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SEDIMENTOLOGY AND STRATIGRAPHY OF THE
VIKING FORMATION, EUREKA FIELD,
SOUTHWESTERN SASKATCHEWAN

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VIKING FORMATION, EUREKA FIELD,
SOUTHWESTERN SASKATCHEWAN

By

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A Thesis

Submitted to the School of Graduate Studies
in Partial Fulfillment of the Requirements

for the Degree

Master of Science

McMaster University

February, 1987

MASTER OF SCIENCE

McMASTER UNIVERSITY

(Geology)

Hamilton, Ontario

TITLE: Sedimentology and Stratigraphy of the
Viking Formation, Eureka field,
Southwestern Saskatchewan

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Windsor)

SUPERVISOR: Dr. R.G. Walker

NUMBER OF PAGES: 161

ABSIRACI

Four distinct packages can be defined within Viking sediments at Eureka on the basis of detailed core and log correlations. These packages are separated by either erosional surfaces or muddy horizons, which are interpreted as the result of changes of relative sea level.

The bulk of Viking sediments at Eureka occur in packages which "offlap" towards the south. The bulk of these packages is composed of 2 main facies: 1) A pervasively bioturbated muddy glauconitic sandstone facies (facies E), and 2) A moderately bioturbated interbedded sand, silt, and mud facies (facies C, I1, and I2). Facies I1 becomes muddier upwards by an overall decrease in the thickness and relative proportion of silt and sand layers while facies C and I2 clean upwards by an overall increase in the thickness and relative proportion of silt and sand layers. These facies show none of the characteristics commonly associated with tidal sediments such as angle of repose cross-bedding, reactivation surfaces, spring-neap cycles, and tidal bundles. The ichnology and degree of bioturbation suggests that these facies belong to the Cruziana ichnofacies defined by Frey and Pemberton (1984).

Facies E constitutes the main sand bodies at Eureka. It is composed of fine-medium grained totally bioturbated glauconitic sand, and coarsens upwards overall. It becomes muddier southwards and intertongues with facies I. An unconformity surface separates facies E from the underlying facies. Within facies E, log-core markers occur which may or may not represent muddy intervals, and which may or may not be sideritized.

In the context of Viking regional paleogeography (which puts the area north of Eureka in an open marine setting), the migration of an offshore bar and the redistribution of barrier island deposits are suggested as two possible origins for the southwards offlapping packages which occur at Eureka.

ACKNOWLEDGEMENTS

This thesis was funded by NSERC operating and strategic grants to Dr. Roger Walker.

Many people have contributed to this thesis in one way or another. Firstly, I would like to thank Dr. Roger Walker for his incredible patience, guidance, and enthusiasm. I would also like to thank Dr. S.G. Pemberton for aiding in identification of several of the trace fauna. Dr. A.G. Plint provided constructive comments and criticisms.

I would like to thank J.E. Christopher and D.F. Paterson at the Saskatchewan Geological Survey, and all the people at the Subsurface Geological Lab in Regina. Thanks also to Dr. Jim Lorsche, Phil and Anne Browne and family, and Jim Macheachern for their friendship and all their help while I was in Regina.

Special thanks go to Mr. Wallace King and all the people at Canadian Roxy Petroleum Ltd. for their logistical support. Texaco Canada Resources Ltd. provided computer print-outs and base maps. Thanks to GeoLand Consulting for the use of the photocopy machine and office space.

I would like to thank many of my friends at McMaster and in Hamilton for their help, encouragement, and friendship, especially Steve, Ruth, Vern and Gwen, Dave, Bernard, and Fereydoun.

I am extremely indebted to Mike Marshall who drafted most of the figures, helped with the typing, and provided much encouragement. Thanks to Jack Whorwood for his expert advice on reproduction of the photographs and figures.

I would like to thank my friends in Calgary, Mike Ferrari and Neil Mason for taking care of the homestead while Nancy and I were away.

Special thanks to my Mom, Dad, and younger brother Gerry for their love and encouragement, and for putting up with me.

Finally, extra special thanks go to my wife Nancy, who provided endless encouragement, and moral and financial support.

TABLE OF CONTENTS

	PAGE
ABSTRACT	
CHAPTER 1. INTRODUCTION	1
1.1 The Problem	1
1.2 Choice of the Viking Formation	3
1.2.1 Choice of the Eureka Area	3
CHAPTER 2. SETTING AND STRATIGRAPHY	7
2.1 Viking Formation	7
2.1.1 Viking Formation Name	7
2.1.2 Viking Formation Setting	7
2.1.3 Age and Biostratigraphy	8
2.1.4 Lithostratigraphy	10
2.1.5 Previous Work	11
CHAPTER 3. FACIES DESCRIPTIONS	17
3.1 Method	17
3.2 Introduction	19
3.3 Facies Descriptions	21
3.3.1 Facies A	21
3.3.2 Interpretation, Facies A	23
3.3.3 Facies B	23
3.3.4 Interpretation, Facies B	25
3.3.5 Facies C	26

3.3.6	Interpretation, Facies C	30
3.3.7	Facies D	30
3.3.8	Interpretation, Facies D	32
3.3.9	Facies E	33
3.3.10	Interpretation, Facies E	36
3.3.11	Facies F	37
3.3.12	Interpretation, Facies F	38
3.3.13	Facies G1	38
3.3.14	Interpretation, Facies G1	40
3.3.15	Facies G2	41
3.3.16	Interpretation, Facies G2	43
3.3.17	Facies I1	43
3.3.18	Interpretation, Facies I1	46
3.3.19	Facies I2	46
3.3.20	Interpretation, Facies I2	50
3.3.21	Facies N	52
3.3.22	Interpretation, Facies N	54
3.4	Discussion	54
3.4.1	Ichnology	54
3.4.2	The occurrence of glauconitic material and the similarity between facies C, G1/G2, and I1/I2	57
3.4.3	Bentonites	57
3.4.4	Siderites	59
CHAPTER 4. FACIES GEOMETRY		61
4.1	Introduction	61

4.2	Construction of detailed cross-section	63
4.3	Choice of a datum	63
4.4	Subdivision of the Viking into packages	64
4.4.1	Package 1	65
4.4.2	Package 2	65
4.4.3	Package 3	66
4.4.4	Package 4	68
4.4.5	Package 5	68
4.4.6	Package 6	70
4.4.7	Package 7	71
CHAPTER 5. SUMMARY AND DISCUSSION		81
5.1	Summary	81
5.2	Discussion	83
CHAPTER 6. INTERPRETATION		85
6.1	Viking Paleogeography	85
6.1.1	Previous Interpretations of Viking sediments: Position of known shorelines and possible source areas	85
6.1.2	Discussion	88
6.2	Possible interpretations for the genesis of Viking Packages	88
6.2.1	Unconformity near the top of the Viking at Eureka	100
6.2.2	Discussion	101
CHAPTER 7. CONCLUSIONS		103
BIBLIOGRAPHY		104
APPENDIX 1 Additional cored wells		116

LIST OF FIGURES

FIGURE		PAGE
1.1	General Location map of study areas	4
1.2	Location of cores examined and main cross-section	6
2.1	Viking stratigraphy (representative log) at Eureka	9
3.1	Grain size designations used	20
3.2	Facies A	24
3.3	Facies B	24
3.4	Facies C	29
3.5	Facies C	29
3.6	Facies C	31
3.7	Facies D	31
3.8	Facies E	34
3.9	Facies E	34
3.10	Facies E	35
3.11	Facies E	35
3.12	Facies F	39
3.13	Facies G1	39
3.14	Facies G2	42

3.15	Facies G2	42
3.16	Facies I1	49
3.17	Facies I2	49
3.18	Facies E/ Facies I2	51
3.19	Facies N	51
3.20	Facies N	53
4.1	Simplified facies geometry and location of packages	62
4.2	Summary diagram of facies geometry (from logs and core) at Eureka	159
4.3	Detailed core cross-section	160
4.4	Detailed log cross-section	161
4.5	Facies C, D (package 2), E (package 3), G1 (package 6), and G2 (package 7)	72
4.6	Facies A (package 1), C (package 2), and E (package 3)	73
4.7	Facies E, I1 (package 3), and I2 (package 4)	74
4.8	Facies I2 (package 4), G (package 6), and A (package 7)	75
4.9	Facies I1 (package 3), I2 (package 4), and E (package 5)	76
4.10	Facies E (package 5), N, G1 (package 6)	77
4.11	Facies A (package 1), I2 (package 4), and E (package 5)	78
4.12	Facies E, F, I (package 5)	79

4.13	Facies E, F (package 5), G1 (package 6), G2, A, (package 7)	80
6.1	Viking paleogeography	86
6.2	Possible interpretations for the genesis of Viking Packages	89

LIST OF TABLES

TABLE		PAGE
3.1	Facies occurrence of ichnogenera	56
3.2	Bentonites: Major and Trace element chemistry	58

CHAPTER 1: INTRODUCTION

1.1 THE PROBLEM

Numerous examples of long linear shallow marine sand bodies have been described from the Cretaceous Interior Seaway of western North America. These sand bodies are similar in scale and morphology to some of the "linear sand ridges" found on modern storm and tide dominated shelves. Cross-comparison of stratigraphic and sedimentological characteristics between modern ridges and these possible Cretaceous analogues has brought into focus a major problem regarding linear sand ridges, namely, do these sand ridges originate out on the shelf, or do they originate as nearshore or shoreface attached sand bodies which are subsequently transgressed?

Swift (1975) has previously suggested that "linear sand ridges" may have formed as nearshore or shoreface sand ridges which were subsequently transgressed during the Holocene rise of sea level. Similarly, Swift and Field (1981) suggest that the storm dominated ridges of the Delaware-Maryland inner shelf represent shoreface formed ridges which have undergone systematic morphologic changes (relative to distance from shore) during the course of the Holocene transgression. However, regarding the ancient examples from the Cretaceous Interior Seaway, Walker (1984)

has pointed out that "where there is evidence of contemporaneous shorelines, the sand bodies appear to have formed many tens of kilometers offshore." Swift's shoreface attached ridges appear to be rooted in an unconformable transgressive surface (probably with a lag), whereas many Cretaceous sand bodies are described as "rooted" in offshore muds, which "grade up into" the sand body, and therefore are unlikely to be transgressive in origin.

The formation of these sand ridges out on the shelf tens of kilometers from shore requires the transport of large volumes of sand across the shoreface, a process which is thought to be related exclusively to infrequent (on a daily time scale), largely storm-generated currents. Present workers generally invoke two possible mechanisms for moving sediment across the shoreface out onto the shelf.

1) Storm generated wind-forced-currents, which result in geostrophic flows, and incremental transport of sediment mostly parallel to shore, but with some component perpendicular to shore.

2) Turbidity currents, a type of density current (where the increased density of the flow is due to suspended sediment) which may be generated at or near the shoreface by storm waves or other processes, and which subsequently transport sediment offshore during a single short-lived event.

In addition to moving sediment from the shoreface to offshore areas, another problem is the "focussing" of this sediment into the long narrow features which we see preserved in the geologic record, and the development of coarsening-upward sequences within these ridges.

Alternatively, if the linear sand bodies originate as shoreface attached or nearshore ridges described by Swift, the problem of their isolation on the shelf is more concerned with the record of sea level fluctuations.

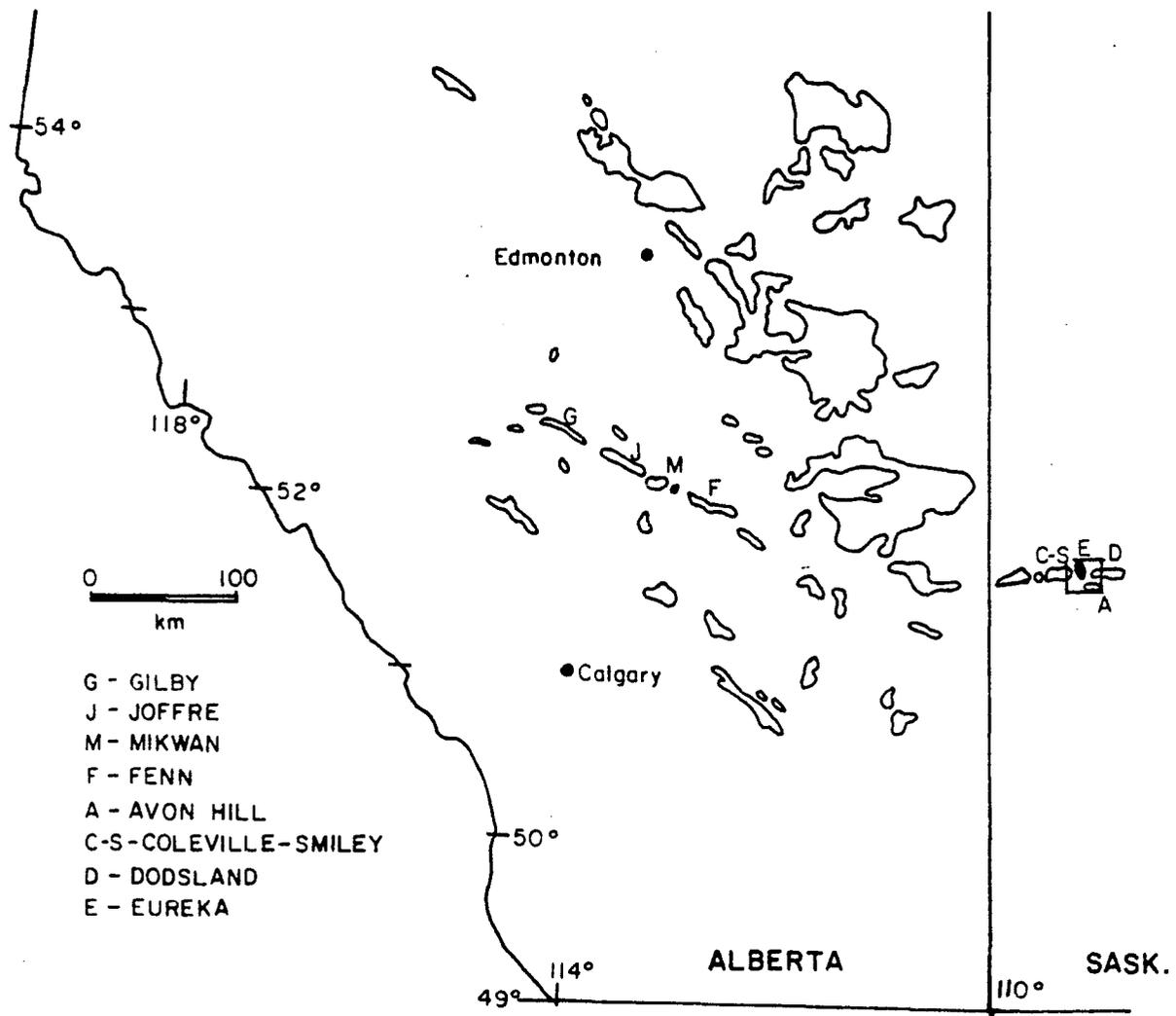
1.2 CHOICE OF THE VIKING FORMATION

The Viking Formation has generally been interpreted as "shallow marine". The interpretation of transport processes and depositional environments for the Viking are varied. Also, as discussed in section 1.1 the origin of these shallow marine sand bodies is in question. The wealth of subsurface geological data generated by exploration for petroleum resources within the Western Canadian sedimentary basin provides a good opportunity to study the stratigraphy and sedimentology of ancient shallow marine sand bodies, such as the Viking Formation. Also this study will provide another example to be added to the catalogue of examples which will be used to generate a facies model for shallow marine sand bodies.

1.2.1 CHOICE OF THE EUREKA AREA

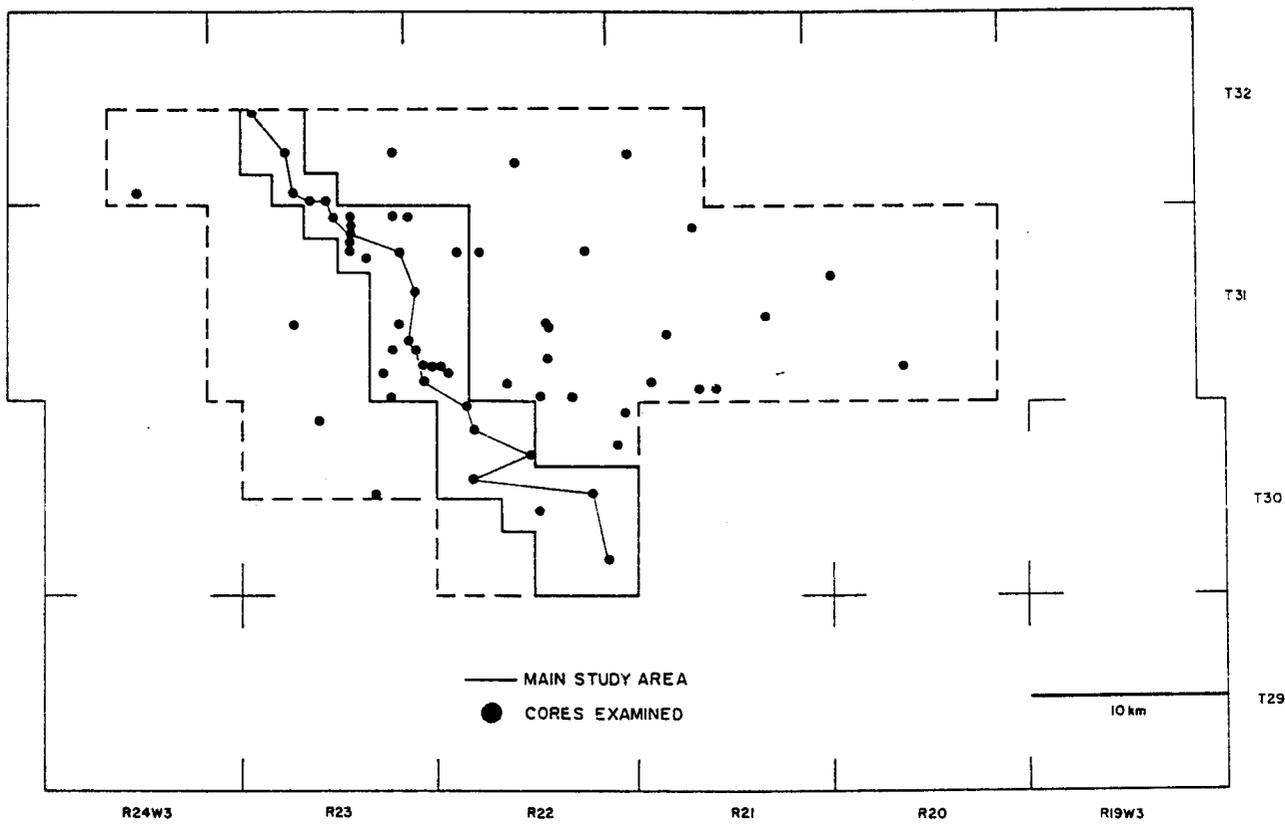
The Eureka field which produces from the Viking Formation is located in southwestern Saskatchewan (Figure

Figure 1.1. Location of the study area, at Eureka, Saskatchewan, and the distribution of Viking sand bodies in Alberta and Saskatchewan as delineated from E.R.C.B. production data. Most of these sand bodies show a distinct northwest-southeast linearity.



1.1). The previous interpretation of a series of long linear sandstone bodies deposited in a "relatively far from shore marine environment" (Evans, 1970) which are similar in dimension to modern day shelf sandstone bodies makes this area ideally suited to study. Also from a preliminary investigation using computer printouts, well logs, and well data cards, most of the wells with continuous core through the entire Viking Formation interval occur within the Coleville-Smiley, Eureka, and Dodsland producing fields. This thesis deals primarily with the stratigraphy of the Eureka field, however the discussion of wells outside of the Eureka field proper shows that the stratigraphy can be extrapolated at least partly to the Coleville-Smiley and Dodsland producing areas (Figure 1.2). All well locations referred to in the text are west of the third meridian.

Figure 1.2. Location of cores examined within (solid line) and outside (dashed line) the Eureka area, and the location of the cross-section discussed in chapter 4.



CHAPTER 2: SETTING AND STRATIGRAPHY

2.1 THE VIKING FORMATION

2.1.1 VIKING FORMATION NAME

The Viking sandstone was named by S.E. Slipper in 1918 when he referred to the "Viking gas sand", the upper gas producing horizon of the Colorado Group in the Viking-Kinsella field, located near the town of Viking in east-central Alberta. The sand thus designated occurs about 140 feet above the base of the Colorado Group at Viking-Kinsella.

2.1.2 VIKING FORMATION SETTING

The Viking Formation was deposited in a shallow Epeiric sea which covered much of the North American craton during the Cretaceous. This sea was bounded on the west by the cordilleran orogen and on the east by the emergent centre of the craton. The Viking Formation extends from central Alberta to southeastern and east-central Saskatchewan. The Formation has a maximum thickness of about 75 meters in southern Alberta, and is roughly 40 meters thick in southwestern Saskatchewan. Regionally the Viking Formation thins northeastwards and eastwards. The northern limit of the Viking in Saskatchewan runs roughly northwest-southeast from township 51 at the

Alberta-Saskatchewan border to about Township 36 approximately 40km directly east of Saskatoon.

The Viking Formation sediments of southwestern Saskatchewan constitute part of the undeformed Lower Cretaceous sediments of the Central Plains. Thicker Lower Colorado sediments in southeastern Alberta suggest that the Williston Basin was actively subsiding when these sediments were deposited (Glaister, 1959). This subsidence may have also affected the thickness of Lower Colorado sediments in southwestern Saskatchewan.

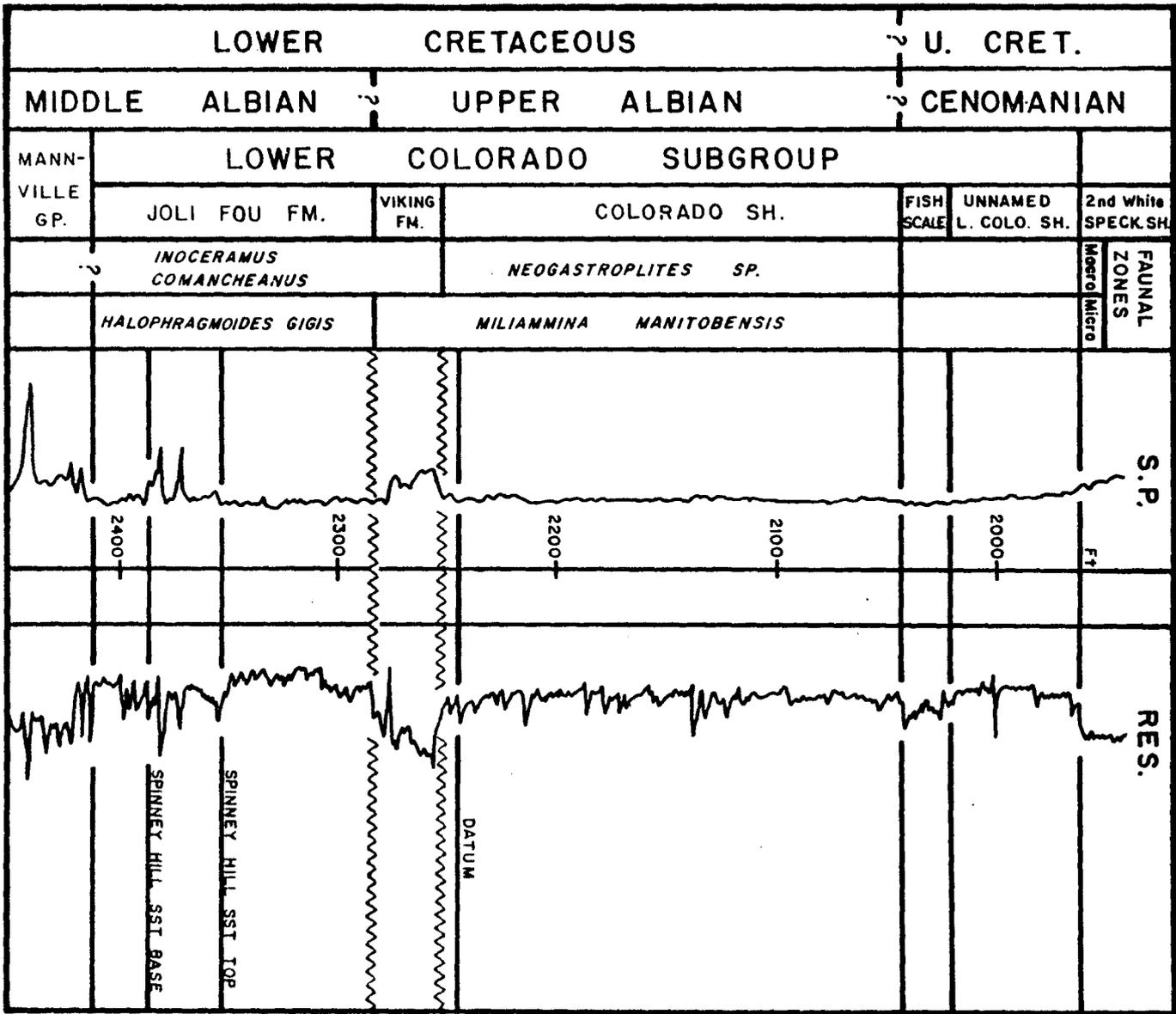
Tooth and Kavanagh (1984) have suggested that the paleogeographically high Cordilleran region was the source for most of the sediments supplied to the basin during Viking Formation time as the formation thickens towards this westerly source. Jones (1961) has also suggested non-marine strata of "probable equivalent age" on the Sweetgrass Arch as a possible sediment source.

2.1.3 AGE AND BIOSTRATIGRAPHY

Stelck (1958) has placed the Viking Formation of the Alberta plains at the base of the Upper Albian stage on the basis of microfossil evidence (Figure 2.1).

Potassium-argon dating of bentonites within the formation gives a radiometric age of approximately 100 million years (Tizzard and Lerbekmo, 1975).

Figure 2.1. Stratigraphic context of the Viking Formation at Eureka, and the location of the datum. The well location is Golden Eagle Refining Co. Inc., G.E.R. Worldwide Eureka, 9-19-31-22 W3.



2.1.4 LITHOSTRATIGRAPHY

The Early Cretaceous Viking Formation is underlain by the Joli Fou shales and overlain by shales of the Colorado Group (Figure 2.1). Toothe et al. (1984) have stated that the Colorado shale conformably overlies the Viking, but the contact with the underlying Viking is unconformable. Both Simpson (1982) and Jones (1961) have noted that the Viking Formation thins in a general northeasterly direction in southern Saskatchewan.

The Viking Formation of central Alberta and Saskatchewan is equivalent to the Newcastle and Muddy Formations of Wyoming and Montana, the Bow Island Formation of southern Alberta, the Pelican Formation of northern Alberta and in part the Paddy Formation of northwestern Alberta.

The Viking was initially classified as a member of the Colorado Group (Reasoner and Hunt, 1954; Gammel, 1955), but was later reclassified to formation status (Magditch, 1955; Stelck, 1958; Jones, 1961). The Colorado Group is divided into an upper and lower part, the division being marked by the base of the widespread Second White Speckled Shale. In Saskatchewan, the Colorado Group overlies sandstones of the Mannville-Blairmore succession (Aptian-Albian), and is followed by the sandstones and siltstones of the Milk River Formation, and equivalent mudstones of the Lea Park Formation (Santonian-Campanian) of the Montana Group.

2.1.5 PREVIOUS WORK

The wealth of subsurface geological data generated by exploration for petroleum resources within the Western Canadian Sedimentary Basin provides an excellent opportunity to study the stratigraphy and sedimentology of ancient shallow marine sand bodies. Two hydrocarbon producing horizons in particular, the Cardium and Viking Formations, have been studied relatively extensively in Alberta, by government, industry, and academia. Previously published studies of the Cardium Formation include those of Berven (1966), Swagor (1975), Griffith (1981), Krause (1982 and 1983), Walker (1983a,b,c), Krause and Nelson (1984), Bergman and Walker (1986, and in press), and Flint et al. (1986). Some of the Viking Formation studies in Alberta and Saskatchewan include those of Beach (1955), Roessingh (1959), Jones (1961), Evans (1970), Tizzard and Lerbekmo (1975), Koldijk (1976), Simpson (1978, 1981, 1982), Amajor and Lerbekmo (1980), Reinson et al. (1983), Beaumont (1984), and Amajor (1986).

Like the Cardium Formation, the interpretation of sediment transport processes and depositional environments for the Viking are varied. In this section, I will briefly review some of these interpretations.

In a 1950 publication of experimental and field observations, Keunen and Migliorini introduced the concept of turbidity currents as a cause of graded bedding.

Shortly thereafter, Beach (1955) published the first "turbidite" interpretation of Western Canadian Basin sediments in a paper entitled "Cardium a turbidity current deposit." In this paper Beach inferred that Viking Formation sediments were probably distributed by turbidity currents also. However DeWiel (1956) challenged Beach's interpretation and inferred that Viking Sea depths and particularly bottom slopes would not have been sufficient to sustain a turbidity current once it was initiated. In a reply to DeWiel, Beach (1956) proposed that turbidity currents could account for the "unusual sequence of grain size", conglomerate sized material, and the close stratigraphic association of sand with bentonites (corresponding to concurrent source area uplift and associated volcanic activity) observed in Viking sediments over much of Alberta and Saskatchewan. Also Roessingh (1959) in a study of Viking sediments of the South Alberta plains, appears to favour a turbidity current hypothesis, although he does not state this explicitly.

In contrast to the process oriented (turbidity current) interpretations discussed above, Stelck (1958) and Tizzard and Lerbekmo (1975) have proposed more morphologically oriented interpretations, choosing to call Viking sediment accumulations "offshore bar deposits". Stelck has suggested that the shore and offshore bars of the Viking, Pelican, and Bow Island Formations developed

along the borders of the "early Joli-Fou" seaway. In a comparative study with recent Galveston Island sediments, Tizzard and Lerbekmo (1975) interpreted the "Lower" and "Upper" Viking sands of the Suffield area of Alberta as a "northwest trending barrier bar", and "an eastward prograding barrier bar" respectively.

Aside from these morphologically oriented interpretations by Stelck, and Tizzard and Lerbekmo, the majority of interpretations of Viking sediments relate to the different types of currents which move sediments on modern shelves. Following the early turbidity current hypotheses, the evolution of ideas on Viking depositional processes closely parallels both the evolution of ideas traced by Walker (1983a) for the Cardium Formation, and the evolution of ideas on shelf sediment transport processes in general.

Tidal settings and tidal currents are the focus of three separate papers published between 1960 and 1975, which deal specifically with Viking sediments in Saskatchewan. In a study of Viking sediments in southwest Saskatchewan, Jones (1961) suggested "probable deposition in a neritic or littoral environment". In a now classic paper, Evans (1970) interpreted the "unusual west-southwest-east-northeast trend" of the individual "members" as resulting from "east flowing tidal currents in a relatively far from shore marine environment." In a

more regional study of the Colorado Group in Saskatchewan, Simpson (1975) described the Viking sand bodies as "nearshore sands" and "tidal sand ridges" which rest on a thin reworked relict sediment layer.

Since 1975, storm processes as well as storm and tidal processes combined, have been a common interpretation for Viking sediments in the Western Canadian Sedimentary Basin. In a study of the Gilby Viking "B" pool in southwest Alberta, Koldijk (1976) interpreted deposition of Viking sediments in an "offshore setting" with transport by "intermittent" storm currents. Beaumont (1984) suggests "episodic storm generated currents possibly augmented by tidal currents" for the Viking deposits of central Alberta. Simpson (1982) invokes "storm surge augmented tidal currents" as the main mechanisms responsible for sediment transport, which form "large scale sand ridges" and "tidal channel deposits" in Viking sediments in Saskatchewan. Another recently published "combined process" interpretation is that of Reinson et al. (1983) who suggest that sediments of the Joffre and Caroline fields in Alberta were emplaced by density currents, with subsequent modification by tidal currents.

Another idea which has been discussed to varying degrees in some of the above mentioned interpretations is the relationship between sea-level fluctuations and the stratigraphic position of Viking sediment accumulations.

DeWiel (1956) has suggested that Viking sediments represent a "regressive stage" of sea level where sediment was "distributed by longshore currents in front of a shifting strandline." Glaister (1959) suggested a similar interpretation, namely that the Bow Island (Viking aged equivalent) was deposited during slow regressions, followed by rapid transgressions. More recently, Simpson (1982) stated that Viking deposition occurred "mostly during regression on the western shelf." In a more integrated interpretation, Beaumont (1984) explained the retrogradational character of individual "sand sheets" (each of which contains several linear sand bodies) as having been formed during a "transgression punctuated by minor regressions or stillstands" during which shoreline sediment was reworked.

In summary, Cardium and Viking sedimentary deposits have been attributed to varied depositional environments and/or processes. In a north-northwest-southsoutheast trending cross-section through the Eureka field, Evans (1970, figure 3, p. 472-473) illustrates six imbricate "members" defined on the basis of detailed well log correlations. However, Evans does not provide detailed facies descriptions of these six "members" and only two of 16 wells (11-9-32-23W3 and 2-16-30-22W3) in his cross-section are cored. There are numerous cored wells in close proximity to the wells used in Evans' original

cross-section, and it was decided to construct a cross-section parallel to Evans' original line, but using many more cored wells. In this way, the facies geometry defined by core observations could be checked against the "imbricate" pattern as defined by Evans.

CHAPTER 3. FACIES DESCRIPTIONS

3.1 METHOD

The objective of this study is to delineate, describe, and document the stratigraphic relationships between the individual sedimentary facies within the Viking Formation of the Eureka area of southwest Saskatchewan. A preliminary investigation of townships 24-34, ranges 15-29 W3 in May 1984 using computer printouts, well logs, and well data cards allowed the identification of 87 wells (of the approximately 430 cored wells in the area at this time) with continuous core through the entire Viking Formation interval. Most of these 87 wells occur within the Dodsland, Eureka, Coleville-Smiley, and Smiley-Dewar producing areas, or roughly speaking townships 30-32, ranges 18-25 W3. The following is a brief description of the core examining procedure used.

After checking the order of the core boxes on the core examining table, pertinent information such as well name, location, number of cores cut, number of boxes in each core, and the cored interval were recorded. Next the core was thoroughly washed, and the total length of core in the boxes and the empty space in each box was measured and recorded. The recovery, expressed as the measured length of core, as a percentage of the cored interval listed on

the box, was then recorded. The core was then examined for any useful "marker" horizons (primarily bentonitic and sideritic zones) and lithologic contacts which might be used to correlate the cored interval with the log response, and adjust the cored depths to the well log to obtain the actual cored interval. The distances between these marker horizons were then measured and recorded. Marker beds such as the bentonites and siderite zones were easily tied into gamma, sonic, and resistivity logs, while the author attempted to correlate core lithology and facies unit contacts to all logs, especially the gamma-ray. This step was necessary to facilitate the accurate correlation of lithofacies units to uncored wells, and to wells with only one type of geophysical well log. Every effort was made to insure accurate depth adjustment of core to the log response. Following this step, the core was subdivided into distinct facies units on the basis of lithological and biological characteristics. Each facies unit was then measured, studied, and described. The description of each unit included the gross lithology, colour, bed thickness, physical sedimentary structures, relative trace fossil abundance diversity and size, grain size, sorting and roundness, accessory constituents, unusual sedimentary features, and vertical changes or trends upwards through the unit in any of the above mentioned characteristics. Grain sizes were taken using a 20X hand lense, a binocular

microscope (when available), and an CANSTRAT plastic grain size card. The diagram in Figure 3.1 shows the relationship between the letter designation of grain size used in the facies descriptions and the corresponding phi and micron grain size values. In the facies descriptions, a range in grain size is designated with a dash i.e. vfl-fl, and means the grain size ranges between and includes the sizes at both ends of that range. Any grain size designated with a slash i.e. vfl/fl means that the grain sizes in the sample are neither vfl nor fl, but fall between these two sizes. Following the description, colour and black and white photographs were taken of each facies unit, and any extraordinary features which were noted. On the basis of these examinations, I was able to identify eleven distinct facies units within the study area. Chapter three is a description of the sedimentary characteristics of each of these units.

3.2 INTRODUCTION

Gressly used the term facies to imply the sum total of the lithological and paleontological aspects of a stratigraphic unit (Walker, 1984). The scale of facies subdivision depends on the objective of the study, and the abundance of physical and biological structures in the rock. An understanding of the lateral and vertical facies associations is the key to environmental interpretation of a stratigraphic unit. In this study, the various facies

Figure 3.1. Relationship between the letter designation of grain size used in the facies descriptions, and the corresponding micron and phi grain size values.

$$\underline{vcU = 1410 - 2000\mu = -0.5 - -1.0\emptyset}$$

$$\underline{vcL = 1000 - 1410\mu = 0.0 - -0.5\emptyset}$$

$$\underline{cU = 710 - 1000\mu = 0.5 - 0.0\emptyset}$$

$$\underline{cL = 500 - 710\mu = 1.0 - 0.5\emptyset}$$

$$\underline{mU = 350 - 500\mu = 1.5 - 1.0\emptyset}$$

$$\underline{mL = 250 - 350\mu = 2.0 - 1.5\emptyset}$$

$$\underline{fU = 177 - 250\mu = 2.5 - 2.0\emptyset}$$

$$\underline{fL = 125 - 177\mu = 3.0 - 2.5\emptyset}$$

$$\underline{vfU = 88 - 125\mu = 3.5 - 3.0\emptyset}$$

$$\underline{vfL = 62 - 88\mu = 4.0 - 3.5\emptyset}$$

are defined on the basis of lithology, sedimentary structures, trace fossils and degree of bioturbation present in the rocks. As specific facies within several of the cores logged were missing significant thicknesses of core, where possible, the facies thicknesses are taken from the logs in order to improve data accuracy. The term "glaucconitic" is used to describe the occurrence of any glauconitic material observed, since the specific mineralogy of this glauconitic material has not been determined. In the description of sedimentary structures observed in each facies, unless otherwise noted, the lower and upper contacts of beds are not preserved in core.

3.3 FACIES DESCRIPTIONS

3.3.1 FACIES A: Silty bentonitic mudstone, Figure 3.2.

This facies consists of silty bentonitic mudstone with a minimum thickness of 14.2 m. Generally, this facies is lightly to moderately disturbed by organisms, and may have a "washed out" appearance presumably resulting from the preferential disaggregation of bioturbated portions during coring. In places this facies has a "blocky" or "massive" appearance, with only faint lamination observable. The variable appearance of this facies in core can likely be attributed to variations in three properties;

- a) silt content
- b) bentonite content or soapiness
- c) degree of bioturbation

Silt content (estimated from colour and grittiness) is estimated to vary between 5 and 25 percent. The variation in soapiness to the touch is here considered a function of the bentonitic (?) clay content, and ranges from only very slightly soapy, to extremely soapy or greasy feeling, in which case the core swells dramatically and instantly when wetted. This facies contains extremely rare siltstone and fine sandstone layers up to 2 cm in thickness. These layers mostly have sharp scoured bases and sharp or bioturbated tops, but in places are sharp based graded beds. The thinner layers generally show a very gently undulating subparallel internal stratification, or are strongly bioturbated. The thicker layers (1-2 cm) commonly contain cosets (several mm in thickness) of subparallel, gently undulating laminae where the laminae of each set are truncated by the base of the overlying set. One or two occurrences of the ichnogenus Terebellina were noted in several of the cores. These were basically oval in shape, but ranged in dimensions from 3 cm long by 2 mm in width to 5 mm in length by 2 mm in width. Straight or slightly curved trails of silt or fine sand (one grain layer thick, and 2-4 mm in width) interpreted as Planolites, were noted on parting planes within the mudstone in a few of the cores. Pyrite(?) concretions were observed in several of the cores. Green mineralisation (chlorite ?) and yellow powdery mineralisation (sulfur ?) occurred on a few parting

planes. Where preserved, the contact with the overlying facies is sharp. The well at 11-28-31-22 contains the greatest cored thickness (14.2 m) of this facies within the study area.

3.3.2 INTERPRETATION: FACIES A

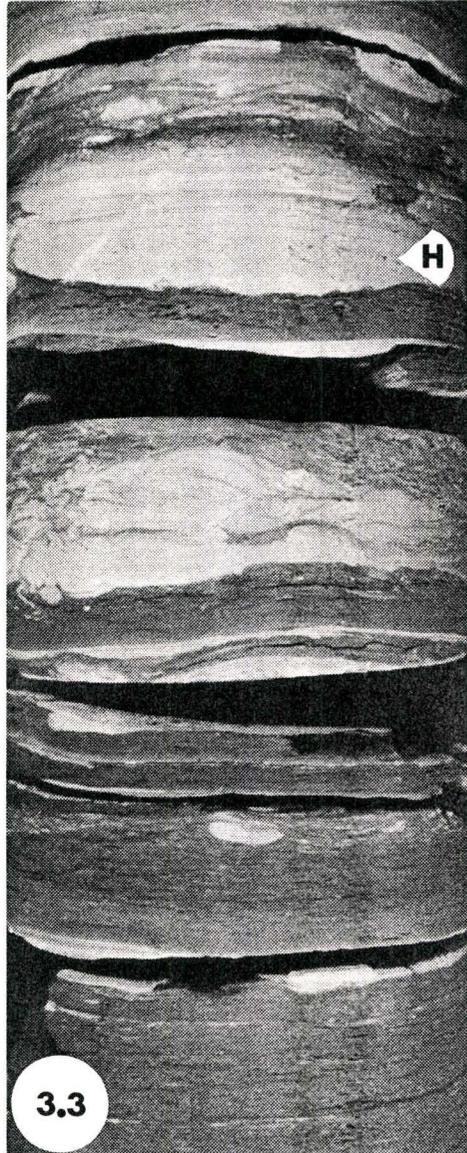
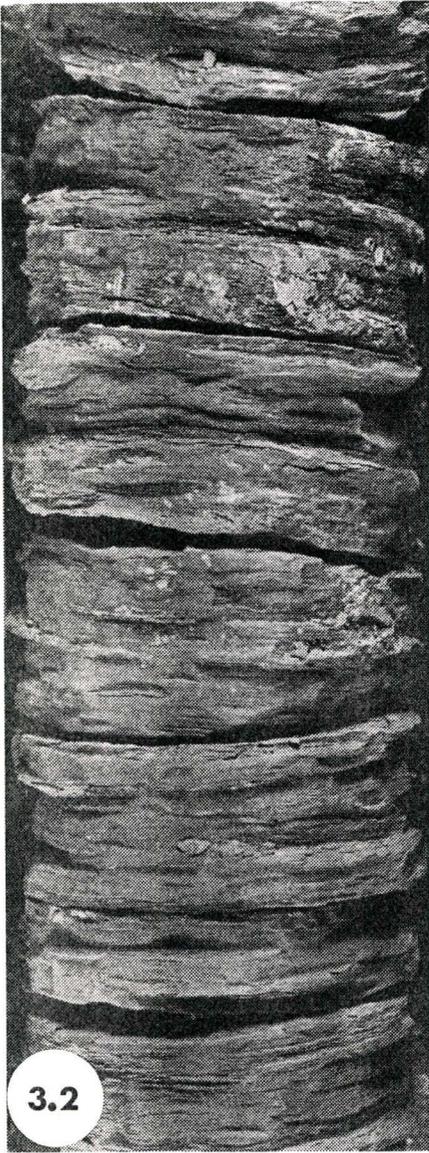
Facies A constitutes the shales which underlie and overlie the Viking Formation in southwestern Saskatchewan. These shales have been interpreted or described as offshore marine shales by several authors including Stelck (1958), Evans (1970), and Simpson (1982). The thin siltstone and fine sandstone interbeds and intercalations of the Joli Fou Formation and Lower Colorado Group shales probably represent sediment transported into an offshore setting during storms.

3.3.3 FACIES B: Laminated mudstone, Figure 3.3.

This facies ranges from 0.2 to 0.45 m in thickness. It consists of black mudstone alternating with silt and fine sand layers 1 mm to 3 cm in thickness. The silt and fine sand layers have sharp bases and tops, or sharp bases and graded tops. One of the thicker beds (2.5 cm) shows inverse grading, in which the lower (finer) laminae are convoluted and change upwards into horizontal even parallel lamination. Internal stratification of these silt-very fine sand layers varies in roughly equal proportions from slightly wavy nearly parallel to even parallel laminae which may terminate against the base of the bed at a low

Figure 3.2. Silty bentonitic mudstone, Facies A. Note the irregular disaggregation ("weathering") which is typical of facies A. Core width is 5.7 cm. Photo is from 666.3 m (2186 feet) in 11-25-31-22.

Figure 3.3. Laminated mudstone, Facies B. This facies is characterized by graded silt beds with sharp sometimes scoured bases, in mudstone. Note the occurrence of Helminthopsis (H) in the thickest bed near the top of the photo. Core width is 7.5 cm. Photo is from 736.85 m (2417.5 feet) in 11-9-32-23.



angle (less than fifteen degrees), particularly where nearly horizontal laminae infill a scoured base. No massive sand beds or cross-laminated beds were noted. A very poorly sorted, matrix supported black chert pebble conglomerate layer 2-3 mm in thickness occurs at the base of this facies. Maximum clast size is 1.6 cm. This facies is essentially non bioturbated except for one Teichichnus burrow (4 cm deep and .75 cm wide, cutting diagonally across a 2.5 cm thick graded bed), one elongate Terebellina (3 cm long and 3 mm wide), and the ichnogenus Helminthopsis, which is sparsely distributed in the upper finely laminated portions of the silty layers. The contact of this facies with facies A was not preserved in core.

3.3.4 INTERPRETATION: FACIES B

The interbedding of sharp based graded silt and fine sand beds and structureless mudstone suggests alternating periods of rapid and slow deposition, with silt and fine sand probably transported by storms. The lack of current ripples and the roughly equal proportion of plane lamination and slightly wavy lamination suggests deposition below fair weather wave base, and possibly near storm wave base. The undulating silty laminae suggest deposition from suspension under the influence of weak oscillatory currents. The lack of bioturbation suggests an environment unfavourable to organisms.

3.3.5 FACIES C: Bioturbated interbedded siltstone-very fine sandstone and mudstone, Figures 3.4.-3.6.

This facies ranges from 0.3 m (minimum observed thickness) to 5.48 m thick, and consists of layers of silt and very fine sand (mm to cm scale) in a background of silty bioturbated mudstone. The only glauconitic sand observed in this facies occurs in the upper few centimeters or decimeters of the facies where the facies is thickest. Where preserved, the lower contact of this facies with facies A is sharp and commonly marked by a thin veneer (1-2 mm) of poorly sorted matrix supported black chert pebble conglomerate, with a maximum clast size of 5 to 6 mm. This facies shows an overall coarsening and thickening upwards. The lower 0.3-0.6 m of the facies usually contains 1 to 2 mm thick non-bioturbated silt laminae. As the laminae thicken and become more frequent upwards, the unit becomes increasingly bioturbated and most physical sedimentary structures have been destroyed. However in the upper part of the unit, the thicker beds (3 to 5 cm average, maximum 7 cm) are relatively less bioturbated, with internal stratification wholly or partly preserved. Grain size coarsens upwards overall from silt-vfl sand towards the base of the facies to vfl-vfu sized sand at the top. These silt and very fine sand intercalations mostly show sharp scoured bases and graded tops (commonly bioturbated by Helminthopsis), or sharp tops disrupted by bioturbation. A

very few of these beds contain small mud rip-ups.

Teichichnus burrows 1-1.5 cm wide, and 3-6 cm deep (averaging 5 cm) appear near the base of the facies, and increase in abundance upwards, as does Helminthopsis.

Teichichnus are always retrusive in form. Terebellina was also noted, and increases in abundance upwards, but is much rarer than either Teichichnus or Helminthopsis.

Several different types of sedimentary structures were observed within this facies:

a) Parallel undulating lamination

One example is a 3 cm thick bed of silt-vfl sand seen in 14-26-31-23 at about 726.6 m (2384 feet). The lower contact of this bed is not present in core, but the cleaved bottom of the bed is wavy and the top of the bed is bioturbated. Internal lamination is parallel gently undulating laminae. Another good example occurs in 10-12-31-23 where a cm scale bed of silt-vfl sand has a sharp scoured base with a graded top, and parallel undulating internal lamination. In facies C numerous beds approaching plane bed were observed, however the lamination in all of these beds showed at least some degree of undulation.

b) Pinch and swell lamination

The best example of this stratification type was observed in a 5 cm thick bed of silt-vfl sand near the top of this facies in 4-3-32-23 (Figure 3.6). The lamination

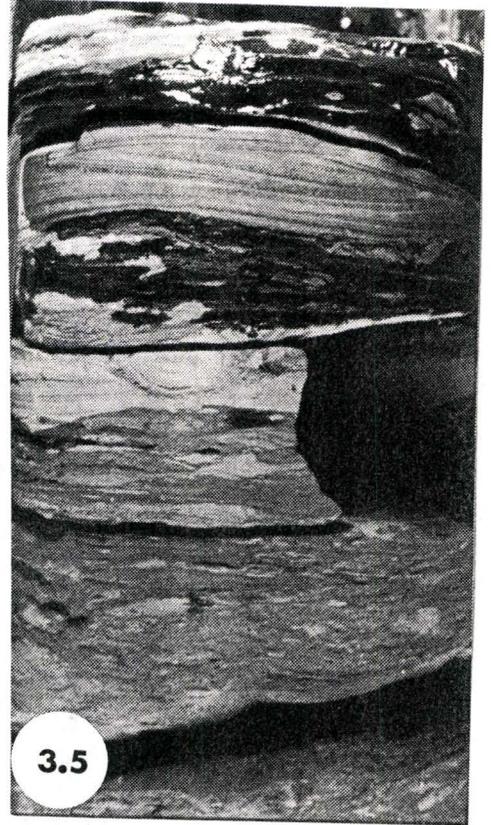
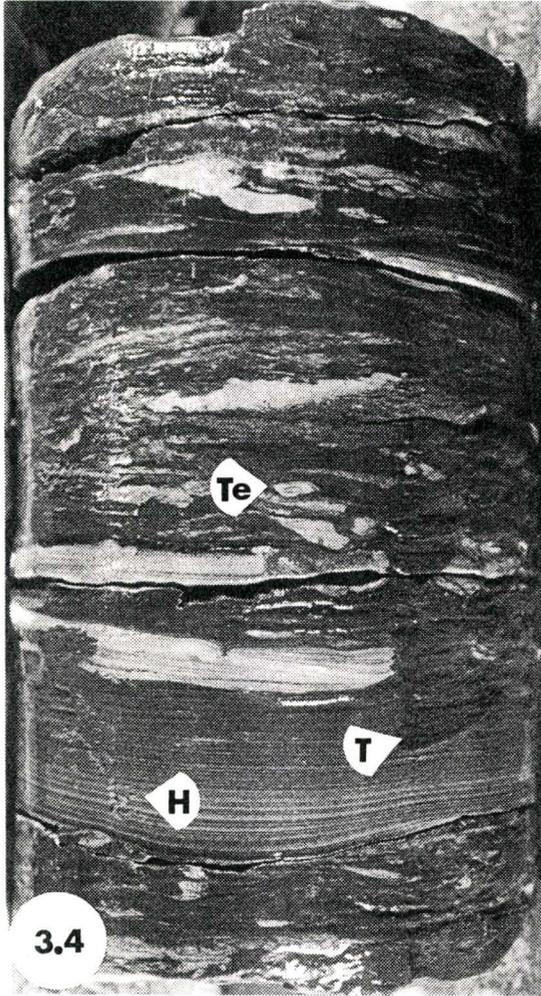
in this bed changes upwards through the bed. The bed has a sharp irregular base with the lower third of the bed showing parallel gently wavy laminae which meet the base of the bed at a very low angle (less than 5 degrees). The separation between individual laminae at the crest of each wave increases upwards into the middle third of the bed which as a result shows a distinct pinch and swell of the laminae. From the middle of the bed the undulations gradually flatten upwards and the laminae become more parallel and nearly horizontal in the upper graded part of the bed.

c) Cosets of subparallel wavy lamination showing low angle truncation between sets.

A good example of this structure is a wedge shaped bed (maximum thickness 2 cm, minimum 3 mm) of very fine sand in 11-9 (Figure 3.5) which occurs very near the top of the facies in this well. This sand bed has a sharp wavy base and graded wavy top. Internally the bed consists of mm-cm scale sets of wavy laminae which show a pinch and swell pattern within each set. The laminae in the lower set converge with the base of the bed at a very low angle (less than 5 degrees). Each set is in turn truncated by the base of the successive set. The maximum inclination of any set boundary is about 13 degrees. The laminae at the top of the upper set parallel the top of the bed, and are graded over a couple of mm. This type of lamination occurs largely in

Figure 3.4. Lightly to moderately bioturbated interbedded siltstone, fine sandstone, and mudstone, Facies C. Note the general lack of preserved physical structure. The muddy vertical burrow (T) is Teichichnus. The doughnut shaped burrow (Te) is Terebellina. The fine black specks (H) on the left hand side of the graded bed near the base of the photo are Helminthopsis. Width of core is 7.6 cm. Photo is from 732.7 m (2404 feet) in 11-9-32-23.

Figure 3.5. Lightly to moderately bioturbated interbedded siltstone, fine sandstone, and mudstone, Facies C. The well preserved bed near the top of the photo shows a coset of subparallel wavy lamination with low angle truncation between sets. Photo is from 732.7 m (2404 feet) in 11-9-32-23.



the upper third of the facies, but was observed lower (within the upper half of the facies) in a very few cases.

In 11-9-32-23 a change upwards through the facies from beds showing parallel undulating lamination to beds showing structure c (described above) was observed.

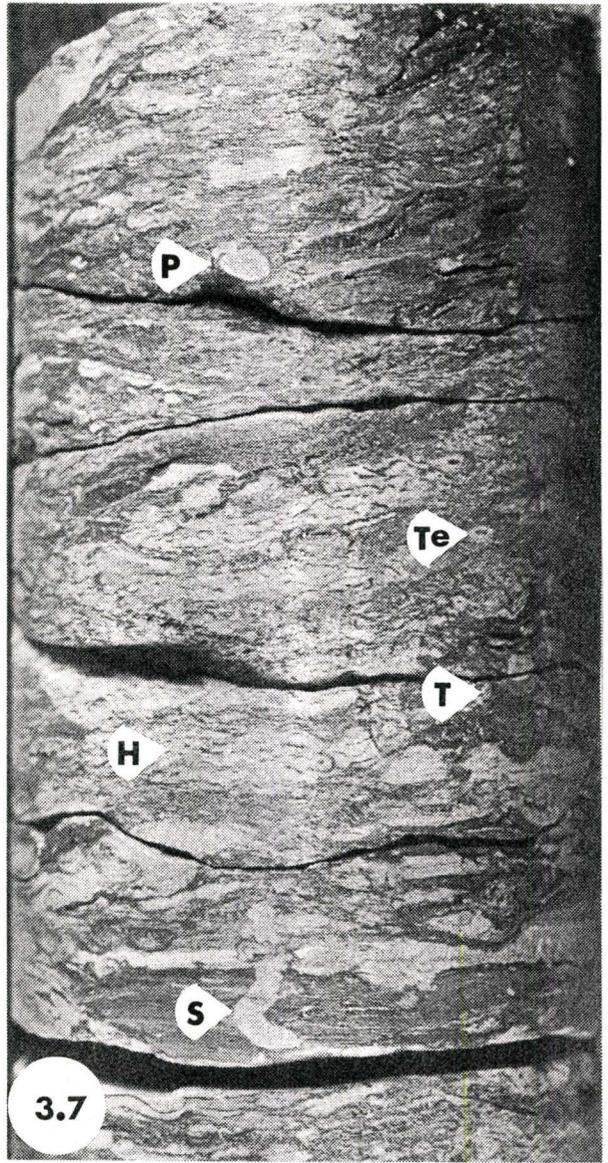
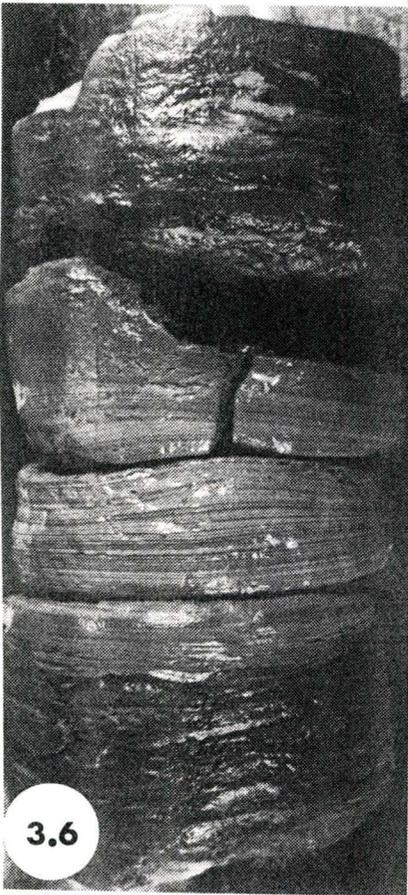
3.3.6 INTERPRETATION: FACIES C

The non-systematic upwards increase in the thickness of sharp based silt-vfl sand beds suggests these beds were deposited by events of variable magnitude, probably storms. The parallel undulating lamination and pinch and swell lamination described above suggest deposition from suspension under the influence of weak oscillatory currents. The cosets of subparallel wavy lamination with low angle truncation are interpreted as wave ripple lamination. The slight overall increase in grain size upwards suggests that this facies represents mostly aggradational deposits with perhaps a slight shoaling upwards. The presence of mud rip-ups in some of these beds suggests that these silts and sands were not transported large distances. The general lack of physical sedimentary structure suggests deposition within the Cruziana ichnofacies (Frey and Pemberton, in Walker, 1984, figure 5, pp. 192).

3.3.7 FACIES D: Transitional Teichichnus-Helminthopsis facies, Figure 3.7.

Figure 3.6. Lightly to moderately bioturbated interbedded siltstone, fine sandstone, and mudstone, Facies C. The well preserved bed in the center of the photo shows the "pinch and swell" lamination described in facies C. Photo is from 735.2 m (2412 feet) in 4-3-32-23.

Figure 3.7. Strongly--Pervasively bioturbated muddy sandstone, Facies D. Note the remnant interbeds of sand and mud (near the base of the photo) within an overall intensely bioturbated facies. Some of the trace fossils which occur in this photo include: Teichichnus (T), Ierebellina (Te), Helminthopsis (H), Skolithos (S), and Paleophycus (P). Width of core is 7.8 cm. Photo is from 728.16 m (2389 feet) in 7-4-32-23.



This facies ranges from 0.15 m to 0.86 m in thickness, and is an intensely bioturbated fine grained muddy salt and pepper sandstone, with a variable proportion of mud. It has a "blended" appearance due to the intense bioturbation, but remnants of sharp based thin beds, and remnant stratification do occur. The proportion of mud decreases upwards from 20 to 30 percent near the unit base, to about 10 percent at the unit top (visual estimate). The sand in this facies is exclusively in the vfu-vf1 size range, and is only very rarely glauconitic. Remnant beds are 1-2 cm in thickness, having sharp bases and bioturbated tops. The only preserved physical structure observed was a 1 cm thick bed showing symmetrical wave ripple lamination. Teichichnus and Helminthopsis are the dominant traces. Teichichnus increases in abundance upwards, as does the intensity of bioturbation. Teichichnus burrows are 3-4 cm deep (maximum 5 cm) and 1 cm wide, with exclusively retrusive spreiten. Terebellina (3-4 mm long, 1-2 mm wide) were also noted, and one diagonal Zoophycos(?), 2 cm long and 1 cm wide, was noted. Several other unidentified traces occur within this facies. This facies is differentiated from facies C by the increase in abundance of Teichichnus burrows, and intensity of bioturbation.

3.3.8 INTERPRETATION: FACIES D

The strongly-totally bioturbated nature of the facies with only remnants of original bedding, suggests an

episodic supply of silt and sand (probably by storms) with sufficient time between these events for organisms to completely destroy any physical sedimentary structures. The strong bioturbation also suggests that this facies was deposited below fair weather wave base where biogenic processes were dominant, probably within the Cruziana ichnofacies. In the absence of a coarsening upwards trend, the change upwards in the proportion of mud may reflect a change in the nature of the sediment source.

3.3.9 FACIES E: Pervasively bioturbated glauconitic sand, Figures 3.8-3.11, and 3.18.

This facies ranges from 10 cm (minimum observed thickness) to a maximum thickness of 5.8 m. It consists of pervasively bioturbated glauconitic salt and pepper sand containing a variable proportion of mud (10-50 percent, visual estimate). This facies shows an overall coarsening upwards, from very fine sand (vfl-vfu) at the base, to medium grained sand (ml-mu) at the top. In a few wells matrix supported black chert granules are sparsely dispersed throughout the entire facies. In some of these cores the dispersed granules were most abundant in the lower part of the facies. Where mud content is relatively low, this facies is quite friable. Physical sedimentary structures are extremely rare, and consist primarily of individual cm-scale beds of parallel very gently undulating laminae. These beds showed sharp scoured bases and sharp

Figure 3.8. Pervasively bioturbated muddy glauconitic sandstone, Facies E. The Teichichnus (T) in the center of the photo is roughly 15 cm deep. Width of core is 7.75 cm. Photo is from 722.7m (2371 feet) in 11-26-31-23.

Figure 3.9. Pervasively bioturbated muddy glauconitic sandstone, Facies E. Note the abundant Terebellina and the lack of Teichichnus. Width of core is 5.5 cm. Photo is from 707.1 m (2320 feet) in 13-7-31-22.

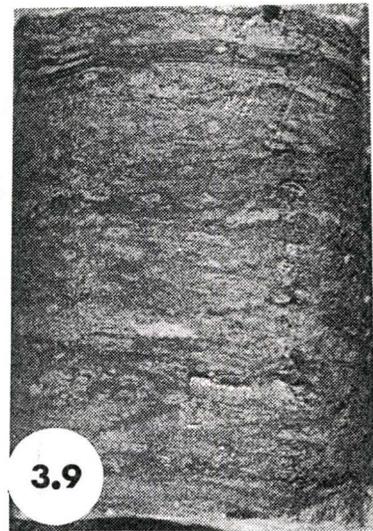
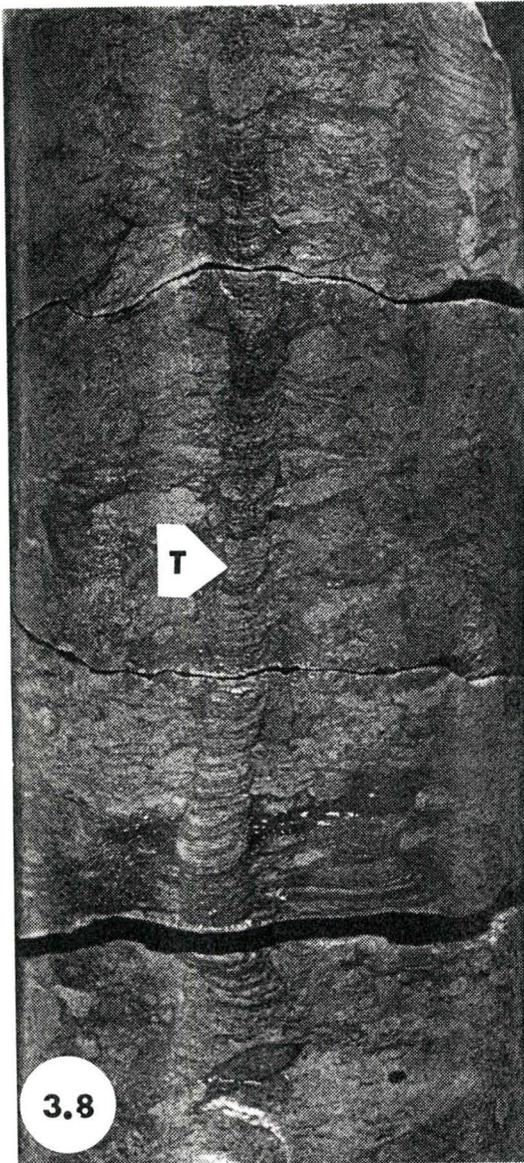
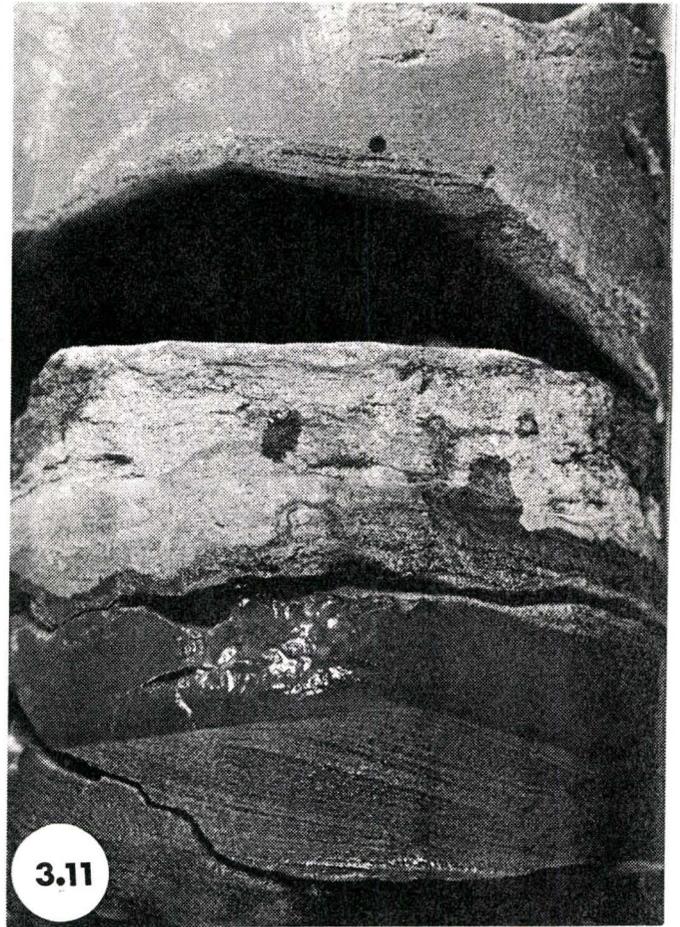
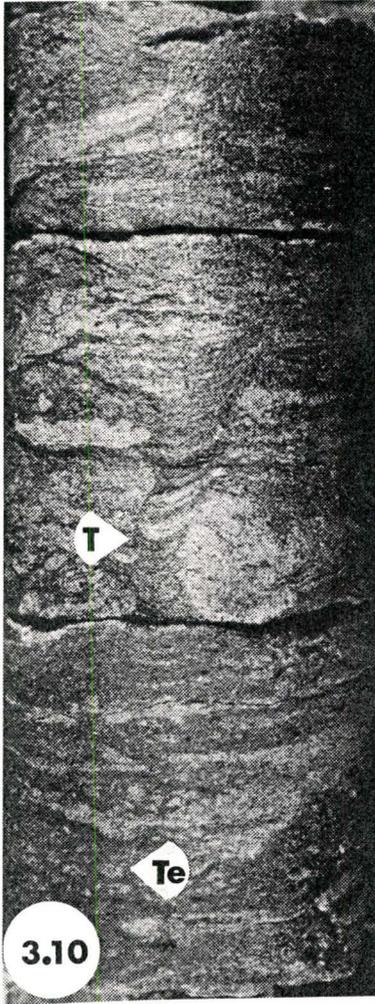


Figure 3.10. Pervasively bioturbated muddy glauconitic sandstone, Facies E. Note the relatively muddy nature of facies E in this photo as compared to facies E in Figure 3.8. Traces include Teichichnus (T) in the center of the photo, and Terebellina (Te) near the base of the photo. Width of core is 5.5 cm. Photo is from 705 m (2313 feet) in 11-7-31-22.

Figure 3.11. Pervasively bioturbated muddy glauconitic sandstone, Facies E. One of the few examples of physical sedimentary structure within facies E. This photo shows ripple cross-lamination (maximum inclination 15 degrees) draped by sideritized mud. The structureless bed at the top of the photo is also sideritized mud. Width of core is 8 cm. Photo is from 727.9 m (2388 feet) in 9-34-31-23.



or bioturbated tops. A 3 cm thick (minimum) bed in 9-34-31-23 shows wave ripple lamination (maximum inclination 15 degrees), capped by sideritized mudstone (Figure 3.11). This facies is always a tan or medium brown colour, with a greenish tinge. Glauconitic material varies in concentration from trace quantities to 40 percent (visual estimate). In some cases where physical sedimentary structure is preserved, glauconitic sand is concentrated to form distinctly green laminae within individual beds. Also, where physical structure is preserved, the sandstone is composed of well sorted, subrounded grains. Coal fragments were noted in a few of the cores. Rock fragments occur at the top of this facies in 10-6-31-22. Mud rip-ups were present in the uppermost occurrence of facies E in 4-32. The most prominent and easily identifiable trace fossils are Teichichnus and Ierebellina. Teichichnus averages 1 cm in width, and attains a maximum observed depth of 15 cm (in 11-26-31-23). Other trace fossils include Paleophycus, Zoophycos, Skolithos, and Asterosoma. Where preserved, the basal contact of this facies with the underlying facies is always sharp.

3.3.10 INTERPRETATION: FACIES E

The ichnogenera in this facies suggests an offshore setting, possibly near the proximal end of the Cruziana ichnofacies (S.G. Pemberton, pers comm.). The absence of

Helminthopsis, and Chondrites as compared to the underlying facies C, D, and I2 suggests a shoaler higher energy setting as compared to these facies. The observed coarsening upwards through facies E suggests a shoaling upwards.

3.3.11 FACIES F: Strongly bioturbated muddy glauconitic sandstone, Figure 3.12.

This facies consists of strongly to pervasively bioturbated muddy glauconitic sandstone and contains no preserved physical sedimentary structures. The ratio of sand and silt to mud varies from 30/70 percent to 50/50 percent (visual estimate). The degree of bioturbation in this facies increases with increasing sand content. Where less bioturbated, this facies contains remnant arenaceous ribs up to 0.5 cm thick, none of which are continuous across the core, and none of which show any physical sedimentary structures. These ribs may appear as lighter coloured remnants ("ghost" ribs) of thin beds in a background of totally blended sandstone, siltstone and mudstone. They are mostly vfu-vf1 glauconitic sand. This facies is muddier and less bioturbated than facies E, in the sense that it contains these "ghost" ribs. This facies is also different from facies D in that it contains abundant glauconitic sand. Traces observed in this facies

include Paleophycos/Planolites, Teichichnus, Terebellina, and Helminthopsis.

3.3.12 INTERPRETATION: FACIES F

This facies is transitional between facies E and I. The absence of physical sedimentary structures suggests that this facies was deposited below fair weather wave base where biological processes overwhelmed any physical reworking of the sediment.

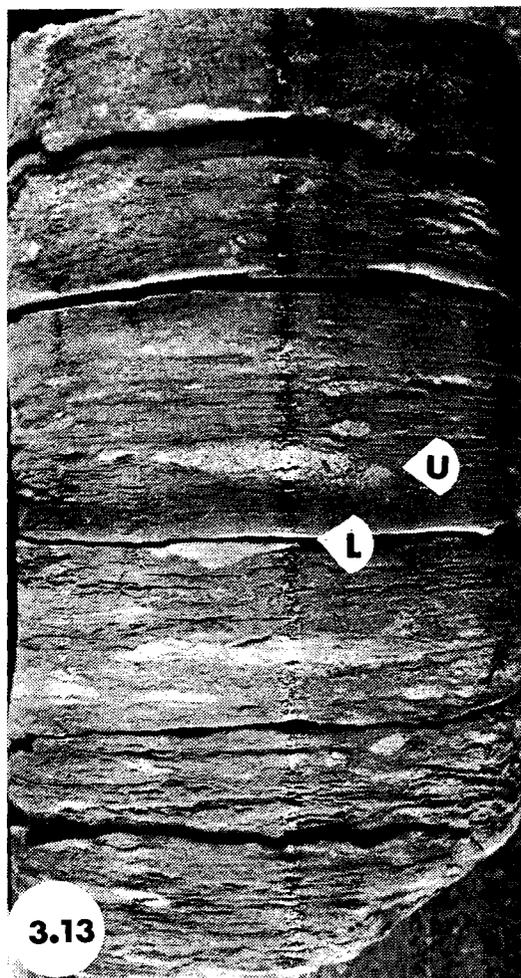
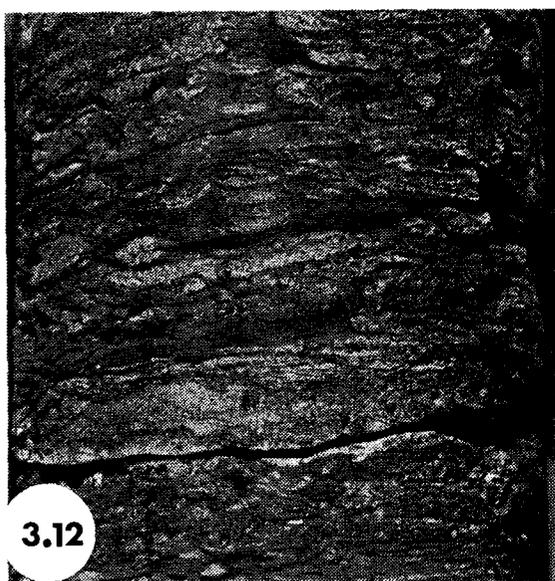
3.3.13 FACIES G1

Figure 3.13. This facies consists of coarser grained (generally vfu and larger) glauconitic sand blebs, and apparently non-glauconitic silt and silt-vfl sand in a background of silty mudstone. This facies has a maximum thickness of 1.1 m.

The coarser grained glauconitic interbeds consist generally of subrounded to rounded sand, are totally bioturbated and never extend across the width of the core. These interbeds decrease upwards overall in thickness, proportion, and grain size. Their thickness ranges from 6-7 mm towards the base of the facies to 2-4 mm towards the top. The maximum grain size observed occurs at the base of this facies where well rounded black chert granules up to 5 mm in diameter occur in a poorly sorted glauconitic sand matrix. The grain size of these sandy interbeds decreases overall upwards to vfu-fl sized sand towards the top of the facies.

Figure 3.12. Strongly bioturbated muddy glauconitic sandstone, Facies F. Note that any remnant sand ribs are discontinuous across the width of the core and lack any physical sedimentary structures. Width of core is 7.5 cm. Photo is from 698 m (2290 feet) in 2-23-30-22.

Figure 3.13. Moderately bioturbated silty-sandy mudstone, Facies G1. Note the difference in texture between the two remnant beds towards the middle of the photo. The lower (L) lighter coloured bed is silt while the upper (U) darker coloured bed (more "sugary" texture) is fine grained glauconitic sand. Width of core is 7.4 cm. Photo is from 730.6 m (2397 feet) in 11-9-32-23.



The silt-very fine sand interbeds are nearly always sharp based graded beds, with rare sharp based-sharp topped beds, and are almost always bioturbated by Helminthopsis. These beds are always plane laminated and no massive or cross laminated beds were noted. These interbeds decrease overall in thickness and proportion upwards ranging from 6-7 mm towards the base to 1-2 mm towards the top. No coarsening or fining upwards of these silt-very fine sand interbeds could be discerned.

The proportion of mud increases overall upwards through this facies. The thickness of mud interbeds increases from 3-5 mm towards the base to about 1 cm towards the top. Other trace fossils found in this facies include Chondrites, Planolites, Teichichnus (only one observed), and possibly Zoophycos.

3.3.14 INTERPRETATION: FACIES G1

The ichnofossils within this facies constitute an "offshore" assemblage, probably towards the distal edge of the Cruziana ichnofacies at or near storm wave base (S.G. Pemberton, pers comm.). The sharp based plane laminated graded silt beds in this facies probably represent silt transported as suspended load into an offshore setting during storms, and deposited below storm wave base.

3.3.15 FACIES G2

Laminated mudstone with glauconitic sandy blebs.

Figure 3.14 and 3.15. This facies consists of interbedded coarser grained glauconitic sand, apparently non-glauconitic silt-very fine sand (mostly silt), and silty mudstone, and has a maximum thickness of 4.9 m. It is differentiated from facies B by the presence of coarser grained (generally greater than vfl) glauconitic sand blebs.

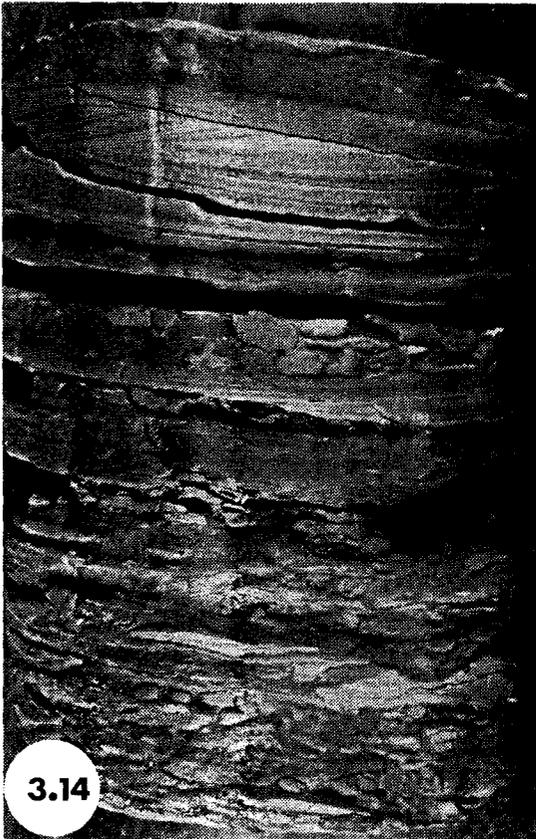
The coarser grained glauconitic interbeds are totally bioturbated and never extend across the width of the core. These interbeds decrease overall in thickness, proportion, and grain size upwards. Their thickness ranges from 2-4 mm towards the base of the facies to 1-2 mm towards the top. These interbeds show a slight decrease of grain size upwards from vfu-f1 sand towards the base of the facies to vfl sand towards the top.

The silt-very fine sand interbeds are nearly always sharp based graded beds, with rare sharp based sharp topped beds, and are almost always bioturbated by Helminthopsis. These interbeds increase overall in thickness and proportion upwards ranging from 1-2 mm towards the base of the facies to 5 cm towards the top. Some of the structures observed within these interbeds include;

- 1) Plane bed in either graded or sharp topped beds.

Figure 3.14. Laminated mudstone with glauconitic sand blebs, Facies G2. The bed near the top of the photo has a sharp base and graded top, and is composed of sets of subparallel wavy lamination where the base of each set truncates the underlying set at a low angle. This is the only example of this structure noted in facies G2 and it occurs very near the top of the facies, where it is thickest. Width of core is 8 cm. Photo is from 688.5 m (2259 feet) in 2-23-30-22.

Figure 3.15. Laminated mudstone with glauconitic sand blebs, Facies G2. The main differences from facies B are; 1) Nearly every silt-very fine sand interbed is a sharp based graded bed showing plane lamination, and is partly bioturbated by Helminthopsis, and 2) This facies contains blebs of coarser (generally larger than vfu size) glauconitic sand. Note the occurrence of Helminthopsis (H) in the thicker bed. Width of core is 7.9 cm. Photo is from 671.2 m (2202 feet) in 4-1-31-22.



- 2) Sharp scoured bases infilled with horizontal even-parallel laminae which show a low angle discordance with the scoured base of the bed.
- 3) Cosets 3-5 cm thick composed of sets (0.5-1.5 cm thick) where the base of each coset truncates the laminae of the underlying set. The laminae within each set are parallel or subparallel to the set base, are wavy and divergent in nature, and may grow into miniature hummocks or swales. The maximum inclination of any set base is about 15 degrees.

The coset bedding described in 3) above was only noted in 2-23-30-22 (Figure 3.14) and only occurred very near the top of the facies in this well. No massive or cross-laminated beds were noted in this facies. The thickness of the mud interbeds decreases slightly overall upwards. Other trace fossils found in this facies include Terebellina, Paleophycos, and Teichichnus.

3.3.16 INTERPRETATION: FACIES G2

A similar ichnofossil assemblage and similar sedimentary structures as in facies G1 suggests deposition in an offshore setting, below or near storm wave base.

3.3.17 FACIES I1: Strongly to moderately bioturbated intercalated siltstone, sandstone, and mudstone, Figure 3.16.

This facies contains two distinctly different types of arenaceous interbeds. It consists of interbedded coarser

grained (vfu and larger) glauconitic sand, apparently non-glauconitic silt-vfl sand, and silty mudstone, and has a maximum thickness of 2 m. The coarser grained glauconitic sand is usually totally bioturbated, or where remnant beds are preserved, is almost always structureless. The silt-vfl sand interbeds are either graded or non-graded, and almost always bioturbated by the ichnogenus Helminthopsis. The coarser glauconitic interbeds show an overall decrease in thickness, proportion, and grain size upwards. Their thickness ranges from a maximum of about 2 cm at the base of the facies to 4-5 mm at the top. The grain size of these glauconitic beds shows a slight decrease upwards from vfu-fu with some ml sized grains to vfu-fu sized material. The silt-vfl sand interbeds show an overall decrease in thickness and proportion upwards. The thickness of these ranges from a maximum of 3 cm towards the base to around 0.5 cm towards the top, although beds up to 1.5 cm are found in the upper part of the facies. No coarsening or fining upwards of these silt-very fine sand interbeds could be documented. Coarser glauconitic sand and non-glauconitic silt-very fine sand is occasionally mixed in this facies, usually as cm scale graded cosets with each set grading upwards from glauconitic very fine-fine sand into non-glauconitic silt-very fine sand. In some cases these sets showed grading back and forth between fine sand and silt-very fine sand over the

thickness of the set. Some of the structures observed in these mixed beds were:

- a) A lower set composed of vfu-f1 ripple cross-laminated sand grading up into silt-vf1 plane lamination.
- b) Structureless vf1-f1 sand grading up into parallel gently undulating vf1-vfu laminae.
- c) Structureless vfu sand grading up into wavy silty laminae with a pinching and swelling of the laminae.

Structures observed in unmixed beds include:

- a) Sharp based plane laminated silt-very fine sand beds with the lower laminae converging with the base of the bed at a very low angle (less than 5 degrees).
- b) Lenticular sharp based beds with sharp asymmetrical tops showing ripple cross-lamination (cross-laminae dips less than thirty degrees).
- c) silt-vf1 and vf1-vfu sand beds with parallel undulating lamination.
- d) occasional silt-vf1 sand beds showing wavy pinch and swell lamination.
- e) A silt-very fine sand bed composed of 1 cm thick sets, where the laminae within each set are parallel to the base of the set and the base of each successive set truncates or cuts across the laminae of the underlying set. The maximum inclination of any set base, or truncation surface is fifteen degrees.

Although distinct purely muddy interbeds are rare due to bioturbation and mixing of silt, sand, and mud remnant mud interbeds show an overall increase in thickness and proportion upwards ranging in thickness from a few mm towards the base of the unit to a maximum of about 1 cm at the top of the unit. This facies shows an overall decrease in the degree of bioturbation upwards from strongly bioturbated at the base to moderately bioturbated at the top. Other traces observed in this facies include Teichichnus, Planolites, and Chondrites.

3.3.18 INTERPRETATION: FACIES I1

All of the sedimentary structures described above with the exception of a) in the mixed beds and a) and b) in the unmixed beds are interpreted as wave ripple lamination. The exceptions noted above could be interpreted as unidirectional current ripples. The strong degree of bioturbation suggests deposition within the Cruziana ichnofacies (Frey and Pemberton, in Walker, 1984). The muddying upwards trend suggests that this facies was probably deposited under transgressive conditions. The decrease in thickness and proportion of coarser glauconitic interbeds upwards suggests that this glauconitic material is reworked, possibly from the underlying facies E.

3.3.19 FACIES I2

Moderately to strongly bioturbated intercalated siltstone, sandstone, and mudstone, Figures 3.17 and 3.18.

As in facies I1, this facies consists of interbedded coarser grained (larger than vfu) glauconitic sand, apparently non-glauconitic silt-very fine sand, and silty mudstone, and has a maximum thickness of 3.65 m. The coarser glauconitic sand is usually totally bioturbated (disseminated) or where remnant beds (usually discontinuous across the width of the core) occur, is structureless. As in facies C the silt-very fine sand interbeds are graded or non-graded and are almost always bioturbated by Helminthopsis. The coarser glauconitic interbeds decrease in thickness and proportion upwards ranging from 4-5 mm in thickness towards the base of the facies to 1-2 mm in thickness towards the top of the facies, although remnant beds to 1.5 cm were observed. The grain size of these glauconitic interbeds appears to decrease overall upwards from vfu-m1 sized sand towards the base to vfl-fl sized sand towards the top. The silt-very fine sand interbeds increase overall in thickness and proportion upwards, ranging from 1-2 mm minimum thickness towards the base of the facies to 5 cm maximum thickness towards the top. The silty mud interbeds decrease overall in thickness and proportion upwards through this facies, from about 1 cm maximum at the base to mm thick pinstripe laminae towards the top. As in facies I1 silt-very fine sand and coarser glauconitic sand is occasionally mixed in this facies in cm (4-5) scale cosets. In these beds, cm (4-5 cm thick) scale

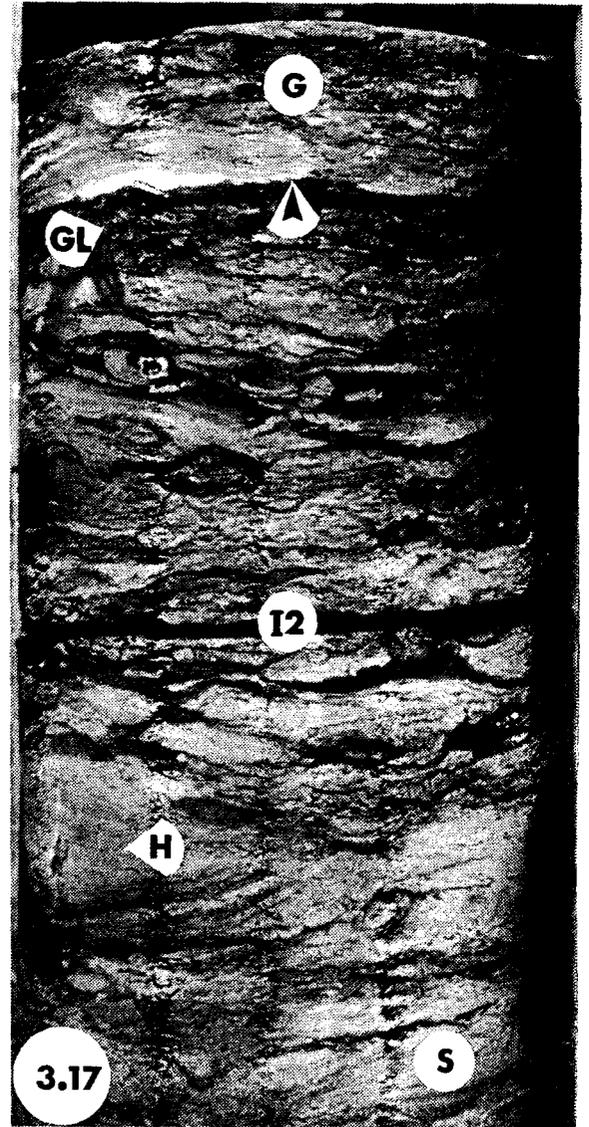
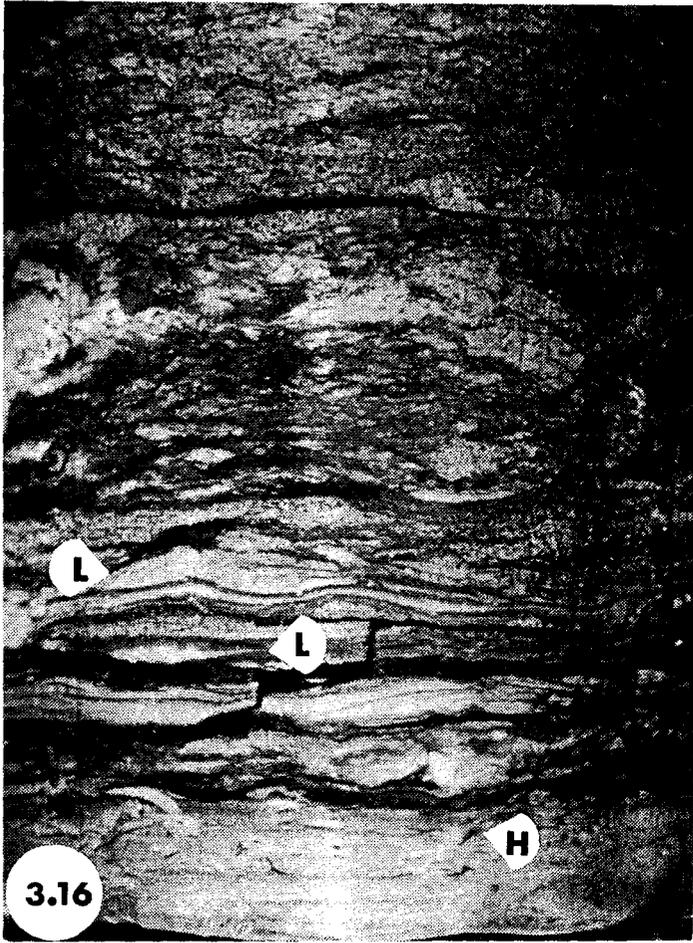
cosets are composed of 1-2 cm thick sets where fine sand in the lower set grades upwards into silt of the upper set. The laminae in each set show a wavy pinch and swell configuration (see facies C description) and the base of each set truncates the laminae of the underlying set. The maximum inclination of any truncating surface seen in such sets is seventeen degrees, and the top of the upper set is sharp and wavy (concave upwards). Other sedimentary structures observed within this facies include:

- a) Silt-very fine sand beds which show parallel undulating lamination.
- b) Silt-very fine sand beds which show wavy pinch and swell lamination.
- c) Silt-very fine sand beds with plane lamination.

This facies shows an overall increase in the degree of bioturbation upwards, except in the upper one-third of the facies in some wells where the silt-very fine sand beds are largely amalgamated. Although the primary form of these beds is preserved, little physical structure is preserved in the upper part of this facies. This facies reaches a maximum thickness of 3.35 m. In 11-26-31-23 some sand layers containing mud rip-ups were noted. Other trace fossils noted include Teichichnus, Chondrites and Asterosoma.

Figure 3.16. Moderately to strongly bioturbated interbedded siltstone, sandstone, and mudstone, Facies I1. The lighter coloured layers are silt-very fine sand while the darker "sugary" textured layers are coarser glauconitic sand. Note the lenticular beds (L) near the middle of the diagram. The lowermost bed is bioturbated by Helminthopsis (H). Width of core is 8 cm. Photo is from 721 m (2365.5 feet) in 11-26-31-23.

Figure 3.17. This photo shows the sharp contact (at arrow) between facies I2 (package 4) and G (package 6) in 9-25 (section 4.). The lighter coloured layers (S) are silt or silt-very fine sand. The darker "sugary" textured blebs (G1) are coarser glauconitic sand. Note the lack of physical structures and the strong bioturbation by Helminthopsis (H). Width of core is 8 cm. Photo is from 701.65 m (2302 feet) in 9-25-31-23.

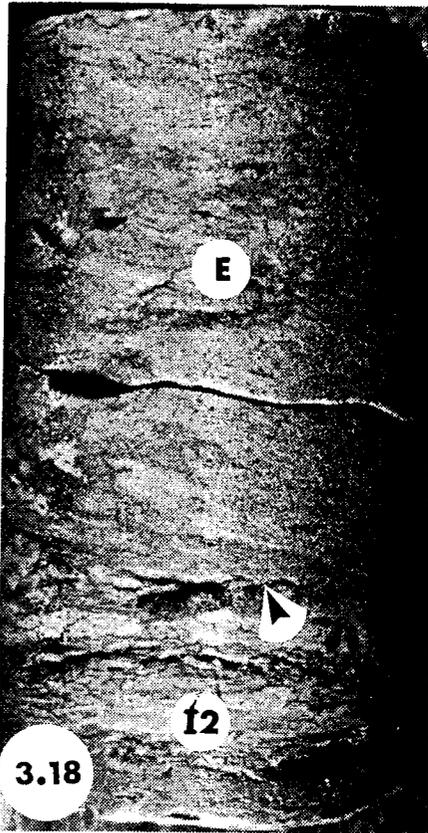


3.3.20 INTERPRETATION: FACIES I2

The general lack of physical sedimentary structures suggests deposition within the Cruziana ichnofacies (Frey and Pemberton, in Walker, 1984). The beds showing parallel undulating lamination and pinch and swell lamination as described above, are interpreted as being deposited by suspension under the influence of weak oscillatory currents. The lack of coarsening upwards suggests that this facies represents mostly aggradational deposits. Unlike facies C which appears to contain virtually no glauconitic material, the amalgamation of non-glauconitic fine sand and glauconitic coarser sand in some beds suggests that the glauconitic sand in this facies is reworked from facies E. The general upwards increase in thickness, and greater amalgamation of sand beds within this facies suggests that the events which transported this sediment became more erosive or more frequent (or both) through time. The gradational base of this facies (in contrast to the erosional base of facies C) suggests a gradual reversal between rates of sediment influx and relative sea level rise, from conditions where the rate of relative sea level rise was greater than the rate of sediment influx (facies I1), to a situation where the rate of sediment influx was greater than the rate of relative sea level rise.

Figure 3.18. Facies E / Facies I2. Note the sharp slightly erosional contact between these two facies (at arrow). This photo shows the contact between packages 4 and 5 in 13-7 (Figure 4.2). Width of core is 6 cm. Photo is from 707.75 m (2322 feet) in 13-7-31-22.

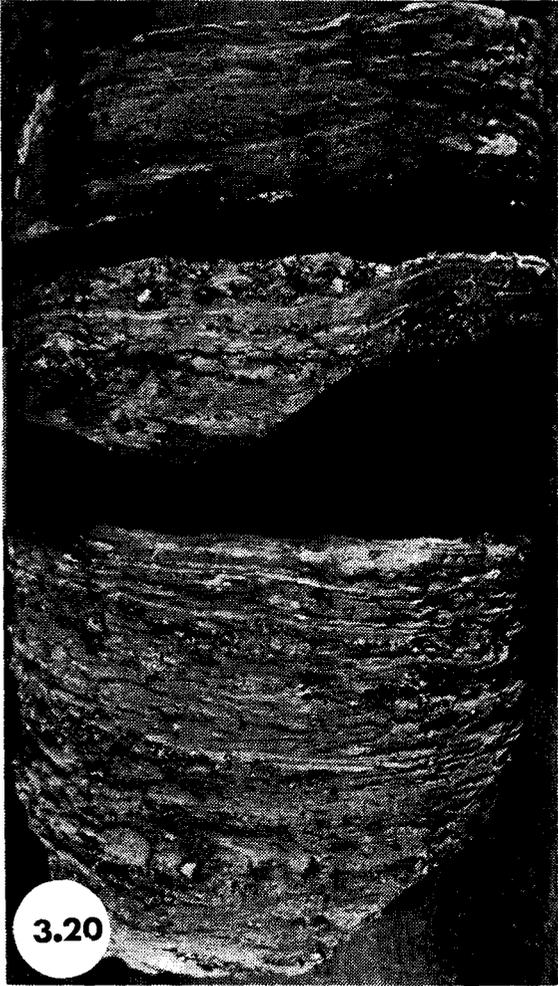
Figure 3.19. Facies N. The lighter coloured layers are silt-very fine sand, while the darker "sugary" textured layers are coarser glauconitic sand. Note the lack of physical and biological structures and the occurrence of chert granules, especially the concentration of granules on the parting plane (G) in the middle of the photo. Width of core is 8.15 cm. Photo is from 708 m (2323 feet) in 10-6-31-22 .



3.3.21 FACIES N

Intercalated siltstone and mudstone with conglomeratic layers, Figures 3.19 and 3.20. This facies is lightly to moderately bioturbated, consists of intercalations of mudstone, silt-very fine sand, and poorly sorted conglomeratic layers, and has a maximum thickness of 1.5 m. The silt-very fine sand layers have sharp bases and tops, and range from 1 mm in thickness up to about 1 cm, averaging 2-3 mm. These layers appear to be variably bioturbated. The thinner layers (1-3 mm) are mostly non-bioturbated, while the thicker layers (5-7 mm) tend to be relatively more strongly bioturbated. Where these "thicker layers" are non-bioturbated, preserved physical structure is either plane lamination, or poorly developed ripple cross-lamination. The conglomeratic layers are mostly matrix supported (a few are clast supported) and contain subrounded to well rounded black chert grains which average 4-5 mm in maximum diameter (maximum 7 mm). These layers are very poorly sorted, and grain size appears to grade from granule sized material to silt sized material. None of the granule layers showed any preferred fabric or physical sedimentary structures. This facies exhibits an interesting vertical trend, good examples of which are found in 12-20-30-22 and 2-23-30-22. In these wells, the facies consists of intercalated conglomeratic and mudstone layers with a few silt-very fine sand layers. The

Figure 3.20. Facies N. The lighter coloured laminae are silt and silt-very fine sand. Note the concentration of granules in thin discontinuous stringers. This photo comes from the uppermost part of facies N in package 3 in 2-23 (Figure 4.2). Width of core is 7.85 cm. Photo is from 698.75 m (2292.5 feet) in 2-23-30-22.



conglomeratic layers decrease in thickness and proportion upwards while the silt-very fine sand layers increase in thickness and porportion upwards. It should be noted that the lower part of this facies immediately overlying the Joli Fou shales was never preserved in core, however the log response suggests a sharp (erosive) basal contact, and possibly the development of a thin conglomeratic horizon.

3.3.22 INTERPRETATION: FACIES N

Poorly sorted conglomeratic stringers in mudstone (with rare silt laminae) could have at least two possible interpretations; a) The granule layers were transported long distances offshore during storms, or b) The granules were transported to an offshore setting during a lowstand of sea level, and were redistributed during transgression. The interpreted sharp basal contact for this facies, and the observed muddying upwards trend would suggest that the latter interpretation is more likely.

3.4 DISCUSSION

3.4.1 ICHNOLOGY

The Viking Formation at Eureka is relatively more bioturbated than in Alberta (S.G. Pemberton, pers. comm., 1985). Table 3.1 summarizes the facies occurrence of 12 ichnogenera identified in the Viking Formation at Eureka. All traces, with the exception of Thalassinoides, Cylindrichnus, and Rhizocorallium were observed in more than one facies.

The main changes between facies or within facies are in the relative abundance of an ichnogenera, and the degree of bioturbation. Regarding a change in relative abundance between facies, up to 9 individual Teichichnus were observed in facies E as compared to only 2 or 3 in facies C, over roughly the same thickness of core. Facies E is also a good example of a change in the relative abundance of an ichnogenera within a facies. Facies E (package 5) shows a dramatic lateral change in the abundance of Terebellina relative to Teichichnus. This change is discussed in greater detail in section 4.4.5.

Between different facies an increase in the degree of bioturbation occurs with an overall increase in the proportion of silt and sand relative to mud. Also within the interbedded facies as the proportion of silt and sand increase relative to mud so does the degree of bioturbation. The exception is that where relatively thicker beds occur, (roughly 2-3 cm or thicker) they are relatively non-bioturbated. Also with an increase in the proportion of silt and sand relative to mud there appears to be an increase in the density and diversity of trace fauna. These generalizations are based solely on observations from core.

	FACIES										
	A	B	C	D	E	F	G1	G2	I1	I2	N
ASTEROSOMA				XO	XO						0
CHONDRITES			0	0			0		0	0	
CYLINDRICHNUS			0								
HELMINTHOPSIS		X	XO	XO		X	XO	X	XO	XO	
PALEOPHYCUS				0	0	0		0			
PLANOLITES	0		0	0	0	0	0		0	0	
RHIZOCORALLIUM			0								
SKOLITHOS			XO	XO	XO						
TEICHICHNUS		XO	XO	X	XO	X	0	X	X	XO	
TEREBELLINA	X	X	XO	XO	XO	X		X	X		
THALASSINOIDES			0								
ZOOPHYCOS			0	X	XO	X			X		

Table 3.1. Thalassinoides, Rhizocorallium, and Cylindrichnus were identified by S.G. Pemberton (pers comm., 1985) in facies C only.

Chondrites was not initially recognized by myself, and Paleophycus and Planolites were not initially distinguished by myself. All three were later identified by S.G. Pemberton (pers comm., 1985) from slides.

X- Identified by author 0- Confirmed by S.G. Pemberton

3.4.2 THE OCCURRENCE OF GLAUCONITIC MATERIAL AND THE SIMILARITY BETWEEN FACIES C, G1/G2, AND I1/I2.

In each of the facies pairs G1/G2 and I1/I2, the thickness and proportion of glauconitic sandy blebs or beds decreases upwards through the pair. Facies C is virtually identical to facies I2 in aspect except that glauconitic material was only observed in 1 or 2 cores, where the facies is thickest, and then only in the upper few cms of the facies. Together with observations on facies geometry, these observations suggest that the glaucony^{ite} in facies G1/G2 and I1/I2 may be reworked.

3.4.3 BENTONITES: DISCUSSION

Evans (1970) described two bentonites in the Viking at Eureka, the M-N and the K bentonite. At least three other bentonites occur in more than one well. These lie between the M-N and K bentonites and are labelled the L, Z, and O bentonites in ascending order in all Figures. These "bentonites" were correlated using core and logs only. The detailed stratigraphy of these bentonites is discussed in chapter 4.

Table 3.2. shows the results of geochemical analysis of thirty-three different bentonite samples collected from Viking sediments at Eureka. Twenty-seven samples were analysed for ten major elements and five trace elements, while five additional samples were analysed for ten major elements.

LOCATION	SA. #	NAME	DEPTH (m)	DEPTH (feet)	WEIGHT %											PPM				
					SiO2	Al2O3	Fe2O3	MgO	CaO	Na2O	K2O	TiO2	MnO	P2O5	SUM	RB	SR	Y	ZR	NB
11-9-32-23	1	M-N	731.5	2400	63.05	25.54	4.04	3.35	0.62	2.47	0.60	0.24	0.01	0.08	100.00	23.	283.	17.	326.	20.
7-4-32-23	3	M-N	729	2392	63.67	25.48	3.66	2.68	0.57	2.80	0.76	0.28	0.01	0.09	100.00	25.	287.	21.	345.	21.
4-3-32-23	4	M-N	732.1	2502	64.03	26.04	3.48	2.55	0.64	2.25	0.66	0.25	0.01	0.08	100.00	24.	301.	19.	327.	20.
9-25-31-23	8	M-N	706.8	2319	63.84	25.76	3.83	2.48	0.48	2.66	0.69	0.20	0.00	0.06	100.00	26.	281.	9.	292.	15.
11-25-31-22	22	M-N	678.5	2226	66.61	22.45	4.55	1.95	0.46	2.46	1.04	0.34	0.00	0.13	100.00	35.	215.	27.	355.	13.
13-7-31-22	10	M-N	712.3	2337	64.58	25.62	3.28	2.53	0.53	2.51	0.64	0.22	0.01	0.07	100.00	25.	293.	13.	304.	18.
1-7-31-22	11	M-N?	713.4	2340.5	64.01	25.74	3.41	2.74	0.57	2.56	0.65	0.24	0.00	0.08	100.00	24.	301.	20.	301.	18.
11-9-32-23	2	K	728.6	2390.5	69.31	15.87	6.36	1.60	1.94	1.29	2.63	0.78	0.06	0.16	100.00	113.	209.	26.	237.	20.
4-3-32-23	5	K	727.6	2387	63.54	25.55	3.73	2.67	0.56	2.69	0.75	0.43	0.01	0.06	100.00	27.	248.	13.	359.	27.
9-34-31-23	7	K	726	2382	63.41	25.49	3.83	2.50	0.72	2.54	0.78	0.62	0.00	0.11	100.00	28.	274.	21.	372.	37.
9-25-31-23	9	K	701	2300	64.09	25.41	3.69	2.39	0.61	2.56	0.76	0.41	0.01	0.07	100.00	29.	297.	18.	366.	26.
11-25-31-22	23	K	673.15	2208.5	63.65	25.67	3.94	2.06	0.51	3.02	0.73	0.35	0.01	0.05	100.00	27.	252.	6.	328.	15.
14-1-31-23	30	L?	711.5	2334.3	65.76	22.82	5.86	.51	0.69	2.50	1.19	.52	.02	.14	100.00					
14-5-31-22	14	L	696.8	2286	66.31	22.76	4.53	1.89	0.50	2.16	1.20	0.52	0.00	0.13	100.00	42.	234.	19.	248.	13.
4-2-31-22	31	L	681.5	2236	64.54	25.04	4.10	1.93	0.61	2.67	.72	.27	.00	.12	100.00					
9-14-31-21	29	L	676.5	2219.5	64.64	26.33	3.85	1.10	0.45	2.70	.58	.23	.02	.10	100.00					
6-3-31-21	33	L	673.45	2209.5	64.79	25.29	4.60	.79	0.53	2.65	.76	.48	.00	.11	100.00					
4-32-30-22	17	L	716	2349	64.46	24.19	4.57	2.14	0.75	2.47	0.85	0.45	0.00	0.13	100.00	32.	247.	13.	268.	13.
4-32-30-22	28	L	716	2349	64.92	24.60	4.32	1.35	.68	2.63	.89	.45	.02	.16	100.00					
16-31-30-22	15	L	703	2306.4	69.54	19.50	4.49	1.57	0.59	1.74	1.79	0.63	0.00	0.16	100.00	59.	230.	24.	297.	13.
11-5-31-21	25	O?	672	2204.7	70.93	17.47	5.58	1.40	0.61	1.57	1.76	0.43	0.00	0.25	100.00	53.	214.	25.	247.	12.
4-32-30-22	18	O	710.6	2331.5	64.92	24.33	4.21	2.05	0.63	2.34	1.12	0.29	0.01	0.11	100.00	37.	221.	8.	173.	13.
2-23-30-22	32	O	692.5	2272	55.60	22.48	16.43	.91	0.73	2.55	.96	.23	.00	.12	100.00					
12-20-30-22	20	O	729.5	2393.5	67.20	21.44	4.69	2.10	0.50	1.78	1.72	0.42	0.00	0.14	100.00	55.	216.	15.	192.	13.
12-15-30-22	21	O	725	2378.5	63.69	25.34	4.34	2.02	0.70	2.51	1.04	0.26	0.00	0.09	100.00	31.	284.	10.	211.	12.
4-3-32-23	6	UNAMED	729.7	2344	64.10	25.43	3.57	2.41	0.55	2.57	0.83	0.45	0.01	0.08	100.00	30.	273.	27.	388.	30.
8-26-31-23	26	UNAMED	710.95	2332.5	63.39	25.99	3.65	2.47	0.51	2.80	0.67	0.41	0.01	0.09	100.00	27.	277.	19.	285.	16.
1-7-31-22	12	UNAMED	712.8	2338.5	63.88	25.16	4.08	2.60	0.51	2.70	0.71	0.26	0.01	0.08	100.00	25.	265.	22.	322.	18.
1-7-31-22	13	UNAMED	712.3	2337	63.43	20.90	9.11	1.83	0.50	2.42	1.19	0.49	0.00	0.12	100.00	44.	305.	11.	231.	13.
10-6-31-22	27	UNAMED	718.7	2358	58.47	20.74	15.05	1.88	0.42	2.13	0.99	0.24	0.00	0.09	100.00	34.	255.	6.	167.	8.
4-32-30-22	19	UNAMED	710.3	2330.5	64.83	24.57	3.99	2.02	0.58	2.45	1.03	0.40	0.01	0.11	100.00	36.	197.	5.	176.	13.
16-31-30-22	16	UNAMED	696	2283.5	70.89	17.94	4.39	1.37	0.80	1.59	2.17	0.50	0.01	0.34	100.00	67.	218.	33.	266.	11.
2-23-30-22	24	Z	696.9	2286.5	66.03	23.84	4.23	1.90	0.50	2.23	0.75	0.41	0.01	0.09	100.00	29.	241.	6.	269.	11.
																196.	4335.	43.	9623.	746. NI
																2198.	16.	32.	530.	263. MI
																12.	303.	2.	91.	9. NI
																134.	639.	44.	1549.	237. ST

Table 3.2. Major and Trace element chemistry of thirty-three bentonite samples by XRF analysis. Box in the lower right hand corner are trace element standards.

It was initially hoped that these analyses could be used as an independent chemical correlation of the bentonites in support of the log and core correlations. However, replicate analyses were not run, leaving no way to check for precision of analysis, which would be critical to conclusive chemical correlation. After the initial analyses, it was decided that the replicate analysis together with the statistical treatment of the data required to verify the chemical correlation of the bentonites (Glass, 1981) was beyond the scope of this thesis, and should be a consideration for future work.

3.4.4 SIDERITES: DISCUSSION

The term "siderite" here refers to sideritized sediments, identified from hand specimen only. Siderites are quite common in the Viking Formation and Lower Colorado mudstones which overlie the Viking at Eureka. They occur almost always as the bedded variety insofar as they are continuous across the width of the core with a fairly flat base and top. These siderites range in thickness from less than 1 cm to a maximum of about 20 cm. In almost all cases siderite occurs where mudstone or silty mudstone overlies or is in contact with bioturbated or non-bioturbated sandstone. It is the mudstones which are sideritized in almost all cases.

There are only a few places within the Viking where siderites occur consistently at or about the same

stratigraphic position: this is discussed in greater detail in chapter 4. In the following summary of siderite occurrence, abbreviated well locations refer to wells included in Figures 4.2 through 4.4. Other wells are shown in Appendix 1.

Siderites were observed at muddy intervals within facies E in 2-3, 3-35, 9-34, and 9-25 (Figure 4.3). Siderites were also observed where facies E is abruptly overlain by relatively muddier facies F or I1 in 11-25-30-22, 4-32, 10-36-30-22, 4-2-31-22, 12-3-31-22, and 9-14-31-21. Siderites were observed at the contact between facies E and facies G1 in 2-3, 4-3, and 10-7-32-21. Finally siderites were observed at the contact between facies G2 and A in 11-25-30-22, 4-32, and 6-35-31-23.

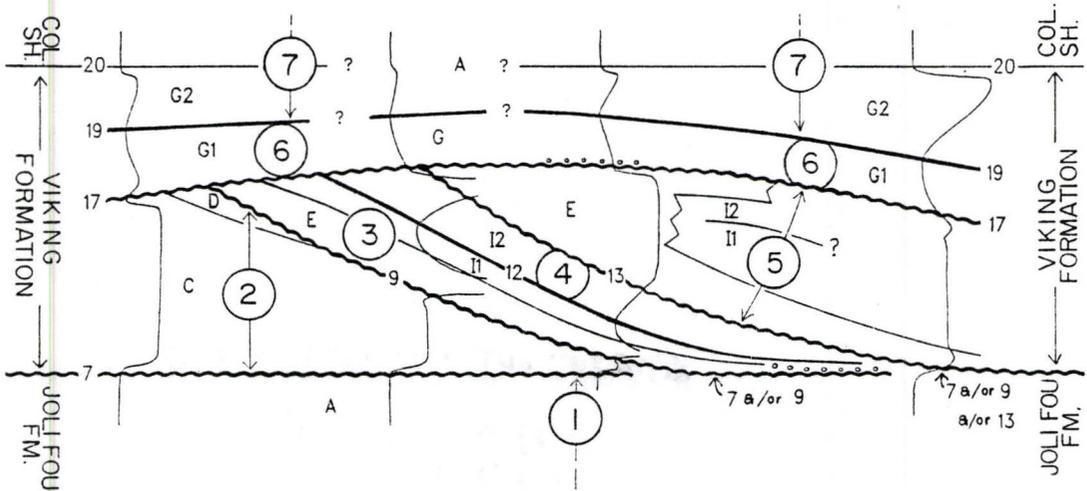
CHAPTER 4. FACIES GEOMETRY

4.1 INTRODUCTION

Figures 4.1 through 4.4 are cross-sections which show the geometry of Viking Formation facies across the Eureka field of southwestern Saskatchewan. Figure 4.1 is a simplified diagram showing the geometry of Viking facies at Eureka. Figure 4.2 is to scale horizontally, and summarizes the data contained in Figures 4.3 and 4.4 which are detailed core and well-log cross-sections. Figure 4.2 is located at the back of the thesis and can be folded out for reference. Figure 4.1 is inserted in the lower right hand corner of Figure 4.2 for reference. Figures 4.3 and 4.4 are in pouches in the back of the thesis.

On the basis of well log correlations, Evans (1970) described the Viking Formation in this area as a series of continuously imbricated linear sand bodies. Figures 4.2 shows that the bulk of Viking Formation facies in this area lie between two unconformable surfaces, one at the base and the other near the top of the Viking Formation, and that there are several unconformable surfaces within the Viking. The Viking can be subdivided into groups of facies or "packages" whose boundaries are either unconformable surfaces or muddy horizons.

Figure 4.1. This figure is a simplified diagram of the facies geometry within the Viking formation at Eureka. It shows the location of the seven "packages" and their bounding surfaces as discussed in the text. The squiggly lines represent either unconformable or disconformable surfaces and the thicker lines represent "muddy horizons". The thin vertical lines represent the characteristic resistivity log response at different locations along the line of section.



4.2 CONSTRUCTION OF DETAILED CROSS-SECTIONS

Detailed core and well log cross-sections trending basically parallel to Evans' 1970 cross-section through the Eureka field were constructed, using a much larger number of cored wells than originally used by Evans. Of the two cored wells in Evans' original cross-section, only 11-9-32-23 was examined, as the other (2-16-30-22) was an incomplete core. The purpose of this cross-section is to document the facies geometry, and allow comparison of this facies geometry to the "imbricate" geometry of the "six members" defined by Evans from detailed geophysical well log correlations. Facies as interpreted from logs for uncored wells, uncored intervals or missing core are included in these Figures.

The datum for these cross-sections is a prominent sonic/electric log marker which occurs near the base of the black mudstones which immediately overlie the Viking Formation in this area. The reasons for choosing this datum will be explained in the following discussion.

4.3 CHOICE OF A DATUM

There are four prominent persistent sonic/resistivity log markers within the mudstones overlying the Viking Formation in this area. These are labelled as the "datum" and lines 21, 22, and 23 in all Figures. From core examination these markers can be equated with thin bioturbated silty or sandy intervals within these

mudstones. Correlation of these markers results in a group of parallel to subparallel lines. This relative parallelism and flatness makes any of these markers a reasonable choice to illustrate the depositional geometry of Viking sediments in the Eureka area. Also the persistence and correlatability of these markers makes any of them a good choice for a datum. All four of these markers occur in all the wells examined except for 2-3-32-23 where the datum does not occur. In 2-3 the approximate stratigraphic position of the datum was determined by correlation with nearby wells.

4.4 SUBDIVISION OF THE VIKING INTO "PACKAGES"

Figures 4.1 through 4.4 show that the Viking Formation in this area is bounded at the base and near the top by unconformable surfaces, and that between these surfaces the Viking can be subdivided into packages consisting of groups of facies which are separated either by unconformable surfaces or by muddy horizons. Both the unconformities and muddy horizons will be interpreted as "breaks or pauses in deposition." For descriptive purposes, the facies overlying and underlying the Viking Formation will also be grouped into packages. These packages are shown in Figure 4.1 and are labelled 1 through 7.

In the box core photos included at the end of this chapter, "up" is towards the top of the page. The base of

the core is the bottom of the left-most core box while the top of the core is the top of the right-most core box. The facies arrows are placed at or as close as possible (so as not to obscure any contacts) to the base of the facies. The packages to which the facies belong are listed in brackets in the Figure caption, and the reader can refer to Figure 4.2 to locate the appropriate package while examining the box photos.

4.4.1 PACKAGE 1

The unconformity which marks the base of the Viking is variably line 7 and/or 9 and/or 13 (Figure 4.2). Package 1 consists of facies A, D, and B below this unconformity. There are four persistent log markers within facies A which are labelled as lines 1, 2, 3, and 4 in ascending order (Figure 4.2). Generally speaking facies A between line 3 and the base of the Viking thins south-southeastwards. The unconformable nature of the Viking base is demonstrated by the erosion of facies B and D and marker 4. Facies A, D and B are therefore considered part of the Joli-Fou Formation and form a succession of variably bioturbated shelf facies. This unconformity (line 7 and/or 9 and/or 13) also forms the contact between package 1 and 2.

4.4.2 PACKAGE 2

Package 2 lies above line 7 and is bounded laterally by line 9 and vertically by the unconformity labelled line 17 in Figure 4.2. Package 2 consists of an overall

coarsening upwards sequence of facies C and D. The M-N bentonite occurs near the top of facies C in all wells, has a maximum observed thickness of 16 cm and generally thins south-southeastwards. Facies C thins from a minimum of 5.48 m to zero south-southeastwards. This is interpreted as mostly depositional thinning because of the stratigraphic position of the M-N bentonite. As facies C thins laterally south-southeastwards, the silt-very fine sand interbeds become thinner and discontinuous, and the facies becomes muddier overall. The thinning and disappearance of facies D, the thinning of facies C between the M-N bentonite and line 9, and the disappearance of the M-N bentonite sequentially south-southeastwards demonstrates the unconformable nature of line 9. This unconformity forms the contact between packages 2 and 3.

4.4.3 PACKAGE 3

Package 3 lies above line 9 and is bounded laterally and vertically by the muddy horizon shown by line 12 in Figure 4.2. It consists of coarsening-upwards facies E, and facies N which are both overlain by muddying-upwards facies I1 which contains the L bentonite.

Line 10 represents a log/core marker which occurs in facies E. This marker occurs on most logs of facies E, and coincides in core with sideritized mudstone, with a maximum thickness of 15cm. It is the only sideritized mudstone observed in three of the wells shown in figure 4.2. This

sideritized mudstone occurs at roughly the same stratigraphic level in three of these wells (Figure 4.2). The top of facies E and line 10 converge as facies E thins gradually south-southeastwards (Figure 4.1). Facies E thins and becomes muddier laterally south-southeastwards and interfingers with facies I (13-7 and 11-7 area). The exact stratigraphic relationship between facies E and N are unknown, however they are both overlain by facies I1. The basal contact of facies N in package 3 with the underlying facies Joli Fou shales was never preserved in core, however, the log response suggests the possible development of a thin conglomeratic horizon. In 16-31 and 4-32 facies E and N were not noted and facies I1 could not be differentiated. South-southeastwards in 4-12, facies N and I1 do not occur.

As facies I1 thickens south-southeastwards to its maximum thickness (9-25 area) it becomes increasingly sandy and the contact between facies E and I1 changes from abrupt to gradational. South-southeastwards from its thickest development, facies I1 thins and becomes muddier. Facies I1 also becomes muddier upwards to the muddiest point between facies I1 and I2, which forms the contact between packages 3 and 4 (line 12, Figure 4.2; this is a prominent log marker).

4.4.4 PACKAGE 4

Package 4 consists of facies I2. The top of this package is variably line 13 or 17 (Figure 4.2). Line 13 is tentatively interpreted as a disconformity based on the following evidence:

- 1) The disappearance south-southeastwards (4-12) of facies I1 and N of package 3, and facies I2 of package 4.
- 2) The disappearance of marker 4 before 4-12 and the simultaneous thinning of facies A below the basal Viking unconformity.
- 3) Facies I2 and C are similar. The contact between facies C and E (package 3) is demonstrably unconformable. The similarly sharp (with minor erosion) contact between facies E and I2 suggest that line 13 may also represent an unconformable contact.

As facies I2 thickens south-southeastwards to its maximum thickness (13-7 -- 11-6 area) it becomes increasingly sandy. Farther south-southeastwards it thins and becomes muddier. The disconformity shown by line 13 forms the contact between package 4 and 5.

4.4.5 PACKAGE 5

Package 5 consists of facies E, F, I1, I2, and I, and the Z and O bentonites between lines 13 and 17. The muddy horizon between facies I1 and I2 (line 15, Figure 4.2) in BA-28 would be considered the top of package 5, but it is unrecognizable south-southeastwards. Therefore all facies

between line 13 and 17 are included in this package.

Facies "I" is used where facies I1 and I2 could not be differentiated.

As shown in Figure 4.2 thin patches of facies E physically separated from the main sand body may occur (3-35).

Line 14 represents a log/core marker which is a prominent inflection (abrupt increase) on the gamma-ray log of facies E. Below line 14 Terebellina is relatively far more abundant than Teichichnus at the north-northwest end of this package (13-7 area) but Teichichnus increases in relative abundance south-southeastwards. As shown in Figure 4.2 the base of facies E drops stratigraphically and thins rather abruptly relative to the datum (16-31/4-32 area). Further south-southeastwards facies E below line 14 becomes muddier as it thins gradually and passes laterally into facies F, which contains the Z bentonite. Above line 14, facies E may contain distinctly muddier intervals (11-7 area). Further south-southeastwards above line 14 facies E intertongues with facies F and I (4-32 area).

Two other log markers occur in package 5 but these can only be correlated between a few wells. One of these is the muddy horizon between facies I1 and I2 shown as line 15 in Figure 4.2. The other is the base of a "sandy" gamma-ray response (facies E in core) shown by line 16.

South-southeastwards between lines 14 and 15, facies E intertongues with facies F and I then passes laterally into facies I1. Between lines 15 and 16 facies E passes laterally through facies F and I into facies I2. Facies E contains the O bentonite (between lines 16 and 17). The bentonite which occurs in this interval of facies E is tentatively correlated with the bentonite in facies I2 south-southeastwards and is labelled the O bentonite (Figure 4.2).

Line 17 variably represents the contact between package 5 and packages 6 or 7. The truncation of several markers contained in packages 2-5 below this line at the north-northwest end of figure 4.2 shows the unconformable nature of this contact. South-southeast of 13-7 the general parallelism of line 17 and markers in package 5 suggest a more conformable relationship.

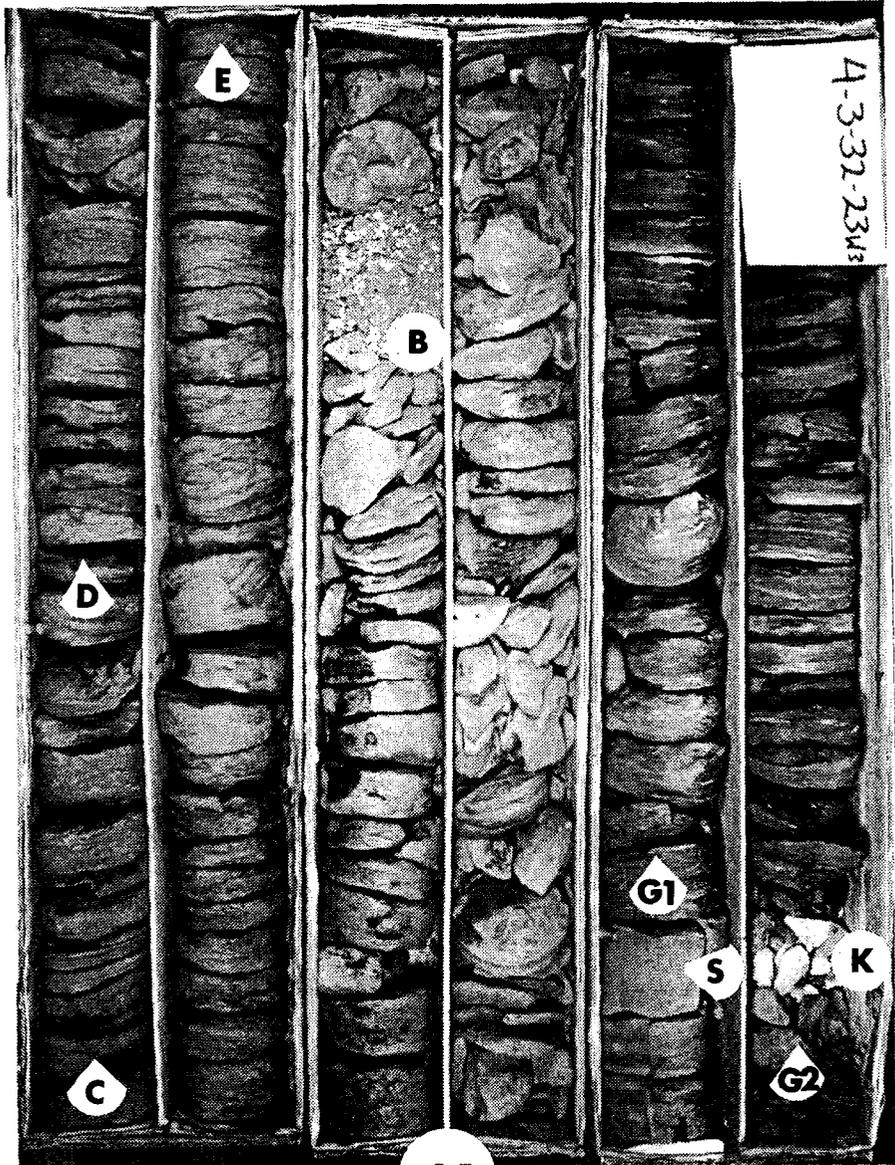
4.4.6 PACKAGE 6

Package 6 lies above line 17. It consists of facies N, G1, and G, and is bounded vertically by the muddy horizon shown by line 19. As shown in Figure 4.2 facies G1 does not occur in all wells. Facies G1 becomes muddier upwards to the muddiest point which forms the contact between packages 6 and 7. Facies "G" is used where the rock does not become distinctly muddier or sandier upwards. The correlation of granule horizons in facies G1 and A with facies N is uncertain.

4.4.7 PACKAGE 7

Package 7 variably overlies lines 17 and 19 and consists of facies G2 and A, and the K bentonite. As shown by the question marks, correlation of the K bentonite in this package is problematic. Facies G2 thickens or thins independantly of other markers such that its top (line 20) remains relatively parallel to the datum. Facies G2 is taken as the top of the Viking Formation in this area and is abruptly overlain by facies A which contains 4 subparallel correlatable log markers labelled "datum" and 21-23 in ascending order in figure 4.2.

Figure 4.5. Facies C and D (package 2), E (package 3), G1 (package 6), and G2 (package 7). Note the progressive increase in the proportion of sand and degree of bioturbation upwards through facies C, D, and E. Facies E is capped by 5 cm of sideritized mudstone (S). The "K" bentonite (K) occurs very near the contact between facies G1 and G2 and is arbitrarily included in facies G2. Note also the occurrence of bentonite chips (B) within facies E near the top of the third column from the left. Photo is of 4-3-32-23.



4.5

Figure 4.6. Facies A (package 1), C (package 2), and E (package 3). In facies C, interbeds of silt-very fine sand thicken and coarsen upwards overall, however relatively thick beds also occur lower in the facies. The "M-N" bentonite (M) occurs near the top of facies C. The contacts between packages are not preserved in core. Photo is of 9-25-31-23.

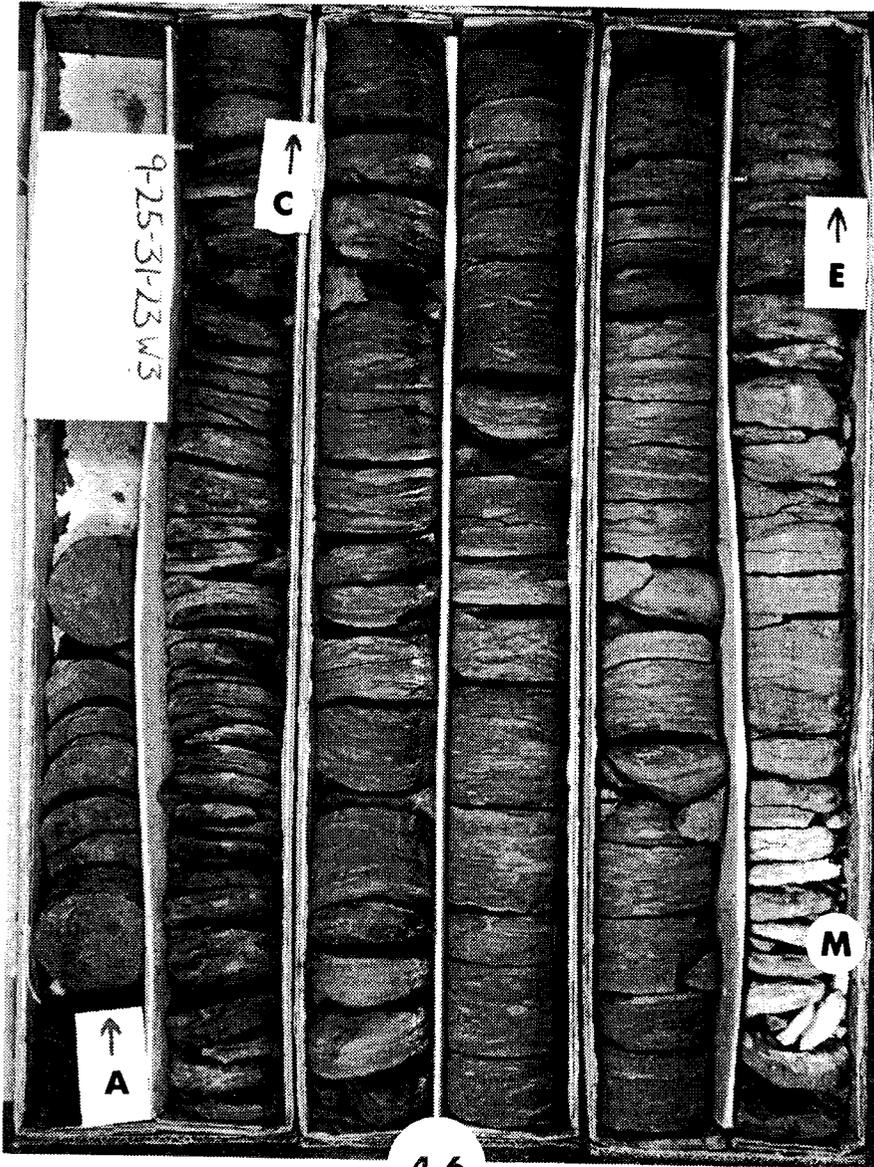
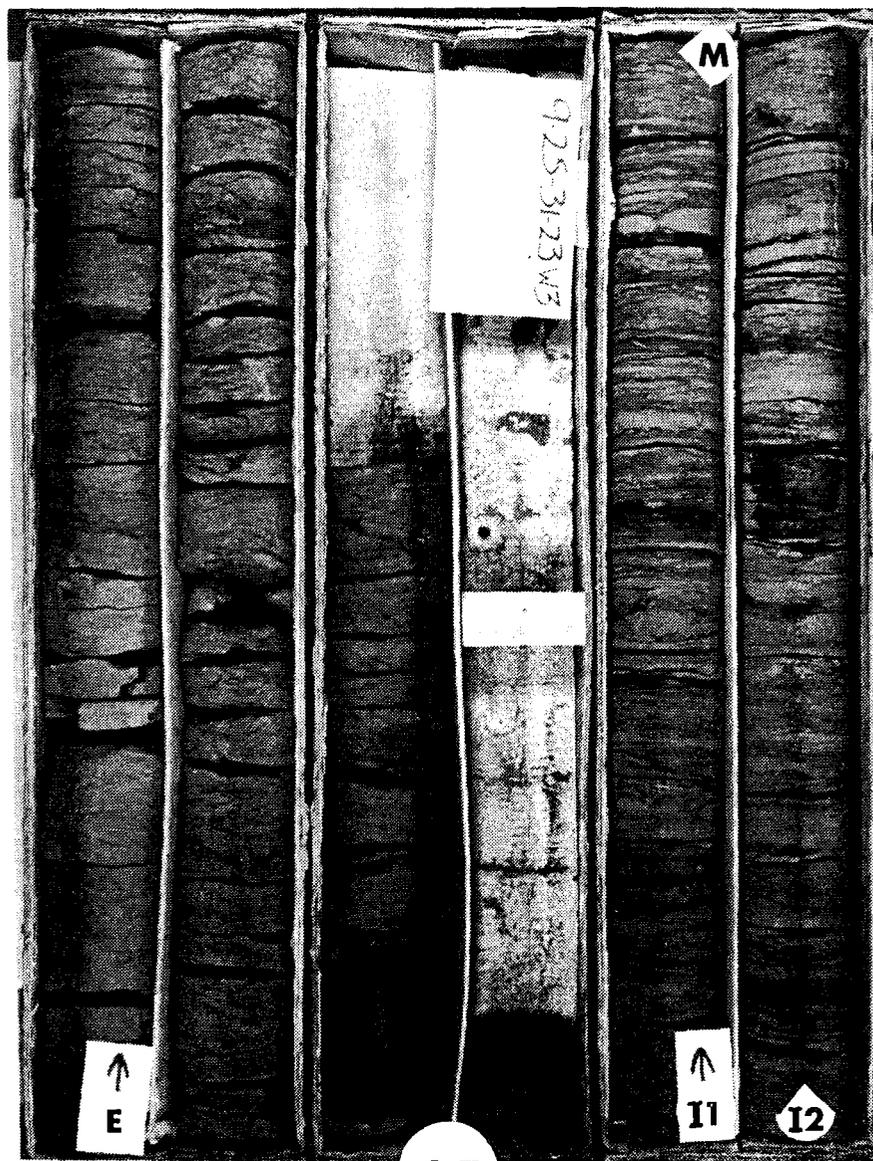


Figure 4.7. Facies E and I1 (package 3), and facies I2 (package 4). Note the absence of physical structures in facies E. The dark (wetted) interval within facies E is 15 cm of sideritized mudstone (704.69m (2312') on the resistivity log). Although the sand interbeds decrease overall in thickness upwards as facies I1 becomes muddier upwards, relatively thick sand interbeds (1-2 cm) occur towards the top of the facies. From this "muddiest point" (M) facies I2 shows a decrease in the proportion of mud upwards and the sand interbeds become amalgamated. Roughly 0.45 m of core is missing from the base of facies I1 (fourth column from the left). Photo is of 9-25-31-23.



4.7

Figure 4.8. Facies I2 (package 4), facies G (package 6), and facies A (package 7). This photo shows the remainder of facies I2 and the overlying facies in 9-25. Facies I2 is sharply overlain by facies G. The contact between facies G and facies A is not preserved. The "K" bentonite (K) occurs in facies A. Photo is of 9-25-31-23.



Figure 4.9. This photo is of facies I1 (package 3), facies I2 (package 4), and facies E (package 5) in 10-6. The increase in proportion of mud upwards through facies I1, and the decrease upwards through facies I2 is more apparent than in Figure 4.7. The contact between facies E and I2 (C) is sharp, with minor erosion. Photo is of 10-6-31-22.

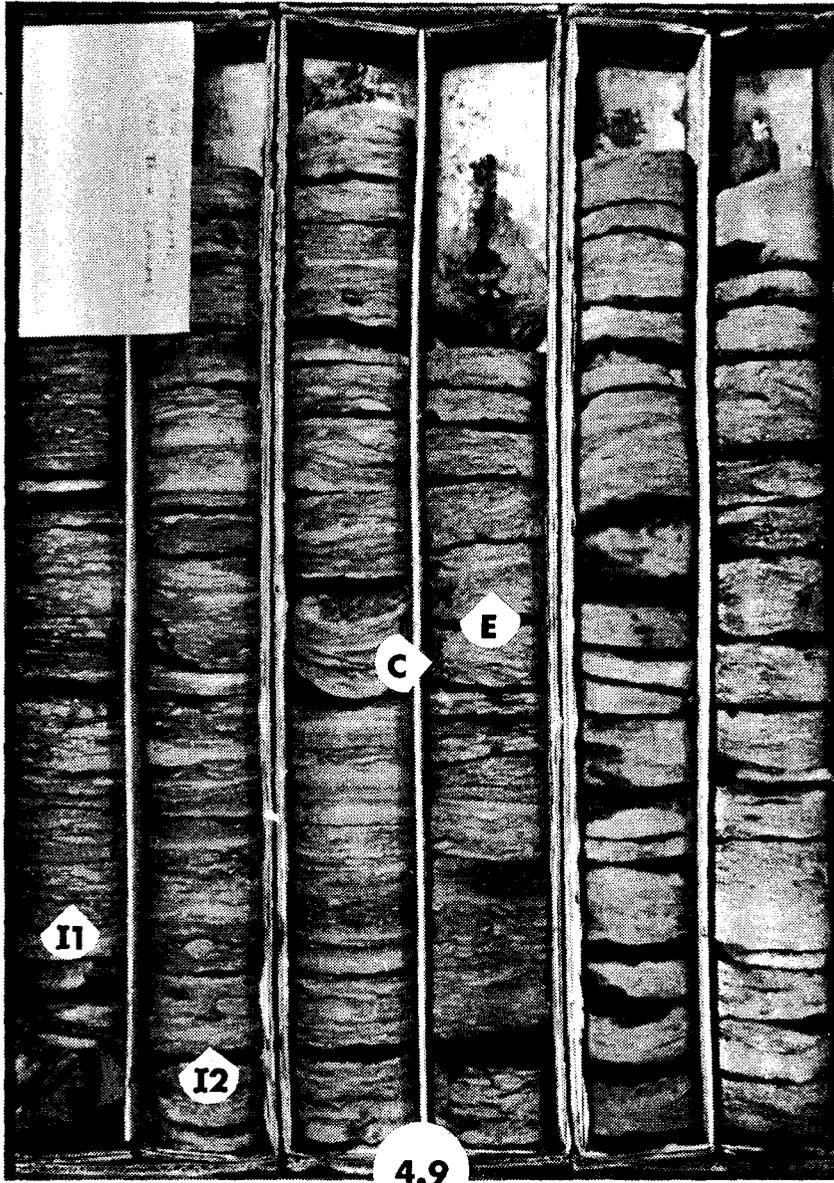


Figure 4.10. Facies E (package 5), and facies N and G1
(package 6). None of the contacts between the three facies
are preserved in core. Photo is of 10-6-31-22.

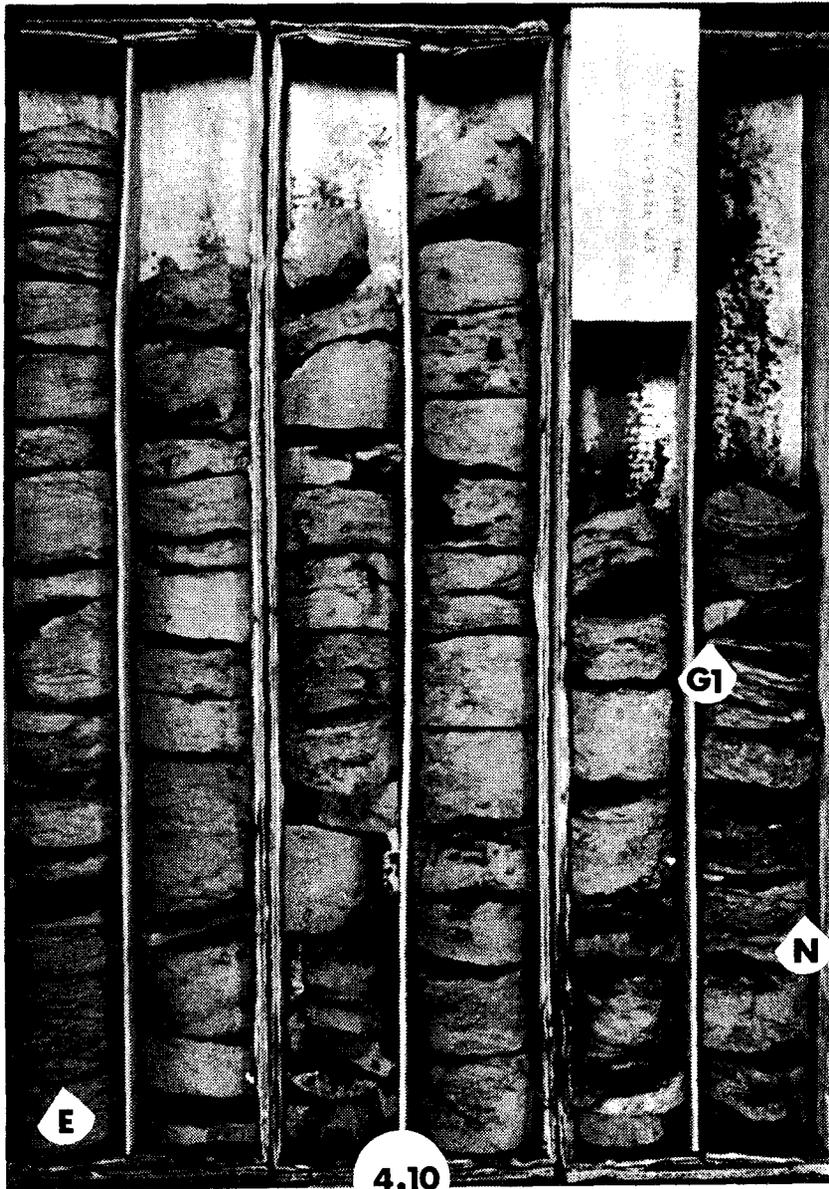


Figure 4.11. Facies A (package 1), facies I2 (and possibly I1) (package 4, or 3 and 4), and facies E (package 5). The contact between facies A and the overlying facies (C) is not preserved. The interval between facies A and E is tentatively interpreted as facies I2. The thickness of this interval is almost exactly the same (2.44 m) as both facies I1 and I2 combined in 10-6 (2.42 m, Figure 4.9), but no "muddying upwards" is apparent in this interval. Also the bentonite (presumably the "L" bentonite) in the third column from the left (L) occurs at roughly the same stratigraphic level (relative to the top of facies A) as the "L" bentonite which occurs near the contact between facies I1 and I2 in other wells. The contact between facies E and I2 (Co) is sharp. Photo is of 4-32-30-22.



Figure 4.12. Facies E, F, and I (package 5). The leftmost box shows the continuation of facies E (from Figure 4.11) up to the sideritized muddy layers (S). Above these sideritized mud layers facies E intertongues with facies F and I. Note the relatively muddy tongue of facies I near the top of the third box from the left. Below this tongue of facies I, tongues of facies F become muddier upwards, while above facies I, tongues of facies F become cleaner upwards. The bentonite (O) in the rightmost column occurs within facies E and is interpreted (based on the stratigraphic position) as the "O" bentonite. Photo is of 4-32-30-22.

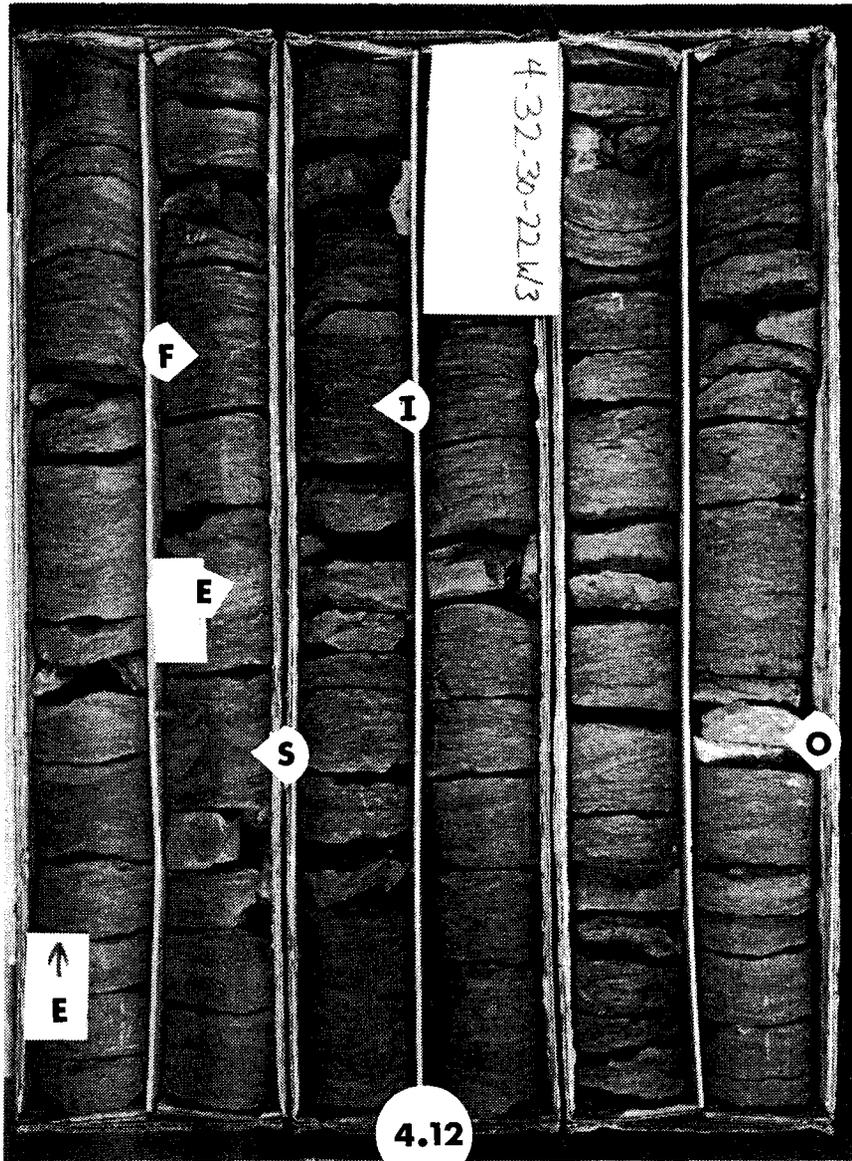
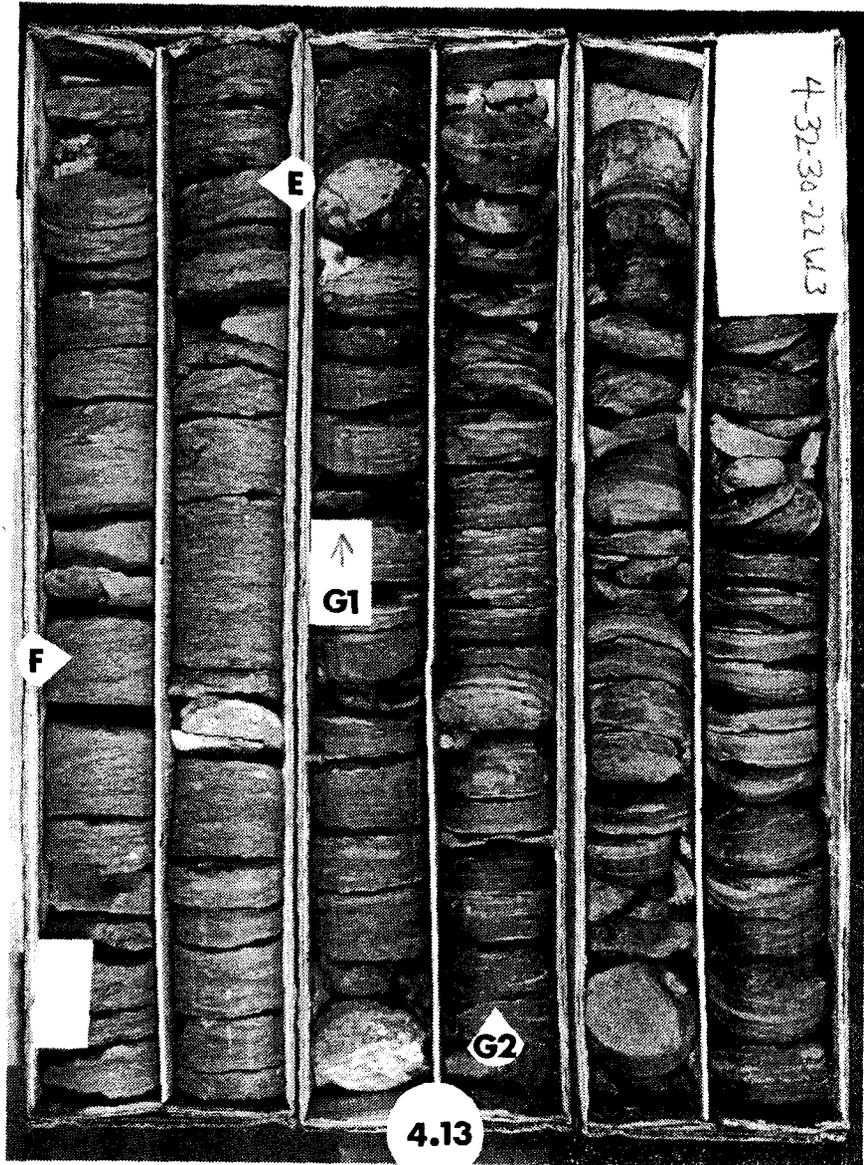


Figure 4.13. Facies E and F (package 5), facies G1 (package 6), and facies G2 (package 7). The leftmost box in this Figure overlaps with the rightmost box in Figure 4.12. The contact between facies G1 and G2 is not preserved, but is taken at the relatively "muddiest point" between the two facies (near the bottom of the fourth column from the left).



CHAPTER 5. SUMMARY AND DISCUSSION

5.1 SUMMARY

Seven packages, bounded by unconformities or muddy horizons can be identified within Viking Formation sediments at Eureka (Figure 4.2). These seven packages can be further grouped into four distinct packages based on:

- A) The facies and facies sequence within these packages,
- B) The overall grain size trends within the packages, and,
- C) The nature of the bounding surfaces between these packages.

These five distinct packages are:

1) PACKAGES 1 AND 7

Both packages consist mostly of offshore muds. The sediments within these packages are relatively flat lying as compared with the other packages (except package 6). Facies A (packages 1 and 7) is interpreted to have been deposited in a quiet offshore setting. Facies G (package 7) represents silt transported as suspended load into an offshore setting during storms and deposited below storm wave base.

2) PACKAGES 2 AND 4

Both packages are composed of the same facies: facies C is the same as facies I2 except that C does not contain glauconite, and facies C forms the bulk of package 2. Both packages are bounded at the base and top by surfaces representing pauses in sedimentation, either unconformity surfaces or muddy horizons. In facies C and I2, the rare occurrence of wave ripple lamination, the absence of angle of repose cross-lamination, and the bioturbated nature of these facies suggests deposition in an offshore setting above storm wave base but below fair-weather wave base, where biological processes overwhelm any physical reworking of the sediments.

3) PACKAGES 3 AND 5

Both packages mostly coarsen upwards with a fining upwards in their upper parts. Both are bounded at the base and top by either unconformity surfaces or muddy horizons. In both packages the facies become muddier southwards and facies E intertongues with facies I. In facies E the bioturbated nature of the sediments and rare wave ripple lamination suggests deposition in an offshore setting below fair-weather wave base but above storm wave base.

PACKAGE 6

Package 6 is bounded at the base by an unconformity and at the top by a muddy horizon. This package becomes

muddier upwards. It is relatively flat lying compared to the other packages (except 1 and 7). The ichnofauna and lack of storm related structures in facies G1 suggests deposition offshore near or below storm wave base. Facies N is interpreted to have been deposited offshore below fair weather wave base.

DISCUSSION

Evans (1970) initially suggested that Viking sediments in the Eureka area were deposited by "east flowing tidal currents", and implied a continuous "imbrication" or building of "members" southwards. This study shows that the Viking packages are not tidal deposits in that they lack any sedimentary features associated with modern and ancient tidal deposits such as cross-bedding, reactivation surfaces, tidal bundles, or spring-neap cycles. Rather this study shows that Viking sediments at Eureka are packages bounded by unconformity surfaces or muddy horizons, deposited entirely offshore. It also shows that the bulk of the sediments at Eureka offlap in a southerly direction, but do so with intermittent pauses in sedimentation. Other working cross-sections drawn from northeast to southwest (but not included in the thesis) also show a southwards offlapping of Viking packages.

Figure 4.2 shows that within these offlapping packages most of granular material (facies N in package 3 and 6), and the granular horizons in 2-23 and 4-12 in package 5

occurs at the southern end of each package, and directly overlies unconformable or disconformable surfaces.

Figure 4.2 shows that aside from the base of package 2 (line 7) the package boundaries between packages 1 and 6 are subparallel. The slope of line 12 (Figure 4.2) between 9-25 and 10-6, relative to the datum and line 4 (Figure 4.2) was calculated. These values were then averaged in order to obtain a representative value of slope for this package boundary. This calculation gives a slope value of 0.035 degrees. This value of slope is discussed briefly in chapter 6.

CHAPTER 6. INTERPRETATION

6.1 VIKING PALEO GEOGRAPHY

6.1.1 PREVIOUS INTERPRETATIONS OF VIKING SEDIMENTS :

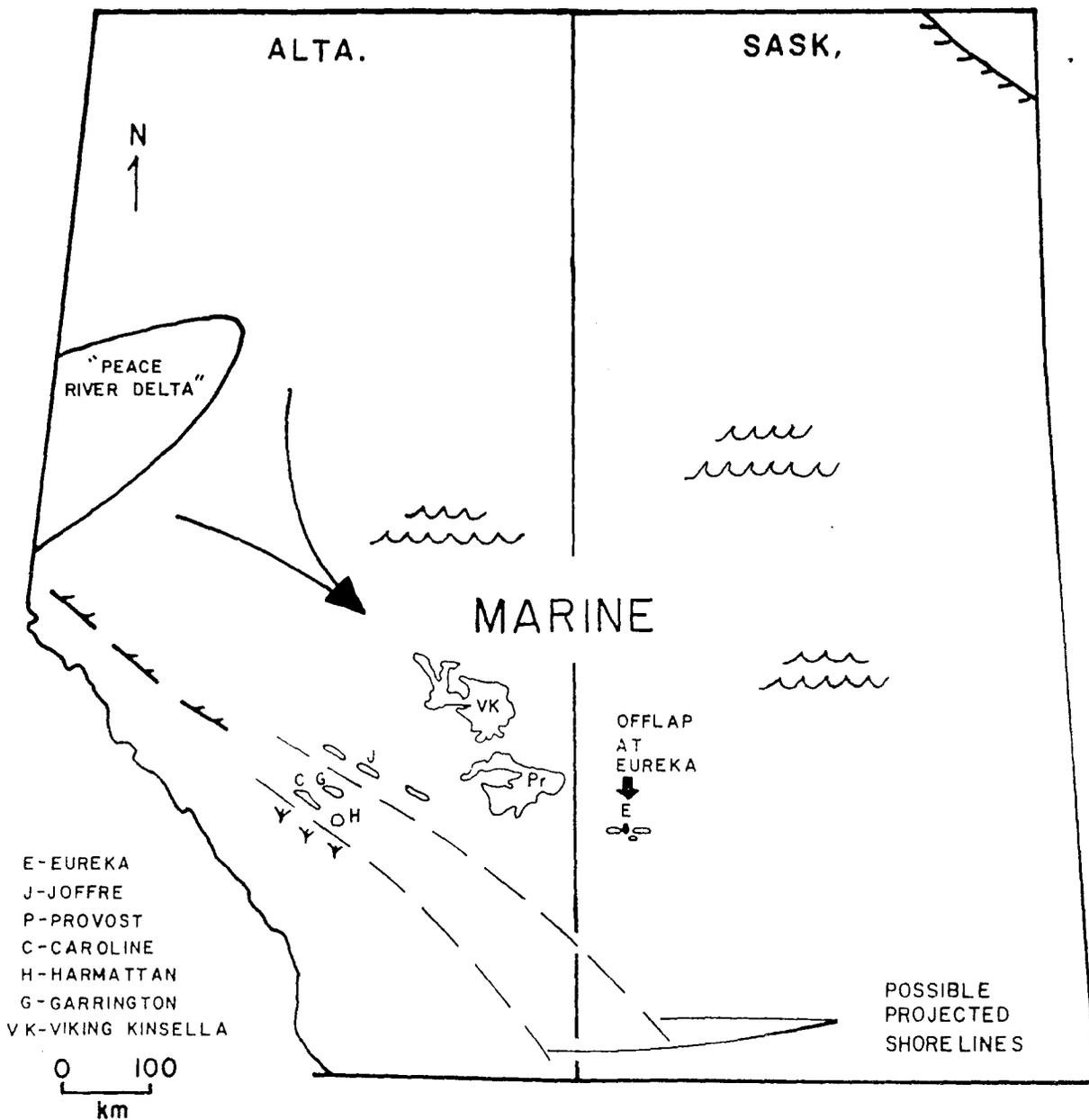
POSITION OF KNOWN SHORELINES AND POSSIBLE SOURCE AREAS

Figure 6.1 shows several reconstructions of Viking Paleogeography. In this Figure, the hatchured lines together with the "possible projected shorelines" shows the areal extent of Viking seas using data from Stelck (1958), Hein (1986), Leckie (1986), and Downing (1986).

Historically, most authors have suggested a westerly or southwesterly source for Viking sediments in southeastern Alberta and southwestern Saskatchewan. The interpretations of shoreline positions and sediment transport directions discussed below show some variability.

On the basis of isopach and isolith maps for the Lower Colorado Group, Lerand (1976) suggested that Viking sediments at Provost in southeastern Alberta were transported southeastwards by "longshore drift" (large arrow) from the "Peace River delta", located in northeastern Alberta. As shown in Figure 5.1, this would require that sediment be transported hundreds of kilometers to the south and east. Current interpretations regarding Viking sand bodies in northern Alberta (for example the Viking-Kinsella field) invoke an "offshore" setting (J.J.

Figure 6.1. This figure summarizes Viking paleogeography as described in chapter 6. The hatchured lines together with the lines labelled "possible projected shorelines" show the extent of the Viking seaway using combined data from Stelck (1975), Hein et al. (1986), Leckie (1986), and Downing (1986). The position of the "Peace River Delta" is taken from Lerand (1976). The large arrow shows the direction of sediment transport by "longshore drift" shown by Lerand (1976) for the Provost field. The small arrow illustrates the southwards offlap of Viking "packages" at Eureka.



Bartlett, pers comm., 1987). Several recent studies interpret shoreline or shoreface settings in the Caroline and Joffre areas of southwestern Alberta. Leckie (1986) interprets "shoreface" sediments in the Caroline area of southwestern Alberta. Likewise Downing (1986) interprets "shoreface" sediments at Joffre Alberta, nearly 100 kilometers to the northeast of Caroline. Hein et al. (1986) interpret "a shoreline attached to a clastic wedge" and an "offshore bar complex" in the Harmattan, Caroline, and Garrington areas. All three of these studies would put the shoreline facing northeast and land to the southwest. Amajor (1986) has interpreted "barrier islands" and "offshore tidal sand ridges" in south central Alberta and southwest Saskatchewan, although his evidence is inconclusive.

During Viking time, the Shield area was covered by carbonates, and supplied little or no clastic sediment, and then only to the eastern shelf area of the Viking seaway (Simpson, 1984, and Jones, 1961).

Consideration of the results of these studies would put the Eureka area in an offshore setting, which makes the possibility of a shoreline to north in Saskatchewan unlikely.

6.1.2 DISCUSSION

As shown above, previous studies of Viking sediments have suggested paleoshorelines and/or sediment sources from directions ranging from from north through west to south. The southwards offlapping of packages at Eureka may be difficult to explain in the context of what is currently known about Viking regional paleogeography. Projection of information about known shorelines suggests that the Viking shoreline most likely lay to the south and west of Eureka.

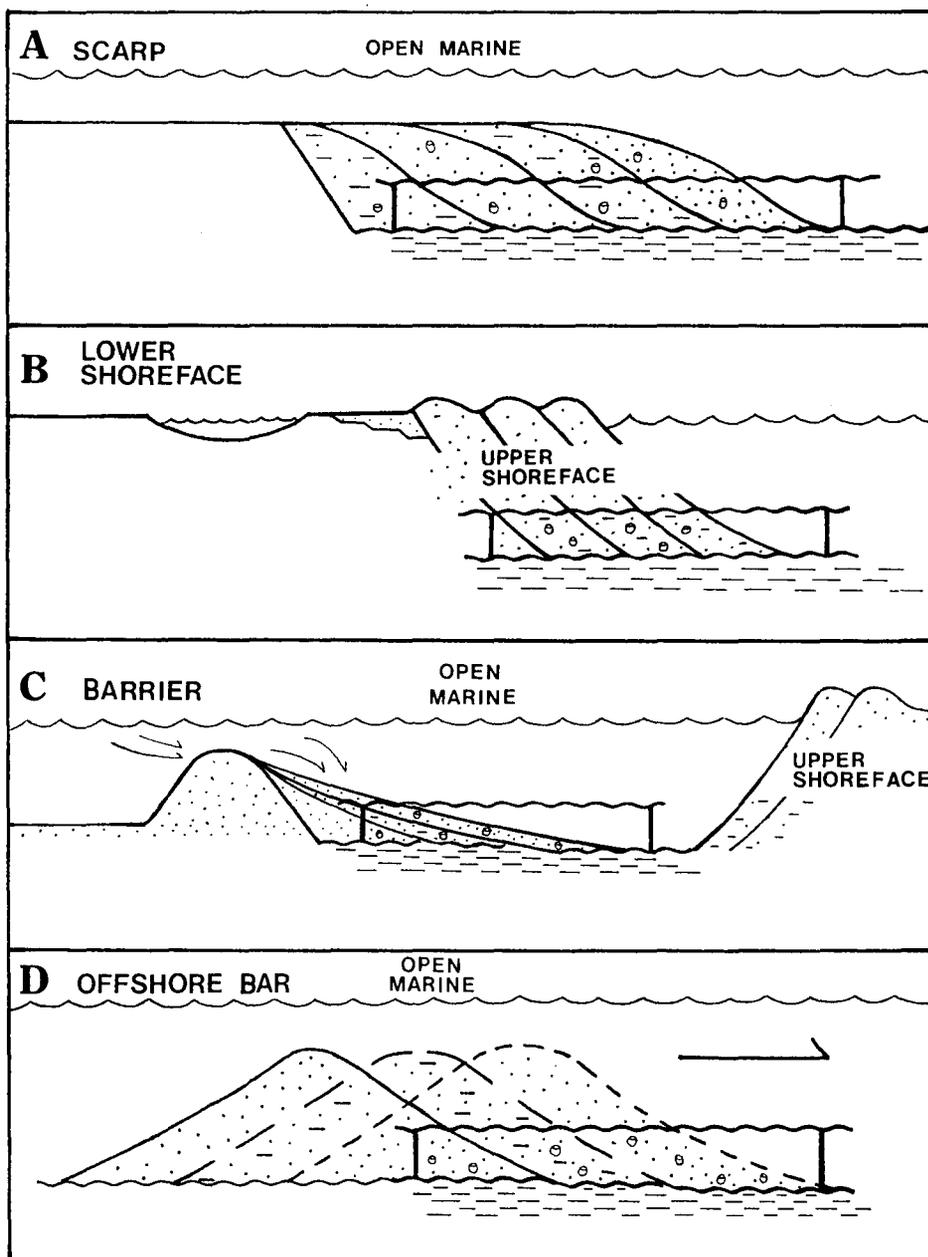
6.2 POSSIBLE INTERPRETATIONS OF VIKING SEDIMENTS AT EUREKA

Figure 6.2 illustrates four possible origins (discussed below) for the southwards offlapping packages observed at Eureka. These are:

- 1) The existence of a southerly facing shelf "scarp" across which Viking sediments prograded.
- 2) Southerly progradation of shoreface deposits.
- 3) Reworking of a barrier island developed on the edge of a submerged delta lobe.
- 4) Southwards migration of an "offshore bar".

In Figure 6.2 the squiggly lines at the top and base of the rectangular boxes represent the unconformities shown in Figure 4.2, which occur at the base (lines 7 and/or 9 and/or 13) and near the top (line 17) of the Viking. The implication is that the geologic record at Eureka

Figure 6.2. This Figure illustrates 4 possible interpretations for the genesis of offlapping Viking packages at Eureka, as discussed in the text.



represents an incomplete record of the environment in which these packages formed.

1) Southerly facing "scarp".

The southwards offlapping of Viking packages could suggest progradational infilling of a southerly facing shelf scarp as shown in Figure 6.2A. Examples of this type of feature are known from the Middle Atlantic Bight (Swift et al., 1973), and the New Jersey continental shelf (Stubblefield et al., 1984).

Swift et al. (1973, figure 2.A-c, p. 228) show a schematic profile of the shelf sector. This profile is similar to that shown in Figure 6.2A and contains two relatively flat shelf segments (resulting from shoreface erosion) separated by a more steeply dipping segment. The relatively flat segments are formed during transgression by erosional shoreface retreat, while the more steeply dipping segment is formed during stillstand. In this example, degraded barriers resting on the scarp surface erosionally overlie lagoonal deposits.

The New Jersey continental shelf scarp (Stubblefield et al., 1984, figure 6, p. 10) has a slightly different geometry. In this example there are two more steeply dipping (seawards) segments separated by a relatively flat segment. However, two of the profiles presented (A and C) show a steep seaward facing scarp. In this example, the

scarp profile is the result of erosional shoreface retreat, with no mention of a stillstand, and the degraded barriers which rest on the scarp overlie foreshore muds.

Both of the profiles described above are the result of erosional shoreface retreat, and hence both could account for the erosive base of the Viking observed at Eureka. Once such a scarp was cut, it could be infilled with offlapping sediment packages during periods of progradation. Minor increases in the magnitude of successive relative sea level falls between these progradational events could account for the erosive base of the Viking, and the successively deeper downcutting southwards of younger packages boundaries as observed at Eureka. The muddy horizons observed at Eureka could be explained by relative rises in sea level and transgression.

One problem concerns the fact that in both of these modern examples, the slope of the scarp faces seawards or offshore. Therefore any resulting offlapping geometry would offlap seawards, not shorewards as is apparently the case at Eureka. In light of the regional paleogeography which places the area north of Eureka in an open marine setting, the origin of the postulated scarp would be difficult to explain.

2) Shoreface deposits.

The progradation of shoreface deposits is another possible explanation for the offlapping packages observed at Eureka. This example is illustrated in Figure 6.2B.

Recent studies of the Cardium Formation by Flint et al. (1986) and the Viking by Downing (1986) have documented the existence of several unconformity surfaces described as "lowstand shorefaces". These result from a seawards shift of the shoreline during a lowering of relative sea level. As in example 1, periods of progradation (regression) with minor increases in the magnitude of relative sea level fall between these progradational periods, could generate the offlapping pattern, the erosional Viking base, and the successively deeper downcutting southwards of successively younger package boundaries, as observed at Eureka. As in example 1 above, the muddy horizons could be explained by transgression.

There is no concensus on a definition for the "lower part" of the "lower shoreface" (Walker, 1985), and many workers consider the base of the "lower shoreface" to be storm rather than fair weather influenced. This definition might suggest that Viking sediments at Eureka, particularly facies E (in packages 3 and 5) might be interpreted as lower shoreface sediments where sand is moved only during storms. There would be ample time in between for mud deposition, or complete biological reworking.

Another definition of the shoreface suggests that the base of the lower shoreface be taken at fair weather wave base, above which sand sized sediment moves on a day to day basis. If we accept this definition, one might expect to see more physical sedimentary structure than is preserved in facies E. McCubbin (1982, p. 259) shows current ripple lamination and parallel lamination in lower shoreface deposits for the low wave energy Galveston Island coast.

Also, the regional paleogeography again becomes a problem. If the offlap is southwards, the shoreline must have been north of Eureka.

The dilemma that arises from this discussion is whether the features in the sediments described above so strongly suggest "lower shoreface" that the paleogeography described in section 6.1.1 has to be reconsidered. Alternatively, one may ask whether the paleogeographical evidence outweighs the likelihood that these are lower shoreface sediments.

I would suggest that the paleogeographical evidence, coupled with the lack of physical sedimentary structures preserved in the rock, outweighs the likelihood that Viking sediments at Eureka represent the shoreface deposits of a shoreline located somewhere to the north of Eureka.

3) Reworking of a barrier island.

Another explanation for the offlapping packages observed at Eureka is storm reworking of barriers on the edge of a submerged delta lobe. This possibility is illustrated in Figure 6.2C.

The initial formation of these barriers could be explained by an example such as the Lafourche or St. Bernard lobes of the Mississippi River delta. During active lobe building, sediment supply causes the lobe to build outwards. If the sediment supply to the lobe is cut-off (by channel avulsion and lobe switching), the lobe subsides, and the sands at the edge of the lobe are winnowed by waves and reworked into a beach ridge. If the lobe behind the ridge subsides further, the former beach ridge may become morphologically detached from the lobe, resulting in the formation of a barrier island.

The submergence of a Mississippi sized delta lobe could account for several of the characteristics of Viking packages at Eureka. The Lafourche and St. Bernard lobes are tens of kilometers in diameter. Submergence of such areally extensive lobes could result in a large open sound shorewards of the barrier, and the landwards displacement of the shoreline. Such a large open sound could have a high wave energy climate. Scouring by storm waves could result in erosional shoreface retreat and erosion through any delta-top deposits (such as rooted or vegetated zones)

from the submerged delta lobe, down into the underlying prodelta or offshore muds. This erosion could be responsible for the unconformity which occurs at the base of the Viking. This "open marine" setting could also account for the moderate-totally bioturbated or "offshore" character the of sediments at Eureka.

In a barrier island setting, the granules observed within sediments at Eureka could be supplied from the initial barrier island deposits, and could be incorporated into the offlapping packages during the destructive redistribution shorewards of the barrier sediments.

The reworking of barrier island deposits may not account for the abundance of glauconite observed within Viking sediments at Eureka. One might expect that wave reworking and winnowing of a barrier would result in a dearth of the parent substrates from which glauconitic sediments are generated. One example is fecal pellets. In an environment of wave reworking and winnowing, there would probably be little mud available to the system, and hence little biological reworking of the sediment, resulting in a dearth of fecal pellet material. The wave reworking and winnowing of a barrier island might however generate substantial shell debris, which is also known to be a "parent substrate" (K. Downing, pers comm.) for the formation of glauconitic material.

Redistribution of barrier sediments shorewards by storm waves as shown in Figure 6.2C could account for the observed shorewards offlap of sediments at Eureka. Minor increases in the magnitude of a series of relative sea level falls alternating with periods of barrier reworking (and the formation of offlapping packages) could account for the successively deeper downcutting southwards as exhibited by successively younger package boundaries at Eureka. The unconformity at line 17 in Figure 4.2 could result from a relative sea level fall and erosion of the top of the shorewards offlapping packages to give the preserved portion of the total stratigraphy, as shown in the box in Figure 6.2C.

In summary, this discussion shows that the destructive reworking of a barrier island on the edge of a submerged deltaic lobe could account for all of the features observed within Viking sediments at Eureka, as well as the apparent shorewards offlap of the packages.

4) Southwards migrating "offshore bar"

The migration of an "offshore bar" as illustrated in Figure 6.2D is another possible explanation for the genesis of the shorewards offlapping packages observed at Eureka.

Most examples of offshore bars from the modern represent former barrier islands or shoreface attached linear sand ridges formed during the Pleistocene lowstand,

and abandoned offshore by transgression and erosional shoreface retreat during the Holocene rise of sea level.

Three prominent examples of transgressed barriers and shoreface detached ridges include the Maryland continental shelf (Swift and Field, 1981), the New Jersey continental shelf (Stubblefield et al., 1984), and the Gulf of Mexico (Penland et al., 1986). All of these barriers or shoreface detached ridges have been abandoned offshore by the mechanism of erosional shoreface retreat described above. Erosional shoreface retreat could account for the erosional unconformity underlying the offlapping packages at Eureka. In all three examples described above, the barriers overlie lagoonal deposits or Pleistocene strata erosionaly.

Examination of changes in sea floor bathymetry (from bathymetric charts) over roughly a one-hundred year period shows that both the Maryland ridges (Swift and Field, 1981), and Ship Shoal (Penland et al., 1986) have shifted position on the sea floor. On the Maryland continental shelf, Swift and Field (1981) have documented the migration of offshore ridges between 1850 and 1933 (figure 6, p. 469). The problem is that these offshore ridges have migrated seawards and downdrift, not shorewards as would be required for the offlapping packages at Eureka. However, Ship Shoal has migrated 1.5 km landwards since 1850 (Penland et al., 1986). Shorewards migration of the front

of such a shoal during storms could account for the offlapping pattern of Viking packages.

Swift and Field (1981) describe megaripples and sand waves in the swales between ridges. They suggest that there were long periods of quiet conditions and biological activity between the flows which moved sediment, and generated the megaripples and sand waves. The biological reworking of any structures resulting from storm flows could account for the moderate to total degree of bioturbation observed within Viking sediments at Eureka. In Ship Shoal, two of the three facies within the migrating Shoal are at or below fair weather wave base and are strongly bioturbated (Penland et al., 1986). Presumably, any structures related to the postulated original barrier or linear ridge would be destroyed due to reworking during shoal migration. In Ship Shoal, no in situ barrier shoreline deposits were found within the Shoal.

The abundance of glauconite observed within Viking facies is difficult to explain in the context of sediments derived from former barrier islands and shoreface attached ridges. In their discussion of the Shannon Sandstone, Tillman and Martinsen (1984) state that interpreted shoreline deposits of the Cretaceous Seaway contain very little glauconite, and that soft clay grains such as glauconite are removed by "attrition" in a shoreline setting. Swift and Field (1981) describe "thicker mud

deposits" in the troughs between ridges. The presence of mud suggests relatively low sedimentation rates in the troughs. Increased biological activity between storm flows as described by Swift and Field (1981) could generate large volumes of fecal pellets. Under conditions of low sedimentation rates, glauconite could be generated from these fecal pellets. This glauconite could then be incorporated into the structure of the bar during migration. This mechanism might account for some of the glauconite observed within Viking facies at Eureka.

The muddy horizons between packages could result from a relative rise in sea level and transgression. These transgressive deposits could blanket the entire offshore bar, or possibly blanket only the flanks since the bar tops would be relatively higher (relative to sea level) than the associated flanks, and possibly within the reach of storm waves. If completely blanketed by transgressive muds, rejuvenation of the sandier source for facies E could be attributed to a lowering of sea level. This would result in erosion and removal of this muddy blanket overlying the crest of the bar, followed by reworking of the bar top and a new sand supply.

The erosional bases of package 3 and 5 could be attributed to wave scour due to a lowering of relative sea level. As for the reworked barrier in Figure 6.2D, the unconformity represented by line 17 in Figure 4.2, could

result from a lowering of sea level, and erosion by wave scour, of all but the shorewards offlapping portion of the bar, as shown in Figure 6.2D

The granule layers within interpreted "offshore" sediments at Eureka could be transported into an offshore setting during such a lowstand of sea level. Once offshore, these granules could be spread out as a lag during transgression, and reworked into an offshore bar during migration.

This discussion shows that like the reworking of a barrier island on the edge of a submerged deltaic lobe, the shorewards migration of an offshore bar could account for all of the features of Viking sediment packages at Eureka. This model could also account for the apparent shorewards offlap of the packages

6.2.1 UNCONFORMITY NEAR THE TOP OF THE VIKING AT EUREKA

Although not discussed in detail above, the unconformity which occurs near the top of the Viking (line 17 in Figure 4.2) has a similar interpretation to the other unconformities observed within these sediments. This unconformity is probably the result of wave scouring due to a lowering of relative sea level. The granules overlying this unconformity (such as in facies N) were probably transported to this area as a result of this lowstand of sea level, and reworked during the subsequent transgression.

6.2.2 DISCUSSION

Four models for the possible genesis of southwards offlapping Viking sediment packages at Eureka are presented. The progradational infilling of a southwards facing shelf scarp, and deposition in a southwards facing shoreface are rejected in light of the regional paleogeography, which puts the area north of Eureka in an open marine setting. A shoreface origin for Viking sediments is also rejected on the basis of the "offshore" character of Viking sediments. In the context of Viking regional paleogeography, the southwards redistribution of barrier island sediments or the southwards migration of an "offshore bar" are two possibilities which seem to account for all the the features observed within Viking sediments at Eureka, as well as the apparent shorewards offlap of the packages.

Evans (1970) initially suggested that Viking sediments in the Eureka area were deposited by "east flowing tidal currents" in a relatively "far from shore" marine environment. This study shows that Viking sediments at Eureka are not tidal deposits in that they lack any sedimentary features associated with modern and ancient tidal deposits, such as angle of repose cross-bedding, reactivation surfaces, tidal bundles, or spring-neap cycles.

Belderson (1986) gives a comparison of tidal sand ridges and "storm generated" sand ridges (table 2, p. 296). In this comparison he gives slope angles of approximately 6 degrees for tidal sand banks. The slope values given for storm generated sand ridges are 2 degrees or less, with a mean slope of 0.05 degrees for offshore ridges. The slope values quoted for offshore storm generated ridges are from the ridges of the Maryland continental shelf (Swift and Field, 1981). A slope of 0.05 degrees agrees well with the slope of 0.035 degrees calculated for the boundary between package 3 and 4 in chapter 5. This observation provides further evidence in support of a storm (not tidal) origin for the offlapping packages observed at Eureka.

CHAPTER 7. CONCLUSIONS

- 1) Viking sediments at Eureka are not tidal deposits but rather show characteristics of storm deposits.
- 2) At least 5 distinct "packages" bounded by unconformity surfaces or muddy horizons can be recognized at Eureka.
- 3) Two of these packages form the bulk of Viking sediments at Eureka, and "offlap" to the south.
- 4) In light of Viking regional paleogeography, the southwards redistribution of barrier island sediments, or the southwards migration of an "offshore bar" could account for all of the features of Viking sediments at Eureka, as well as the apparent shorewards offlap of the packages.
- 5) The presence of unconformities and muddy horizons within the Viking can be explained by minor fluctuations of relative sea level.

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APPENDIX 1

This appendix contains the additional cored wells examined outside the main Eureka field as shown in Figure 1.2. The letters in the center column between the log responses refer to the facies. The numbers and vertical arrows on the left side of the page shows the extent of the packages described in chapter 4, and shown in Figures 4.1 and 4.2. The letter "S" on the right hand log response refers to any siderites which occur, as described in section 3.4.4. The letters M-N, K, L, O, and Z on the right hand log response refer to the bentonites described in section 3.4.3, and shown in Figures 4.2-4.4. Depths in the two-thousand range are in feet, while depths in the hundreds are in meters. Facies, contact type, bentonites, and log markers outside the cored interval are interpreted from the logs.

CONTACT TYPE

 UNCONFORMITY OR DISCONFORMITY

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 GRADATIONAL

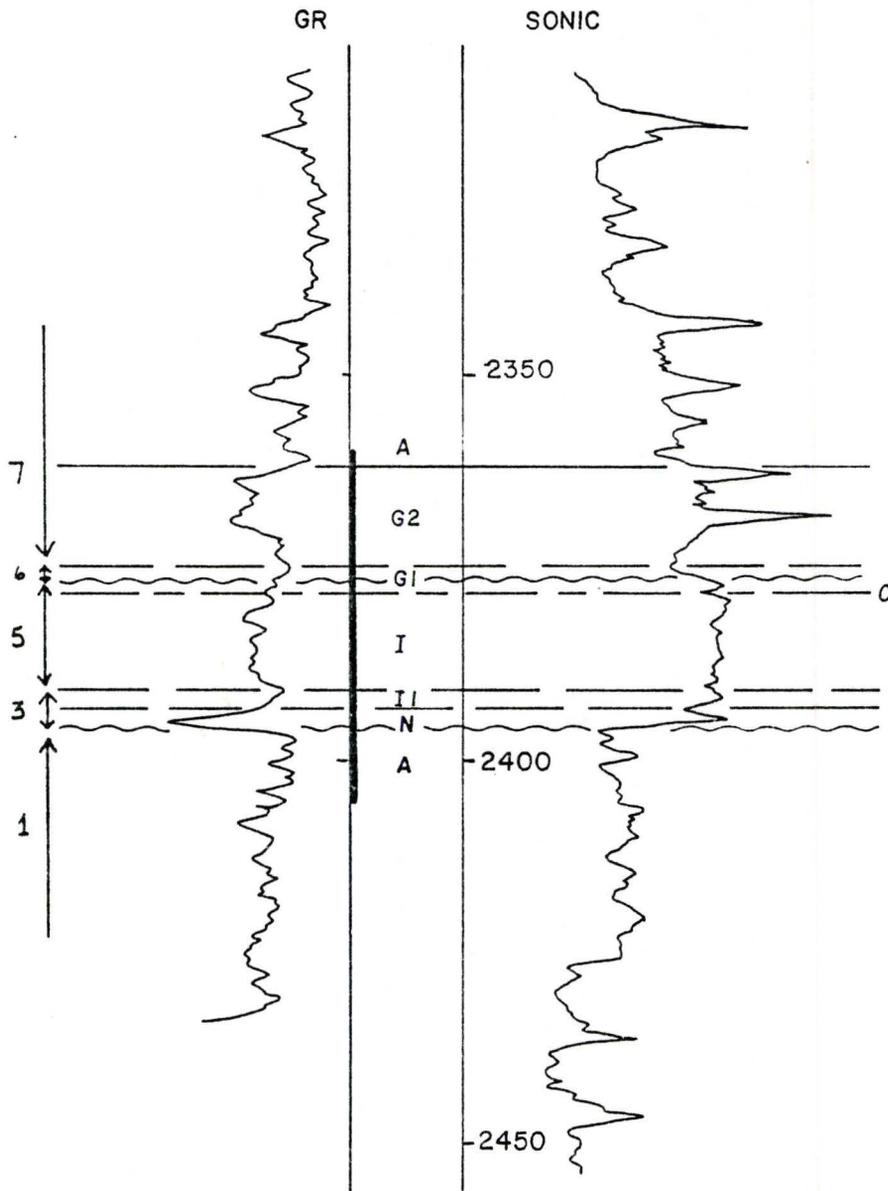
 BENTONITE

 LOG-CORE MARKER

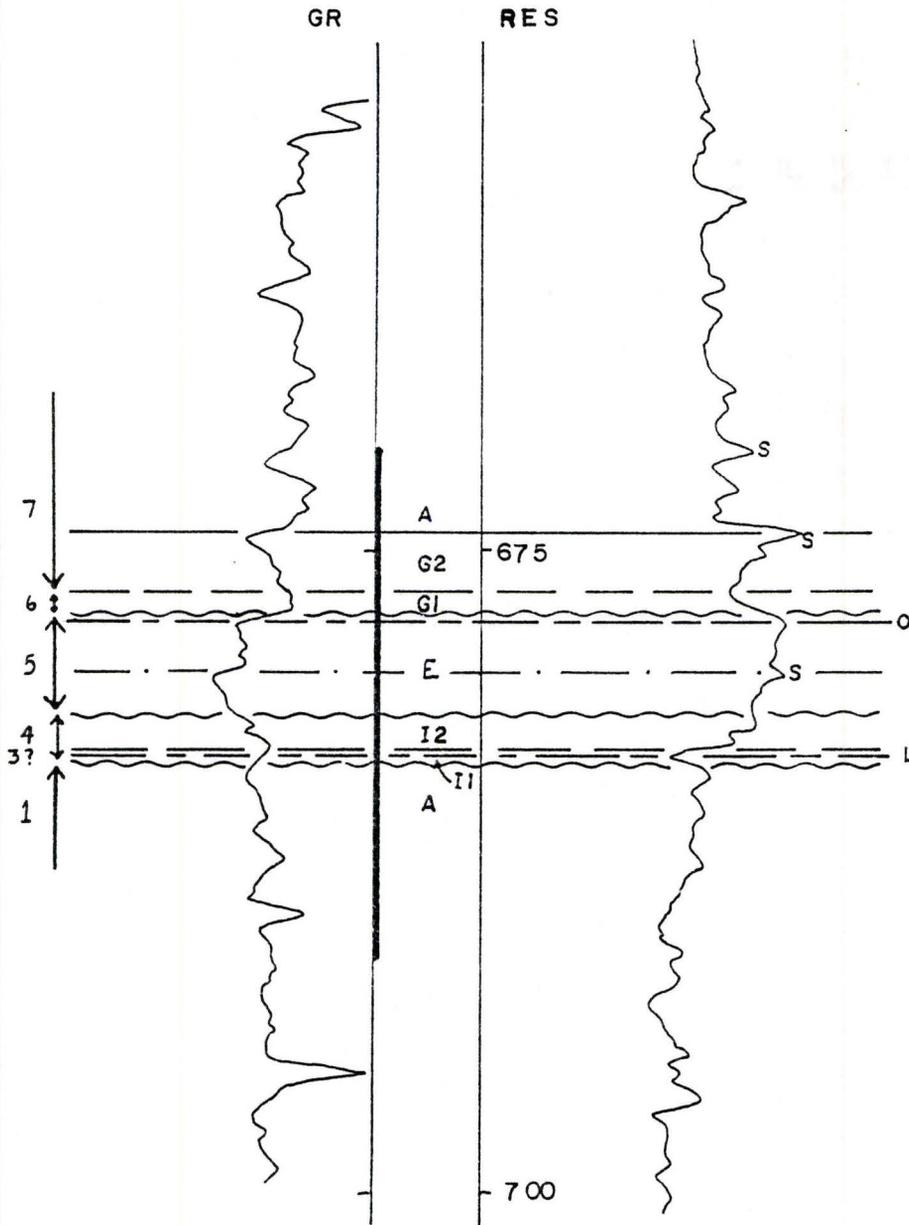
 CORED INTERVAL

MSG - MISSING CORE

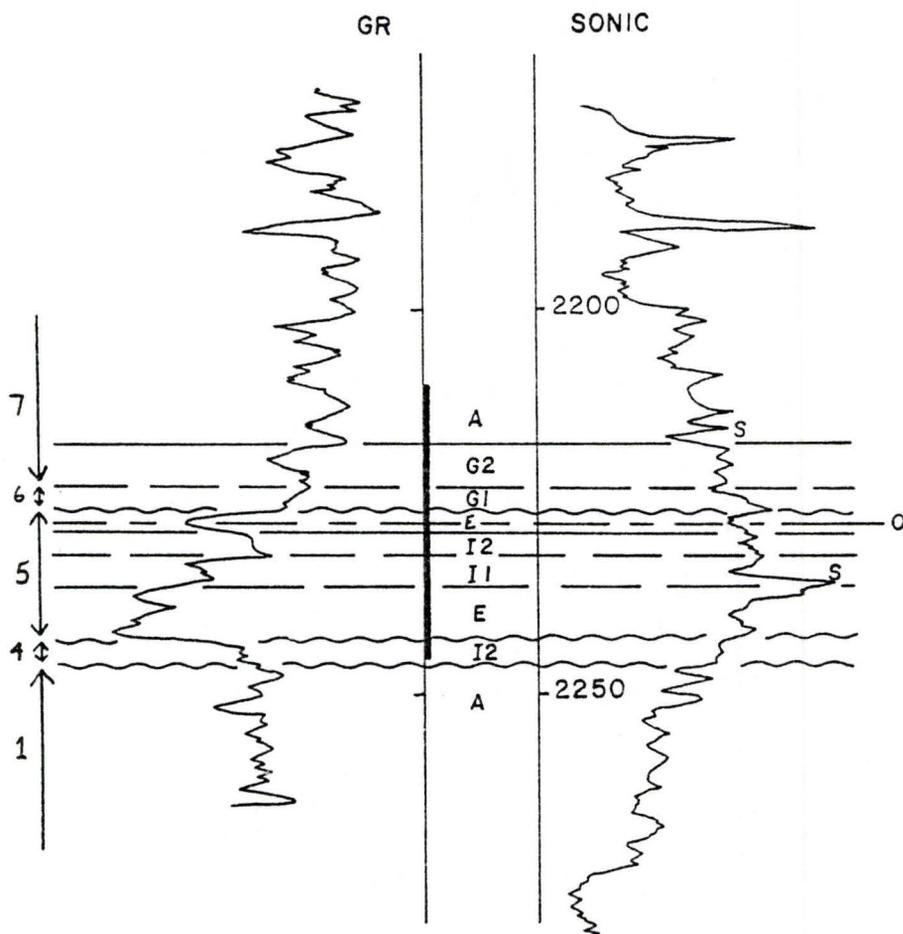
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11-25-30-22 W3



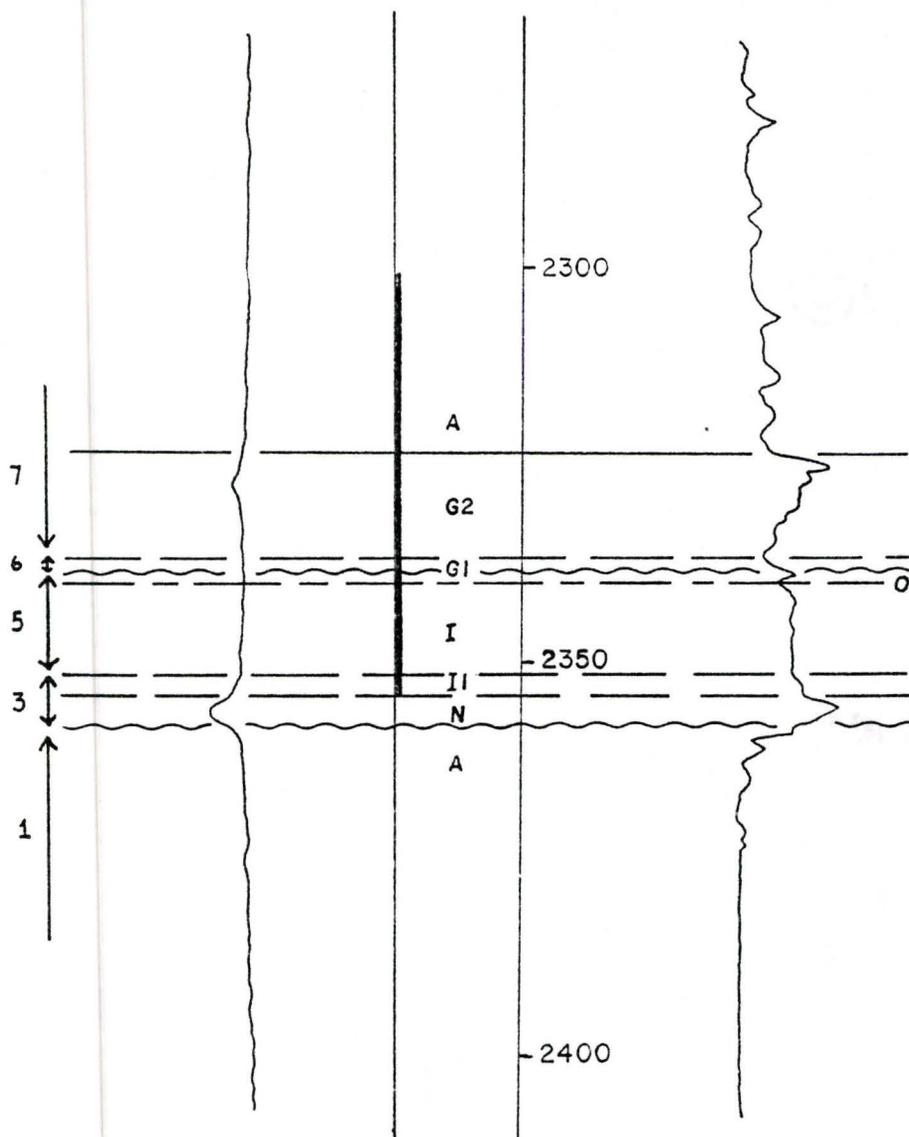
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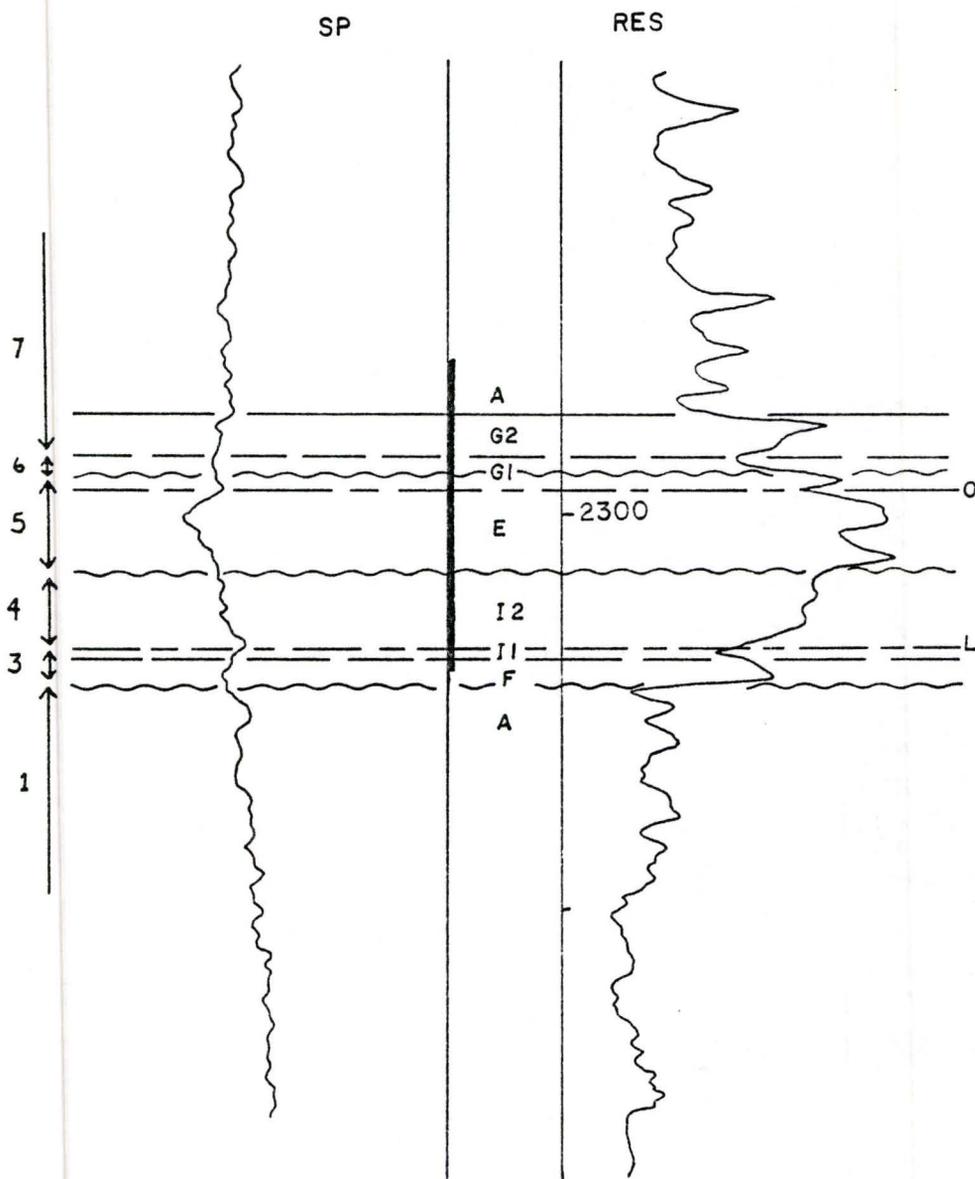
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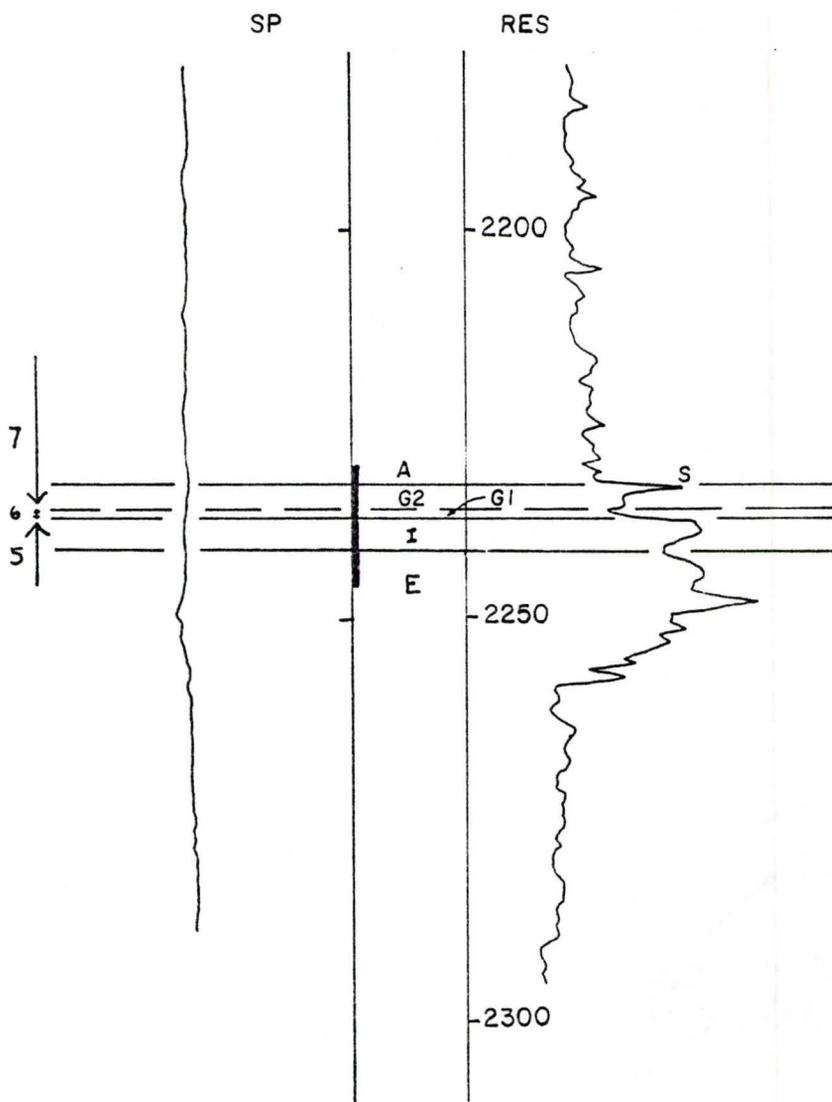
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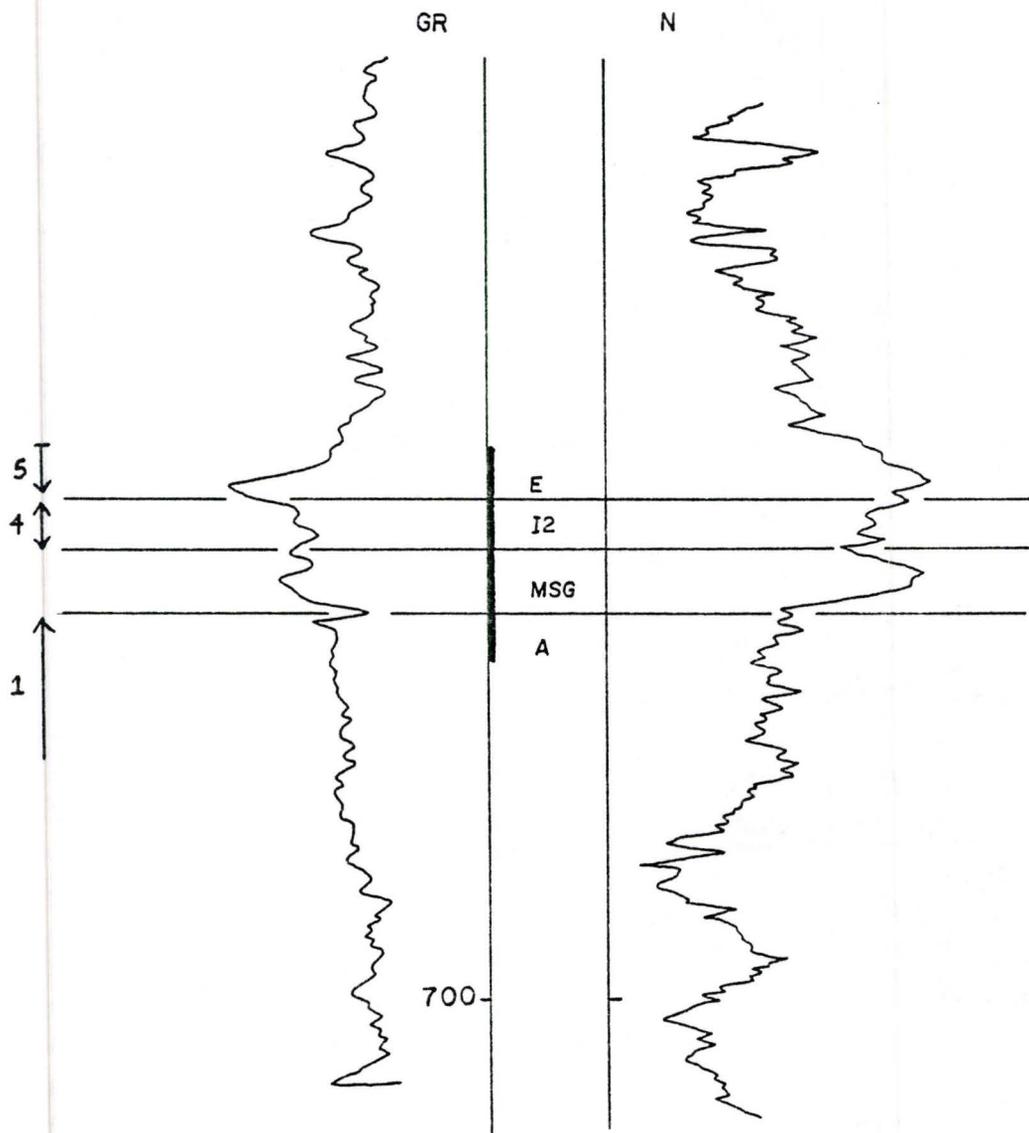
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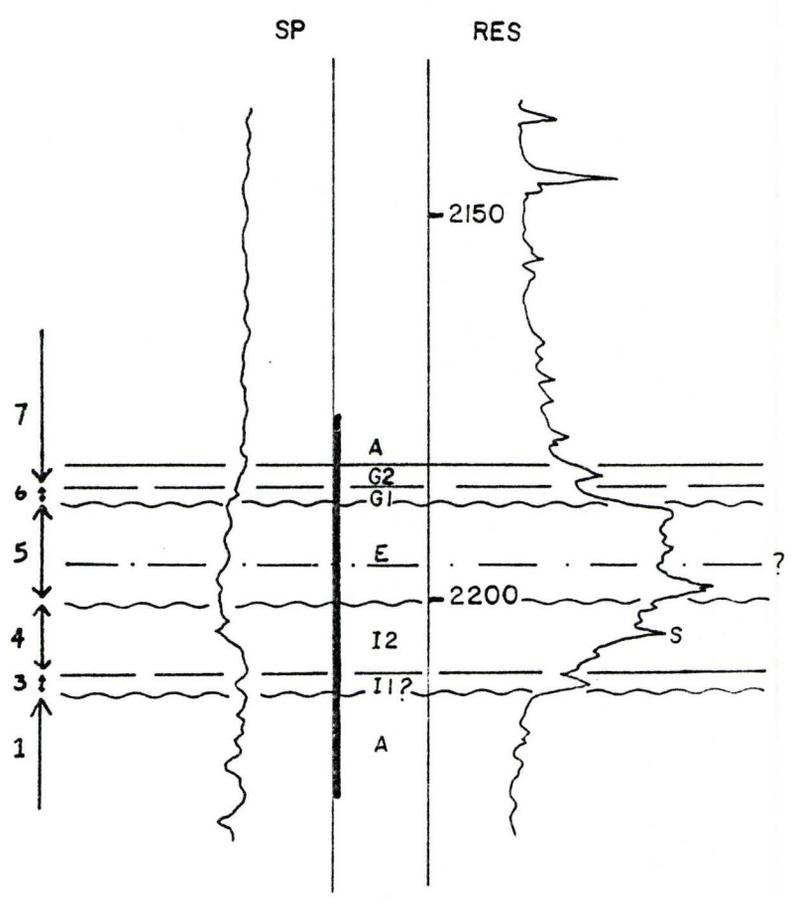
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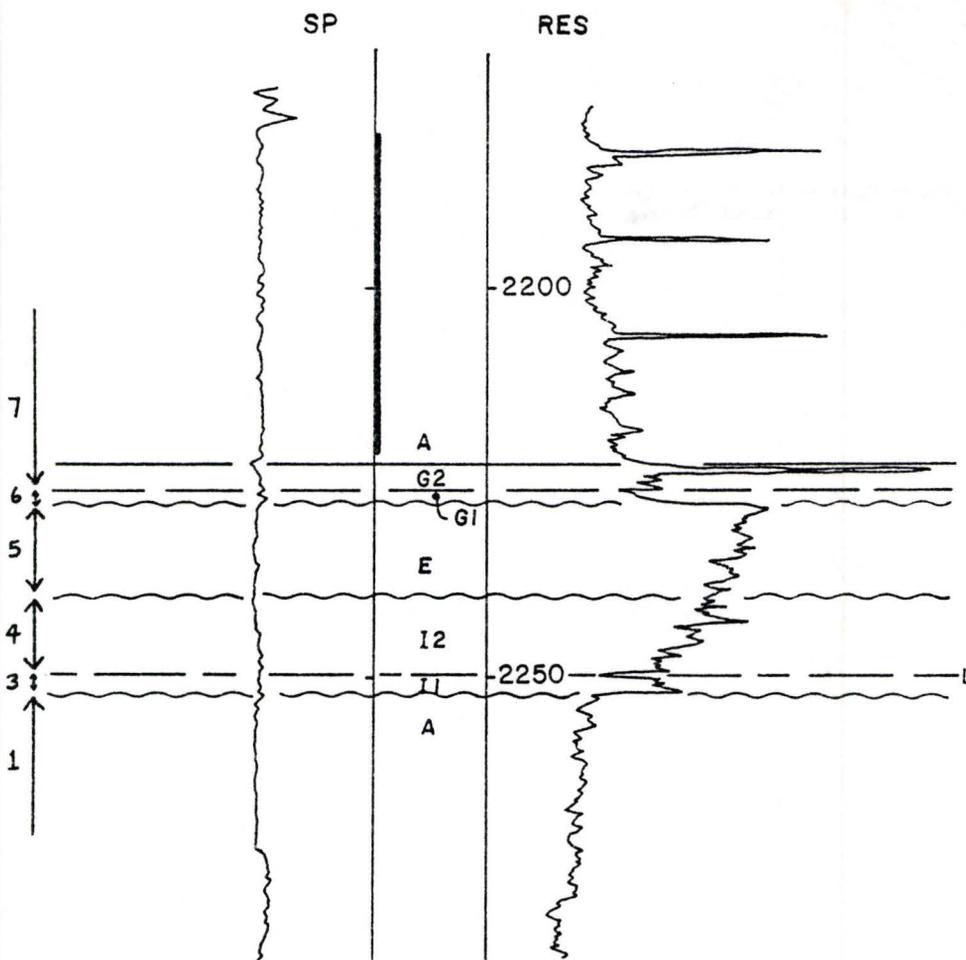
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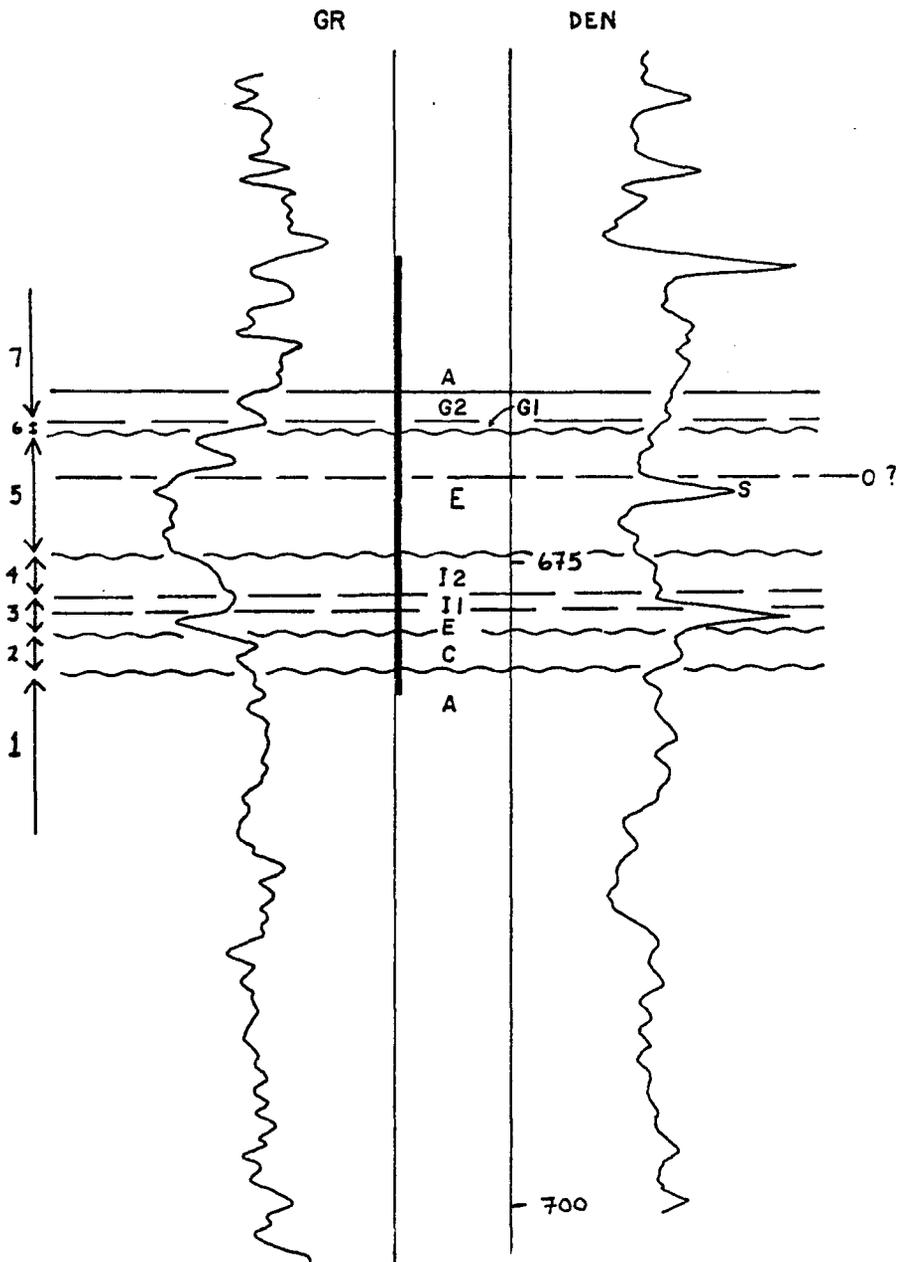
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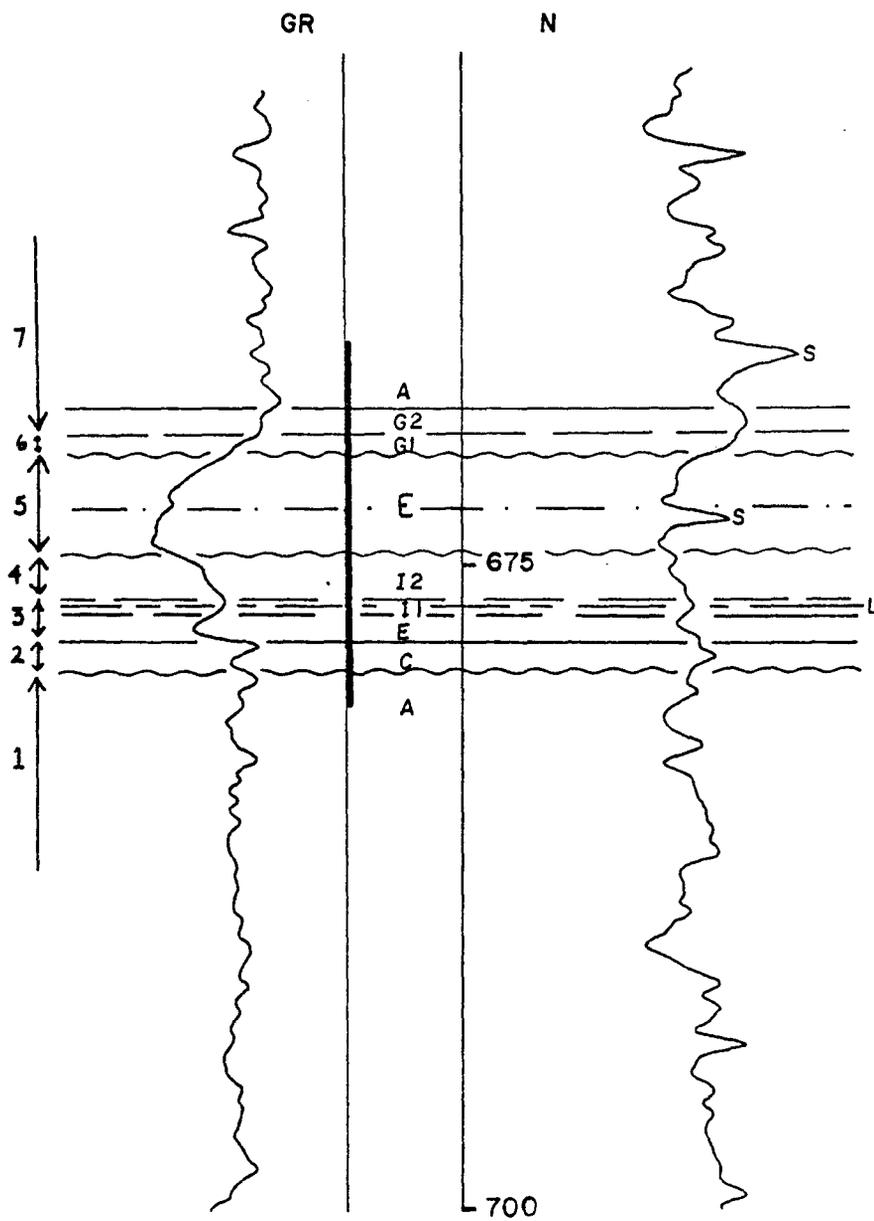
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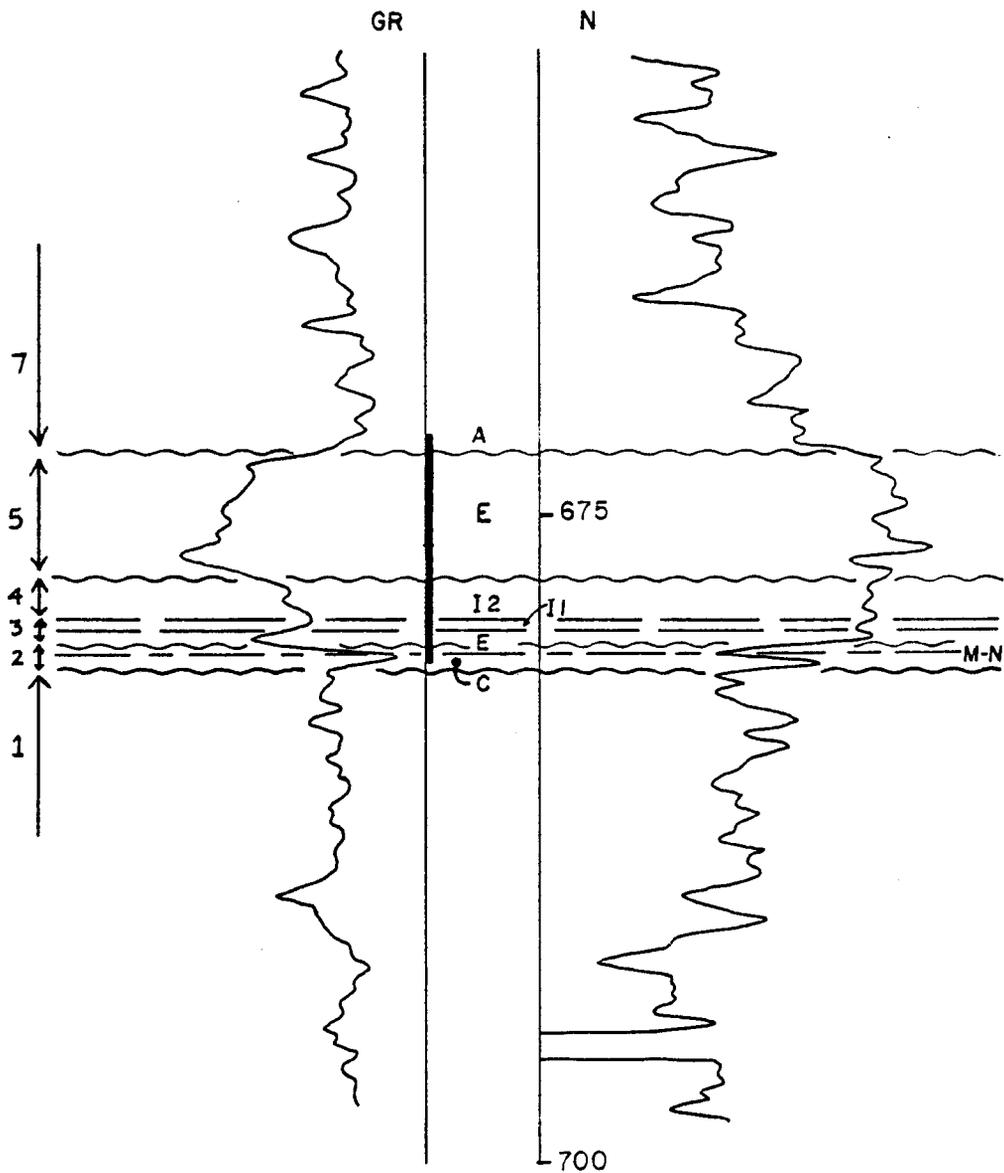
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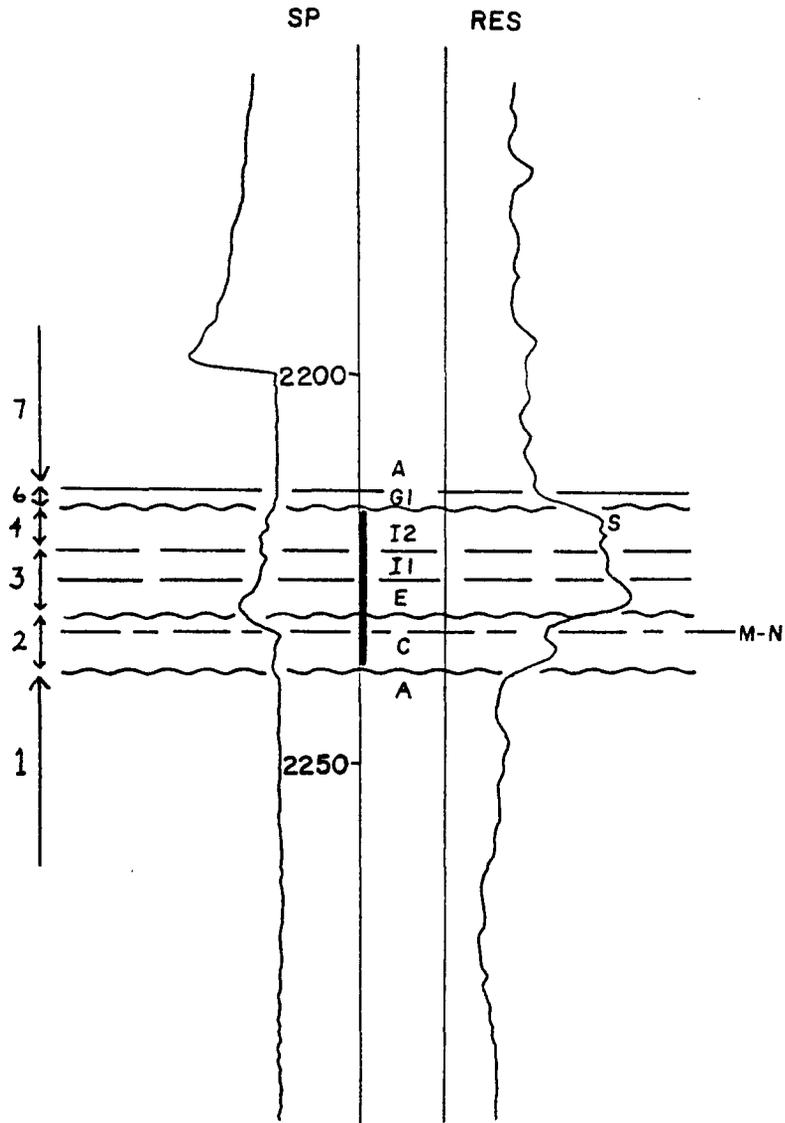
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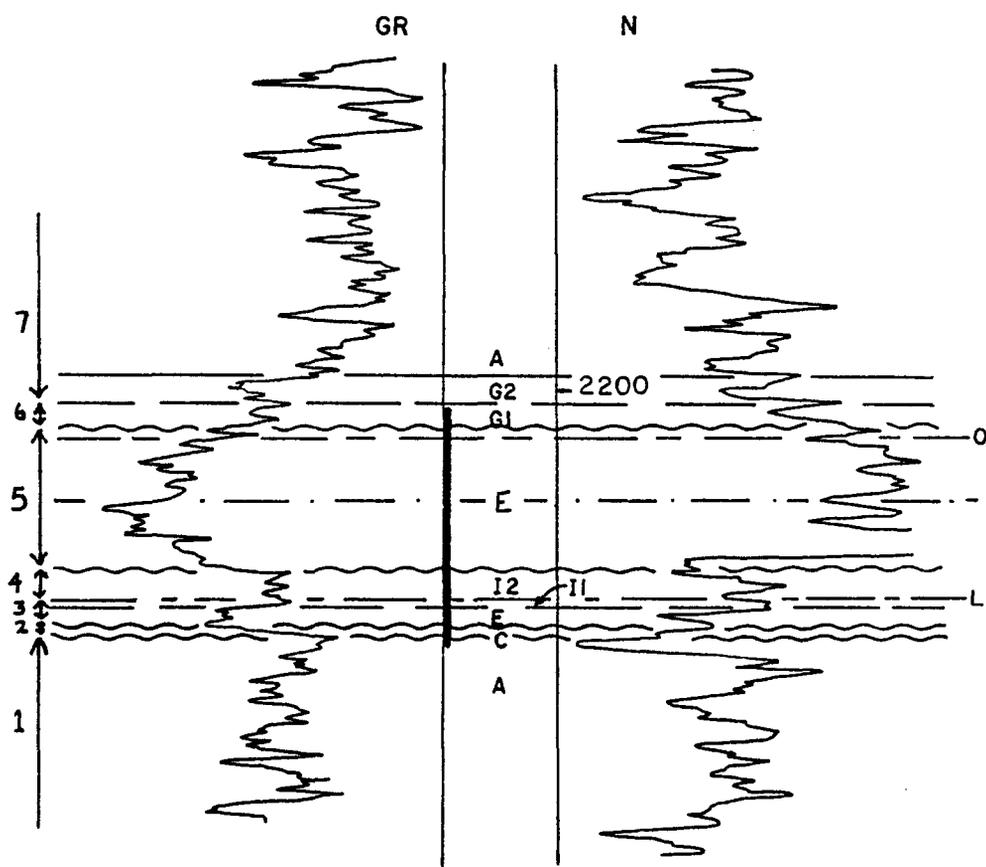
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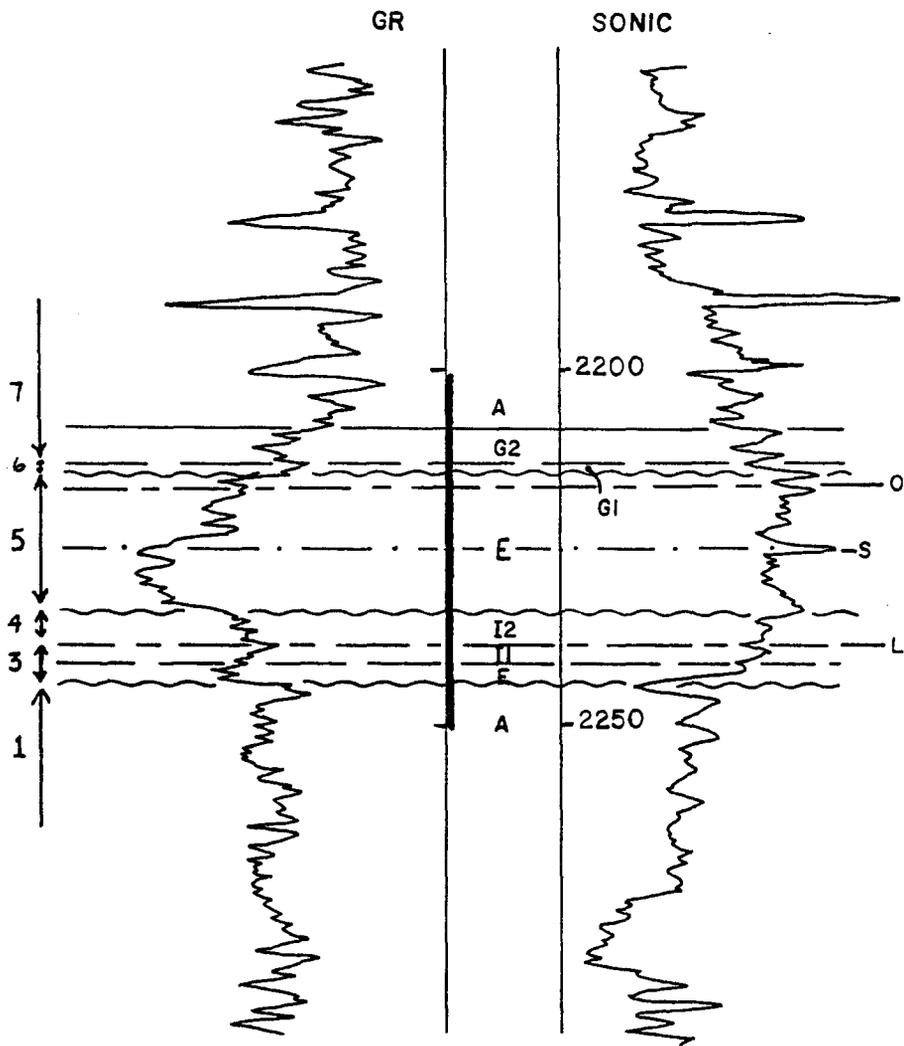
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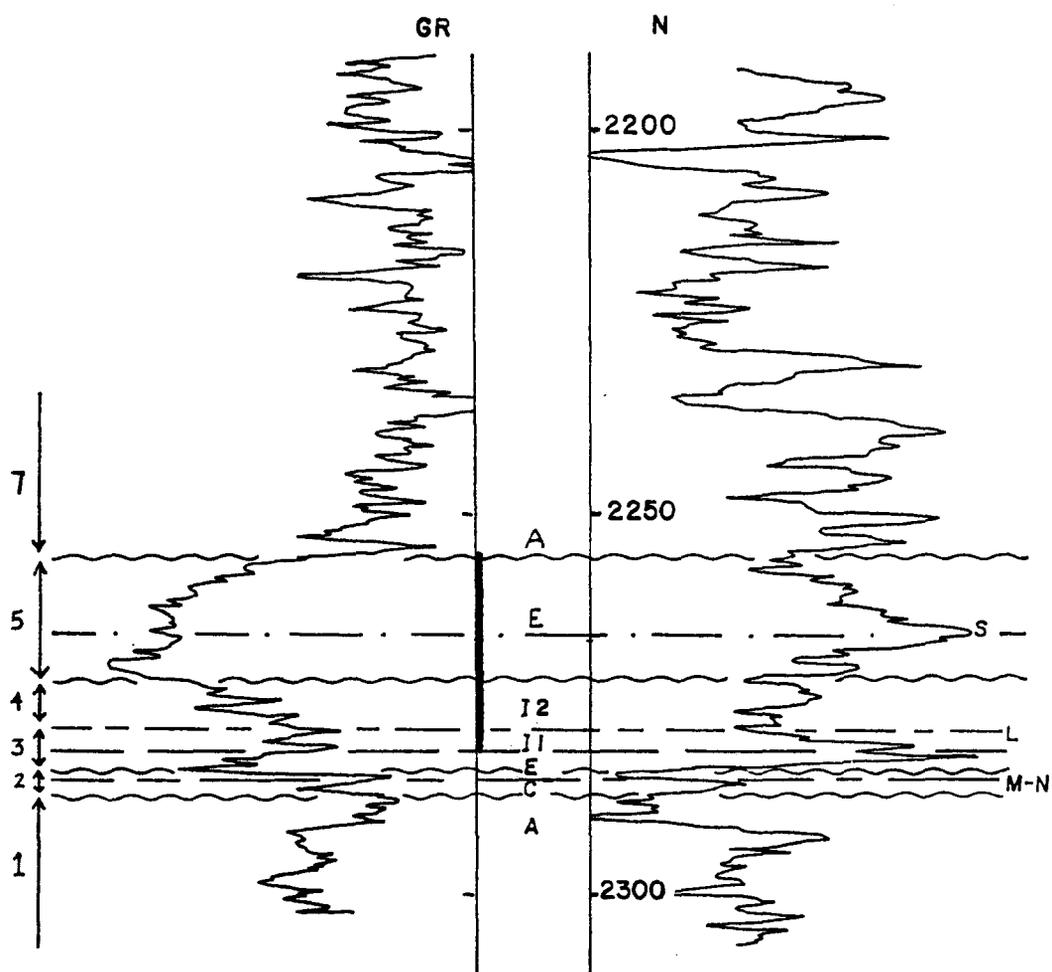
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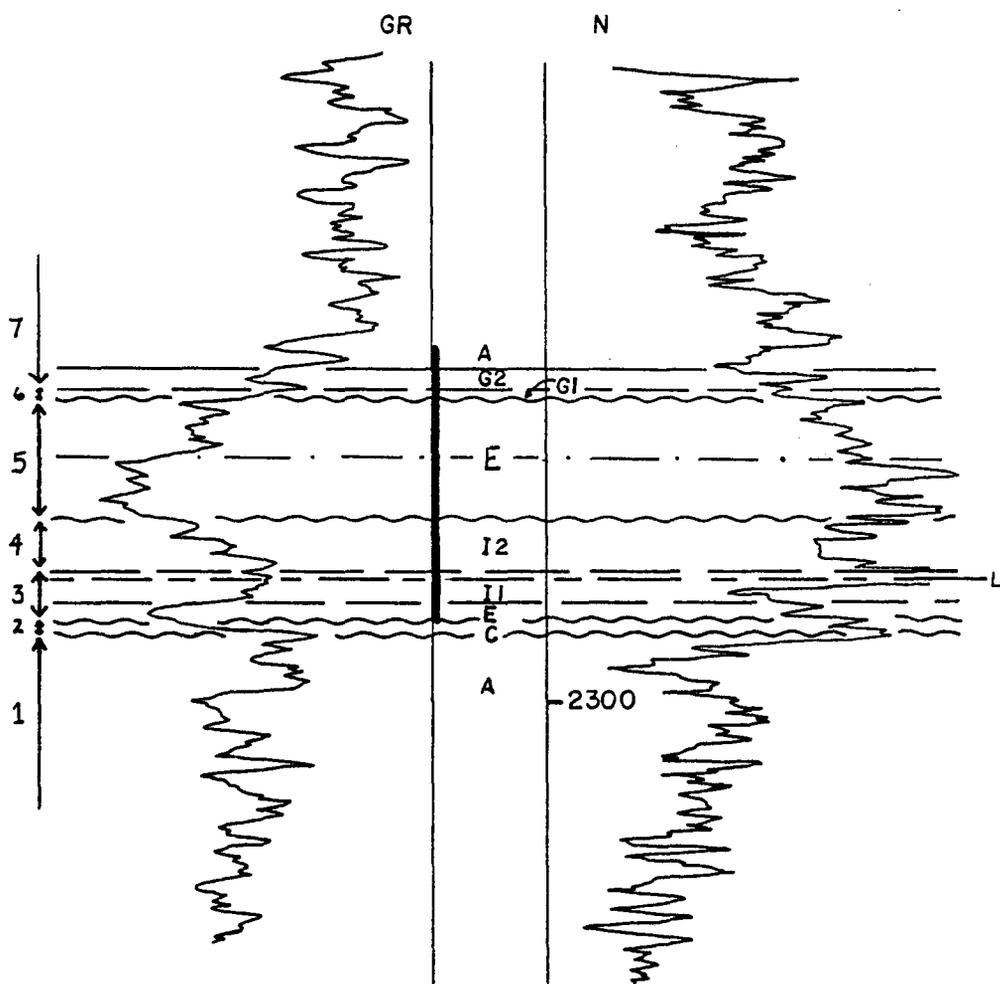
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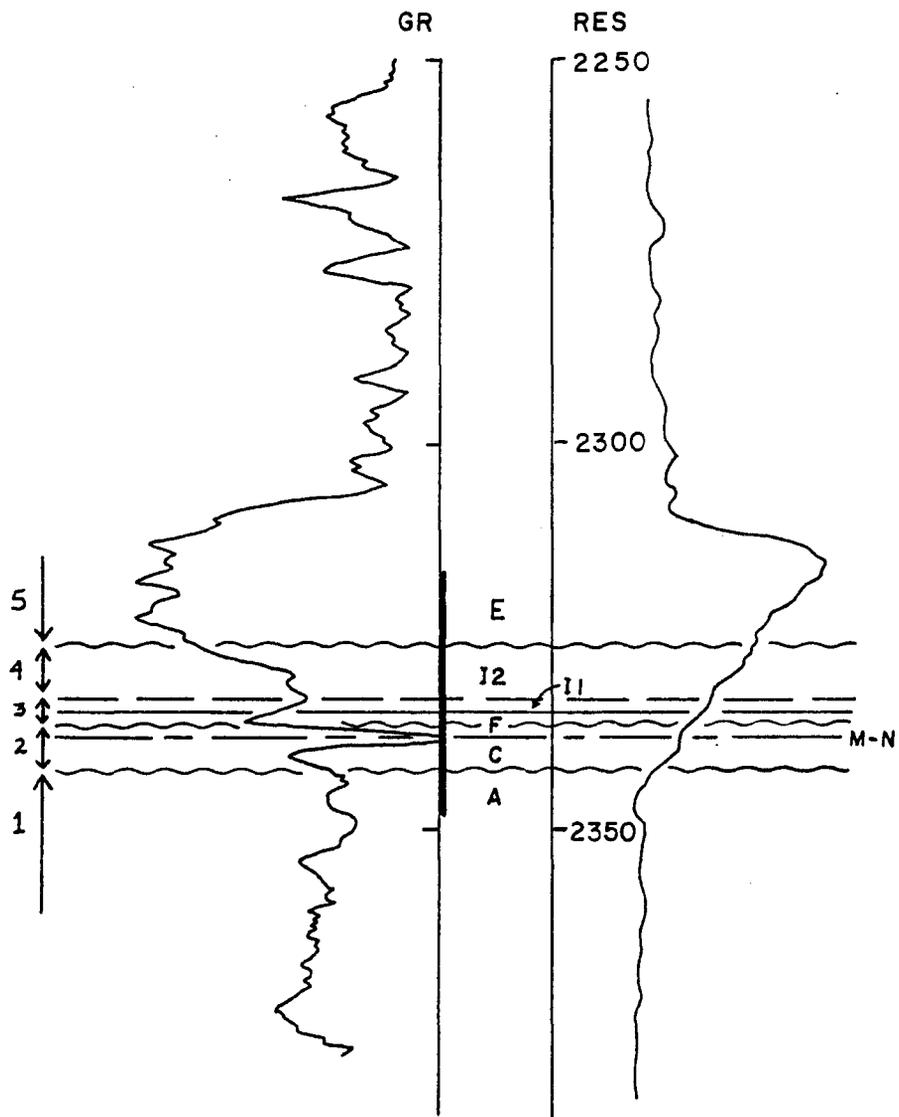
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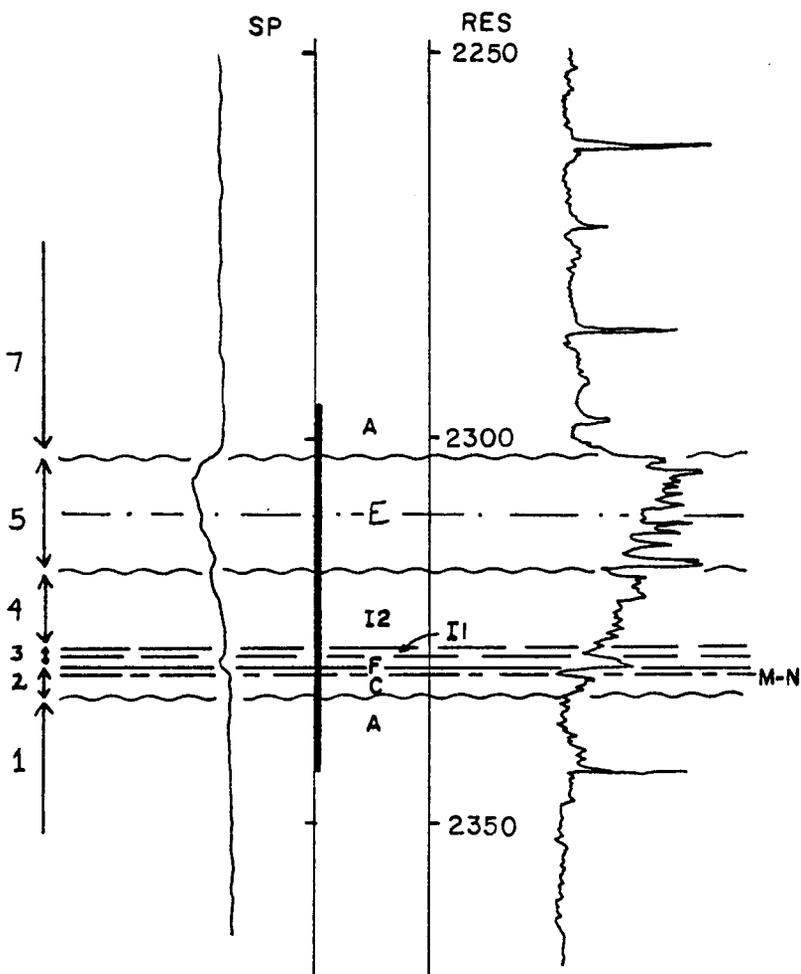
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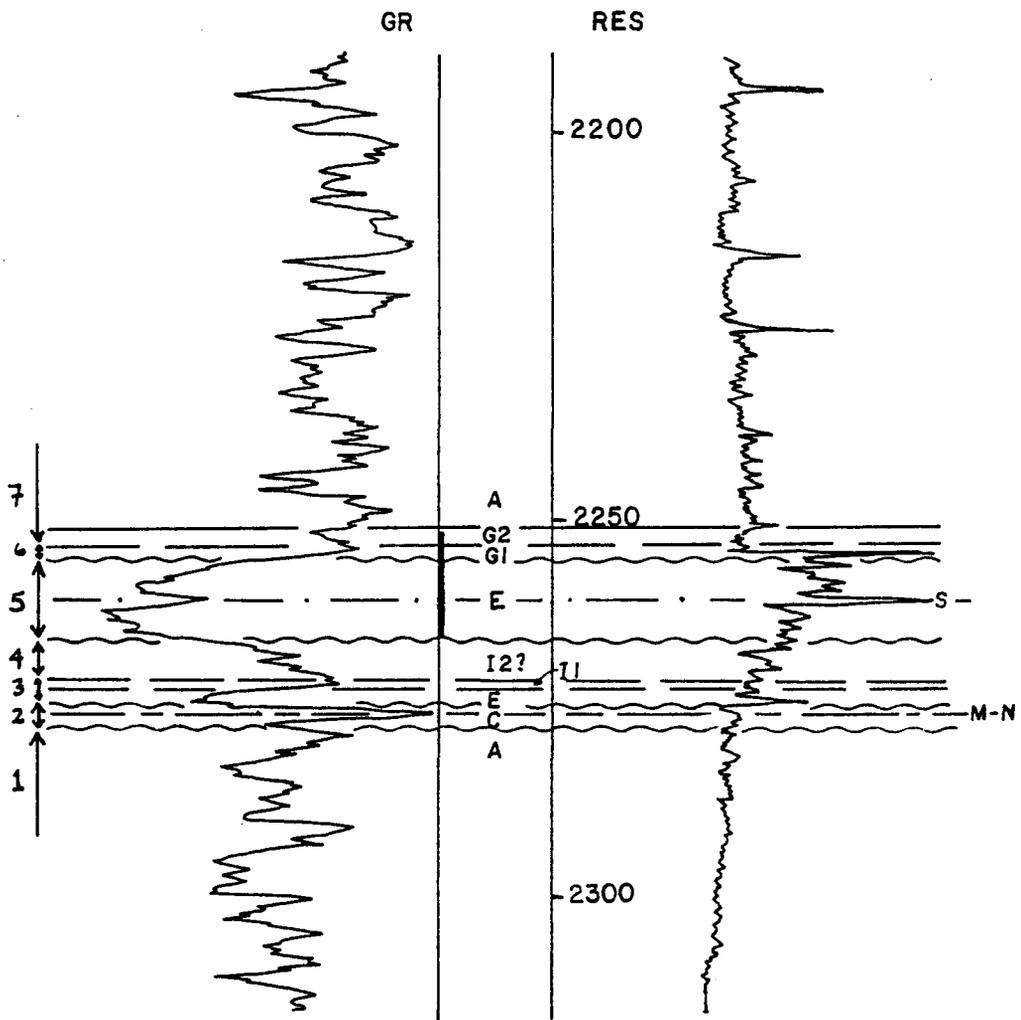
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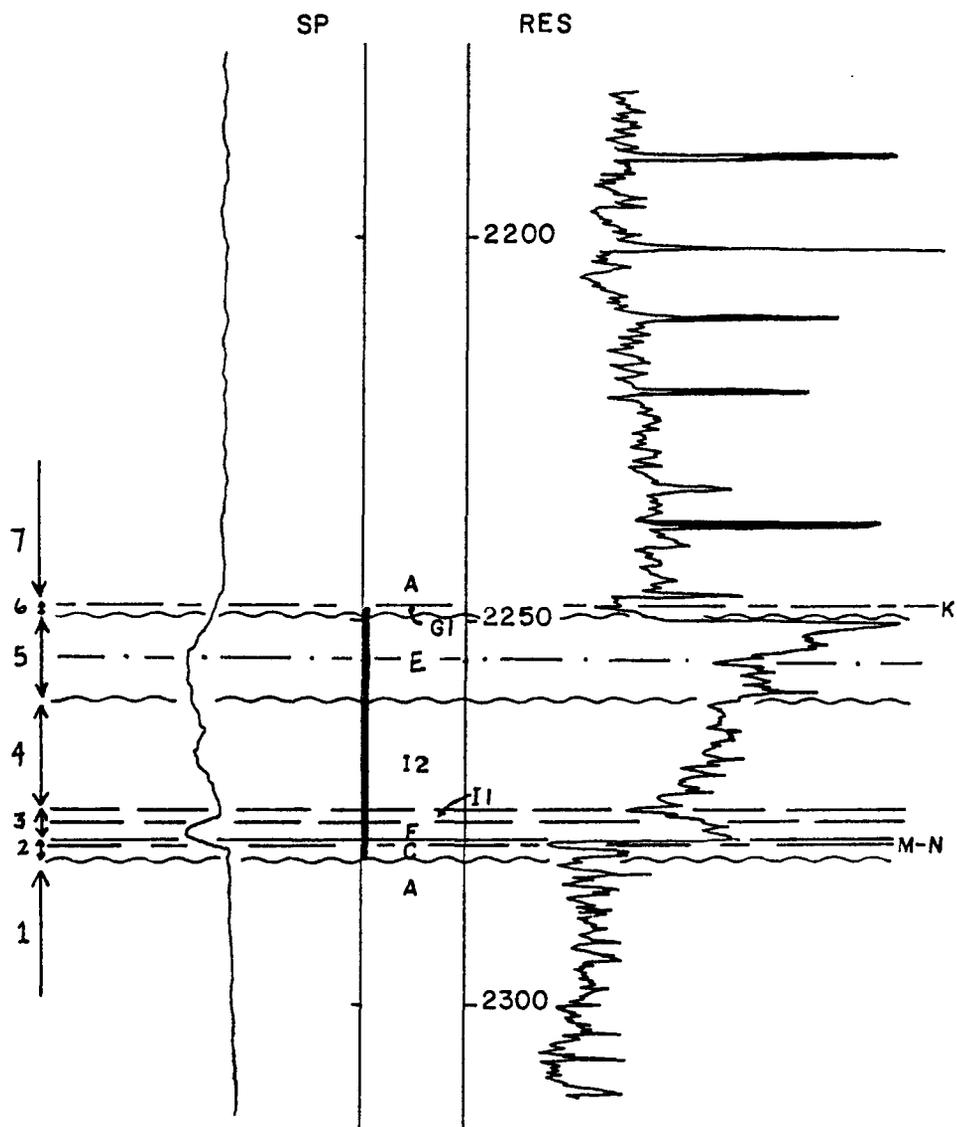
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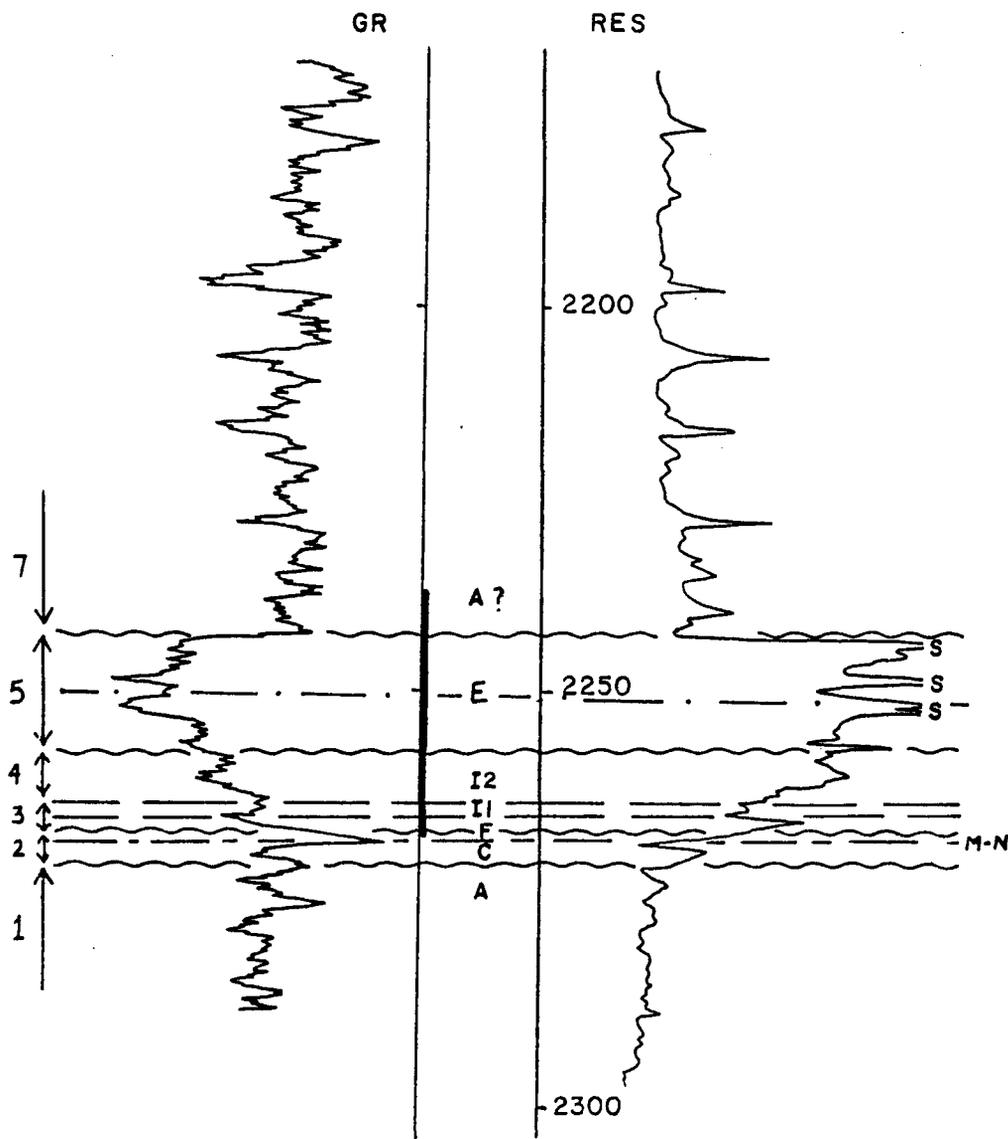
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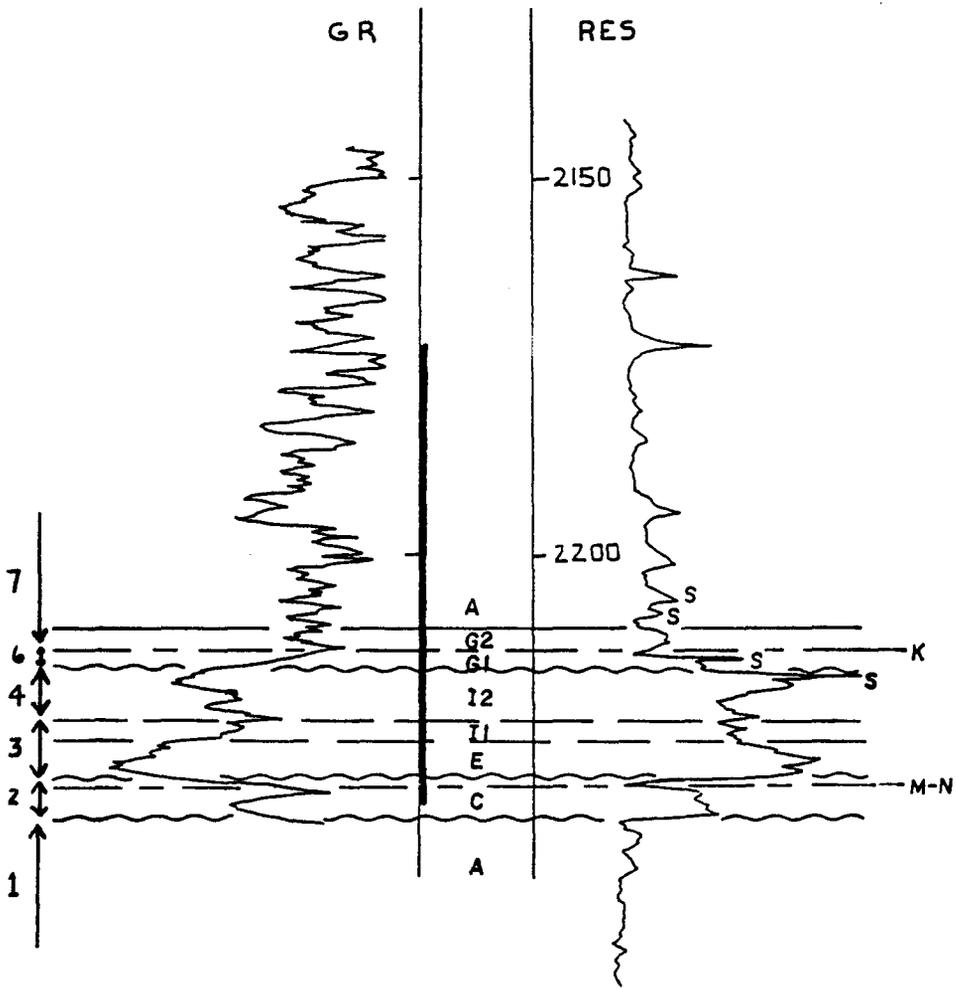
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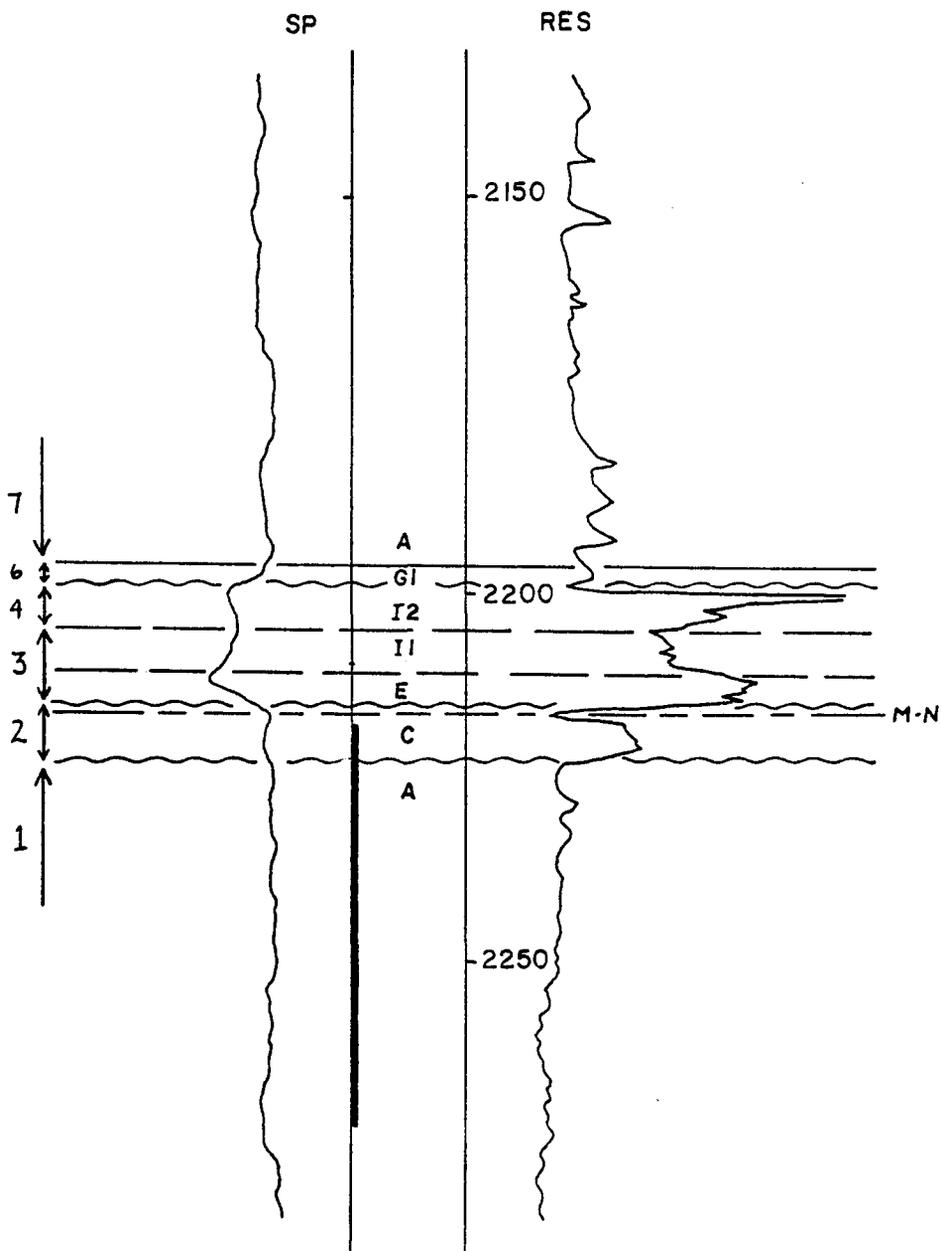
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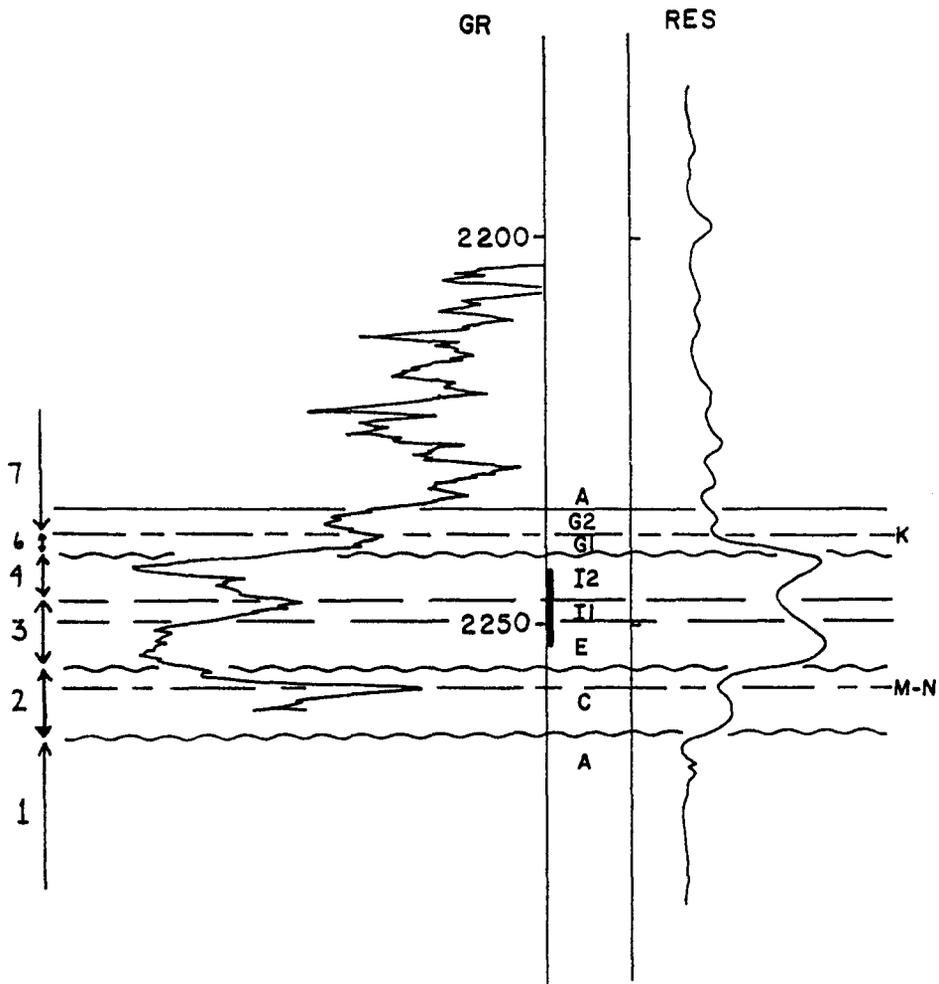
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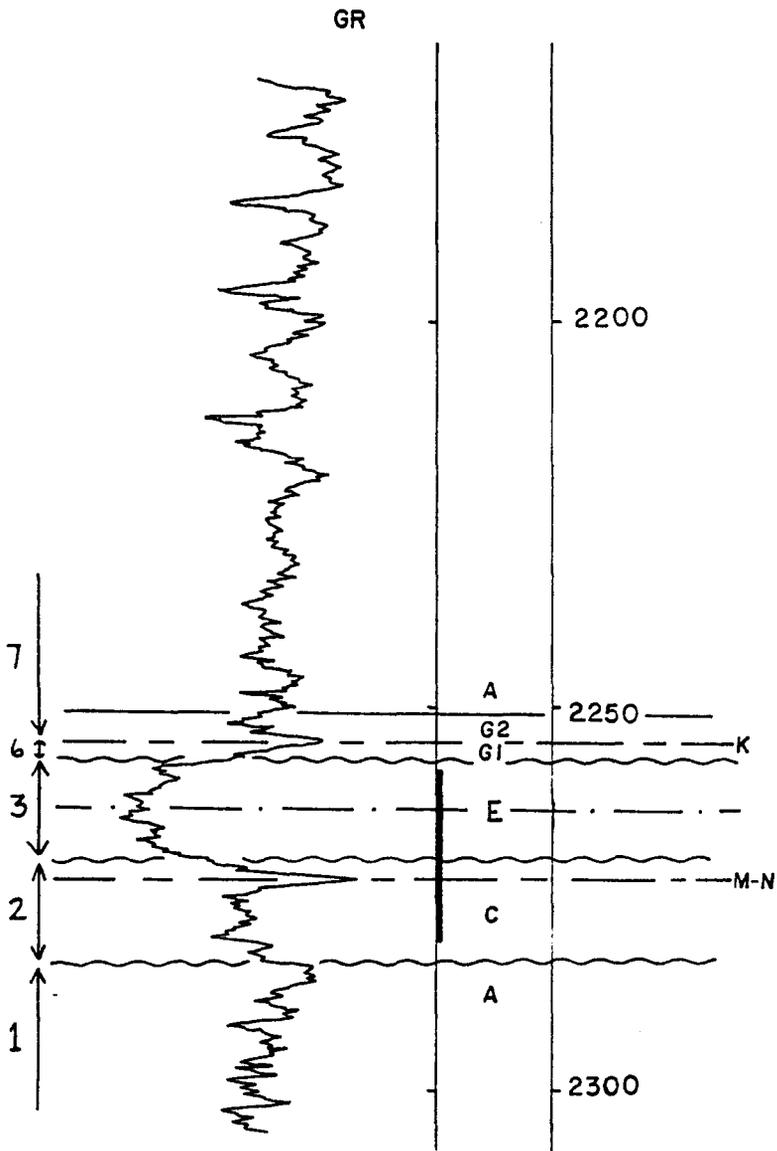
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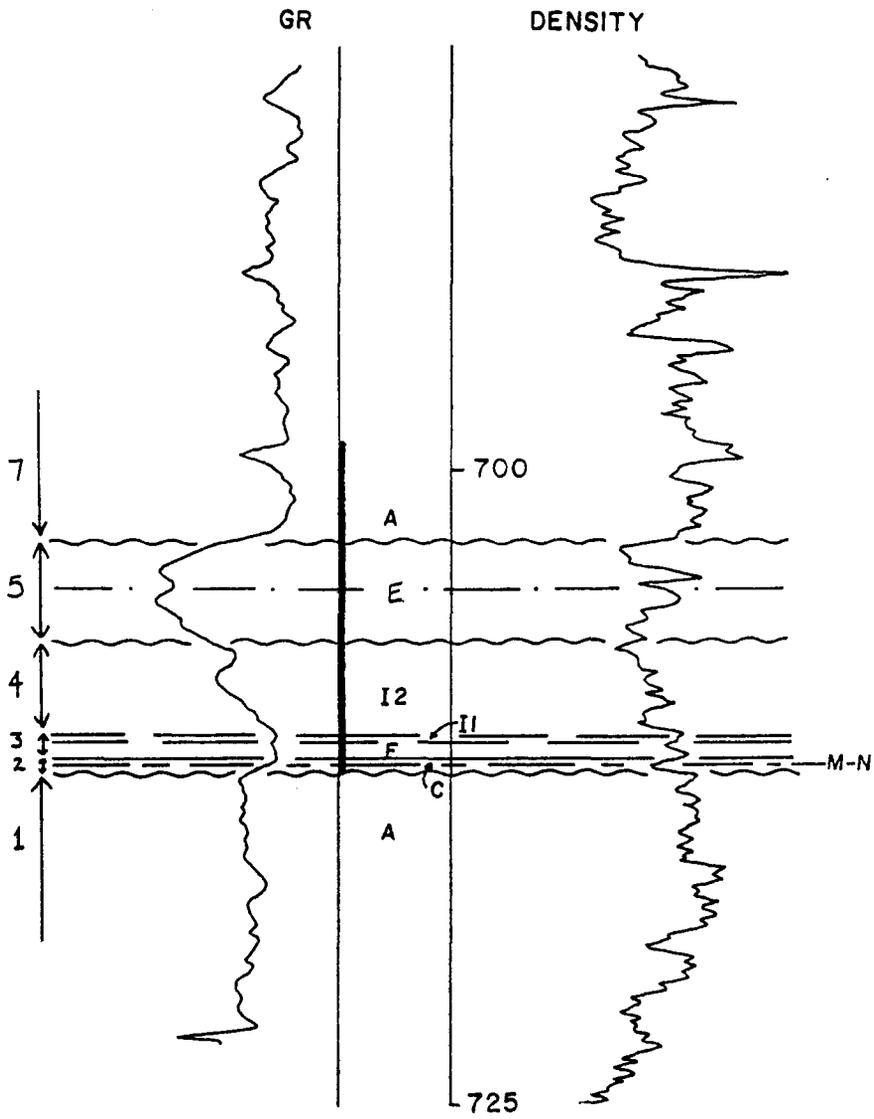
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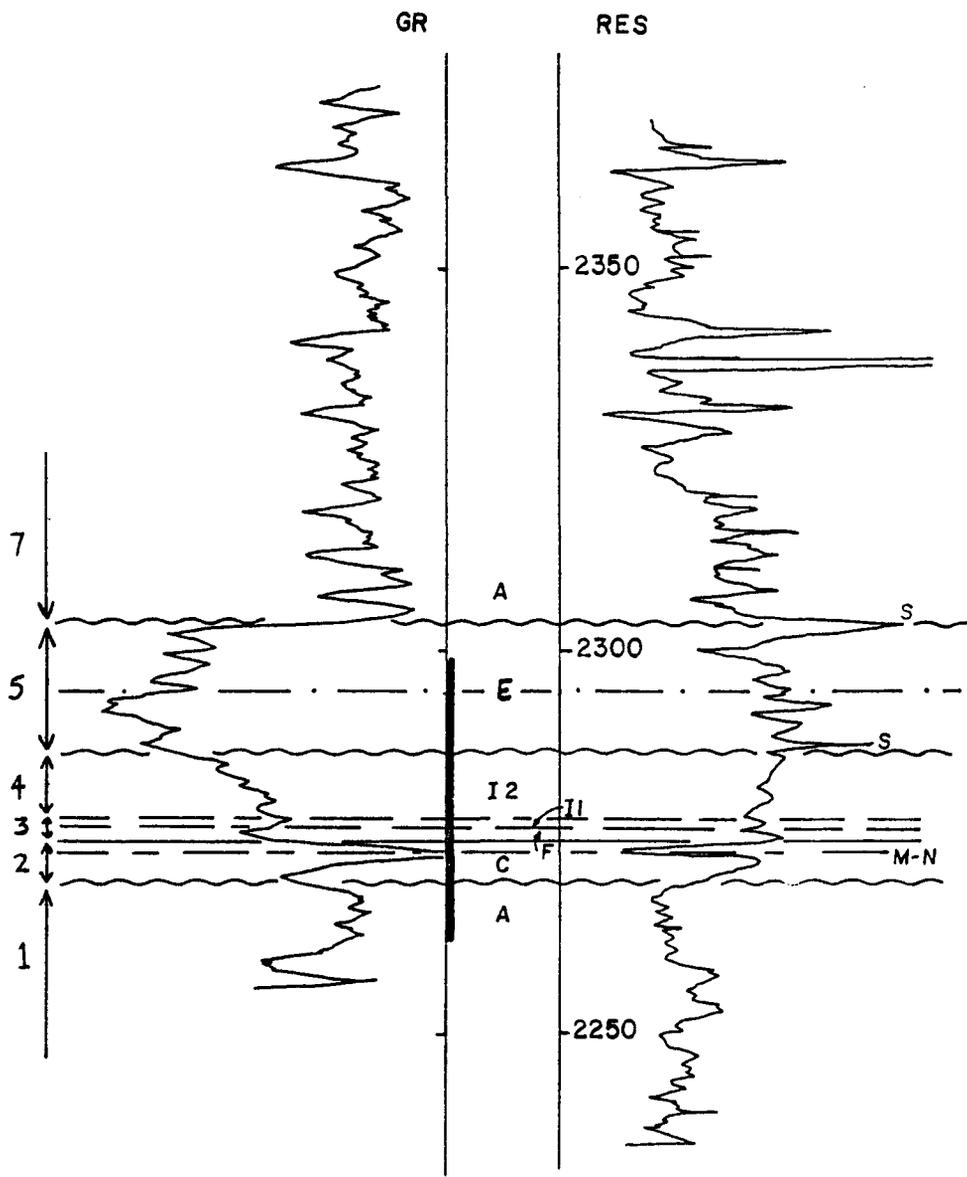
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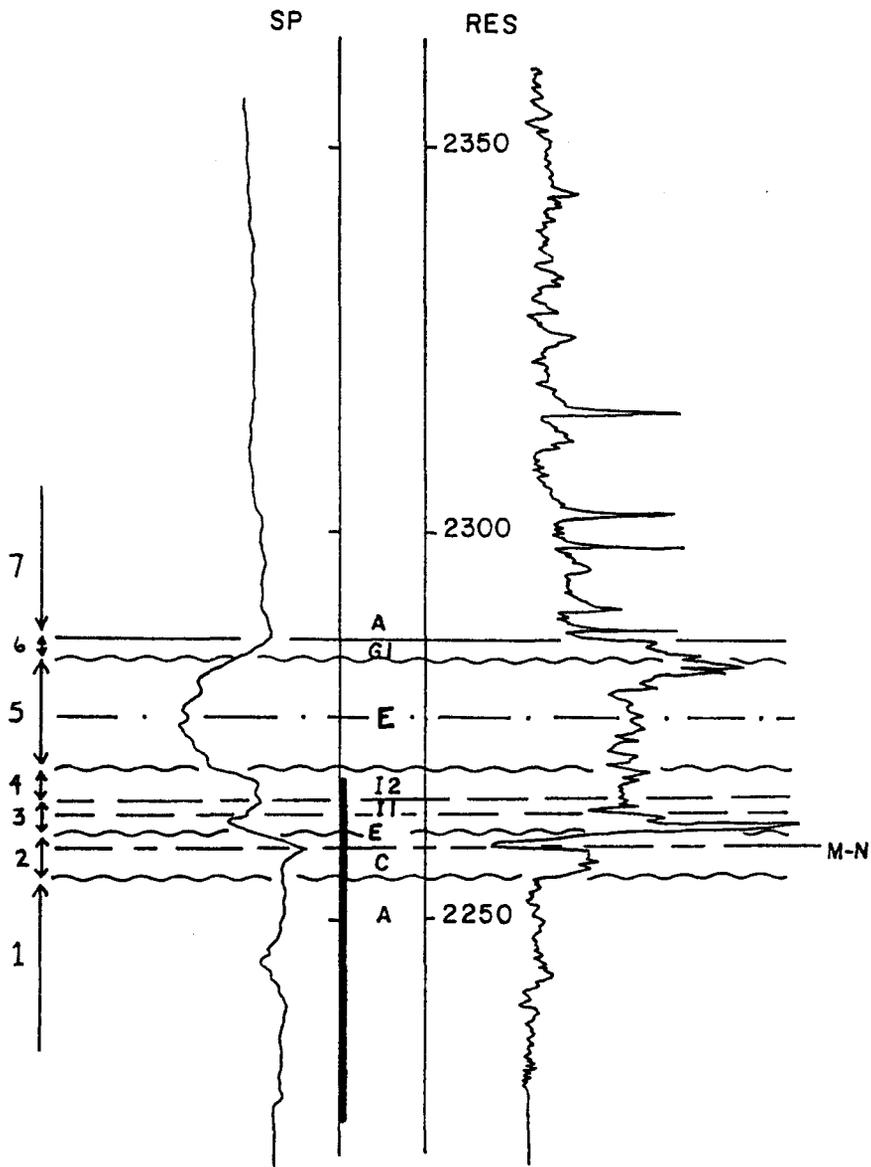
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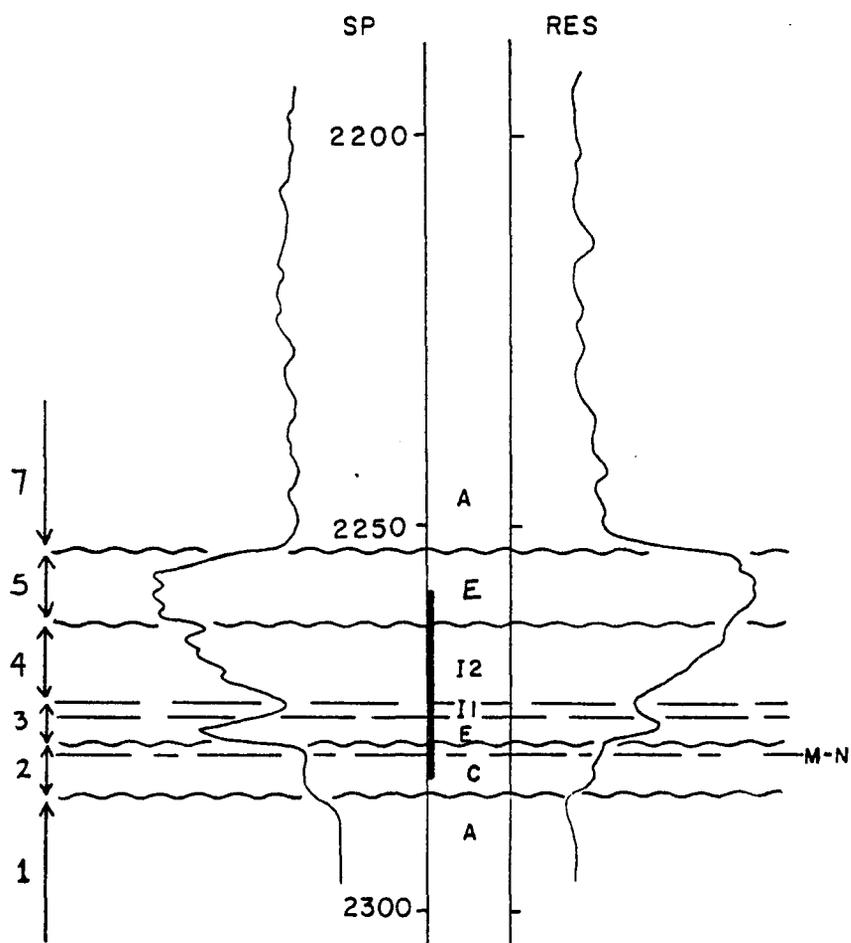
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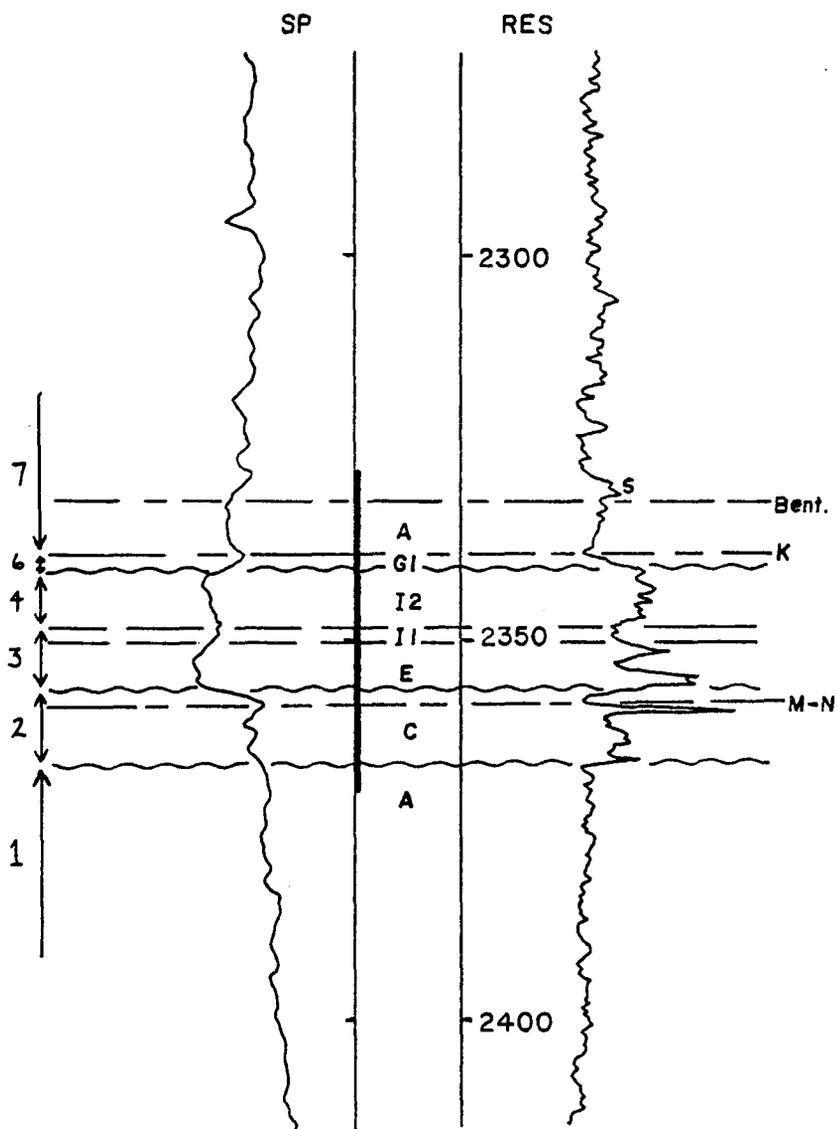
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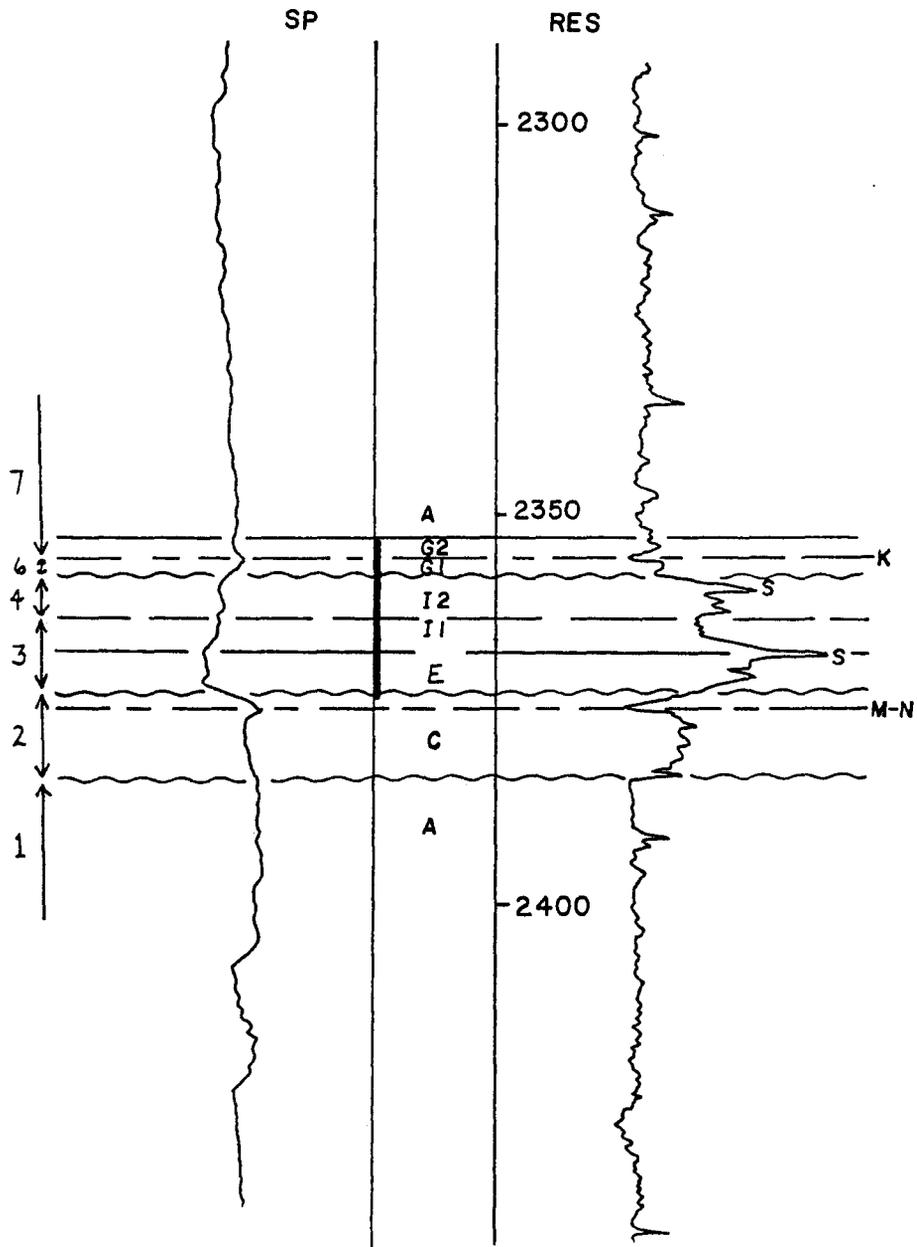
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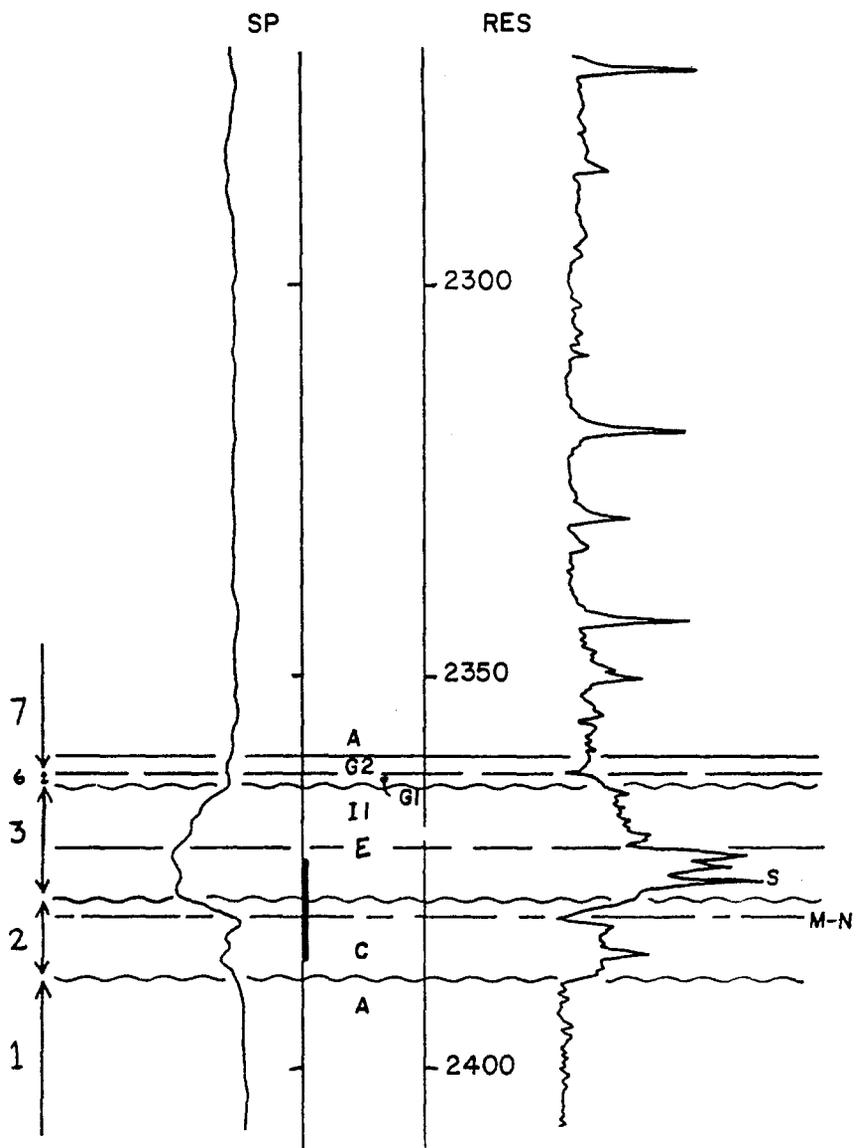
8-26-31-23W3



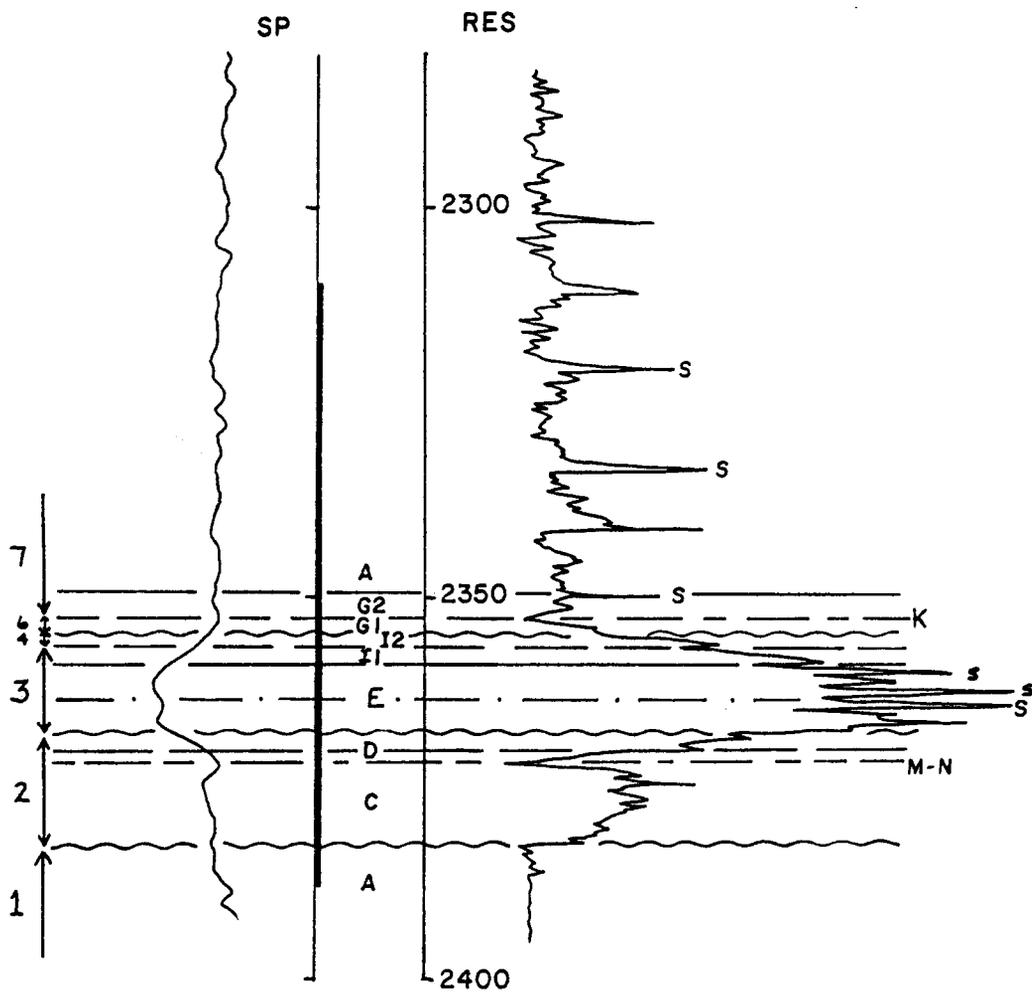
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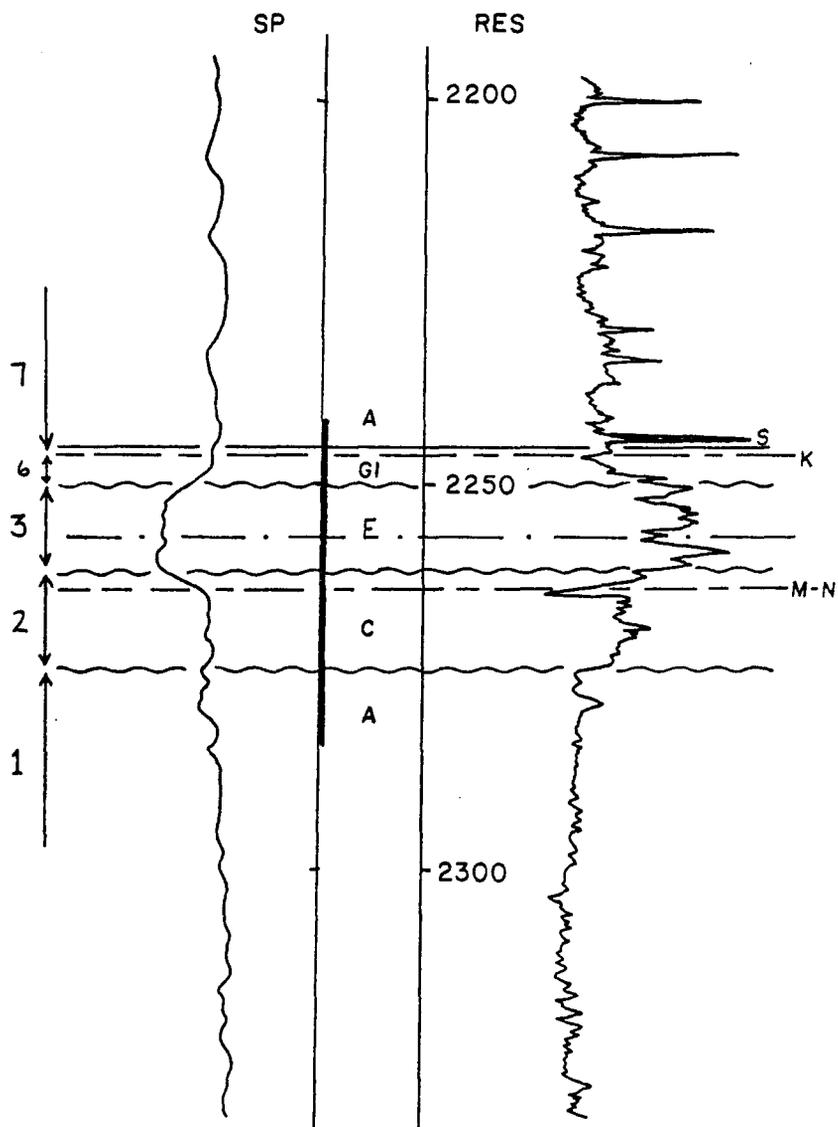
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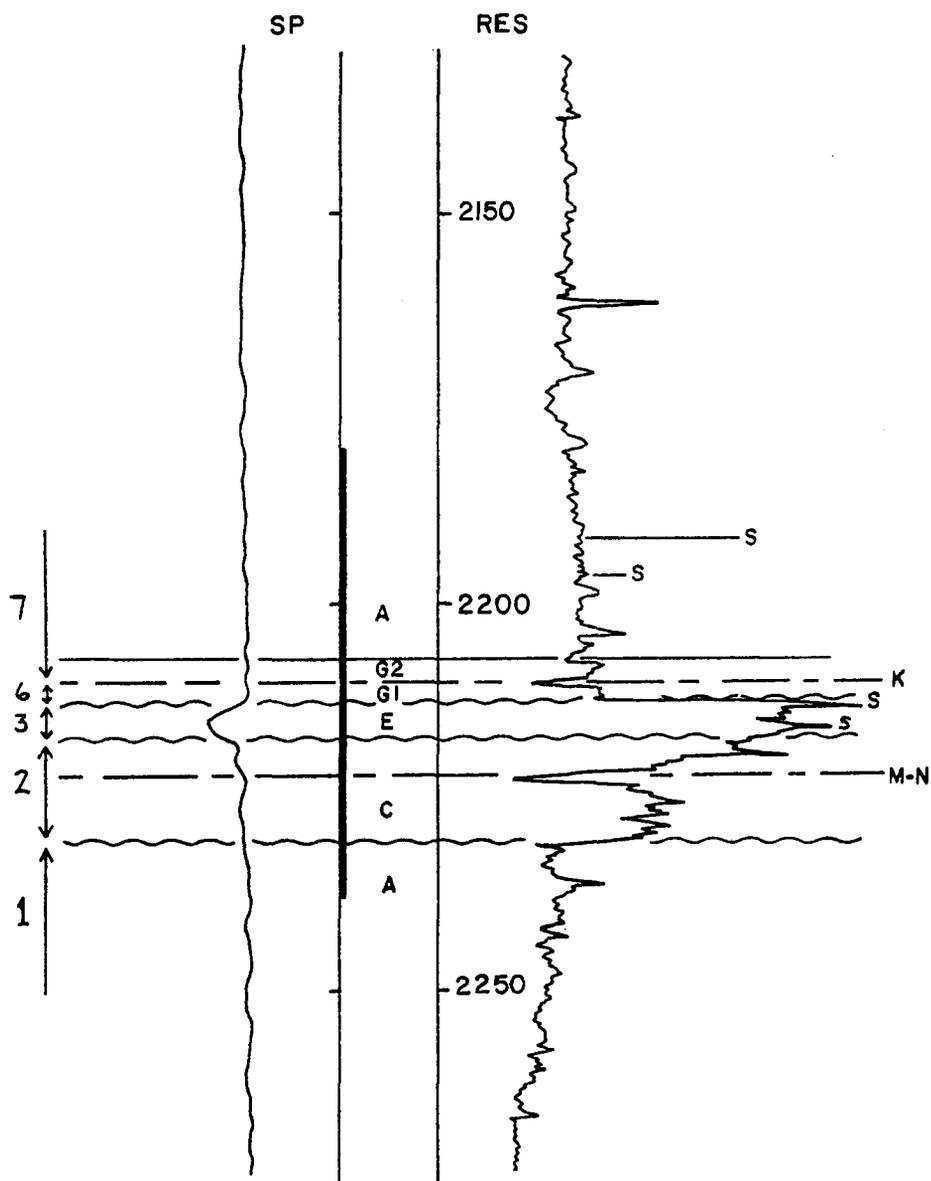
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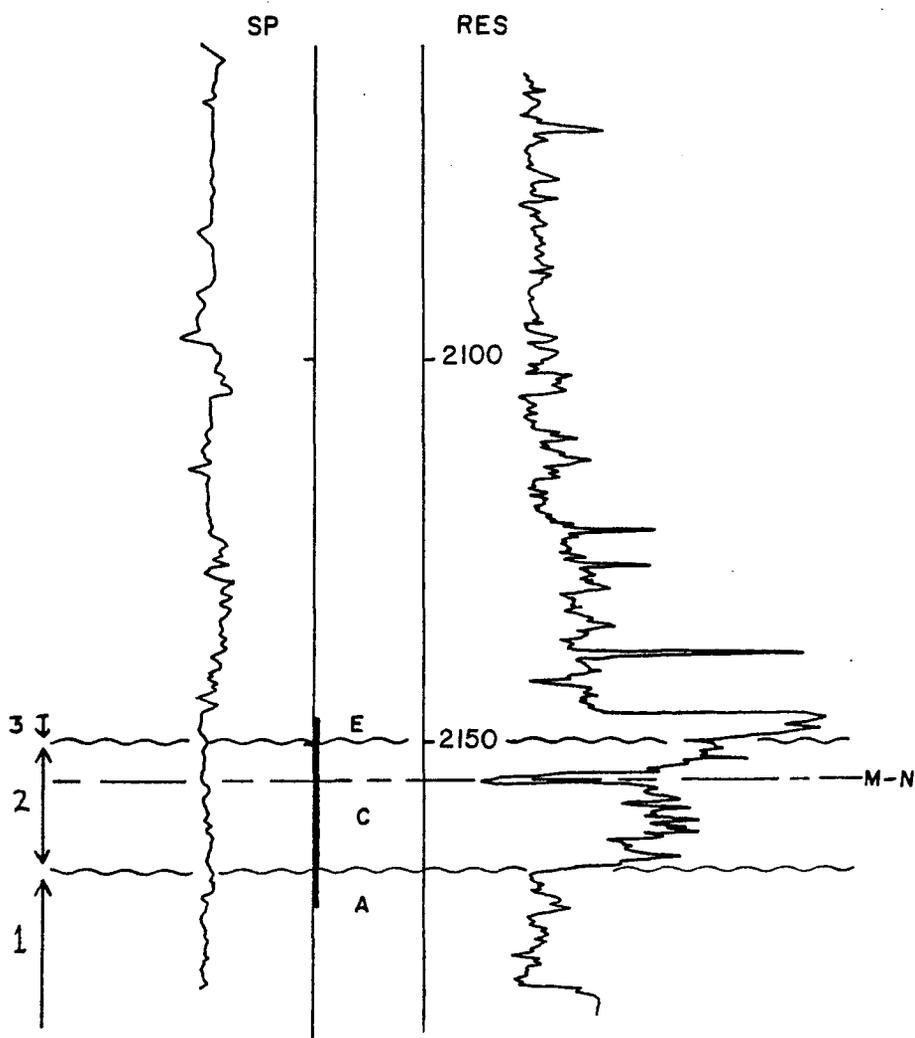
10-36-31-23W3



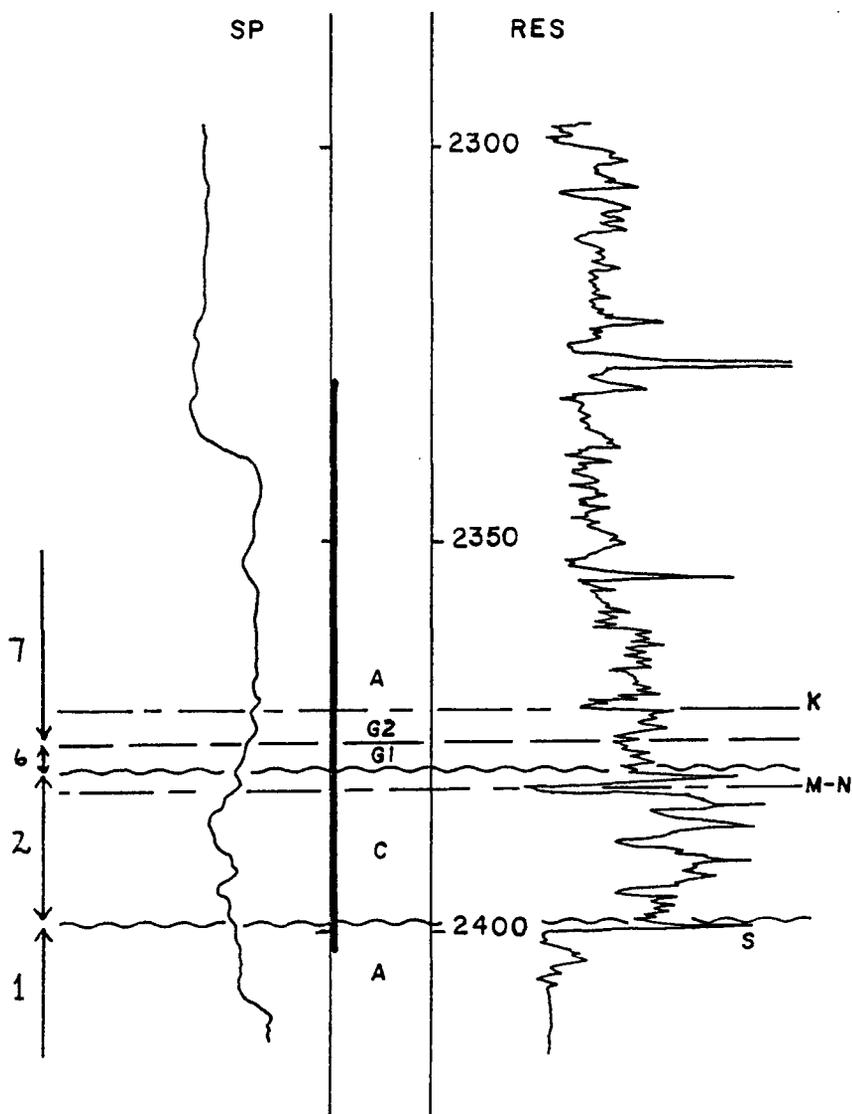
10-7-32-2IW3



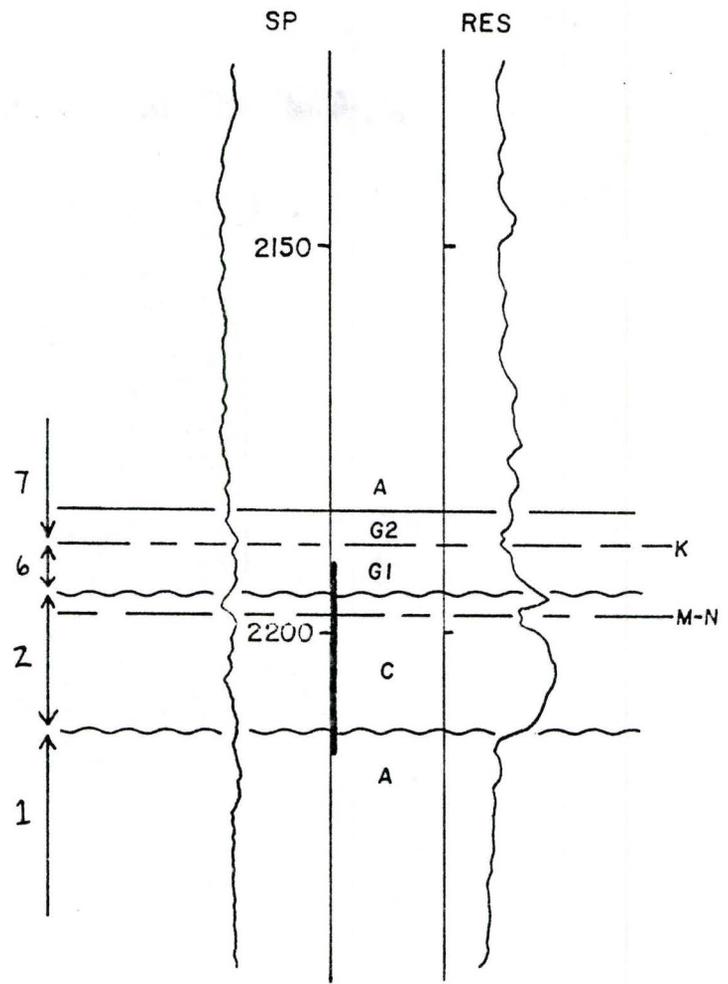
6-10-32-22W3



7-9-32-23W3



10-12-32-23W3



8-3-32-24W3

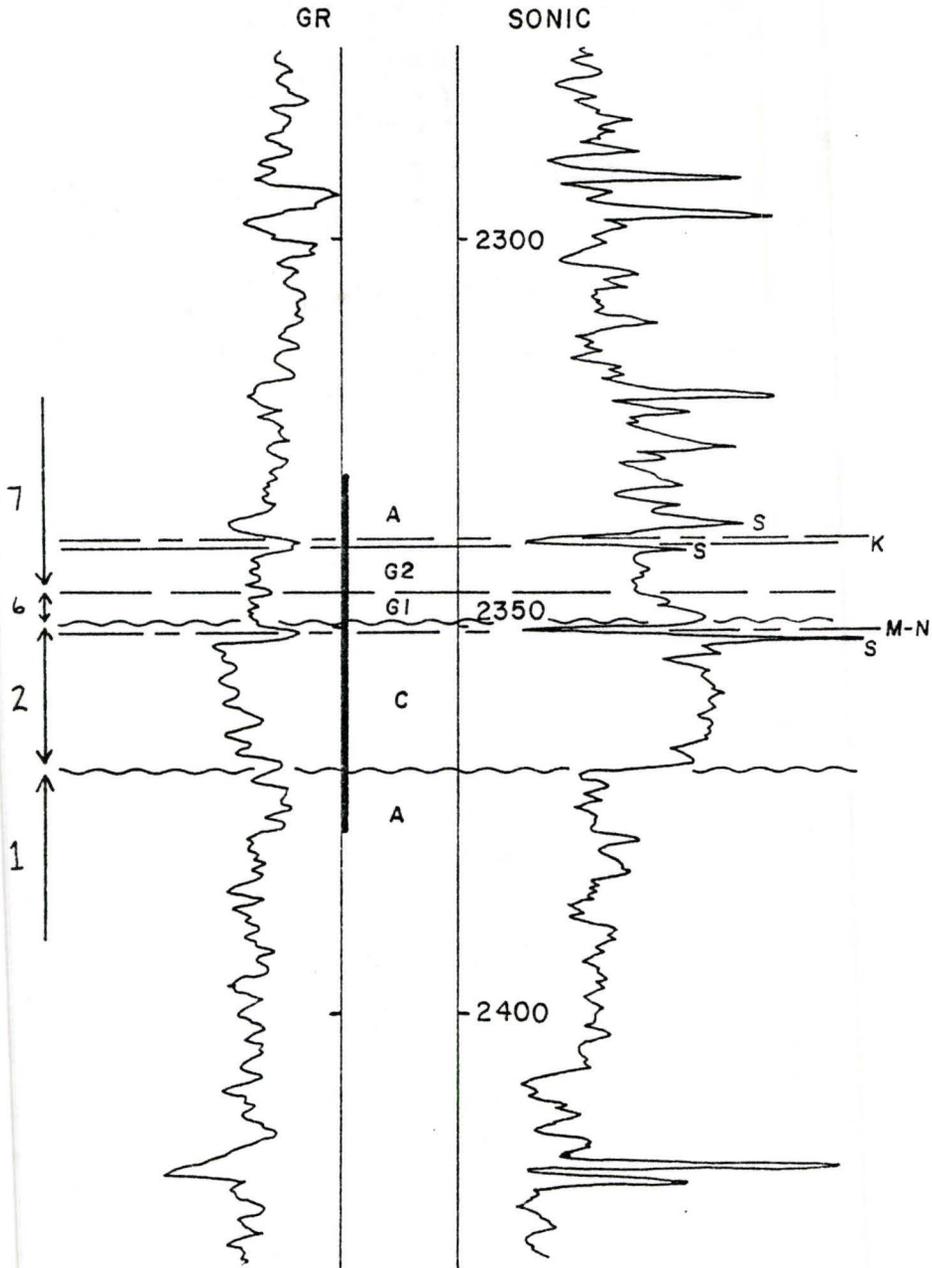
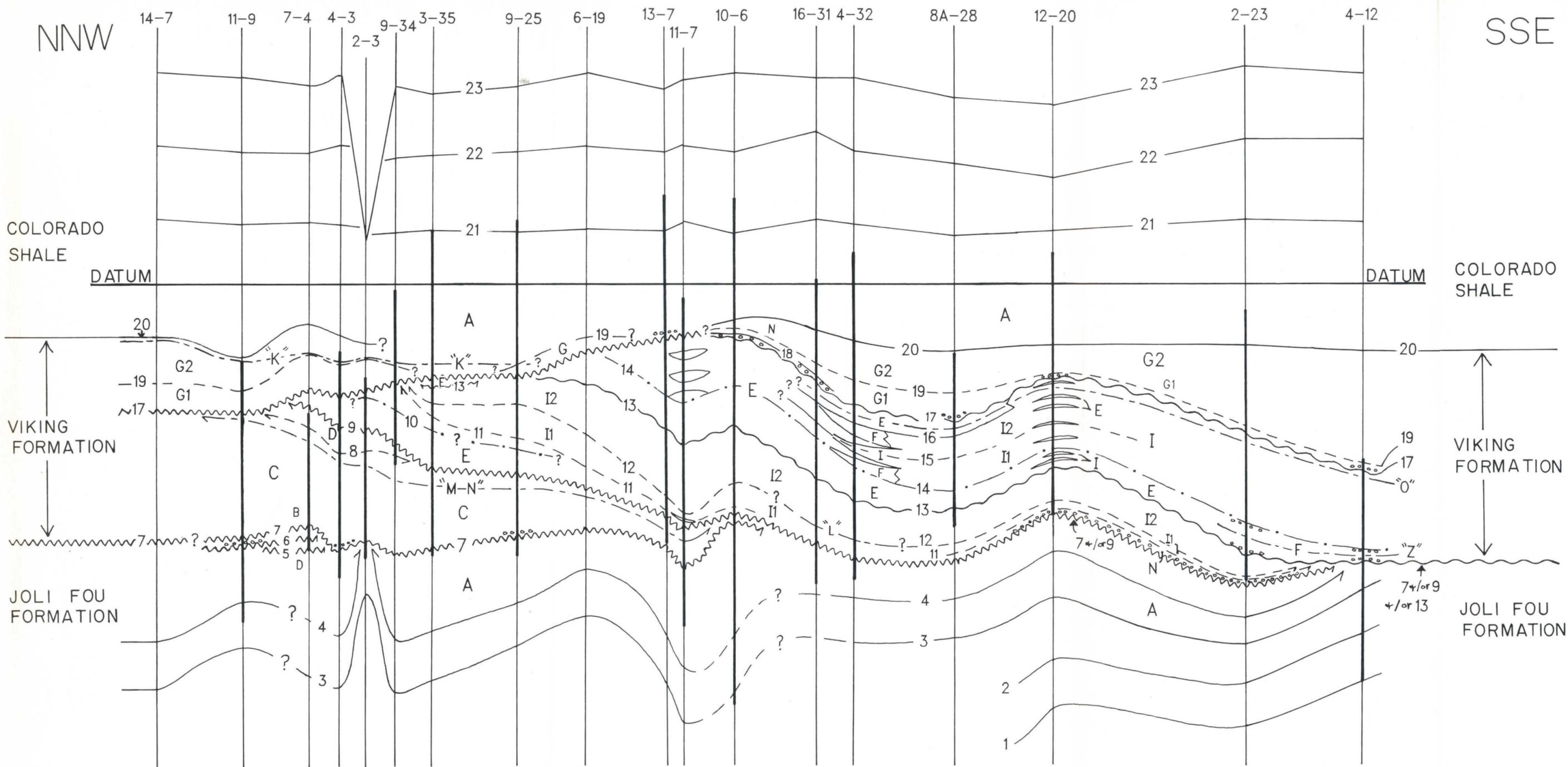


Figure 4.2. This figure summarizes the core and well log data contained in figures 4.3 and 4.4. It shows the facies geometry and types of contacts found within the Viking Formation at Eureka. It also shows location of the bentonites, log-core markers, granule horizons, and correlatable log markers (contained within facies A) discussed in chapter 4. Figure 4.1 is included in the lower right hand corner for reference.



LEGEND

CONTACTS

- UNCONFORMITY
- DISCONFORMITY
- SHARP
- GRADATIONAL

MARKERS

- LOG-CORE MARKER
- BENTONITE
- GRANULE HORIZON

OTHER

- CORED INTERVAL

VERTICAL SCALE 1/2 CM = 0.6 M
 HORIZONTAL SCALE 2 CM = 1.6 KM

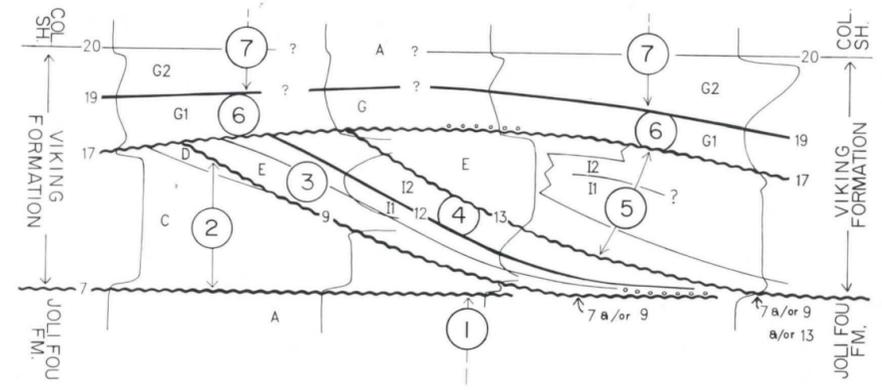
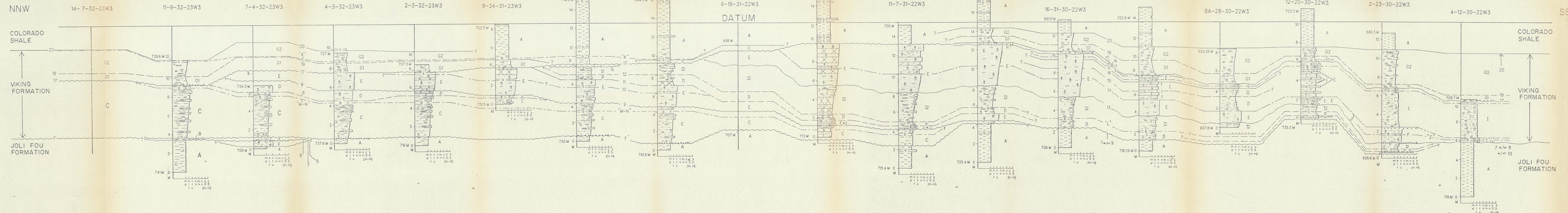


Figure 4.3. Detailed core cross-section.

In facies C, I1/I2, and G1/G2, the shape of the profile upwards reflects the change in the proportion of mud upwards. Curvature to the left and upwards designates an increasing proportion of mud upwards, while curvature to the right and upwards designates a decreasing proportion of mud upwards. In facies B, G1, and G2, a greater bed thickness, is designated by a greater number of slashes. All graded beds are plane laminated unless otherwise indicated. Vertical scale is in meters. No horizontal scale is implied.

Fig. 43



LEGEND

	MUDSTONE		PLANE LAMINATION
	INTERBEDDED SILTSTONE SANDSTONE + MUDSTONE		PARALLEL UNDULATING LAMINATION
	LAMINATED MUDSTONE		LOW ANGLE TRUNCATION
	SANDSTONE		PINCH AND SWELL LAMINATION
	MUDDY SANDSTONE		LIGHTLY BIOTURBATED
	GRANULE HORIZONS		MODERATELY BIOTURBATED
	GLAUCONITIC BLEDS		STRONGLY BIOTURBATED
	b BENTONITE		TOTALLY BIOTURBATED
	S SIDERITE		CONTACTS
	MISSING CORE		DISCONFORMITY
			UNCONFORMITY
			SHARP CONTACT
			BENTONITE
			LOG-CORE MARKER

Figure 4.4. Detailed well log cross-section of figure 4.2.

