THE EFFECTS OF SEA LEVEL CHANGES ON THE SEDIMENTOLOGY OF THE CARDIUM FORMATION; NORTHEASTERN PEMBINA, ALBERTA

THE EFFECTS OF SEA LEVEL CHANGES ON THE SEDIMENTOLOGY OF THE CARDIUM FORMATION; NORTHEASTERN PEMBINA, ALBERTA

By

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ABSTRACT

Examination of 32 cores and over 100 well logs in Northeastern Pembina allowed 8 facies to be distinguished. The facies within the Raven River Member comprise a shelf sequence which begins with dark bioturbated muddy siltstones, and coarsens upward into pervasively bioturbated muddy sandstones, bioturbated sandstones and nonbioturbated sandstones. The most characteristic sedimentary structure in the nonbioturbated sandstones is hummocky cross stratification which is formed during storm reworking of offshore sediments.

An erosion surface separates the Raven River Member from the overlying conglomerates of the Carrot Creek Member. Maximum erosion on this surface occurs within a drilling gap present in northeastern Pembina and off the northern boundary of the field. On either side of the drilling gap, facies 7 is present beneath the conglomerates. However, within the drilling gap there is a pronounced thinning or complete absence of facies 7. Conglomerates form a very thin veneer on top of the erosion surface which may indicate a second period of erosion after deposition of the conglomerates. Off the northern boundary of the field, the Cardium sequence is partially or completely absent. The origin of the erosion surface may be due to a relative lowering of sea level in the Alberta Basin. This would cause the shoreline to advance many kilometres basinward and a new shoreface to become established on sediments which

were previously offshore. Newly incised rivers could then carry sand and gravel to the new shoreface.

The Carrot Creek Member is overlain by the Dismal Rat Member, the base of which is characterized by pebbly mudstones that fine upwards into laminated dark mudstones and massive dark mudstones. This sequence may represent a relative rise of sea level within the Alberta basin. Pebbly mudstones may be the result of gravel on top of the erosion surface being reworked by storms into the transgressive muds.

The morphology of the datum (used for correlation of well logs) in northeastern Pembina is characterized by undulations and discontinuities. These structures were originally thought to be tectonic. However, the topography mimics that found on the erosion surface above the Raven River Member. The morphology of the datum may represent the draping of sediments on top of the erosion surface above the Raven River Member. Alternatively, the morphology of the datum may reflect erosion on this surface.

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CHAPTER 1: INTRODUCTION

1.1 Scope Of The Study

This theses is part of an ongoing study, under the supervision of Dr. R.G. Walker, of the Upper Cretaceous Cardium Formation, within the Western Interior Seaway of Alberta. The Cardium Formation is one of many Interior Seaway deposits and appears to be composed of long, linear, en echelon sand ridges or bars, totally encased in marine mudstones. For simplicity, the term "ridges" will be used throughout the rest of this thesis. The ridges contain coarsening upward sequences that are capped by sandstones and conglomerates, and they appear to have formed several kilometres seaward of any apparent time-equivalent shoreline. If the ridges were initially deposited "offshore", two major problems arise:

1) how were the sediments transported across the shelf? and

2) how were the sediments focussed into long, narrow ridges?

The purpose of this study is to evaluate the depositional history of the Cardium Formation in the northeastern region of Pembina oil field, in light of the problems listed above, associated with transport and focussing of sediments. In particular, the sand body geometry and both lateral and vertical facies relationships will be examined. The hypothesis that these sediments were deposited many tens of kilometres from the shoreline will be evaluated in view of their observed geometry, facies relationships, and overall stratigraphic position.

1.2 Problems With Linear Ridges

Linear ridges similar to those recognized in the Cardium Formation have been noted in other formations within the Western Interior Seaway and include: the Viking Formation (Raddysh, 1986), the Shannon Formation (Tillman and Martinsen, 1984), the Frontier, Ferron, and Gallup Formations (references in Slatt, 1984). Traditionally, these ridges have been described as long, narrow, offshore bars which trend obliquely or parallel to the time-equivalent shoreline. Marine shales totally encase the ridges, which appear to lie many kilometres from the nearest documented shoreline. Originally, it was thought that the ridges represented progressive coarsening upward sequences with sandstones and conglomerates at the top of the sequences. However, it was not clear why these sequences occurred. One interpretation suggested that the ridges formed due to an overall aggradation of the sea floor within the Western Interior Seaway (Swift and Rice, 1984). In addition, it was believed that the sandstone and conglomerate at the top of the ridges had a gradational contact with the underlying marine shales (Tillman and Martinsen, 1984). However, Swagor et al. (1976) recognized an unconformity separating the conglomerates from the underlying mudstones at Carrot Creek field, in Alberta. He interpreted the conglomerates as offshore deposits associated with storm currents.

Bergman (1984) also recognized an erosion surface beneath the Cardium conglomerates at Carrot Creek. If an erosion surface is present below the conglomerates then they are not part of the previously described progressive coarsening upward sequence. The next approach towards an interpretation of the Cardium ridges involved not only the questions of transport and focussing of sediments, but also a mechanism capable of transporting gravel many kilometres from the shoreline and depositing it on top of the previously formed ridges.

1.3 Shelf Processes

Numerous processes interact to transport and rework sediment in the shallow marine environment. Four mechanisms of sediment transport were discussed by Swift et al. (1971) and include:

1) intruding ocean currents

2) tidal currents

3) geostrophic currents

4) turbidity currents

These processes may act separately or combine to transport sediment on the shelf. Intruding ocean currents are rare, having been recognized on only 3% of modern marine shelves. Since they do not represent a common mechanism of sediment transport they will not be discussed further. In the previous section, it was mentioned that the conglomerates were deposited offshore by storms (Swagor, 1976). If the conglomerates were deposited by storms, it is implied that they were deposited below fairweather wave base. Tidal currents can transport and rework sediment but only above fairweather wave base. Thus, tidal currents do not provide a mechanism for transport of the Cardium conglomerates if they are associated with storm deposition below fairweather wave base. Other observations that suggested storm deposition of the Cardium sediments were the nature of the trace fauna, and the presence of hummocky cross stratification in the sands (Harms et al., 1975; Wright and Walker, 1981). Since storm deposition became associated with the Cardium, mechanisms of transport on the shelf became centered on storm dominated shelf processes. Two major mechanisms of sediment transport on storm dominated shelves are:

1) geostrophic flows, and

2) turbidity currents.

Geostrophic flows

Geostrophic flows are set up by wind blowing water onshore. A seaward pressure gradient is created due to elevated coastal waters. There is a resultant bottom return flow which is deflected to the right (in the northern hemisphere) by Coriolis force. The flow then evolves into a geostrophic flow moving parallel to isobaths. Sediment is transported during each storm, incrementally, parallel to the shoreline (Walker, 1984a).

Turbidity currents

Turbidity currents are density driven currents where the excess density of the flow is due to suspended sediment.

These currents are able to transport sediments directly seaward, across isobaths, over long distances even on low angle slopes such as that of the shelf. Turbidity current deposits tend to be characterized by sharp based, graded sandstones that do not contain hummocky cross stratification (Walker, 1984a).

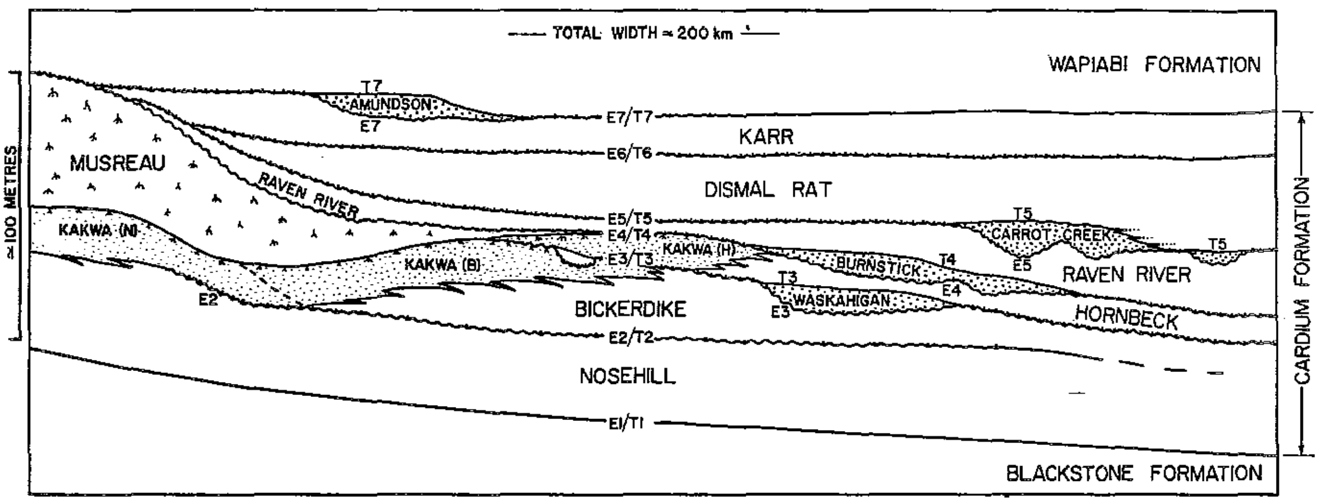
Problems with Geostrophic flows and Turbidity currents

Although both turbidity currents and geostrophic flows can transport sediment below fairweather wave base, they do not account for the linear ridge morphology of the Cardium sediments. There are also problems concerning the generation of turbidity currents on low angle slopes such as that of the Alberta basin (Dewiel, 1956; Walker, 1984a). Deposits below fairweather wave base from both geostrophic flows and turbidity currents can be reworked by storm waves if they are above storm wave base. It was suggested that this may account for the presence of hummocky cross stratification in the sands of the Cardium Formation.

1.4 Effects Of Relative Sea Level Lowering

Extensive study of the Cardium Formation, especially of the Carrot Creek Member (Plint et al., 1986), suggests that the initial approach to the problems of transport and focussing of the Cardium sediments was wrong. Plint et al. (1986) recognized a series of regionally extensive erosion surfaces present in the subsurface (Figure 1), E1 through E7. These surfaces are mostly overlain by a thin veneer of conglomerate, although thicker accumulations up to 19 metres

FIGURE 1: Stratigraphy of the Cardium in the subsurface
(Plint et al., 1986)



TOTAL WIDTH ≈ 200 km
WAPIABI FORMATION
T7
AMUNDSON
E7
E7/T7
KARR
E6/T6
MUSREAU
DISMAL RAT
RAVEN RIVER
E5/T5
T5
CARROT CREEK
T5
KAKWA (N)
E4/T4
E3/T3
KAKWA (H)
KAKWA (B)
BURNSTICK
T4
E5
RAVEN RIVER
T3
E4
WASKAHIGAN
E2
BICKERDIKE
E3
HORNBECK
E2/T2
NOSEHILL
E1/T1
BLACKSTONE FORMATION
≈100 METRES
CARDIUM FORMATION

have been observed (Bergman and Walker, 1986) in the Carrot Creek Member. Plint et al. (1986) suggested that the erosion surfaces are the result of a rapid lowering of sea level, with erosion due to wave scour on the bed. The shoreline advanced rapidly many kilometres basinward and a new shoreface was established on sediments which were previously offshore. As a result of the lowered base level, newly incised rivers supplied sand and gravel to the newly established shoreface. This coarse material was subsequently reworked alongshore by waves. An ensuing transgression transported some of the gravel back across the erosion surface, while storms reworked gravel seaward into transgressive muds. With continued deepening, the entire area became blanketed with mud. At Carrot Creek field, conglomerates rest on an erosion surface, E5, which indicates that they are not part of the underlying basinal aggradational sequence containing hummocky cross stratified sands at the top. These observations can be explained using the hypothesis employed by Plint, where the lowering of sea level causes a new shoreface to become established in sediments which were once previously offshore (ie. hummocky cross stratified sands). Thus, the elongate Cardium ridge deposits appear to represent transgressed, remnant shorefaces which are now totally encased in marine shales and located many kilometres from any time-equivalent shoreline.

There are other examples of erosion surfaces of this type found in Alberta in the Cardium (Plint et al., 1986) and the Badheart Formations (Plint and Walker, in press), the Viking Formation (Raddysh, 1986), and the Gallup and Tocito sandstones of New Mexico (Tillman, 1985). However, there are problems with the recognition of these erosion surfaces, since their expression may be very subtle (Bergman, pers. comm.)

1.5 Pembina

At Pembina oil field, a subsurface study has revealed the existence of an erosion surface, E5, which occurs in the northeastern region of the field. Conglomerates form a thin veneer, approximately 0.67 metres thick, on top of the erosion surface. This same erosion surface has been recognized at Carrot Creek, although the overlying conglomerates are much thicker, up to about 20 metres (Bergman, 1984). It is the purpose of this thesis to study the sand body geometry and facies relationships of northeastern Pembina field in order to define the erosion surface, E5, and its implications on sedimentation. The Cardium deposits appear to occur many kilometres from a time-equivalent shoreline and this will be discussed in light of the hypothesis which proposes sea level changes for the apparent origin of the Cardium Formation ridges.

CHAPTER 2: CARDIUM STRATIGRAPHY

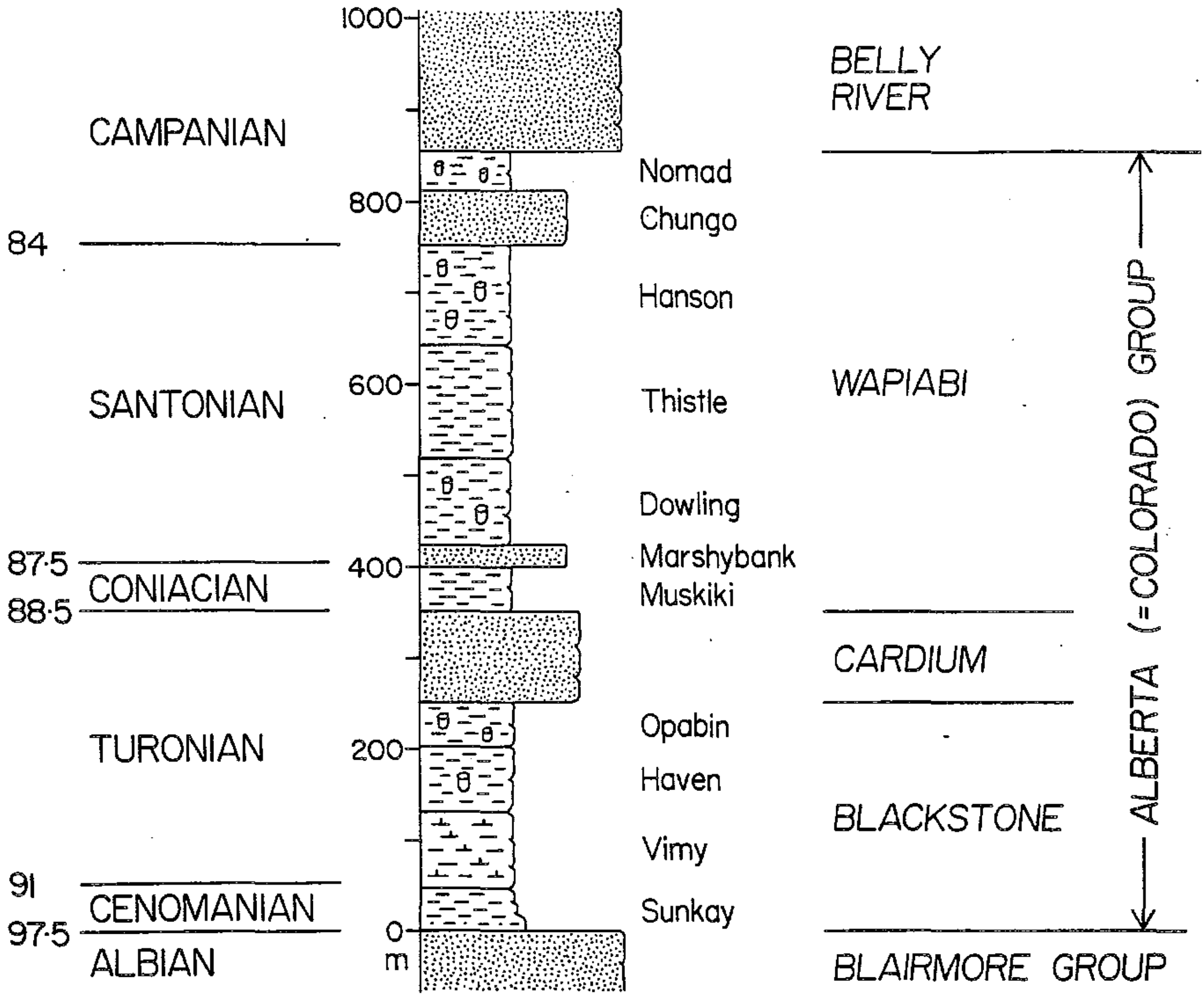
2.1 Regional Setting

The Upper Cretaceous (Turonian, 88.5-91 Ma) Cardium Formation crops out extensively in the Foothills of the Canadian Rockies. It is approximately 100 metres thick in outcrop and contains a maximum of eight coarsening upward sequences (Duke, 1985). Six coarsening upward sequences have been recognized in the subsurface Cardium present in Alberta (Plint et al., 1986). Deposition of the Cardium sediments occurred during a tectonically quiet period within the Western Interior Seaway. The Cardium Formation represents the main sandstone unit of the Alberta (or equivalent, Colorado) Group. Three formations are included within the Alberta Group: the Blackstone, Cardium, and Wapiabi Formations. The Blackstone Formation consists of 250 metres of marine shales and represents the lowest stratigraphic formation. Overlying the Blackstone Formation is the Cardium Formation which comprises approximately 100 metres of interbedded sandstones and shales. The uppermost Wapiabi Formation is 500 metres thick and is composed primarily of shales (Figure 2). Other Turonian equivalents of the Cardium Formation include the Frontier, Ferron, and Gallup Formations which also occur within the Western Interior Seaway.

2.2 Outcrop

Modern outcrop work on the Cardium was initially begun in 1954, a year after the discovery of oil in the Cardium

FIGURE 2: Stratigraphy of the Alberta Group in the Foothills of Alberta. Ages given on the left are from Palmer, 1983 (from Walker, 1984b).



CAMPANIAN
84
SANTONIAN
87·5
CONIACIAN
88·5
TURONIAN
91
CENOMANIAN
97·5
ALBIAN
1000
800
600
400
200
0
m
Nomad
Chungo
Hanson
Thistle
Dowling
Marshybank
Muskiki
Opabin
Haven
Vimy
Sunkay
BELLY RIVER
WAPIABI
CARDIUM
BLACKSTONE
BLAIRMORE GROUP
ALBERTA (=COLORADO) GROUP

Formation at Pembina field. Stott (1963) defined six stratigraphic members, emphasizing the "layer cake stratigraphy" of the Cardium. Later studies of the Cardium in outcrop (Wright and Walker, 1981) pointed towards inconsistencies in Stott's divisions. Stott's Cardium member boundaries crossed coarsening upward depositional sequences. Thus, Stott's scheme was modified by Walker (1983a) and Duke (1985).

2.3 Subsurface

Plint et al. (1986) established a formal stratigraphy for the Cardium Formation in the subsurface of Alberta based on the recognition and correlation of erosional and transgressive surfaces. The Cardium Formation extends roughly from the Grand Prairie area to south of Calgary in the subsurface. The erosion and transgressive surfaces become almost coincident when conglomerate overlying the erosion surface is present as a veneer (these are noted as E2/T2, for example). The E1/T1 surface defines the base of the Cardium Formation and the E7/T7 surface designates the top of the formation (Figure 1).

2.4 Pembina - Subsurface

In the northeastern region of Pembina field, three stratigraphic members have been recognized in the subsurface: the Raven River Member, the Carrot Creek Member, and the Dismal Rat Member (Figure 1). The Raven River Member is defined between the boundary surfaces T4 and E5 and represents a coarsening upward sequence. It begins with dark bioturbated muddy siltstones which grade upwards into pervasively bioturbated muddy sandstones, bioturbated sandstones, and finally into hummocky cross stratified, nonbioturbated sandstones at the top of the sequence. The Carrot Creek Member consists of conglomerates which rest on top of the E5 erosion surface. Conglomerates form a thin veneer, 0.67 m, in northeastern Pembina, approximating a thickness of 1 metre in most Cardium fields, and reaching a maximum thickness of 20 metres at Carrot Creek field (Bergman, 1984). In northeastern Pembina, the base of the Dismal Rat Member is present as a pebbly mudstone and overlies the Carrot Creek Member. Pebbly mudstones fine upwards into laminated dark mudstones and massive dark mudstones. The top of the Dismal Rat Member is designated by the E6/T6 surface, corresponding to the log marker known as Cardium "zone".

CHAPTER 3: HISTORY OF THE CARDIUM

3.1 Previous Ideas

Many hypotheses have been put forth in an effort to explain the apparent linear ridge geometry and sedimentology of the Cardium Formation.

Initial interest in this marine sandstone was generated by the discovery of oil at Pembina field in 1953. Thus, it became important to obtain information on Cardium lithologies and depositional environments.

In 1955, both Harding and Parsons suggested an offshore environment for Cardium deposition, close to a major river mouth and near to wave base.

During the same year, Floyd Beach (1955) suggested Cardium sediments had been deposited by turbidity currents. He based his reasoning on the fact that there existed great uniformity and continuity of pebble horizons in both the Cardium and Viking formations. This criterion, coarse sediments of great lateral uniformity, had been described by Passega (1954) as indicative of turbidity current deposition and Beach emphasized this point.

Dewiel (1956) objected to the turbidity current hypothesis as applied to deposition of Cardium sediments. He pointed out that the main problem with the hypothesis was that the Cardium sea was shallow, possessing too low a slope for the generation of turbidity currents.

The discussion surrounding Cardium deposition then became centered around shallow depositional environments due to problems associated with the generation of turbidity currents within the shallow Cardium sea.

Nielsen (1957) suggested a shallow water environment for the Cardium sediments. He argued that the Cardium sands do not exhibit turbidite characteristics; they do not show grading but are well sorted, the sands and muds are highly irregularly interbedded and there is evidence of scour. He suggested that the sands were initially deposited in a shallow sea followed by uplift and erosion of the sea floor. These events were accompanied by uplift of a source to the west which provided an influx of conglomerate into the sea.

Michaelis (1957) agreed with a shallow water origin for Cardium deposition. He suggested numerous environments including: tidal flats, beaches, distributary channels, beach bars, and offshore shoals.

In a detailed description of Pembina field, Patterson and Arneson (1957) presented conflicting environments for the deposition of Cardium conglomerates and sands. They suggested a nearshore environment due to the conglomeratic nature, lenticularity of the sands, and carbonaceous content of the Cardium sediments. However, the fine grain size and well sorted sands suggested a far offshore environment. Shallow water deposition was indicated by the cleanness of, and sedimentary structures within, the sands. Turbidity currents were also mentioned as a possible mechanism for Cardium deposition but there were problems concerning the maintenance of flows at such great distances from a source.

At this point, the idea of turbidity currents was abandoned for deposition of Cardium sediments due to problems of generation and maintenance of these flows within the shallow, Alberta basin.

Stott (1963) described the sands and gravels of the Cardium as deposits of a transitional environment which included shorelines, beaches, shallow-water nearshore environments, barrier beaches and barrier bars. He suggested that the conglomerates represented beach deposits.

In 1969, interpretations of the Cardium became associated with storm deposition. Michaelis and Dixon (1969) described the sandstones and conglomerates at Pembina as offshore shoals within a shallow sea. They recognized hummocky cross stratification in the sands and scoured surfaces which they associated with storm deposition.

Swagor et al. (1976) described the conglomerates at Carrot Creek field as offshore deposits associated with storm currents. He noted that the conglomerates were separated from the underlying mudstones by an unconformity.

Currents associated with storms were once again suggested as a possible mechanism for deposition of the Cardium sediments. Wright and Walker (1981) noted the presence of hummocky cross stratification in the Cardium sands, in outcrop at Seebe, Alberta, and also noted scour surfaces. They attributed these features to storm current emplacement of the Cardium sands and gravels.

Due to the problems of transporting Cardium sediments many kilometres offshore and then focussing them into linear ridges, hypotheses suggesting storm deposition had to be reassessed.

During a subsurface study of the Cardium Formation, Plint et al. (1986) recognized seven erosion surfaces, E1 through E7 which are overlain by varying thicknesses of conglomerate. They suggested that the surfaces were created as the result of a rapid lowering of sea level. Due to the lowering, the shoreline advanced many kilometres basinward. Newly incised rivers then carried sands and gravels to the new shoreface. A subsequent transgression reworked the gravel until with progressive deepening the area was finally blanketed by mud.

Using this hypothesis, the original problems of sediment transport and focussing of the sediments into ridges no longer apply. Problems are now centered on the origin and implications of rapid sea level changes.

3.2 Recent Work

Recent work on the Cardium Formation includes a detailed conglomerate study at Carrot Creek by K.M. Bergman (Ph.D. in prep), a study at Pembina field by S.M. Leggitt (M.Sc. in prep), details of the transgressive surfaces in the Cardium Formation by J.J. Bartlett (M.Sc. in prep), and a study of Ferrier field by D.J. McLean (M.Sc. in prep).

3.3 Pembina - A History Of Ideas

The discovery of oil in the Cardium Formation at Pembina field, 1953, generated interest in this marine sandstone and it became important to obtain information on stratigraphy and sedimentation. Since much of the history of Pembina is included in the previous section on the history of the Cardium, only major contributions will be briefly discussed here.

The Cardium sediments at Pembina field were initially associated with an offshore environment near to wave base (Harding, 1955; Parsons, 1955). Beach (1955) suggested that the Cardium was emplaced by turbidity currents. Possible depositional environments then became shallower due to problems associated with the generation of turbidity currents in the shallow Cardium sea. Michaelis (1957) suggested various shallow settings for deposition, including delta, tidal and beach environments. Interpretations of the Cardium Formation sediments then became associated with storm current deposition. Michaelis and Dixon (1969) described the Cardium deposits at Pembina as offshore shoals characterized by hummocky cross stratified sands and scour surfaces. These features they attributed to storm deposition.

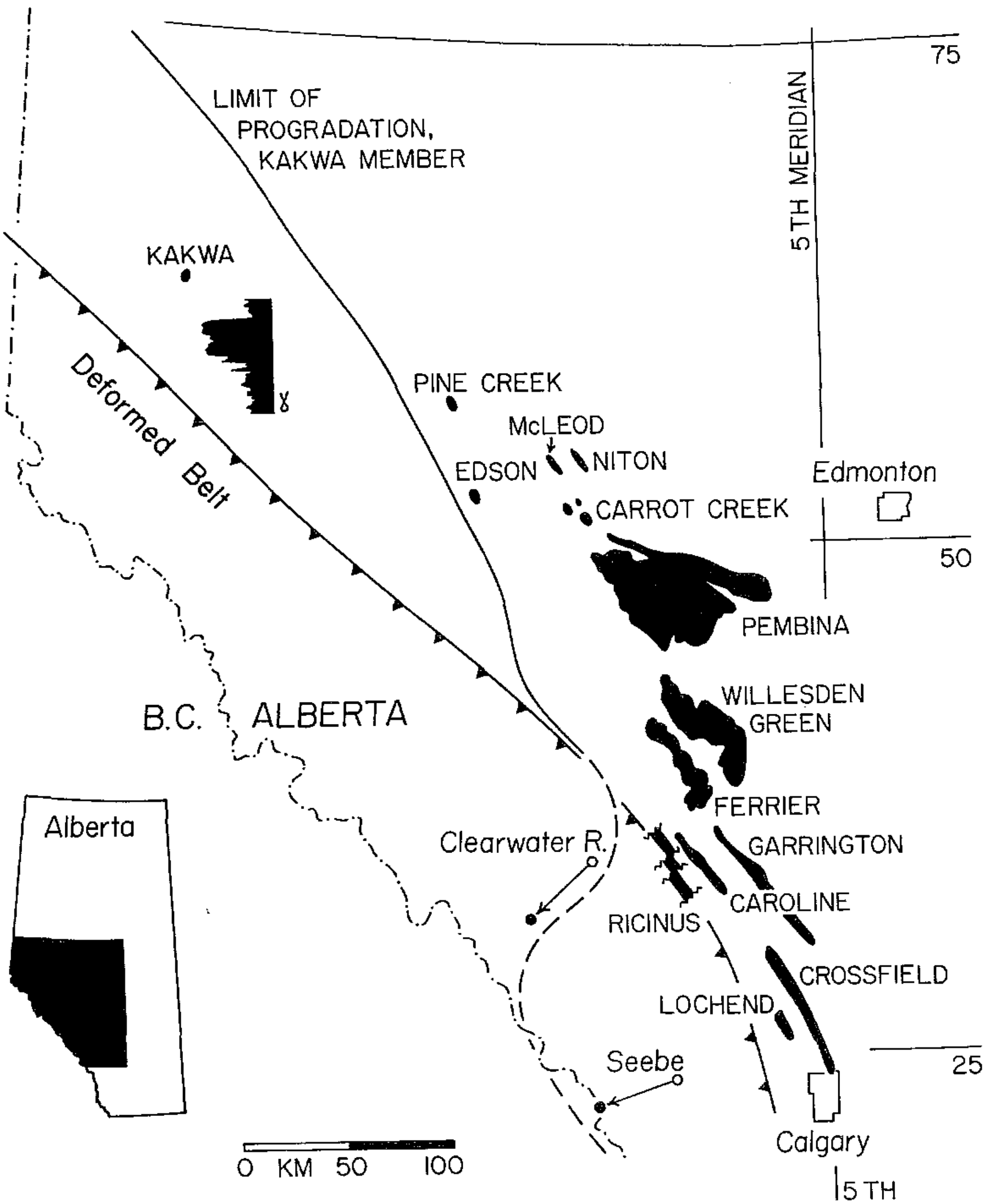
Krause (1984) suggested Cardium deposition at Pembina field by geostrophic flows, high discharges from seasonal river floods, and shifts in shorelines due to changes in sea level. He specifically mentioned that the conglomerates were transported by geostrophic flows and then reworked by storms.

3.4 Field Area

The focus of this study is the northeastern region of Pembina (Figure 3). Pembina oil field was discovered in May, 1953. The discovery well was Socony-Seaboard's Pembina No. 1, 4-16-48-8W5. The field has an area of more than 2,331 square kilometres, making it the largest single oil field in western Canada. Production occurs from approximately four separate sands and a conglomerate. Reservoirs are separated by shale breaks.

The data for this study includes 32 cores and over 100 well logs. Well logs include mostly resistivity log signatures and gamma log signatures when available. The gamma ray log signature essentially mirrors the resistivity signature and is of scarce availability. Thus, resistivity logs (and gamma ray logs, when resistivity logs were unavailable) are correlated in the cross sections presented.

FIGURE 3: Location of Pembina field. The inset to the left shows the location of the region in the figure. Positions of Calgary and Edmonton are included for reference and the approximate eastern limit of the deformed belt (thrust belt) of the Rocky Mountains is shown. The positions of two Foothills Cardium exposures, Clearwater River and Seebe are shown. In black are approximate locations of producing Cardium fields (Plint et al., 1986).



75
5TH MERIDIAN
LIMIT OF
PROGRADATION,
KAKWA MEMBER
KAKWA
Deformed Belt
PINE CREEK
McLEOD
NITON
EDSON
Edmonton
CARROT CREEK
50
PEMBINA
WILLESDEN
GREEN
B.C.
ALBERTA
FERRIER
Alberta
Clearwater R.
GARRINGTON
CAROLINE
RICINUS
CROSSFIELD
LOCHEND
Seebe
25
0 KM 50 100
Calgary
5 TH

CHAPTER 4: FACIES DESCRIPTIONS

4.1 Definition Of Facies

Facies are distinguished by the lithology, sedimentary structures and paleontological characteristics of a group of rocks (de Raaf et al., 1965).

4.2 Method

Measuring and describing drill core involves dividing up the rock into a series of units characterized by distinct or gradational breaks between recognizable facies in the rock sequence. Facies are first distinguished according to lithology and then each lithological unit is studied in more detail. Grain size of sands are measured, sedimentary structures are described, the degree of bioturbation is noted and any distinct fossils are recorded. This method was used to describe the 32 cores studied in the study area.

4.3 Facies In Northeastern Pembina

In the northeastern region of Pembina, eight facies were recognized from the 32 drill cores studied. These facies are identical to facies 1,2,3,3P,4,5,7 and 8 described by Walker (1983b) and (Bergman and Walker, 1986).

Facies 1: Massive Dark Mudstones (Figure 4A)

This facies consists of monotonous dark gray to black mudstones. Evidence of bioturbation is indicated by a background mottling. Trace fossils include the pin worm *Gordia*, and some indistinct, pyritized burrows. Sometimes this facies contains a few scattered, sharp based sand laminae which show grading. Facies 1 is somewhat rare in northeastern Pembina, having been recognized in only two of the 32 cores studied. When present, it overlies facies 2 in the Dismal Rat Member. It has recorded thicknesses of 2.85 and 3.39 m.

Facies 2: Laminated Dark Mudstones (Figure 4B)

This facies is recognized by thin sand laminae (vfU-fL) encased in black mudstone. Most laminae are 2 - 3 mm, but thicker laminae/beds of 5 - 15 mm also occur. Many of the laminae are sharp based and show grading while others have a "chewed" appearance due to bioturbation. Ten out of 28 cores in which this facies is present show an increase in the number of sand laminae upwards. Five of the 28 cores contain gritty horizons (Figure 8A), three of which occur at the top of the unit. Body fossils include *Inoceramus*, pelecypods (rare, Figure 9B) and an ammonite (present in only one core). The only distinguishible trace fossil is *Gordia*. The average thickness of this unit is 3.9 m.

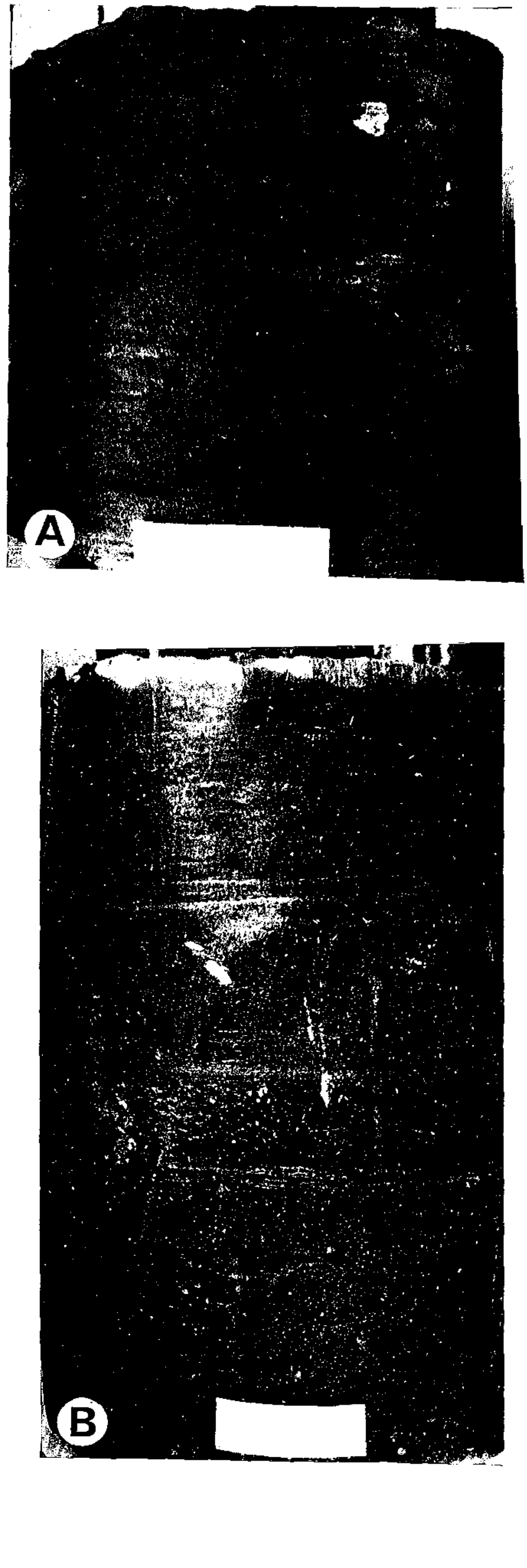
Due to the presence of thicker sand laminae, the above description deviates from the original description of facies 2 by Walker (1983b). However, since the facies occurs at the same stratigraphic horizon as the facies 2 described by Walker, it can be considered equivalent.

Facies 3: Dark Bioturbated Muddy Siltstones (Figure 5A)

Facies 3 is recognized in 11 of the 32 cores studied. It is characterized by patchy, discontinuous sand laminae (vFU-fL) with average thicknesses of 3 - 5 mm surrounded by dark mudstones. Thicker sand beds 20 - 60 mm are present

FIGURE 4: A: Facies 1, massive dark mudstones. Note the absence of any lamination. Sand laminae are rare and patchy. From above the Carrot Creek Member, 16-17-49-7W5, 4640 Ft. Scale in cm.

B: Facies 2, laminated dark mudstones. Note the sharply based fine sand laminae (2 - 3 mm). Thicker laminae/beds of 5 - 15 mm also occur. Discontinuous laminae suggest bioturbation. 16-20-49-7W5, 4593 Ft. Scale in cm.


A
B

but few in number. Nodules and layers (6.4 - 24 cm) of siderite occur in 4 of the 11 cores. One core contains a very thick layer (24 cm) of gritty siderite. Trace fossils include Rhizocorallium, Zoophycos, Helminthopsis, Skolithos and Teichichnus. Bioturbation appears most intense in the sand laminae. The average thickness of facies 3 is 3.15 m. Facies 3 has a gradational contact with facies 4 which overlies it.

Facies 3P: Pebbly Dark Bioturbated Muddy Siltstones

Facies 3P averages 1.33 metres in thickness and is recognized in 10 of the 32 cores studied. It is characterized by scattered pebbles in a mud matrix. This facies is sometimes distinguished by only one pebble or by a single, isolated pebble stringer present in dark, bioturbated muddy siltstones. Facies 3P lies above the conglomerate (facies 8) when it is present.

Facies 4: Pervasively Bioturbated Muddy Sandstone (Figure 5B)

Facies 4 averages 4.19 metres in thickness and contains equal proportions of sand (vfU-fL) and mud. This facies is present in 31 of the 32 cores studied. Thicker sand beds (2 - 8 cm) are quite common and may show hummocky cross stratification and wave ripples. Alternating muddier and sandier portions of this facies occur with a general sandier trend near the top of the unit. Almost all cores show abundant siderite nodules and layers (3 - 21 cm) including "patchy" siderite or partially sideritized sand. Gritty siderite occurs in only one core and two gritty horizons are notable in two other cores (Figure 8B). Trace fossils include Rhizocorallium, Zoophycos (Figure 9A), Teichichnus, Skolithos, Helminthopsis, Ophiomorpha, Paleophycus, Chondrites, Planolites and Terebellina. Bioturbation is extensive in this facies. A gradational contact occurs between facies 4 and the overlying facies 5.

Facies 5: Bioturbated Sandstones (Figure 5C)

This facies is characterized by sand (80 - 85 %) and mud. Facies 5 occurs in 31 of the 32 cores which were studied. Many cores contain thicker sand beds (vfU-fL) with thicknesses of 1 - 10 cm and they may show sharp bases, grading, parallel lamination, wave ripples, hummocky cross stratification, or intense bioturbation. Alternating muddier and sandier portions of the facies occur with an increase in sand near the top of the unit. Siderite is abundant throughout facies 5 as nodules, partially sideritized sand, and layers (4.5 - 12 cm). Five cores contain gritty horizons within this facies, one of which also contains a gritty siderite (Figure 8C). Trace fossils include Rhizocorallium, Zoophycos, Teichichnus, Terebellina, Skolithos, Paleophycus, Chondrites, and Helminthopsis. Bioturbation is pervasive in this facies. The average thickness of this unit is 4.49 m.

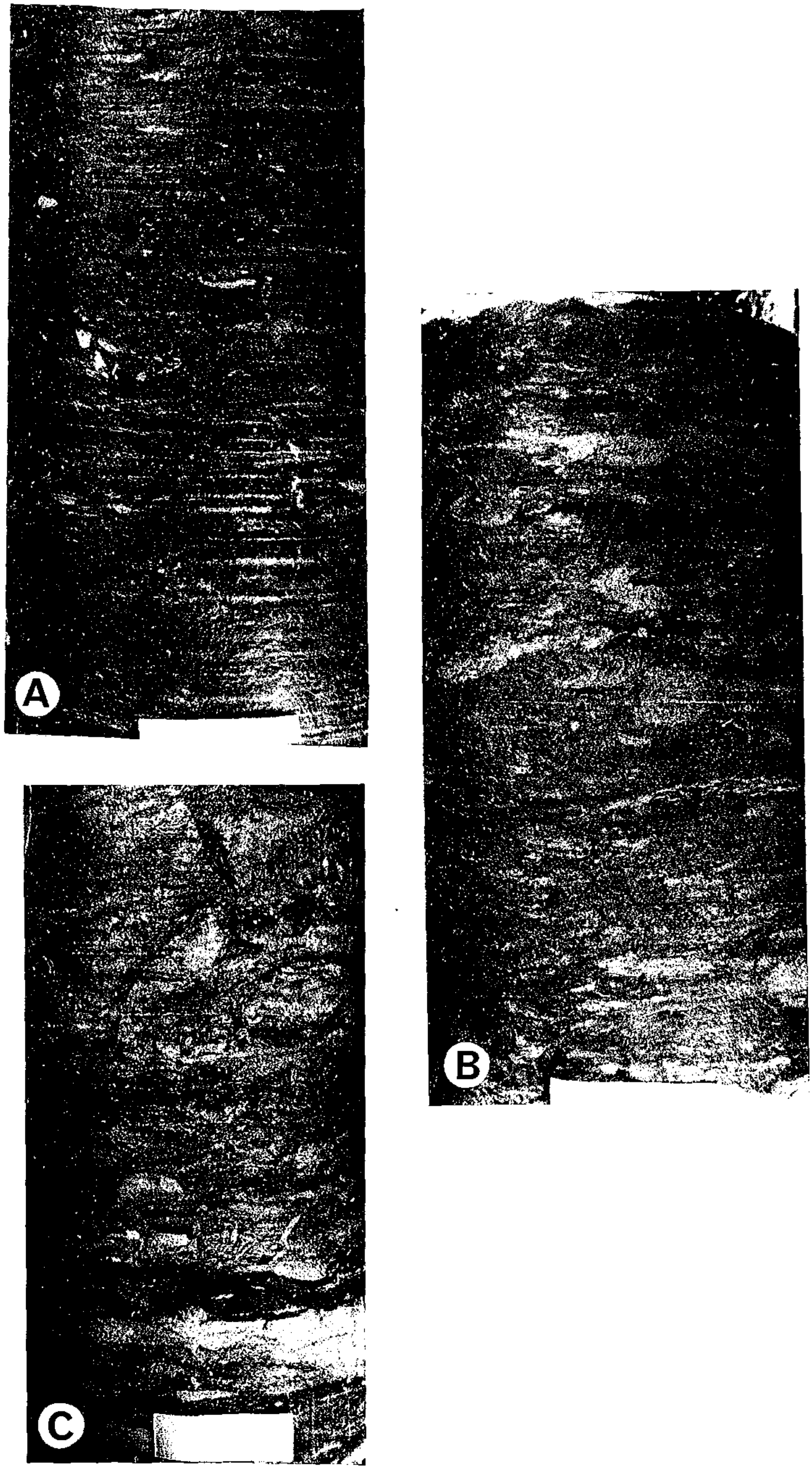
Facies 7: Nonbioturbated Sandstones (Figure 6)

Facies 7 consists of sand (vfU-fL) with 3 mm - 3 cm shale partings and occurs in 10 of the 32 cores studied. Most sections of facies 7 show hummocky cross stratification

FIGURE 5: A: Facies 3, dark bioturbated muddy siltstones. Note the mottled appearance and only few partially preserved fine sandstone laminae (3 -5 mm). Thicker sand beds (20 - 60 mm) are present but few in number. Bioturbation appears most intense in the sand laminae. 12-26-49-7W5, 4486 Ft. Scale in cm.

B: Facies 4, pervasively bioturbated muddy sandstones. Note thoroughly churned appearance and remanant sand laminae. A Rhizocorallium burrow is present near the centre of the core. 12-26-49-7W5, 4476 Ft. Scale in cm.

C: Facies 5, bioturbated sandstones. Note the intense bioturbation with no preservation of original laminae. 12-26-49-7W5, 4450 Ft. Scale in cm.


A
B
C

and wave ripples. Siderite is common as nodules and layers (2.5 - 10 cm) and partially sideritized sand. Also, gritty horizons occur in two cores at the top of the unit. Trace fossils include Ophiomorpha, Paleophycus, Skolithos and Chondrites. Most bioturbation is evident in the shale partings. Facies 7 averages 0.61 m in thickness and forms a sharp contact with the underlying facies 5. In some cores facies 7 is interbedded with facies 5.

Facies 8: Conglomerates (Figure 7)

Facies 8 is a thin unit, averaging 0.67 m, of mostly mud-supported conglomerate. Clasts show no preferred fabric or imbrication and range in size from 1 to 50 mm. Clast supported pebble stringers and layers appear in 10 cores. Two other cores show clast supported openwork, and clast supported closedwork pebble layers with a sand matrix. A noticable trend of larger clasts towards the top of the unit is present in five of the cores. This facies is contained in 26 of the 32 cores studied. The body fossil, Inoceramus is recognized in some cores. Trace fossils are scarce but include Gordia and pyritized indistinguishable burrows. Facies 8 has a sharp contact with underlying units, facies 5 and facies 7. Facies 3P overlies facies 8 in ten cores studied and forms a gradational contact. Facies 2 commonly overlies facies 8 and has a sharp contact with this unit.

FIGURE 6: A: Facies 7, nonbioturbated sandstones. Note the very subtle low angle intersections of sand laminae which could represent hummocky cross stratification. Sideritized sand occurs at the base of the core. Note the sideritized mud rip ups present above the massive siderite. 6-20-49-7, 4722 Ft. Scale in cm.

B: Facies 7, nonbioturbated sandstones. Note shale partings (1 cm). Chondrites is present in the centre shale layer, on the left side (small, circular sand-filled burrows). 6-14-49-7, 4253 Ft. Scale in cm.

C: Facies 7, nonbioturbated sandstones. Wave ripples distinguished by symmetrical draping of foreset beds. 16-17-49-7, 4673 Ft. Scale in cm.

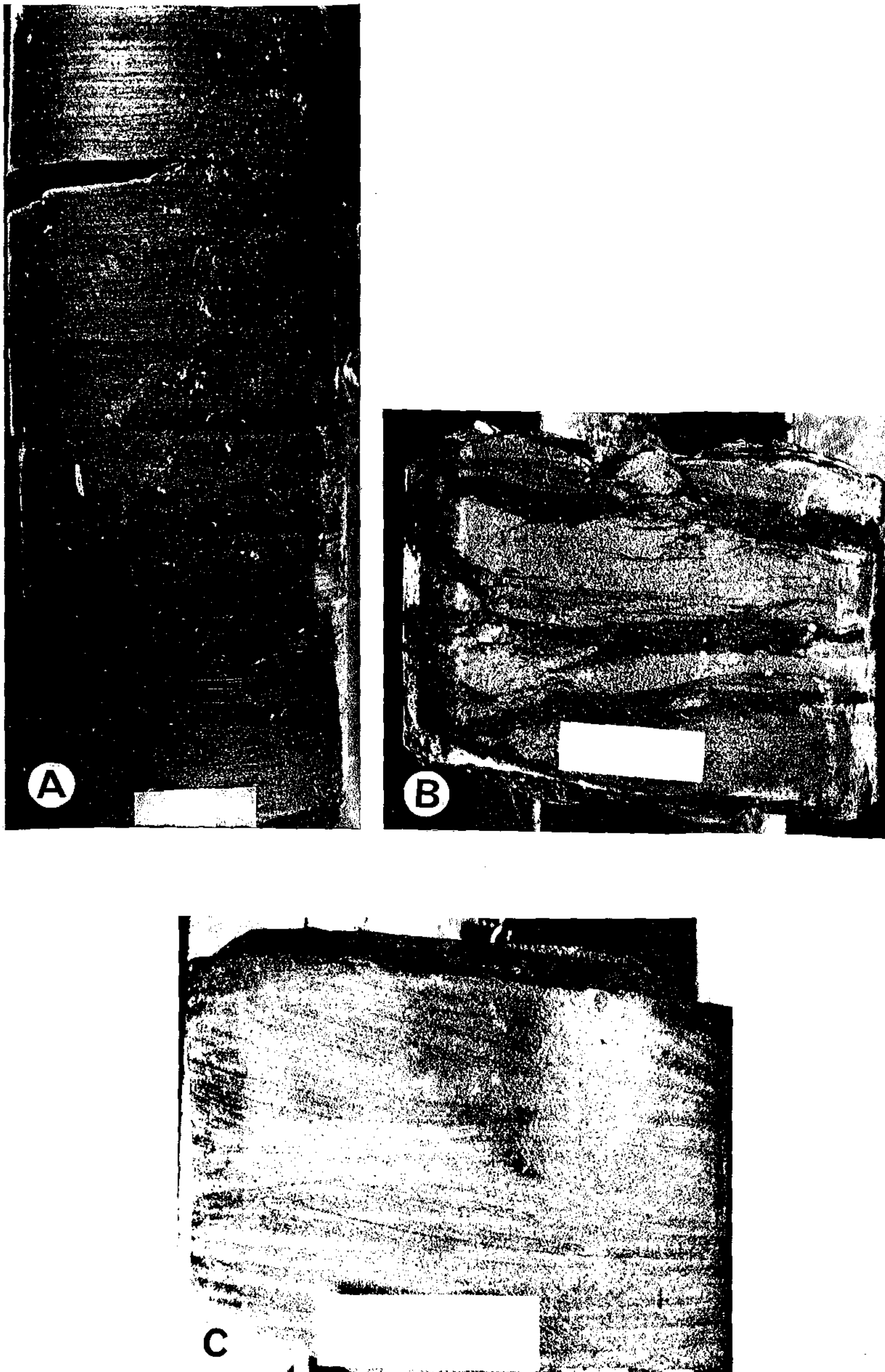
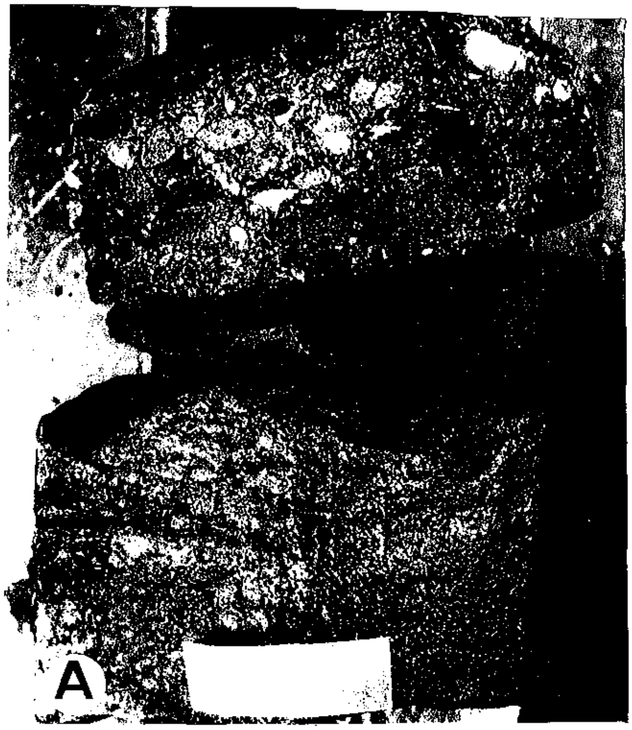

A
B
C

FIGURE 7: A: Facies 8, mud supported conglomerate. Note the random orientation of the pebbles. Some pebbles are scattered into the underlying unit, facies 5. 16-30-49-6, 4265 Ft. Scale in cm.

B: Facies 8, mud supported conglomerate. Pebbles are randomly oriented and are scattered into the top of facies 5, the underlying unit. Maximum pebble size is 3 cm. 16-20-49-7; 4594 Ft. Scale in cm.


A


B

FIGURE 8: A: Gritty horizon in facies 2 of 16-21-49-7W5. 4556 Ft. Scale in cm.

B: Gritty horizon in facies 4 of 12-6-50-6W5 Note the sideritized sand below the gritty horizon. 4076 Ft. Scale in cm

C: Gritty siderite in facies 5 of 16-30-49-6W5 4271 Ft. Scale in cm.

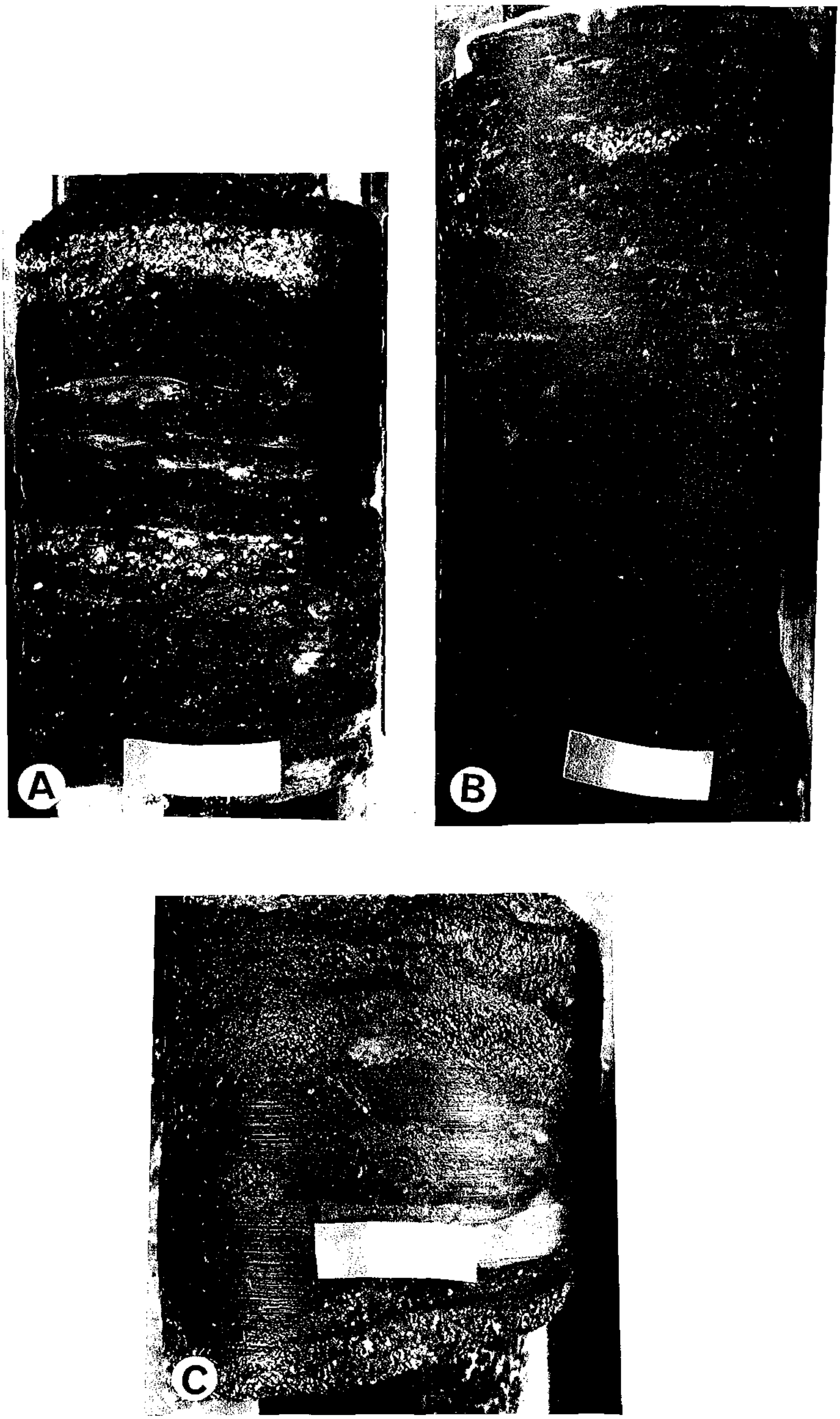
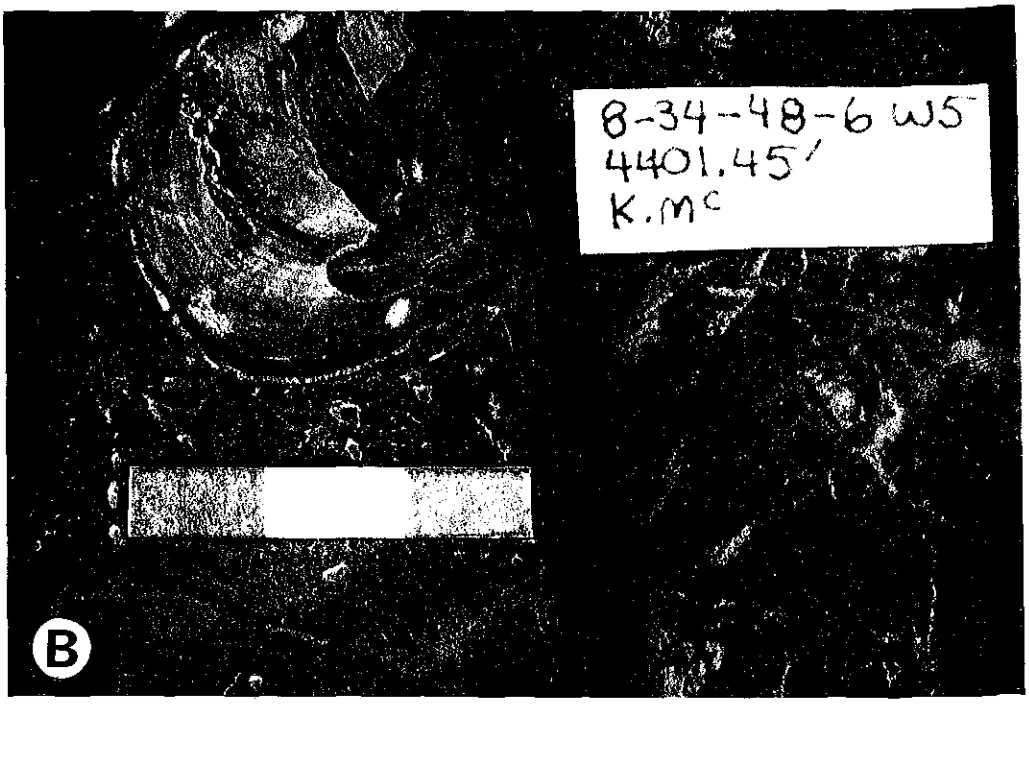

A
B
C

FIGURE 9: A: Trace fossil - _Zoophycos_ burrow (centre of photo). 8-34-48-6W5, 4352 Ft.

B: Body fossil - pelecypod, in 8-34-48-6W5, 4401 Ft. Scale in cm.


A


B
8-34-48-6 W5
4401.45'
K.Mc

4.4 Facies Sequences and Depositional Environments

The typical facies sequence in northeastern Pembina begins with facies 3, dark bioturbated muddy siltstones and coarsens upwards into facies 4, pervasively bioturbated muddy sandstones, facies 5, bioturbated sandstones, and facies 7, nonbioturbated sandstones. Hummocky cross stratification is characteristic of facies 7 and is associated with storm reworking of sands present in an offshore environment below fairweather wave base (Harms et al., 1975). Thus the sequence seems to indicate a shelf environment below fairweather wave base but above storm wave base.

Conglomerates (facies 8), which are indicative of shoreface deposits, rest on top of an erosion surface which separates them from the underlying sequence of shelf deposits. Their presence above shelf deposits can be explained using the hypothesis employed by Plint (Plint et al., 1986) which suggests a rapid relative lowering of sea level. During a lowering of sea level, the shoreline could advance many kilometres basinward and a new shoreface could be established on sediments which were previously offshore. Newly incised rivers could then carry sand and gravel to the newly established shoreface.

Above the conglomerates, pebbly mudstones, facies 3P, fine upwards into laminated dark mudstones, facies 2, and massive dark mudstones, facies 1. Mudstones characterize a low energy environment, offshore and below fairweather wave base (Walker, 1984a). This sequence may represent a relative rise of sea level within the Alberta basin. Pebbly mudstones may be the result of gravel from the shoreface being reworked by storms into the transgressive muds (Plint et al., 1986).

CHAPTER 5: LOG AND CORE CORRELATIONS

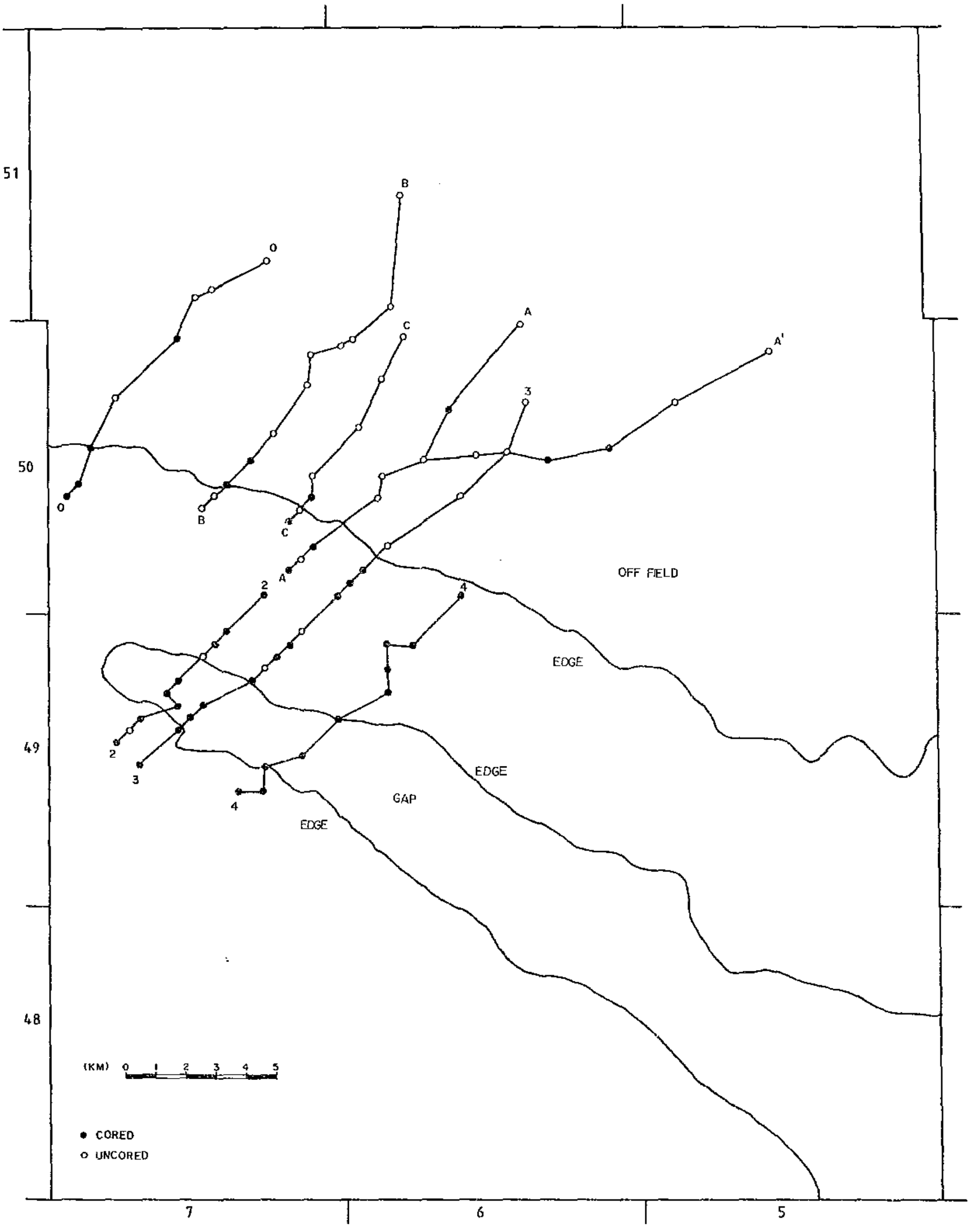
5.1 Log And Core Markers

Eight cross-sections (Figure 10) were constructed with correlation based on markers in the induction - resistivity log signatures. Separation between wells on the cross-sections does not represent true distance between wells. Core lines were constructed for three corresponding log cross-sections (Figures 12, 14, 16). Cross-sections were drawn from the southwest to the northeast.

The Cardium sequence is represented on the resistivity log by a large, blocky deflection to the right of the scale. Four induction log markers were noted above the main Cardium sequence. The Cardium "zone" induction log marker was used as a regional datum for both cross-sections and core sections. This datum will be referred to as E6/T6, using the terminology of Plint et al. (1986). The marker that lies above E6/T6 correlates with Plint's E7/T7 log marker. Two induction - resistivity log markers were noted below the main Cardium sequence. These only appear in four of the eight cross sections since not all wells penetrate below the Cardium. These markers correlate with Plint's E1/T1 and E3/T3-E4/T4 log markers.

A solid bar indicates the cored interval in each well. Core depths were adjusted to the corresponding well log depths by choosing an obvious core and log marker, the top of the conglomerate. This marker is recognized on the resistivity log by a sharp deflection back towards the scale at the top of the blocky response representing the Cardium

FIGURE 10: Location of cross-sections in northeastern Pembina field. Twp. 48-51, Ranges 5,6, and 7 W5. "Gap" refers to a gap in drilling in this region of the field. "Edge" refers to the boundaries of the field. Solid circles represent cored wells and open circles represent uncored wells.


51
50
49
48
7
6
5
B
O
C
A
A'
3
2
4
OFF FIELD
EDGE
EDGE
GAP
EDGE
(KM) 0 1 2 3 4 5
CORED
UNCORED

sequence. In core, the marker occurs at the contact between the top of the conglomerate (facies 8) and the base of the overlying laminated dark mudstones (facies 2) or pebbly laminated dark mudstones (facies 3P). Each cross section will be discussed individually.

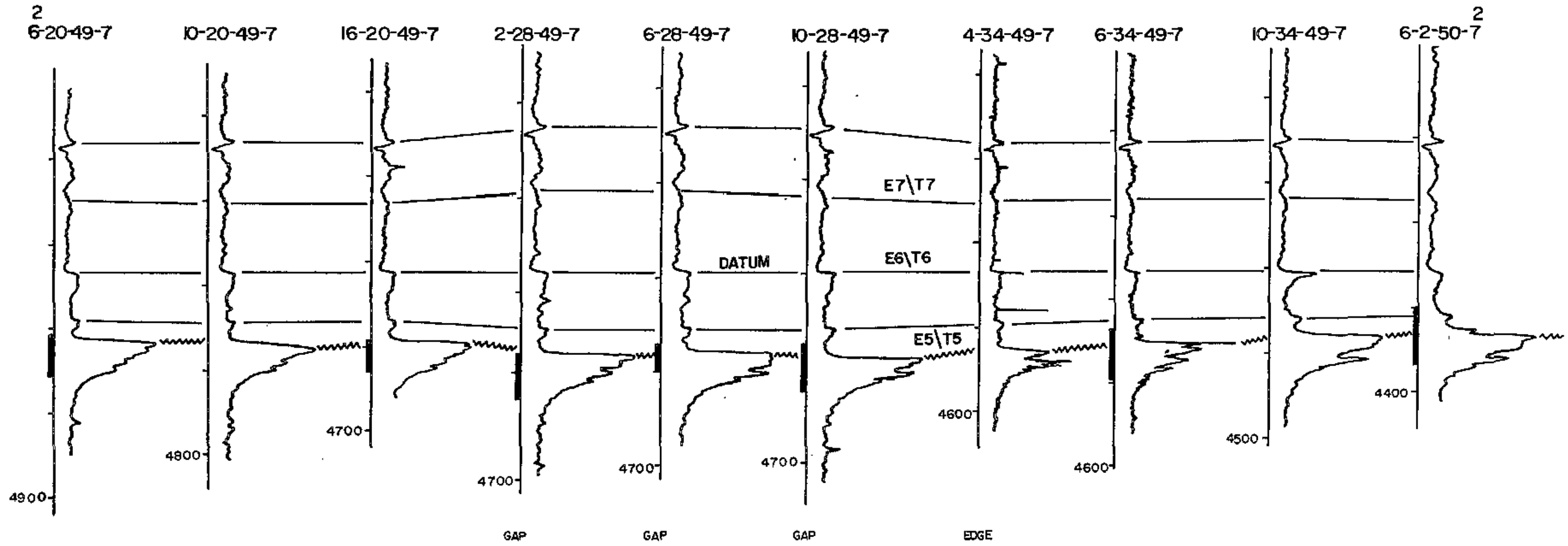
5.2 Cross-Sections

Cross-section 2 (Figures 11 and 12)

Core was studied in conjunction with the resistivity logs along this cross-section. The sequence begins with dark bioturbated muddy siltstones (facies 3), and coarsens upward into pervasively bioturbated muddy sandstones (facies 4), bioturbated sandstones (facies 5), and non-bioturbated sandstones (facies 7). Conglomerate (facies 8) overlies facies 7 and the top of the Cardium sequence is covered by facies 3P, pebbly laminated dark mudstones, then laminated dark mudstones (facies 2).

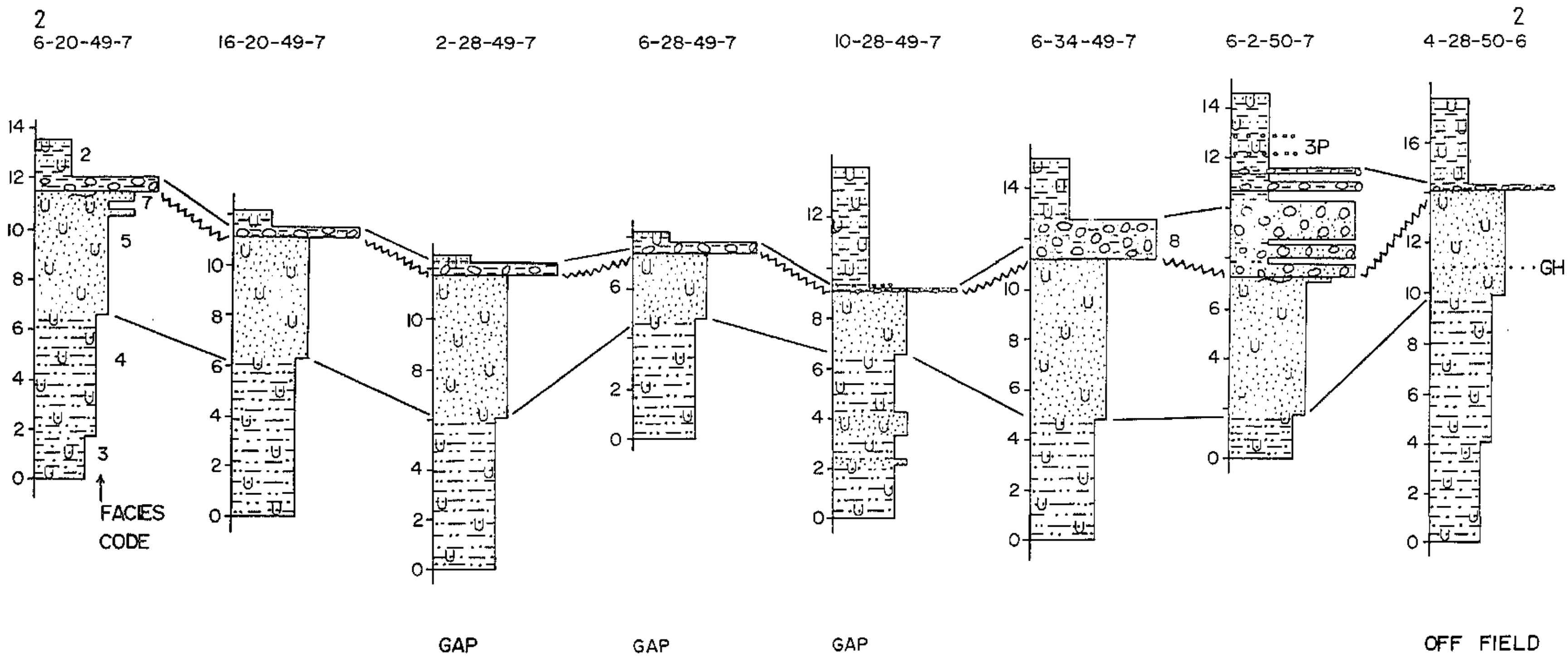
The top of the conglomerate is essentially flat with respect to the datum if lateral distance between wells is taken into account. However, the base of the conglomerate appears to be scoured as it cuts out core markers such as facies 7 (compare wells 6-20-49-7 and 16-20-49-7) and rests on the same facies but at different distances below the datum (see wells 10-28-49-7 and 6-34-49-7). The base of the conglomerate usually rests on facies 5, but also occurs above facies 7 (see wells 6-20-49-7 and 6-2-50-7). There is a notable thinning of the conglomerate and facies 5 in 10-28-49-7. The log response shows an erosional hollow on

FIGURE 11: Cross-section 2 : A solid bar indicates the cored interval in each well. Scales for each log are marked off in 100 Ft. intervals. The E7/T7 log marker denotes the top of the Cardium Formation and E6/T6 represents the regional datum. A jagged line indicates erosion on the E5/T5 surface. The section is hung on the E6/T6 marker. Note that maximum erosion occurs at 10-28-49-7. Cross-section 2 is located in Figure 10.



2
6-20-49-7
10-20-49-7
16-20-49-7
2-28-49-7
6-28-49-7
10-28-49-7
4-34-49-7
6-34-49-7
10-34-49-7
2
6-2-50-7
E7\T7
DATUM
E6\T6
E5\T5
4900
4800
4700
4700
4700
4700
4600
4600
4500
4400
GAP
GAP
GAP
EDGE

FIGURE 12: Core section 2 : Scales for each core are marked off in 2 m intervals. The section is hung on the E6/T6 marker. Facies are designated by their corresponding numbers on the right side of the core section. GH represents a gritty horizon. The jagged line beneath the conglomerates denotes the E5/T5 surface. A sideways "S" symbol represents hummocky cross stratification in facies 7. "Gap" refers to core located within the drilling gap. Note the scouring of facies 7 between 6-20-49-7 and 16-20-49-7, and the thinning of facies 8 in 10-28-49-7 (within the drilling gap).



2
6-20-49-7
16-20-49-7
2-28-49-7
6-28-49-7
10-28-49-7
6-34-49-7
6-2-50-7
2
4-28-50-6
2
7
5
4
3
FACIES
CODE
8
3P
GH
GAP
GAP
GAP
OFF FIELD

the E5/T5 surface in 10-28-49-7 which represents a maximum erosion on the E5/T5 surface of 4.18 m, along this cross-section. This well is located in the gap (Figure 10). Facies 8 thickens to 4.3 m in 6-2-50-7. The last well, 4-28-50-6 actually occurs on log cross-section A - A', located off the edge of the field. It was included on the core line to show the contrast in the thickness of the conglomerate from the northern boundary of the oil field to a location off the edge of this boundary. Facies 8 thins to a veneer (0.11 m) in this well. A gritty horizon is also present in facies 5 of 4-28-50-6.

Cross-section 3 (Figures 13 and 14)

Core was studied in conjunction with this log cross-section. The sequence is the same as that described for cross-section 2 and coarsens upward from facies 3. Facies 8 (conglomerate) overlies facies 7 and the whole sequence is covered by facies 2, then facies 1.

The top of the conglomerate is essentially flat with respect to the datum if lateral distance between wells is accounted for. The base of the conglomerate appears scoured as it cuts out core markers such as facies 7 (see wells 10-21-49-7 and 16-21-49-7, also wells 2-35-49-7 and 12-6-50-6). In 16-17-49-7, facies 7 is present and facies 8 is only represented by one pebble. From 16-17-49-7 to 10-21-49-7, facies 8 becomes a thin veneer of pebbles (0.19 m) and facies 7 is greatly reduced from 1.79 m to 0.16 m.

FIGURE 13: Cross-section 3 : Located in Figure 10. The relief on the E5/T5 surface within the drilling gap is 2.98 m (averaged from 10-21-49-7, 16-21-49-7, and 4-27-49-7). Maximum relief on the E5/T5 surface is 6.63 m, and occurs off the northern boundary of the field, in 6-16-50-6. The section is hung on the E6/T6 marker.

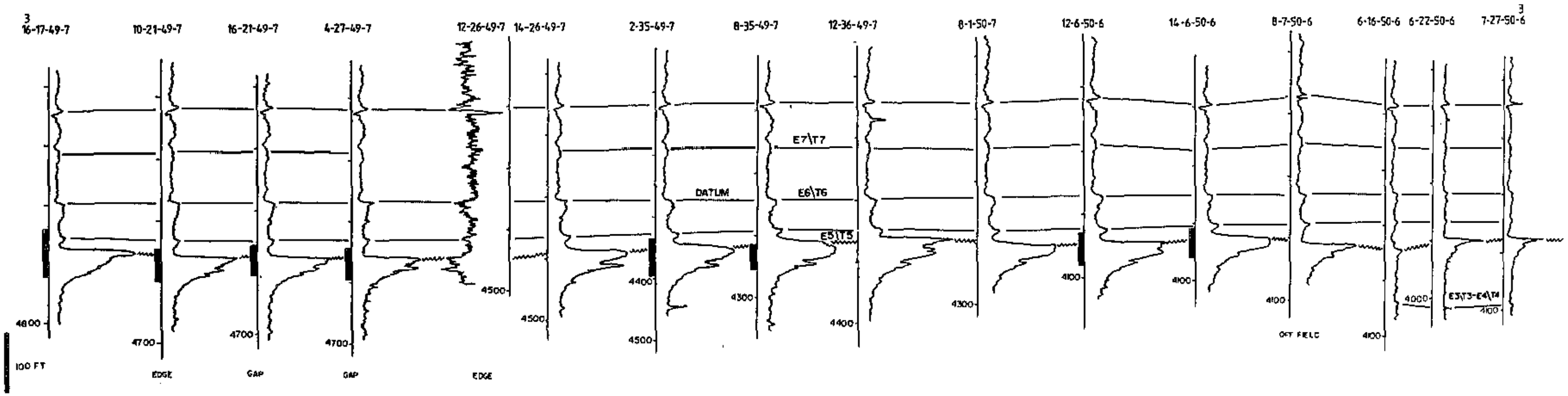
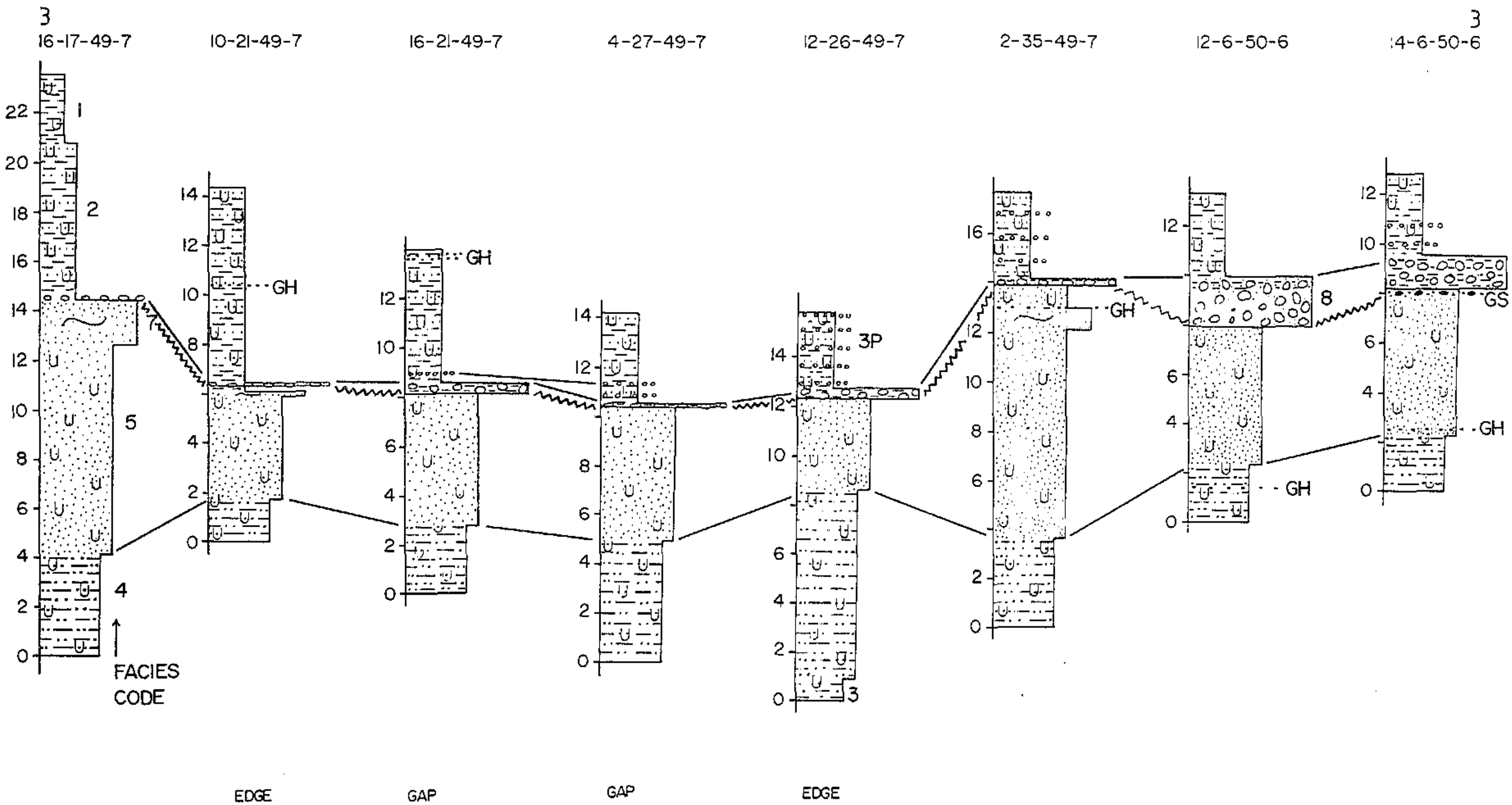

16-17-49-7
10-21-49-7
16-21-49-7
4-27-49-7
12-26-49-7
14-26-49-7
2-35-49-7
8-35-49-7
12-36-49-7
8-1-50-7
12-6-50-6
14-6-50-6
8-7-50-6
6-16-50-6
6-22-50-6
7-27-50-6
E7\T7
DATUM
E6\T6
E5\T5
E3\T3-E4\T4
100 FT
EDGE
GAP
GAP
EDGE
OFF FIELD
4800
4700
4700
4700
4500
4500
4400
4500
4300
4400
4300
4100
4100
4100
4100
4000
4100

FIGURE 14: Core section 3 : GS represents a gritty siderite. Note the absence of facies 7 and the thinning of facies 8 within the gap. Gritty horizons in 10-21-49-7 and 16-21-49-7 may correlate. Similarly, gritty horizons in 12-6-50-6 and 14-6-50-6 may also correlate. Since the horizons are not laterally continuous, correlations are ambiguous. The section is hung on the E6/T6 marker.



3
16-17-49-7
10-21-49-7
16-21-49-7
4-27-49-7
12-26-49-7
2-35-49-7
12-6-50-6
3
14-6-50-6
1
2
5
4
FACIES
CODE
GH
GH
3P
3
GH
8
GS
GH
GH
EDGE
GAP
GAP
EDGE

On the log cross-section, a bump on the E5/T5 surface occurs in 16-17-49-7 and an erosional hollow on E5/T5 is noted in 10-21-49-7. From the core section, it appears that facies 7 is being scoured with the subsequent deposition of facies 8. In 16-21-49-7, the conglomerate thickens to 0.43 m and facies 7 is absent. The conglomerate thins again in 4-27-49-7 to 0.11 m. Both wells, 16-21-49-7 and 4-27-49-7 are located within the drilling gap in the study area (Figure 10). There is an erosional hollow on the E5/T5 surface within the drilling gap of 2.98 m measured from 4-27-49-7. The conglomerate then thickens slightly in 12-26-49-7 and there is a reappearance of facies 7 (0.88 m) and a thinning of facies 8 (to 0.29 metres) in 2-35-49-7. On the log cross-section, a bump on the E5/T5 surface is noted in 2-35-49-7. The conglomerate thickens to 2 m in 12-6-50-6. On the log section, an erosional hollow occurs on the E5/T5 surface in this well. In 14-6-50-6, the conglomerate thins slightly to 1.26 m and the log section shows a bump on the E5/T5 surface. Maximum relief on the E5/T5 surface is 6.63 m, along this cross-section, and occurs in 6-16-50-6.

A gritty horizon in 2-35-49-7, at the top of facies 7, seems to lie at the same level below the datum as another gritty siderite in 14-6-50-6, which occurs near the top of facies 5. In 12-6-50-6, a gritty horizon is present within facies 4 and may correlate with the gritty horizon at the base of facies 5 in 14-6-50-6. Gritty horizons in facies 2 of 10-21-49-7 and 16-21-49-7 may also be correlative. Since the gritty horizons are not ubiquitous, correlations are ambiguous.

Cross-section 4 (Figures 15 and 16)

Both cores and resistivity logs were correlated for this cross-section. The core sequence is identical to the description for the two previous cross-sections. The sequence begins with facies 3 and coarsens upward through facies 4, facies 5 and facies 7. Facies 8 (conglomerate) overlies facies 7 and the top of the Cardium sequence is covered by facies 3P, then facies 2 (laminated dark mudstone).

The top of the conglomerate is essentially flat with respect to the datum if lateral distance between wells is accounted for. The base of the conglomerate appears scoured as it cuts out core markers, for example, facies 7 (see wells 8-15-49-7, 6-14-49-7, and 4-24-49-7). The base of the conglomerate rests on different facies (facies 5 and facies 7) which can be seen in wells 6-32-49-6 and 6-4-50-6. The conglomerate thins progressively across the section from 2.43 m in 6-14-49-7 to a thin pebble veneer of 0.20 m at 6-32-49-6 and 0.10 m at 6-4-50-6, to a few scattered pebbles at 6-24-50-6. There is a notable thinning of the conglomerate and facies 5 in 4-24-49-7 to 0.19 m. On the log section, a bump on the E5/T5 surface is noted in 6-14-49-7 and an erosional hollow of 10.55 m occurs in 4-24-49-7. This represents the maximum relief on the E5/T5

FIGURE 15: Cross-section 4 : The cross-section is located on Figure 10. Maximum relief on the E5/T5 surface is 10.55 m in 4-24-49-7 (located in the gap). The section is hung on the E6/T6 marker.

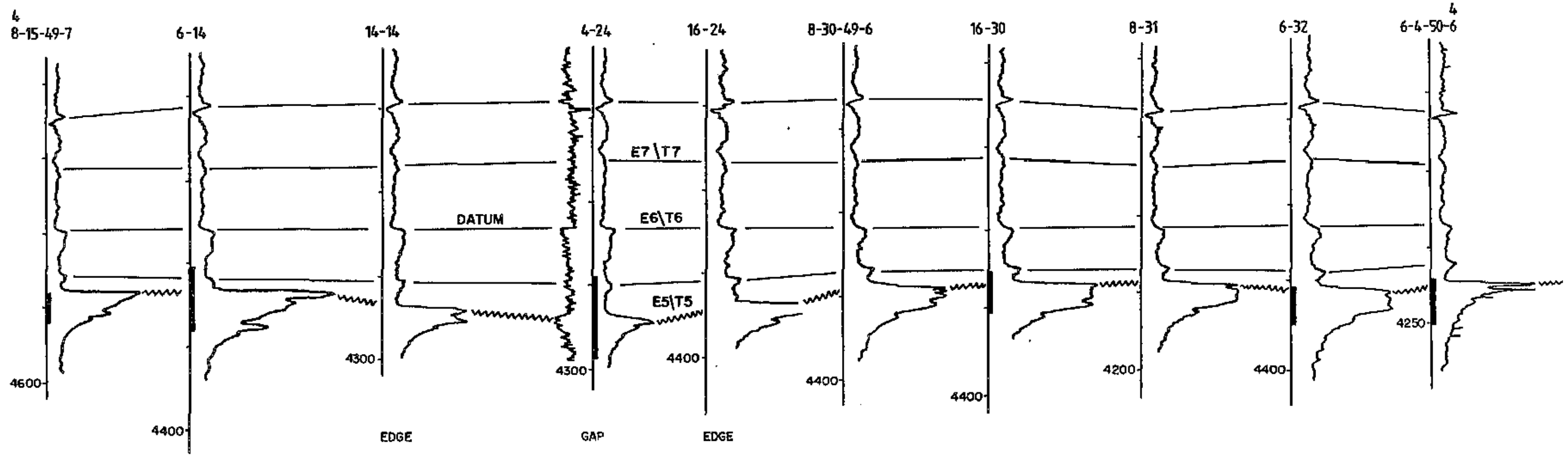
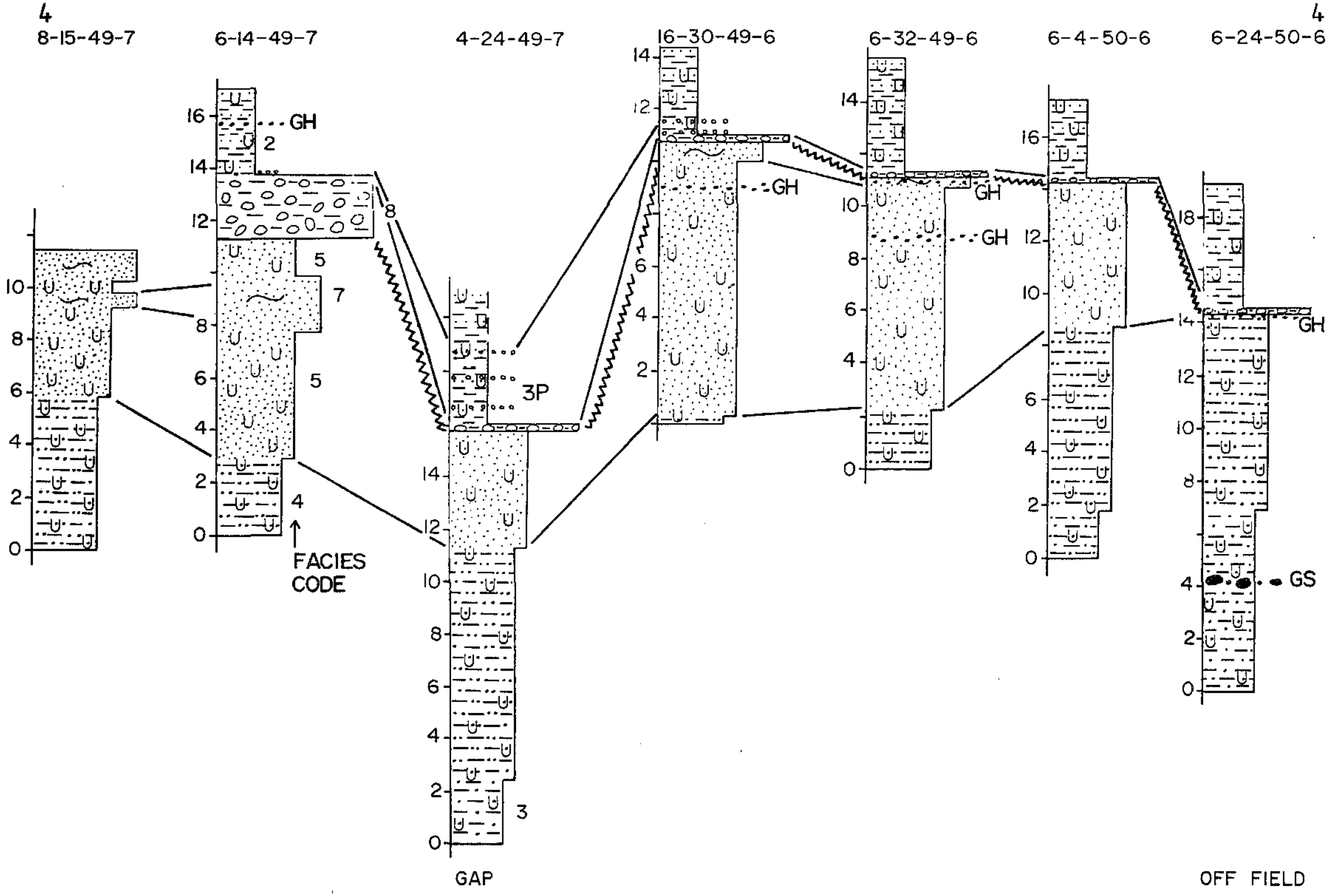

4
8-15-49-7
6-14
14-14
4-24
16-24
8-30-49-6
16-30
8-31
6-32
4
6-4-50-6
E7\T7
DATUM
E6\T6
E5\T5
4600
4400
4300
4300
4400
4400
4400
4200
4400
4250
EDGE
GAP
EDGE

FIGURE 16: <u>Core section 4</u> : Note the absence of facies 7 and thinning of facies 8 (from 6-14-49-7 to 4-24-49-7) within the drilling gap. Facies 5 disappears from the sequence off the northern boundary of the field. Gritty horizons in 16-30-49-6 and 6-32-49-6 may be correlative. The section is hung on the E6/T6 marker.


4
8-15-49-7
6-14-49-7
4-24-49-7
16-30-49-6
6-32-49-6
6-4-50-6
6-24-50-6
4
GH
2
5
7
5
4
FACIES CODE
8
3P
3
GH
GH
GH
GH
GS
GAP
OFF FIELD

surface within the drilling gap. However, note that this is the maximum erosional relief obtained when the section is hung on the E6/T6 marker. If the section is hung on the junction between facies 4 and facies 5, the maximum relief on the E5/T5 surface is reduced to approximately 7 m.

Facies 7 decreases in thickness between 16-30-49-6 and 6-32-49-6 from 0.79 m to 0.61 m. By contrast, the conglomerate thickens between these same two wells from 0.18 m to 0.20 m. The conglomerate appears to scour out facies 7. Facies 5 decreases in thickness from wells 6-32-49-6 to 6-4-50-6, and disappears at 6-24-50-6. This last well occurs on log cross-section A′ but was added to the core line to show the change in the facies sequence off the northern edge of the field. A gritty siderite was noted in facies 3 of this well.

Wells 16-30-49-6 and 6-32-49-6 show gritty horizons in facies 5. They may correlate although they are laterally discontinuous. Isolated gritty horizons occur in 6-32-49-6 (within facies 7), 6-14-49-7 (within facies 2), and 6-24-50-6 (at the top of facies 4).

<u>Conglomerate thickness and relief on the E5/T5 surface</u>

From the cross-sections with corresponding core sections note that the thickness of conglomerate above the E5/T5 surface does not indicate relief on the surface. For example, on core section 3, the thickness of conglomerate in 4-27-49-7 is 0.11 m whereas an erosional hollow of 2.98 m is noted on E5/T5. Similarly, on core section 4, the thickness of conglomerate in 4-24-49-7 is 0.19 m whereas the relief on the E5/T5 surface is 10.55 m. Thickness of the conglomerate also varies on top of bumps on the E5/T5 surface. For example, in 2-35-49-7 (core section 3), the conglomerate thickness is 0.29 m whereas in 6-14-49-7 (core section 4), the conglomerate thickness is 2.43 m.

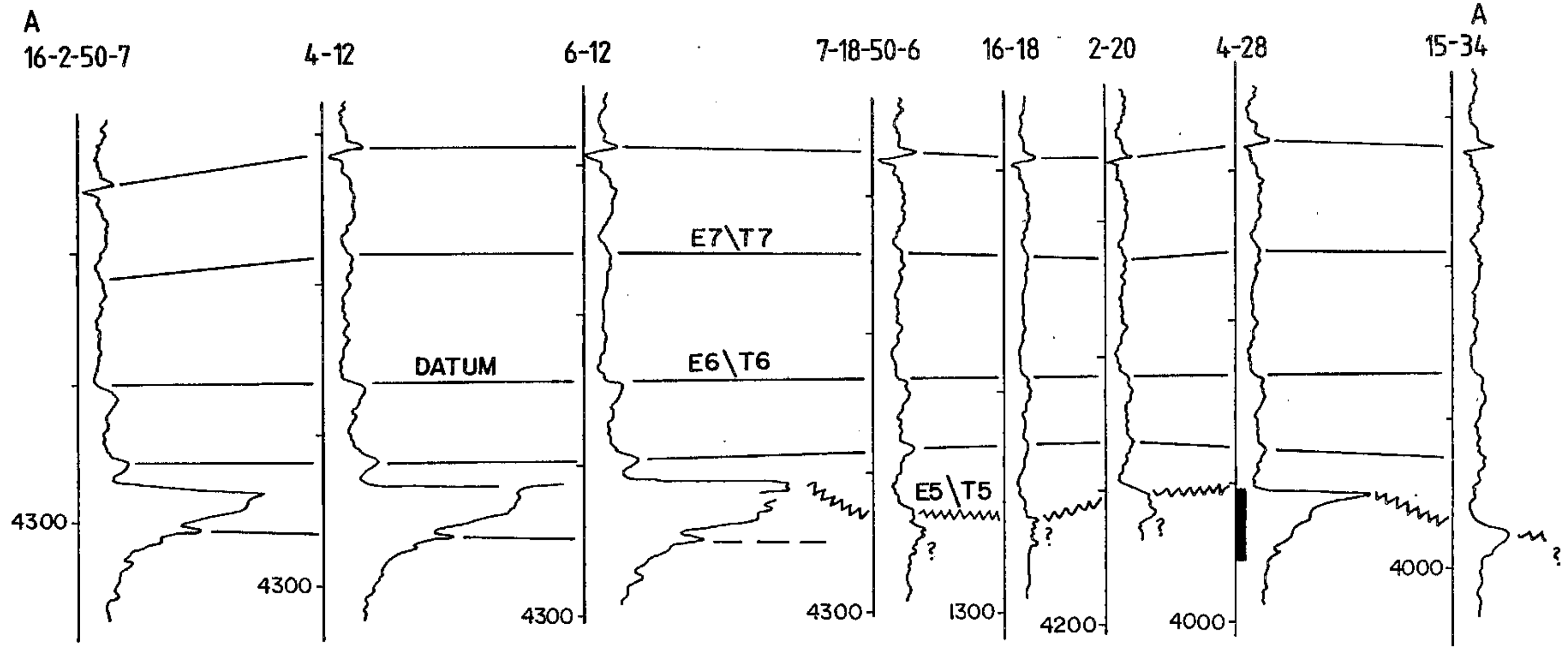
Cross-section A (Figure 17)

A normal Cardium response, characterized by a coarsening upward sequence, is present in 16-2-50-7, 4-12-50-7, and 6-12-50-7. The Cardium response is absent in 7-18-50-6, 16-18-50-6, and 2-20-50-6. A reduced response occurs in 4-28-50-6. From the corresponding core (Figure 12) it is noted that the Cardium sequence coarsens upward from facies 3, through facies 4, and facies 5 (containing a gritty horizon). Facies 8 (conglomerate) is only represented by a 0.11 m veneer of pebbles. The whole sequence is covered by facies 2. This well is located off the northern boundary of the oil field. A reduced Cardium response occurs in 15-34-50-6 and probably indicates partial erosion of the Cardium sequence. The maximum relief on the E5/T5 surface is 10.65 m, along this cross-section, and is noted in 15-34-50-6.

Cross-section A' (Figure 18)

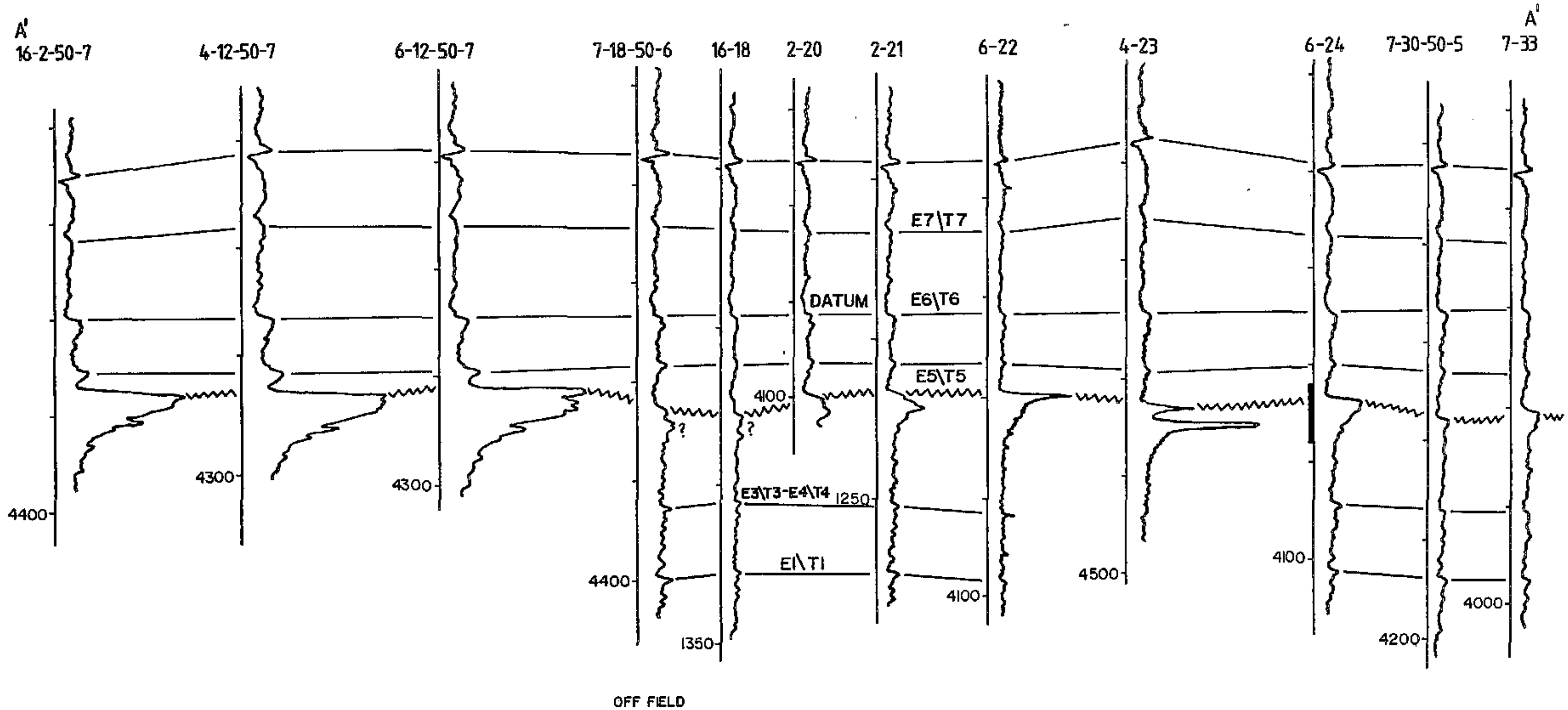
The first six wells of this log cross section represent cross-section A and were previously discussed. In 2-21-50-6, and 6-22-50-6, the Cardium sequence reappears as a reduced response and is recognized as two reduced peaks in

FIGURE 17: Cross-section A : Well 16-18-50-6 is marked off in 50 m intervals. Note the absence of a Cardium response in 7-18-50-6, 16-18-50-6, and 2-20-50-6. A reduced response is noted in 4-28-50-6 and 15-34-50-6. Maximum relief on E5/T5 is 10.65 m in 15-34-50-6 (off the northern boundary of the field). The section is hung on the E6/T6 marker.


A
16-2-50-7
4-12
6-12
7-18-50-6
16-18
2-20
4-28
A
15-34
E7\T7
DATUM
E6\T6
E5\T5
4300
4300
4300
4300
1300
4200
4000
4000
?

OFF FIELD

FIGURE 18: Cross-section A' : Well 2-21-50-6 is marked off in 50 m intervals. Note the absence of the Cardium response from 7-18-50-6 to 2-20-50-6 and from 7-30-50-5 to 7-33-50-5. Reduced responses occur from 2-21-50-6 to 6-24-50-6. Maximum relief on the E5/T5 surface is 7.23 m in 16-18-50-6 (located off the northern boundary of the field). The section is hung on the E6/T6 marker.



A'
16-2-50-7
4-12-50-7
6-12-50-7
7-18-50-6
16-18
2-20
2-21
6-22
4-23
6-24
7-30-50-5
7-33
A'
E7\T7
DATUM
E6\T6
E5\T5
E3\T3-E4\T4
E1\T1
4400
4300
4300
4400
4100
1250
1350
4100
4500
4100
4200
4000
OFF FIELD

4-23-50-6. This may indicate a double coarsening upward sequence. The Cardium response is absent in 7-30-50-5, and 7-33-50-5. In 6-24-50-6, a reduced Cardium response is noted. The corresponding core (Figure 16) shows the sequence beginning with facies 3, and coarsening into facies 4. Facies 3 contains a gritty siderite, and facies 4 contains a gritty horizon at its upper contact. Facies 5 is completely absent from the sequence. Facies 8 is represented by a few pebbles and the whole sequence is covered by facies 2. Maximum relief on the E5/T5 surface is 7.23 m, along the cross-section, and is noted in 16-18-50-6.

Cross-section D (Figure 19)

Unfortunately, available core for this cross-section was not studied. However, by inference from previously discussed cross-sections it is noted that 6-18-50-7, 10-18-50-7, and 18-19-50-7 show a normal, coarsening upward Cardium log response. The Cardium response is absent in 6-29-50-7, 10-33-50-7, and 1-11-51-7. This may indicate erosion of the entire Cardium sequence in this region off the northern boundary of the field. A greatly reduced log response is noted in 6-3-51-7 and 10-3-51-7. This may represent erosion of part of the Cardium sequence. Maximum erosion on the E5/T5 surface is 8 m, along this cross-section, and occurs in 1-11-51-7. This well is located off the northern edge of the field.

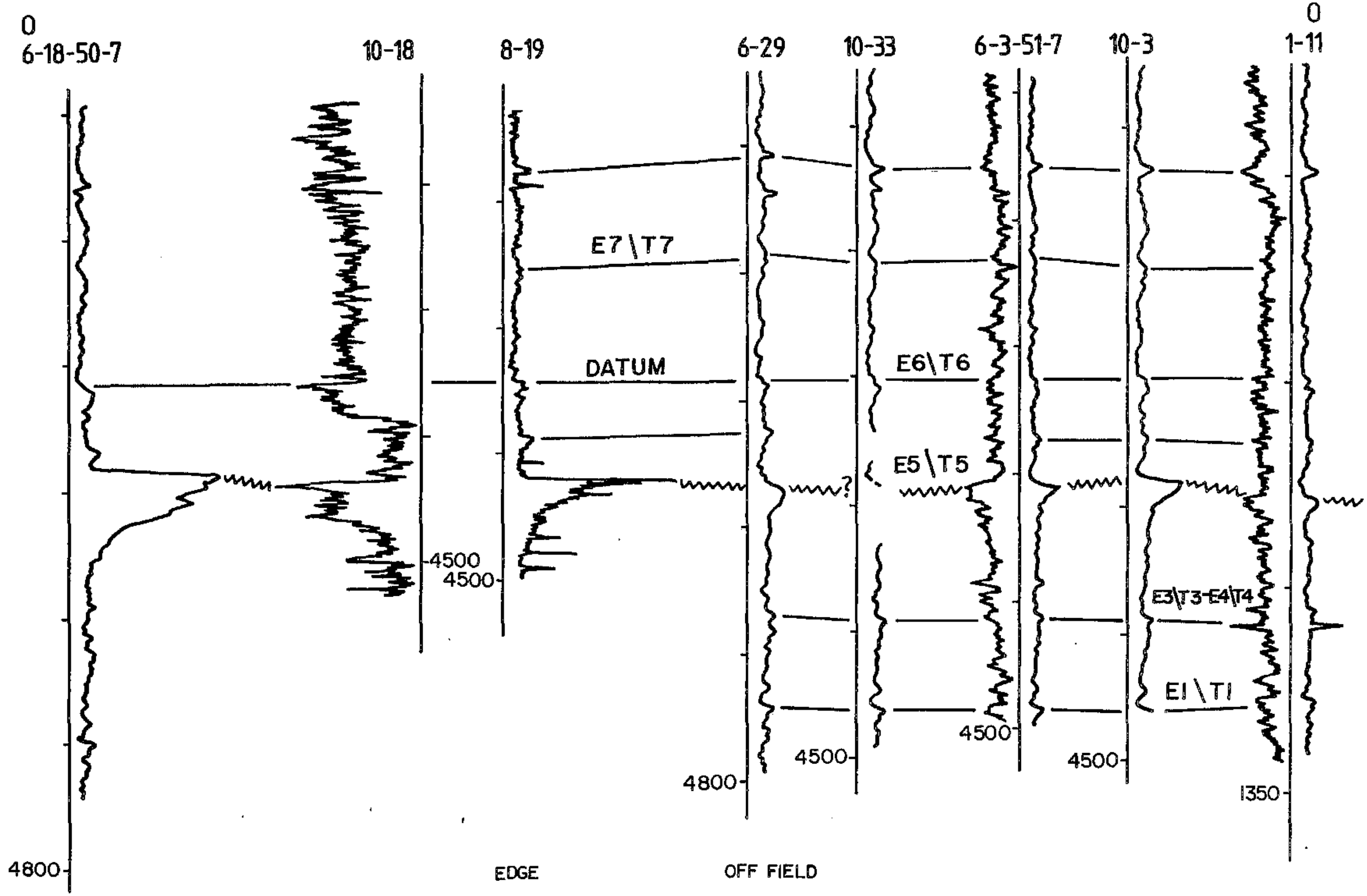
Cross-section B (Figure 20)

The Cardium response shows a normal coarsening upward sequence, by inference from previous cross-sections, in the first two wells. A reduced Cardium response occurs in 10-15-50-7, and 11-25-50-7 to 8-36-50-7 (sensitivity of the resistivity response is high in this well). The Cardium log response is absent in 4-23-50-7, 10-23-50-7, and 12-31-50-6 to 11-17-51-6. The reduced response probably indicates erosion of part of the Cardium sequence and the absent response probably indicates total erosion of the Cardium sequence. Maximum erosion on E5/T5 is 14.47 m, and occurs in 10-23-50-7. The well is located off the northern edge of the oil field and represents the maximum erosion on E5/T5 in the study area.

Cross-section C (Figure 21)

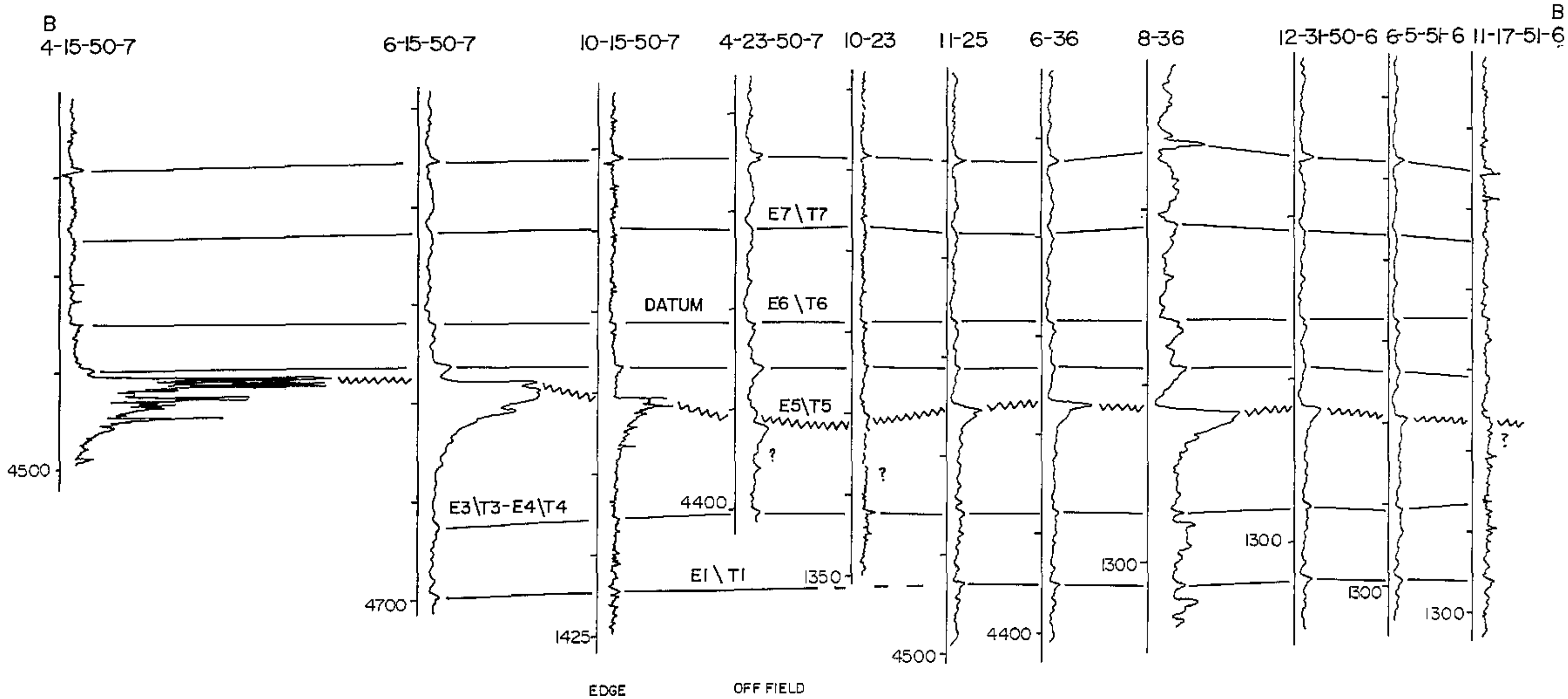
The Cardium response shows a normal coarsening upward sequence, by inference from previous cross-sections, in 16-11-50-7, and 4-13-50-7. Reduced log responses occur in 6-13-50-7 and 16-30-50-6 (sensitivity of the resistivity response is high in this well). The Cardium log response is absent from 14-13-50-7, 14-19-50-6, and 12-32-50-6. The reduced response probably indicates erosion of part of the Cardium sequence. Total erosion of the Cardium sequence is probably represented by the absence of a response. Maximum erosion on the E5/T5 surface is 13.82 m, and is noted in 14-13-50-7. This well is located off the northern edge of the field.

FIGURE 19: Cross-section O : Well 1-11-51-7 is marked off in 50 m intervals. The Cardium response is absent in 6-29-50-7, 10-33-50-7, and 1-11-51-7. Reduced responses occur in 6-3-51-7 and 10-3-51-7. Maximum erosion on the E5/T5 surface is 8 m in 1-11-51-7, located off the northern boundary of the field. The section is hung on the E6/T6 marker.



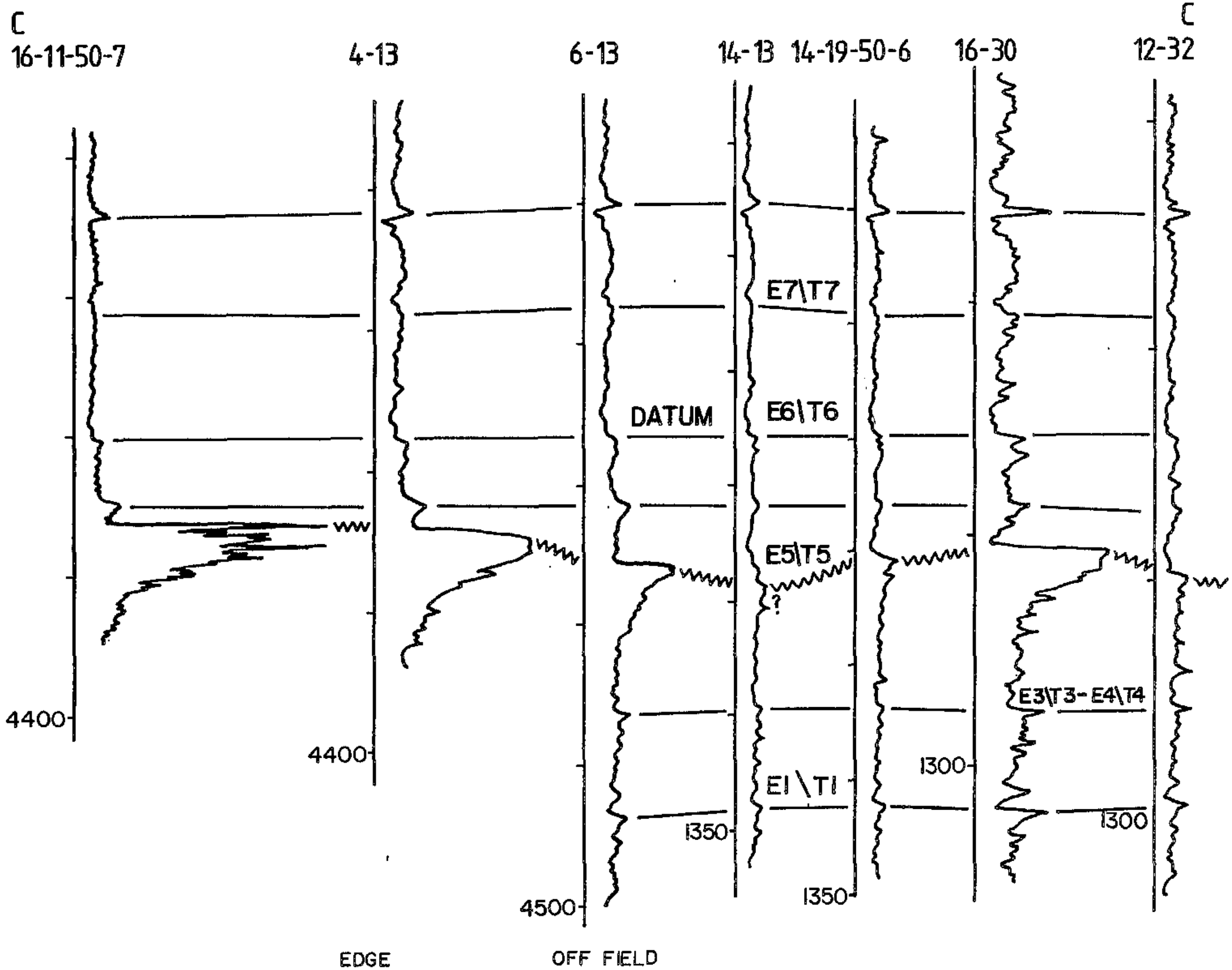
0
6-18-50-7
10-18
8-19
6-29
10-33
6-3-51-7
10-3
0
1-11
E7\T7
DATUM
E6\T6
E5\T5
E3\T3-E4\T4
E1\T1
4500
4500
4500
4500
4500
4800
4800
1350
EDGE
OFF FIELD

FIGURE 20: Cross-section B : Wells 10-15-50-7, 10-23-50-7, and 8-36-50-7 to 11-17-51-6 are marked off in 50 m intervals. Note the absence of a Cardium response from 4-23-50-7 to 10-23-50-7 and from 12-31-50-6 to 11-17-51-6. Reduced responses are recognized from 11-25-50-7 to 8-36-50-7. The maximum relief on the E5/T5 surface is 14.47 m in 10-23-50-7. This represents the maximum erosion on E5/T5 in the entire study area and occurs off the northern boundary of the field. The section is hung on the E6/T6 marker.



B
4-15-50-7
6-15-50-7
10-15-50-7
4-23-50-7
10-23
11-25
6-36
8-36
12-31-50-6
6-5-51-6
11-17-51-6
B
E7\T7
DATUM
E6\T6
E5\T5
E3\T3-E4\T4
E1\T1
4500
4700
1425
4400
1350
4500
4400
1300
1300
1300
1300
EDGE
OFF FIELD

FIGURE 21: Cross-section C : Wells 14-13-50-7 to 12-32-50-6 are marked off in 50 m intervals. Note the absence of the Cardium response in 14-13-50-7, 14-19-50-6, and 12-32-50-6. Reduced responses occur in 6-13-50-7 and 16-30-50-6. Maximum erosion on E5/T5 is 13.82 m in 14-13-50-7, located off the northern boundary of the field. The section is hung on the E6/T6 marker.


C
16-11-50-7
4-13
6-13
14-13
14-19-50-6
16-30
C
12-32
E7\T7
DATUM
E6\T6
E5\T5
?
E3\T3-E4\T4
E1\T1
4400
4400
1350
1300
1350
1300
4500
EDGE
OFF FIELD

CHAPTER 6: MORPHOLOGY OF THE E6/T6 SURFACE

6.1 Fluctuations Of The Datum

While constructing correlation lines of resistivity logs in the study area, changes in the stratigraphic position of the Raven River Member below the E6/T6 log marker were noted. Lines hung on sea level were constructed in order to investigate the possibility of tectonism.

6.2 Construction Of Subsea Cross-sections

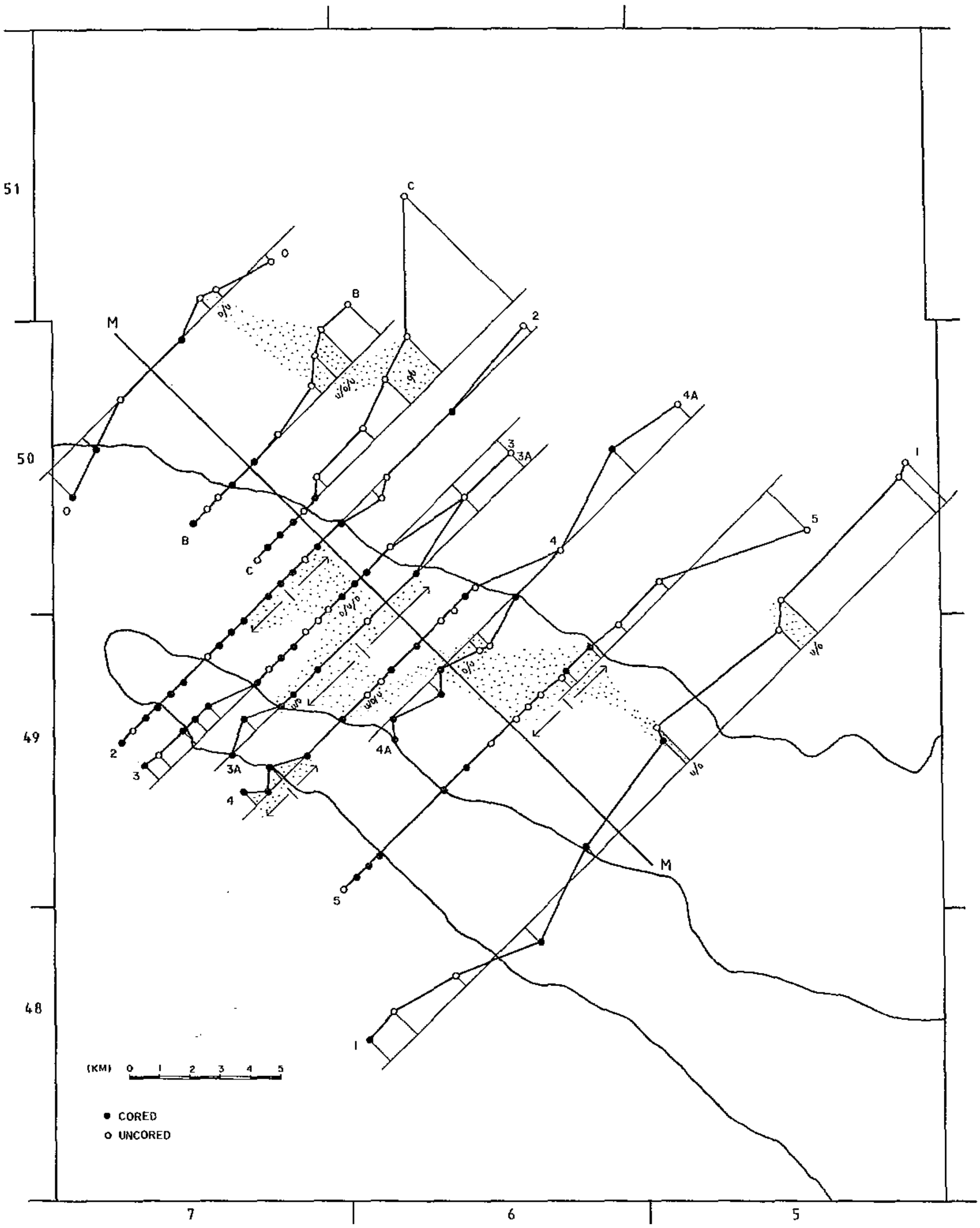
Ten cross-sections were constructed across the location area from townships 48 to 51, ranges 6 and 7, W5, (Figure 22). A reference line, M, shown in the figure, was drawn parallel to strike so that the cross-sections could be superimposed on one page (Figure 23). Cross-sections show the depth of the E6/T6 horizon below sea level. This was calculated by subtracting the Kelly Bushing from the recorded footage of the E6/T6 marker in each well. Individual wells were projected onto an "average" straight line (Figure 22), perpendicular to the reference line, M, in order to accurately measure horizontal distances between wells along each cross-section.

6.3 Results

The average dip on the E6/T6 surface from all the cross-sections is 0.45 degrees southwestward. This figure compares well to the regional dip of Pembina as discussed by Nielson (1957), of 0.5 (30 feet per mile) degrees to the southwest.

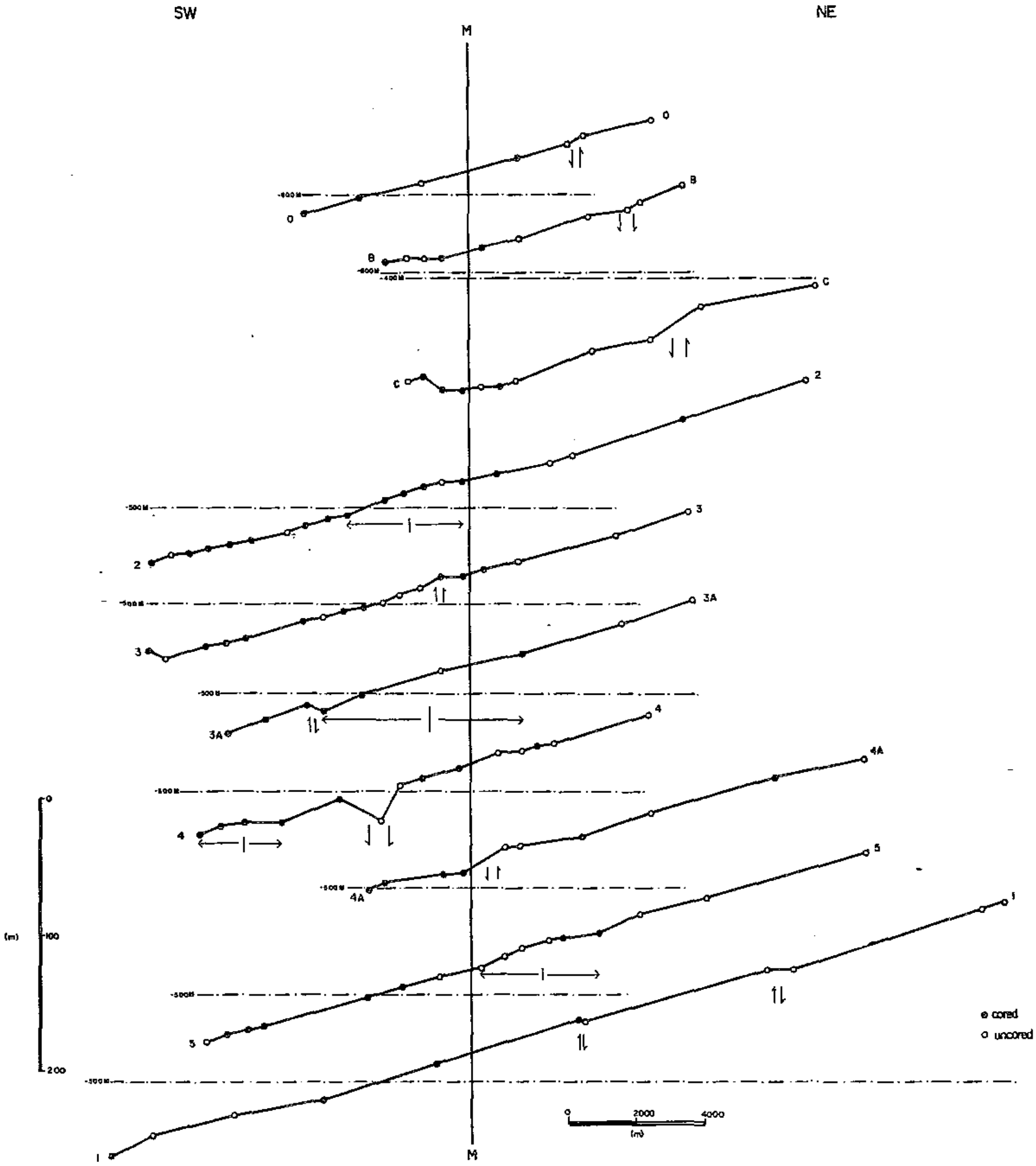
There appear to be three types of structure present

FIGURE 22: Location of E6/T6 subsea cross-sections. Twp. 48-51, Ranges 5-7, W5. Reference line M is parallel to strike so that cross-sections could be superimposed on one page (Figure 23). Horizontal distances between wells were measured by projecting cross sections onto "average" straight lines. Outward-pointing arrow symbols represent undulations along the E6/T6 surface. U/D and D/U symbols stand for discontinuities along the E6/T6 surface. U (up) and D (down) simply gives the sense of the discontinuity relative to the wells involved. U/D/U and D/U/D represent isolated discontinuities where one well is offset above (D/U/D), or below (U/D/U) the trend of the E6/T6 surface. Trends are shown by the stippled areas and are discussed in the text.



51
50
49
48
7
6
5
M
O
B
C
2
3
3A
4
4A
5
1
u/o
(KM) 0 1 2 3 4 5
● CORED
○ UNCORED

FIGURE 23: E6/T6 subsea cross-sections. Reference line M now appears as a vertical cross-section and subsea-sections have been superimposed along it. Each section represents a subsea cross-section of the E6/T6 surface and a reference depth is indicated in each section by a dash-dot line. Note that the -400 m depth line corresponds to cross-section C. Outward-pointing arrow symbols represent undulations along the E6/T6 surface and double arrows indicate discontinuities along the surface. The sense of the discontinuities is noted from the direction of the arrow tips. Note that the vertical scale is exaggerated with respect to the horizontal scale and is discontinuous between subsea cross-sections.



SW
NE
M
M
cored
uncored
(m)
0
100
200
0
2000
4000
(m)

from observation of the cross-sections (Figure 23). The first type of structure is recognized by sharp discontinuities in the gentle, southwesterly dipping E6/T6 surfaces. Cross-sections 1, 4A, 3A, C, and O all exhibit discontinuities. Cross-section 1 shows two discontinuities of 2.5 and 5 metres. Line O shows a discontiniuity of 2.5 metres. Maximum discontinuities of 9 metres on cross-section 3A, 14 metres on cross-section 4A, and 17.5 metres on cross-section C are recognized.

Between other wells, there are isolated discontinuities which appear as offsets above or below the general southwesterly dipping trend of the cross-sections. A 4 metre offset is noted in cross-section 3, above the general trend of the section in 8-1-50-7. By contrast, cross-section B shows a 3 metre offset below the regional trend of the section in 6-36-50-7. Cross-section 4 displays a maximum offset, below the section, of 25 metres in 6-30-49-6.

The third type of structure occurs as a gentle upward undulation along the otherwise shallow, southwesterly dipping E6/T6 surfaces. The undulation generally is recognized only in areas with a high concentration of wells. Cross-section 5 shows an undulation of approximately 7 metres between well locations 14-22-49-6 and 8-35-49-6 which includes six wells over a distance of 3600 metres. Limbs have dips of 1.15 degrees SW and 1.05 degrees NE. In cross-section 4, an undulation of 11.5 metres occurs between wells 8-15-49-7 and 4-24-49-7 which includes four wells over a distance of 2400 metres. Limbs dip at 1.15 degrees SW and 1.35 degrees NE. An undulation of 7 metres is noted in cross-section 3A between wells 8-26-49-7, and 14-5-50-6 which includes four wells over a distance of 6040 metres. Limbs dip at 1.05 degrees SW and 0.95 degrees NE. Cross-section 2 shows an undulation of 7.5 metres between wells 16-34-49-7 and 6-12-50-7 which includes six wells over a distance of 3550 metres. Limbs dip at 1.15 degrees SW and 1.35 degrees NE.

6.4 Interpretations

Results were compiled on a base map (Figure 22). It appears that the undulations form a trend along the northeastern limb of the field. A second trend of discontinuities is recognized off the northern boundary of the field. Both trends are approximately parallel to strike. Undulations and discontinuities could represent folding and faulting. However, the region where the undulations occur is between the gap and off the edge of the field. These two areas represent regions of maximum erosion of the Cardium sequence on the E5/T5 surface. By comparison, undulations and discontinuities on the E6/T6 surface may represent the erosional topography of this surface. Alternatively, sediments deposited on E5/T5 may have mimicked its topography. Thus, undulations and discontinuities on E6/T6 may simply represent the draping of sediments on top of the E5/T5 surface which exhibits maximum erosion on either side of the northeastern limb.

CHAPTER 7: INTERPRETATIONS AND CONCLUSIONS

There are 8 typical facies present in northeastern Pembina. The facies within the Raven River Member comprise a shelf sequence which begins with facies 3, dark bioturbated muddy siltstones, and coarsens upward into pervasively bioturbated muddy sandstones (facies 4), bioturbated sandstones (facies 5), and nonbioturbated sandstones (facies 7). Hummocky cross stratification is a characteristic structure found in facies 7 and suggests storm reworking of offshore sands (Harms et al., 1975), below fairweather wave base.

Observations from core and log lines show the conglomerates of the Carrot Creek Member resting on different facies and cutting out both core and log markers. It appears that there is an erosion surface below the conglomerate. This same erosion surface has been documented in other Cardium studies, for example, Carrot Creek (Bergman, 1984). It is referred to as E5/T5 (Plint et al., 1986) and the maximum relief on the surface in northeastern Pembina is approximately 15 metres (off the edge of the field). This is comparable but less than the maximum relief on the E5/T5 surface at Carrot Creek, approximately 19 metres (Bergman, 1984). Due to the existence of this erosion surface, the conglomerate does not appear to be genetically related to the underlying coarsening upward sequence. Above the conglomerate the entire sequence is blanketed by the base of the Dismal Rat Member which is characterized by pebbly mudstones (facies 3P) that fine upwards into laminated dark mudstones (facies 2), and massive dark mudstones (facies 1).

The idea of sea level changes (Plint et al., 1986) seems to best explain the observed facies sequences in northeastern Pembina. During a rapid lowering of sea level, the original shoreline advanced many kilometres into the Alberta basin towards northeastern Pembina, which created an erosion surface (E5/T5). Erosion was due to wave scour on the bed. A new shoreface was established in sediments which lay previously offshore (evidenced by the presence of hummocky cross stratification in facies 7). Newly incised rivers supplied gravel (facies 8) to the newly established shoreface. An ensuing transgression transported some of the gravel back across the erosion surface while storms reworked gravel seaward into transgressive muds (creating facies 3P). With continued deepening, the entire area became blanketed with mud (facies 2 and facies 1).

Gravels were probably supplied to northeastern Pembina from Carrot Creek which lies to the northwest. Carrot Creek seems to be the most likely source since the maximum thickness of conglomerate there is 19 metres. Carrot Creek is thought to represent another shoreface which was created due to erosion by a rapid lowering of sea level. During a subsequent transgression, gravels from Carrot Creek may have been carried towards northeastern Pembina by storms, and deposited on top of the E5/T5 erosion surface.

However, the thickness of the conglomerate in northeastern Pembina is only a veneer averaging 0.67 metres, while the relief on the erosion surface is a maximum of 15 metres. In addition, log lines where a Cardium response is absent, off the northern edge of the field, probably represent total erosion of the Raven River Member and of any conglomerate deposited subsequently. These observations suggest a second period of erosion after the deposition of the conglomerate. This event was followed by a transgression which deposited muds on top of a second erosion surface.

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