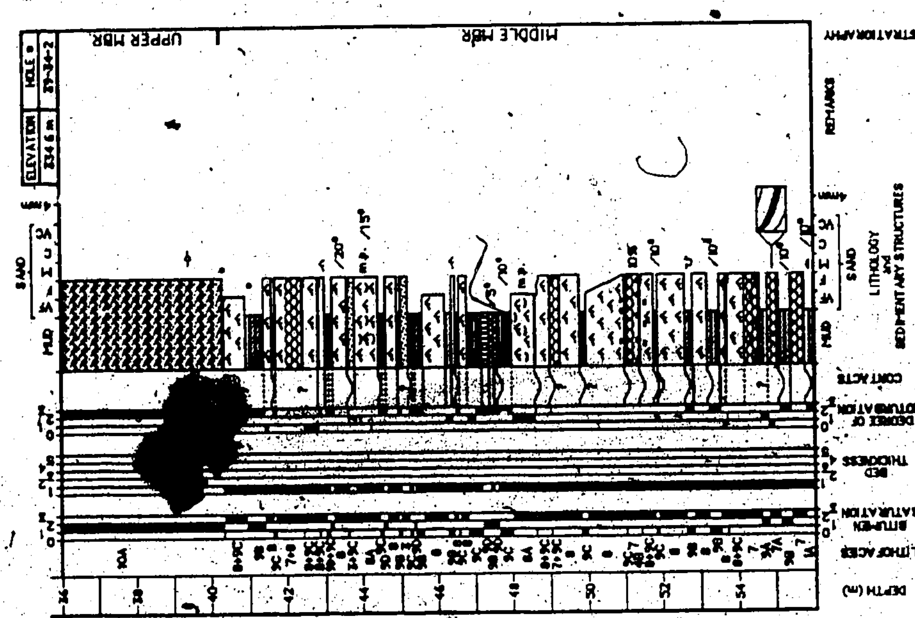
DEPTH (m)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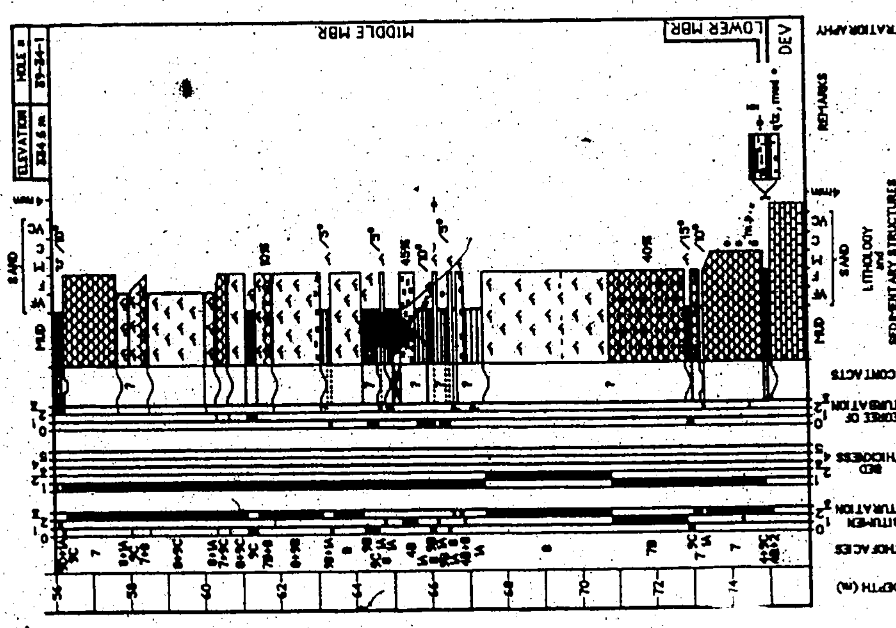
DEPTH (m)


MIDDLE MBR
LOWER MBR
DEV
STRATIGRAPHY
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BED THICKNESS
BITUMEN SATURATION
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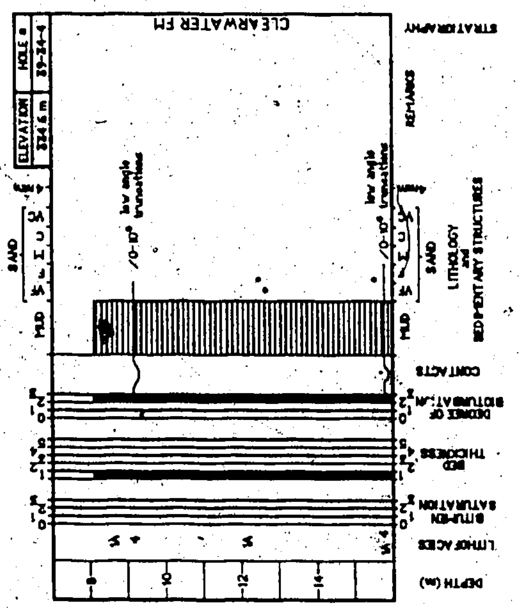
DEPTH (m)


ELEVATION
334.6 m
HOLE #
CLEARWATER FM
STRATIGRAPHY
REMARKS
low angle truncations
LITHOLOGY and SEDIMENTARY STRUCTURES
SAND
MUD
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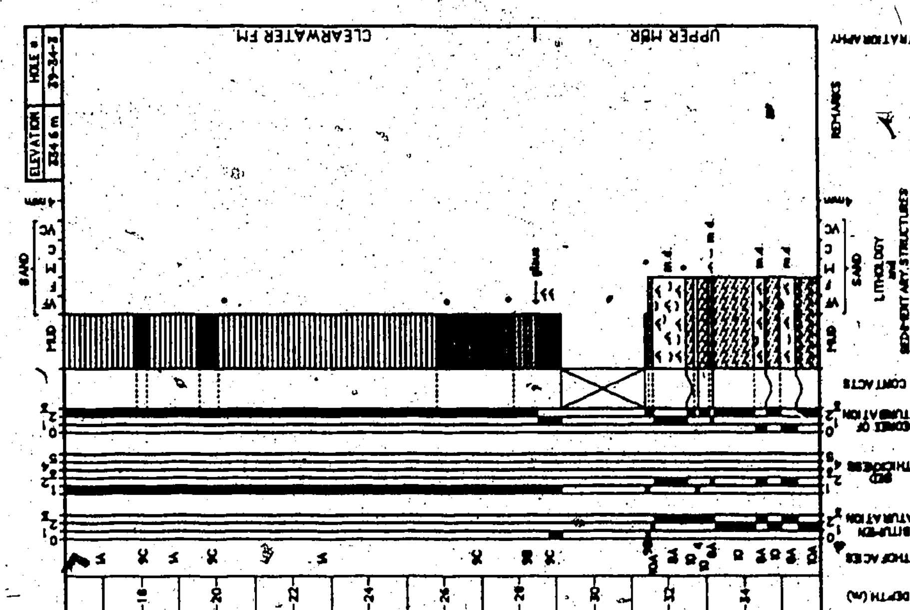
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)
8
10
12
14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LITHOLOGY and SEDIMENTARY STRUCTURES
SAND
MUD
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)
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24
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32
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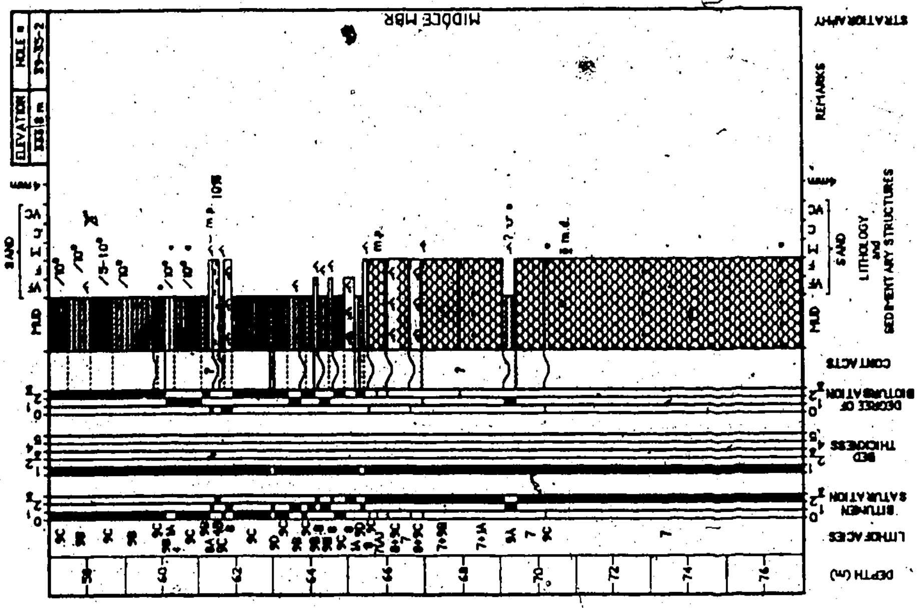
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MUD
CONTACTS
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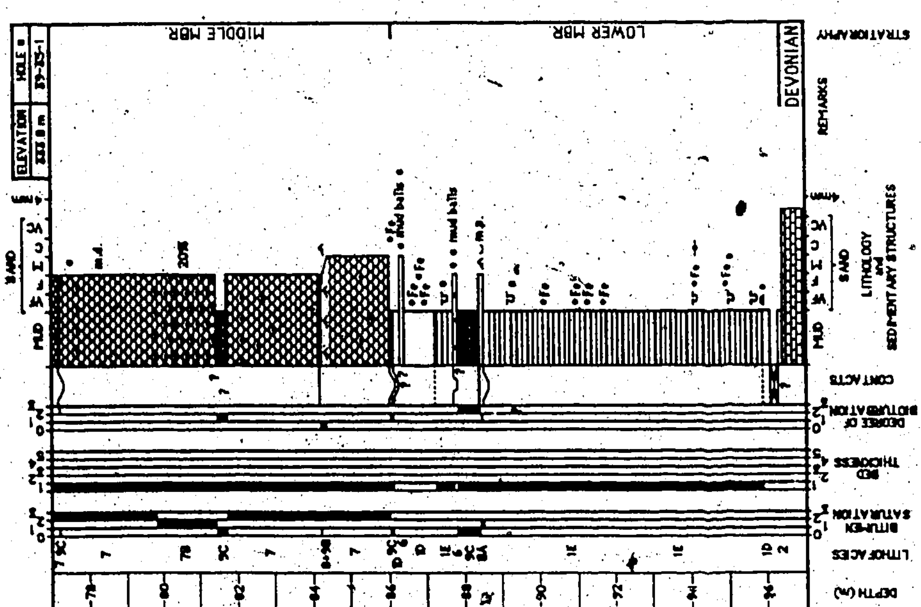
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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LOWER MBR
DEVONIAN
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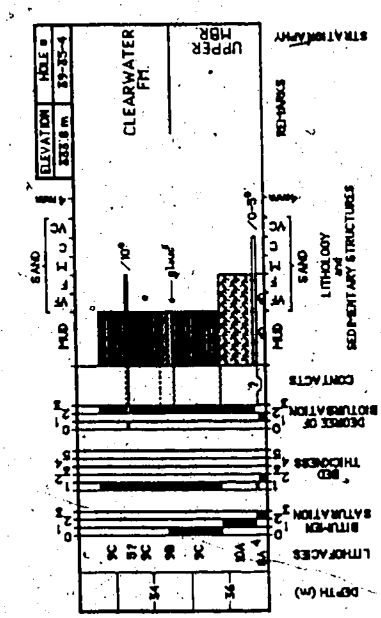
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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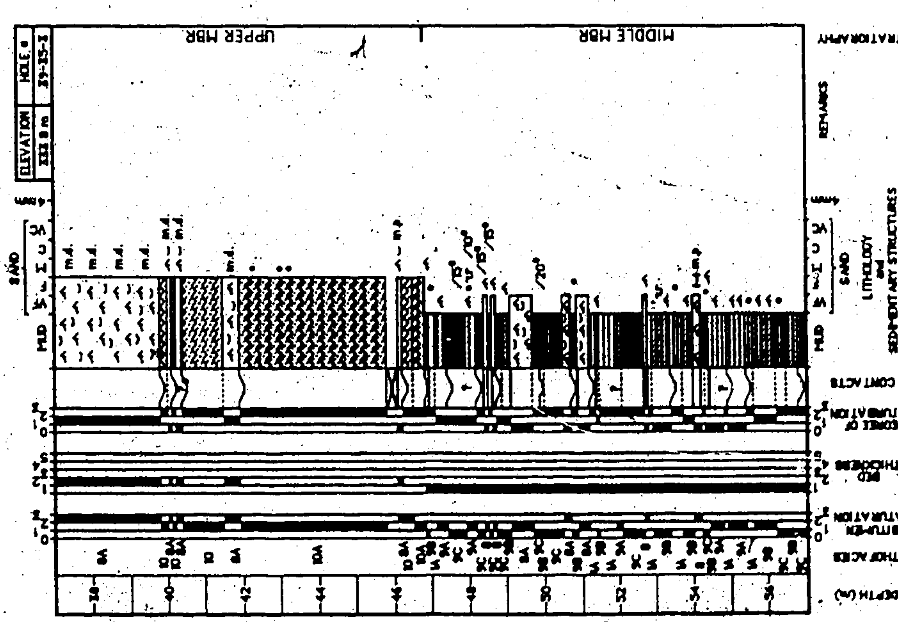
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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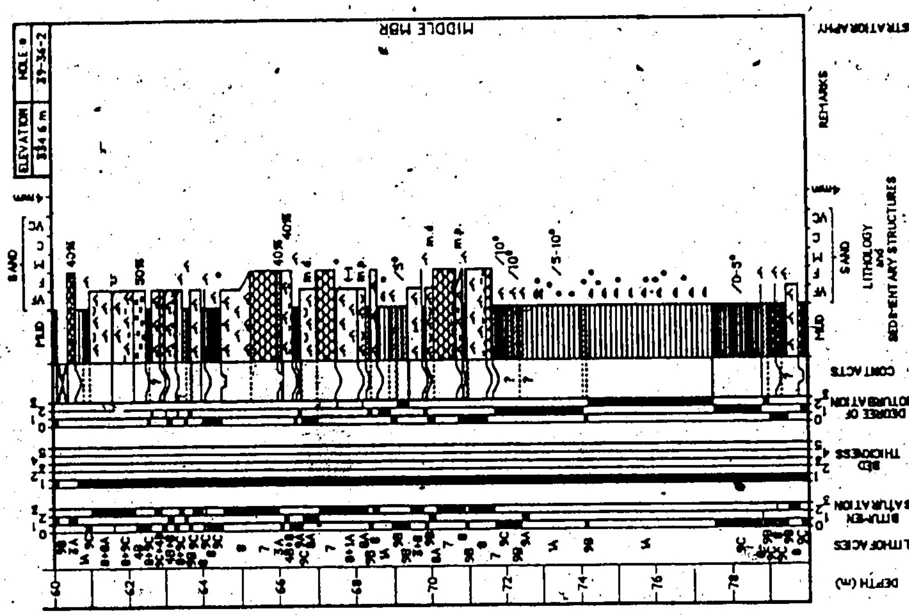
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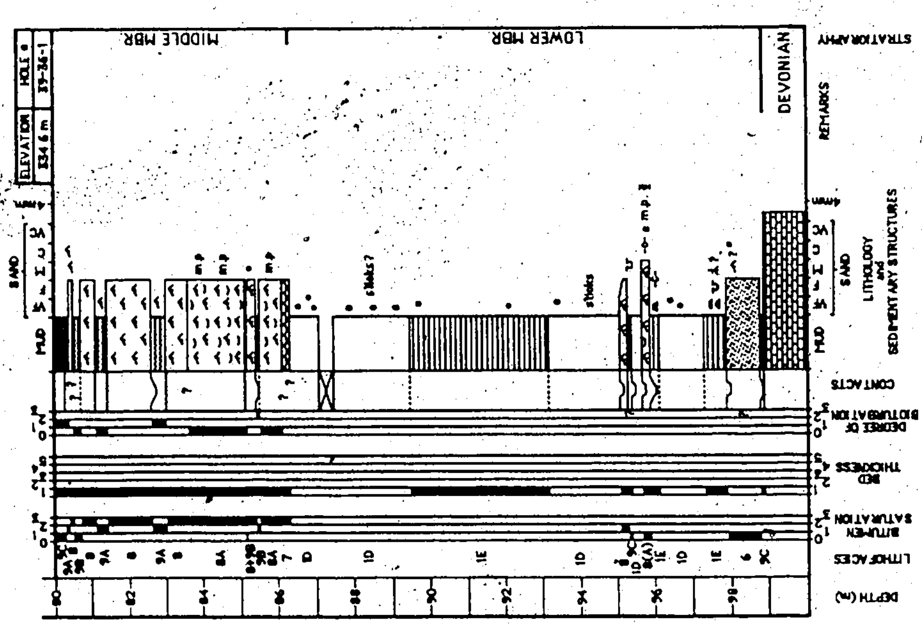
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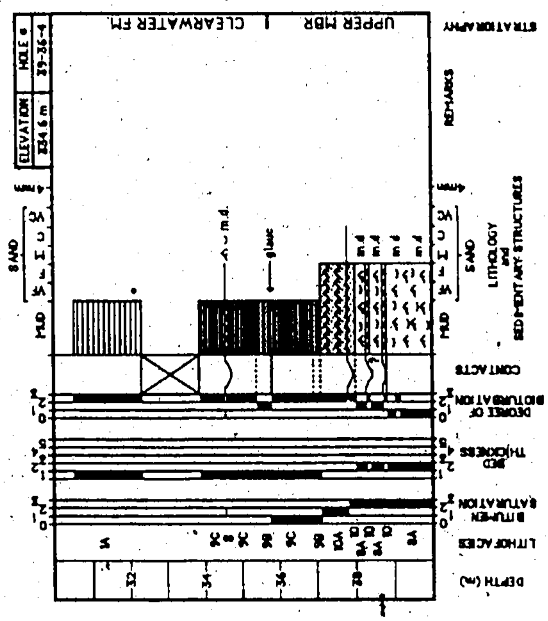
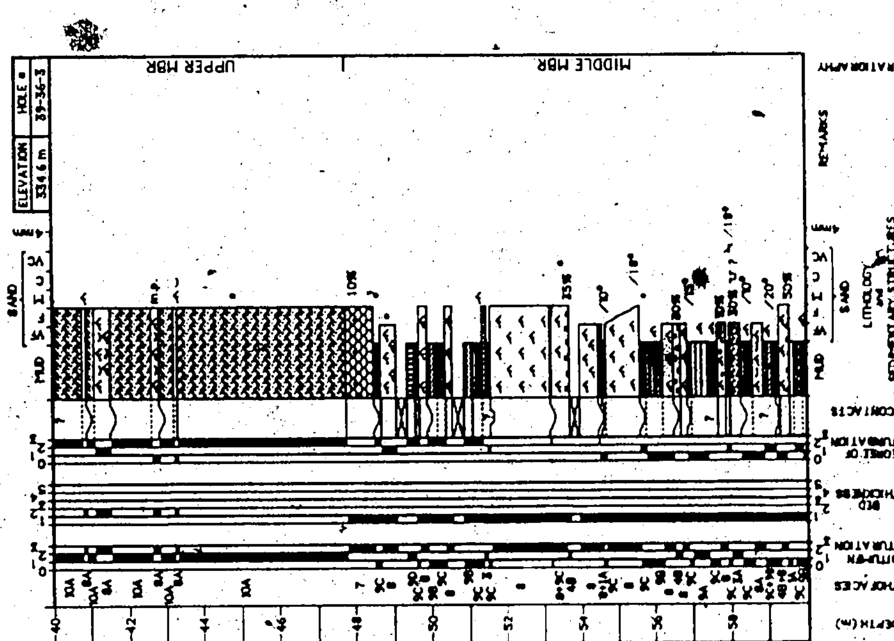
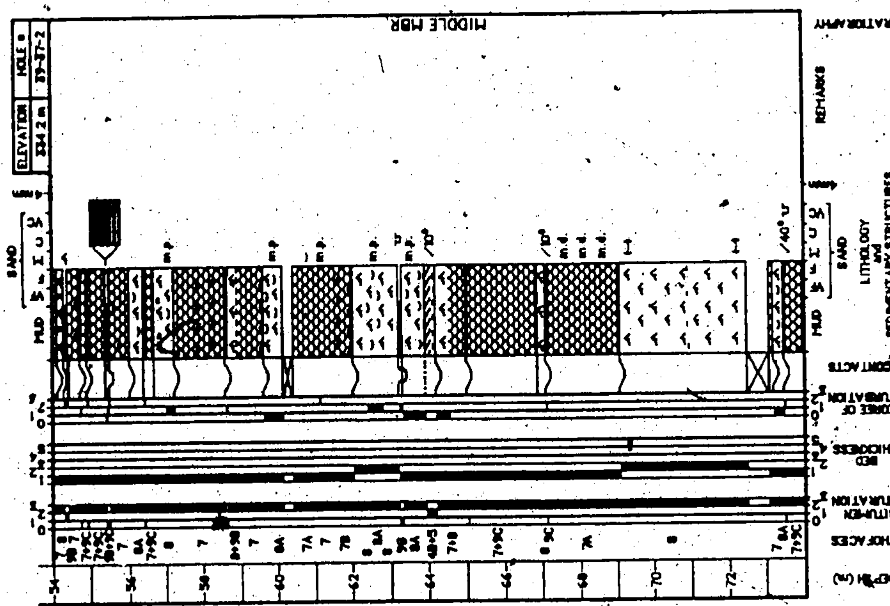
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)



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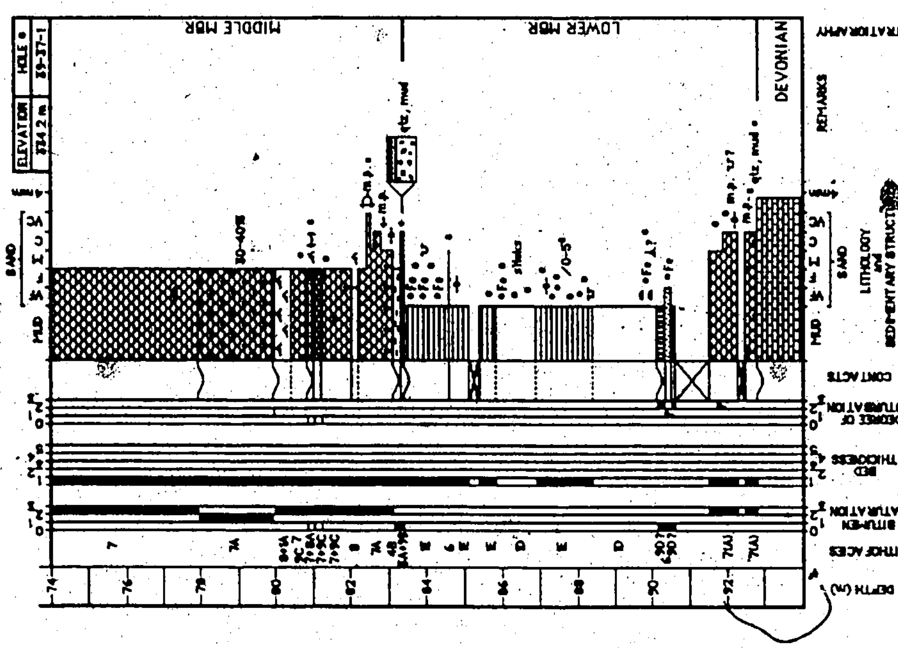
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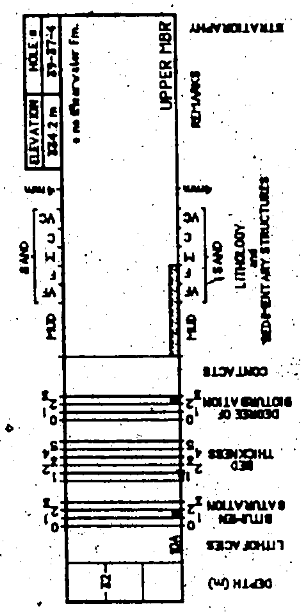
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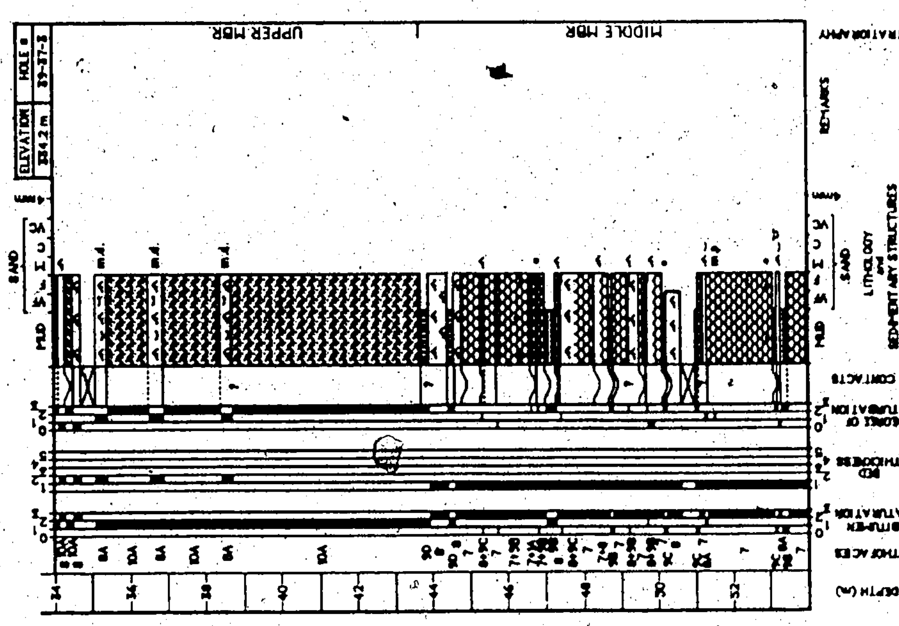
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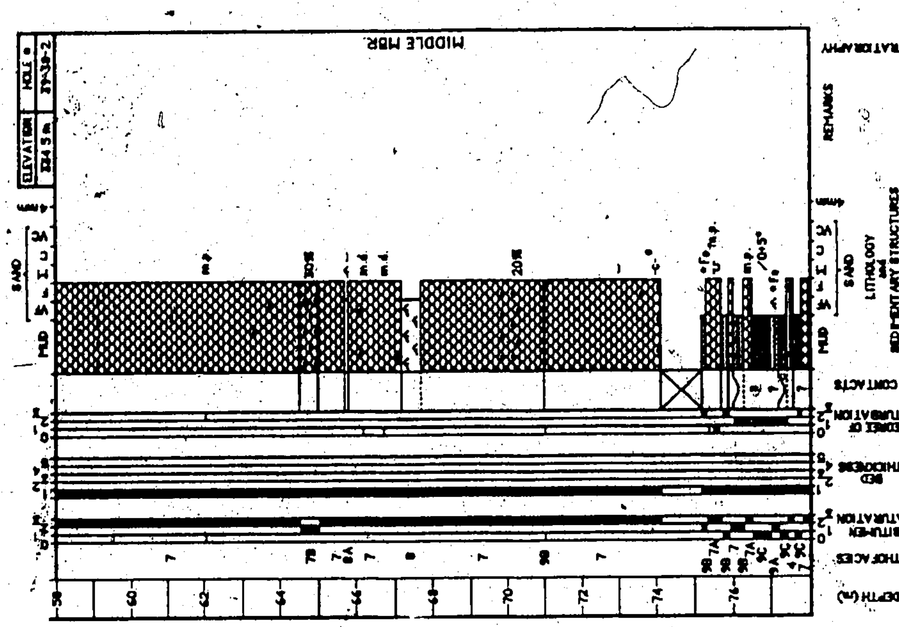
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DEPTH (m)
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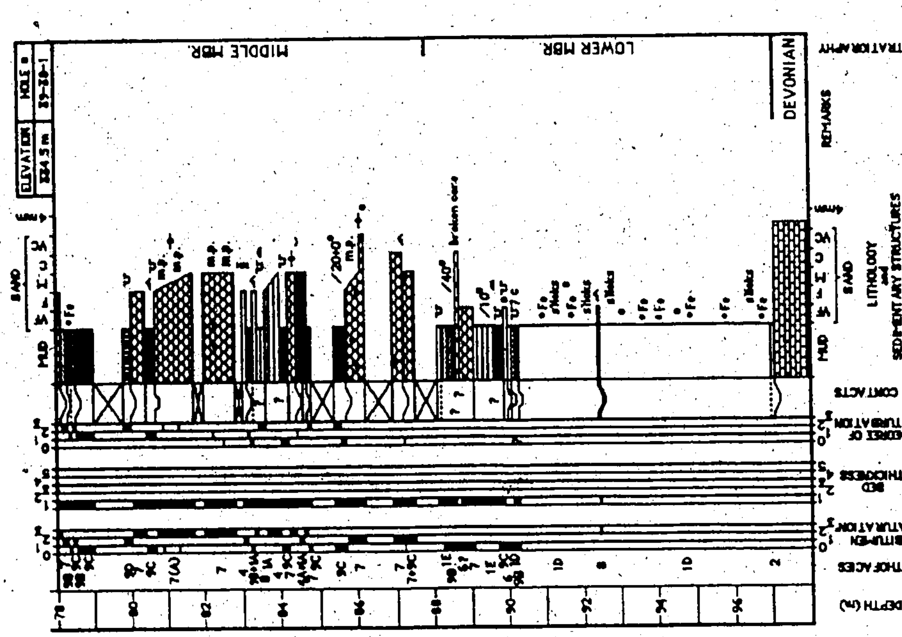
ELEVATION
HOLE #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LOWER MBR.
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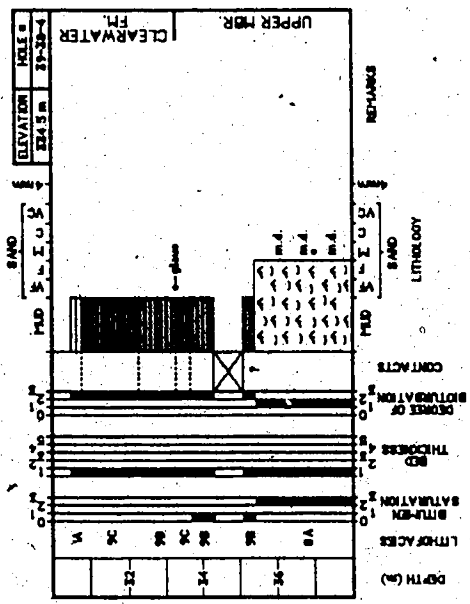
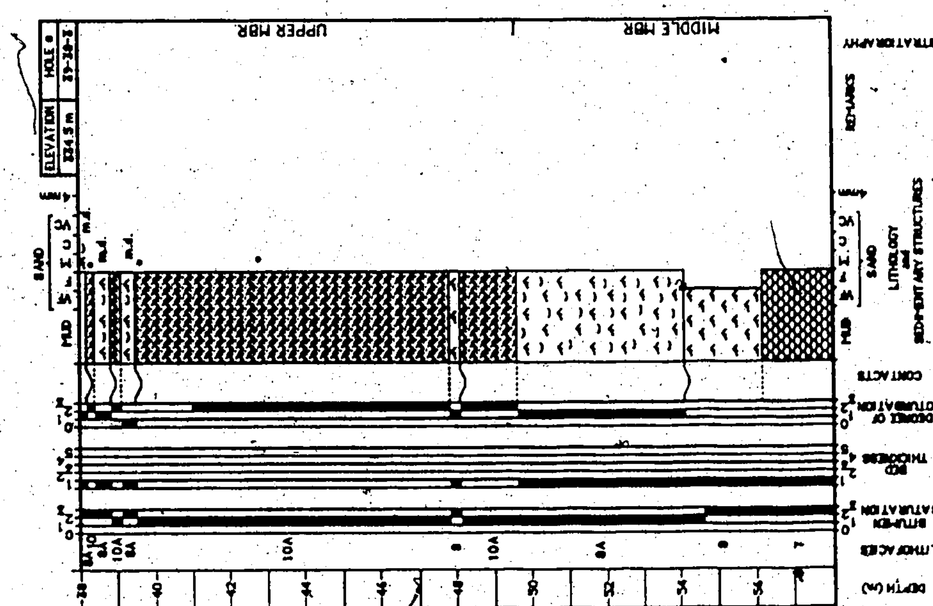
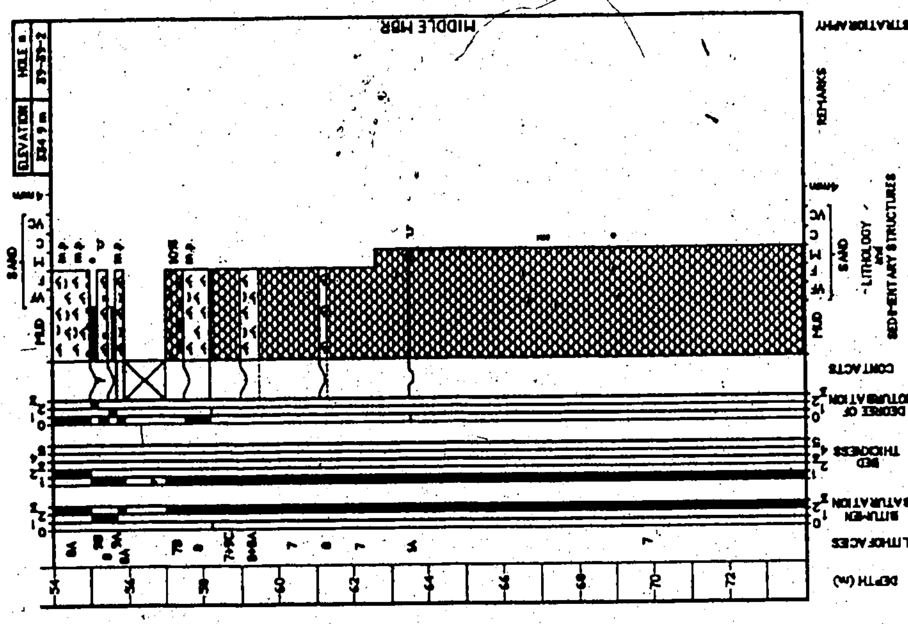
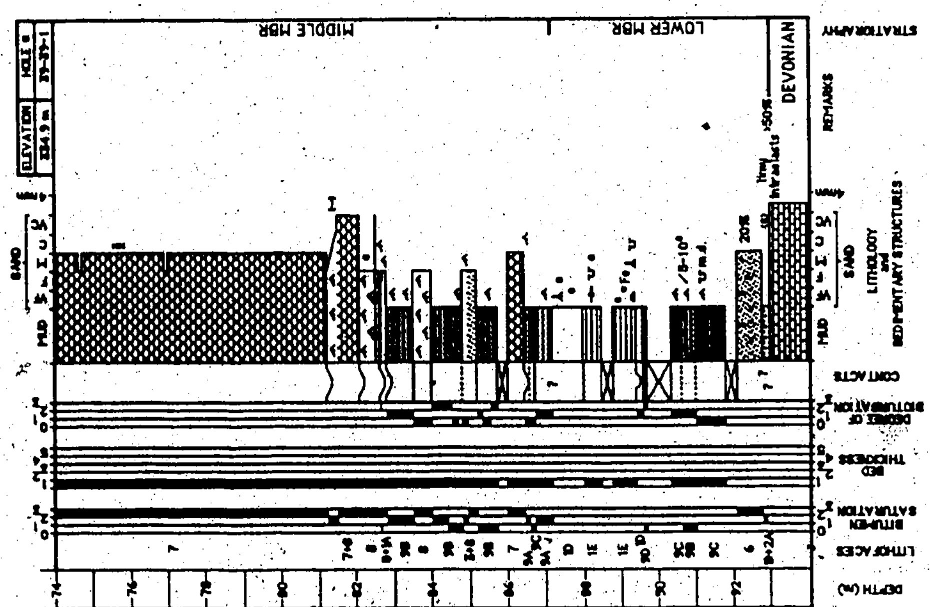
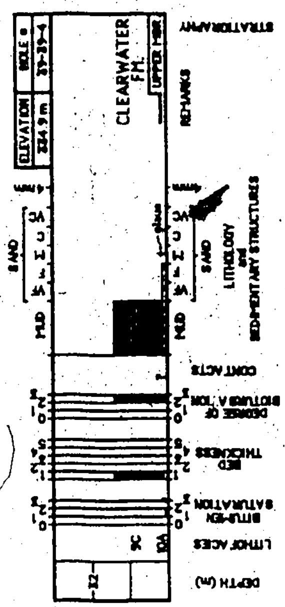
ELEVATION
HOLE #

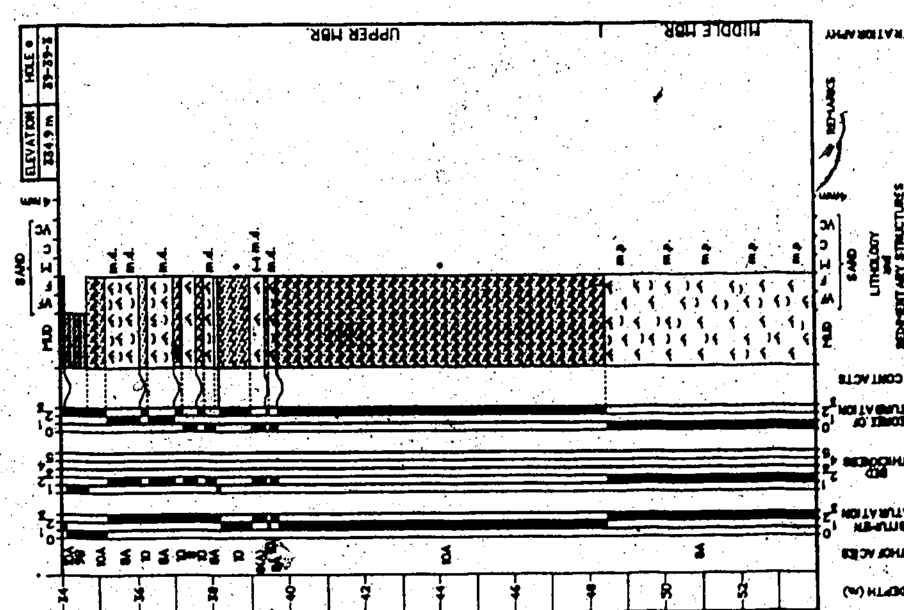


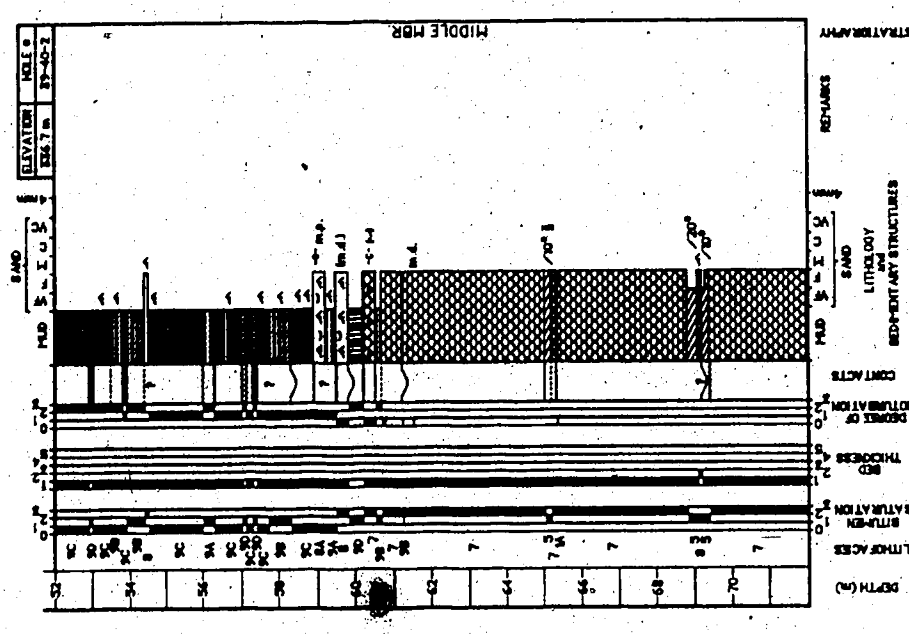








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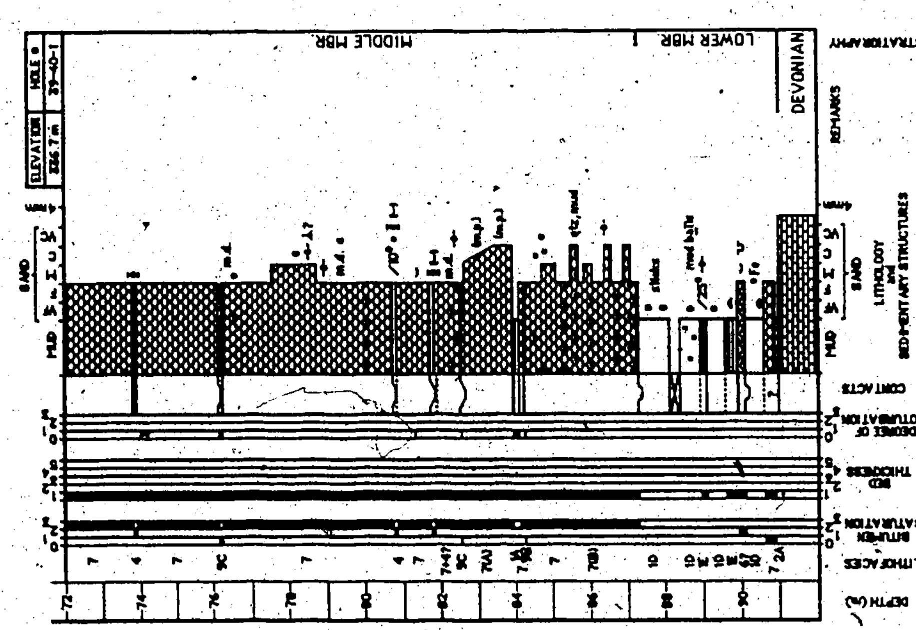
DEPTH (m)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BITUMEN SATURATION
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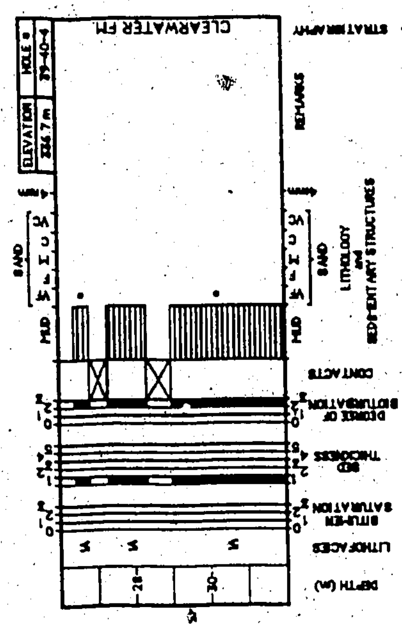
DEPTH (m)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BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)
28
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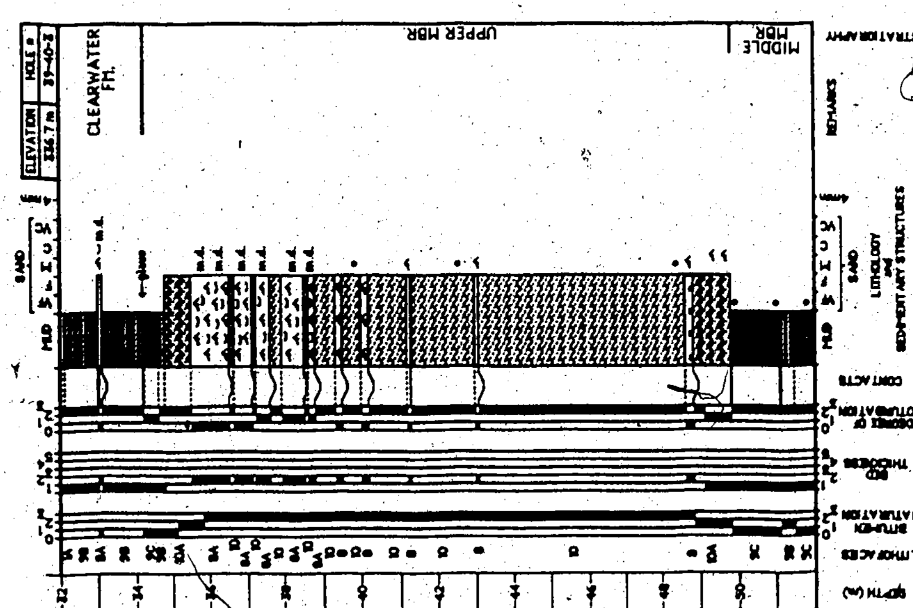
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CLEARWATER FM.
UPPER MBR
MIDDLE MBR
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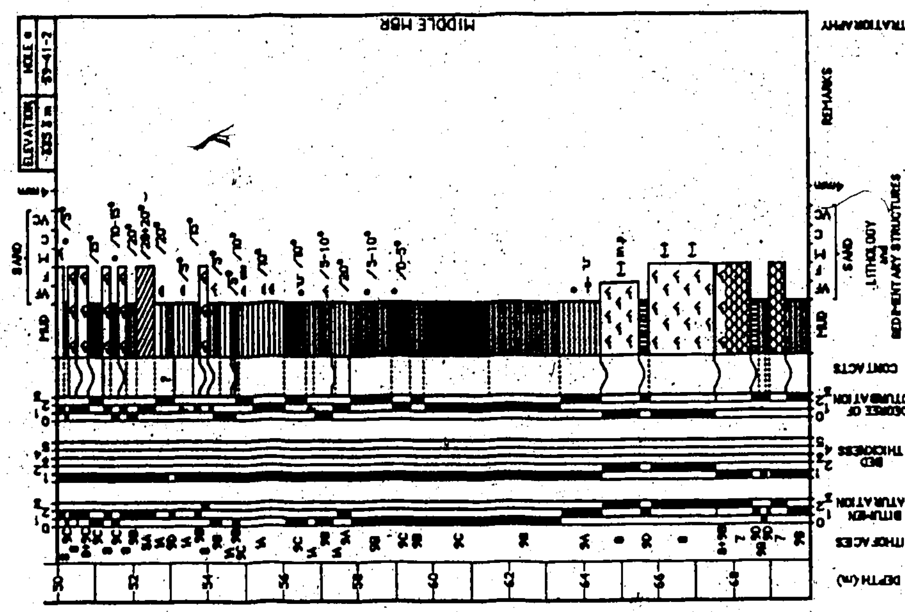
DEPTH (m)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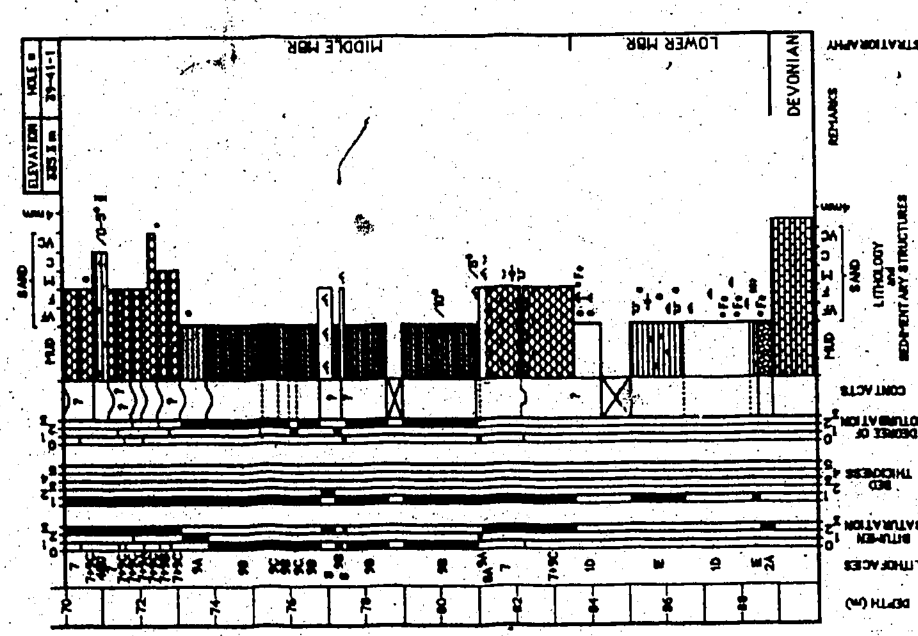
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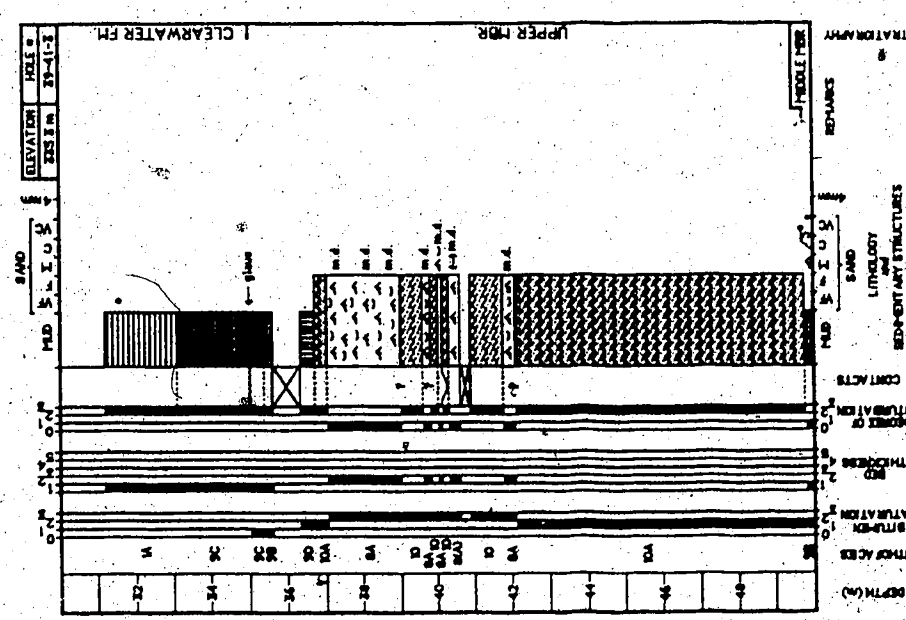
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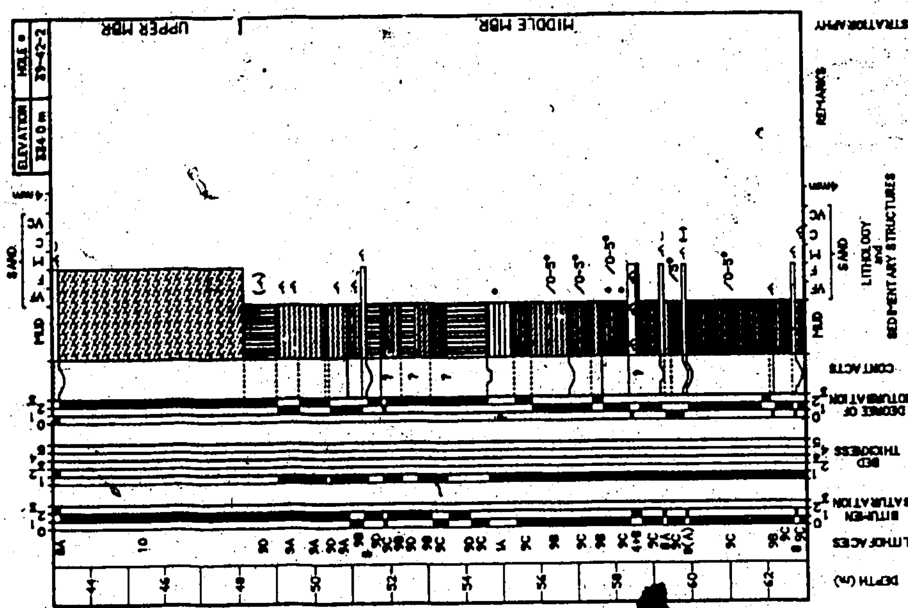
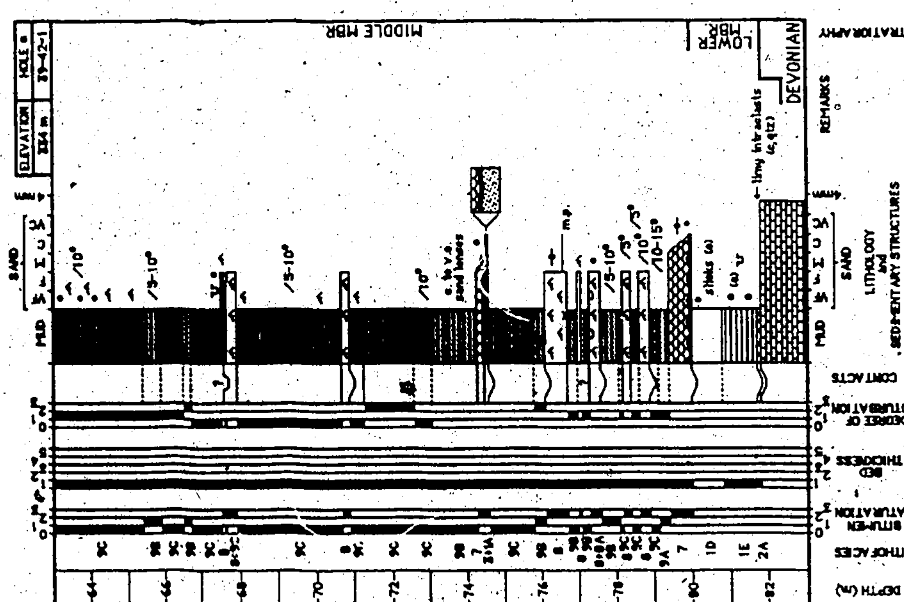
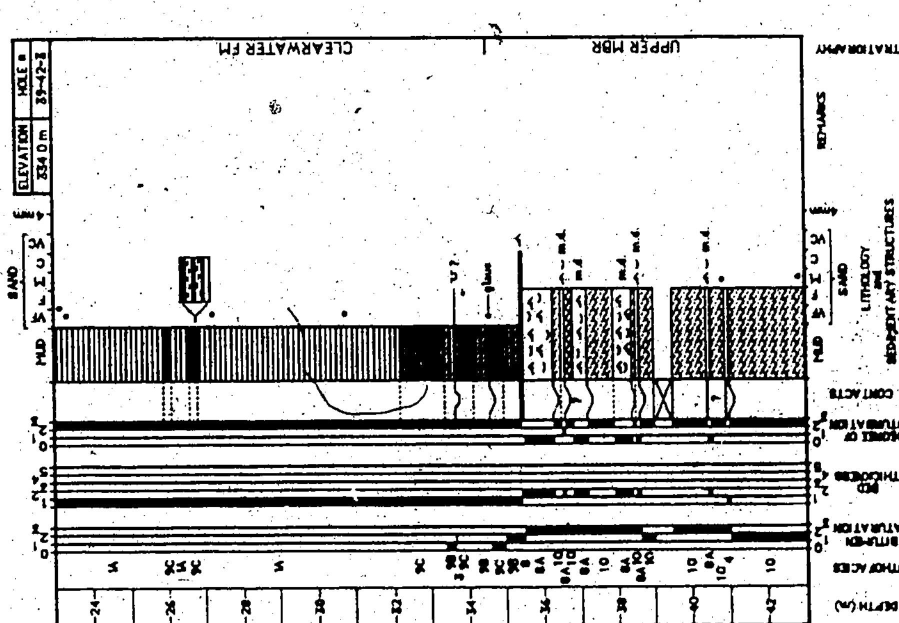
DEPTH (m)



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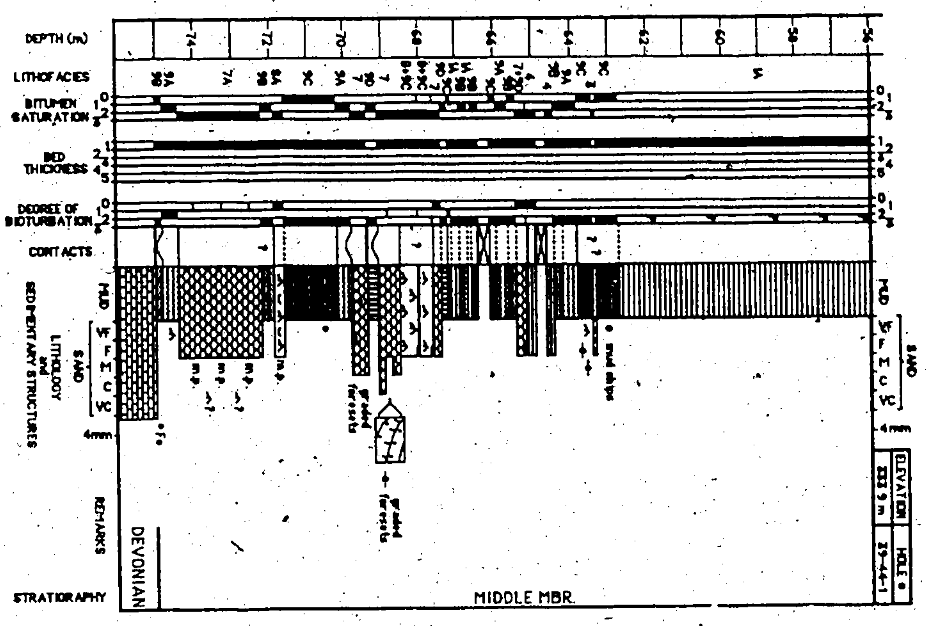
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BITUMEN SATURATION
BED THICKNESS
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REMARKS
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MIDDLE MBR.
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HOLE #
29-44-1
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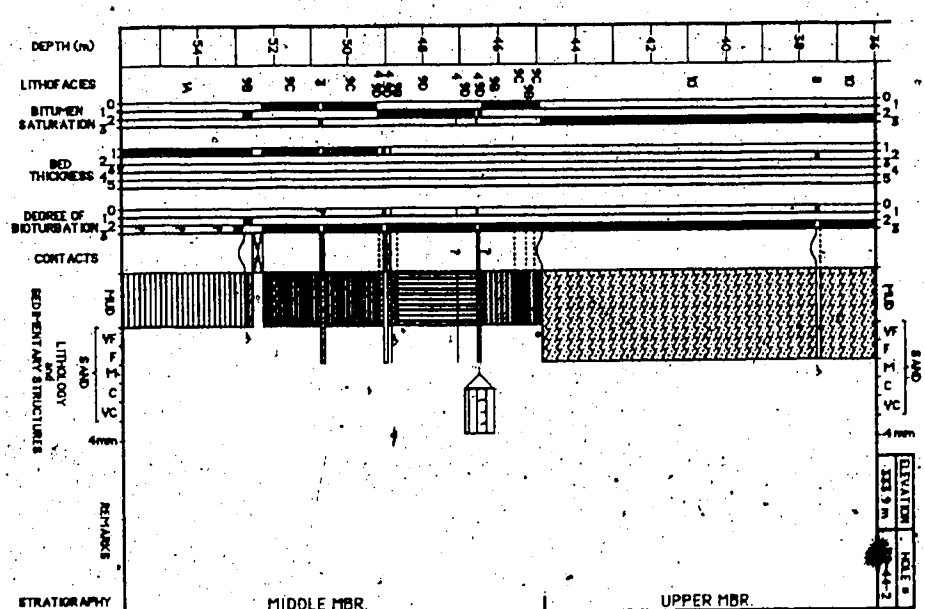
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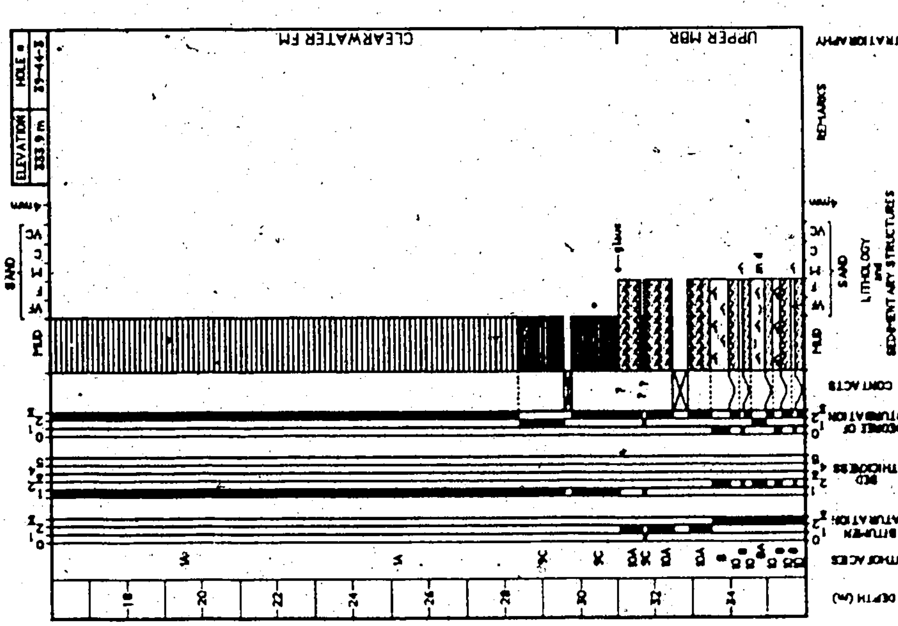
333.9 m
HOLE #



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ELEVATION
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MUD
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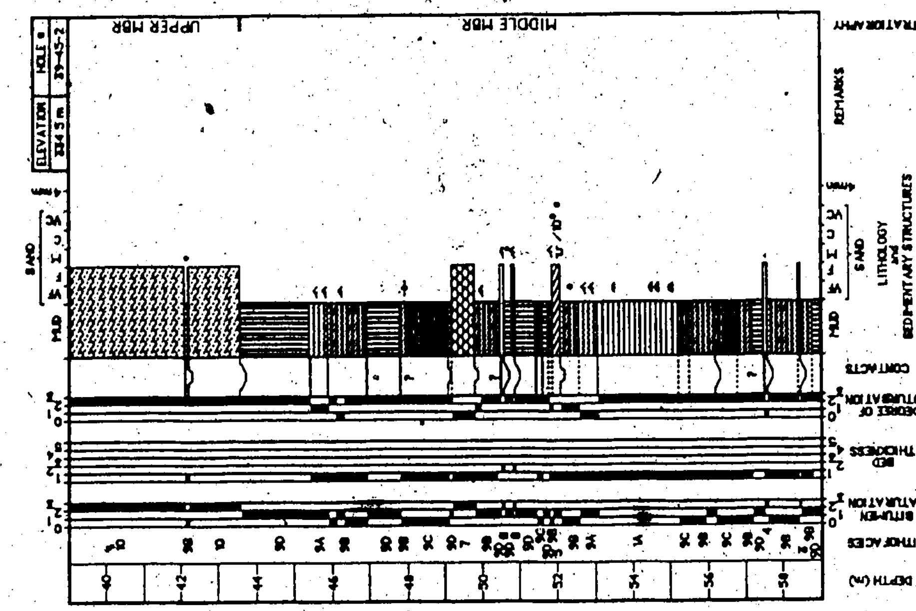
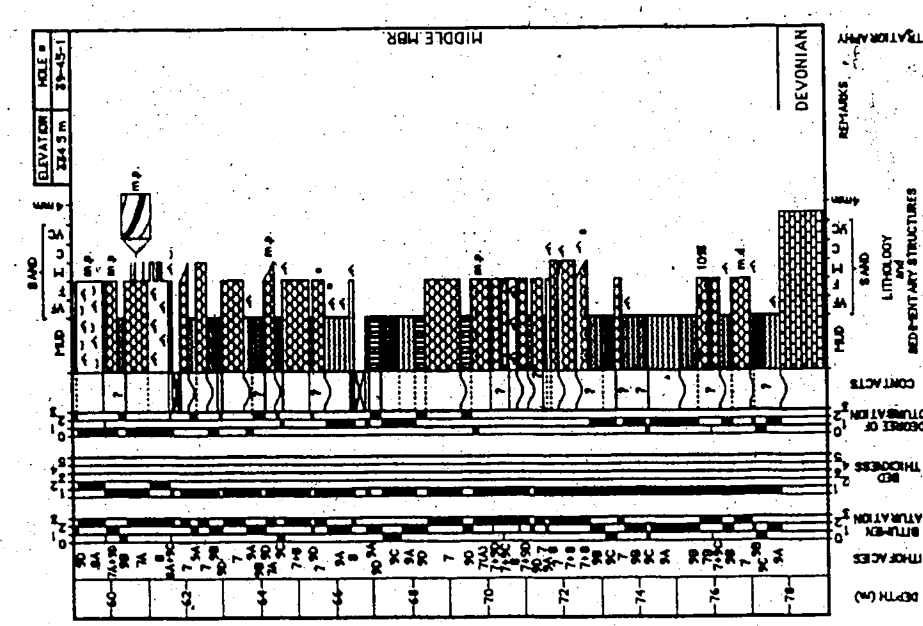
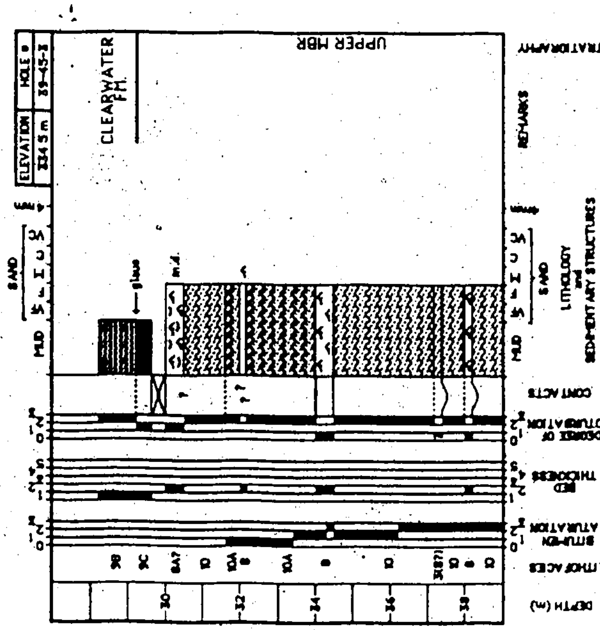
LITHOFACIES
DEPTH (M)



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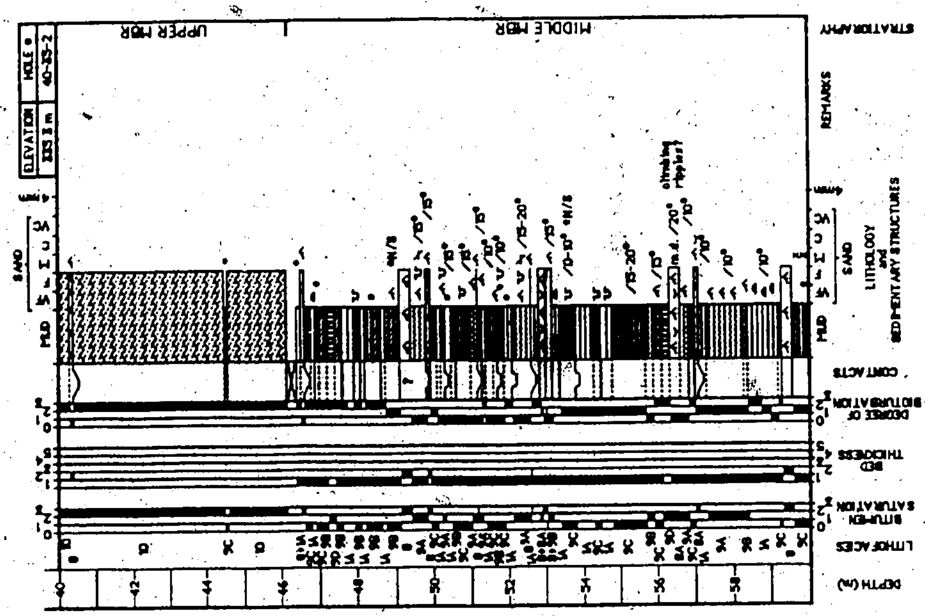
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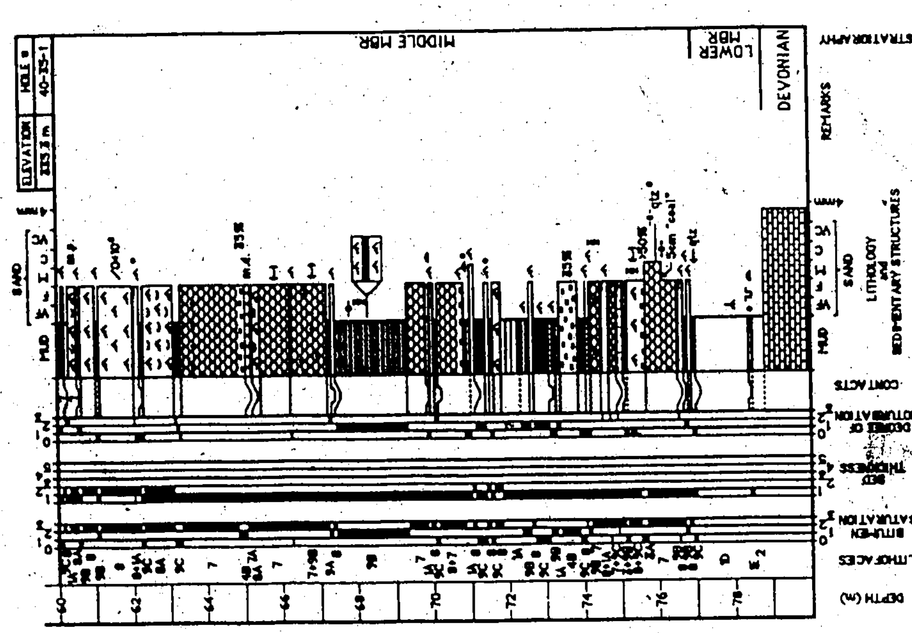
DEPTH (m)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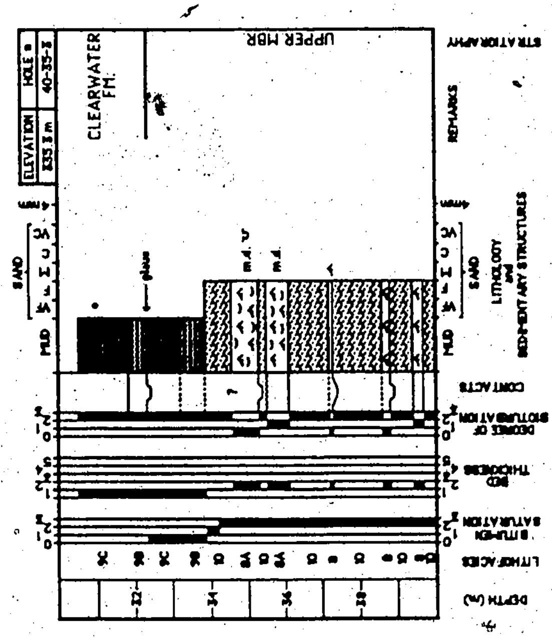
DEPTH (m)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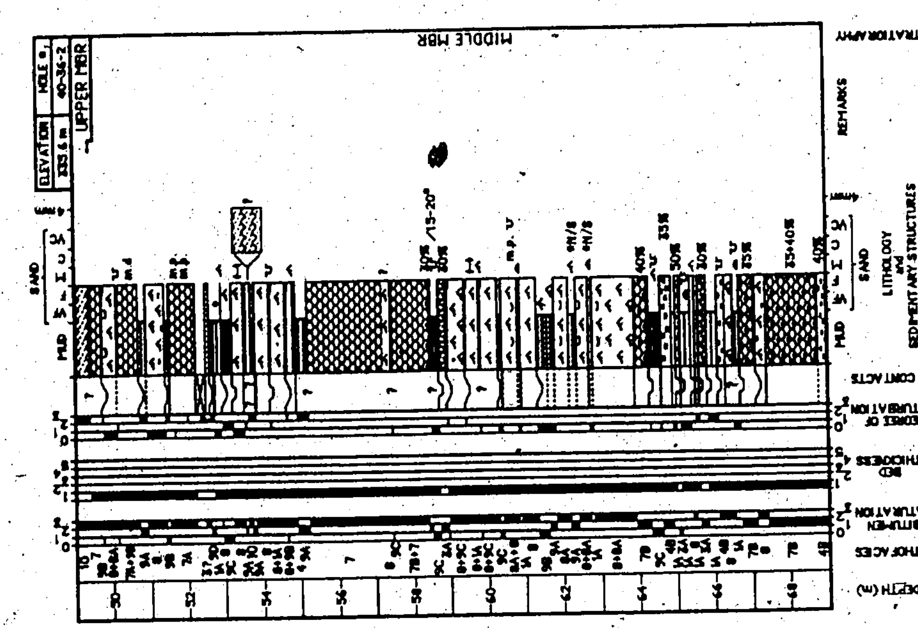
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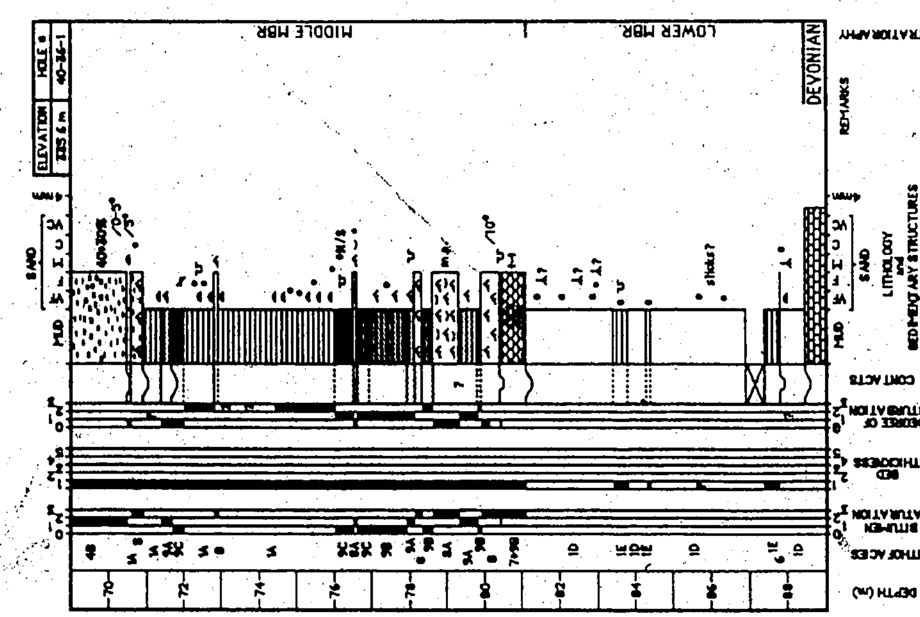
LITHOFACIES
DEPTH (m)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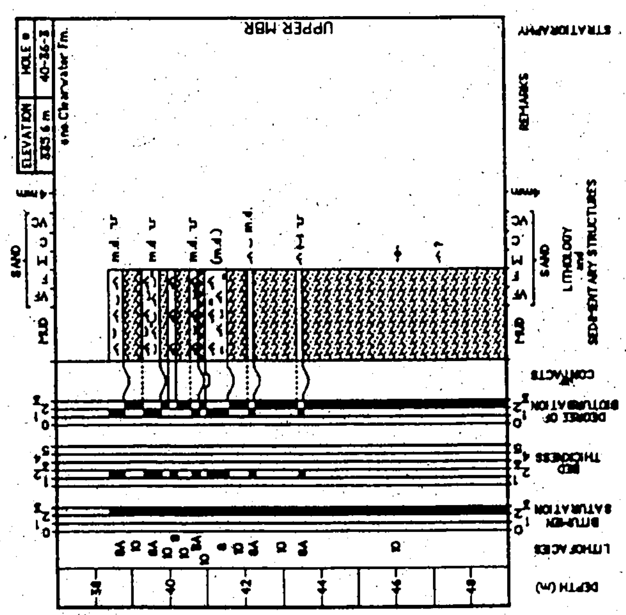
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UPPER MBR
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MUD
SAND
VF F M C VC
4mm
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)
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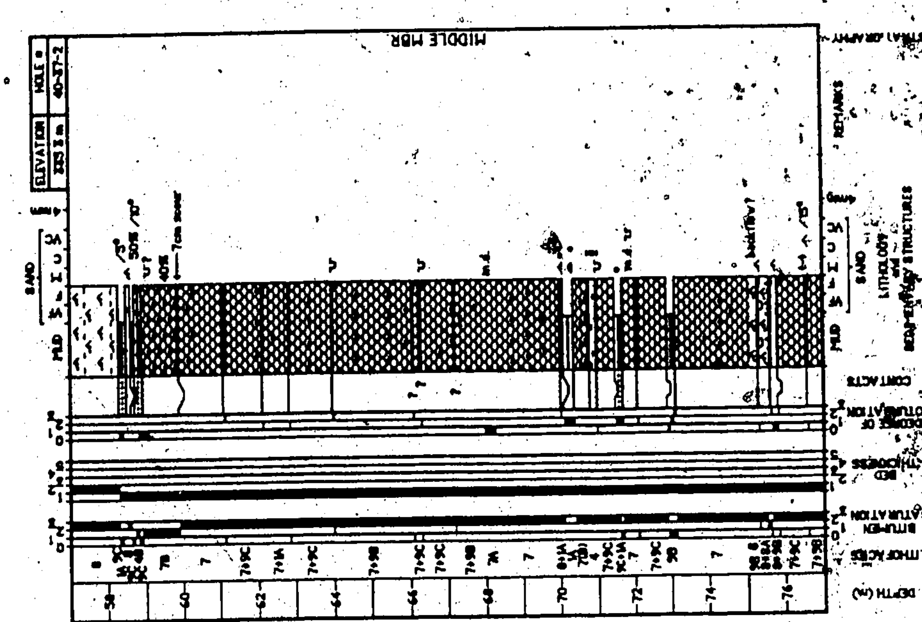
42
44
46
48


STRATIGRAPHY
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MIDDLE MBR
ELEVATION
HOLE
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MUD
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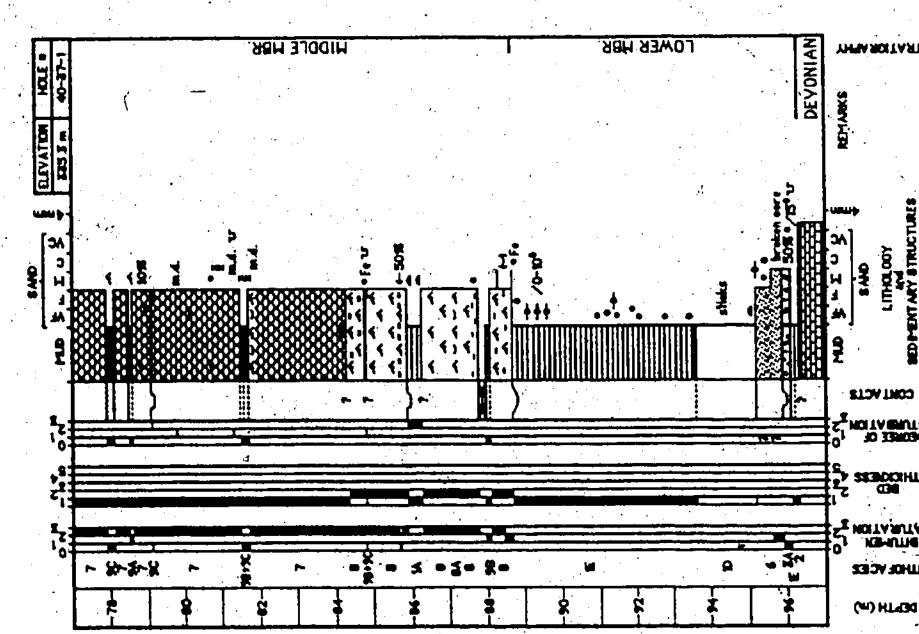
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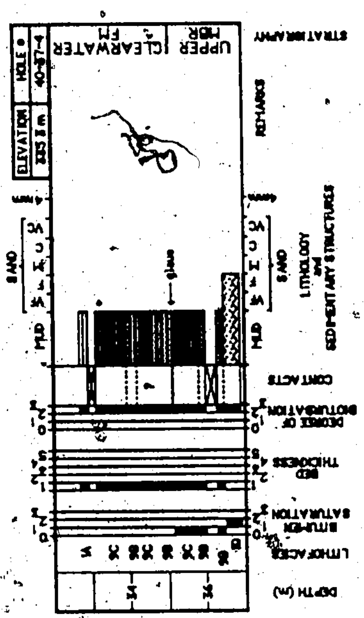
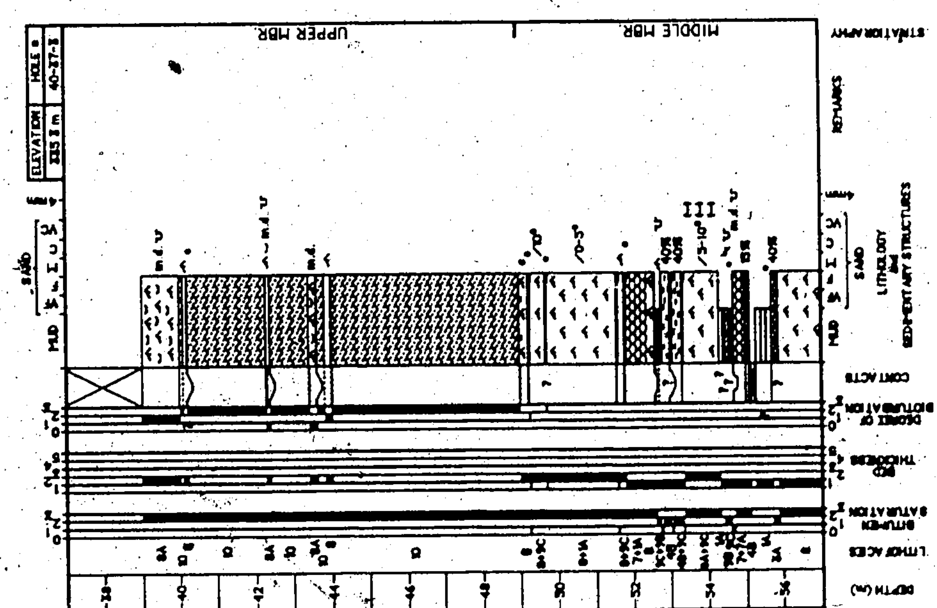
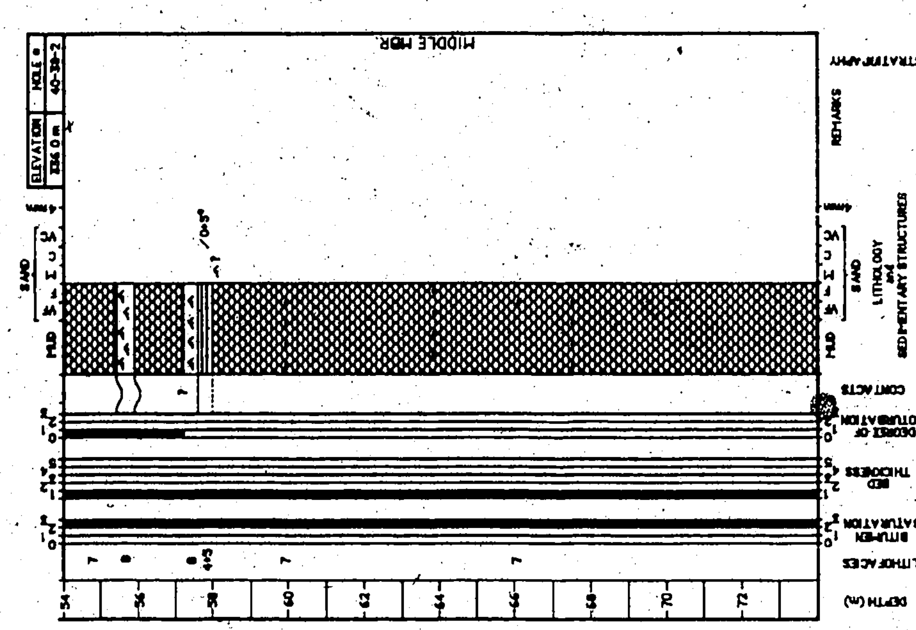
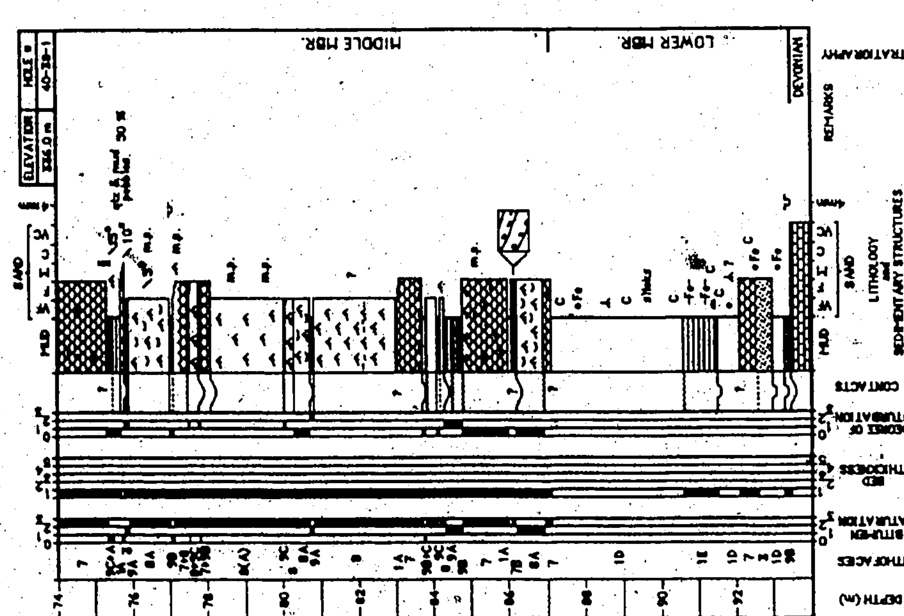
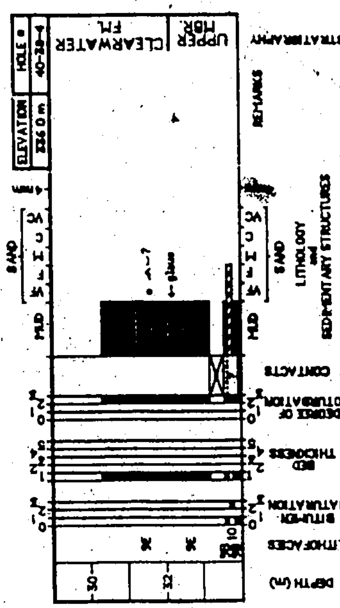
MIDDLE MBR
LOWER MBR
DEVONIAN
ELEVATION
HOLE
SAND
MUD
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)







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336.0 m
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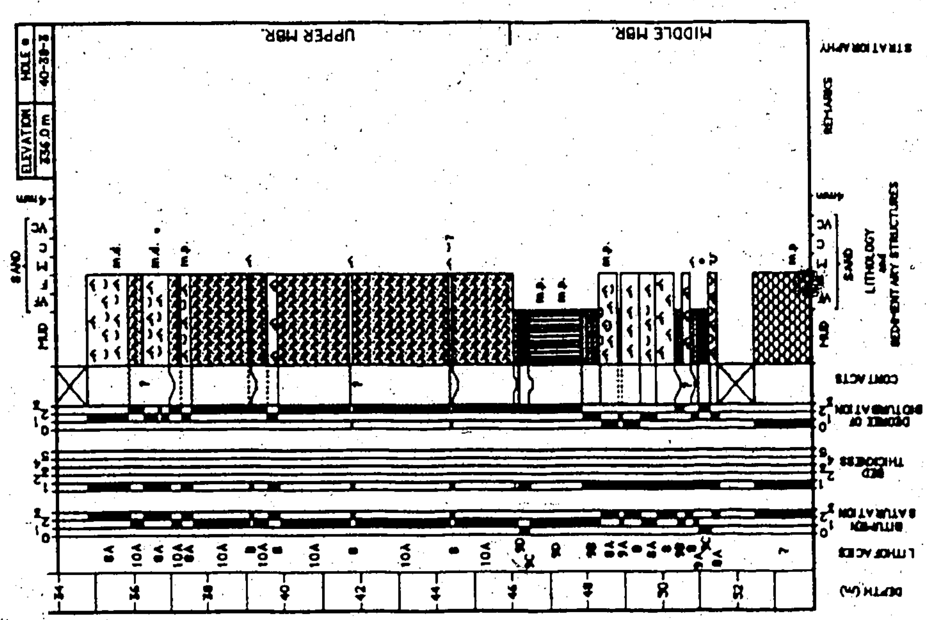
CLEARWATER FM.
STRATIGRAPHY
REMARKS
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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MIDDLE MBR.
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CONTACTS
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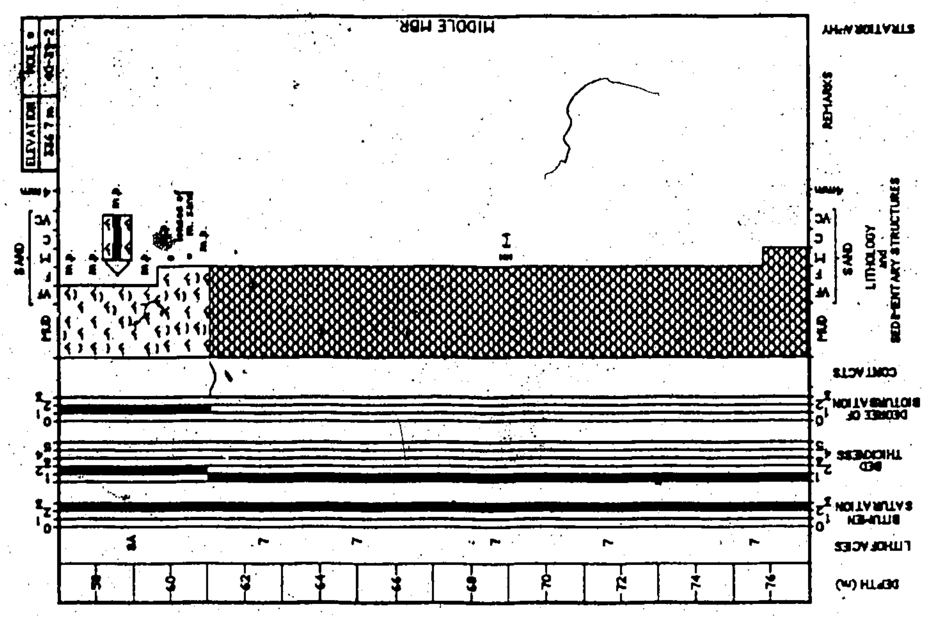
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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SAND
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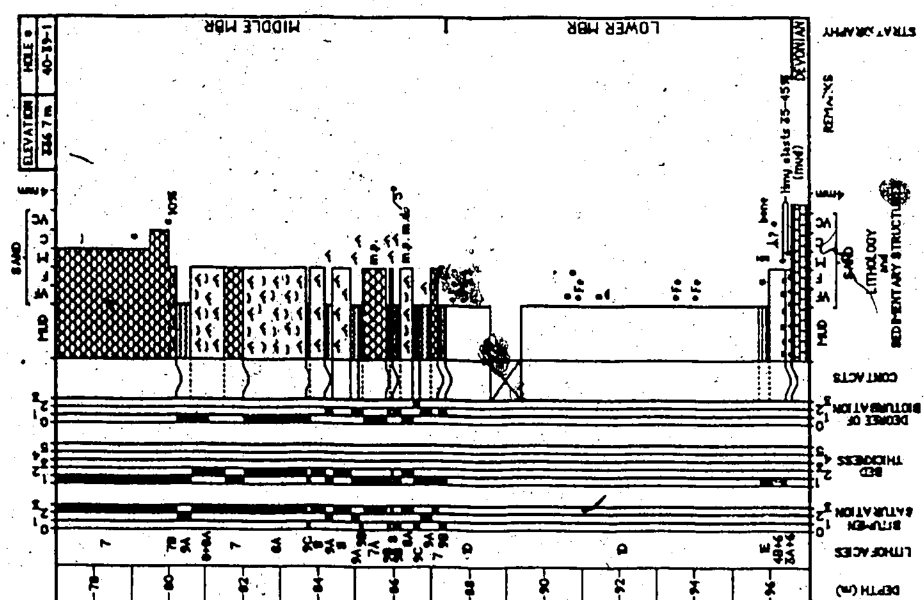
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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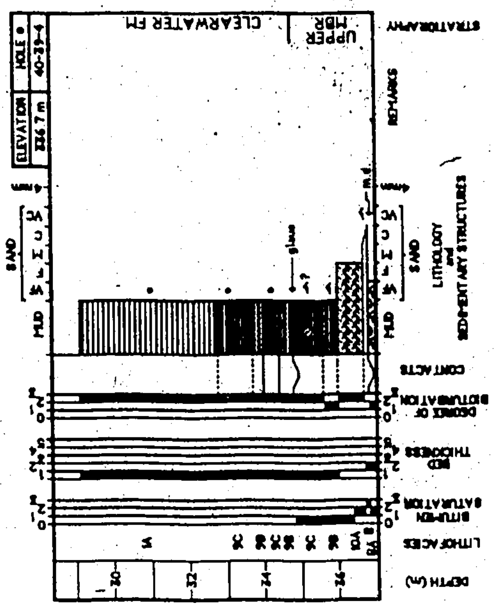
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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CLEARWATER FM
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STRATIGRAPHY
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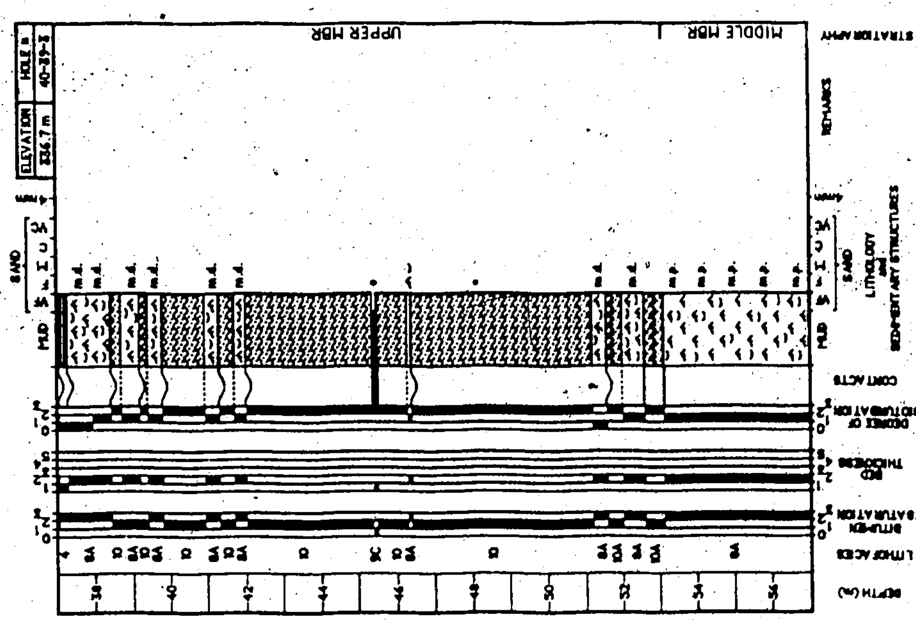
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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336.7 m
HOLE #
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STRATIGRAPHY
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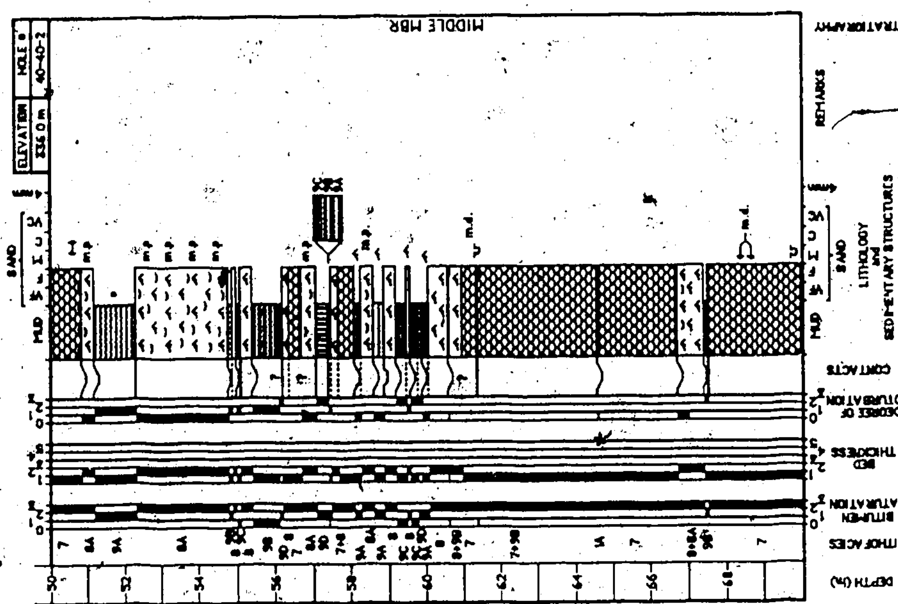
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BITUMEN SATURATION
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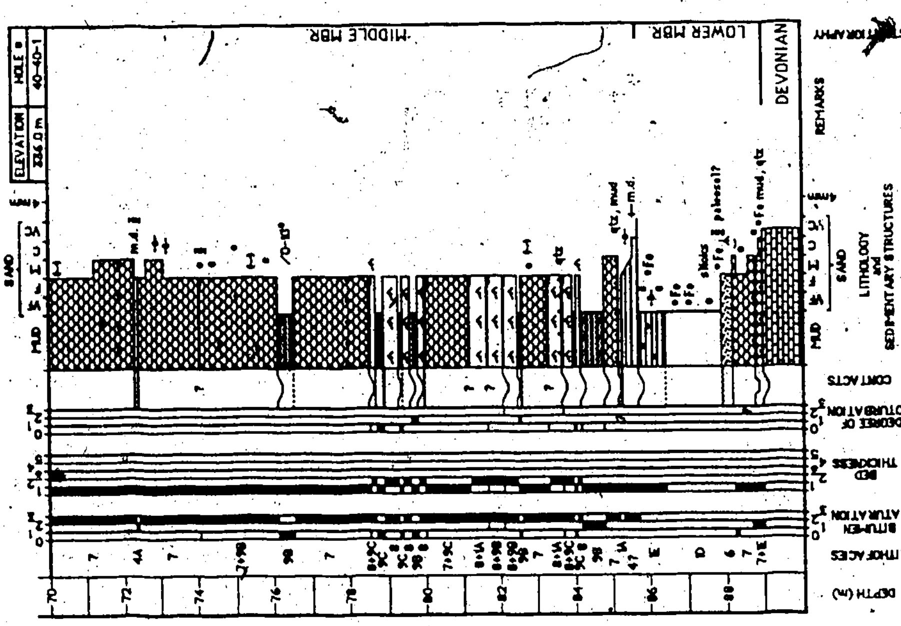
DEPTH (m)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MIDDLE MBR.
LOWER MBR.
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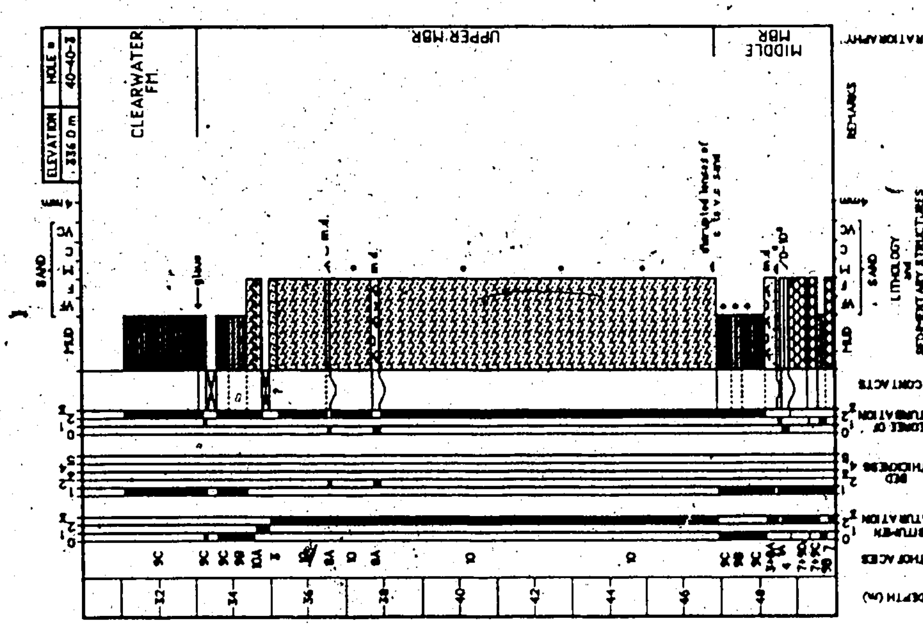
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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UPPER MBR
MIDDLE MBR
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REMARKS
ELEVATION
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MUD
SAND
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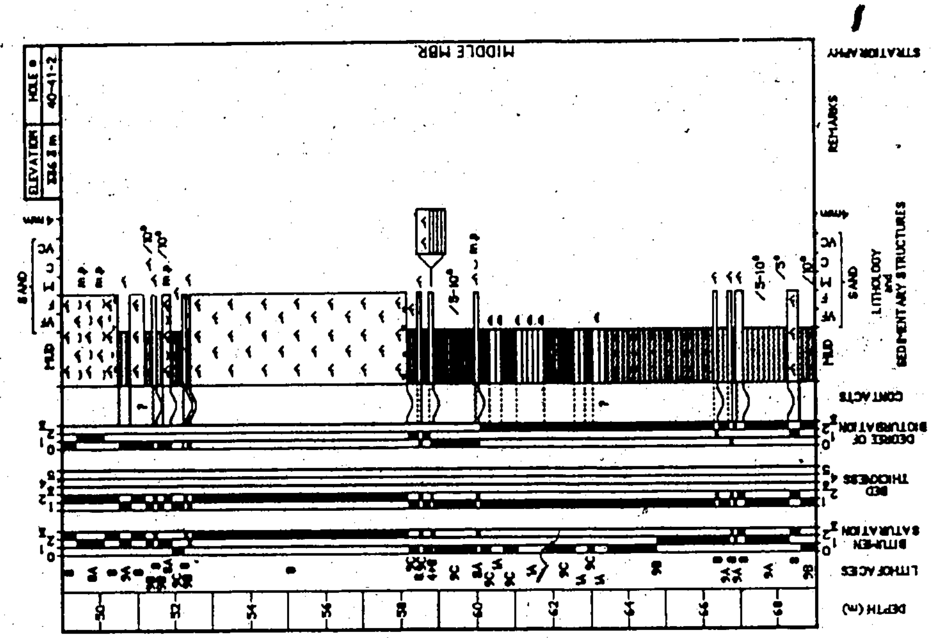
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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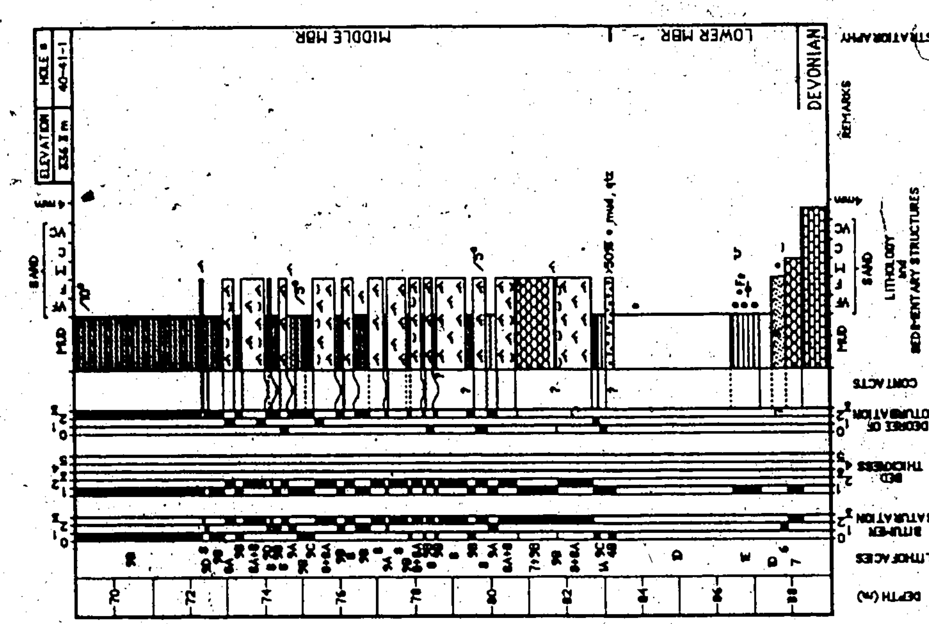
DEPTH (m)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HOLE
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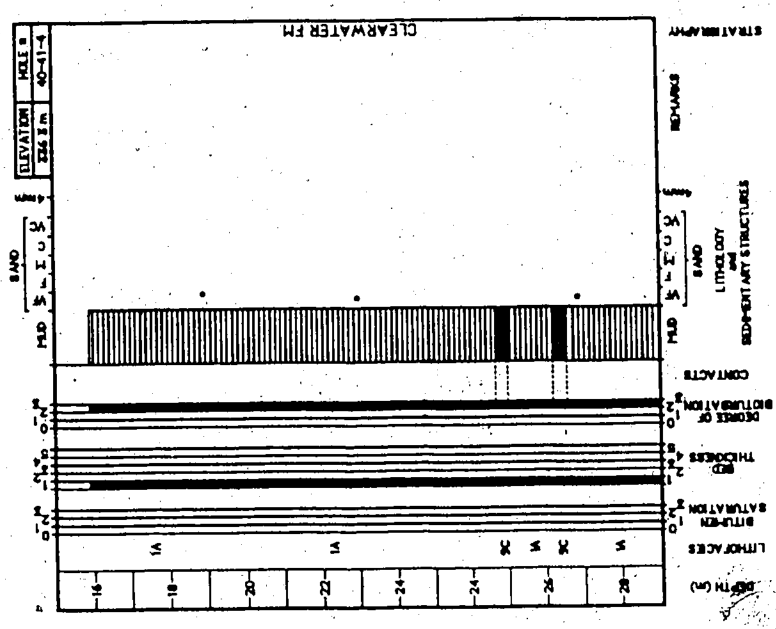
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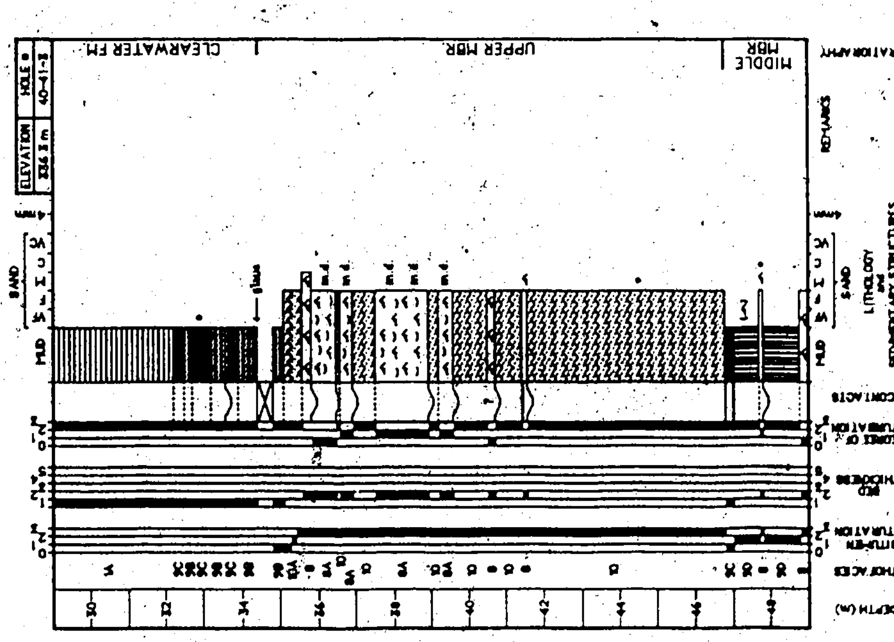
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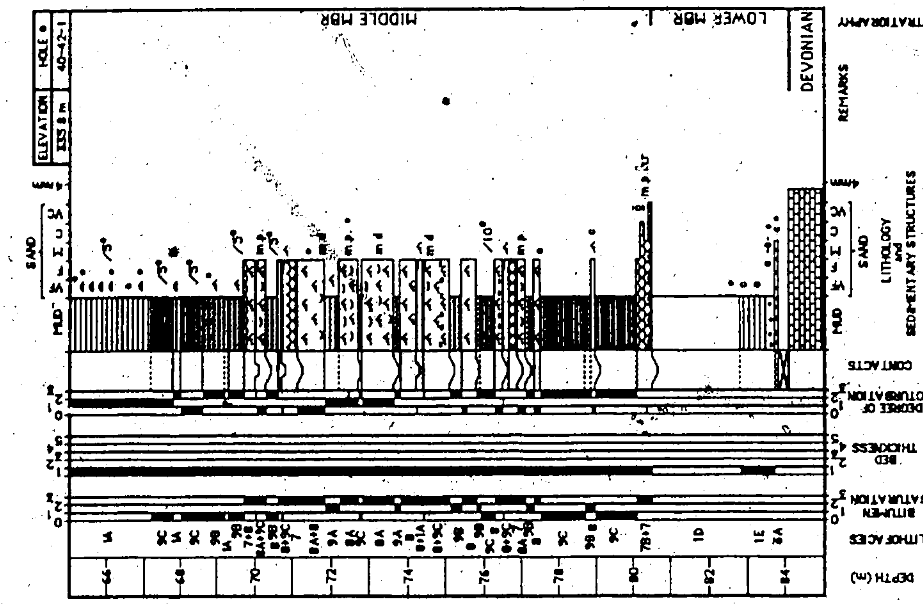
DEPTH (m)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HOLE 40-42-1
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LOWER MBR
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CONTACTS
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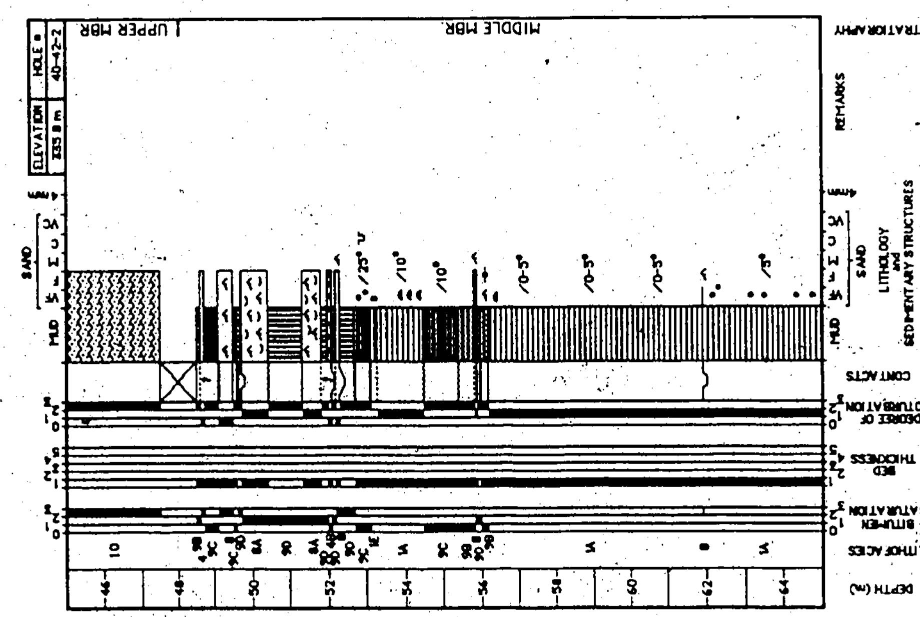
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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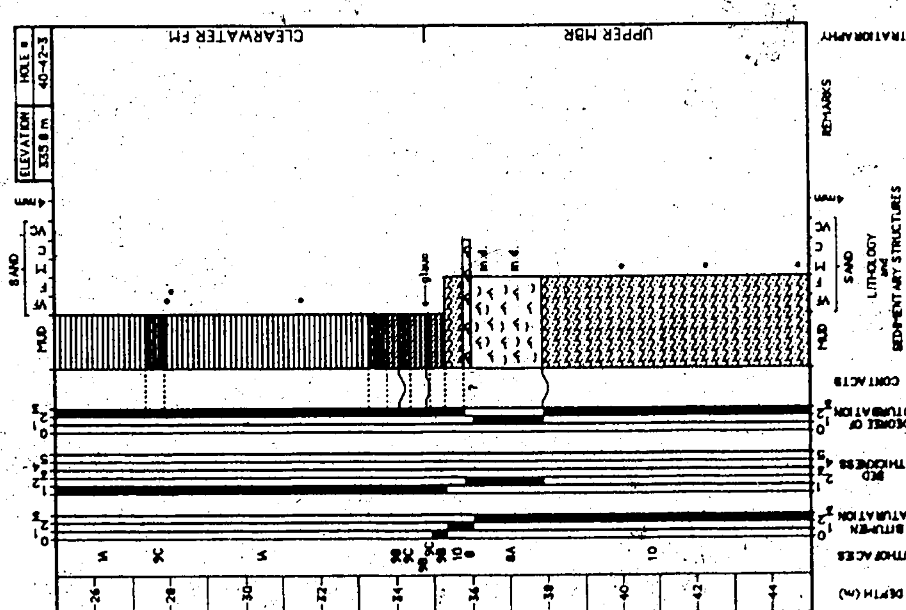
DEPTH (m)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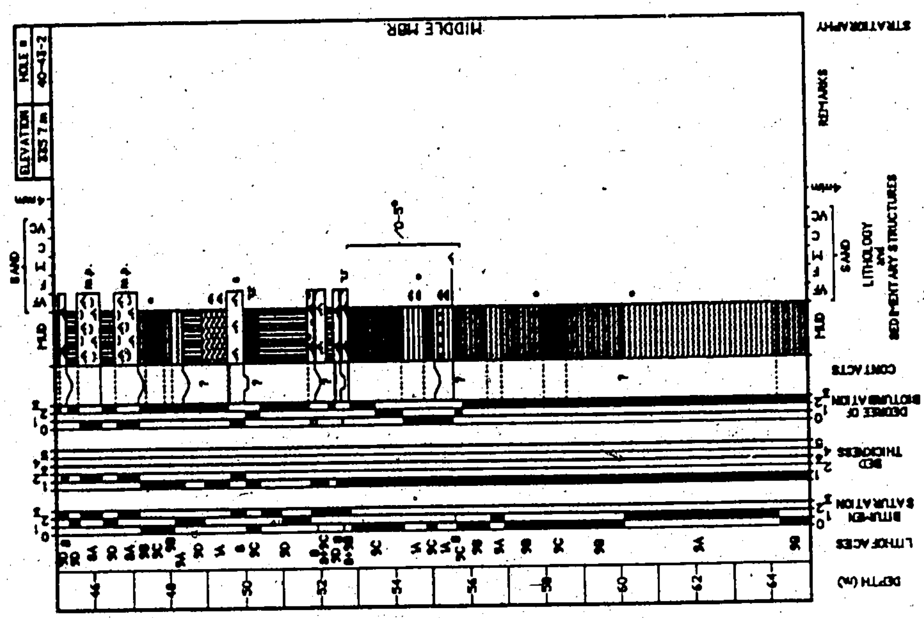
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CONTACTS
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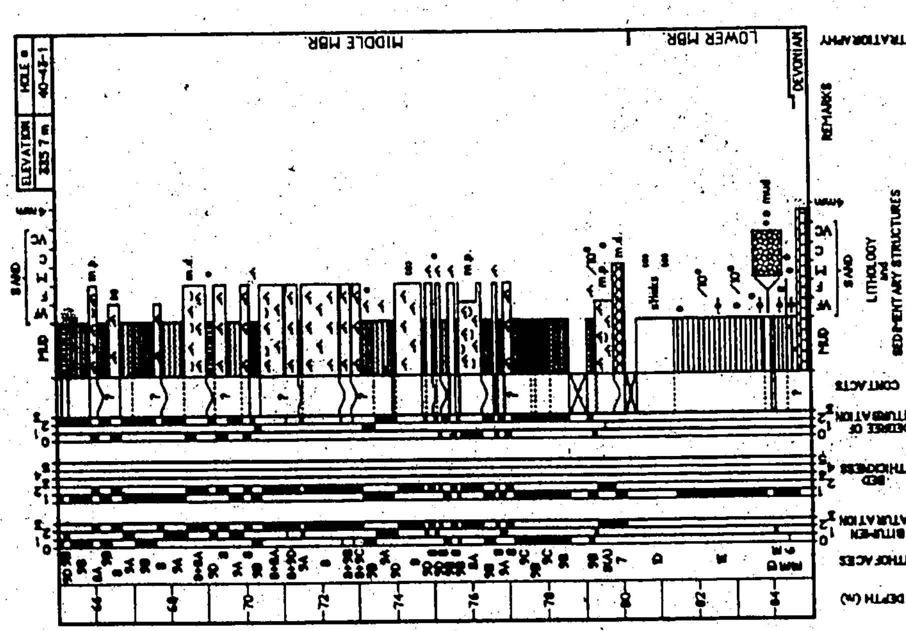
DEPTH (m)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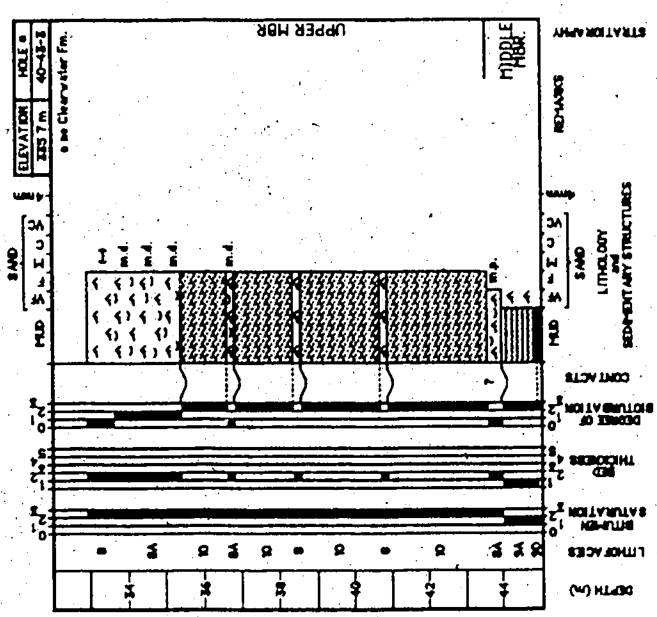
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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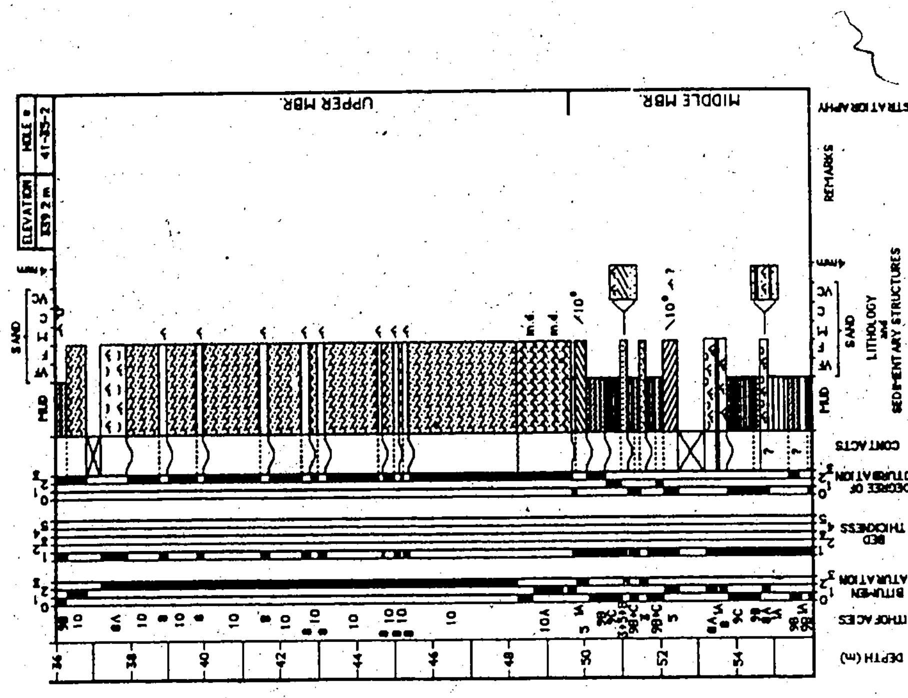
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)



ELEVATION 339.2 m
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MIDDLE MBR.
STRATIGRAPHY
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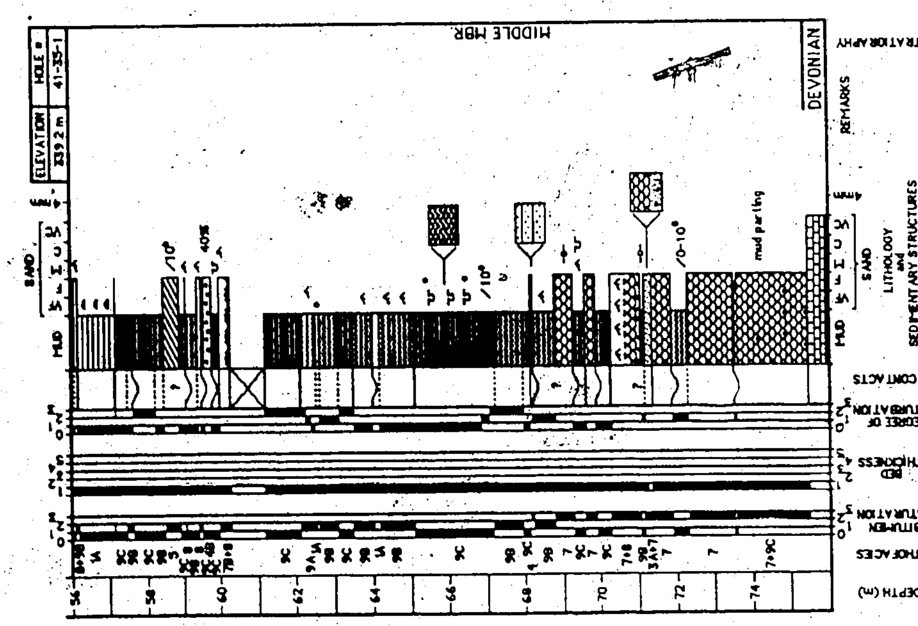

ELEVATION 339.2 m
HOLE # 41-35-1
MIDDLE MBR.
DEVONIAN
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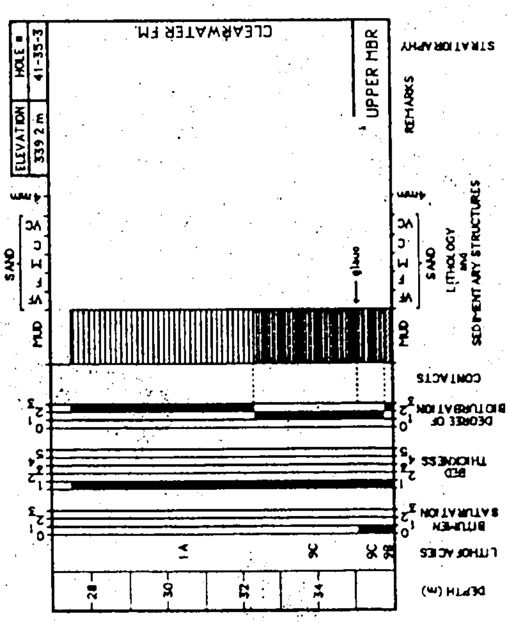
DEPTH (m)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339.2 m
HOLE #
41-35-3
CLEARWATER FM.
UPPER MBR
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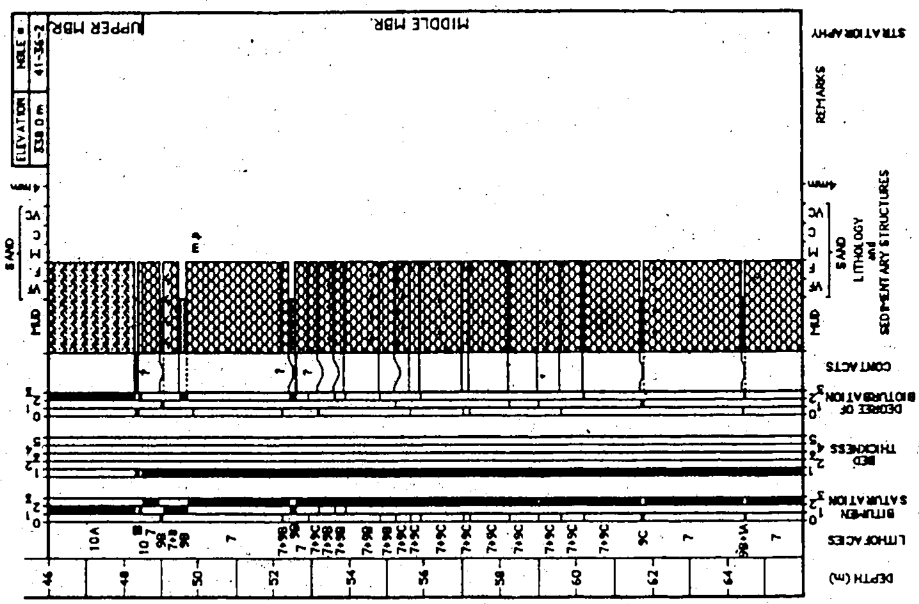
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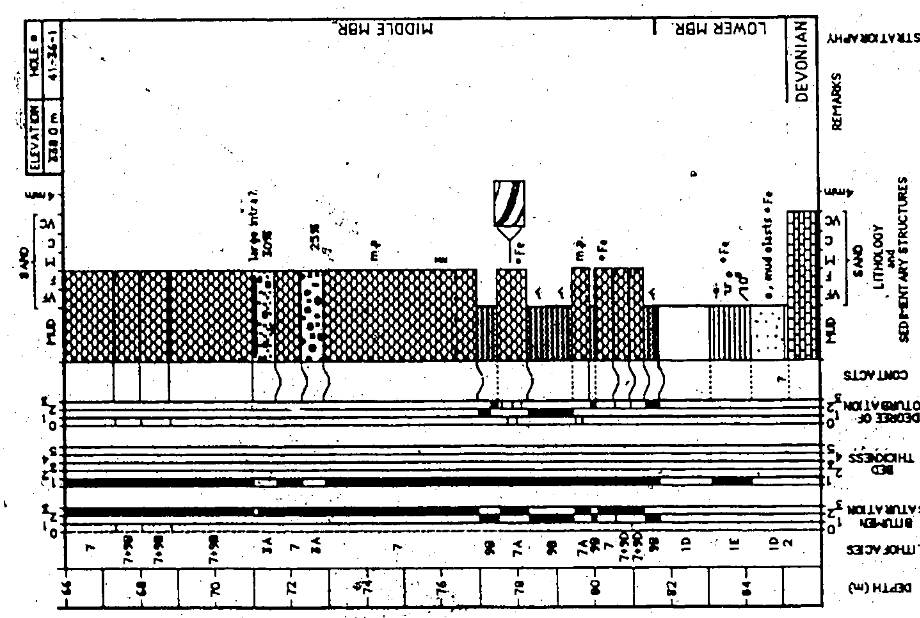
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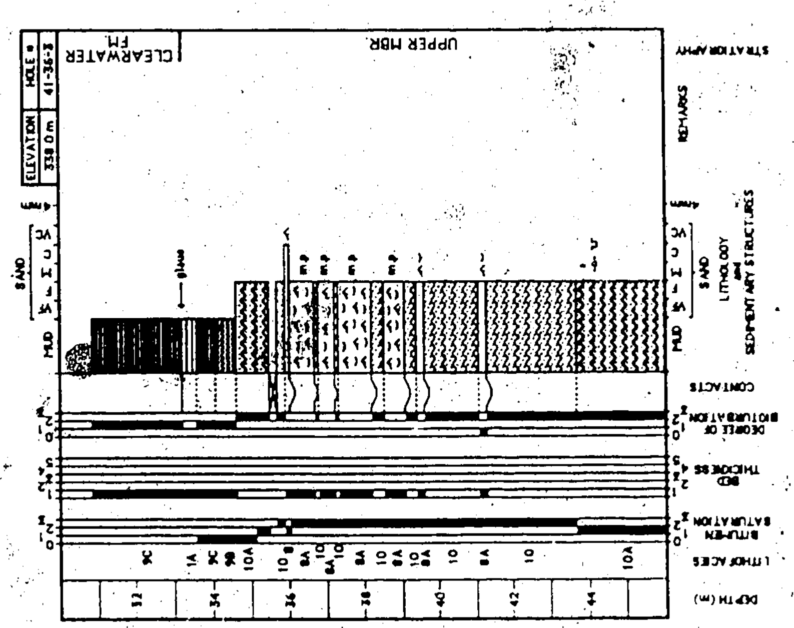
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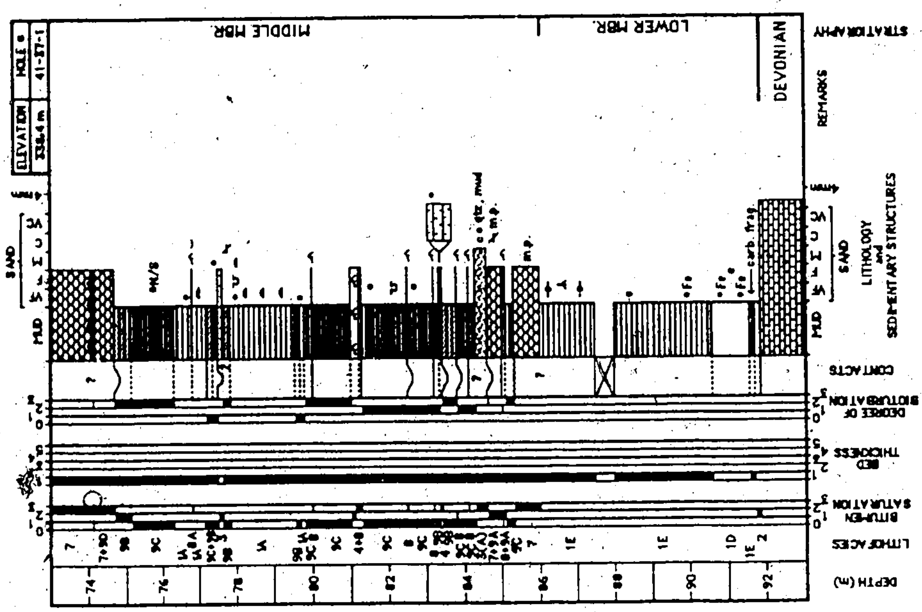

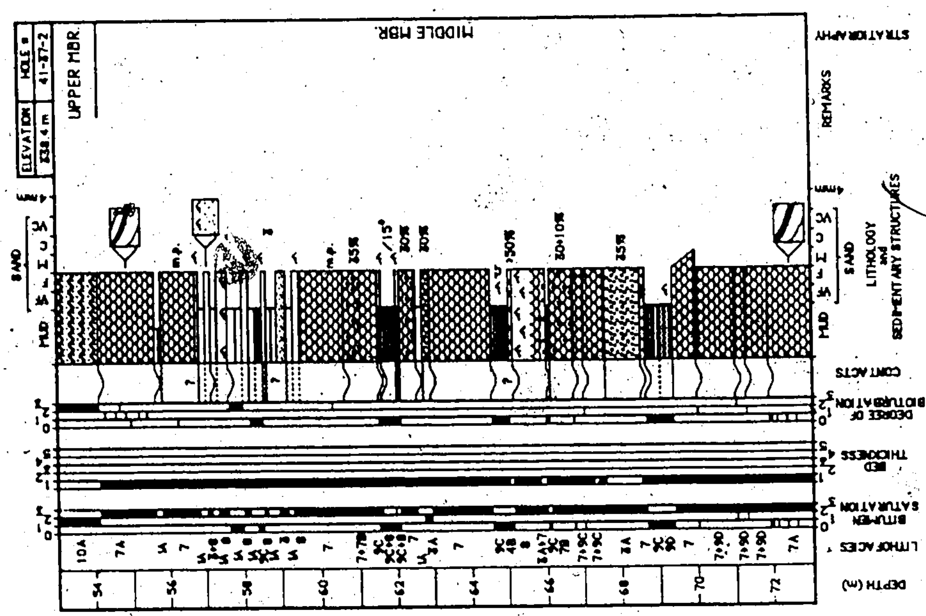

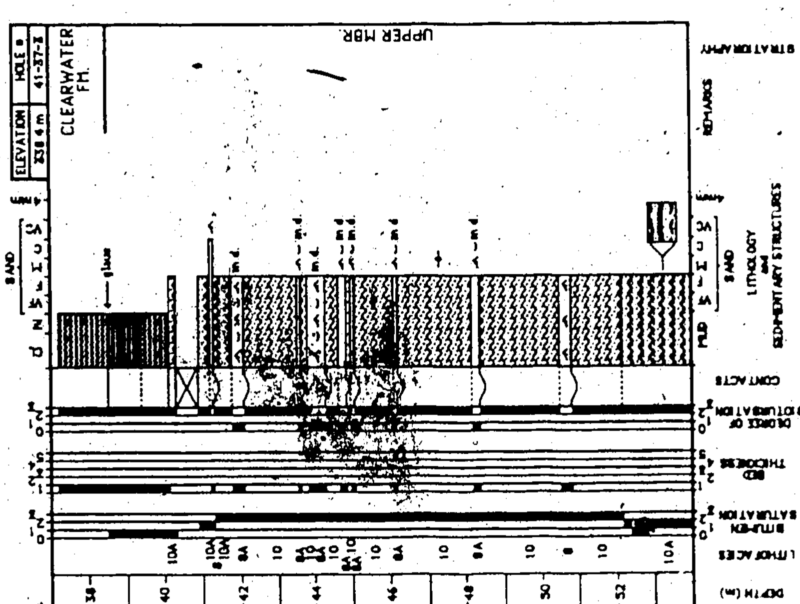

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HOLE #
CLEARWATER FM.
UPPER MBR.
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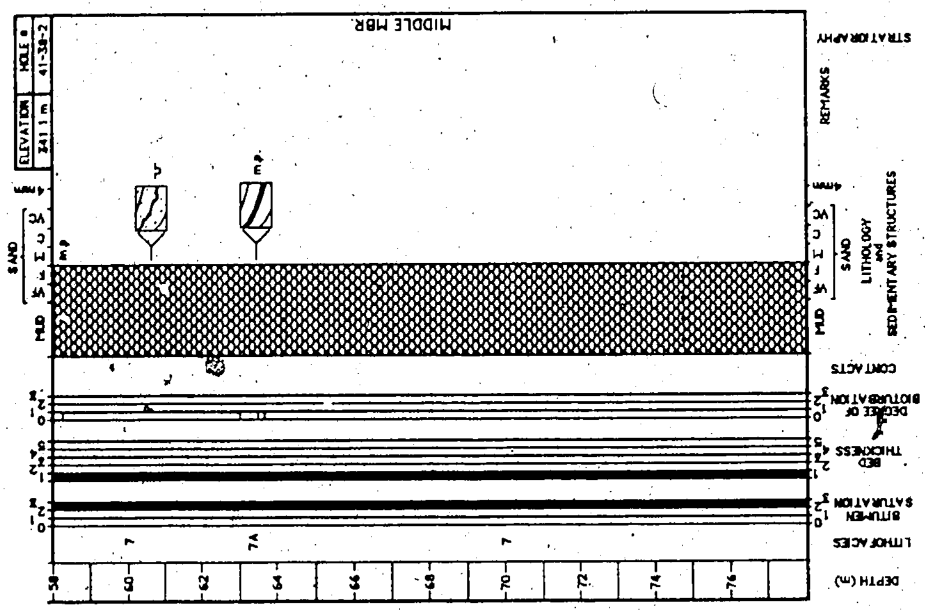
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HOLE #
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MIDDLE MBR.
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BITUMEN SATURATION
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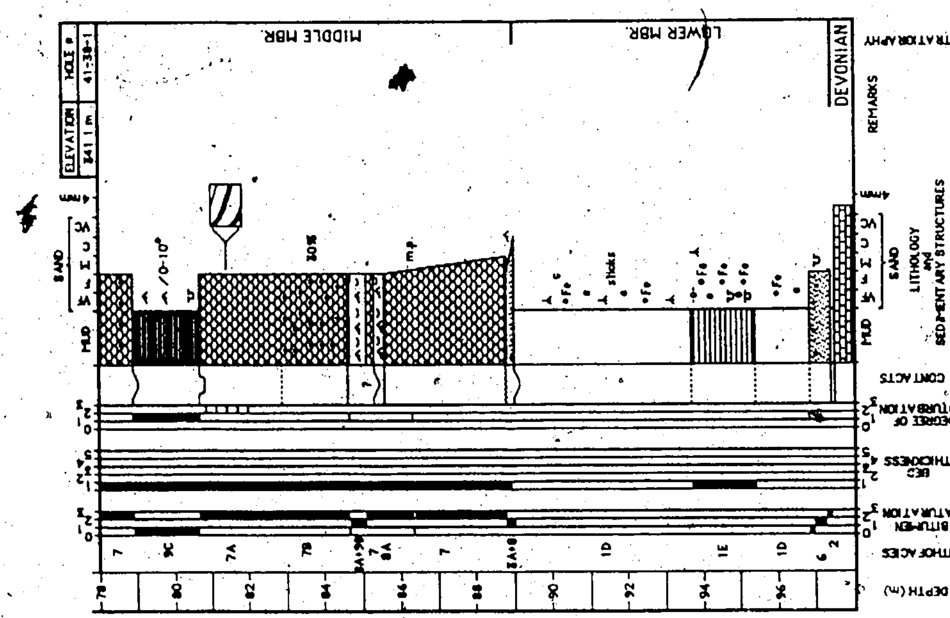
DEPTH (m)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HOLE #
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LOWER MBR.
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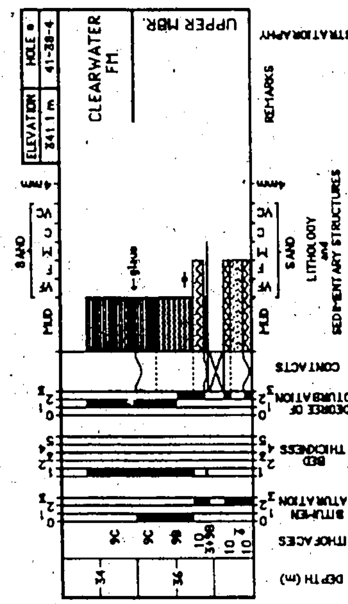
DEPTH (m)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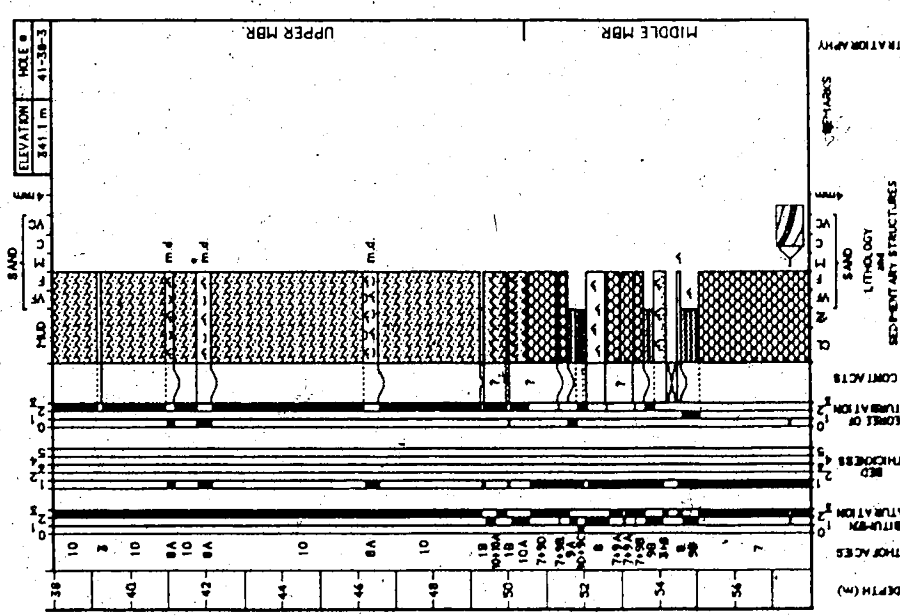
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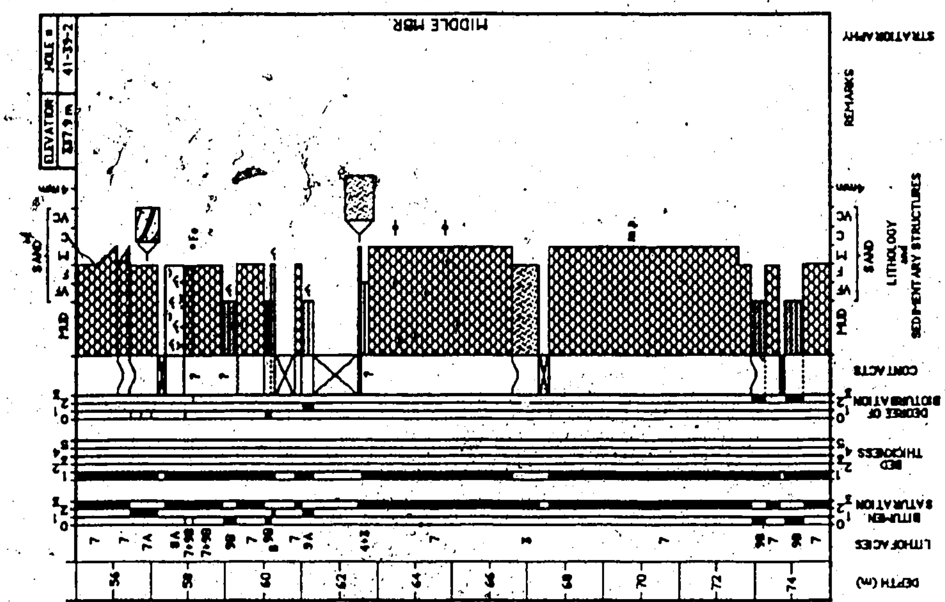
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MIDDLE MBR.
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REMARKS
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CONTACTS
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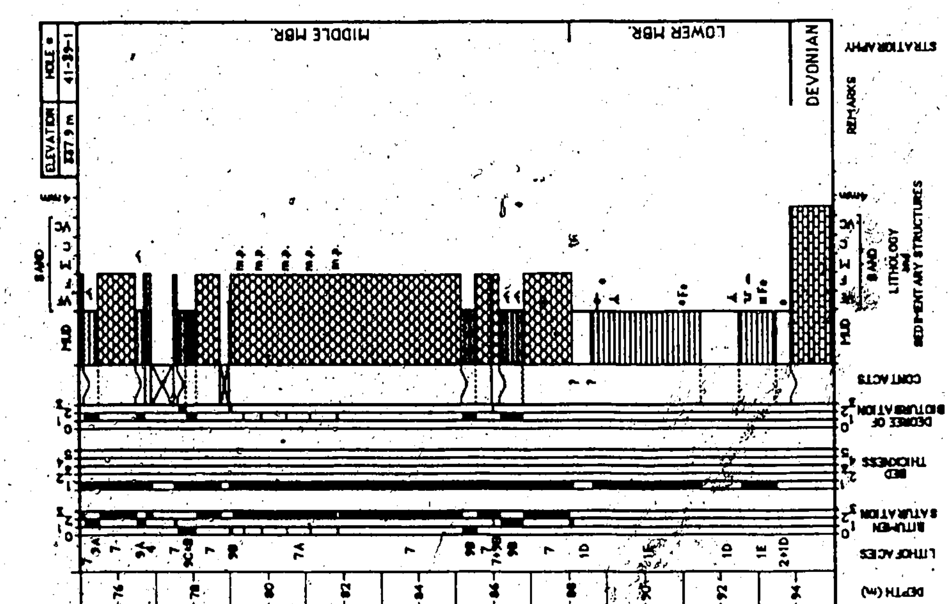
LITHOFACIES
DEPTH (m)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LOWER MBR.
DEVONIAN
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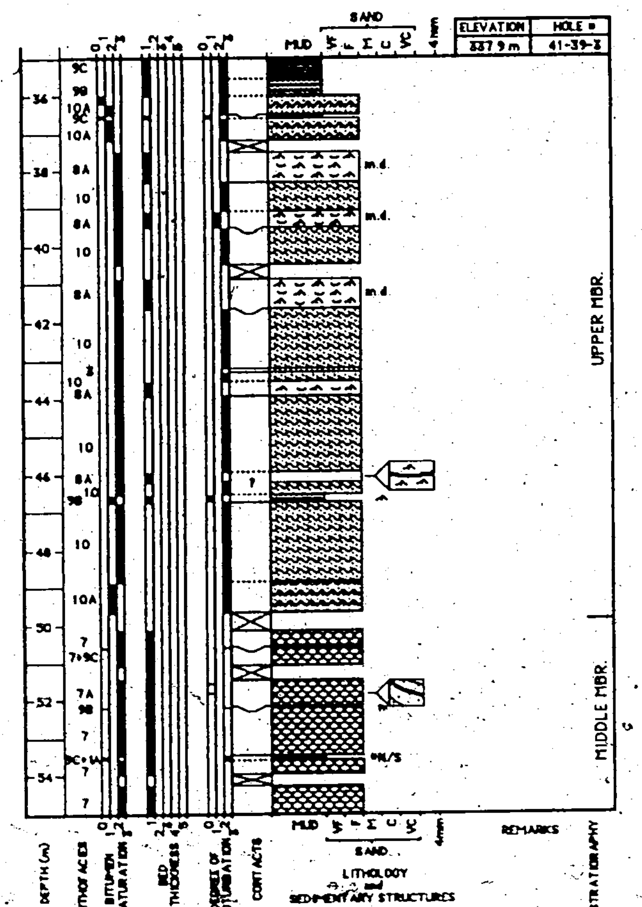
DEPTH (m)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MIDDLE MBR.
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BITUMEN SATURATION
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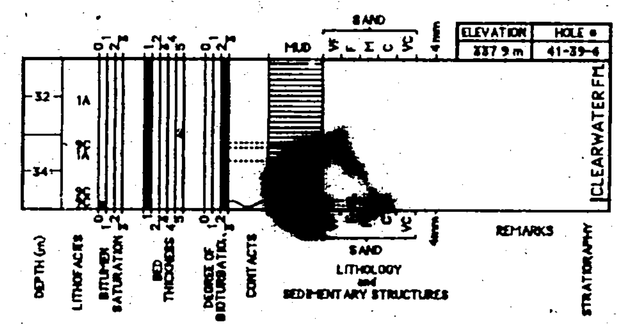
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337.9 m
HOLE #
41-39-4
CLEARWATER FM.
DEPTH (m)
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BITUMEN SATURATION
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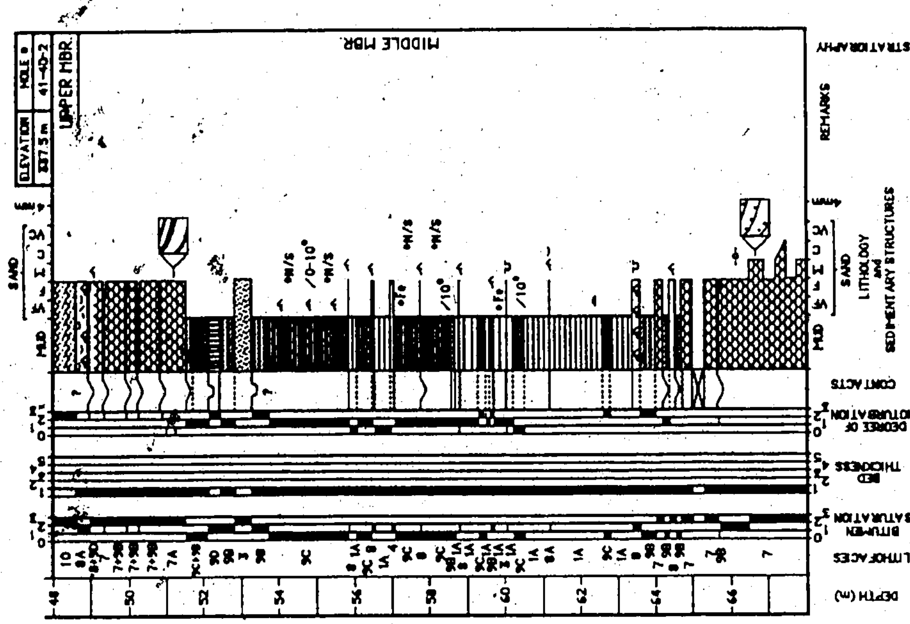
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MIDDLE MBR.
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REMARKS
LITHOLOGY and SEDIMENTARY STRUCTURES
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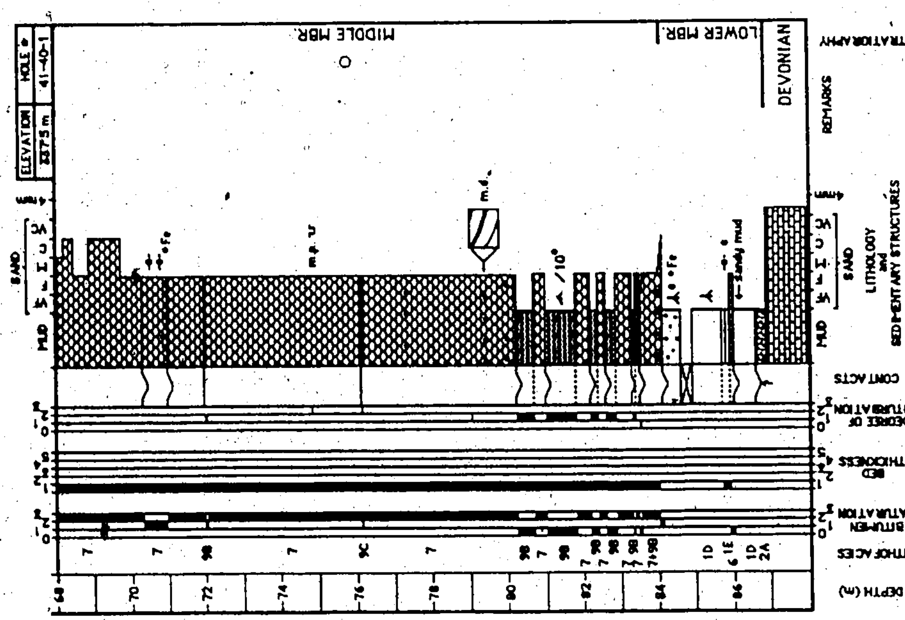
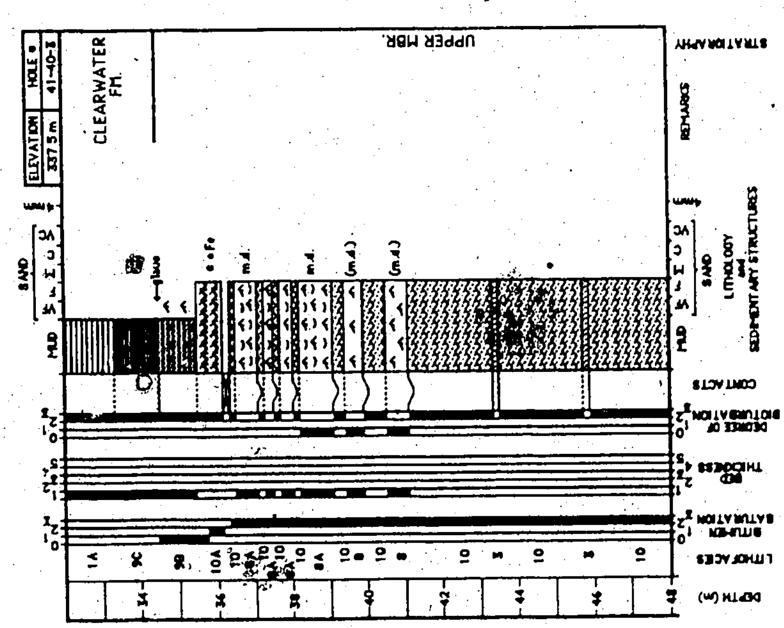
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
337.5 m
HOLE #
41-40-1
MIDDLE MBR.
LOWER MBR.
DEVONIAN
STRATIGRAPHY
REMARKS
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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UPPER MBR.
REMARKS
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CONTACTS
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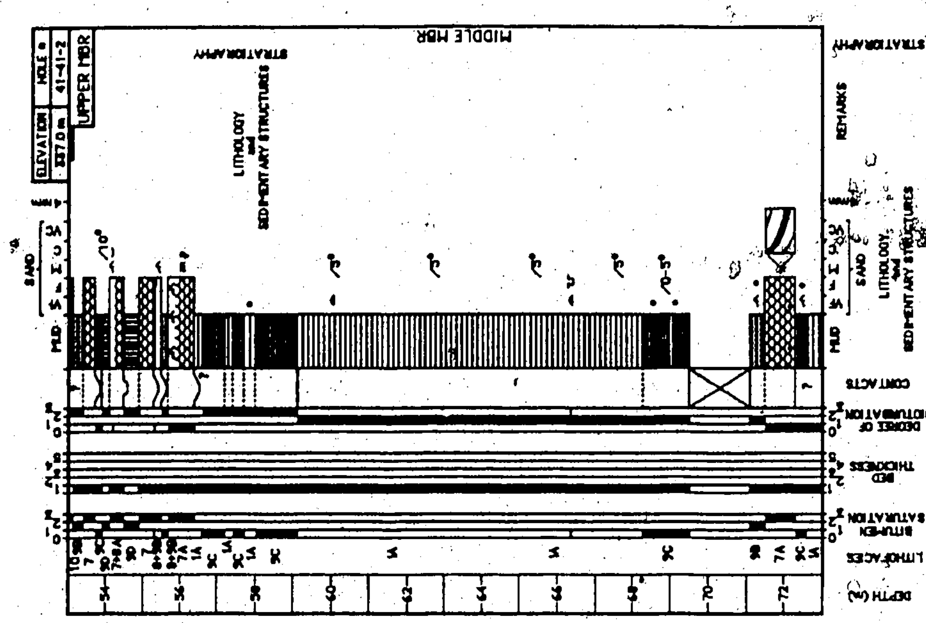
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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UPPER MBR
MIDDLE MBR
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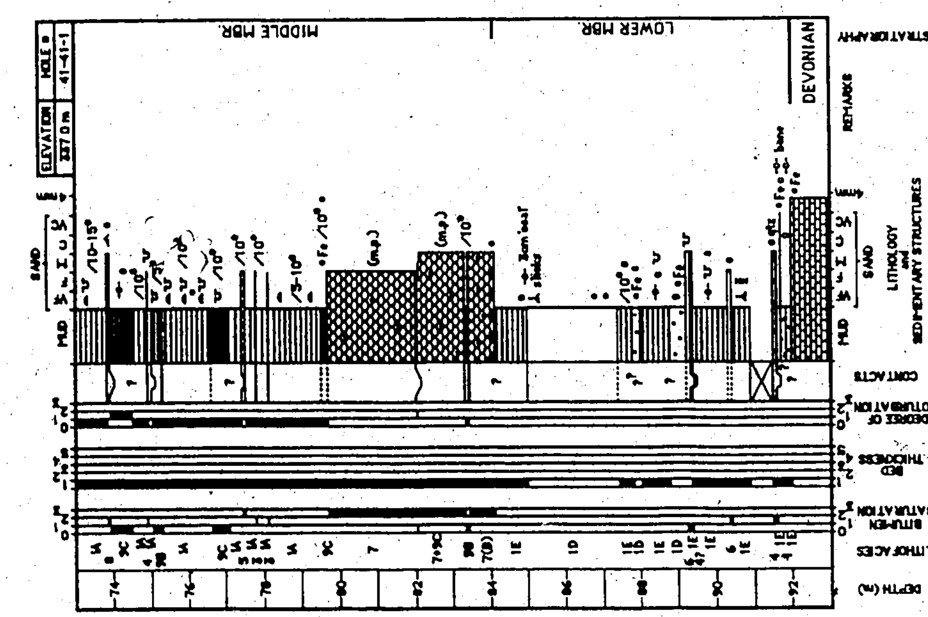
REMARKS
LITHOLOGY and SEDIMENTARY STRUCTURES
MUD
SAND
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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LOWER MBR.
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REMARKS
LITHOLOGY and SEDIMENTARY STRUCTURES
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CONTACTS
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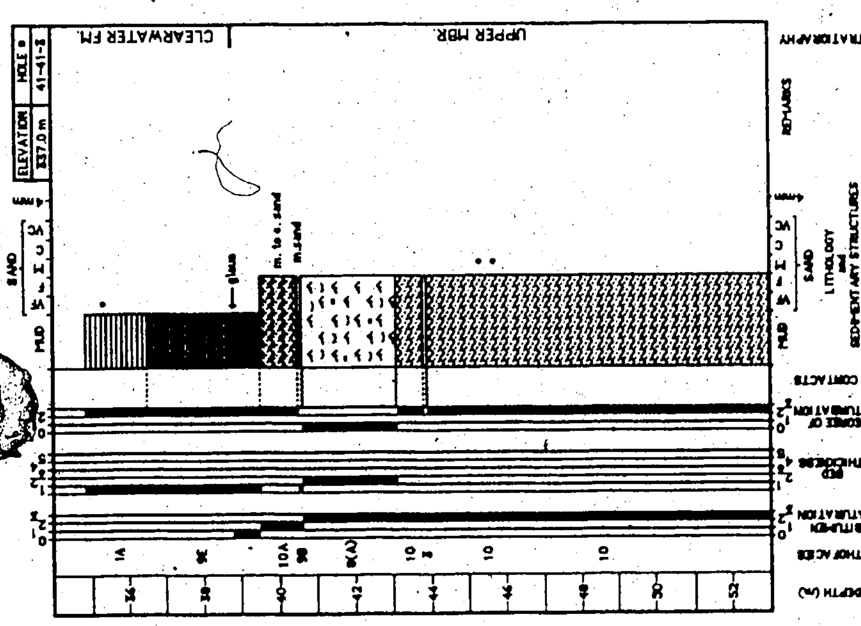
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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UPPER MBR.
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ELEVATION
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REMARKS
MUD
SAND
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CONTACTS
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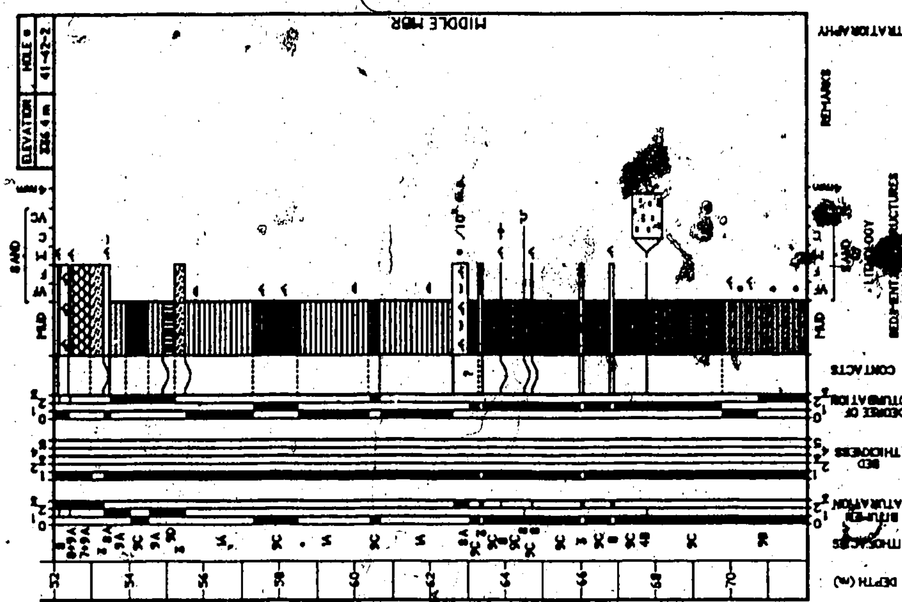
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
336.4 m
HOLE #
41-42-2
MIDDLE MBR
STRATIGRAPHY
REMARKS
MUD
SAND
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
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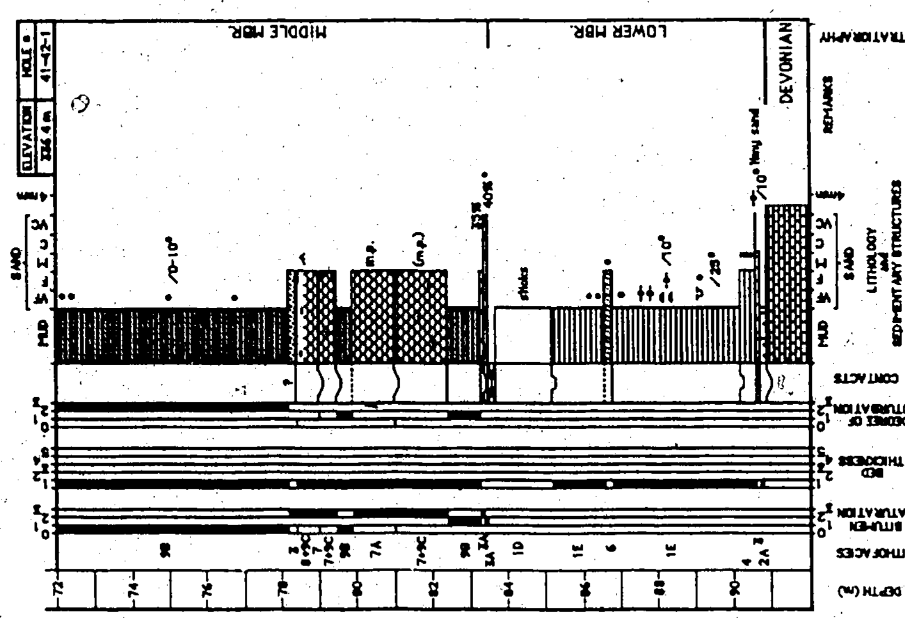
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
336.4 m
HOLE #
41-42-1
MIDDLE MBR.
LOWER MBR.
DEVONIAN
STRATIGRAPHY
REMARKS
MUD
SAND
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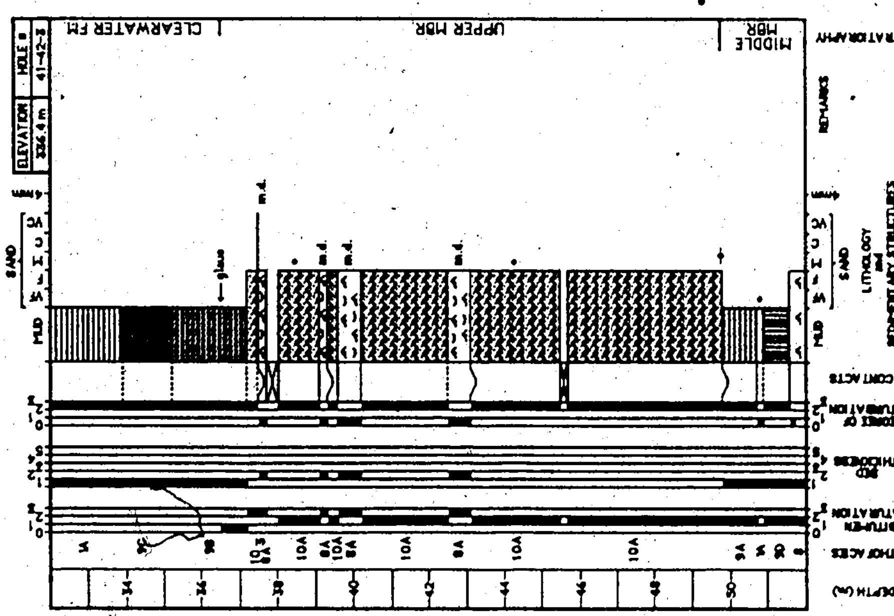
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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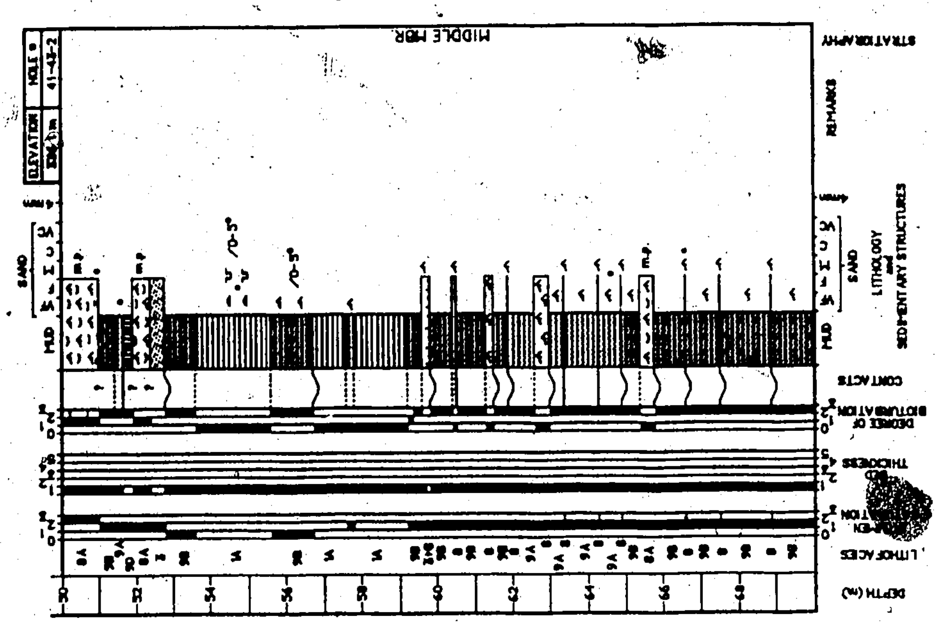
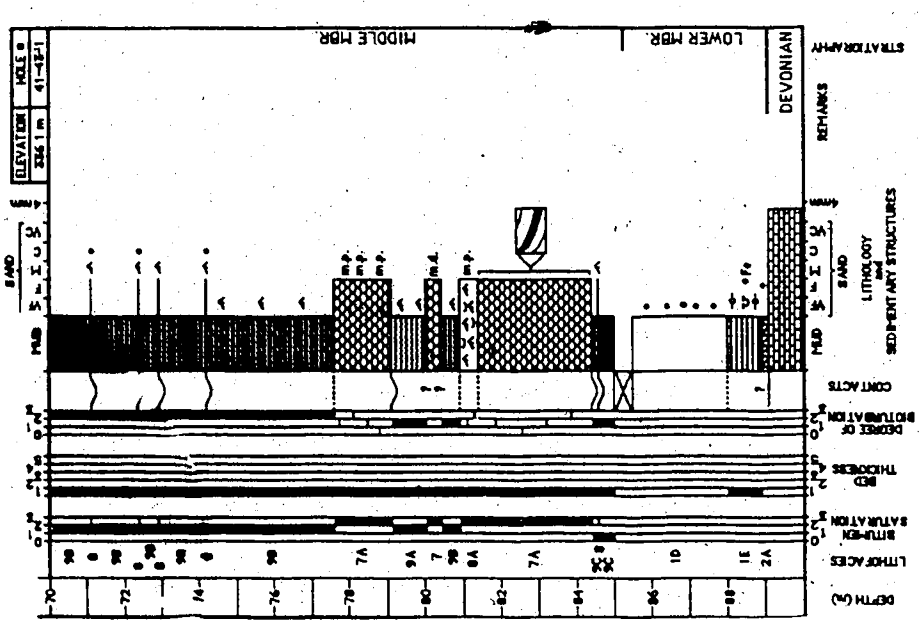
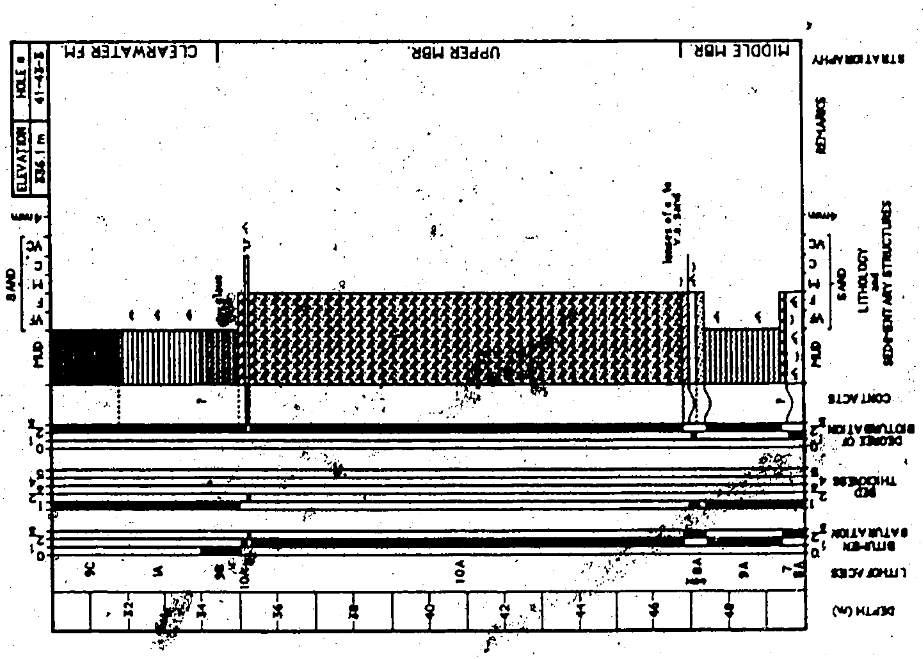
MIDDLE MBR
STRATIGRAPHY
REMARKS
CONTACTS
LITHOFACIES
DEPTH (m)



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MIDDLE MBR.
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LITHOLOGY and SEDIMENTARY STRUCTURES
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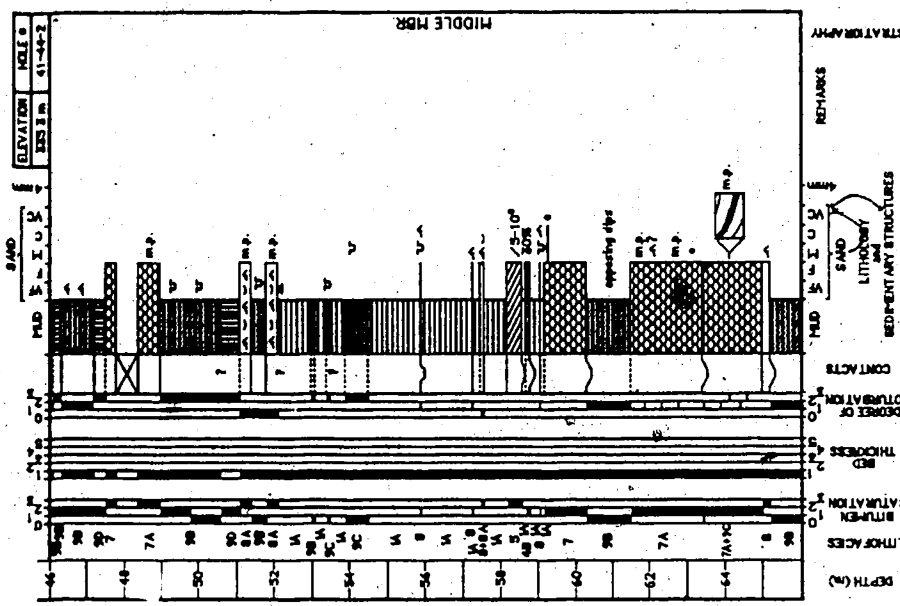
SAND
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)
ELEVATION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HOLE #
41-44-2
MIDDLE MBR
STRATIGRAPHY
REMARKS
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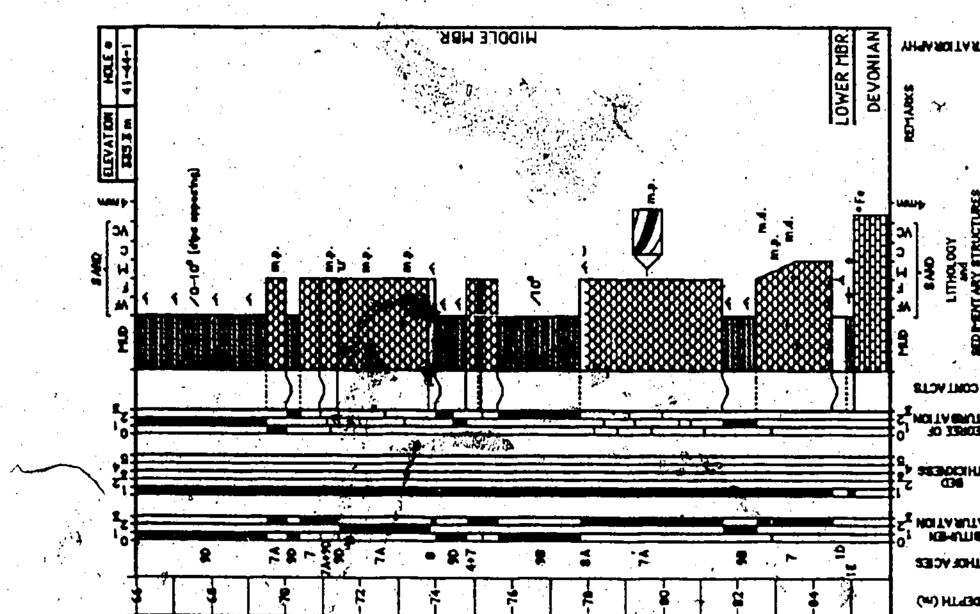
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
HOLE #
41-44-1
MIDDLE MBR
LOWER MBR
DEVONIAN
STRATIGRAPHY
REMARKS
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
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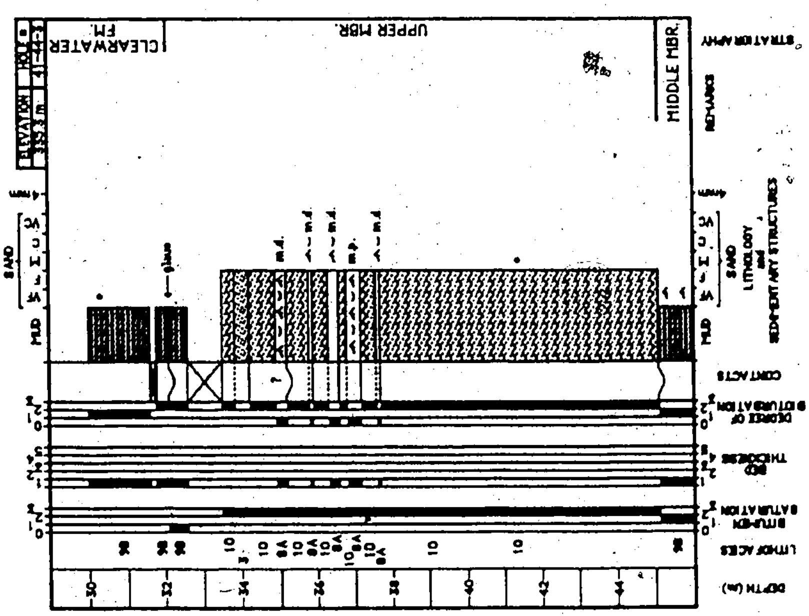
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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UPPER MBR.
CLEARWATER FM.
MUD
SAND
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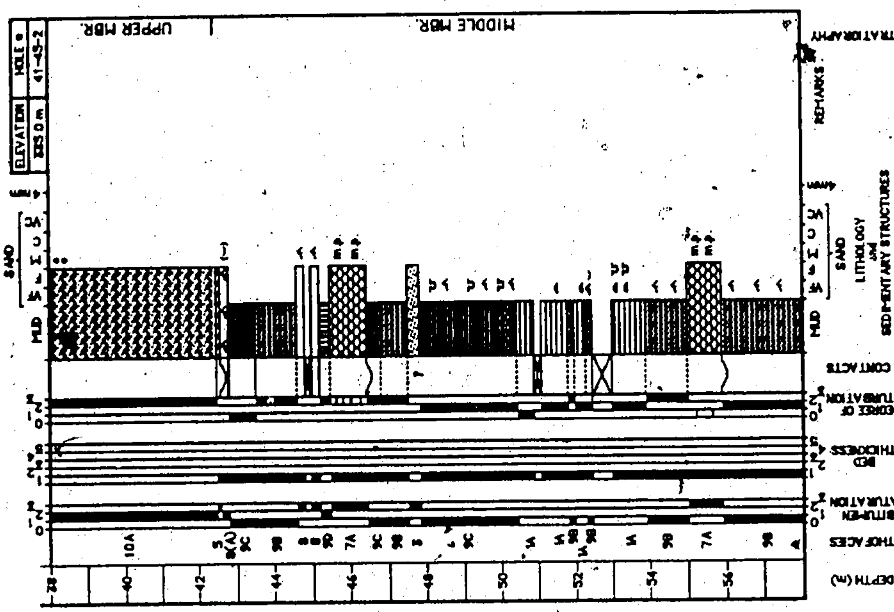
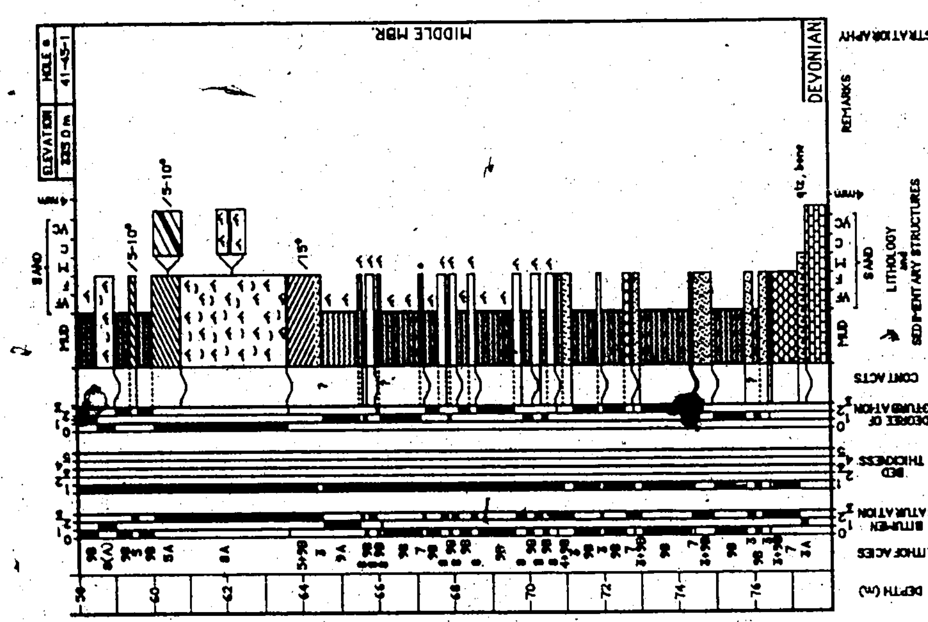
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
335.0 m
HOLE #
41-45-2
UPPER MBR.
MIDDLE MBR.
STRATIGRAPHY
REMARKS
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
335.0 m
HOLE #
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MIDDLE MBR.
DEVONIAN
STRATIGRAPHY
REMARKS
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CONTACTS
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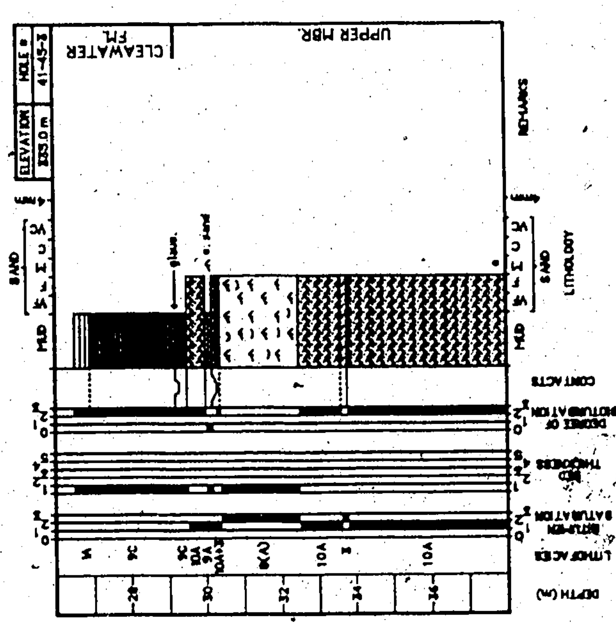
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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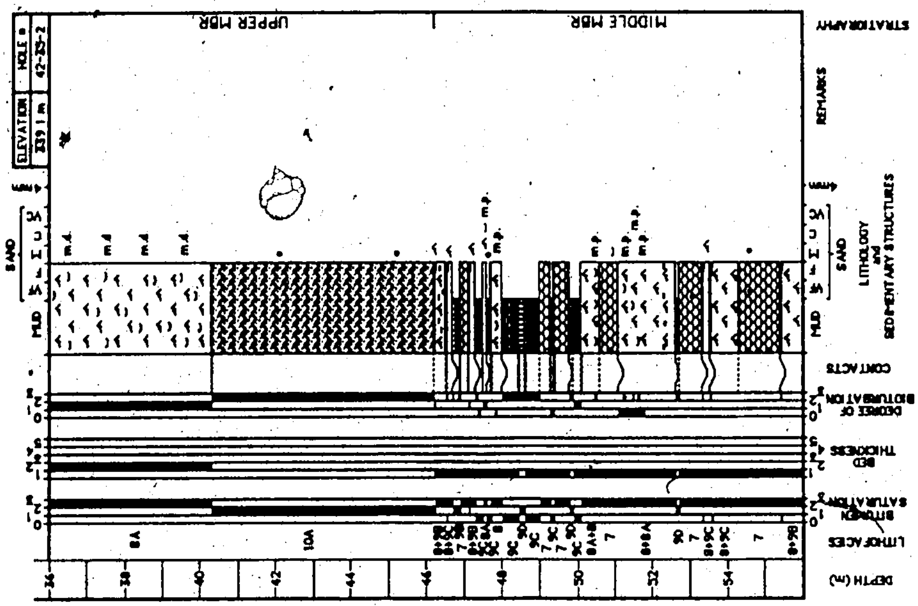
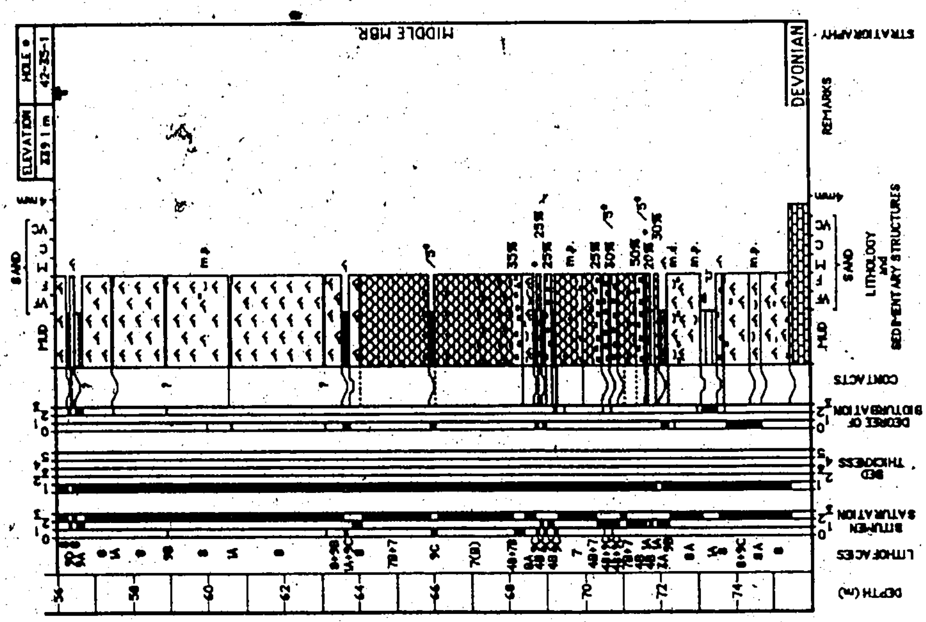
LITHOLOGY
CONTACTS
LITHOFACIES
DEPTH (m)



STRATIGRAPHY
UPPER MBR
MIDDLE MBR
REMARKS
ELEVATION
HOLE #
42-25-2
LITHOLOGY and SEDIMENTARY STRUCTURES
MUD
SAND
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)



STRATIGRAPHY
MIDDLE MBR
DEVONIAN
REMARKS
ELEVATION
HOLE #
42-25-1
LITHOLOGY and SEDIMENTARY STRUCTURES
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SAND
CONTACTS
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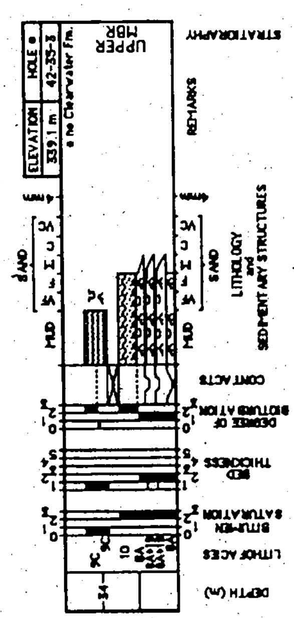
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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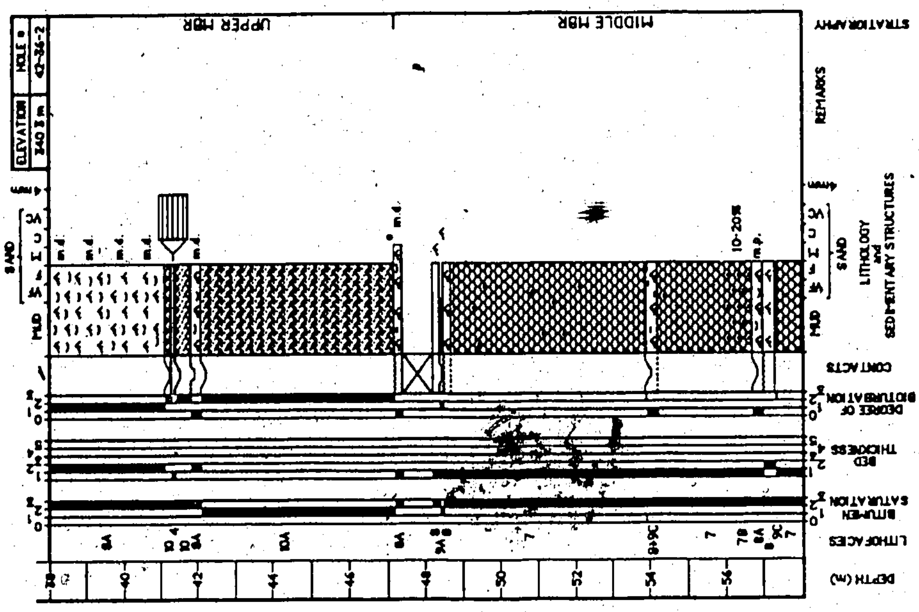
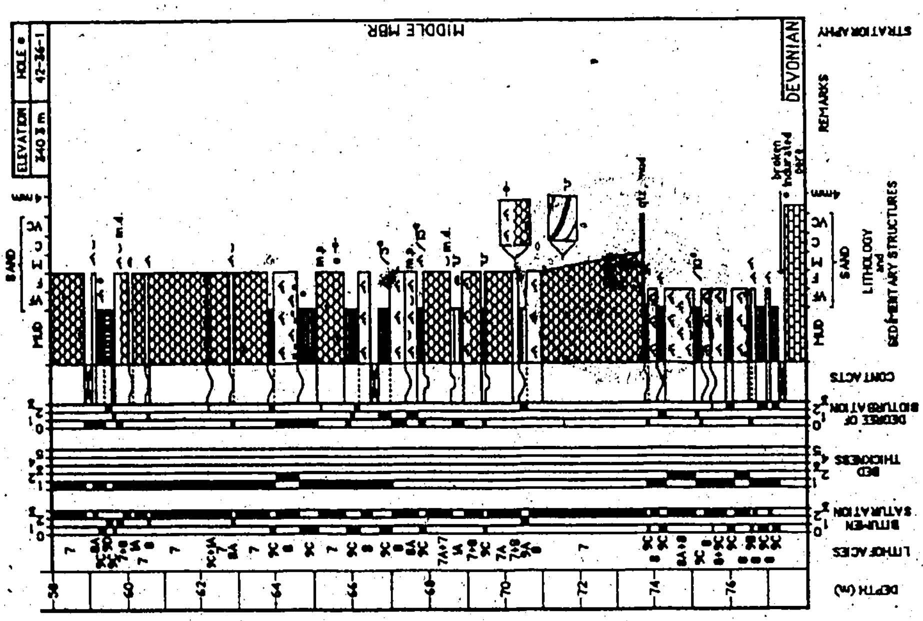
SAND
MUD
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)
ELEVATION
339.1 m
HOLE #



ELEVATION 340.8 m
HOLE 42-36-2
UPPER MBR
MIDDLE MBR
STRATIGRAPHY
REMARKS
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)



ELEVATION 340.8 m
HOLE 42-36-1
MIDDLE MBR.
DEVONIAN
STRATIGRAPHY
REMARKS
broken indurated pcs
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
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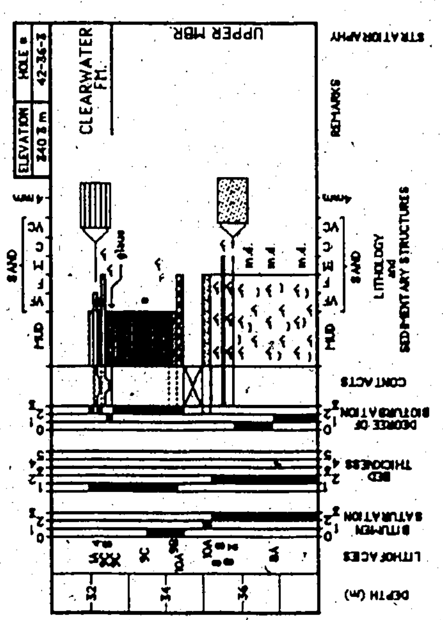
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
HOLE #
CLEARWATER FM.
UPPER MBR.
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SAND
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CONTACTS
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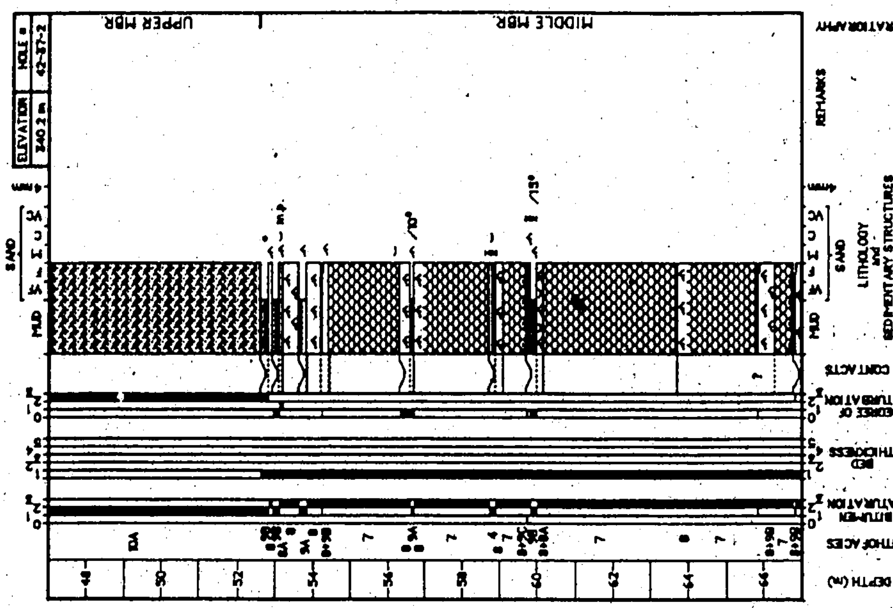
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
340.2 m
UPPER MBR.
MIDDLE MBR.
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CONTACTS
DEGREE OF BIOTURBATION
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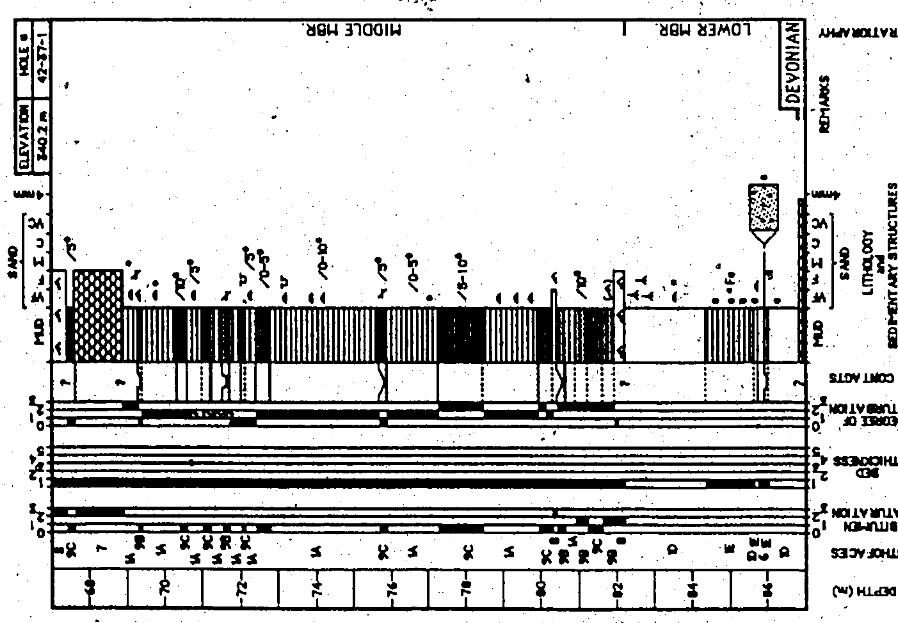
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
340.2 m
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LOWER MBR.
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STRATIGRAPHY
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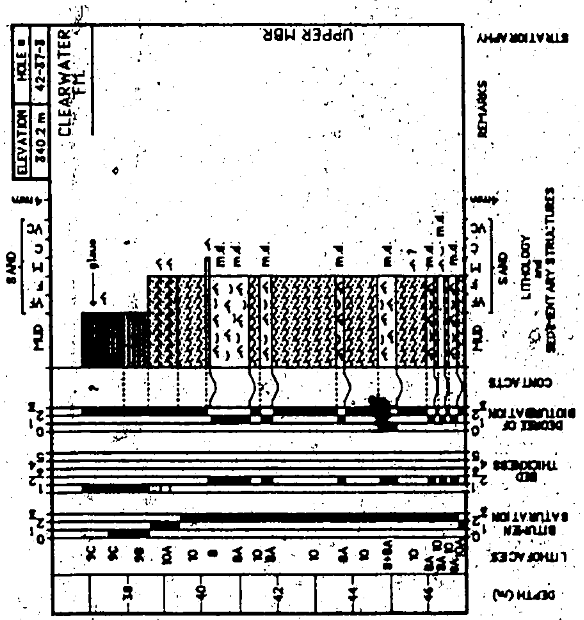
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
840.2 m
HOLE #
CLEARWATER FM
UPPER MBR
STRATIGRAPHY
REMARKS
MUD
SAND
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
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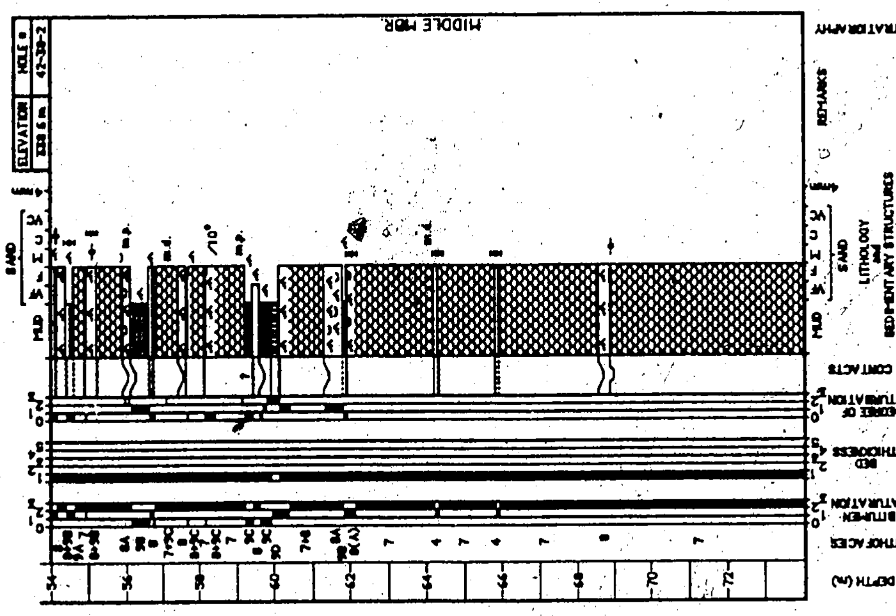
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
338.6 m
HOLE #
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MIDDLE MBR.
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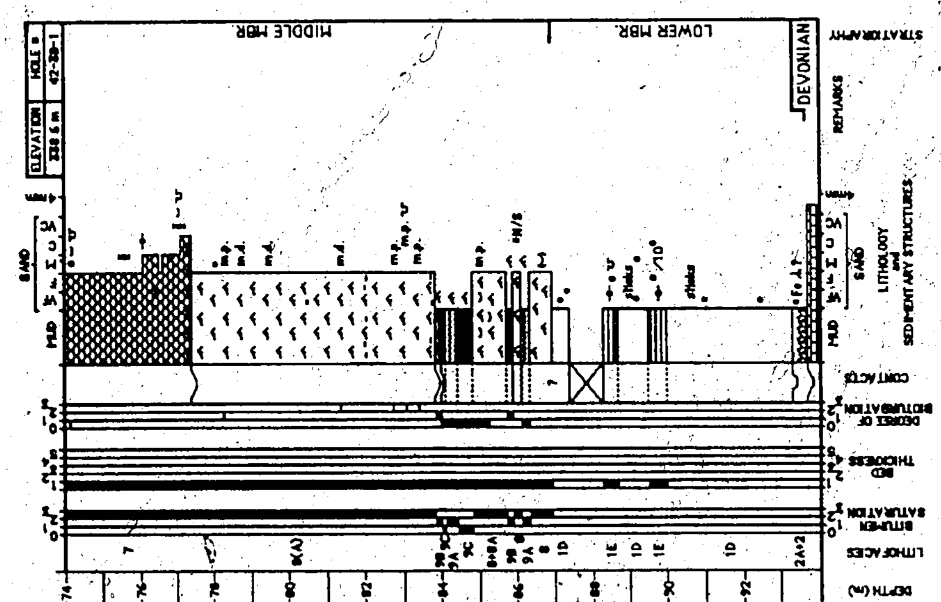
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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338.6 m
HOLE #
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LOWER MBR.
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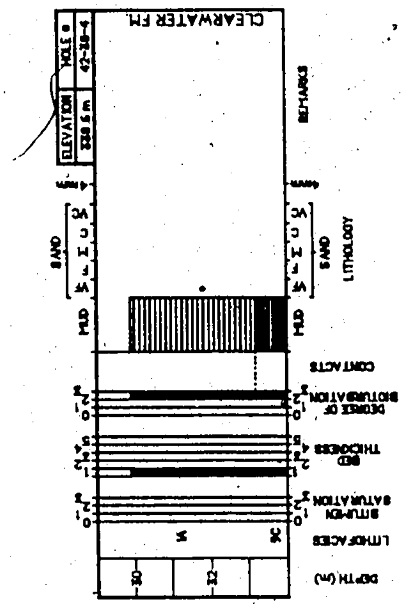
DEPTH (m)


ELEVATION
338.6 m
HOLE #
42-38-4
CLEARWATER FM.
REMARKS
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CONTACTS
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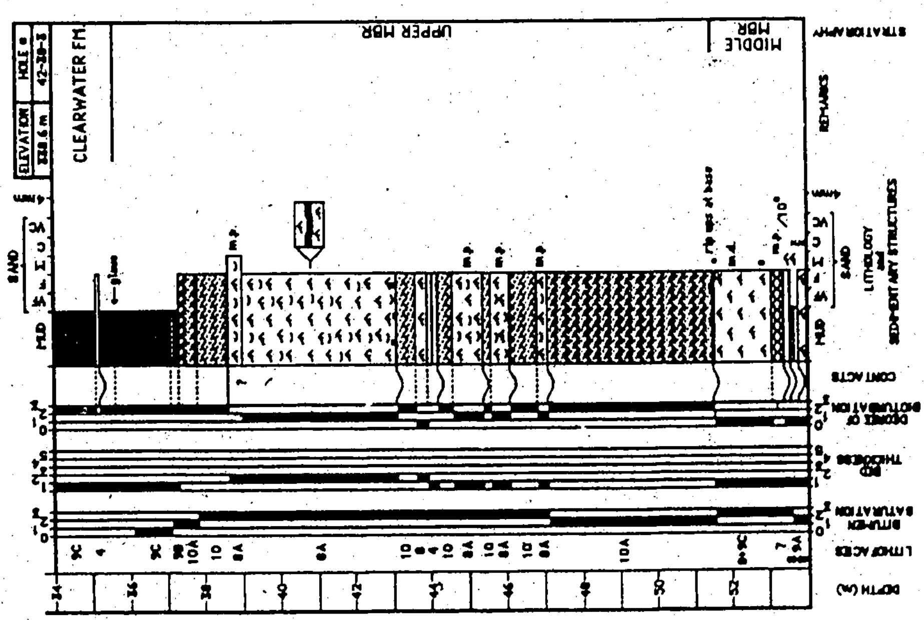
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
338.6 m
HOLE #
CLEARWATER FM.
UPPER MBR
MIDDLE MBR
STRATIGRAPHY
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MUD
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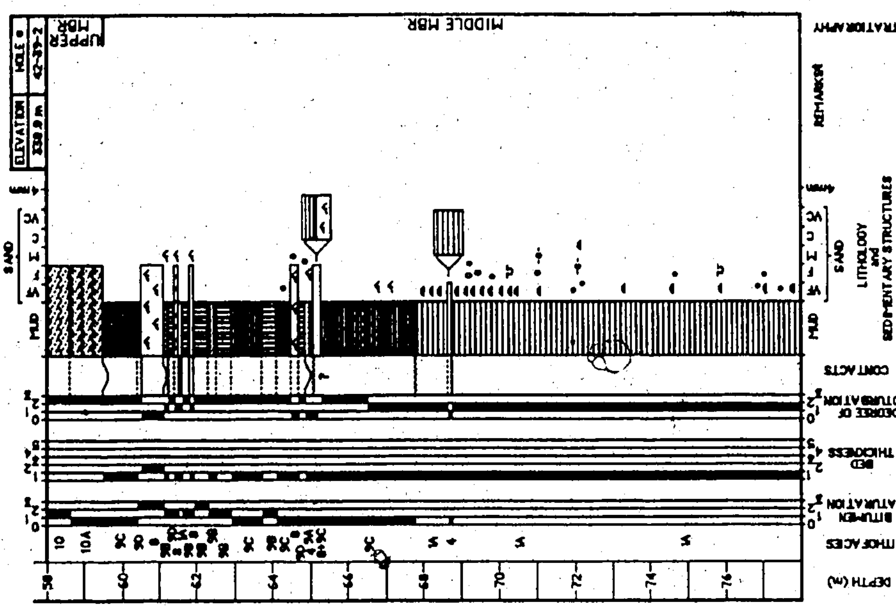
LITHOFACIES
DEPTH (m)


ELEVATION
338.9 m
HOLE #
42-39-2
UPPER MBR.
MIDDLE MBR.
STRATIGRAPHY
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LITHOLOGY and SEDIMENTARY STRUCTURES
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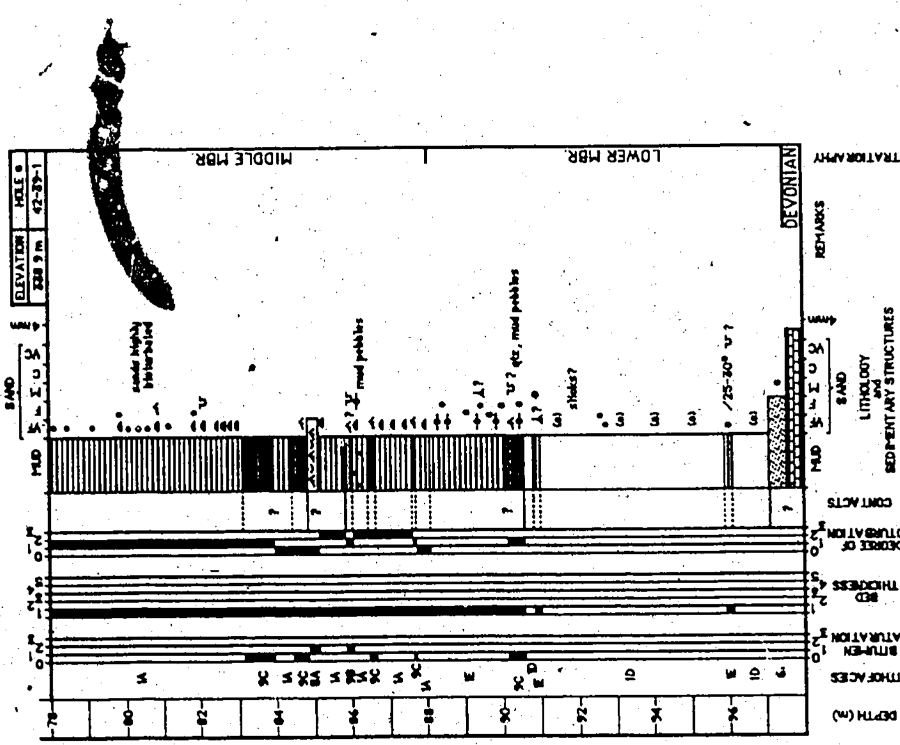
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
338.9 m
HOLE #
42-39-1
MIDDLE MBR.
LOWER MBR.
DEVONIAN
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mud pebbles
qtz., mud pebbles
LITHOLOGY and SEDIMENTARY STRUCTURES
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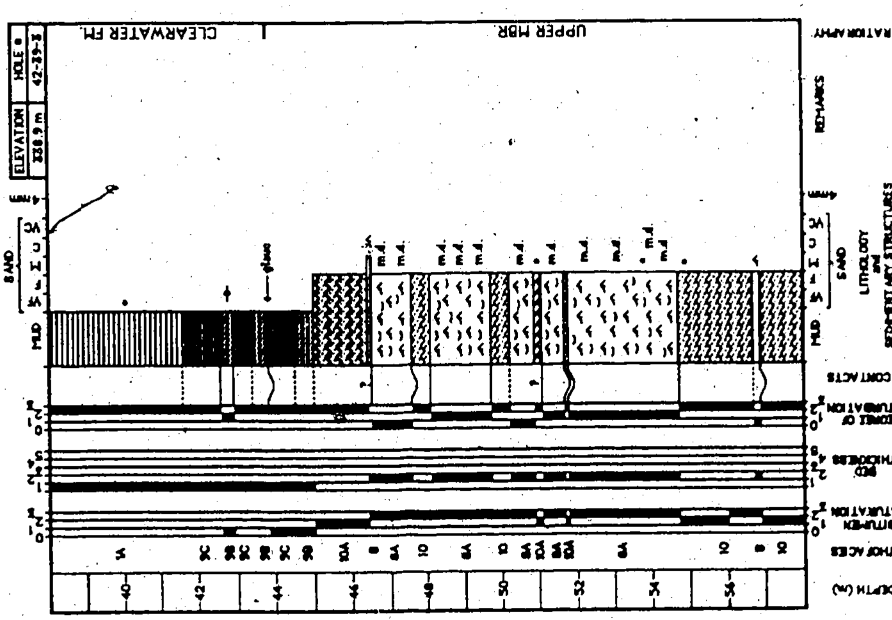
DEPTH (m)



CLEARWATER FM.
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ELEVATION
HOLE #
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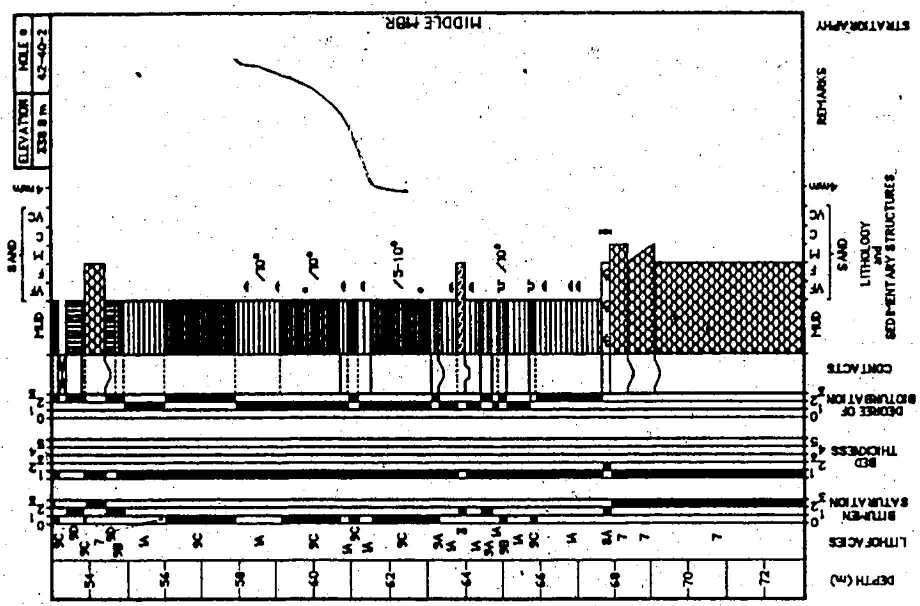
DEPTH (m)


ELEVATION 338.8 m
HOLE # 42-40-2
MIDDLE MBR
STRATIGRAPHY
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CONTACTS
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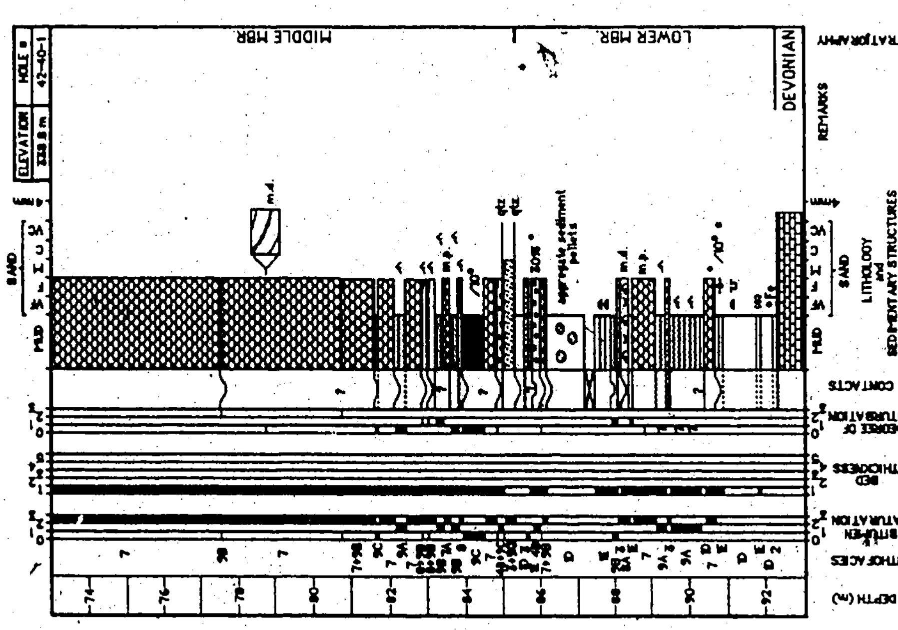
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION 338.8 m
HOLE # 42-40-1
MIDDLE MBR
LOWER MBR
DEVONIAN
aggregate sediment pellets
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BITUMEN SATURATION
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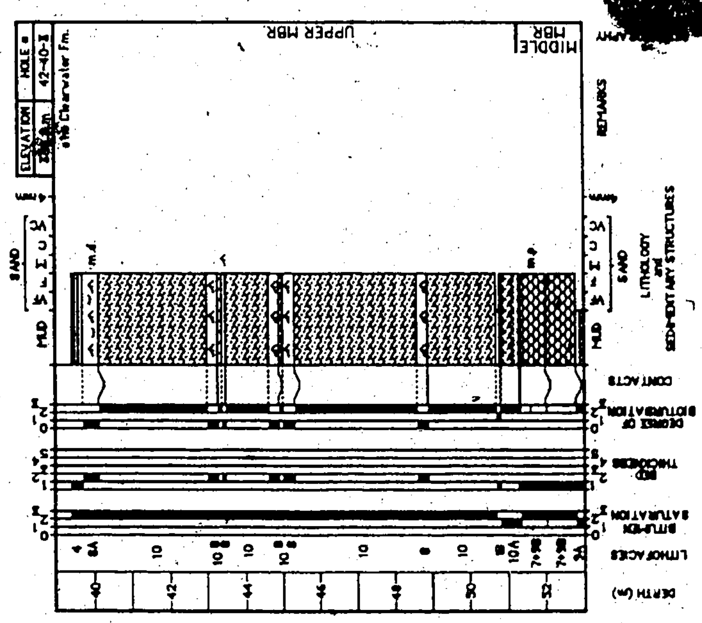
DEPTH (m)


UPPER MBR
MIDDLE MBR
REMARKS
ELEVATION
HOLE #
MUD
SAND
LITHOLOGY
and
SEDIMENTARY STRUCTURES
CONTACTS
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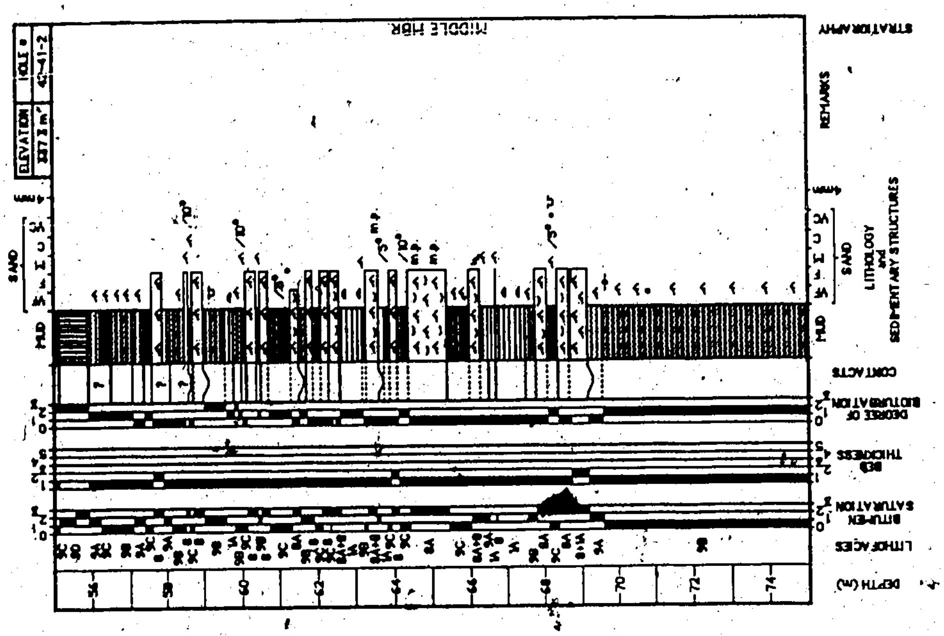
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
HOLE #
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MIDDLE MBR.
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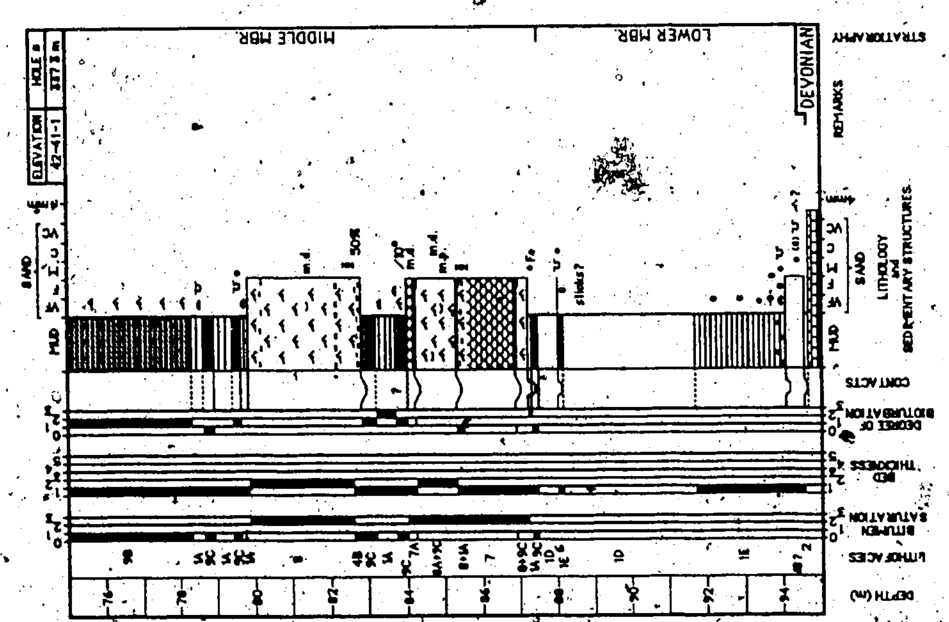
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)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LOWER MBR.
DEVONIAN
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LITHOLOGY and SEDIMENTARY STRUCTURES
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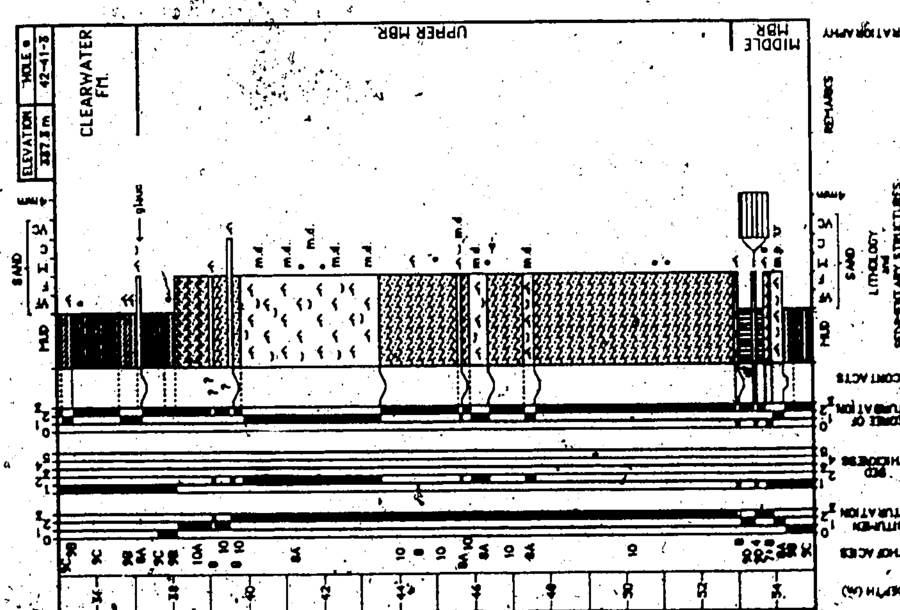
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
HOLE #
CLEARWATER FM.
UPPER MBR.
MIDDLE MBR
STRATIGRAPHY
REMARKS
LITHOLOGY and SEDIMENTARY STRUCTURES
MUD
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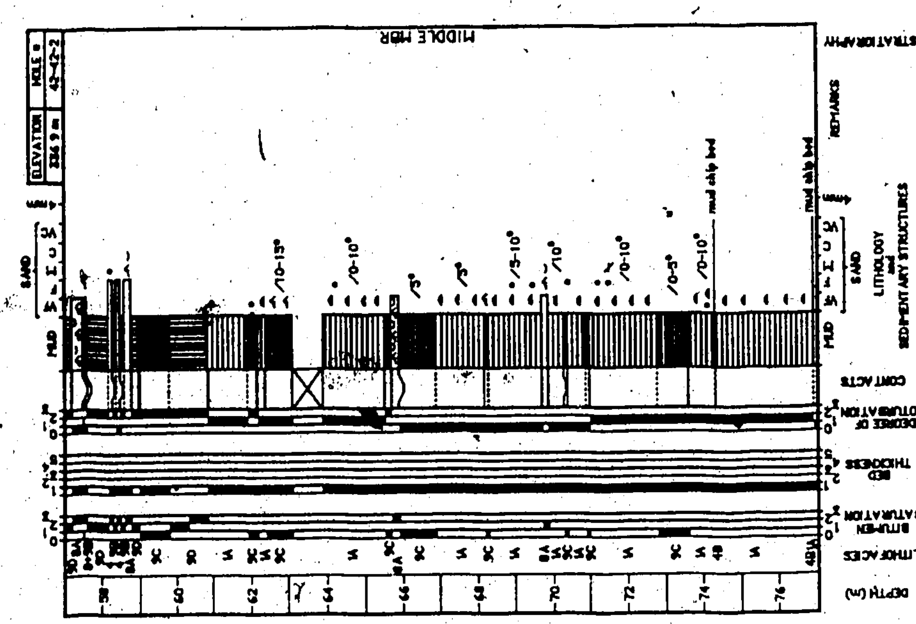
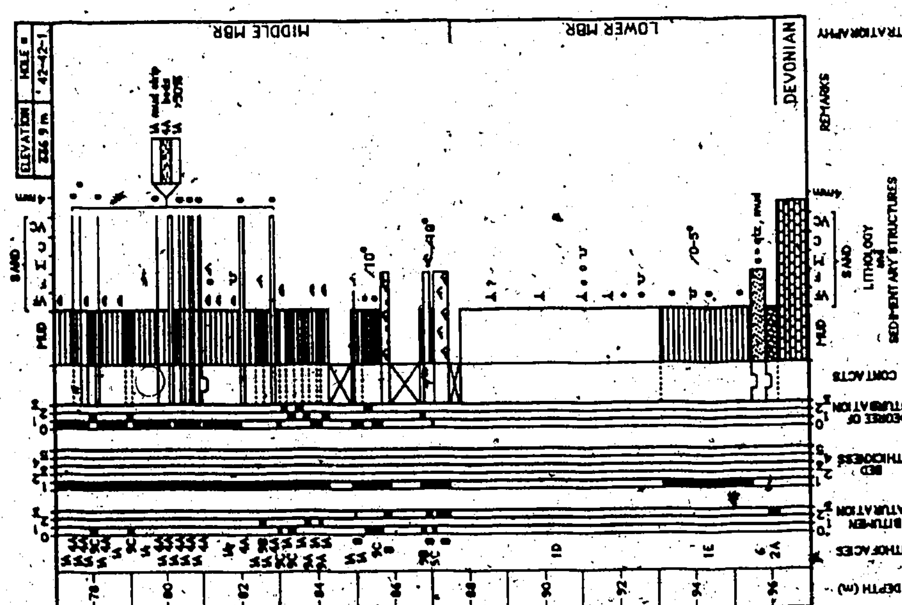
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION 336.9 m
HOLE # 42-42-2
MIDDLE MBR
STRATIGRAPHY
REMARKS
mud chip bed
LITHOLOGY and SEDIMENTARY STRUCTURES
MUD
SAND
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION 336.9 m
HOLE # 42-42-1
MIDDLE MBR.
LOWER MBR.
DEVONIAN
STRATIGRAPHY
REMARKS
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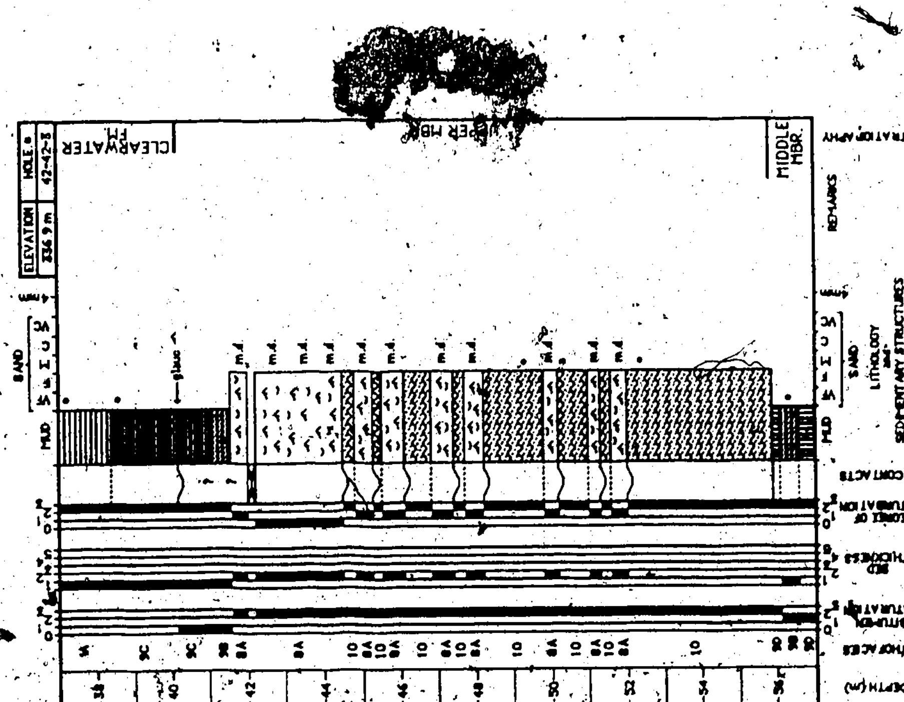
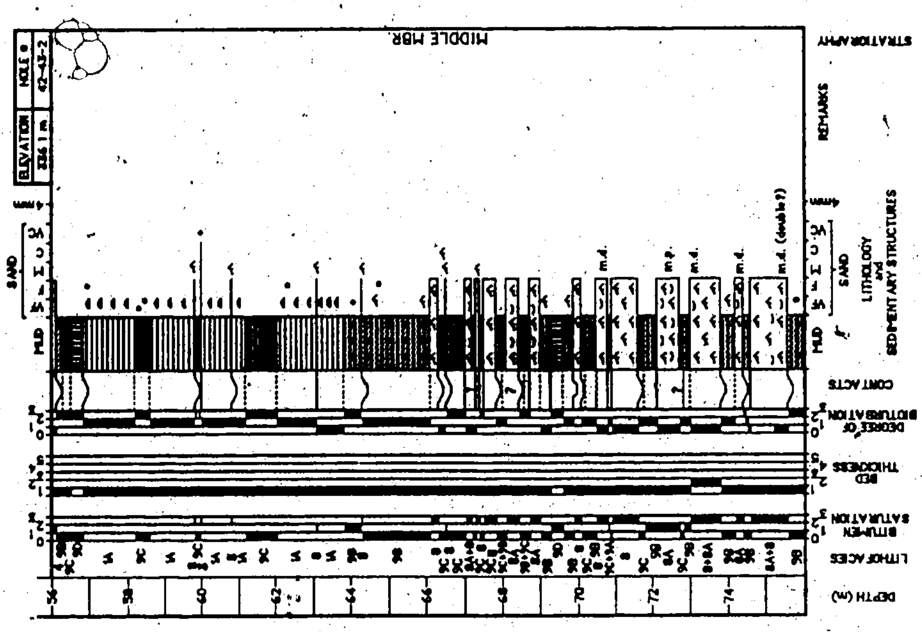
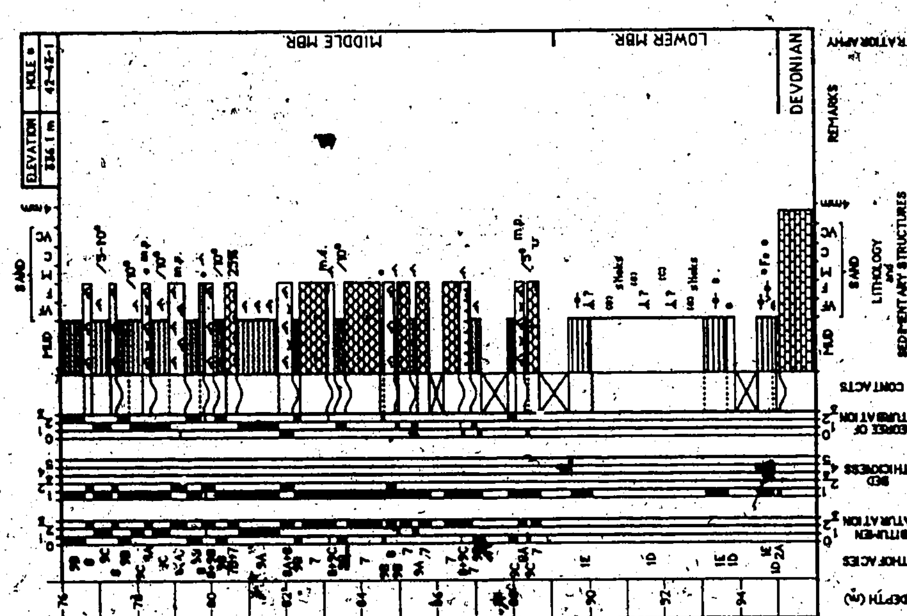
LITHOLOGY and SEDIMENTARY STRUCTURES
MUD
SAND
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)




ELEVATION 336.1 m
HOLE # 42-43-2
MIDDLE MBR.
STRATIGRAPHY
REMARKS
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESSES
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION 336.1 m
HOLE # 42-43-1
MIDDLE MBR.
LOWER MBR.
DEVONIAN
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REMARKS
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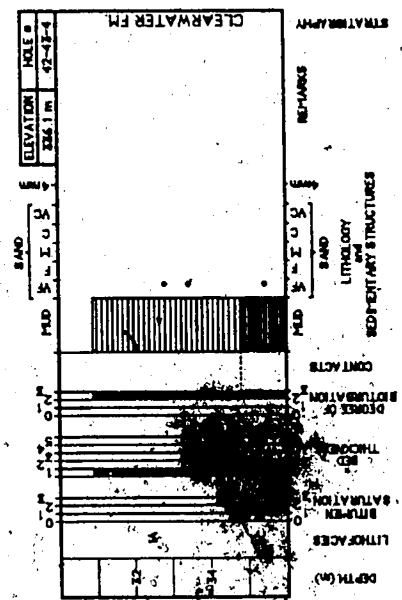
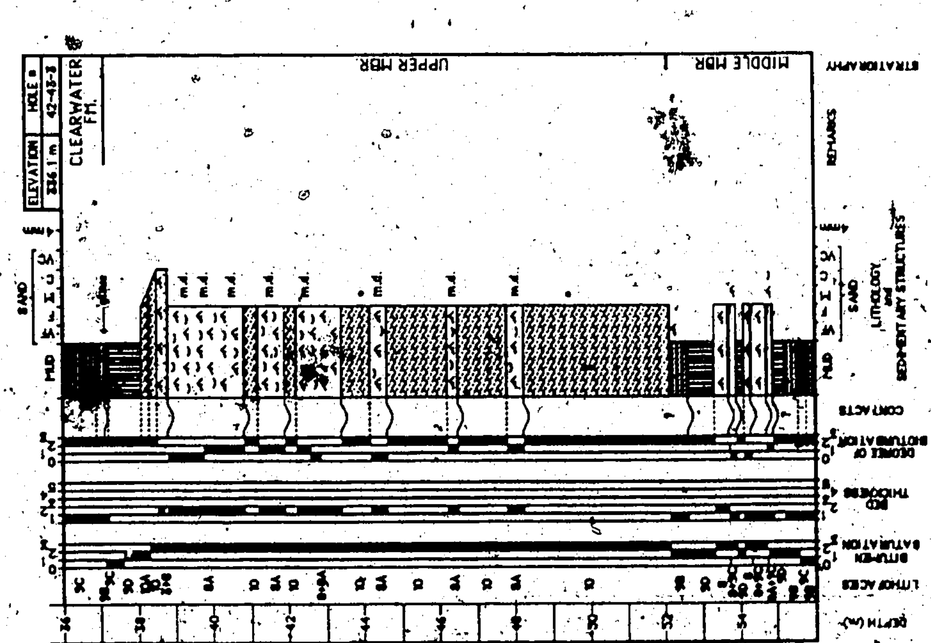
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESSES
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


CLEARWATER FM.
ELEVATION
HOLE #
STRATIGRAPHY
REMARKS
SAND
MUD
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


CLEARWATER FM.
ELEVATION
HOLE #
UPPER MBR
MIDDLE MBR
STRATIGRAPHY
REMARKS
SAND
MUD
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
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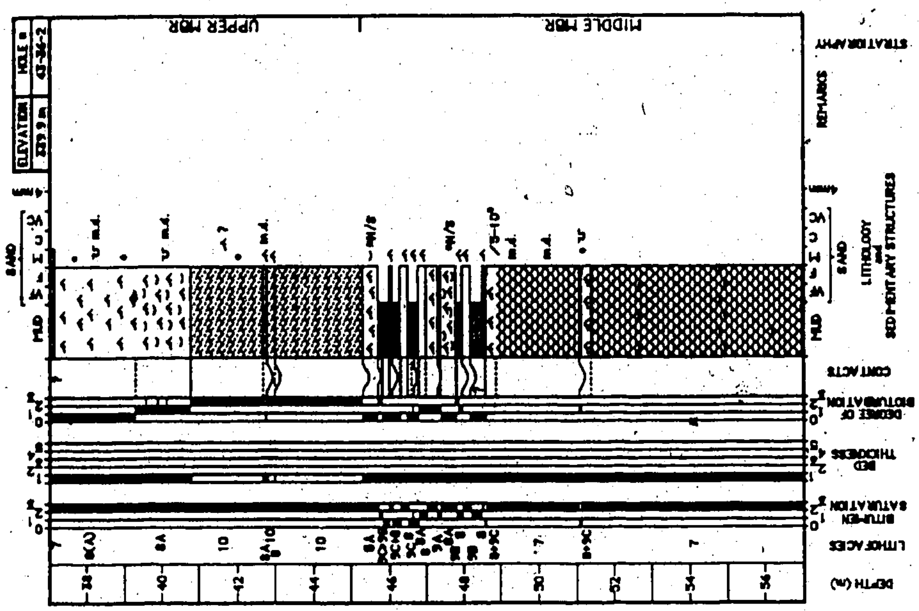
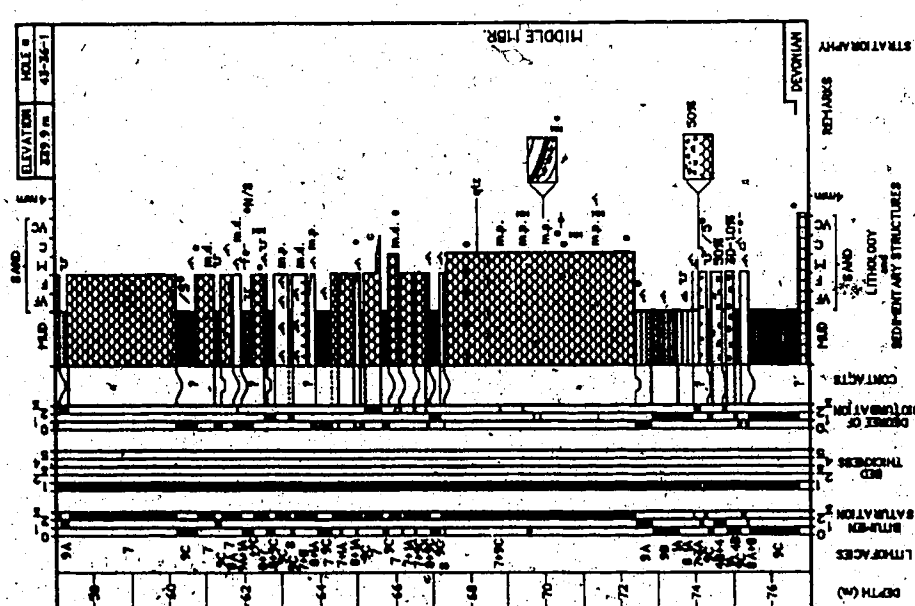
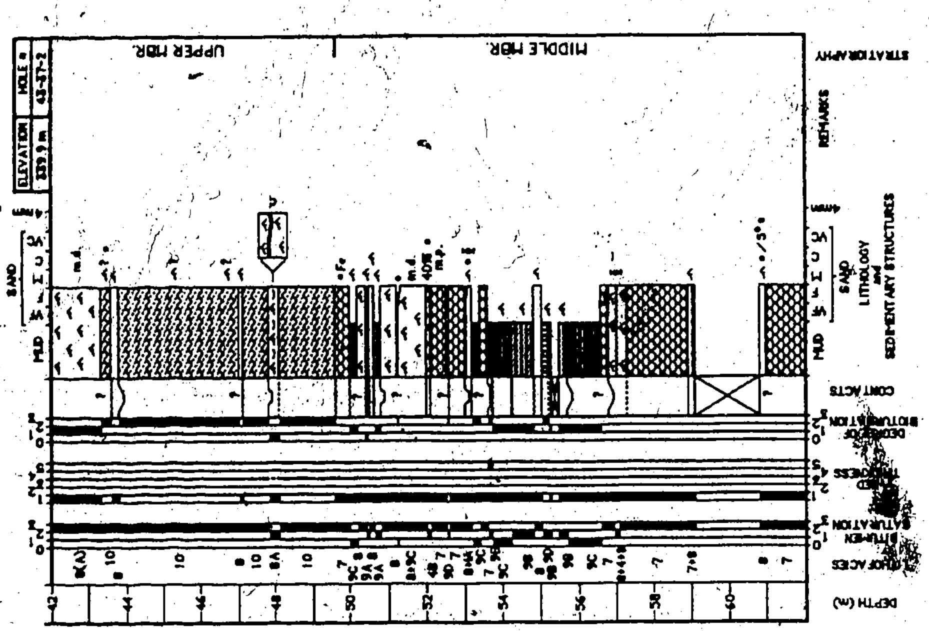
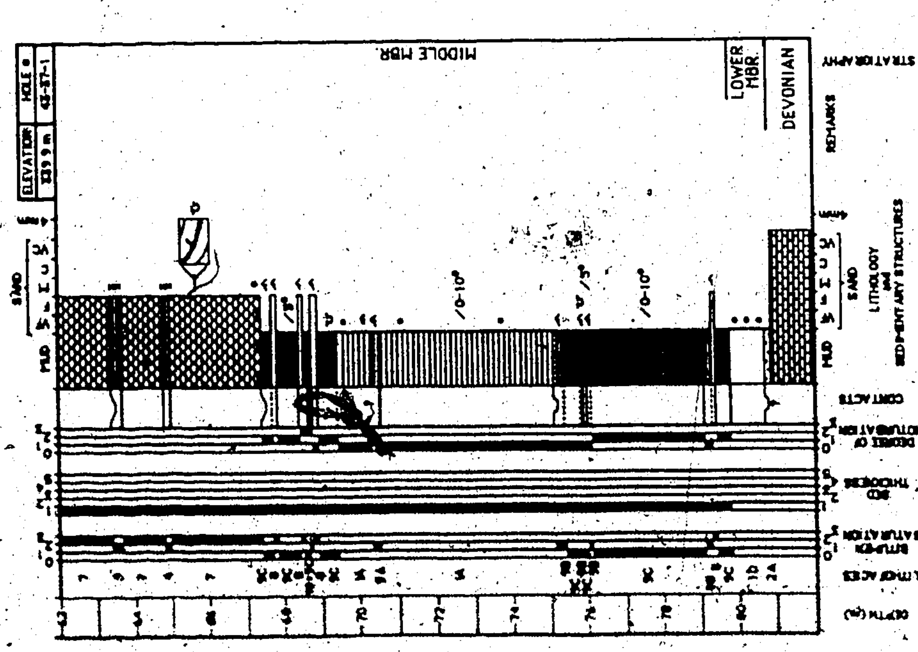
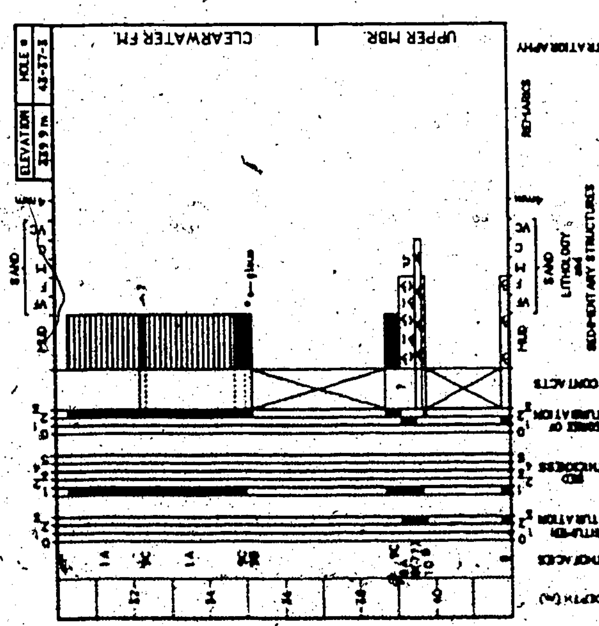
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
239.9 m
HOLE #
43-36-2
UPPER MBR
MIDDLE MBR
STRATIGRAPHY
REMARKS
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION
239.9 m
HOLE #
43-36-1
MIDDLE MBR.
DEVONIAN
STRATIGRAPHY
REMARKS
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)



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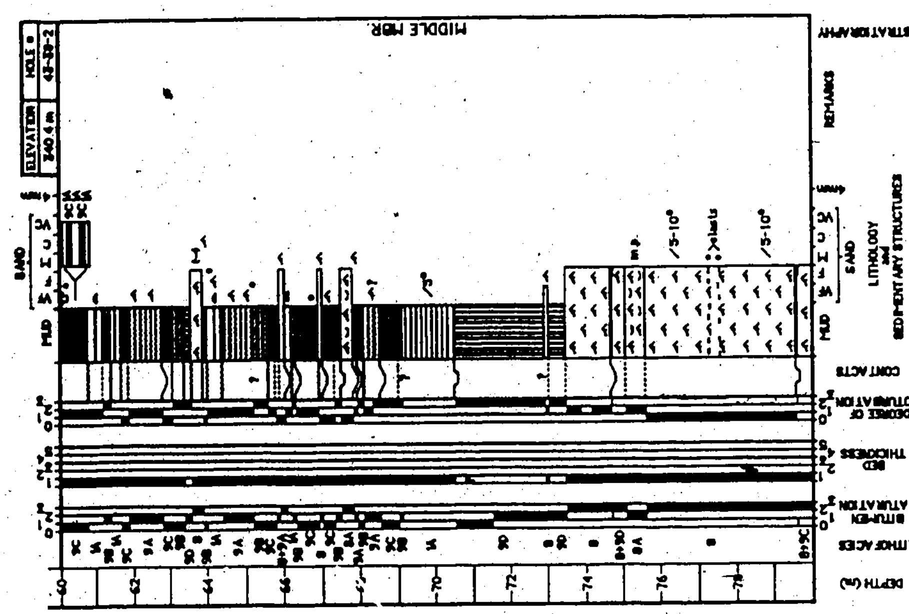
ELEVATION
HOLE #
CONTACTS
DEPTH (m)


MIDDLE MBR.
ELEVATION 340.4 m
HOLE # 43-38-2
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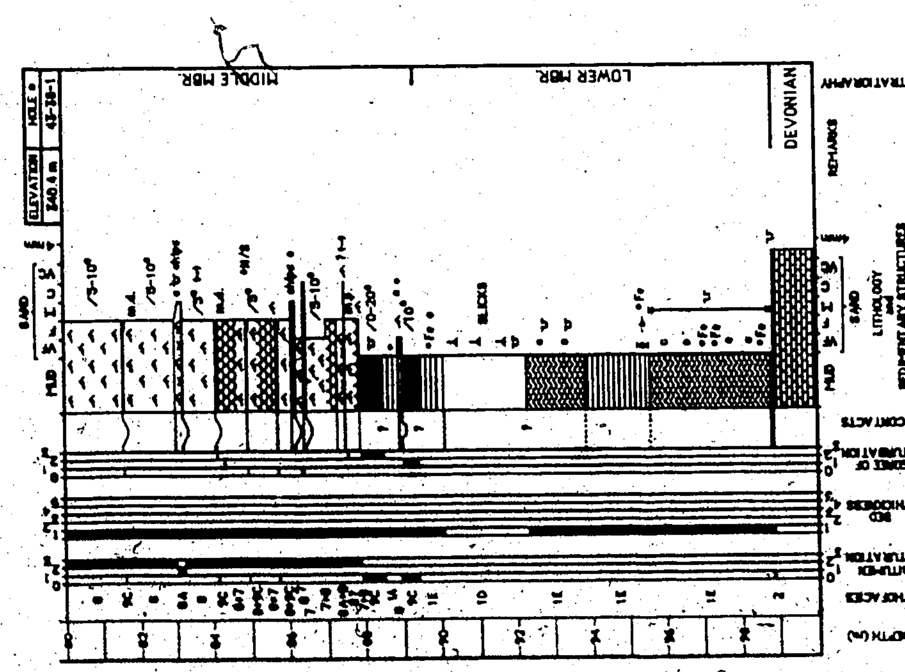
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


MIDDLE MBR.
LOWER MBR.
DEVONIAN
ELEVATION 340.4 m
HOLE # 43-38-1
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BED THICKNESS
BITUMEN SATURATION
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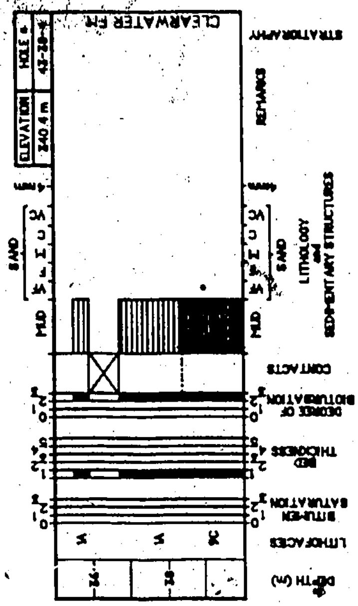
DEPTH (m)


ELEVATION 340.4 m
HOLE
CLEARWATER FM.
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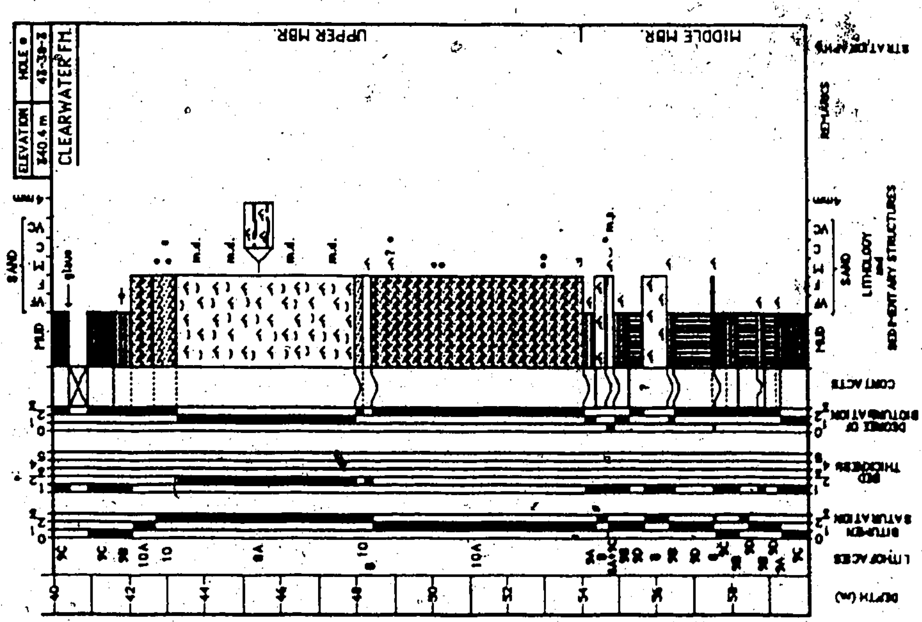
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION 340.4 m
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CLEARWATER FM.
UPPER MBR.
MIDDLE MBR.
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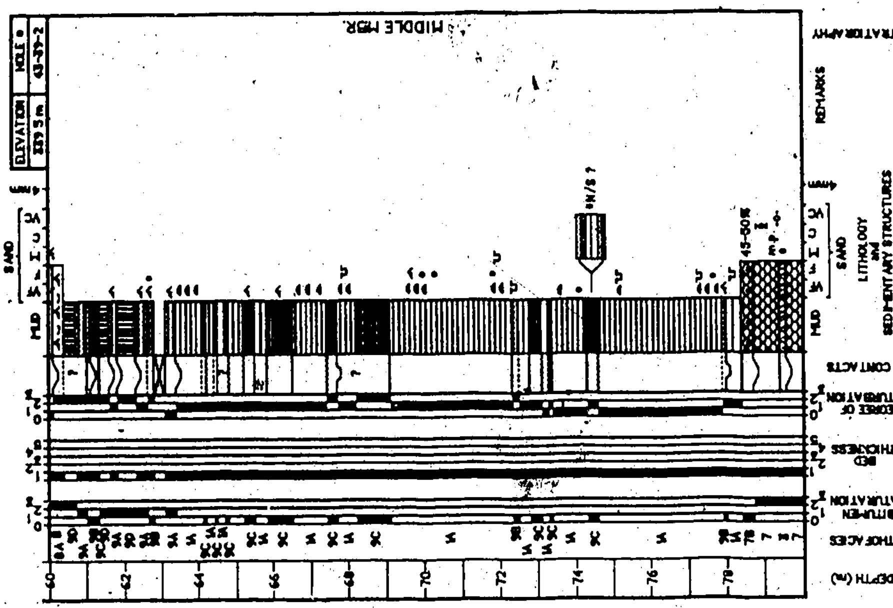
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION 339.5 m
HOLE # 43-89-2
MIDDLE MBR.
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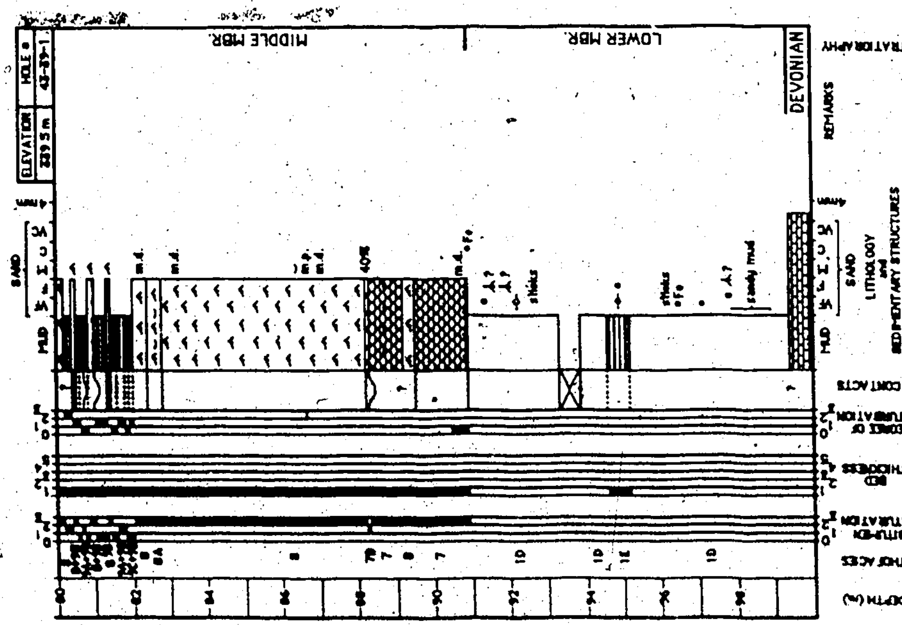
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)


ELEVATION 339.5 m
HOLE # 43-89-1
MIDDLE MBR.
LOWER MBR.
DEVONIAN
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CONTACTS
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BED THICKNESS
BITUMEN SATURATION
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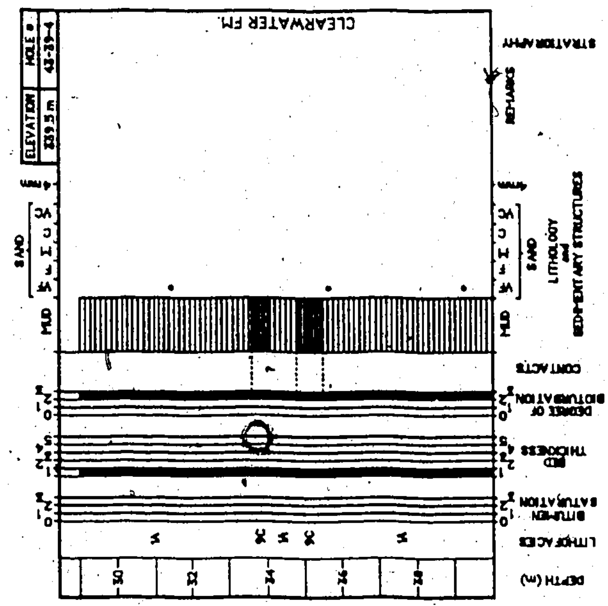
DEPTH (m)


CLEARWATER FM.
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HOLE #
DEPTH (m)
LITHOFACIES
BITUMEN SATURATION
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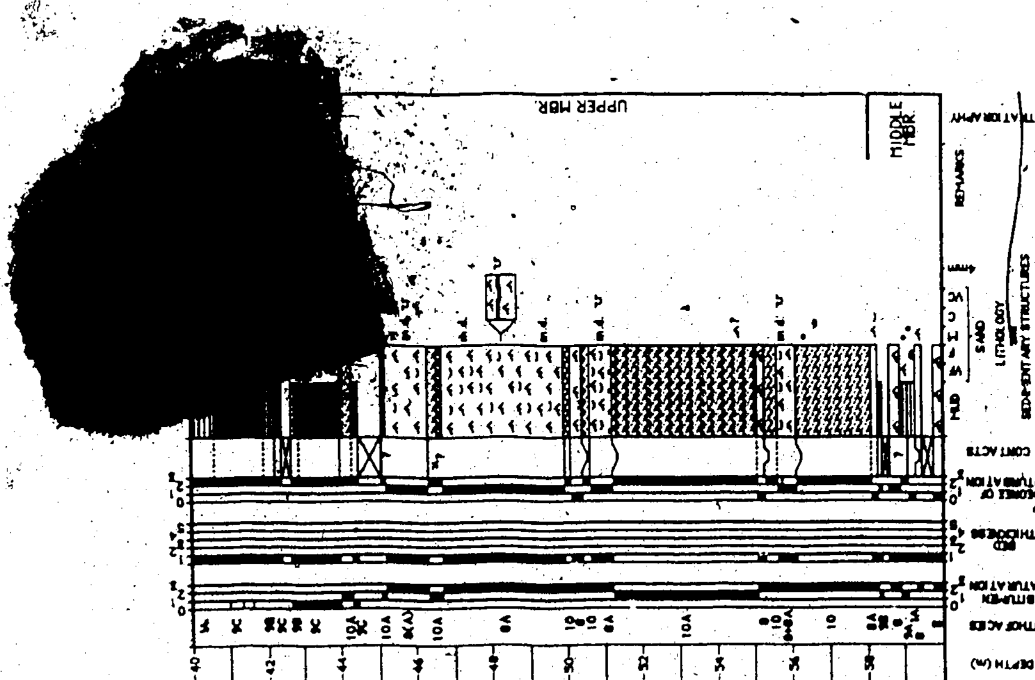
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DEPTH (m)
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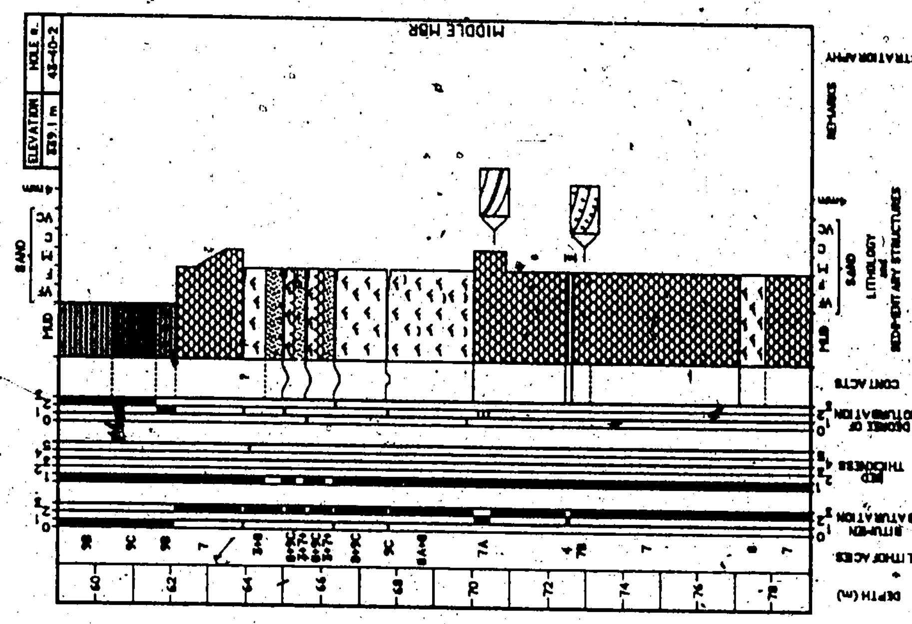
ELEVATION
339.1 m
HOLE #
43-40-2
MIDDLE MBR
STRATIGRAPHY
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LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
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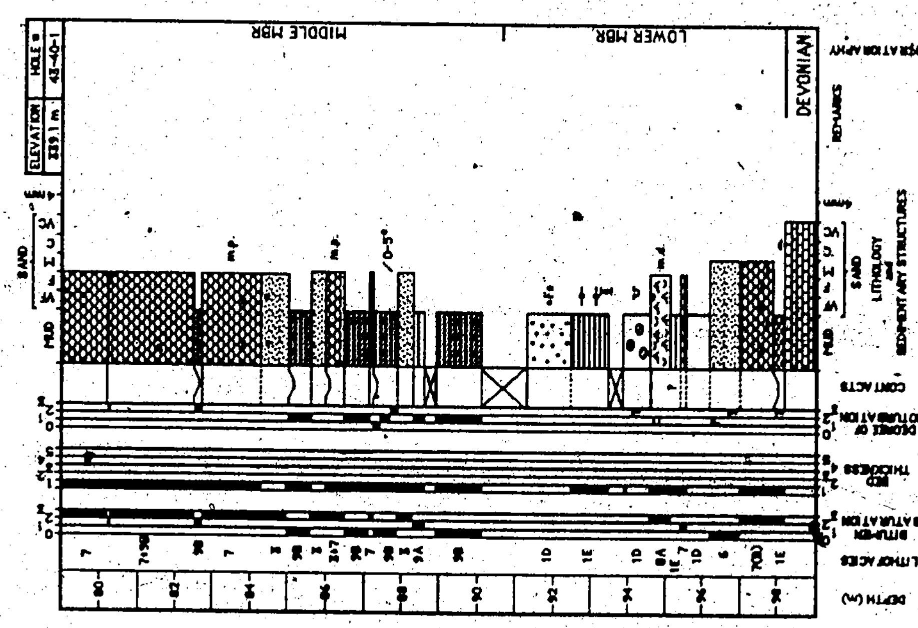
DEPTH (m)


ELEVATION
339.1 m
HOLE #
43-40-1
MIDDLE MBR
LOWER MBR
DEVONIAN
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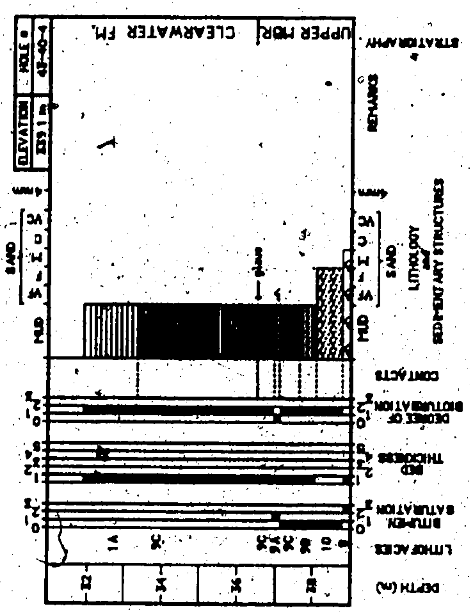
DEPTH (m)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HOLE #
UPPER MBR.
CLEARWATER FM.
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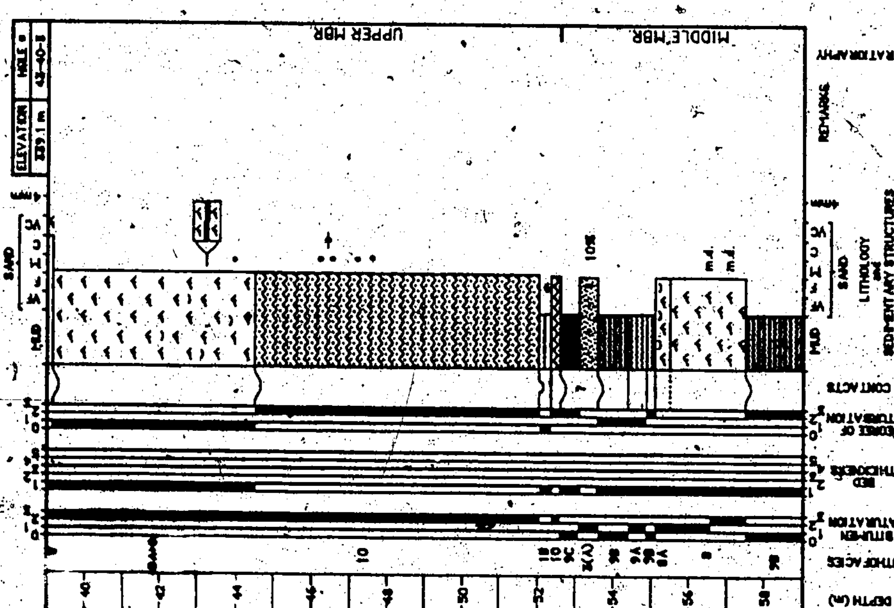
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)
32
34
36
38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HOLE #
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MIDDLE MBR.
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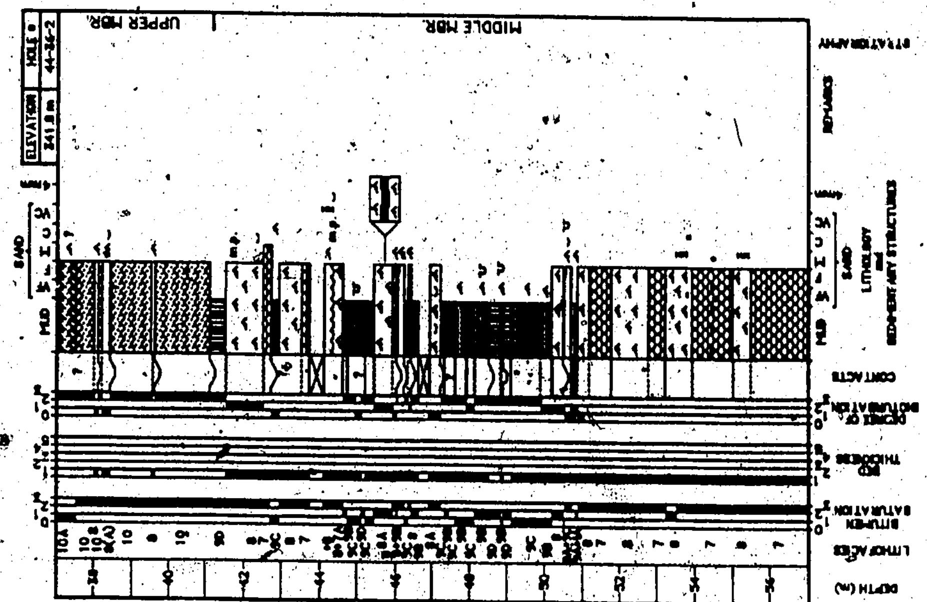
LITHOLOGY and SEDIMENTARY STRUCTURES
CONTACTS
DEGREE OF BIOTURBATION
BED THICKNESS
BITUMEN SATURATION
LITHOFACIES
DEPTH (m)
40
42
44
46
48
50
52
54
56
58


ELEVATION
341.8 m
HOLE #
44-34-2
UPPER MBR.
MIDDLE MBR.
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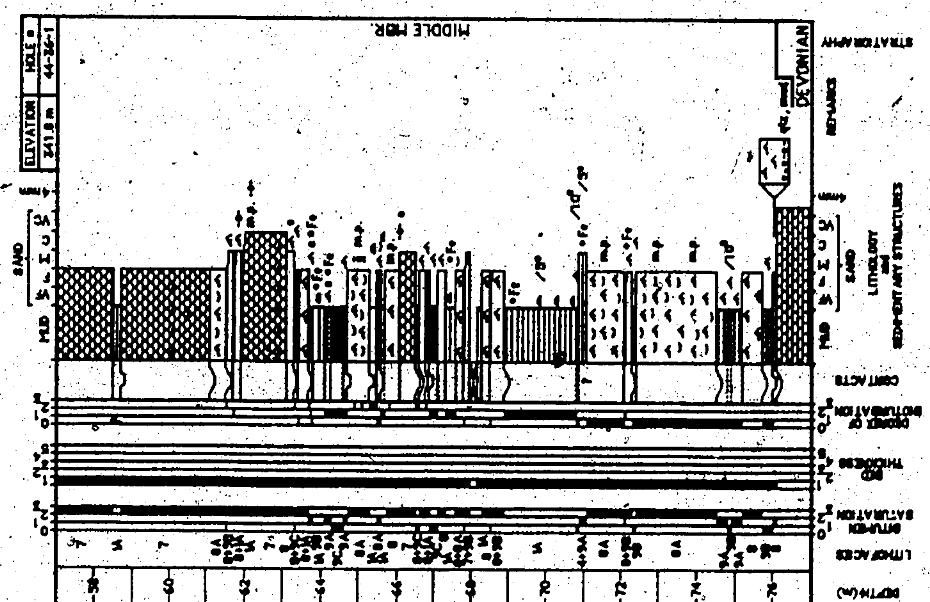
DEPTH (m)


ELEVATION
341.8 m
HOLE #
44-34-1
MIDDLE MBR.
DEVONIAN
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BITUMEN SATURATION
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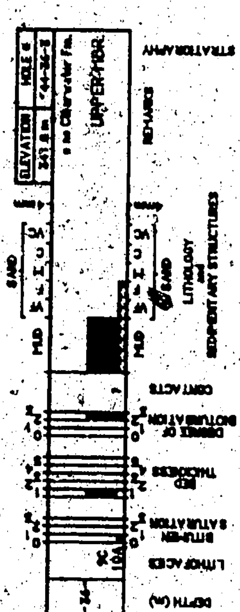
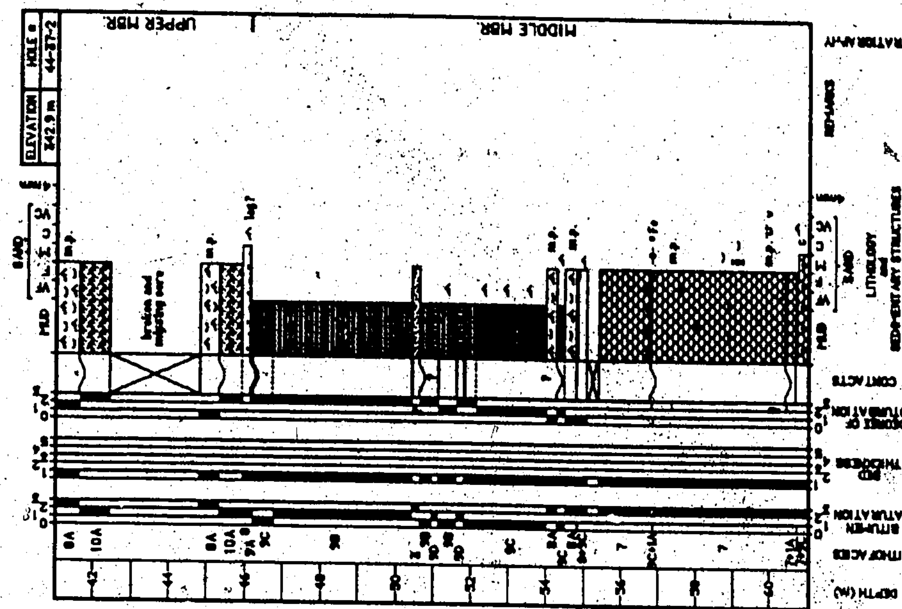
DEPTH (m)




ELEVATION 342.9 m
HOLE # 44-37-2
UPPER MBR.
MIDDLE MBR.
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BITUMEN SATURATION
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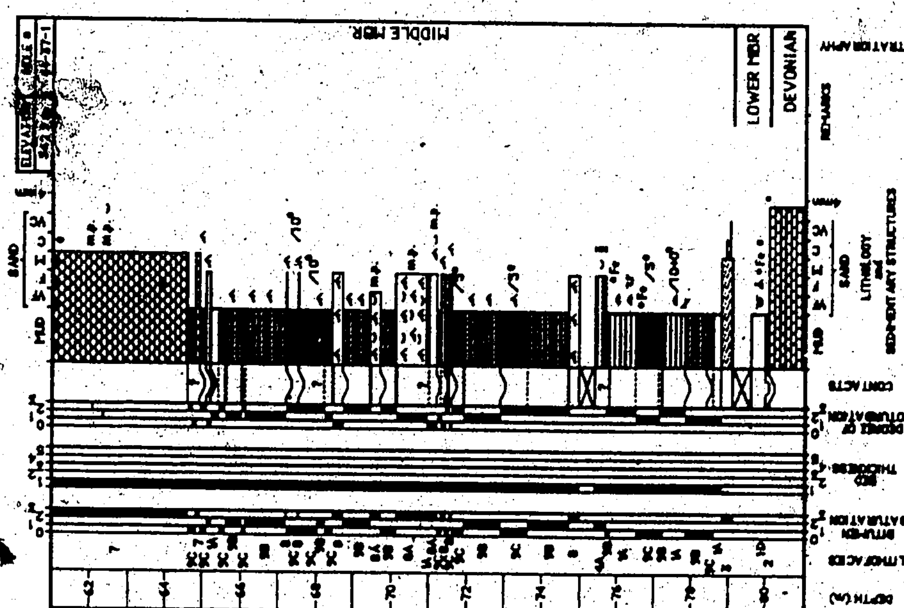
DEPTH (M)


MIDDLE MBR.
LOWER MBR
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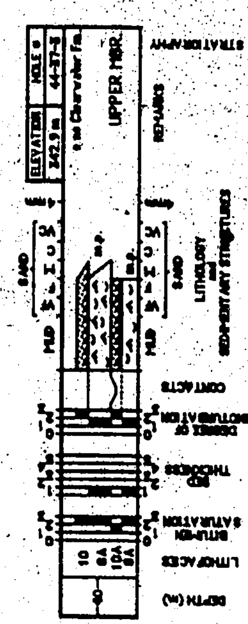
DEPTH (M)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UPPER MBR.
REMARKS
ELEVATION
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and
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CONTACTS
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BED
THICKNESS
BITUMEN
SATURATION
LITHOFACIES
DEPTH (m)