Sedimentology and allostratigraphy of regional, valley-fill, shoreface and transgressive deposits of the Viking Formation (Lower Cretaceous), central Alberta.

By

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SEDIMENTOLOGY AND ALLOSTRATIGRAPHY OF REGIONAL, VALLEY-FILL, SHOREFACE AND TRANSGRESSIVE DEPOSITS OF THE VIKING FORMATION (LOWER CRETACEOUS), CENTRAL ALBERTA.

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ABSTRACT

The Viking Formation (Upper Albian) is overlain by the marine mudstones of the Lower Colorado shales and is underlain by the marine mudstones of the Joli Fou Formation. The Viking sediments form a third-order regressive-transgressive cycle that can be correlated with the global sea level curve, specifically with the third-order eustatic fall and rise of sea level at 97-98 Ma. The absolute duration of the Viking is estimated at 1.2 million years.

The sediments of the Viking are subdivided into four different packages; regional, valley-fill, shoreface and transgressive deposits. The packages are separated by bounding discontinuities labelled VE2, VE3 and VE4.

The regional deposits consist of bioturbated mudstones, siltstones and sandstones, forming 12 coarsening-upward, shelf to shoreface successions. These deposits form a progradational parasequence set that offlaps towards the east. Regional shoreline trends are oriented N-S or NNE-SSW.

A large relative fall in sea level followed the deposition of the regional deposits. It was triggered by the 98 Ma eustatic fall in sea level, and was enhanced by uplift in southwestern Alberta. This sea level fall resulted in the cutting of the VE2 erosion surface, re-orientation of the Viking shoreline trends to NW-SE and introduction of coarse-grained sediments into the study area.

Deposits filling the lowstand incised valleys are located at Crystal, Cyn-Pem, Sundance and Edson. A first phase of incision took place during the "VE2" lowstand, and a second phase of incision and filling occurred during the "VE3" transgression. The valley-fill deposits consist of conglomerates, sandstones and mudstones. Tripartite facies geometries (sand-mud-sand) exist in the Crystal, Sundance and Edson valley-fill deposits.

Shoreface deposits related to the VE3 transgression are located along the Joarcam, Sunnybrook "B", Sunnybrook "A", Chigwell, Wolf Creek/Gilby-Joffre, Bickerdike and Caroline-Garrington trends. The shoreface sediments were deposited during stillstands and regressions that were superimposed onto the "VE3" transgression. They consist of bioturbated mudstones and sandstones, and are oriented NW-SE.

The transgressive deposits occur in localized patches and are the uppermost sediments of the Viking. These sediments consist of thinly bedded mudstones, siltstones, sandstones and conglomerates, and were deposited during the latter stages of the "VE3" transgression.

The Viking sediments consist of 19 parasequences; 12 regional cycles and 7 shoreface cycles. Each parasequence was deposited in approximately 63,000 years. This cyclicity may have been caused by glacio-eustatic mechanisms, differential subsidence or autocyclic processes; the exact mechanism or combination of mechanisms that produced this cyclicity is unknown.

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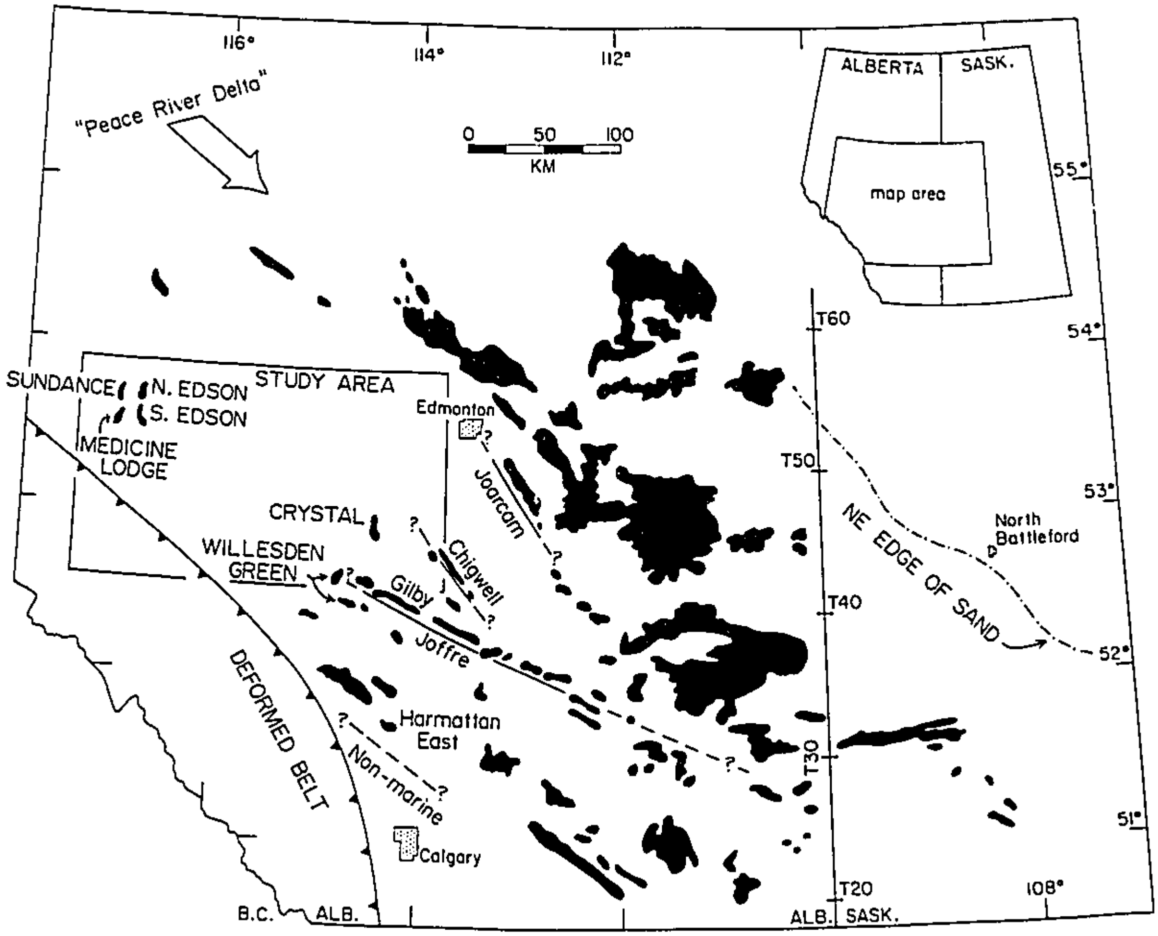
CHAPTER 1 - INTRODUCTION

Various styles of sand deposition are preserved in the Cretaceous sediments of the Alberta Foreland Basin. The Viking Formation is particularly interesting because of the variety of depositional environments preserved, including lowstand incised valleys, shorefaces, and open shallow marine settings. However, the internal stratigraphy of the Viking has never been documented, leaving the relationship between the various depositional environments poorly understood. Also, the sedimentology of these deposits has not been studied in detail, except for studies of isolated fields, such as Joffre (Downing and Walker, 1988). Therefore, this thesis will attempt to unravel the internal stratigraphy and sedimentology of the Viking Formation throughout a large area of central Alberta (Fig. 1.1). Specific problems will be addressed in chapter 2; the remainder of this chapter will describe the regional setting, stratigraphy and paleogeography of the Viking sediments.

1.1 Oil & Gas Fields

The Viking Formation in the subsurface of Alberta contains numerous oil and gas fields (Fig. 1.1). Most are stratigraphic traps, of two main types; valley-fill and shoreface deposits. Estimated initial oil and gas in place in all of the Viking reservoirs is 2.8×10^8 m^3 (1.8 billion bbl) of oil and 3.8×10^{11} m^3 (13 tcf) of gas (Podruski et


116°
114°
112°
"Peace River Delta"
0 50 100
KM
ALBERTA
SASK.
map area
55°
54°
53°
52°
51°
T60
T50
T40
T30
T20
108°
SUNDANCE
N. EDSON
S. EDSON
STUDY AREA
MEDICINE LODGE
Edmonton
Joarcam
CRYSTAL
WILLESDEN GREEN
Chigwell
Gilby
Joffre
NE EDGE OF SAND
North Battleford
DEFORMED BELT
Harmattan East
Non-marine
Calgary
B.C.
ALB.
ALB.
SASK.

al., 1987).

There are four gas fields (Sundance, Medicine Lodge, North Edson and South Edson) and one oil and gas field (Crystal) located in the study area (Fig. 1.1). For the purpose of this thesis, the Medicine Lodge and Sundance fields will be referred to as Sundance, and the N. Edson and S. Edson fields will be referred to as Edson.

1.2 Stratigraphy

The following section includes a description of the general stratigraphy, biostratigraphy and chronostratigraphy of the Viking Formation, Joli Fou Formation and the Lower Colorado shales. The allostratigraphy of the Viking has been set up and defined by Boreen and Walker (1991), and this will be discussed in section 3.1.

1.2.1 General Stratigraphy

The Viking Formation (Lower Cretaceous, Upper Albian) is encased above and below by the marine mudstones of the Lower Colorado shales and the Joli Fou Formation, respectively (Fig. 1.2), and they form part of the Lower Colorado Group of central Alberta and Saskatchewan. These three units form a transgressive-regressive-transgressive succession, with the regressive event corresponding to the deposition of the Viking sediments. It has been suggested by Reinson et al. (1988) and Leckie and Reinson (in press) that the unconformity at the base of the valley-fill deposits in the Viking could be time correlative with a major eustatic sea level fall that occurred approximately 98

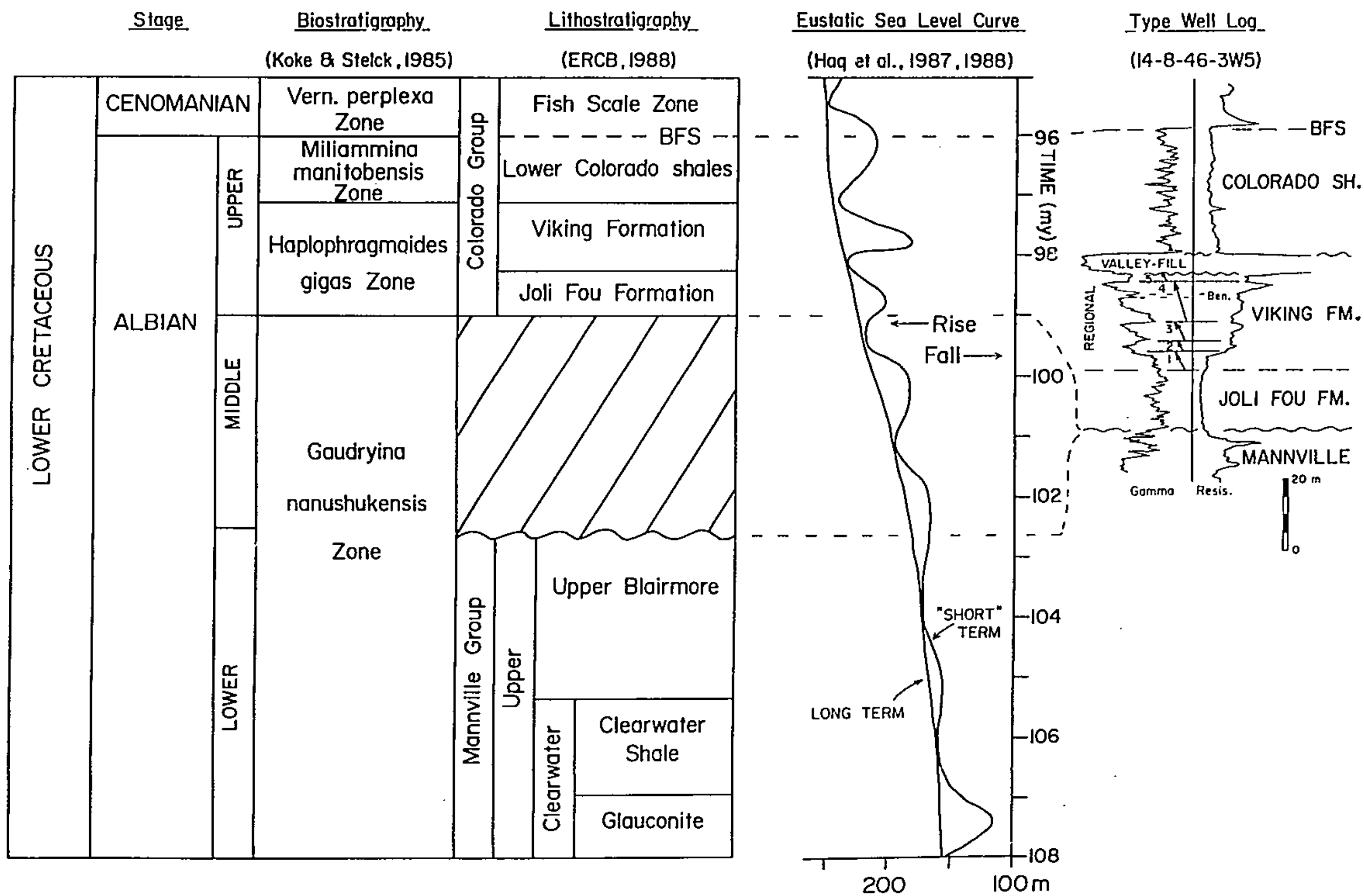

Stage
Biostratigraphy
(Koke & Stelck, 1985)
Lithostratigraphy
(ERCB, 1988)
Eustatic Sea Level Curve
(Haq et al., 1987, 1988)
Type Well Log
(14-8-46-3W5)
LOWER CRETACEOUS
CENOMANIAN
ALBIAN
UPPER
MIDDLE
LOWER
Vern. perplexa Zone
Miliammina manitobensis Zone
Haplophragmoides gigas Zone
Gaudryina nanushukensis Zone
Colorado Group
Fish Scale Zone
BFS
Lower Colorado shales
Viking Formation
Joli Fou Formation
Mannville Group
Upper
Upper Blairmore
Clearwater
Clearwater Shale
Glauconite
Rise
Fall
"SHORT" TERM
LONG TERM
200
100m
TIME (my)
96
98
100
102
104
106
108
BFS
COLORADO SH.
VALLEY-FILL
REGIONAL
Ben.
VIKING FM.
JOLI FOU FM.
MANNVILLE
Gamma
Resis.
20 m
0

Figure 1.2. Litho- and bio-stratigraphy of the Albian Stage in central Alberta. The eustatic sea level curve and the type well log (14-8-46-3W5) from the Crystal area are also shown. Note the position of the Viking Formation relative to a large eustatic sea level drop at approximately 98 Ma. Regional successions 1 to 5 and the Crystal valley-fill deposits are highlighted on the type well log.

million years ago (Vail et al., 1977; Weimer, 1984; Haq et al., 1987, 1988). While it is clear that relative sea level was much lower during the deposition of the Viking (section 1.4), the mechanism that controlled this relative sea level fall, whether regional tectonic, eustatic or a combination of both, remains unclear.

Viking Formation

Slipper (1918) informally gave the name "Viking" to the gas producing sand of the Viking-Kinsella field near Viking, Alberta. These sands were formally named the Viking Formation by Stelck (1958).

The Viking is 10-37 m thick in central Alberta and throughout most of the study area. To the west, the Viking merges with the underlying Mannville Group to form the Blairmore Group of the Foothills (Glaister, 1959; Rudkin, 1964; Mellon, 1967). In the northeast, the Viking pinches or "shales" out at T58, R9W4 (Gammell, 1955), and in the south it becomes thicker (45 m) and merges with the Bow Island Formation (Glaister, 1959; Leckie & Reinson, in press).

Strata equivalent to the Viking Formation in Canada include the Paddy Member of the Peace River Formation in northwestern Alberta (Stelck & Koke, 1987; Leckie & Reinson, in press), and the Bow Island Formation in southwestern Alberta (Glaister, 1959). In the United States, the Viking is time equivalent to the Muddy Sandstone and Newcastle Formation of Montana and Wyoming, and to the J Sandstone of

Colorado (McGookey et al., 1972; Beaumont, 1984; Weimer, 1984).

Joli Fou Formation

Wickenden (1949) first named the widespread black shale that occurs at the base of the Colorado Group as the Joli Fou shale, which at a later time was formally named the Joli Fou Formation (Stelck, 1958). The Joli Fou Formation is 18-36 m thick in central Alberta (Leckie & Reinson, in press), and varies from 10-18 m thick in the Crystal area to 2-6 m thick in the Sundance and Edson area. In western Alberta, the Joli Fou Formation pinches out a few kilometers west of the Sundance valley, and in southern Alberta it merges with the Bow Island Formation.

Strata equivalent to the Joli Fou Formation in the United States include the Skull Creek, Kiowa and Thermopolis Members in Wyoming, Montana and Kansas (McGookey et al., 1972; Beaumont, 1984; Weimer, 1984).

Lower Colorado shales

To date, a formal name has not been proposed for the overlying Colorado Group shales. Various informal names have been used, including the unnamed shale member of the Colorado Group (Evans, 1970; Downing & Walker, 1988), the Colorado Shale (Stelck, 1958), the Lloydminster Shale (Tizzard & Lerbekmo, 1975) and the Lower Colorado shales (Leckie & Reinson, in press).

The term Lower Colorado shales will be used in this thesis; they are 25-38 m thick in the study area, with the thinnest deposits occurring southwest of the Sundance and Edson valleys. The stratigraphic top of these shales is characterized by a prominent marker called the Base of Fish Scales (BFS), which consists of interbedded sandstones and mudstones with abundant phosphatic fish skeletal debris (Simpson, 1979). The BFS forms a distinctive well log response on both resistivity and gamma-ray logs, and can be identified throughout the study area. It also forms the boundary between the Lower and Upper Cretaceous (Stelck & Armstrong, 1981).

Strata equivalent to the Lower Colorado shales in the United States are the Mowry Shales in Montana and Wyoming (McGookey et al., 1972).

1.2.2 Biostratigraphy

There is a large gap in the succession of molluscan assemblages in the sediments of the Viking (Stelck & Koke, 1987). Megafaunal suites are only recognized in time equivalent sediments in northeastern British Columbia (Koke & Stelck, 1985), and are rare or absent in the Viking sediments of Alberta. Therefore, all of the biostratigraphic zones and subzones in the Joli Fou to Lower Colorado shales interval are represented only by microfaunal suites.

The interval including the Joli Fou and Viking formations contains microfaunal assemblages from the *Haplophragmoides gigas* Zone, whereas the Lower Colorado shales contain microfaunal assemblages from the *Miliammina* manitobensis Zone (Stelck, 1958; Caldwell et al., 1978; Koke & Stelck, 1985; Stelck & Koke, 1987; Fig. 1.2). These assemblages consist of arenaceous foraminifera interpreted as mid-neritic to shallow neritic (Stelck & Koke, 1987). The Haplophragmoides gigas Zone has been subdivided into seven subzones, most of which are probably represented in the Joli Fou shales. However, Stelck and Koke (1987) suggest that the Viking sands occur somewhere above the Haplophragmoides gigas gigas Subzone (second oldest of the seven subzones) and below the Miliammina manitobensis Zone. A more accurate refinement and subdivision of the Joli Fou and Viking interval is impossible due to the low numbers of foraminifera in the sediments of the Viking.

1.2.3 Chronostratigraphy

Little work has been done on the chronostratigraphy of the Joli Fou to Lower Colorado shale interval. Tizzard and Lerbekmo (1975) extracted biotite and sanidine crystals from bentonite layers in the Viking and they dated six mineral separates using the potassium-argon method. The Viking was dated between 94-105 Ma, with the "best date" set at 100 Ma ±2 Ma (Tizzard & Lerbekmo, 1975). Their work provides the only published radiometric dates for the Viking Formation.

This radiometric "best date" is consistent with two independent approximations of the age of the Viking. Reinson et al. (1988) and Leckie and Reinson (in press) suggest that the unconformities at the base of the Viking valley-fill deposits were probably cut during a large eustatic drop of sea level which occurred approximately 98 Ma ago (Haq et al., 1987, 1988; Fig. 1.2). Stelck (1975) also dated the overlying Miliammina manitobensis Zone at approximately 98 Ma. These studies agree with the "best date" radiometric age of the Viking determined by Tizzard and Lerbekmo (1975).

1.3 Structure

The Viking Formation is part of a clastic wedge of sediments that was deposited in the Alberta Foreland Basin during the Late Albian. All of these sediments were supplied from the active Cordillera to the west. The Viking deposits in central Alberta are 1500-3100 m below the surface and are located in the tectonically undeformed part of the basin. No evidence of faulting or folding has been observed. The Viking sediments have a regional dip of 0.5-2.0° to the west in the study area, with the dip increasing westward across the basin. Figure 1.3 shows the location of the major structural elements of the Alberta Foreland Basin including the Peace River Arch, the Sweetgrass Arch and the eastward extent of thrusting (deformed belt).

1.4 Paleogeography

The sediments of the Joli Fou and Viking Formations, and the Lower Colorado shales, record a transgressive-regressive-transgressive succession that can be directly related to the paleogeography of the Alberta Foreland Basin during the Late Albian (Fig. 1.4). During the Joli Fou time interval, the Western Interior Seaway was connected with

Figure 1.3. The structural features of the Alberta Foreland Basin (after Leckie, 1989a). Note that the study area is located in a relatively undeformed part of the basin.

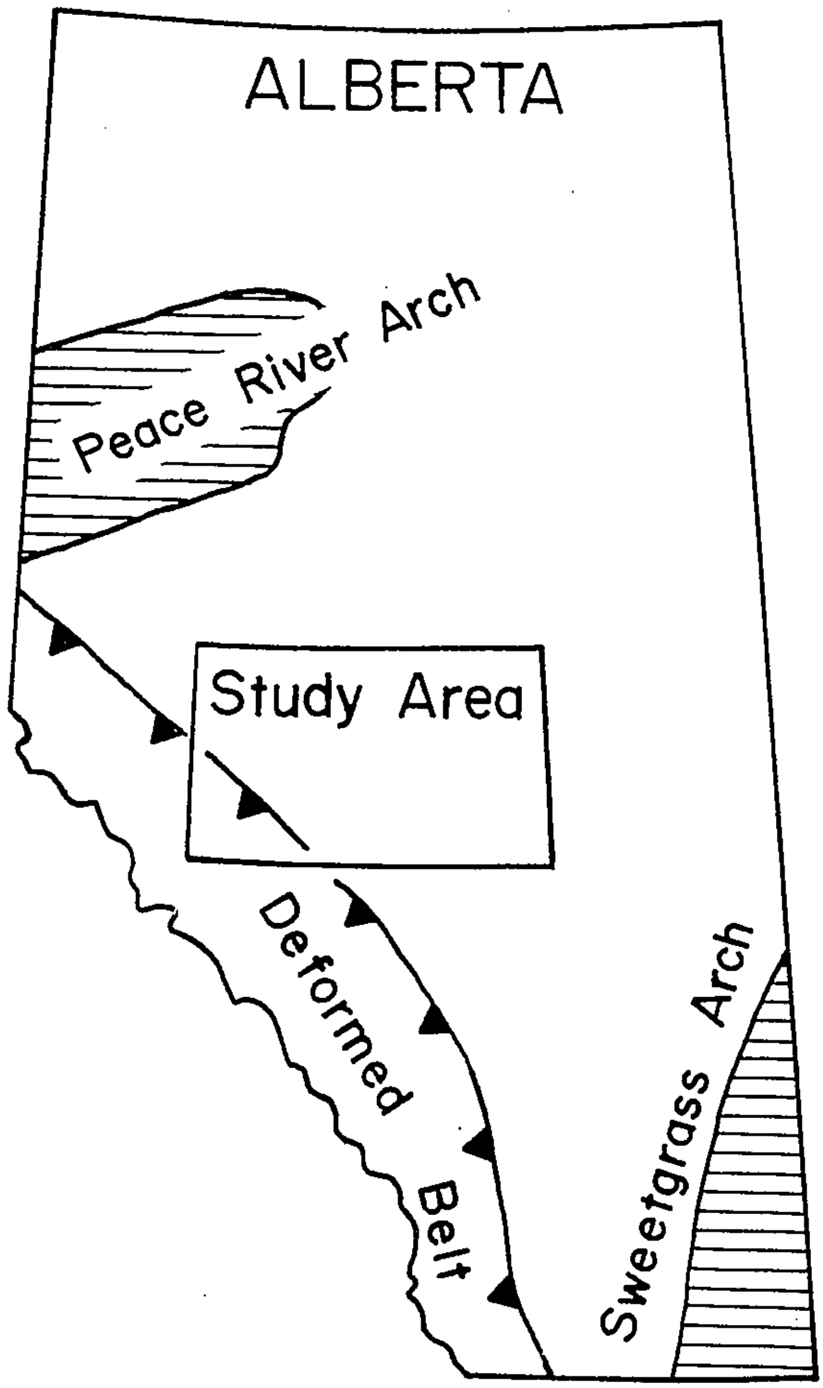
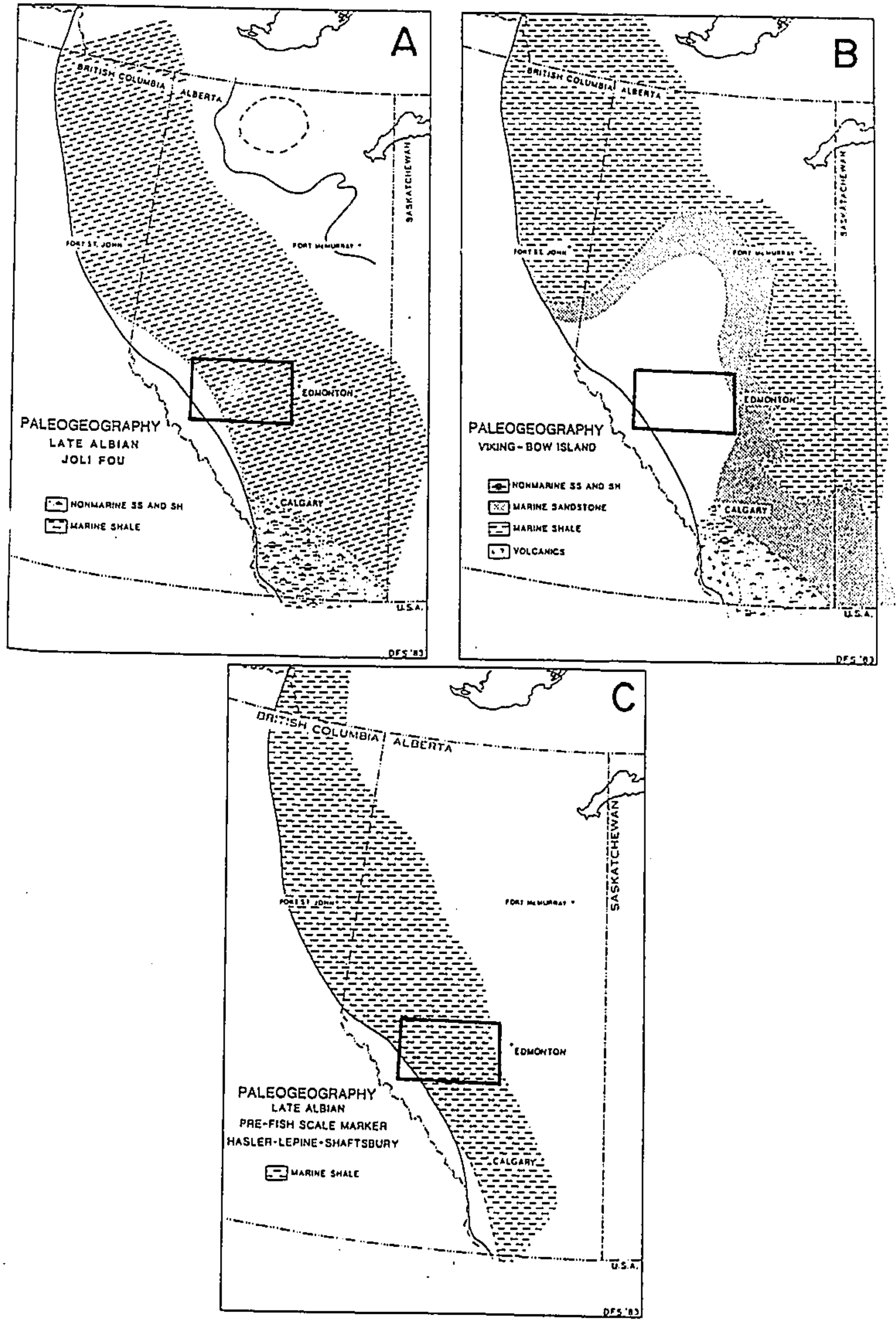

ALBERTA
Peace River Arch
Study Area
Deformed Belt
Sweetgrass Arch

Figure 1.4. Paleogeography of the Alberta Foreland Basin during the deposition of; (A) the Joli Fou mudstones, (B) the Viking and Bow Island sandstones and conglomerates, and (C) the Lower Colorado shales (Stott, 1984). Study area is shown by the inset rectangle.


A
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
FORT ST. JOHN
FORT McMURRAY
EDMONTON
CALGARY
PALEOGEOGRAPHY
LATE ALBIAN
JOLI FOU
NONMARINE SS AND SH
MARINE SHALE
U.S.A.
DFS '83
B
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
FORT ST. JOHN
FORT McMURRAY
EDMONTON
CALGARY
PALEOGEOGRAPHY
VIKING - BOW ISLAND
NONMARINE SS AND SH
MARINE SANDSTONE
MARINE SHALE
VOLCANICS
U.S.A.
DFS '83
C
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
FORT ST. JOHN
FORT McMURRAY
EDMONTON
CALGARY
PALEOGEOGRAPHY
LATE ALBIAN
PRE-FISH SCALE MARKER
HASLER-LEPINE-SHAFTSBURY
MARINE SHALE
U.S.A.
DFS '83

both the Arctic Ocean and Gulf of Mexico (Williams & Stelck, 1975; Stott, 1984; Vuke, 1984; Fig. 1.4A). Stelck (1958) has described this as the "Haplophragmoides gigas sea", which represents one of the most widespread seas during the Lower Cretaceous (Young, 1970; Stott, 1984; Vuke, 1984). This was the only time during the Lower Cretaceous that the seaway was "open" to both the Arctic Ocean and the Gulf of Mexico (Vuke, 1984).

The Viking sediments represent the regressive phase of the succession and were deposited during an interval characterized by relatively low sea levels (Fig. 1.4B). Movement on the Transcontinental Arch of southeastern Wyoming and northwestern Nebraska set up a drainage divide in the Western Interior Seaway (Vuke, 1984), which resulted in an Arctic connection only for the Canadian portion of the seaway. The maximum extent of the relative sea level lowering is probably correlative with the most basinward preserved shoreface deposit in the Viking. To date, the furthest basinward shoreface recognized in the Viking sediments of Alberta corresponds with the Joarcam oil field. However, Posamentier (pers. comm., 1990) suggests that most of central Alberta might have been subaerially exposed during the maximum lowstand in the Viking and, therefore, the lowest-lowstand shoreface might be located northeast of Joarcam.

The Viking sediments were subsequently "drowned" by a relative rise in sea level and the dark marine shales of the

Lower Colorado shales were deposited on top of the Viking (Fig. 1.4C). During the deposition of these shales, the connection between the Arctic Ocean and the Gulf of Mexico was not re-established (Vuke, 1984). Therefore, the Canadian part of the sea, which was named the Mowry sea by Stelck (1958), was only open to the Arctic Ocean.

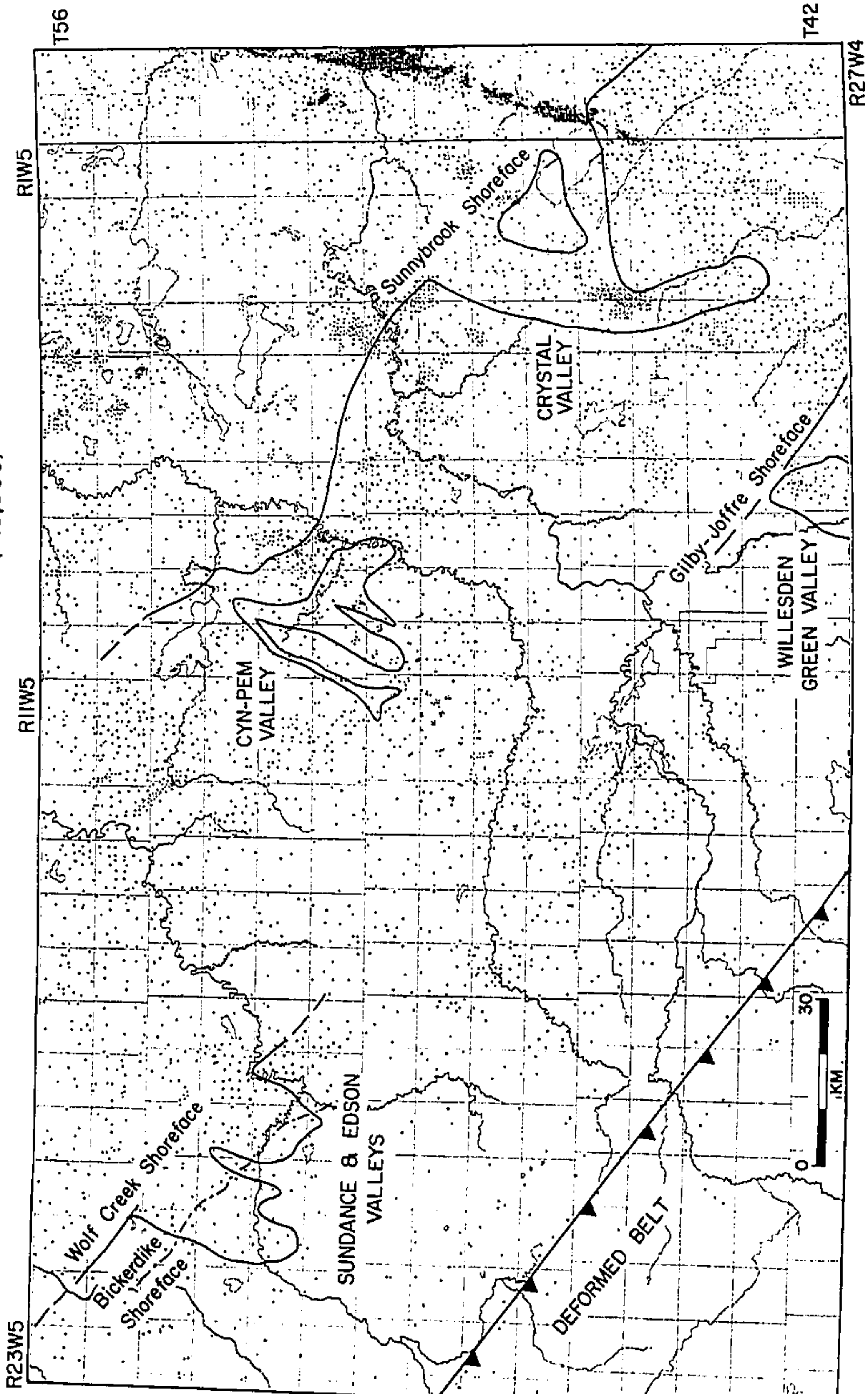
1.5 Study Area & Data Base

The study area was chosen so as to include the valley-fill deposits at Crystal, Cyn-Pem, Sundance and Edson, and the shoreface deposits at Sunnybrook, Wolf Creek and Bickerdike (Figs 1.5 & 1.6).

This research includes both core (Fig. 1.6) and well log (Fig. 1.5) data. The cores are stored at the Alberta Energy Resources Conservation Board Core Research Center in Calgary, and the well log data was collected from Esso Resources Canada Limited in Calgary. Of the 198 cores used in this research, 140 are from the valley-fill deposits (104 Crystal, 34 Sundance & Edson, 2 Cyn-Pem), 55 are from the regional deposits and 3 are from the shoreface deposits (Fig. 1.6). The location and depth of these cores are given in Appendix 1. Over 4000 geophysical well logs (resistivity and gamma-ray) were used to supplement the core data and these are scattered throughout the study area (Fig. 1.5).

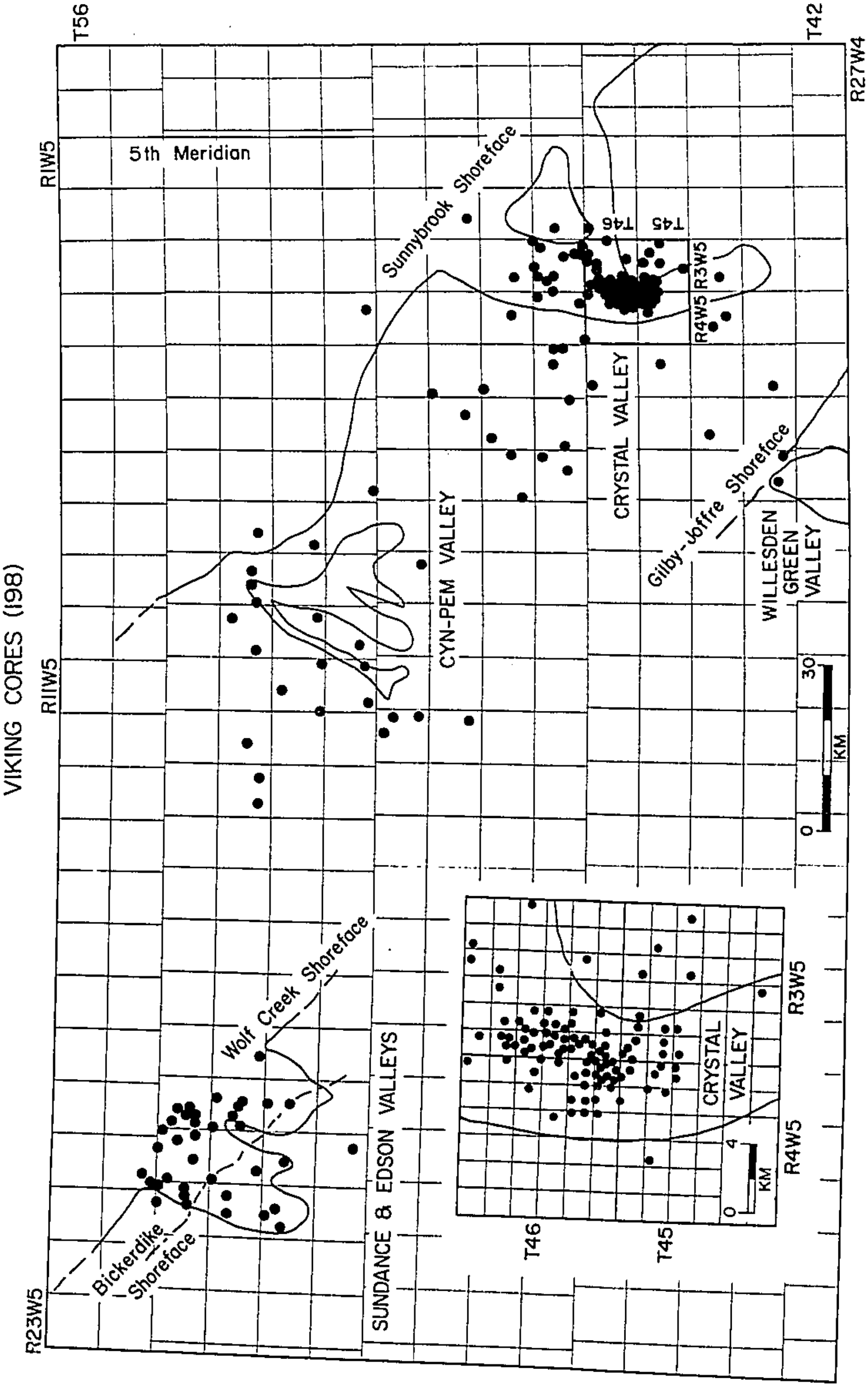
Each of the cores was logged in detail (cm scale) and subdivided into different facies based on the lithology, sedimentary structures, trace fossils and degree of bioturbation. These facies were then combined into ten

Figure 1.5. Distribution of well log data. Over 10,000 wells penetrate the Viking Formation in the study area; most of the 4000 wells used in this research are located near the valleys. The location of the Crystal, Cyn-Pem, Sundance and Edson valley-fill deposits, and the Bickerdike, Wolf Creek and Sunnybrook shoreface deposits are shown. The Willesden Green valley-fill deposits and their associated shoreface deposits at Gilby-Joffre are also outlined (after Boreen, 1990).



VIKING PENETRATION WELLS (≈10,000)

Figure 1.6. Distribution and location of the core data used in this research. Most of the cores are located in the valley-fill deposits (104 Crystal - inset map, 34 Sundance & Edson, 2 Cyn-Pem). Other cores are from the regional (55) or shoreface (3) deposits. Note the high density of cores between Crystal and Cyn-Pem, versus the low density of cores between Cyn-Pem and Edson.


VIKING CORES (198)
T56
T42
R27W4
R1W5
R11W5
R23W5
5th Meridian
Sunnybrook Shoreface
T46
T45
R3W5
R4W5
CRYSTAL VALLEY
CYN-PEM VALLEY
Gilby-Joffre Shoreface
WILLESDEN GREEN VALLEY
0
30
KM
Wolf Creek Shoreface
SUNDANCE & EDSON VALLEYS
Bickerdike Shoreface
CRYSTAL VALLEY
R3W5
R4W5
T46
T45
0
4
KM

different facies associations, which are described and interpreted in chapter 4.

Due to the sparse and scattered core data base, and the much larger well log data base, it became essential to calibrate the vertical facies successions observed in the cores with their corresponding well log responses. For example, a coarsening-upward facies succession usually has a corresponding funnel-shaped resistivity or gamma-ray well log response. Therefore, in areas of no core, a similar well log response would probably be indicative of a coarsening-upward facies succession. Using this technique, it became possible to determine the lithology and the vertical facies succession, in a general sense, in wells that did not have any core available.

CHAPTER 2 - STATEMENT OF THE PROBLEM

Most sandstone and conglomerate bodies (abbreviated as sand bodies) in the Viking Formation of central Alberta are completely encased by marine mudstones. Early interpretations of these sand bodies and other similar sand bodies observed in the Cretaceous strata of the Alberta Foreland Basin (e.g. Cardium Formation) were strongly influenced by the marine character of the surrounding sediments, and were described as turbidites or "offshore bars" (Beach, 1955, 1956, 1962; Berven, 1966).

Recent work by Downing (1986), Downing and Walker (1988), Raddysh (1986, 1988), Reinson et al. (1988), Posamentier and Chamberlain (1989), Boreen and Walker (1991), and Leckie and Reinson (in press) has led to the recognition of bounding erosion surfaces that separate the Viking sand bodies from the surrounding mudstones. The bounding erosion surfaces define four major stratigraphic packages of sediments; regional, valley-fill, shoreface and transgressive deposits. The erosion surfaces occur at the base and the top of the coarse-grained sand bodies and therefore remove any genetic "link" or relationship between the sand bodies and the marine mudstones. As a result, the interpretation of many Viking sand bodies not only depends on the nature of the facies and successions that are observed in the sand body, but also on the interpretation of the bounding erosion surfaces. New interpretations are now possible in the light of the recognition of multiple erosion surfaces.

2.1 Scientific Problem

The main scientific problem of this thesis is to determine the sedimentological and stratigraphic relationships between four types of Viking deposits (regional, valley-fill, shoreface and transgressive) that occur to the north of Willesden Green. Specifically, the basinwide relationships between deposition of the Viking sediments, development of the bounding erosion surfaces, and relative fluctuations in sea level will be examined.

The discovery of the first large incised valley in 1978 (Crystal) and subsequent discoveries of other incised valleys (e.g. Sundance - 1984) has opened up many interesting questions with regards to Viking sedimentation. These include unravelling the nature of the fill (estuarine vs. marine), correlating the bounding discontinuities and determining the relationship between the valley-fill deposits and the surrounding sediments. Specifically, the relationship between the underlying regional deposits, laterally adjacent shoreface deposits and overlying transgressive deposits will be examined.

Other questions that arise from this work include the effect of relative fluctuations in sea level on the detailed stratigraphy of the Viking, not only on an individual field scale but also on a basinwide scale. The location of four valley-fill and three shoreface deposits, and the exceptional core and well log data base in the study area create an ideal situation for answering the aforementioned problems.

2.2 History of Viking Formation Studies

The purpose of this section is to provide a brief summary of some of the key papers written on the Viking Formation. The early interpretations of the Viking sediments were strongly influenced by the marine character of the underlying (Joli Fou Formation) and the overlying (Lower Colorado shales) mudstones. These interpretations included deep water turbidites (Beach, 1956, 1962; Roessingh, 1959), shelf sandstones affected by tidal currents (Evans, 1970), barrier islands (Tizzard & Lerbekmo, 1975), and storm deposits (Koldijk, 1976). Most of these studies assumed that the Viking shoreline was west of the main Viking sand bodies, and that the sand bodies were deposited in an offshore environment.

Beaumont (1984) first introduced the idea that relative fluctuations in sea level influenced the deposition of the Viking sand bodies. He suggested that Viking deltas prograded into eastern Alberta during a relative lowering of sea level and were subsequently reworked into linear shelf sand bodies (e.g. Joarcam and Joffre) during the ensuing transgression. This interpretation fails to explain why the sand bodies at Joarcam and Joffre are long and linear, and does not address the problem of forming sandier upward facies successions within these sand bodies.

A possible solution to these problems was provided by Hein et al. (1986) and Leckie (1986) in their studies of the Viking sand bodies at Caroline, Garrington and Harmattan East. These sand bodies were interpreted as the deposits of a prograding shoreline (Hein et al., 1986), formed during a relative lowering of sea level and subsequently reworked during the ensuing transgression (Leckie, 1986). A transgressive, conglomeratic lag deposit caps the sandier upward shoreface successions.

Hein et al. (1986) and Leckie (1986) documented a general relationship between the deposition of Viking sand bodies and relative fluctuations in sea level. Despite their success, much more work is needed in order to understand not only the depositional environments and histories of most Viking sand bodies, but also the regional or basinwide relationship between these deposits. For example, how were the sediments in the Crystal valley deposited and what is their relationship to the surrounding regional and shoreface deposits? Hein et al. (1986) imply that the valley-fill sediments at Crystal were deposited in a shelf valley that was cut and filled in a submarine environment. Other studies have interpreted the Crystal valley-fill as the deposits of a tidal inlet or channel (Ryer, 1987), or an "estuarine tidal channel bay complex" (Reinson, 1985; Reinson et al., 1988). The interpretations of Reinson (1985) and Reinson et al. (1988) are based on a study of the sedimentology and the reservoir geology in a small area of the Crystal valley (T45-46; R3W5-4W5), and are best considered as local interpretations.

A preliminary regional study was conducted by Leckie and Reinson (in press), who correlated the Viking sediments in the Crystal area with those in the Gilby-Joffre and Caroline areas further to the south. This work provides one of the first sets of well log correlations between geographically "isolated" Viking sand bodies. They recognized two prograding cycles which are separated by an unconformity that can be traced from the Caroline to Crystal areas. Their work suggests that the deposition of the Viking sediments was intimately related to a sequence of sea level fluctuations, possibly involving two lowstand periods.

Many of the recent Viking studies have described the sedimentology and stratigraphy of individual sand bodies such as those at Joffre (Downing, 1986; Downing and Walker, 1988), Joarcam (Power, 1987, 1988; Posamentier & Chamberlain, 1989), Gilby (Raddysh, 1986, 1988), Eureka (Pozzobon, 1987; Pozzobon & Walker, 1990), Chigwell (Raychaudhuri, 1989), Caroline and Garrington (Davies, 1990), Harmattan East (S. Hadley, pers. comm., 1990) and Willesden Green (Boreen, 1990; Boreen & Walker, 1991). Erosionally bounded packages of sedimentary rocks have been recognized in all of these areas. In general, four different sedimentary rock packages can now be defined in the Viking Formation of central Alberta; (1) regional, (2) valley-fill, (3) shoreface, and (4) transgressive deposits.

The erosional surfaces that bound these deposits have been directly linked to relative fluctuations in sea level (Downing & Walker, 1988; Posamentier & Chamberlain, 1989; Pozzobon & Walker, 1990; Boreen & Walker, 1991).

Boreen and Walker (1991) integrated the sedimentology, stratigraphy and interpretation of many isolated Viking sand bodies into a preliminary allostratigraphy. They provided detailed regional correlations of the Viking deposits in the Caroline to Willesden Green area, and also presented preliminary correlations into the Crystal area. Their work provides a framework in which to examine other Viking deposits and is described in more detail in chapter 3.

Many large Viking sand bodies remain unexamined and their relationship to the allostratigraphy developed by Boreen and Walker (1991) is unknown. One of the main goals of this thesis will be to describe and interpret the sedimentology, stratigraphy, sand body geometry and depositional history of seven large Viking sand bodies over a wide area in central Alberta, including four valley-fill (Crystal, Cyn-Pem, Sundance & Edson) and three shoreface (Sunnybrook, Wolf Creek & Bickerdike) deposits.

CHAPTER 3 - ALLOSTRATIGRAPHY & CROSS SECTIONS

The purpose of this chapter is three fold; (1) to briefly describe the Viking Formation allostratigraphy that was defined by Boreen and Walker (1991), (2) to discuss the internal stratigraphy of the Viking sediments in the Crystal, Sundance and Edson areas, using three cross sections, and (3) to integrate the Boreen and Walker (1991) allostratigraphy with the internal stratigraphy of the Viking in the Crystal, Sundance and Edson areas in order to produce a "second generation" or "expanded" Viking allostratigraphy. A more detailed version of the "expanded" allostratigraphy will be presented in chapter 10.

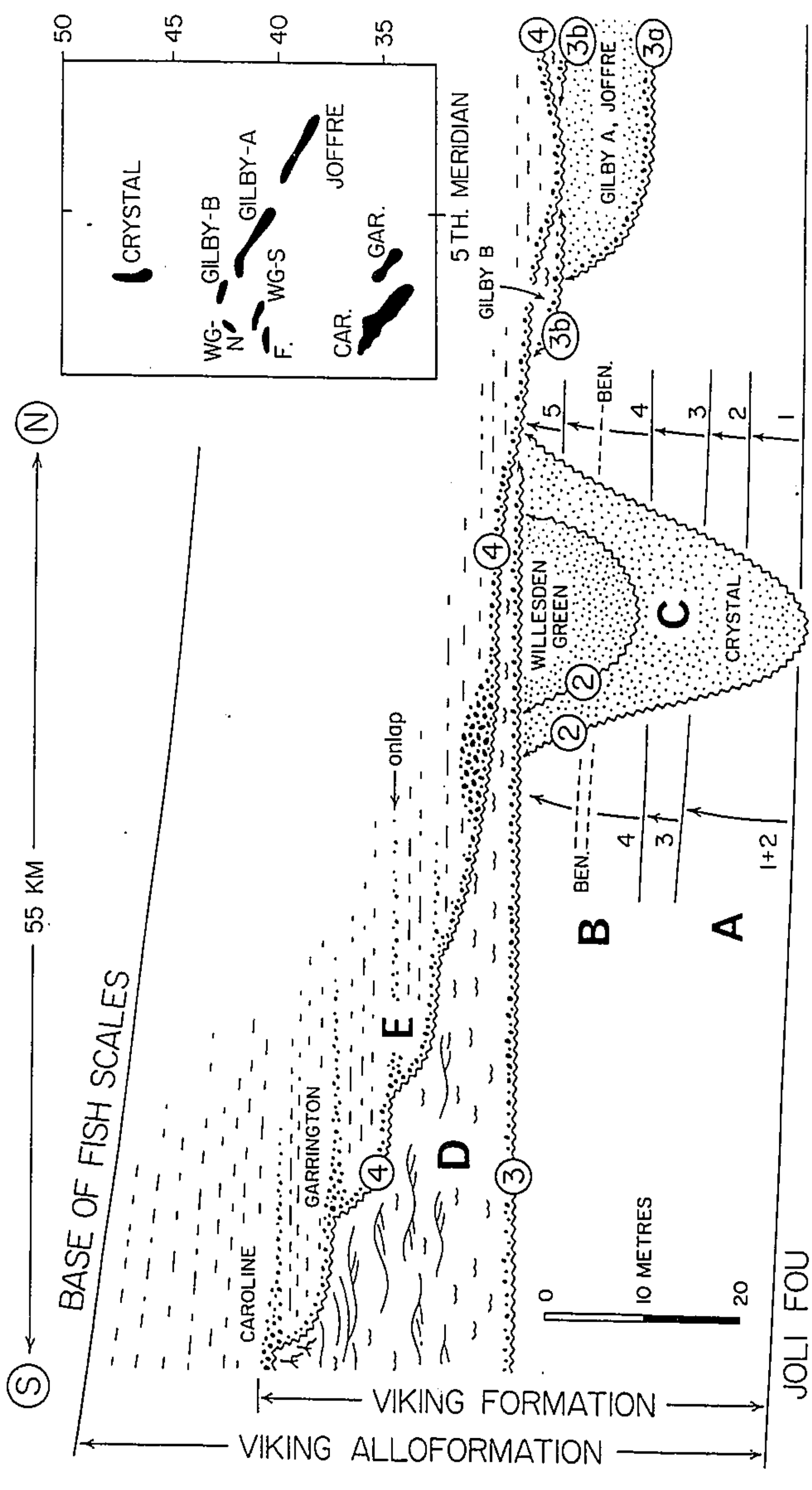
3.1 Existing Viking Formation Allostratigraphy

An allostratigraphic unit is defined as a "mappable stratiform body of sedimentary rock that is defined and identified on the basis of its bounding discontinuities" (NACSN, 1983). Boreen and Walker (1991) defined an allostratigraphy for the Viking sediments in the Caroline to Willesden Green area (Fig. 3.1), based on the recognition of distinctive facies associations that are bounded above and below by erosion surfaces. In this area, they recognized four basinwide erosion surfaces, VE1 through VE4, and five allomembers, A to E (Fig. 3.1).

Allomembers A and B consist of a stack of five coarsening-upward facies successions (Fig. 3.1), and they are the oldest deposits of the Viking. Allomembers A and B

Figure 3.1. The allostratigraphy of the Viking Formation defined by Boreen and Walker (1991). They recognized four basinwide erosion surfaces, VE1 to VE4, which subdivide the Viking into five allomembers, A to E. Erosion surfaces 2, 3 and 4 are represented by circled numbers, and erosion surface 1 occurs as a correlative conformity between regional successions 2 and 3.

Regional successions 1 and 2 are defined as allomember A, successions 3 to 5 are defined as allomember B, valley-fill (Crystal & Willesden Green) and transgressive shoreface (Gilby A & Joffre) deposits are defined as allomember C, prograding shoreface deposits (Caroline & Garrington) are defined as allomember D and transgressive deposits are defined as allomember E.


S
N
55 KM
BASE OF FISH SCALES
VIKING FORMATION
VIKING ALLOFORMATION
JOLI FOU
CAROLINE
GARRINGTON
onlap
E
D
B
A
C
WILLESDEN GREEN
CRYSTAL
GILBY A, JOFFRE
GILBY B
BEN.
4
3
1+2
5
2
1
3b
3a
0
10 METRES
20
CRYSTAL
GILBY-B
GILBY-A
JOFFRE
WG-N
WG-S
F.
CAR.
GAR.
5 TH. MERIDIAN
50
45
40
35

are separated by the VE1 erosion surface (A.D. Reynolds, pers. comm., 1989), but this is not recognized as an erosion surface in the Willesden Green area (Boreen, 1990).

Coarse-grained sandstones and conglomerates occur in allomember C (Fig. 3.1). The deposits of allomember C are bounded by the VE2 or VE3 erosion surface below, and by the VE3 erosion surface above (Fig. 3.1). The VE2 surface is defined as the "first" lowstand incision in the Willesden Green valley (Boreen & Walker, 1991; Fig. 3.1). In contrast, the VE3 surface is defined as a transgressive erosion surface (Boreen & Walker, 1991; Fig. 3.1). Most of the oil and gas producing fields or sand bodies of the Viking in the Caroline to Willesden Green area belong to allomember C.

The upper two allomembers consist of a wave-dominated, progradational shoreface to non-marine package (allomember D; Fig. 3.1), and a transgressive package of interbedded mudstones and conglomerates (allomember E; Fig. 3.1). Allomember D is bounded by the VE3 erosion surface below and by the VE4 erosion surface above. Allomember E is bounded by the VE4 erosion surface below and by the Lower Colorado shales above. Both of these packages thin to the north and are only observed in isolated patches north of the Willesden Green area.

3.1.1 <u>Sedimentary Rock Packages</u>

As well as the allomembers, the Viking can be informally subdivided into four sedimentary rock packages;

regional, valley-fill, shoreface and transgressive deposits. This informal nomenclature will be used throughout the thesis.

The regional deposits consist of bioturbated mudstones and sandstones that form a stack of coarsening-upward, shelf-to-shoreface successions. These deposits occur in allomembers A and B (Boreen & Walker, 1991; Fig. 3.1), and are bounded by the Joli Fou mudstones below and valley-fill, shoreface or transgressive deposits above.

Valley-fill deposits consist of mudstones, sandstones and conglomerates, and have been identified at Willesden Green (Boreen, 1990; Boreen & Walker, 1991), Crystal (Reinson, 1985; Reinson et al., 1988), Cyn-Pem, Sundance and Edson (Figs 1.5 & 1.6). These deposits occur in allomember C (Boreen & Walker, 1991; Fig. 3.1), and are bounded above and below by erosion surfaces.

Shoreface deposits consist of a coarsening-upward succession of bioturbated mudstones, siltstones and sandstones. These deposits also occur in allomember C (Boreen & Walker, 1991; Fig. 3.1), and have been identified at Joffre (Downing, 1986; Downing & Walker, 1988), Gilby (Raddysh, 1986, 1988), Joarcam (Power, 1988; Posamentier & Chamberlain, 1989), Chigwell (Raychaudhuri, 1989), Garrington, Caroline, Harmattan East (Hein et al., 1986; Leckie, 1986; Davies, 1990), Sunnybrook, Wolf Creek and Bickerdike (Figs 1.1, 1.5 & 1.6).

Transgressive deposits consist of interbedded

mudstones, sandstones and conglomerates, and are widespread in areal extent (Reinson et al., 1988; Boreen & Walker, 1991). These deposits occur in allomembers D and E (Boreen & Walker, 1991; Fig. 3.1), and are the uppermost sediments of the Viking Formation.

3.2 Cross Sections

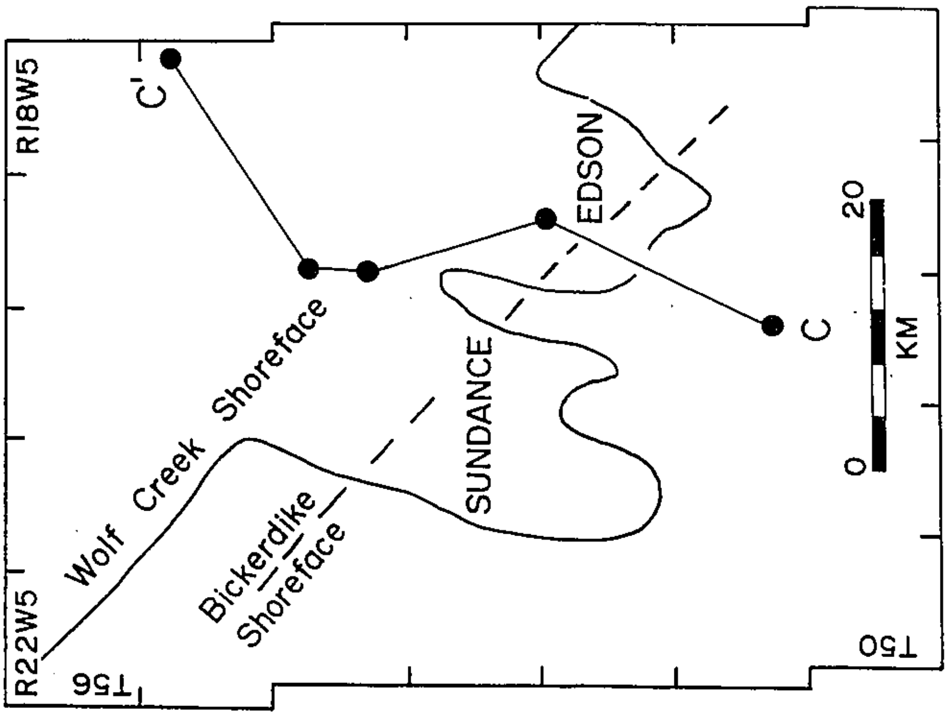
Three cross sections are used to describe the internal stratigraphy of the Viking Formation in the study area. Two of the cross sections are from the Crystal area (AA' & BB'), and the third is from the Sundance and Edson area (CC'). A summary of the methods used to construct the cross sections is provided in Appendix 2, and a legend of the symbols used in the core cross sections is shown in Figure 4.1.

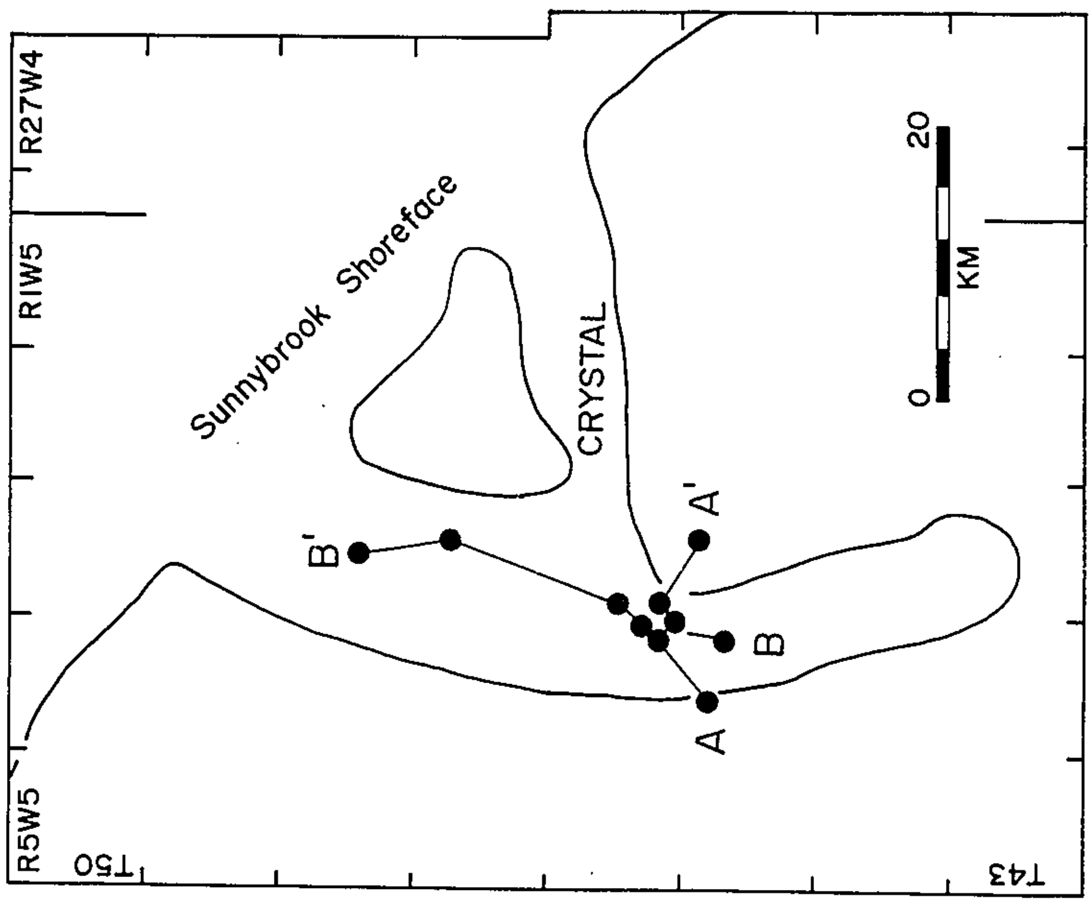
Throughout the study area, a specific and repetitive suite of sedimentary rock packages occurs, each of which is bounded above and below by erosion surfaces. These include regional, valley-fill, shoreface and transgressive deposits. Both the sedimentary rock packages and the bounding erosion surfaces will be defined and briefly described in each cross section. The erosion surfaces are given a numerical designation which is consistent with the erosional surface nomenclature presented in Boreen and Walker (1991) and in the expanded allostratigraphies of sections 3.1 and 3.3. Further discussion and justification of this nomenclature will be provided in subsequent chapters.

3.2.1 Cross Section AA'

Cross section AA' is oriented west to east across the

Figure 3.2. Location of well log and core cross sections AA', BB' and CC' shown in Figures 3.3, 3.5 & 3.6.


R18W5
R22W5
T56
T50
C'
C
Wolf Creek Shoreface
Bickerdike Shoreface
SUNDANCE
EDSON
0
20
KM

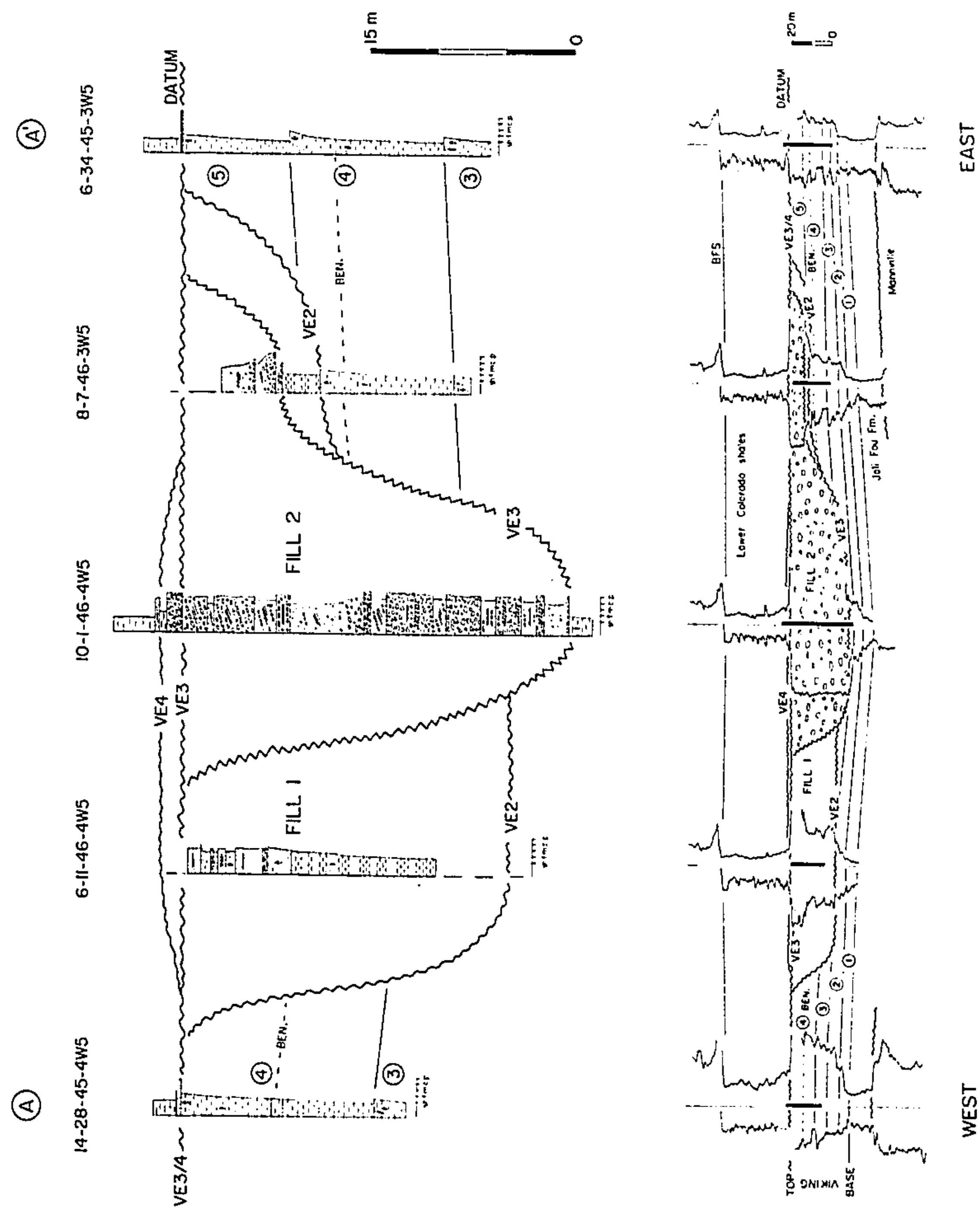

R27W4
R1W5
R5W5
T50
T43
Sunnybrook Shoreface
CRYSTAL
A
A'
B
B'
0
20
KM

Crystal valley (Fig. 3.2) and consists of five wells (Fig. 3.3). The datum for this section is the VE3 or VE3/4 erosion surface.

The western and eastern ends of cross section AA' are characterized by thoroughly bioturbated, CU facies successions that are labelled 1 to 5 (Fig. 3.3). At 14-28-45-4W5, two of these successions occur in core (3 and 4), and two other successions are visible on well logs. At 6-34-45-3W5 all five CU successions are identified, with successions 3 to 5 occurring in core (Fig. 3.3). These successions have a sheet-like geometry, a prominent funnel-shaped well log signature, are up to 14 m thick and lie stratigraphically between the Joli Fou Formation (below) and the Lower Colorado shales. As a sedimentary rock package, the CU successions are called regional deposits because of their extensive lateral continuity. These deposits are defined as facies association 1 and are described in more detail in chapters 4 and 5.

The CU successions are not observed in every well in cross section AA'. For example, successions 3 and 4 are observed in 14-28-45-4W5 but are not observed in 6-11-46-4W5 (Fig. 3.3). These two cores are approximately 5 km apart. The lateral transition between these two wells is very sharp and there is no evidence of lateral facies change between the deposits of each core. On the eastern side of cross section AA', successions 3 and 4 reappear in 8-7-46-3W5 (Fig. 3.3). Once again, an abrupt lateral contact separates

Figure 3.3. Well log and core cross section AA' from the Crystal area (Fig. 3.2). Three Viking erosion surfaces (VE2, VE3 and VE4) divide these sediments into regional successions 1 to 5; Crystal valley-fill 1; Crystal valley-fill 2; and transgressive deposits. The datum is the VE3 or VE3/4 (VE3 and VE4 coplanar) erosion surface, the black bars indicate core positions.



A
A'
14-28-45-4W5
6-11-46-4W5
10-1-46-4W5
8-7-46-3W5
6-34-45-3W5
DATUM
15 m
0
VE3/4
VE4
VE3
VE2
FILL 1
FILL 2
BEN.
20m
0
TOP
VIKING
BASE
WEST
EAST
BFS
Lower Colorado shales
Joli Fou Fm.
Mannville

the CU successions from the coarse-grained sandstones and conglomerates in 10-1-46-4W5.

Sharp vertical contacts also separate the underlying CU successions from the overlying deposits at 6-11-46-4W5, 10-1-46-4W5 and 8-7-46-3W5 (Fig. 3.3). In 10-1-46-4W5, this contact is very sharp and is marked by a lag deposit which consists of granules, pebbles and ripped-up mudstone clasts.

The sharp lateral and vertical contacts between the CU successions and the overlying deposits at 6-11-46-4W5, 10-1-46-4W5 and 8-7-46-3W5 can be explained in one of two different ways, either an abrupt facies change occurs between these deposits, or an unconformity separates them. The latter interpretation is favoured because the contact between these deposits is sharp and erosive. Also, the sheet-like CU successions at the western and eastern margins of the cross section (Fig. 3.3) are abruptly truncated by the overlying deposits in the three central wells (6-11-46-4W5, 10-1-46-4W5 & 8-7-46-3W5; Fig. 3.3), which strongly supports the latter interpretation.

An unconformity or a set of unconformities cuts into the CU successions in the central part of cross section AA' (Fig. 3.3), removing most of regional successions 3, 4 and 5. This unconformity defines a large, north to south oriented scour that is approximately 55 km long, 7 to 12 km wide and has a maximum depth of 32 m. This scour is called the Crystal valley.

Mudstones, sandstones and conglomerates fill the

Crystal valley at 6-11-46-4W5, 10-1-46-4W5 and 8-7-46-3W5 (Fig. 3.3). At 6-11-46-4W5, the valley-fill deposits are relatively fine-grained and consist of interbedded mudstones and fine-grained sandstones (Fig. 3.3). Approximately 2 km to the east, at 10-1-46-4W5, the valley-fill deposits are much coarser-grained and consist entirely of conglomerates and coarse-grained sandstones (Fig. 3.3). In contrast, at 8-7-46-3W5 the valley-fill deposits consist of mudstones and coarse-grained sandstones. The contact between the two deposits at 8-7-46-3W5 is extremely sharp and is marked by pebbles and mudstone intra-clasts. This contact is interpreted as erosional because of the sharp contact between the facies and the presence of mudstone intra-clasts and pebbles at the base of the pebbly sandstone.

Based on the geometry and facies relationships of the valley-fill deposits shown in cross section AA' (Fig. 3.3), it appears that they can be subdivided into two distinct types of deposits, distinguished by their facies and stratigraphic position. They consist of (1) interbedded mudstones and fine-grained sandstones, and (2) interbedded conglomerates and coarse-grained sandstones, and are interpreted as representing two separate episodes of valley filling - fills 1 and 2 of Figure 3.3.

Most of the cores from the Crystal valley consist of the deposits of fill 1, with sediments assigned to facies associations 2, 3, 4 and 5. In contrast, the sediments of fill 2 form a small channel-like deposit in the central part of the valley; these are assigned to facies associations 3, 6, 7 and 8. The facies associations are described in more detail in chapter 4.

Both the lower and upper contacts of the valley-fill deposits are interpreted as erosional. The lower contact is defined by the sharp, erosional transition from the underlying regional deposits into the overlying valley-fill deposits. In fill 1, this contact is labelled VE2 (Fig. 3.3) because the "first" erosion surface of each valley is defined as the VE2 lowstand incision. It is assumed that a VE2 erosion surface occurs at the base of each Viking valley. However, it is not possible to physically map VE2 between the different valleys due to erosion by VE3 and VE4. Therefore, it is not possible to prove or disprove conclusively that VE2 at Crystal is equivalent to VE2 at Willesden Green. Nevertheless, it is reasonable to assume that all of the Viking valleys were initially cut during the same lowstand and, therefore, the "first" incision in each valley is labelled VE2.

In fill 2, the basal contact is labelled VE3 (Fig. 3.3). This surface, which cuts into the VE2 erosion surface, does <u>not</u> represent the "first" or "earliest" valley incision at Crystal, but is interpreted as a falling stage incision which preceeded the subsequent "VE3" transgressive erosion (ravinement). The VE3 surface has a complex origin and is subdivided into smaller erosion surfaces. At Crystal there are at least two VE3's; one defining the falling stage incision at the base of fill 2 ("lower" VE3) and the other defining the transgressive ravinement ("upper" VE3) and incision at the top of the valley (Fig. 3.3). By superimposing falling stage or stillstand conditions on the overall "VE3" transgression, it becomes possible to develop "multiple" VE3 erosion surfaces.

The "upper" VE3 erosion surface is identified by a lag of pebbly sandstone, conglomerate and mudstone clasts that rest sharply on top of the valley-fill and regional deposits (Fig. 3.3). A thin (<2 m) package of muddy conglomerate, striped mudstones and wave rippled sandstones are observed above the "upper" VE3 erosion surface in 10-1-46-4W5 (Fig. 3.3). These sediments are not laterally continuous and are called transgressive deposits. They can be correlated south into the Caroline to Willesden Green area where the wave rippled sandstone and striped mudstone facies thicken to 10-15 m (Boreen, 1990). In this area, they are interpreted as regressive, wave-dominated shoreface deposits of allomember D (Boreen & Walker, 1991; Fig. 3.1), that rest stratigraphically on top of a thin package of transgressive conglomerates and mudstones (Boreen, 1990). This may suggest that the upper part of the transgressive deposits in the Crystal area are the distal equivalent of the regressive shoreface deposits in the Caroline to Willesden Green area. However, for the purpose of this thesis, these deposits will be referred to as transgressive.

The transgressive deposits are sharply overlain by

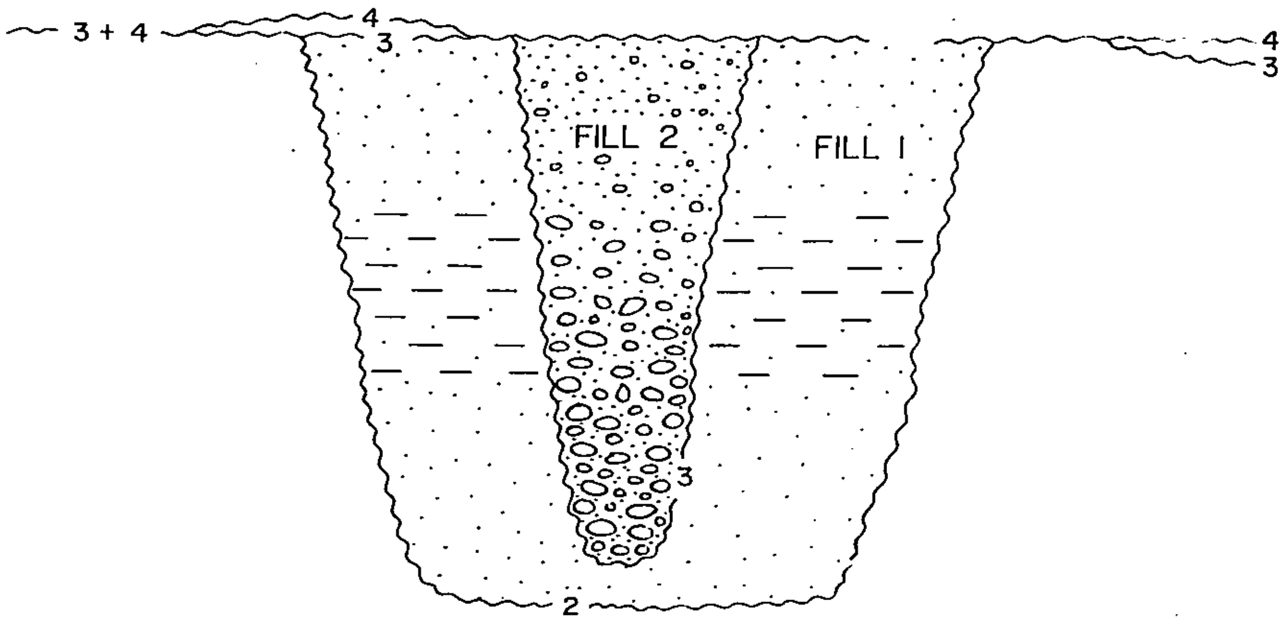
pebbly, coarse-grained, cross bedded sandstones. This contact is defined as the VE4 erosion surface (Boreen & Walker, 1991; Figs 3.1 & 3.3). Evidence for erosion on the VE4 surface includes the presence of sideritized mudstone intra-clasts and chert pebbles in the basal part of the cross bedded sandstones. In some wells, the VE4 erosion surface becomes coplanar with the VE3 surface (e.g. VE3/4 surface, 14-28-45-4W5; Fig. 3.3). Where this occurs, the striped mudstone facies of allomember D is absent and has probably been cut out by the VE4 erosion surface.

Dark mudstones of the Lower Colorado shales are observed above the VE4 erosion surface in the Crystal area. They are 30-40 m thick, and are bounded above by the BFS log marker above (Fig. 3.3).

In summary, the internal stratigraphy of the Viking in the Crystal area consists of four sedimentary rock packages (regional, fill 1, fill 2 and transgressive deposits) that are bounded by three erosion surfaces (VE2, VE3 and VE4; Fig. 3.4). The erosion surface nomenclature is both descriptive and interpretive. The descriptive aspect indicates that erosion surface 3 cuts out erosion surface 2, and erosion surface 4 cuts out surfaces 3 and 2 (Fig. 3.4). The interpretive aspect can be summarized by designating the VE2 erosion surface as the initial lowstand incision (fill 1; Fig. 3.4), and the VE3 erosion surfaces as those cut during the ensuing transgression. The VE3 surface includes the erosion surfaces cut during falling stage (fill 2; Fig.

Figure 3.4. Schematic cross section of the sedimentology and internal stratigraphy of the Crystal valley deposits. The deposits of fills 1 and 2, and three Viking erosion surfaces (VE2, VE3 & VE4) are shown. Note the occurrence of two lowstand incisions (VE2 & VE3), and the "dual" nature of the VE3 surface (lowstand incision #2 & transgressive ravinement). Depth of the valley is approximately 30 m and the width is approximately 10 km.

Crystal Valley-Fill



Erosion Surfaces

2. lowstand incision #1

3. lowstand incision #2 &
transgressive ravinement

4. basinwide erosion

3.4), stillstand (Joffre shoreface; Fig. 3.1) and resumed transgression (top of valley; Fig. 3.4); during the overall VE3 transgression.

3.2.2 Cross Section BB'

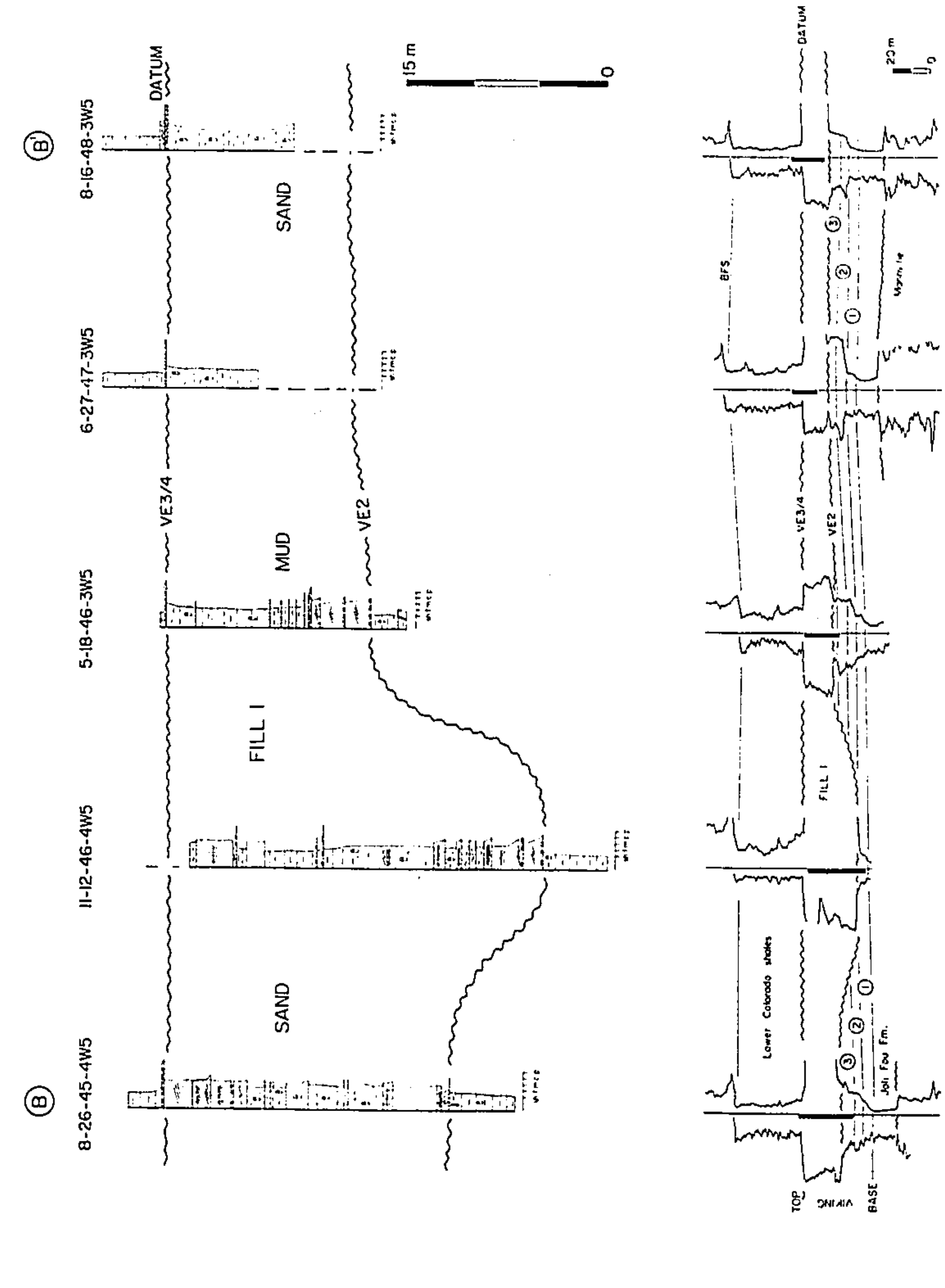
Cross section BB' is oriented south to north through the Crystal valley (Fig. 3.2) and consists of five wells (Fig. 3.5). The stratigraphic datum for this section is the VE3/4 surface, which occurs at the top of the Viking Formation.

The internal stratigraphy of the Viking shown in cross section BB' (Fig. 3.5) is very similar to that in AA' (Fig. 3.3), and consists of regional, valley-fill and transgressive deposits. The main purpose of cross section BB' (Fig. 3.5) is to document the longitudinal facies changes that occur in fill 1 of the Crystal valley.

The regional deposits consist of CU successions 1, 2 and 3, which are laterally continuous along the length of the cross section (Fig. 3.5). These deposits are bounded by the Joli Fou mudstones below, and the VE2 erosion surface above. It appears that CU successions 4 and 5 were cut out by the VE2 unconformity.

The valley-fill deposits occur stratigraphically on top of the regional deposits (Fig. 3.5) and consist of interbedded mudstones and fine-grained sandstones of fill 1. In the southern and northern ends of the valley (8-26-45-4W5 & 8-16-48-3W5; Fig. 3.5), the deposits of fill 1 are mostly fine-grained sandstones, and in the central part of the

Figure 3.5. Well log and core cross section BB' from the Crystal area. This cross section is oriented south to north through the deposits of fill 1 at Crystal (Fig. 3.2). Note the tripartite facies zonation (sand-mud-sand). Viking erosion surfaces VE2 and VE3/4 (datum), and regional successions 1 to 3 are also shown. Black bars on the well logs indicate core positions.



B
B'
8-26-45-4W5
11-12-46-4W5
5-18-46-3W5
6-27-47-3W5
8-16-48-3W5
DATUM
SAND
FILL I
MUD
SAND
VE3/4
VE2
15 m
0
SOUTH
NORTH
TOP
VIKING
BASE
Lower Colorado shales
Joli Fou Fm.
BFS
FILL I
VE3/4
VE2
DATUM
20 m
0

valley (5-18-46-3W5; Fig. 3.5) the deposits of fill 1 are mostly dark mudstones. These lateral facies relationships define a tripartite facies zonation (sand-mud-sand) for the sediments of fill 1 (Fig. 3.5). Gradational facies changes are inferred between the sandstones and mudstones of fill 1.

The valley-fill deposits in cross section BB' are bounded by the VE2 erosion surface below and the VE3/4 erosion surface above (Fig. 3.5). These bounding erosion surfaces correlate with those that encase fill 1 in cross section AA' (Fig. 3.3).

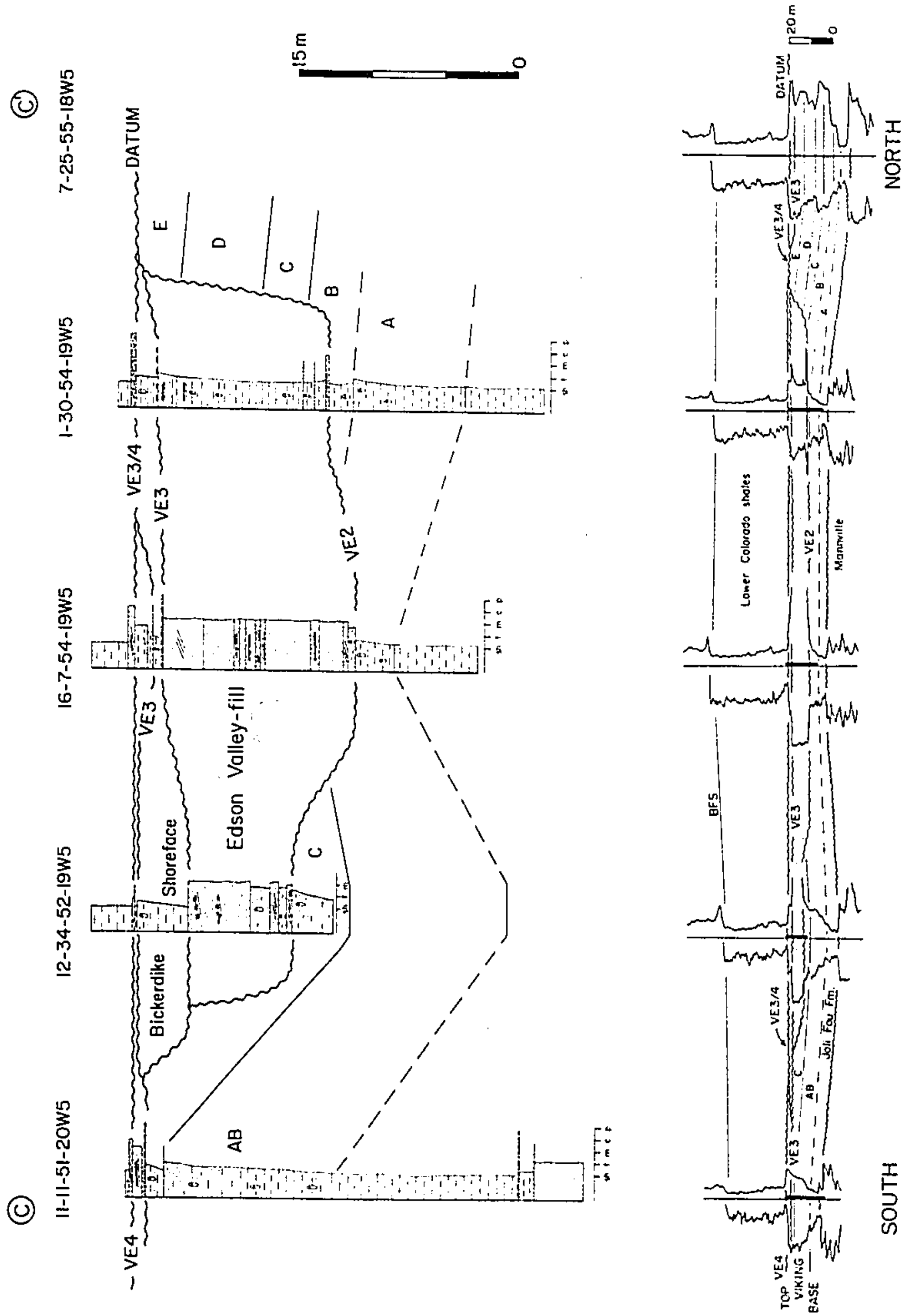
The transgressive deposits are thin or absent in cross section BB' (Fig. 3.5). Thin conglomeratic lags occur in 8-26-45-4W5, 5-18-46-3W5, 6-27-47-3W5 and 8-16-48-3W5 (Fig. 3.5). Only one of these wells (8-16-48-3W5) has a cross bedded sandstone bed on top of the conglomeratic lag.

In summary, the internal stratigraphy of the Viking that is shown in cross section BB' (Fig. 3.5) consists of three sedimentary rock packages (regional, fill 1 and transgressive deposits) that are bounded above and below by two erosion surfaces (VE2 & VE3/4).

3.2.3 <u>Cross Section CC'</u>

Cross section CC' (Fig. 3.6) consists of five wells from the Edson area and is oriented south to north through the Edson valley, Bickerdike shoreface and the Wolf Creek shoreface (Fig. 3.2). This cross section is hung on the VE3/4 or VE4 surface. Both the Viking and Joli Fou Formations are much thinner in the Edson area than in the

Figure 3.6. Well log and core cross section CC' from the Edson area (Fig. 3.2). The Edson valley-fill deposits are bounded by the VE2 (below) and the VE3 erosion surfaces, and are shown as a stippled pattern on the well logs. The Bickerdike shoreface deposits are bounded by the VE3 (below) and the VE3 or the VE3/4 erosion surfaces. Regional successions A to E and transgressive deposits (between VE3 and VE4) are also shown. The VE3/4 or VE4 erosion surface is the datum, black bars on well logs indicate core positions.


C
11-11-51-20W5
12-34-52-19W5
16-7-54-19W5
1-30-54-19W5
7-25-55-18W5
C'
DATUM
VE4
VE3
VE3/4
VE2
Bickerdike
Shoreface
Edson Valley-fill
AB
C
A
B
D
E
15 m
0
SOUTH
NORTH
TOP VE4
VIKING BASE
Lower Colorado shales
Mannville
BFS
Joli Fou Fm.
20 m

Crystal area. In the Edson area, the Viking is 10-27 m thick (30-35 m at Crystal), and the Joli Fou is 2-6 m thick (12-15 m at Crystal).

Large scale, sedimentary rock packages and bounding erosion surfaces are also observed in the Viking sediments of the Edson area. The sedimentology of the Viking in the Edson area is similar to that observed in the Crystal area.

Five CU successions are recognized in the Edson area and these are labelled A to E (Fig. 3.6). The CU successions are 2-10 m thick, thoroughly bioturbated and have a sheet-like geometry. They have a similar sedimentology and occur at the same stratigraphic interval as the regional deposits in the Crystal area (Figs 3.3 & 3.5). However, the regional deposits in the Edson area are thinner than those recognized in the Crystal area.

Only three CU successions (A, B & C) are observed in the southern part of the Edson area and two of these, A and B, merge into a single CU succession (labelled AB) at 11-11-51-20W5 (Fig. 3.6). In contrast, the northern part of the Edson area is characterized by five CU successions. The greater number of regional successions in the northern part of the Edson area corresponds to an increase in the thickness of the Viking Formation from 14 m at 11-11-51-20W5 to 27 m at 7-25-55-18W5 (Fig. 3.6).

The regional deposits are bounded below by the Joli Fou mudstones and above by the VE2, VE3 and VE4 erosion surfaces. The regional deposits are cut by a major unconformity (VE2 erosion surface) which has up to 16 m of relief.

The Edson valley-fill is bounded by the VE2 erosion surface below and by the VE3 erosion surface above (Fig. 3.6). The valley-fill deposits consist of mudstones and fine- to medium-grained sandstones, and are much thinner than the valley-fill deposits at Crystal.

The VE2 erosion surface at Edson represents the "first" or "earliest" lowstand incision in this area, and was initially cut during a relative fall in sea level. It is reasonable to assume that the VE2 surface at Edson was cut during the same lowstand as the VE2 surface at Crystal.

The VE3 erosion surface at the top of the Edson valley-fill was cut during the ensuing transgression, and is a transgressive ravinement surface. This surface has a similar origin to the VE3 surface which occurs at the top of the Crystal valley-fill.

The stratigraphy above the Edson valley-fill deposits is much more complex than the stratigraphy described in the Crystal area. Two shoreface deposits, Wolf Creek (7-25-55-18W5; Fig. 3.6) and Bickerdike (12-34-52-19W5, 16-7-54-19W5 & 1-30-54-19W5; Fig. 3.6), along with a thicker transgressive package of sediments are observed above the Edson valley-fill (Fig. 3.6). These shoreface deposits have sharp and erosive bases, are thoroughly bioturbated, become coarser grained upward and have a high percentage of sandstone, relative to the regional CU successions.

The Wolf Creek shoreface is approximately 2 m thick in 7-25-55-18W5 and is bounded by the VE3 erosion surface below and by the VE3/4 erosion surface above (Fig. 3.6). In contrast, the Bickerdike shoreface has a maximum thickness of 3.5 m in 12-34-52-19W5 and is bounded above and below by the VE3 erosion surface (Fig. 3.6).

The transgressive deposits are the uppermost Viking sediments observed at Edson, and they are best developed in 11-11-51-20W5 and 16-7-54-19W5 (Fig. 3.6). They consist of interbedded mudstones, cross bedded sandstones and conglomerates, and they are encased by the VE3 erosion surface below and the VE4 erosion surface above (e.g. 16-7-54-19W5; Fig. 3.6). The transgressive deposits are up to 3 m thick in the Edson area and are difficult to correlate between adjacent wells.

In summary, the internal stratigraphy of the Viking in the Edson area consists of regional, valley-fill, shoreface and transgressive deposits, which are bounded by the VE2, VE3 and VE4 erosion surfaces. The stratigraphy shown in cross section CC' is representative of the entire Sundance and Edson area.

3.3 Expanded Viking Formation Allostratigraphy

The purpose of this section is to integrate the Viking allostratigraphy defined by Boreen and Walker (1991; Fig. 3.1) with the internal stratigraphy of the Viking in the Crystal, Sundance and Edson areas (Figs 3.2-3.6; section 3.2) to produce an "expanded" Viking allostratigraphy. The expanded version of the Viking allostratigraphy (Fig. 3.7) synthesizes the observations from an area twice as large as the original study area of Boreen and Walker (1991). This allostratigraphy will be further refined in chapter 10.

The original allostratigraphy defined by Boreen and Walker (1991) has not been radically altered because a similar set of sedimentary rock packages and bounding erosion surfaces are observed in the Crystal, Sundance and Edson areas. These include regional, valley-fill, shoreface and transgressive sedimentary rock packages and the VE2, VE3 and VE4 bounding erosion surfaces (Figs 3.3-3.6).

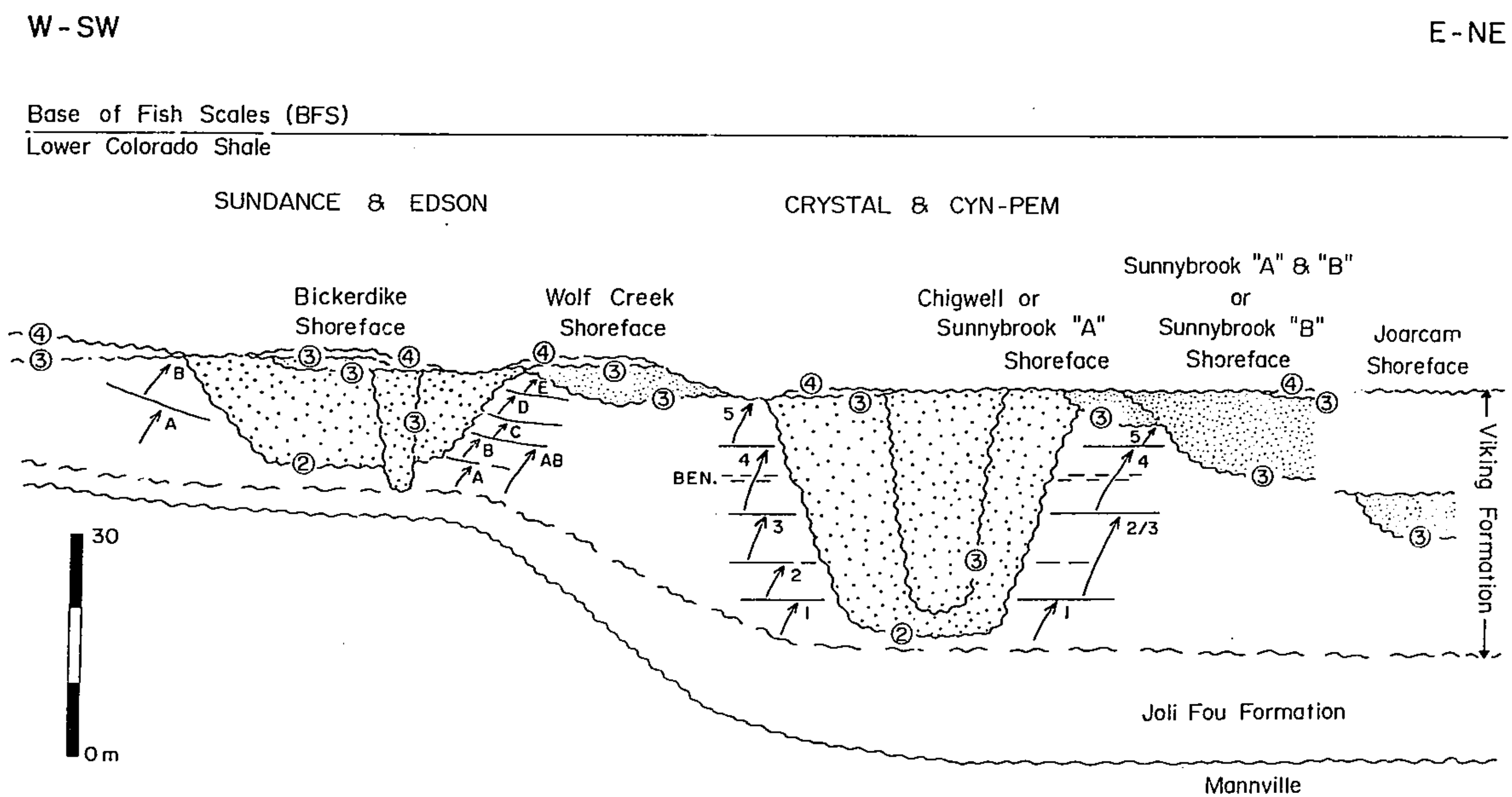
The regional deposits are encased by the Joli Fou mudstones below, and are variously truncated by the VE2, VE3 and VE4 erosion surfaces (Fig. 3.7). These deposits consist of a stack of CU successions, labelled 1 to 5 in the Crystal area, and A to E in the Sundance and Edson area (Fig. 3.7). The correlation of the CU successions between the Crystal, Cyn-Pem, Sundance and Edson areas is difficult because of the sparse well log and core data base, and will be discussed in more detail in chapter 5.

Both the valley-fill and the shoreface deposits rest stratigraphically on top of the regional deposits. The "first" lowstand incision in each valley is defined as the VE2 erosion surface (e.g. fill 1 - Crystal). Subsequent incisions are labelled VE3 (e.g. fill 2 - Crystal). The valley-fill deposits are bounded by the VE3 or VE4 erosion surface above. In contrast, the shoreface deposits are

Figure 3.7. Allostratigraphy of the Viking Formation in the study area. The VE2 erosion surface is defined as the "earliest" or "first" lowstand incision in each valley. The VE3 erosion surface can be subdivided into many smaller surfaces which correspond to lowstand incision (fill 2 - Crystal), transgressive modification, stillstand (shoreface scours) and transgressive ravinement; all of which are cut during the <u>overall</u> VE3 transgression. The VE4 erosion surface is defined as the top of the Viking.

Regional deposits are highlighted by CU successions 1 to 5 in the Crystal area and successions A to E in the Sundance and Edson area. Valley-fill deposits (coarse stipple) are recognized at Crystal, Cyn-Pem, Sundance and Edson, and shoreface deposits (fine stiple) are recognized at Sunnybrook, Chigwell, Wolf Creek and Bickerdike. Transgressive deposits are observed between the VE3 and the VE4 erosion surfaces.

A refined and more detailed version of this allostratigraphy will be presented in chapter 10 (Fig. 10.1). This "second" generation allostratigraphy will include the local and regional correlations described in chapters 5-9.


W-SW
E-NE
Base of Fish Scales (BFS)
Lower Colorado Shale
SUNDANCE & EDSON
CRYSTAL & CYN-PEM
Bickerdike Shoreface
Wolf Creek Shoreface
Chigwell or Sunnybrook "A" Shoreface
Sunnybrook "A" & "B" or Sunnybrook "B" Shoreface
Joarcam Shoreface
Viking Formation
Joli Fou Formation
Mannville
BEN.
30
0 m

associated with the "VE3" transgression and therefore are bounded by the VE3 erosion surface below, and by the VE3 or VE4 erosion surface above (Fig. 3.7).

The complexity of the VE3 erosion surface is shown in Figure 3.7. VE3 was cut during an overall transgression that was punctuated by minor regressions and stillstands. This explains why the VE3 surface can be subdivided into smaller erosion surfaces which are associated with lowstand incision (fill 2 - Crystal), stillstand (shoreface scours) and transgressive ravinement (top of valleys).

The transgressive deposits occur stratigraphically on top of the regional, valley-fill and shoreface deposits. They are the uppermost deposits of the Viking and are bounded by the VE3 erosion surface below, and by the VE4 erosion surface above. In some wells the VE3 and VE4 surfaces are coplanar and the transgressive deposits are absent (e.g. Crystal area; Figs 3.3 & 3.5). The maximum separation between the VE3 and the VE4 erosion surfaces occurs in the Sundance and Edson area (Figs 3.6 & 3.7).

CHAPTER 4 - FACIES ASSOCIATIONS

During the examination of Viking core from the study area, over 40 facies were identified in the regional, valley-fill, shoreface and transgressive deposits. These facies were defined by differences in lithology, sedimentary structures, degree of bioturbation and trace fossil assemblage. Due to the large number of facies and the relatively subtle distinctions between some of them, it became apparent that a meaningful interpretation for each facies was impossible; it was therefore decided to combine the facies into facies associations.

Ten facies associations can be defined in the study area. They form discrete sedimentary packages that consist of single fining-upward (FU) or coarsening-upward (CU) successions, multiple FU or CU successions, or non-sequential successions. One facies association is observed in the regional deposits (facies association 1), seven are observed in the valley-fill deposits (facies associations 2-8), and two are represented in the shoreface or transgressive deposits (facies associations 9 & 10).

The aim of this chapter is to give descriptions and preliminary interpretations of the ten facies associations. These interpretations will be expanded in subsequent chapters when the geometry, lateral extent and contacts between the different associations are examined.

A key to the lithology, sedimentary structures, trace

Figure 4.1. Legend of lithology, sedimentary structures, trace fossils and other symbols used throughout this thesis.

Lithology

- Mudstone
- Sandy Mudstone
- Muddy Sandstone
- Sandstone
- Pebbly Sandstone
- Conglomerate

Trace Fossils

A	Arenicolites
As	Asterosoma
C	Chondrites
Co	Conichnus
Cy	Cylindrichnus
D	Diplocraterion
H	Helminthopsis
M	Macaronichnus
O	Ophiomorpha
Pa	Palaeophycus
P	Planolites
R	Rosselia
S	Skolithos
Tc	Teichichnus
T	Terebellina
Th	Thalassinoides
Z	Zoophycos

Sedimentary Structures

- Cross Bedding
- Horizontal Bedding / LAIS
- Current Ripples
- Wave Ripples
- HCS / SCS
- "PR" Beds
- Synaeresis Cracks
- Loading
- Imbrication

Other Symbols

θθθ	Burrows
	Carbonaceous Material
	Mudstone Clasts
	Siderite Clasts
BBBB	Bentonite
SSSS	Siderite

fossils and other symbols is presented in Figure 4.1. These symbols are used in the type well figures and in core cross sections throughout this thesis.

4.1 Facies Association 1 - Bioturbated CU Successions

Facies association 1 consists of thoroughly bioturbated mudstones, siltstones and sandstones that form a series of CU facies successions (Fig. 4.2). The type well is located southwest of Crystal at 11-17-43-5W5 (Figs 4.2 & 4.3).

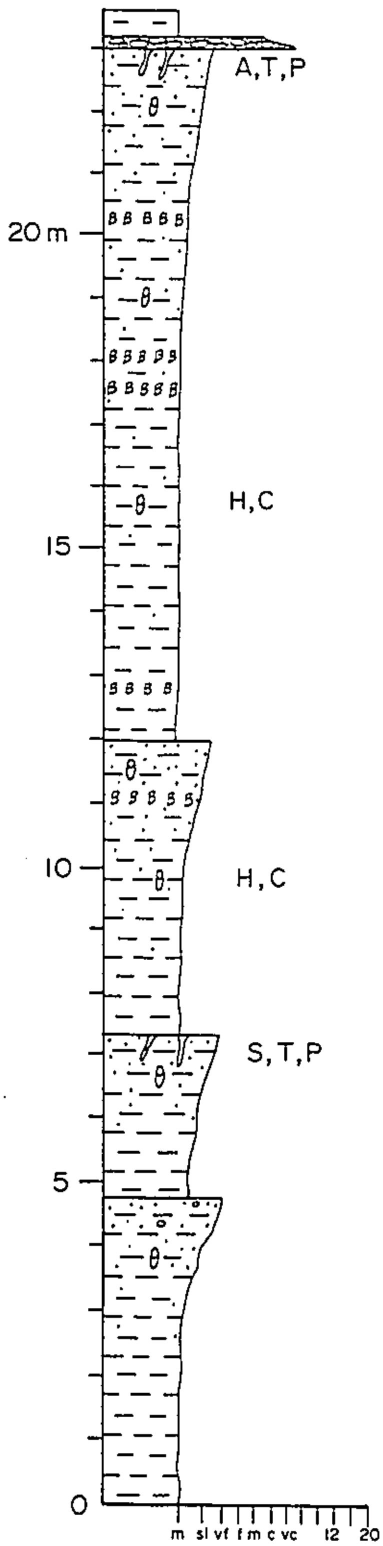
The CU successions pass from dark mudstone at the base, into sandy mudstone or siltstone in the middle, and thence into muddy sandstone at the top. In most successions, the volume of silt and sand varies from two to five percent at the base, up to forty to ninety percent near the top. The sand is dispersed throughout the CU succession, and is very fine- to fine-grained at the base and fine- to medium-grained at the top. The vertical change in grain size is gradational. Bentonite layers (2-30 mm thick) and siderite beds (1-5 cm thick) are also observed.

The CU successions are 4 to 14 m thick, and occur in stacks of 2-6 successions per well. In most stacks, the sandiest succession is located near the top, while the muddiest succession is located near the base. The type well has 4 CU successions (Figs 4.2 & 4.3).

Within each succession, the muddier sediments contain abundant _Helminthopsis_ and _Chondrites_ traces (Fig. 4.4A), and also contain lesser numbers of _Zoophycos_, _Teichichnus_, _Planolites_, _Terebellina_, small _Skolithos_ and _Asterosoma_

Figure 4.2. Type well for facies association 1 from 11-17-43-5W5 (2007-2033 m) showing a stack of CU vertical facies successions. The corresponding resistivity and gamma-ray well logs, and the position of the core (black bar) are also shown. A complete set of core photographs are presented in Figure 4.3, while individual facies photographs are shown in Figure 4.4. H - Helminthopsis, C - Chondrites, A - Arenicolites, T - Terebellina, P - Planolites, S - Skolithos

Facies Association I



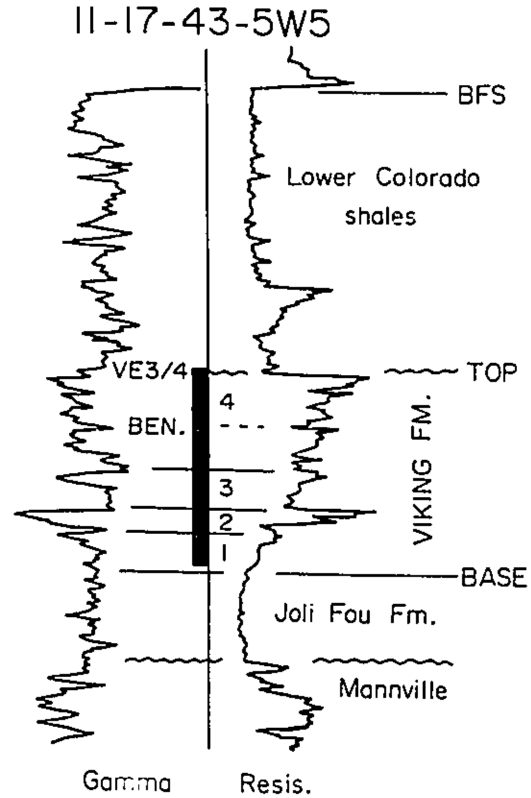
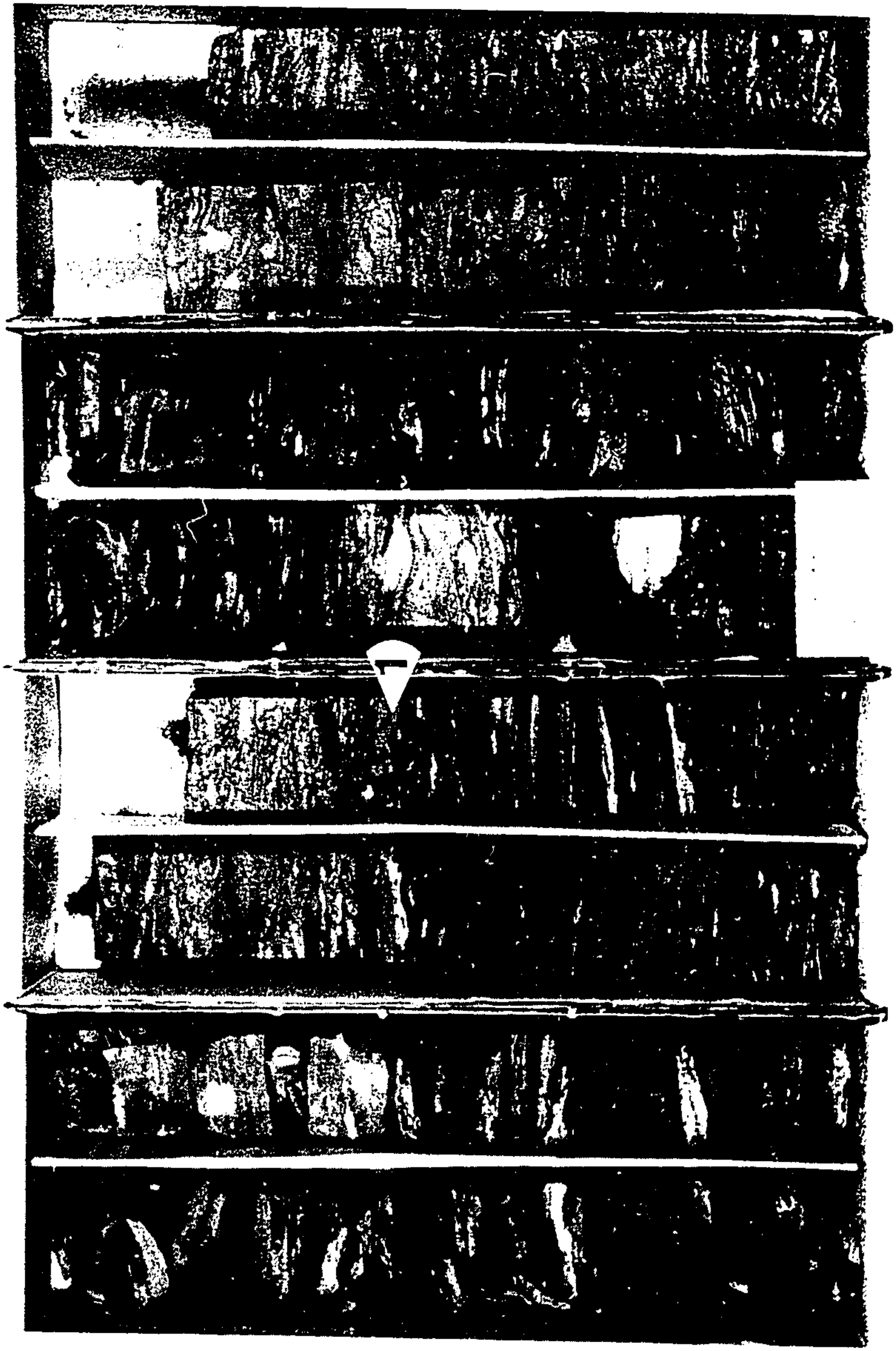
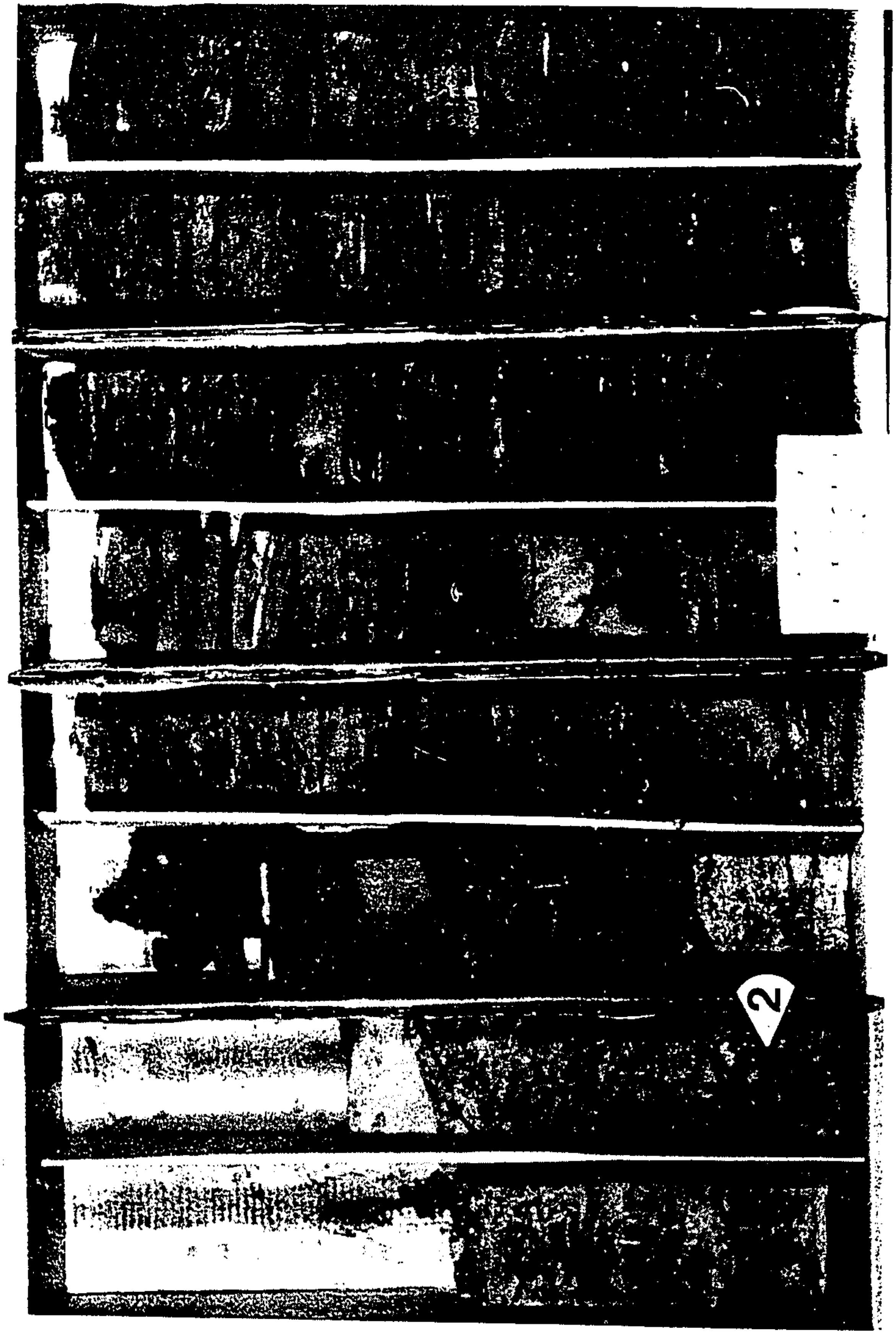
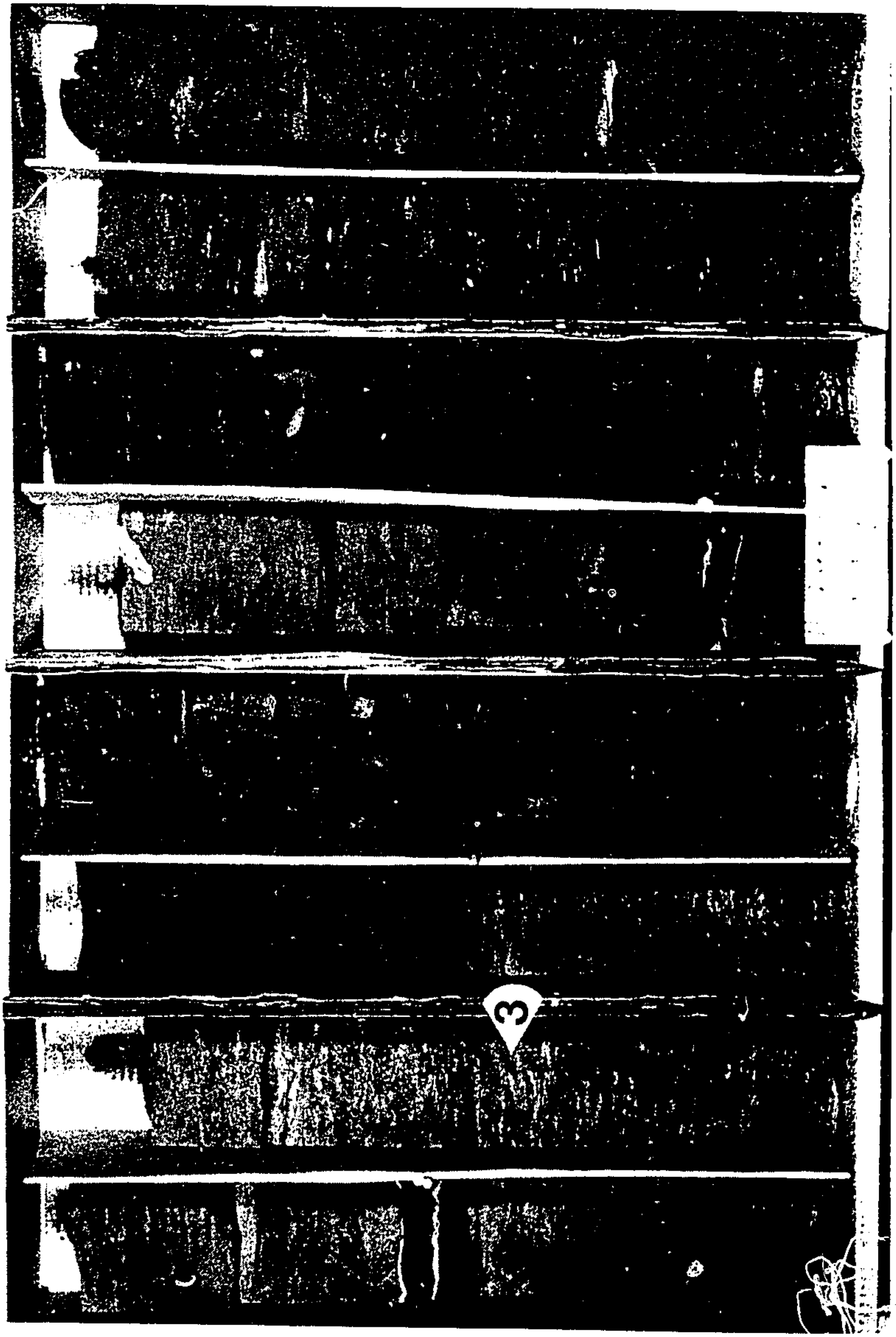
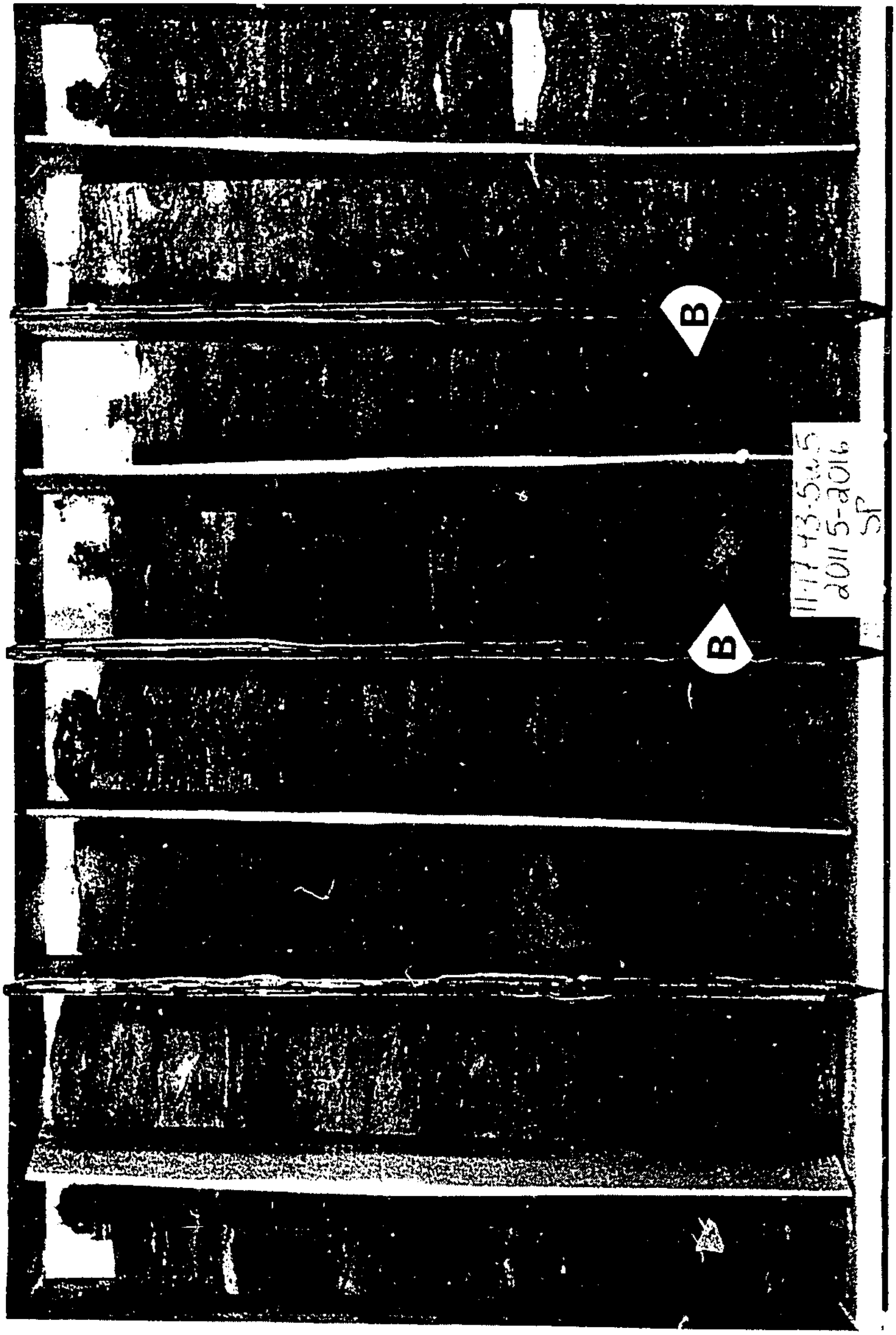


Figure 4.3. The following five pages show a complete set of core photographs for the type well (11-17-43-5W5) of facies association 1. Each core sleeve is approximately 60 cm long and the stratigraphic top is located in the upper right corner of each photograph.









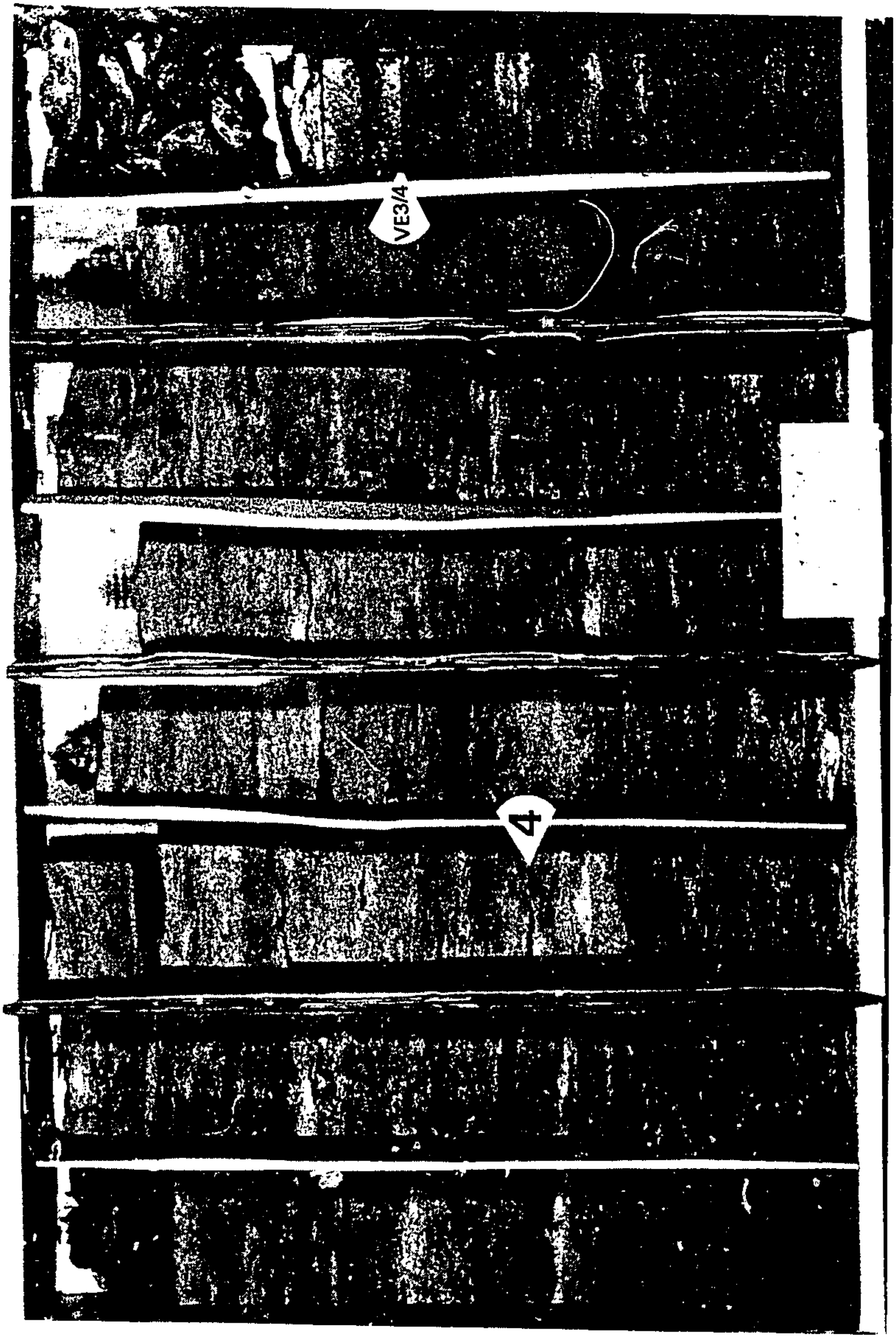
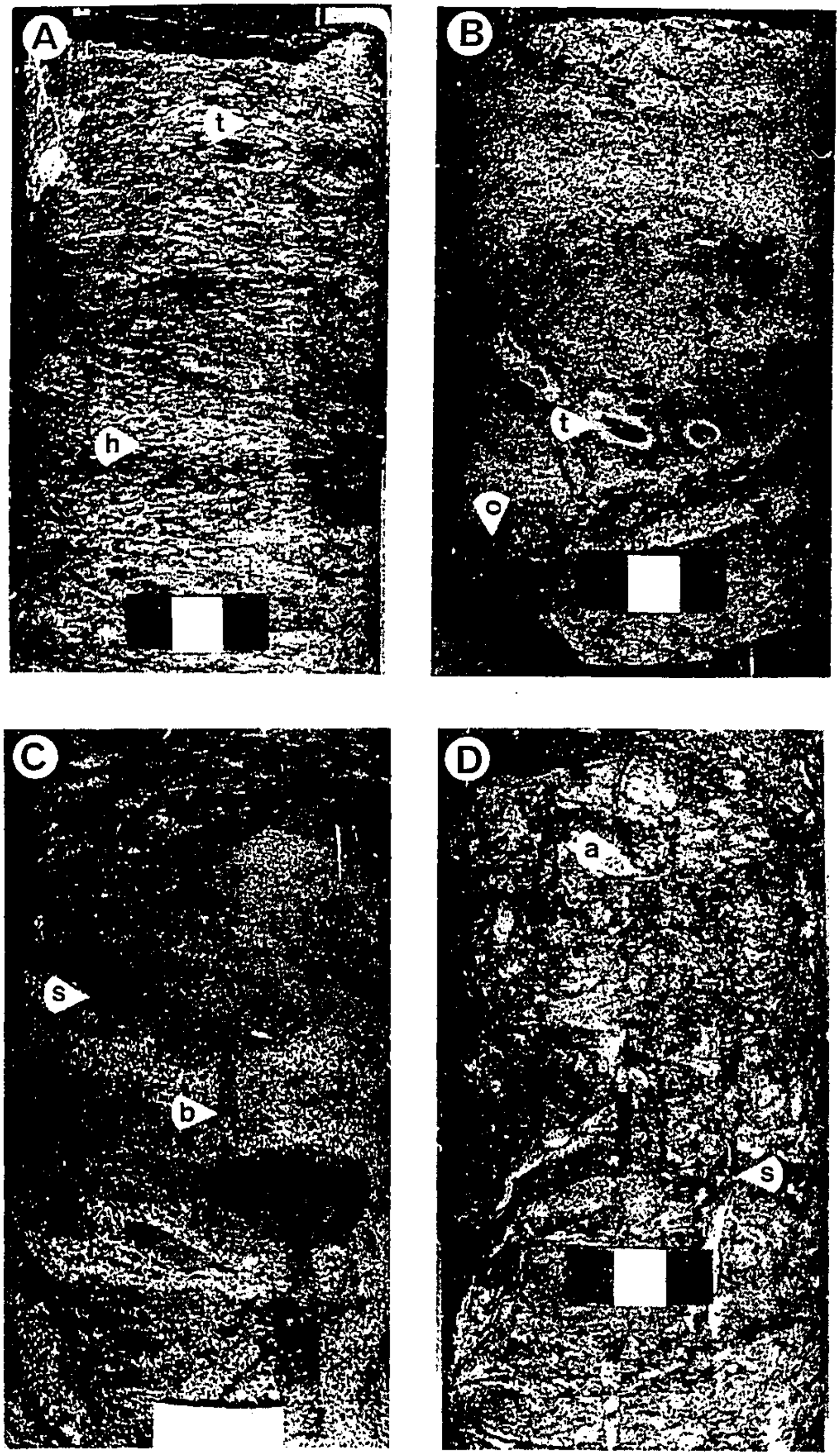

VE3/4
4

Figure 4.4. Sediments of facies association 1. Scale bars are 3 cm long. (A). Pervasively bioturbated, muddy siltstone from 7-32-45-3W5 (1767 m). Note the abundant Helminthopsis (h) and the small Terebellina (t) traces. (B). Thoroughly bioturbated, muddy sandstone from the upper part of a CU succession in 7-32-45-3W5 (1762 m). Note the large Terebellina (t) and Ophiomorpha (o) traces. (C). Erosional lag deposit at the top of a CU succession in 6-29-45-3W5 (1780 m). Large sideritized mudstone clasts (s), coarse sand and vertical burrows (b) are observed. (D). Arenicolites (a) or Skolithos (s) burrows cutting across the Cruziana ichnofacies at the top of a CU succession in 8-10-46-4W5 (1727 m).


A
t
h
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C
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s

traces. In general, the muddier sediments are characterized by small trace fossils that are typical of the Zoophycos and Cruziana ichnofacies (Frey & Pemberton, 1984). In contrast, the sandier sediments are characterized by larger trace fossils that include Ophiomorpha, Terebellina, Rosselia, Cylindrichnus, Arenicolites, Thalassinoides and Skolithos (Fig. 4.4B). These occur in the upper part of each succession and are typical of the Cruziana and Skolithos ichnofacies (Frey & Pemberton, 1984).

In general, few sedimentary structures are preserved in these successions, with the exception of wave rippled sandstone beds in the lower half of the CU successions and hummocky cross stratified (HCS), planar laminated and cross bedded sandstone beds in the upper half. The wave rippled sandstone beds are sharp based, normally graded, consist of very fine- to fine-grained sand and are 2-10 cm thick. The HCS, planar laminated and cross bedded sandstone beds are also sharp based, and consist of fine- to medium-grained sand in beds 5-45 cm thick. Glauconite grains are observed in trace amounts (1-2 %) in both the planar laminated and cross bedded sandstones. The tops of the beds usually have a bioturbated, gradational contact with overlying bioturbated sandstone.

The lowermost CU succession of the Viking Formation in each stack typically has a gradational lower contact with the dark mudstones of the Joli Fou Formation below. Other contacts between individual CU successions are often sharp and erosive. This is shown by the abrupt change in grain size from the sandy top of an underlying succession to the muddy base of the overlying succession. The sandy tops of the CU successions are occasionally overlain by a thin lag (2-10 cm) of sideritized mudstone clasts, coarse-grained sand and pebbles (Fig. 4.4C). Also, Arenicolites and Skolithos burrows, 10-30 cm long, are often observed in the upper part of these CU successions (Fig. 4.4D). The Arenicolites and Skolithos burrows appear to originate from the erosional top of the CU succession, are passively filled with fine- to medium-grained sand (which is slightly coarser than the surrounding sand) and are observed to cut across the Cruziana and Skolithos ichnofacies found at the top of the CU successions (Fig. 4.4D). These characteristics suggest that the Arenicolites and Skolithos traces are typical of the Glossifungites ichnofacies (Frey & Pemberton, 1984).

Interpretation

The abundance and diversity of traces, thorough bioturbation and lack of physical sedimentary structures in the muddier part of each succession suggest deposition below fair weather wave base in a quiet, fully marine environment. The CU nature of each succession is interpreted as representing a shallowing-upward trend that culminates with the deposition of cross bedded sandstone. The coarser sand, decrease in bioturbation and lack of mudstone in the upper part of the succession is indicative of relatively high energy levels. The presence of trace fossils typical of the Skolithos ichnofacies suggest the sediments were deposited above fair weather wave base (Frey & Pemberton, 1984).

4.2 Facies Association 2 - Dark Mudstone

Facies association 2 consists of interbedded dark mudstone, moderately bioturbated mudstone and planar to ripple cross laminated sandstone. The type well is located in the central part of the Crystal valley at 8-31-46-3W5 (Figs 4.5 & 4.6).

The sediments of facies association 2 combine to form a vertical facies succession that is muddier-upward in the lower half and sandier-upward in the upper half. The dark mudstone facies association varies in thickness from 2 to 16.5 m, with the thickest deposits occurring at Crystal in 8-25-46-4W5.

The dark mudstone interbeds consist of monotonous, dark grey to black mudstones with very massive textures, interlaminated with lenses of fine-grained sandstone. These interbeds are 1-10 cm thick, contain five to fifty percent sand and are mildly bioturbated. Recognizable trace fossils are rare and include Chondrites and Planolites. The sandstone lenses are sharp based, wave or current rippled and are 0.5-4.0 cm thick. Some of these sandstone lenses are loaded into the underlying dark mudstone (Fig. 4.7A), while other lenses have synaeresis cracks (Fig. 4.7B). This facies resembles the wavy and lenticular bedding defined by Reineck and Wunderlich (1968).

Figure 4.5. Type well for facies association 2 from 8-31-46-3W5 (1658-1675 m) showing a FU to CU vertical facies succession. The corresponding resistivity and gamma-ray well logs, and the position of the core (black bar) are also shown. A complete set of core photographs is presented in Figure 4.6, while the individual facies photographs are presented in Figure 4.7. O - Ophiomorpha, Tc - Teichichnus, T - Terebellina, P - Planolites, C - Chondrites

Facies Association 2

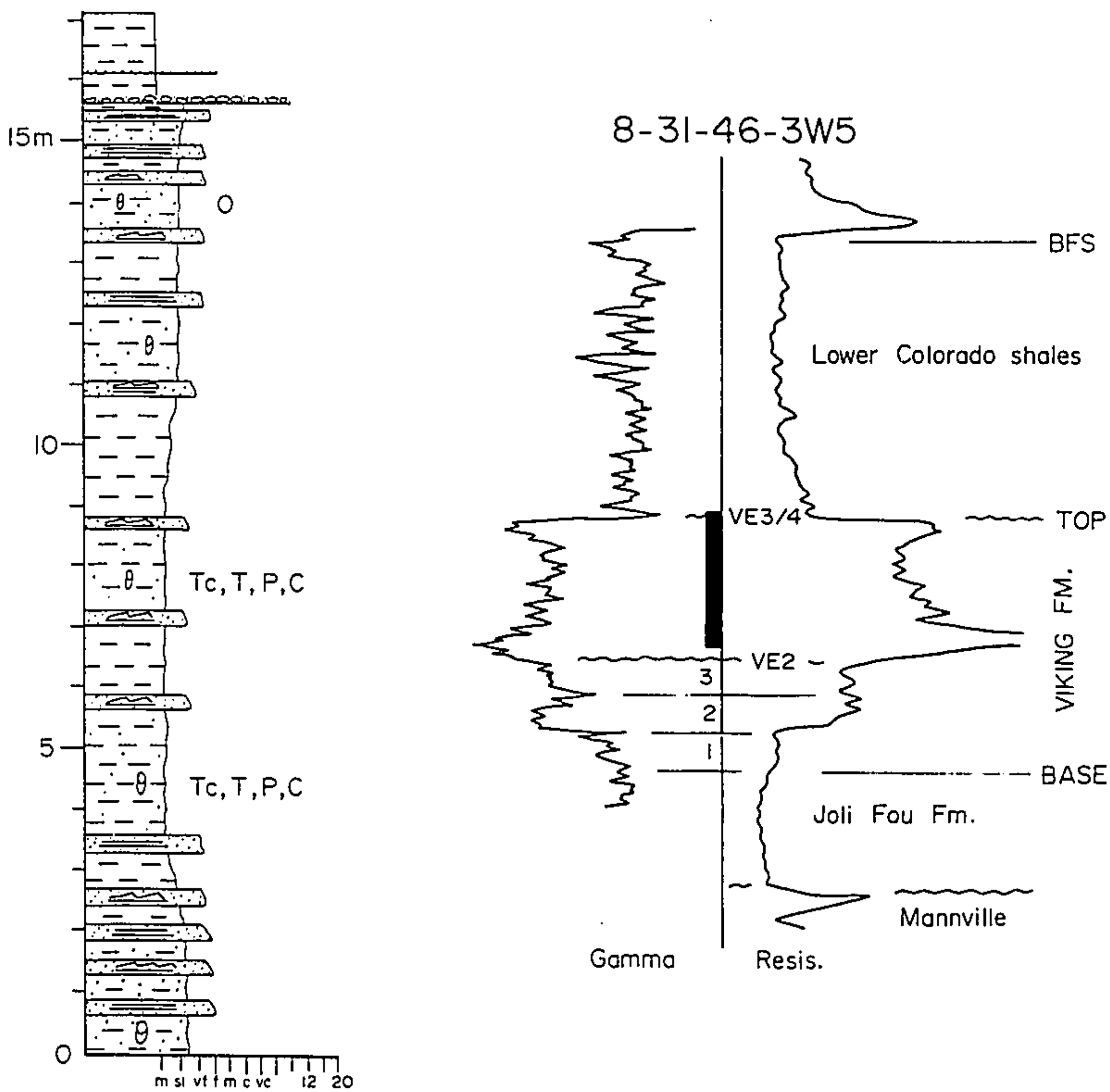
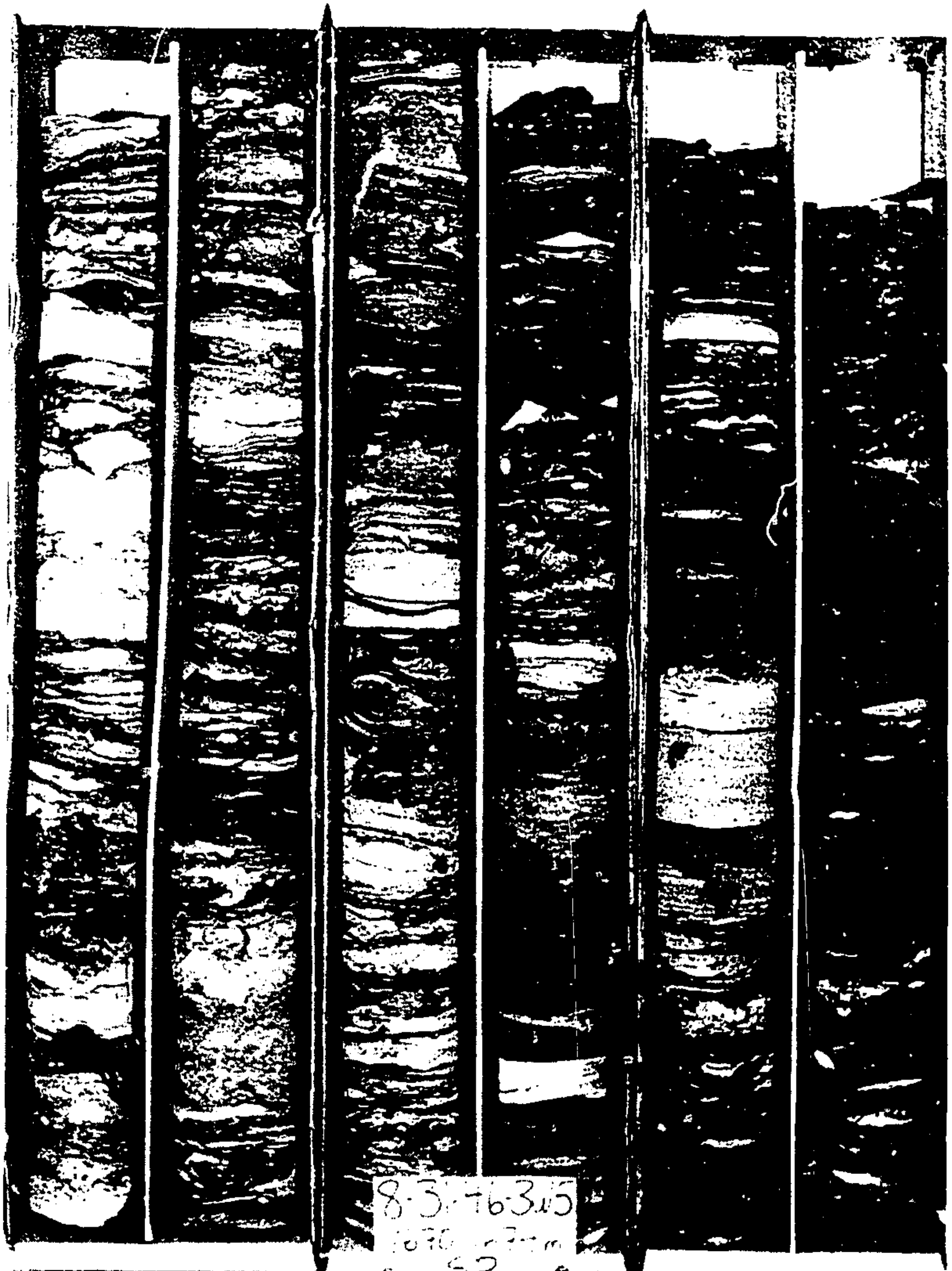
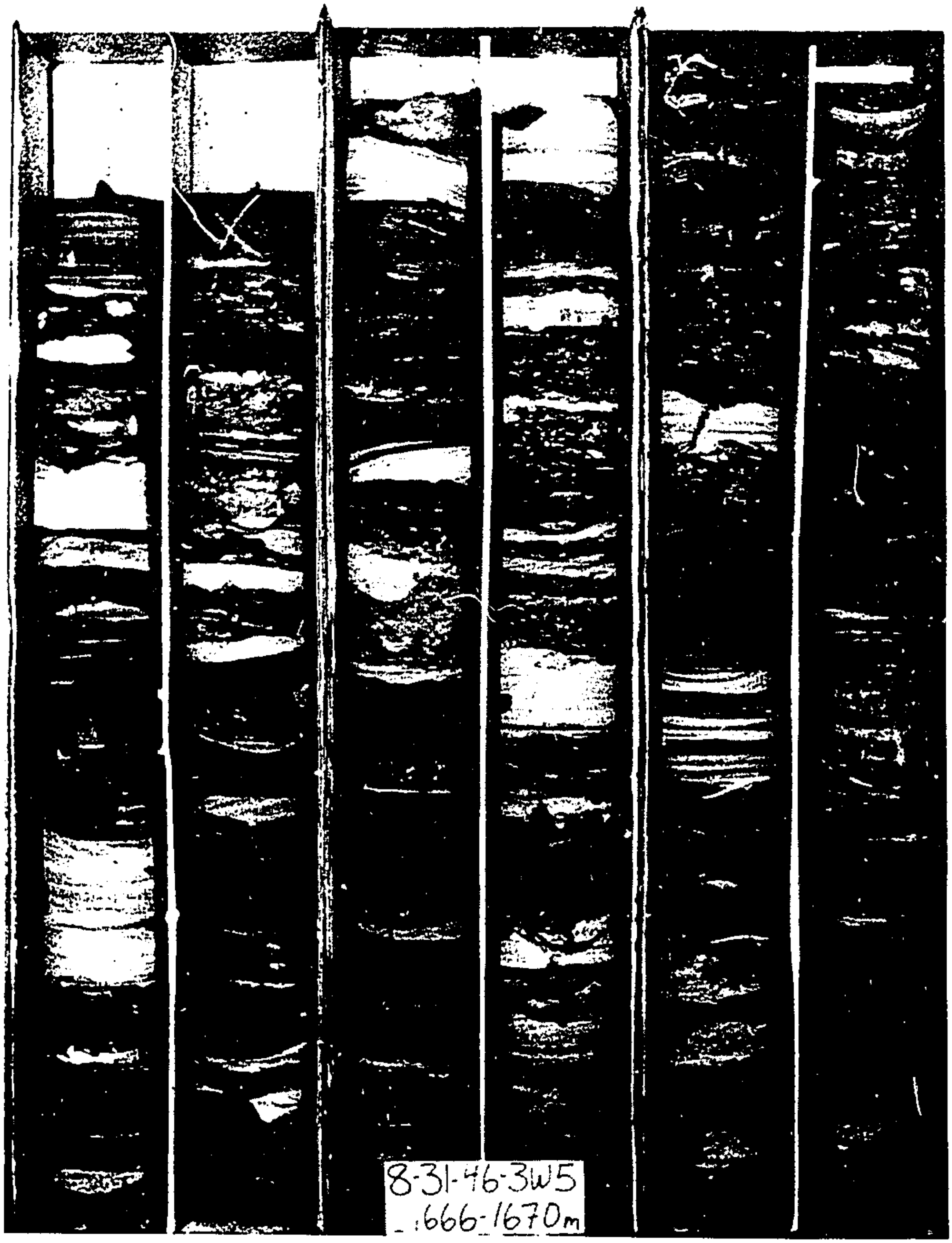
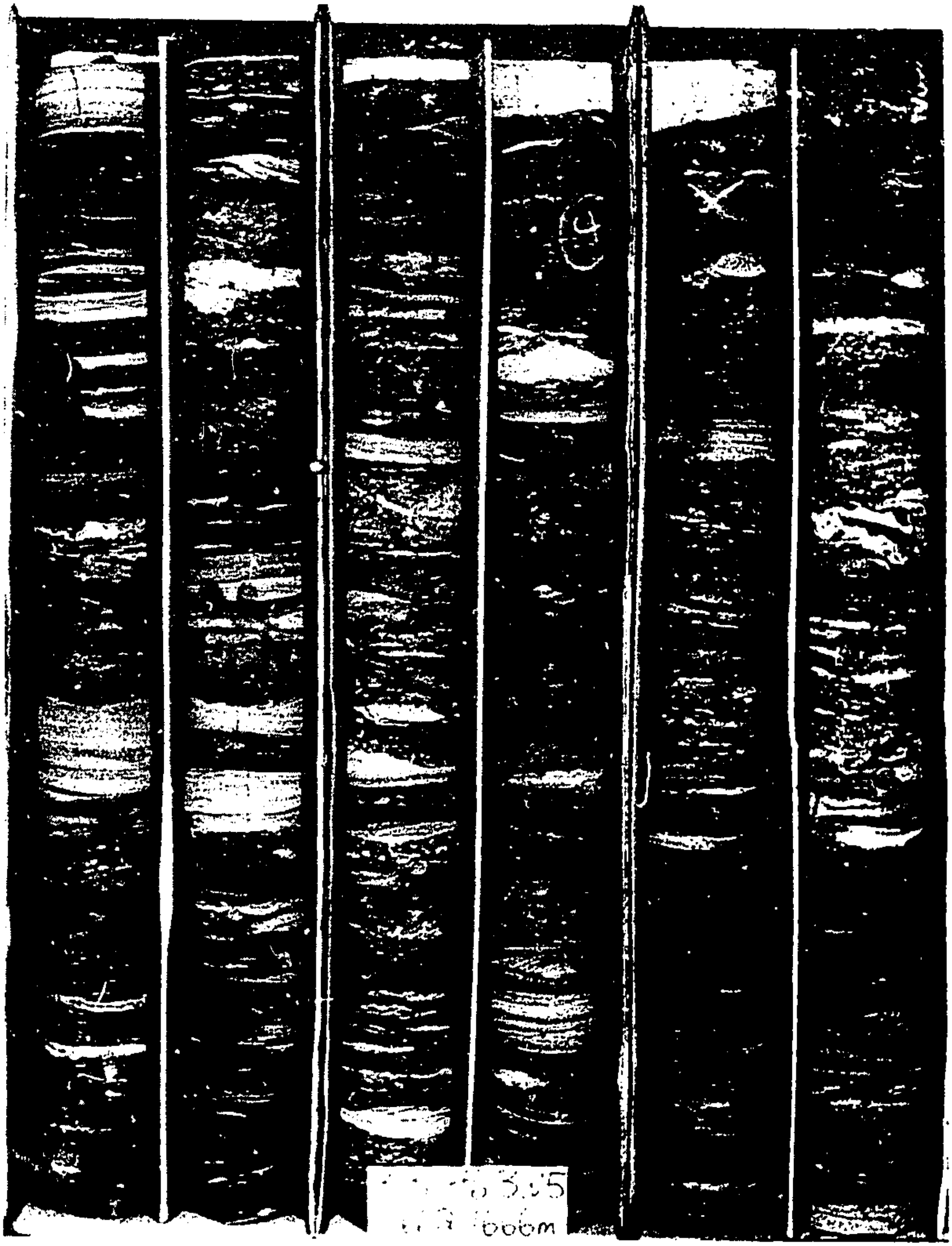


Figure 4.6. The following four pages show a complete set of core photographs for the type well (8-31-46-3W5) of facies association 2. Each core sleeve is approximately 75 cm long and the stratigraphic top is in the upper right corner of each photograph.

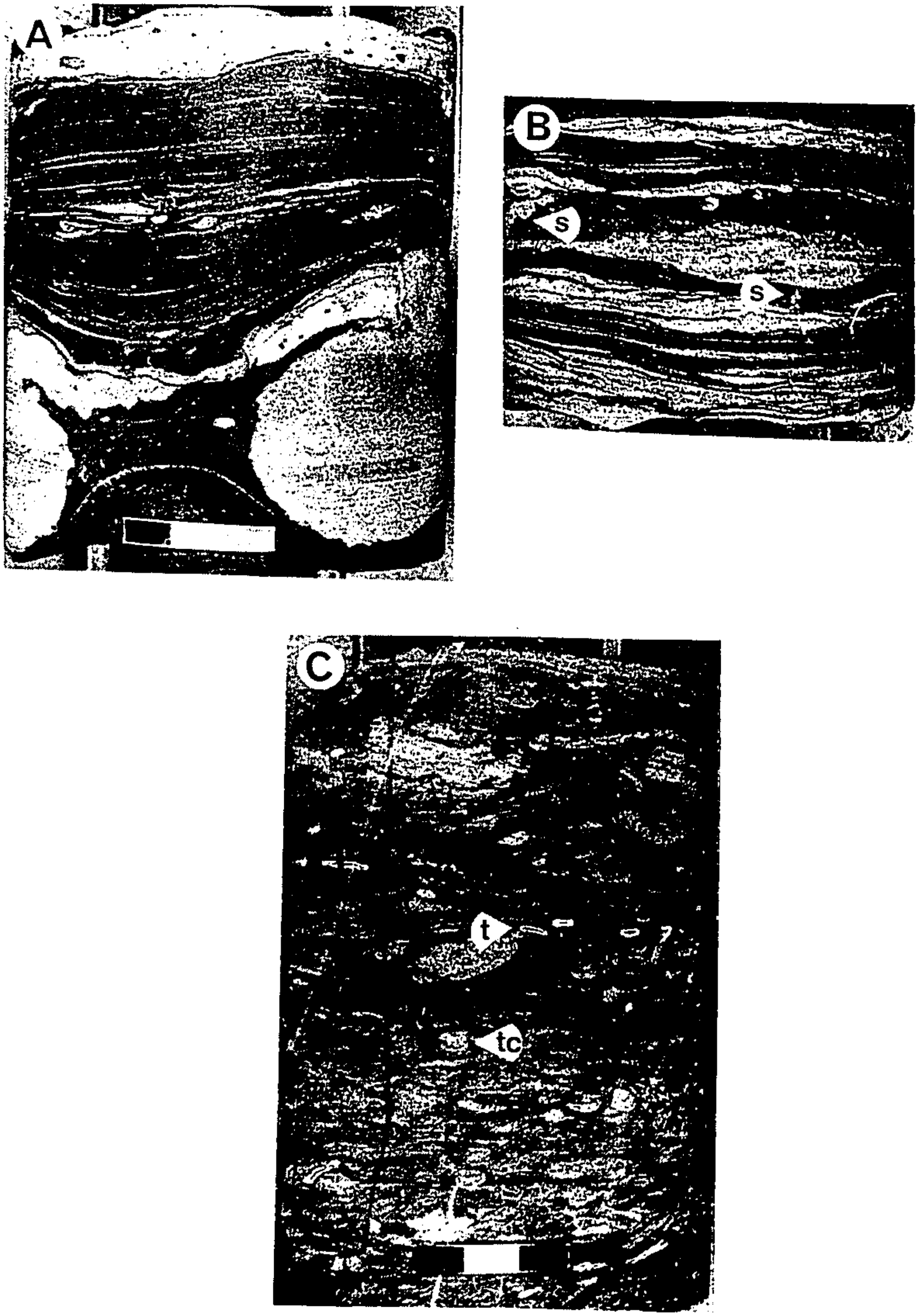



8-31-46-3W5
1666-1670m




VE3/4

Figure 4.7. The following two pages show core photographs of the sediments of facies association 2. Scale bars are 3 cm long. (A). Load-casted, interbedded sandstone and mudstone from 4-1-46-4W5 (1804 m). Note the deformation of the underlying laminae, just above the scale bar. (B). Synaeresis cracks (s) in interlaminated sandstone and mudstone from 8-26-45-4W5 (1832 m). (C). Typical ichnofacies of the moderately bioturbated mudstone facies from 14-19-46-3W5 (1708 m). Note the small and flattened Terebellina (t) and Teichichnus (tc) traces. (D). Two sharp based, planar (p) to ripple (r) cross laminated ("PR") sandstone beds from 8-31-46-3W5 (1667 m). These beds are normally graded, capped by mudstone laminae and are interpreted as waning flow deposits. (E). A thin, sharp based, massive conglomerate bed (arrow) from 14-19-46-3W5 (1709 m). Moderately bioturbated mudstone (bm) and dark mudstone (dm) interbeds are also observed.


A
B
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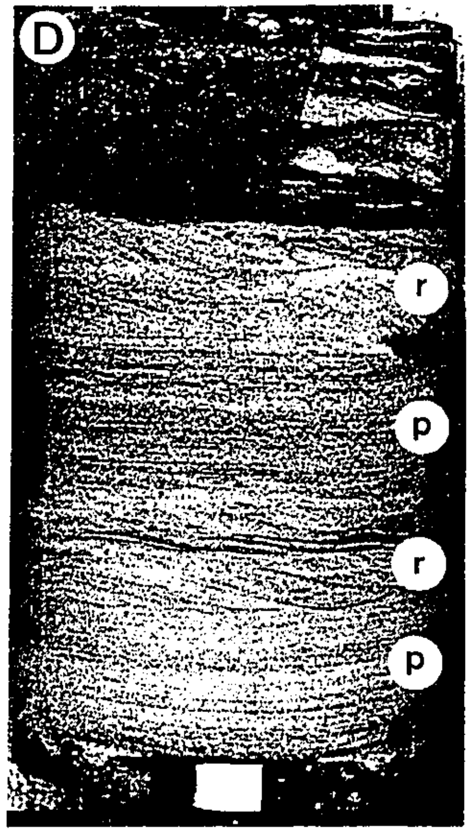
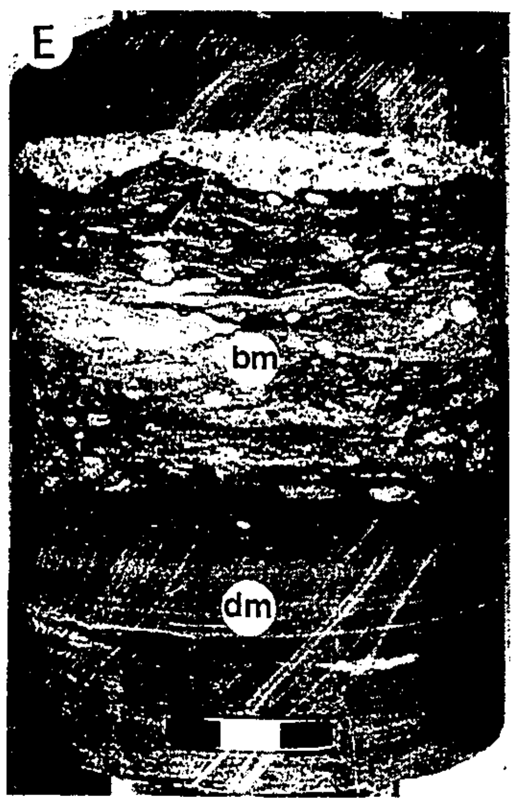
tc


D
r
p
r
p


E
bm
dm

The moderately bioturbated mudstone interbeds contain five to forty percent fine-grained sand which is scattered throughout the mudstone, but can also be concentrated in rare sharp based, current to wave rippled sandstone laminae that are 1-20 mm thick. These interbeds are 3-25 cm thick and have sharp contacts with the dark mudstone interbeds. The moderately bioturbated mudstone facies contains Teichichnus, small and flattened Terebellina, Planolites and Chondrites traces (Fig. 4.7C). The most abundant trace fossil is Teichichnus. These traces are typical of the Cruziana ichnofacies (Frey & Pemberton, 1984).

The sandstone interbeds consist of very fine- to fine-grained sand which is wave rippled, current rippled or planar laminated. Most of the sandstone interbeds have sharp bases, consist of planar to ripple cross laminated ("PR") sandstones, and are capped by dark mudstone laminae or very fine-grained, wave rippled sand (Fig. 4.7D). The "PR" beds are normally graded, 8-25 cm thick, and descriptively resemble the B and C divisions of the Bouma sequence for turbidites (Bouma, 1962).

In about ten percent of facies association 2 cores, matrix- to clast-supported, massive conglomerate beds are observed towards the base. These are sharp based, occur in beds 1-25 cm thick and are concentrated in the lower 4 m of facies association 2 (Fig. 4.7E).

In general, the dark mudstone and moderately bioturbated mudstone facies are most abundant in the central part of this association, while the sandstone facies are most abundant towards the base and the top of the association (Figs 4.5 & 4.6). Contacts between the facies are gradational to sharp.

Interpretation

The low to moderate degree of bioturbation, Cruziana ichnofacies, small size of Terebellina traces, low diversity of traces and abundance of mudstone suggest deposition in a low to moderate energy, restricted marine environment. Further support for this interpretation comes from the presence of synaeresis cracks at the base of some of the fine-grained sandstone beds. These cracks usually form by clay volume shrinkage resulting from the dewatering of clays or salinity changes in the water column (Collinson & Thompson, 1982). A restricted marine environment provides an ideal location for the latter process to occur.

In a larger context, the vertical facies succession goes from fining- to coarsening-upward, perhaps relecting a deepening event, followed by a shallowing event or a change in the sedimentation rate. In general, the sediments of facies association 2 are interpreted as low to moderate energy, restricted marine deposits that could have been deposited in an estuarine or bay environment.

4.3 Facies Association 3 - Bioturbated Muddy Sandstone

Facies association 3 consists of interbedded bioturbated sandstone, non-bioturbated sandstone, and interlaminated dark mudstone and fine-grained sandstone beds. The type well is located in the north part of the Crystal valley at 8-16-48-3W5 (Figs 4.8 & 4.9). Individual beds are 2-30 cm thick and they exhibit a wide range of grain sizes. This association varies in thickness from 2-22 m and usually forms an FU facies succession. However, some cores also show a CU succession, while other cores have both an FU and CU succession.

The bioturbated sandstone beds are moderately to thoroughly bioturbated, very fine- to medium-grained, moderately sorted and contain numerous trace fossils including Ophiomorpha (Fig. 4.10A), Paleophycus (Figs 4.10A & B), Planolites and Skolithos. These traces are typical of the Skolithos ichnofacies (Frey & Pemberton, 1984). Crude beds or lenses of sandstone are preserved in this facies, forming sharp based, elongate pods of sand that have bioturbated tops (Fig. 4.10A). Dark, convoluted mudstone laminae are also observed in this facies.

The non-bioturbated sandstone interbeds are sharp based, very fine- to medium-grained, moderately to well sorted and are ripple cross laminated, planar laminated or cross bedded. The planar and ripple cross laminated sandstone beds are the most common, while the cross bedded sandstone beds only occur in a few wells. Some of the sandstone beds exhibit normal grading and resemble the "PR" beds described in facies association 2 (Fig. 4.10C). The cross bedded sandstone beds are the coarsest deposits in facies association 3, and consist of medium-grained

Figure 4.8. Type well for facies association 3 from 8-16-48-3W5 (1513-1534 m), showing a FU to CU vertical facies succession. The corresponding resistivity and gamma-ray well logs, and the position of the core (black bar) are also shown. A complete set of core photographs are presented in Figure 4.9, while individual facies photographs are shown in Figure 4.10. O - *Ophiomorpha*, Pa - *Palaeophycus*, S - *Skolithos*, P - *Planolites*

Facies Association 3

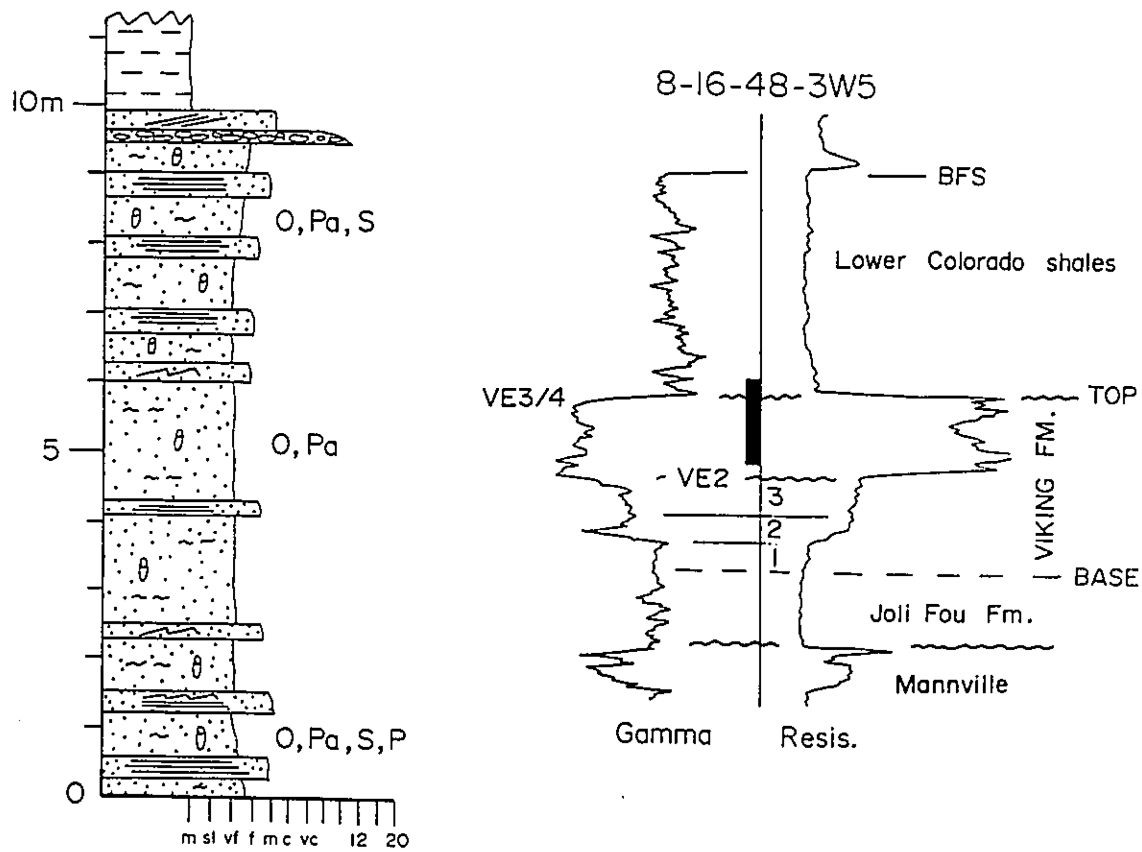
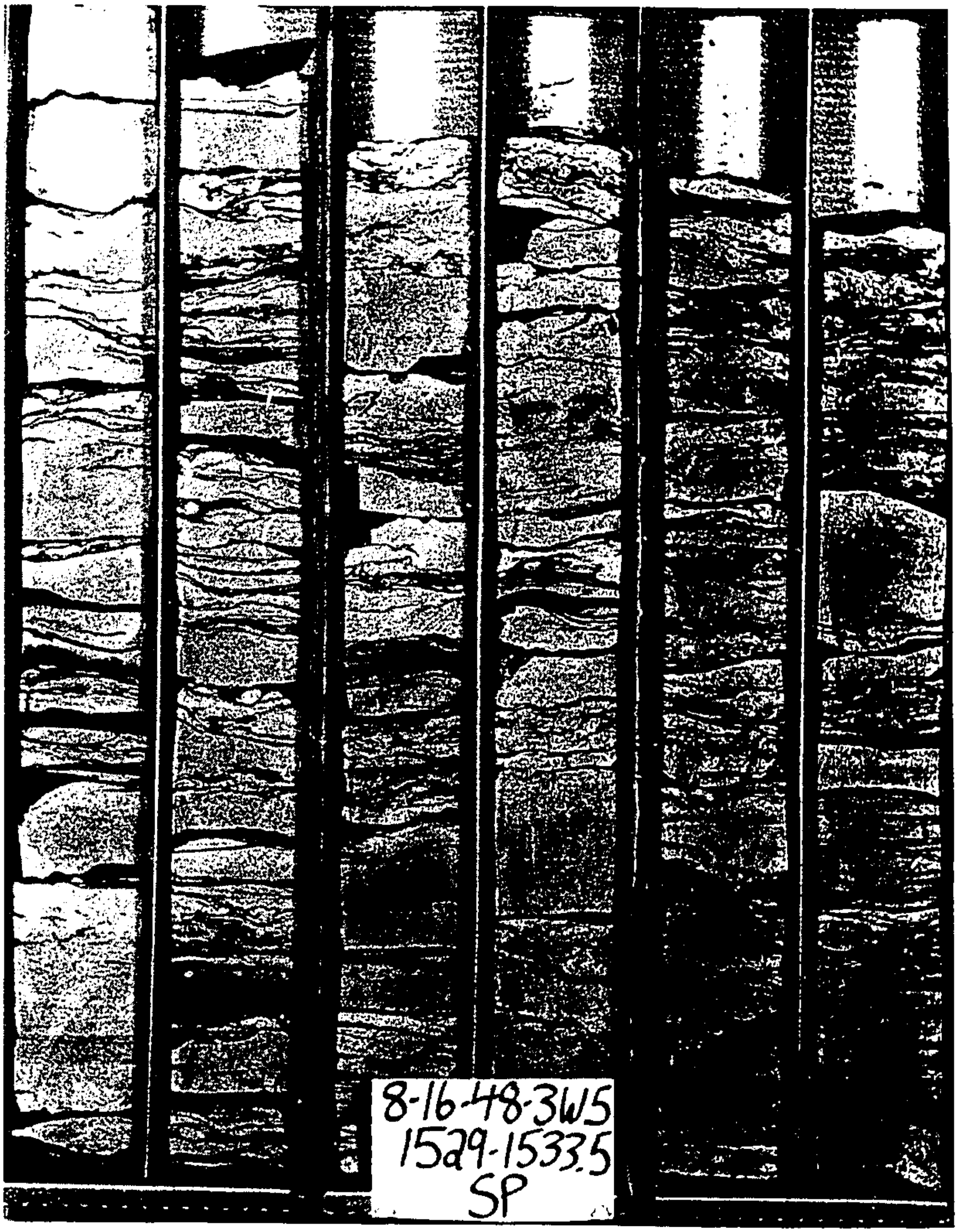
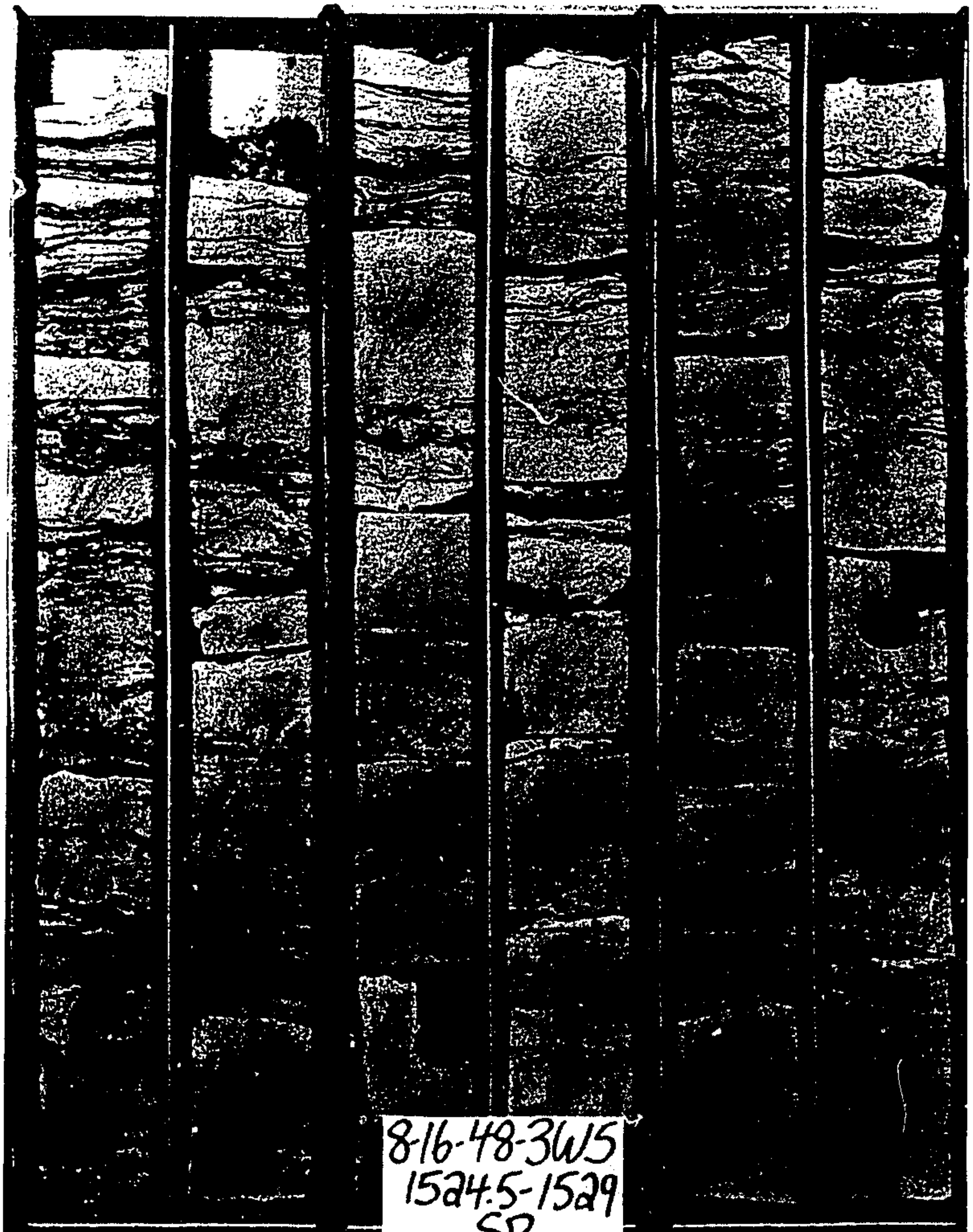


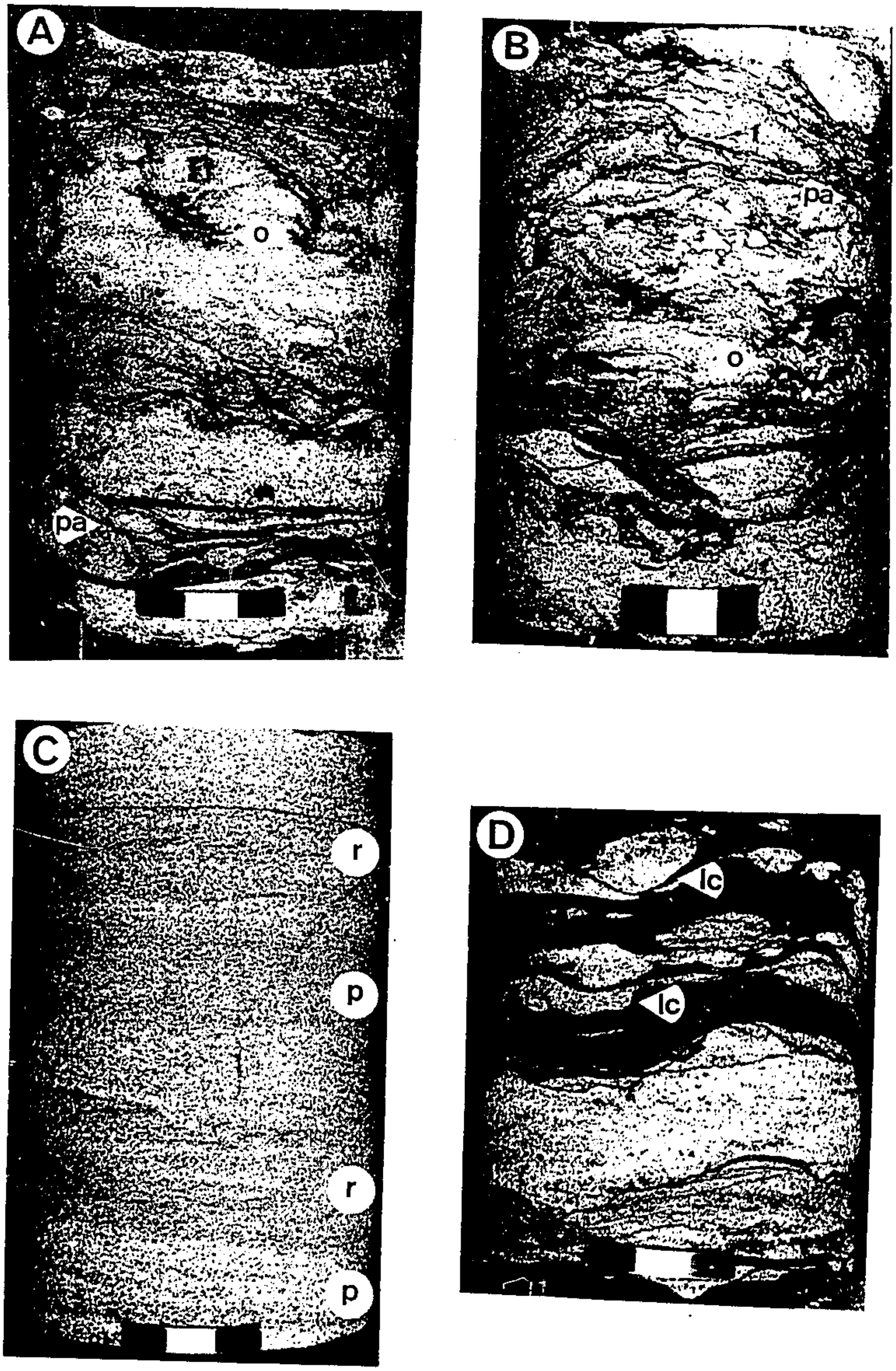
Figure 4.9. The following three pages show a complete set of core photographs for the type well (8-16-48-3W5) of facies association 3. Each core sleeve is approximately 75 cm long and the stratigraphic top is in the upper right corner of each photograph.


8-16-48-3W5
1529-1533.5
SP


8-16-48-3W5
1524.5-1529
SP


VE3/4
8-16-48

Figure 4.10. Sediments of facies association 3. Scale bars are 3 cm long. (A). Moderately to thoroughly bioturbated, muddy sandstone from 4-1-47-3W5 (1580 m). Note the crude beds or lenses of sandstone, interlaminated dark mudstone, Ophiomorpha (o) and Paleophycus (pa) traces. (B). Thoroughly bioturbated muddy sandstone from 5-18-46-3W5 (1692 m) showing Paleophycus (pa) and Ophiomorpha (o) traces. (C). "PR" sandstone beds from 8-32-47-3W5 (1570 m), showing sharp bases and planar (p) to ripple (r) cross laminations. (D). Interlaminated dark mudstone and fine-grained sandstone from 4-1-47-3W5 (1577 m). Note the load-casts (lc), delicate mudstone laminae and the sharp based sandstone beds.


A
o
pa
B
pa
o
C
r
p
r
p
D
lc
lc

sandstone, with some scattered granules and pebbles. The cross beds are uni- and bi-directional, and often have carbonaceous or mudstone laminae draping the foresets. These sediments are similar to the cross bedded sandstones described in facies association 6.

The interlaminated dark mudstone and fine-grained sandstone beds are the least abundant facies in this association. These deposits consist of mildly to moderately bioturbated, sharp based sandstone lenses or beds that are massive, current rippled or wave rippled (Fig. 4.10D). Some of the sandstone beds are loaded into the underlying mudstone, while others have synaeresis cracks at the base. The interlaminated mudstone is dark, often convoluted and contains rare Planolites and Chondrites trace fossils, typical of the Cruziana ichnofacies (Frey & Pemberton, 1984). Some of these mudstone laminae are sideritized (Fig. 4.9). This facies resembles the wavy and lenticular bedding described by Reineck and Wunderlich (1968).

Interpretation

The varying degree of bioturbation, synaeresis cracks, Skolithos and Cruziana ichnofacies, and abundance of sandstone suggest deposition in a moderate to high energy, marginal marine environment. The wavy and lenticular bedding, carbonaceous or mudstone drapes on cross beds and the presence of bi-directional cross bedding are all consistent with deposition in a tidally-influenced environment. The thoroughly bioturbated nature of some muddy sandstone beds, the presence of wave rippled sandstone beds, and the Skolithos ichnofacies are consistent with deposition in a wave-dominated, marine environment. The sharp based, "PR" sandstone beds imply that sand was periodically transported and deposited by waning currents, perhaps generated by storms or floods.

4.4 Facies Association 4 - Fine-Grained Sandstone

Facies association 4 consists of interbedded mildly to moderately bioturbated, muddy sandstone and non-bioturbated sandstone which forms an overall sandier-upward succession. The type well is located in the southern part of the Crystal valley at 16-24-45-4W5 (Figs 4.11 & 4.12).

The lower half of this association is dominated by muddy sandstone, while the upper half is dominated by cross bedded sandstone. A subtle increase in grain size also occurs upward, from fine-grained sand near the base, to medium-grained sand near the top. Also, the degree of bioturbation decreases upward. Most of the deposits are 5-20 m thick, and the maximum thickness is 27.4 m in 10-25-45-4W5.

The lower half of this association is characterized by a monotonous sequence of very fine- to fine-grained, muddy sandstone, which is interbedded with fine-grained, massive, planar laminated, ripple cross laminated or planar to ripple cross laminated ("PR") sandstone beds (Fig. 4.13A).

The muddy sandstone facies contains mildly to moderately undulating, thin (1-5 mm) mudstone laminae which

Figure 4.11. Type well for facies association 4 from 16-24-45-4W5 (1787-1809.5 m), showing a sandying-upward vertical facies succession. The corresponding resistivity and gamma-ray well logs, and the position of the core (black bar) are also shown. A complete set of core photographs are presented in Figure 4.12, while the individual facies photographs are presented in Figure 4.13. O - Ophiomorpha, Pa - Palaeophycus, S - Skolithos, Tc - Teichichnus

Facies Association 4

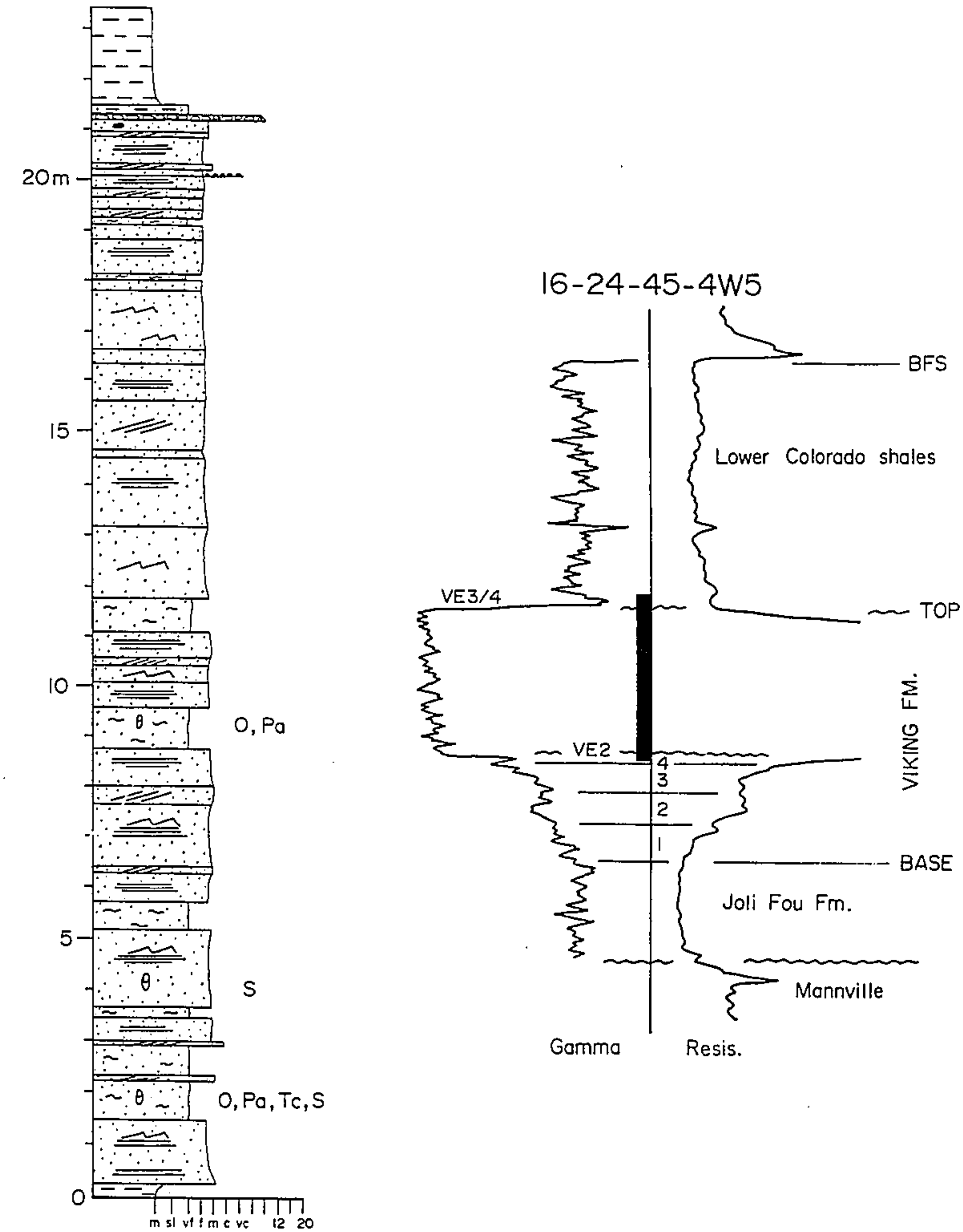
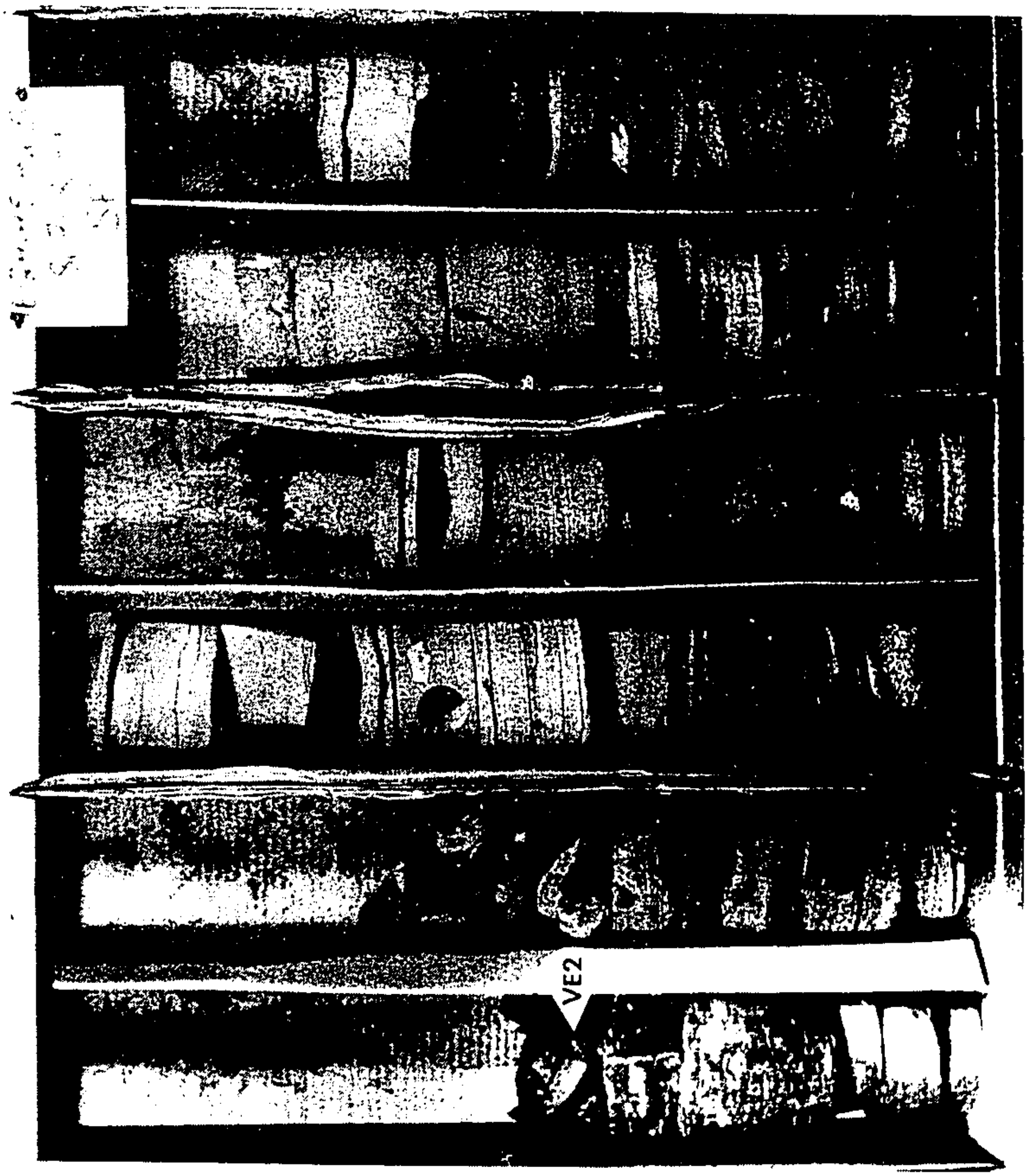
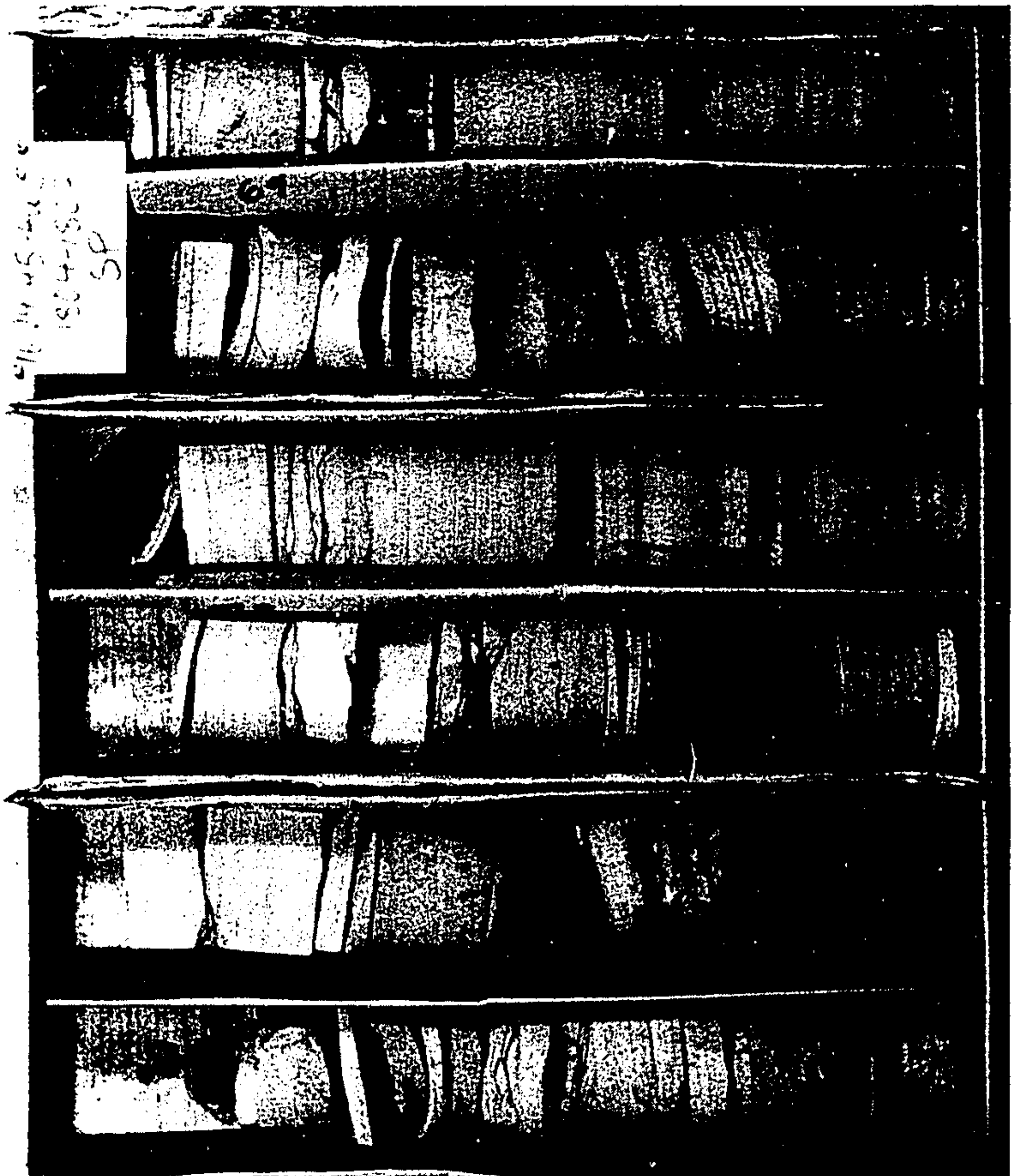
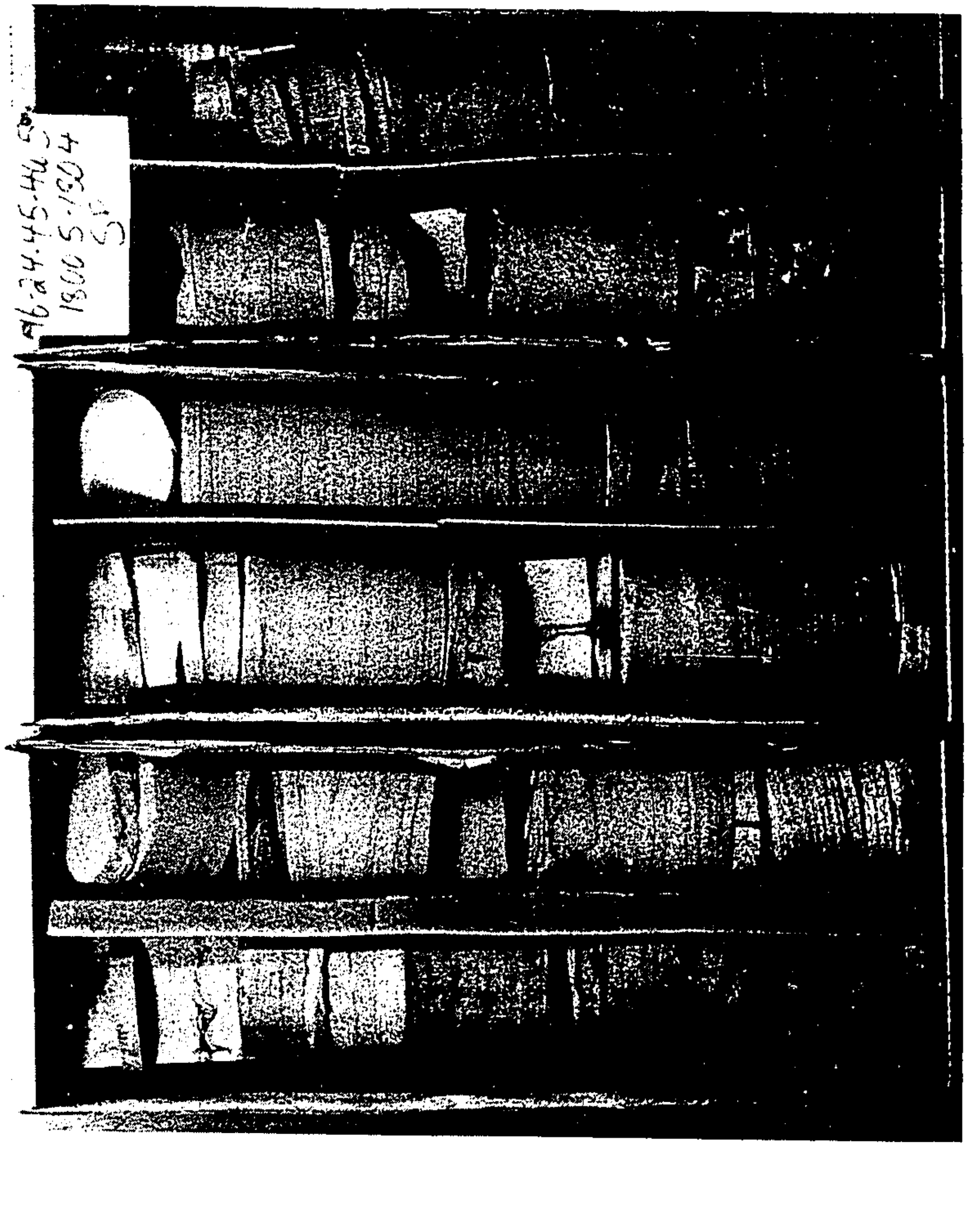
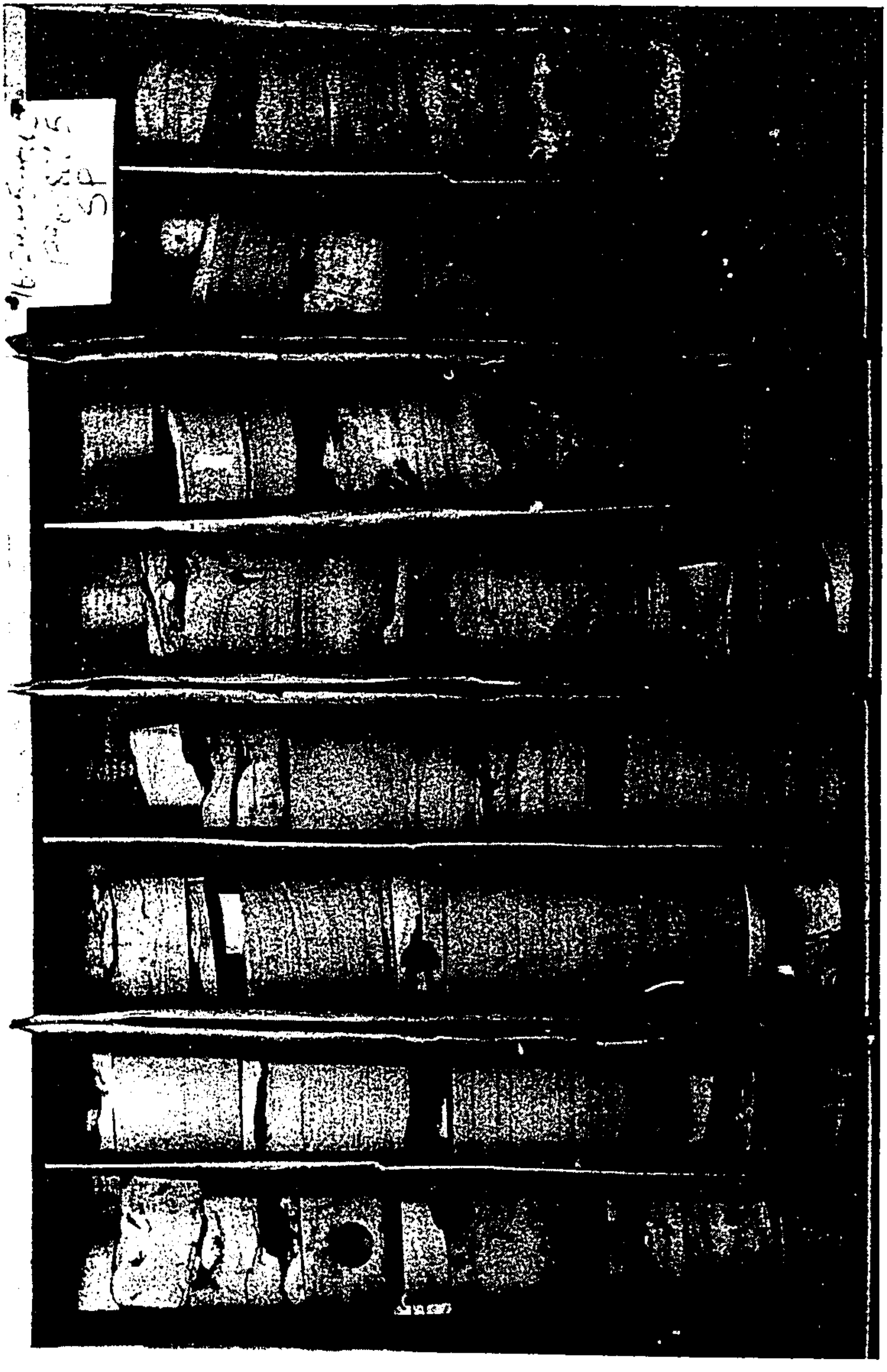


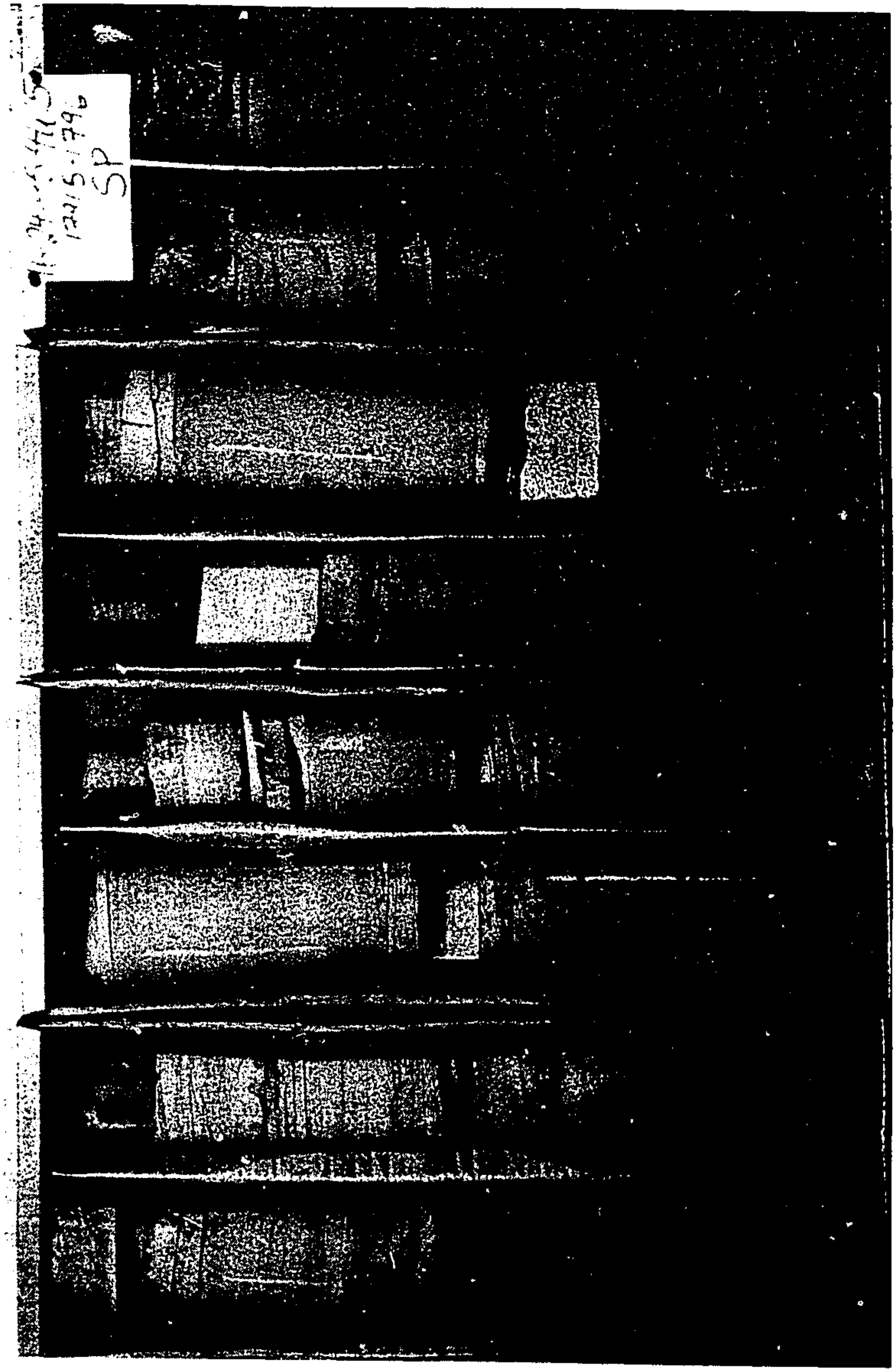
Figure 4.12. The following six pages show a complete set of core photographs for the type well (16-24-45-4W5) of facies association 4. Each core sleeve is approximately 60 cm long and the stratigraphic top is in the upper right corner of each photograph.


VE2









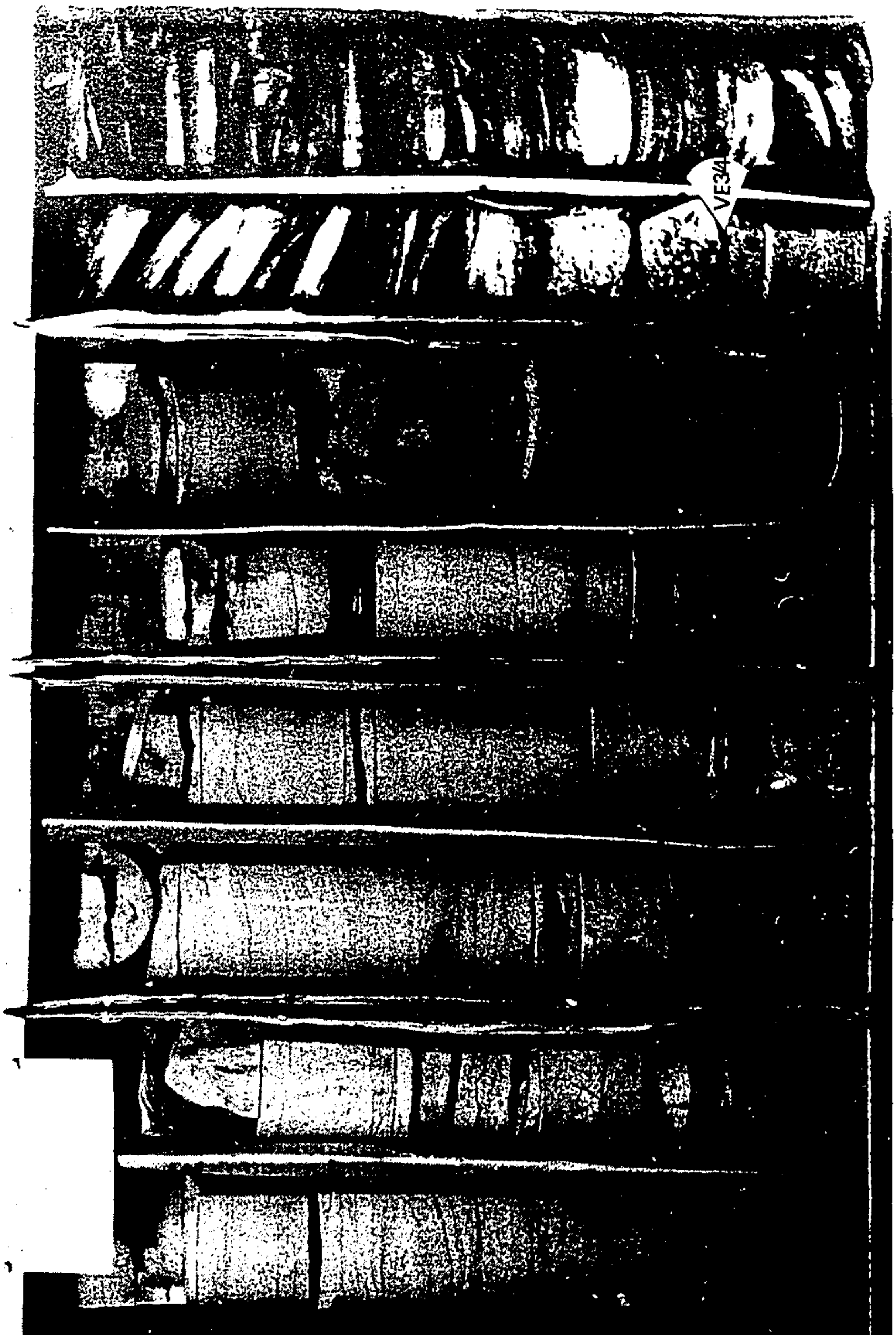
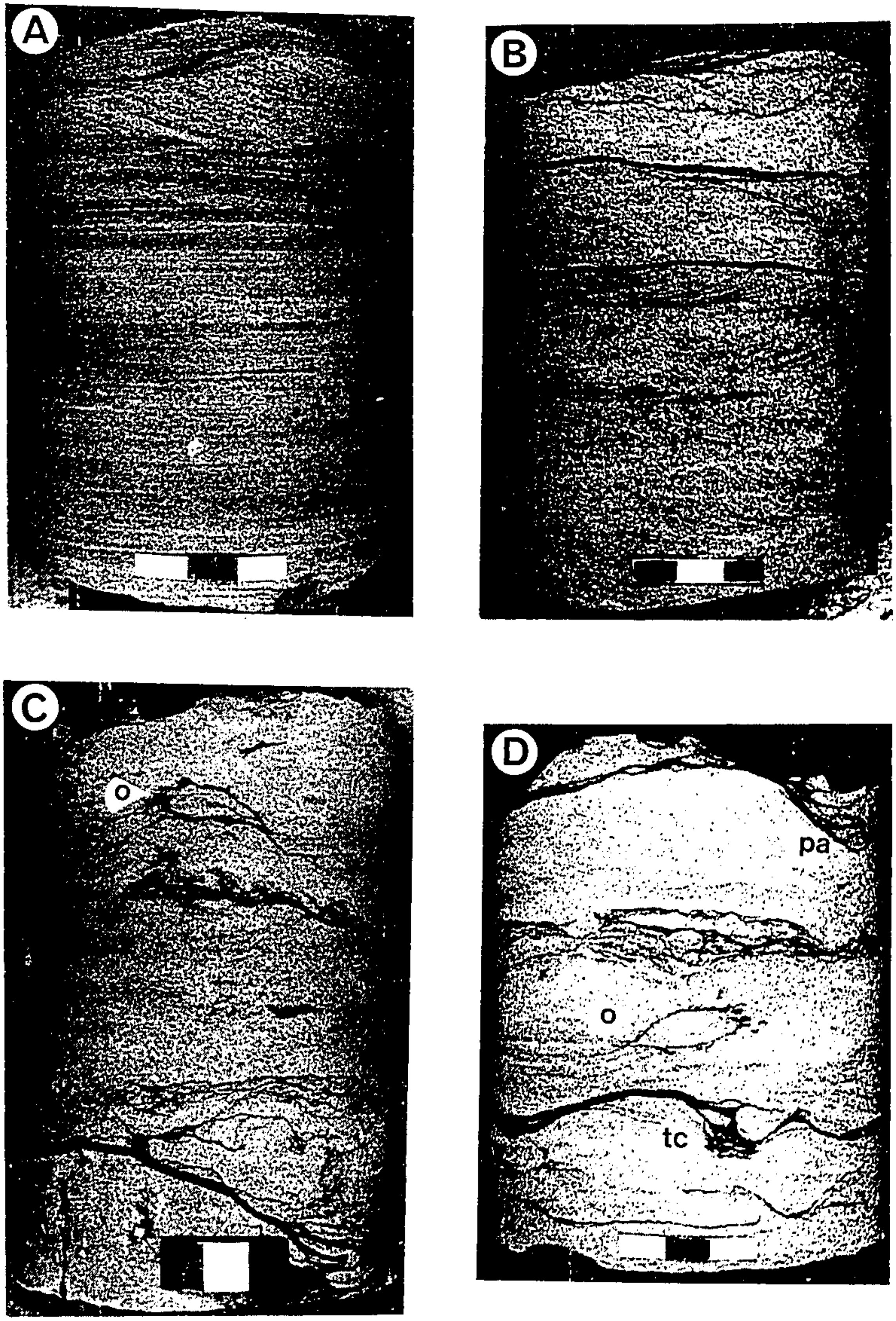

VE3/4

Figure 4.13. Sediments of facies association 4. Scale bars are 3 cm long. (A). Planar to ripple cross laminated ("PR") sandstone bed from 8-2-46-4W5 (1781 m). (B). Thin mudstone laminae draping ripple cross laminated sandstone in 4-1-46-4W5 (1791.5 m). (C). Muddy sandstone facies from 6-12-46-4W5 (1723 m). Note the randomly distributed mudstone laminae and the *Ophiomorpha* (o) trace fossil. (D). Muddy sandstone facies from 16-26-45-4W5 (1830 m) with *Ophiomorpha* (o), *Teichichnus* (tc) and *Paleophycus* (pa) traces.


A
B
C
o
D
pa
o
tc

impart a "wispy" or "lacy" appearance to these sediments. The mudstone laminae may drape bedforms (Fig. 4.13B), may occur apparently randomly (Fig. 4.13C), or may outline Ophiomorpha burrows (Figs 4.13C & D). They constitute approximately five percent of the facies volume. The muddy sandstone interbeds are mildly to moderately bioturbated and the most common traces are Ophiomorpha, Skolithos, Teichichnus and Paleophycos (Fig. 4.13D); rarely observed traces include Macaronichnus, Arenicolites, Conichnus, Cylindrichnus, Planolites and Diplocraterion. Most of these traces belong to the Skolithos ichnofacies (Frey & Pemberton, 1984). Muddy sandstone interbeds are 5-120 cm thick, have gradational contacts with the surrounding facies and are most abundant in the lower half of facies association 4 (forty to sixty percent by volume).

In contrast, the upper half of this association is characterized by interbedded massive, planar laminated, ripple cross laminated, cross bedded and muddy sandstone (Figs 4.11 & 4.12). Most of these facies consist of fine-grained sand and form beds that are 10-150 cm thick. Contacts between the facies are gradational.

Cross bedded sandstone is the dominant facies in the extreme upper part of facies association 4. These beds consist of medium-grained sand, occur in sets that are 10-20 cm thick, are uni-directional and contain rare sideritized mudstone clasts (1-5cm) and pebbles. The laminae dip at 10-25°.

Interpretation

The low degree of bioturbation, Skolithos ichnofacies, abundance of fine-grained sandstone and presence of mudstone laminae suggest deposition in a moderate energy, marginal marine environment. The fine-grained nature and abundance of mudstone in the lower half of the succession suggest a relatively low to moderate energy environment. The mudstone laminae were probably deposited out of suspension during periods of quiescence. Their abundance and thinness suggest frequent oscillations in the energy of the environment. These oscillations are also expressed by the sharp based, normally graded, "PR" beds that are interpreted as waning flow deposits produced during flood or storm conditions.

In contrast, the upper part of the succession is coarser grained, less bioturbated and has thicker sandstone beds, which indicate deposition in a moderate to high energy environment. The cross bedded sandstone beds indicate the presence of relatively strong, uni-directional currents that were capable of forming small scale dunes or sand waves. The sandier-upward nature of the succession suggests that the environment of deposition is becoming shallower upward.

4.5 Facies Association 5 - Interbedded Sandstones

Facies association 5 consists of interbedded sandstones with minor amounts of conglomerate and dark mudstone. The type well is located in the central part of the Crystal valley at 11-12-46-4W5 (Figs 4.14 & 4.15).

Six facies are present in this association including

Figure 4.14. Type well for facies association 5 from 11-12-46-4W5 (1710.5-1733 m) showing a FU vertical facies succession. The corresponding resistivity and gamma-ray well logs, and the position of the core (black bar) are also shown. A complete set of core photographs for the type well are presented in Figure 4.15, while individual facies photographs are presented in Figure 4.16. Tc - Teichichnus, Pa - Palaeophycus, O - Ophiomorpha, S - Skolithos, P - Planolites

Facies Association 5

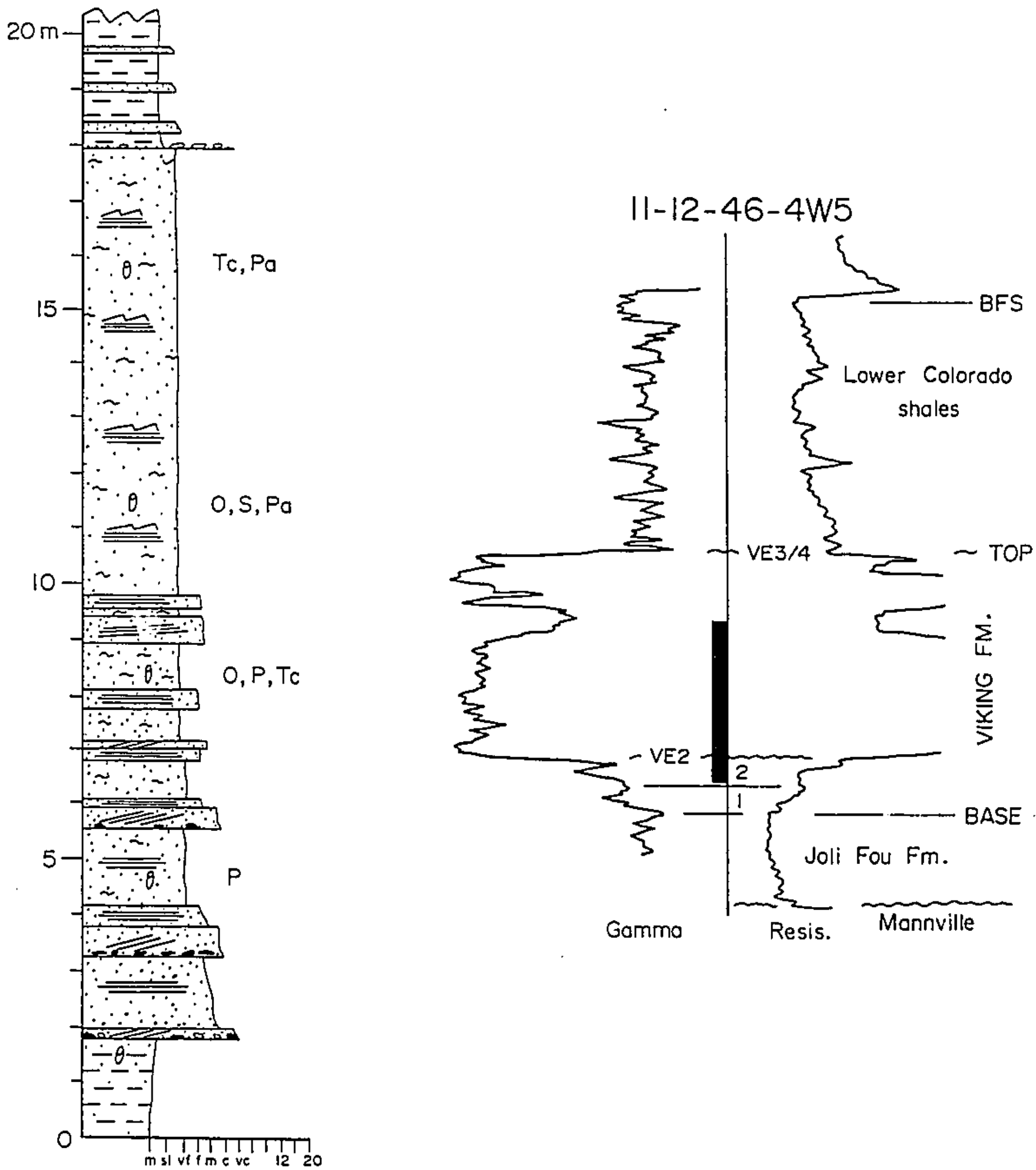
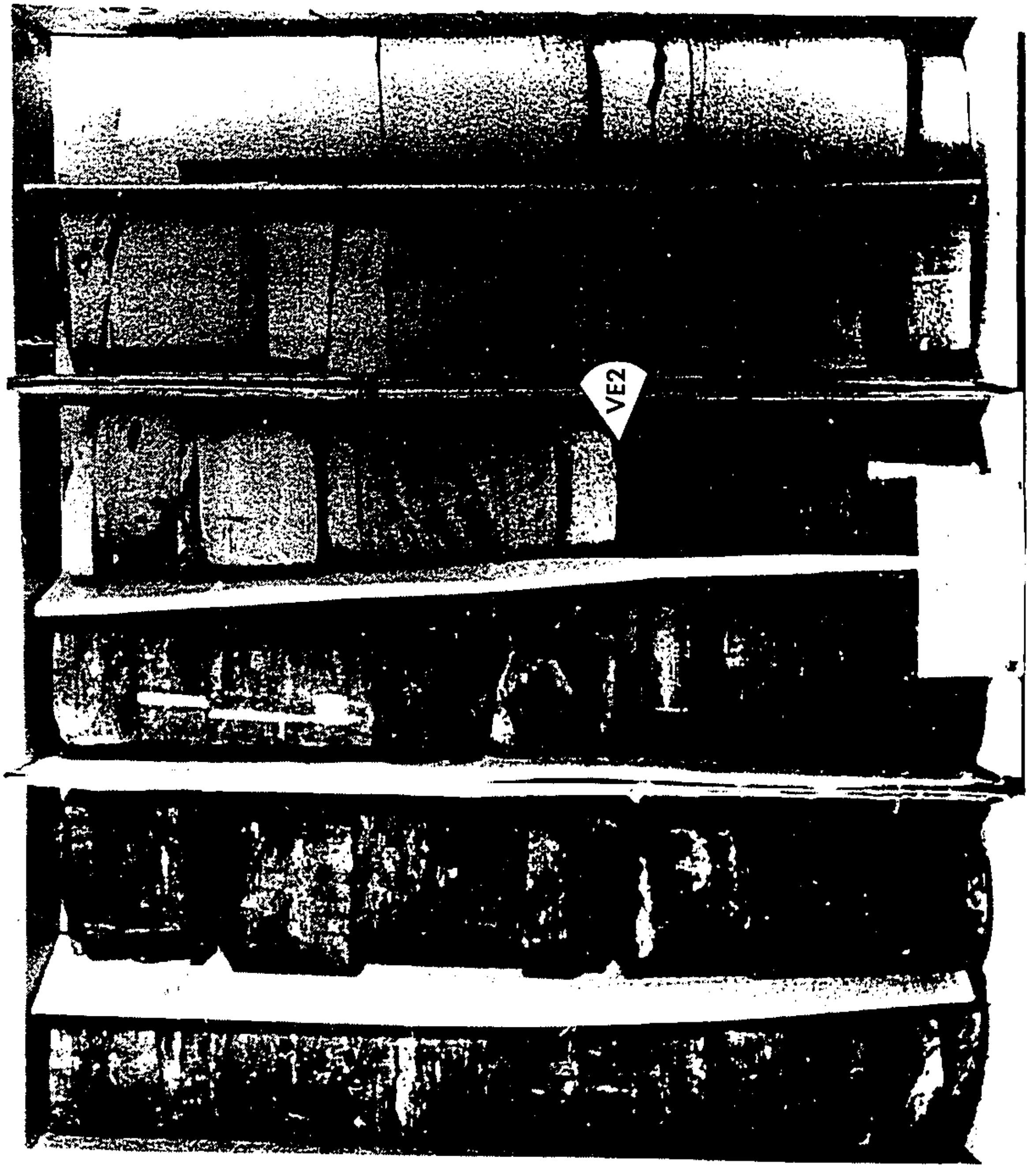
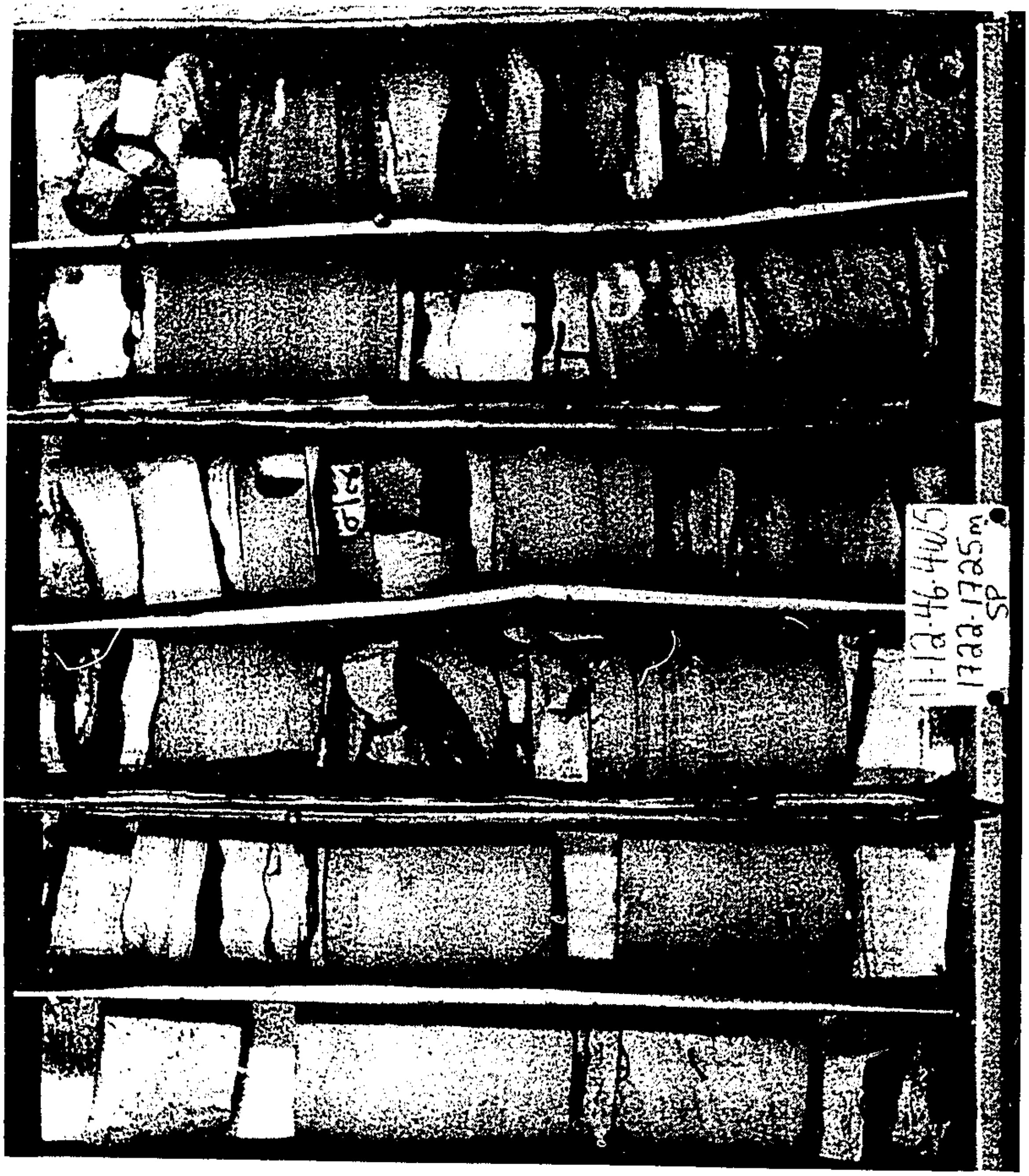
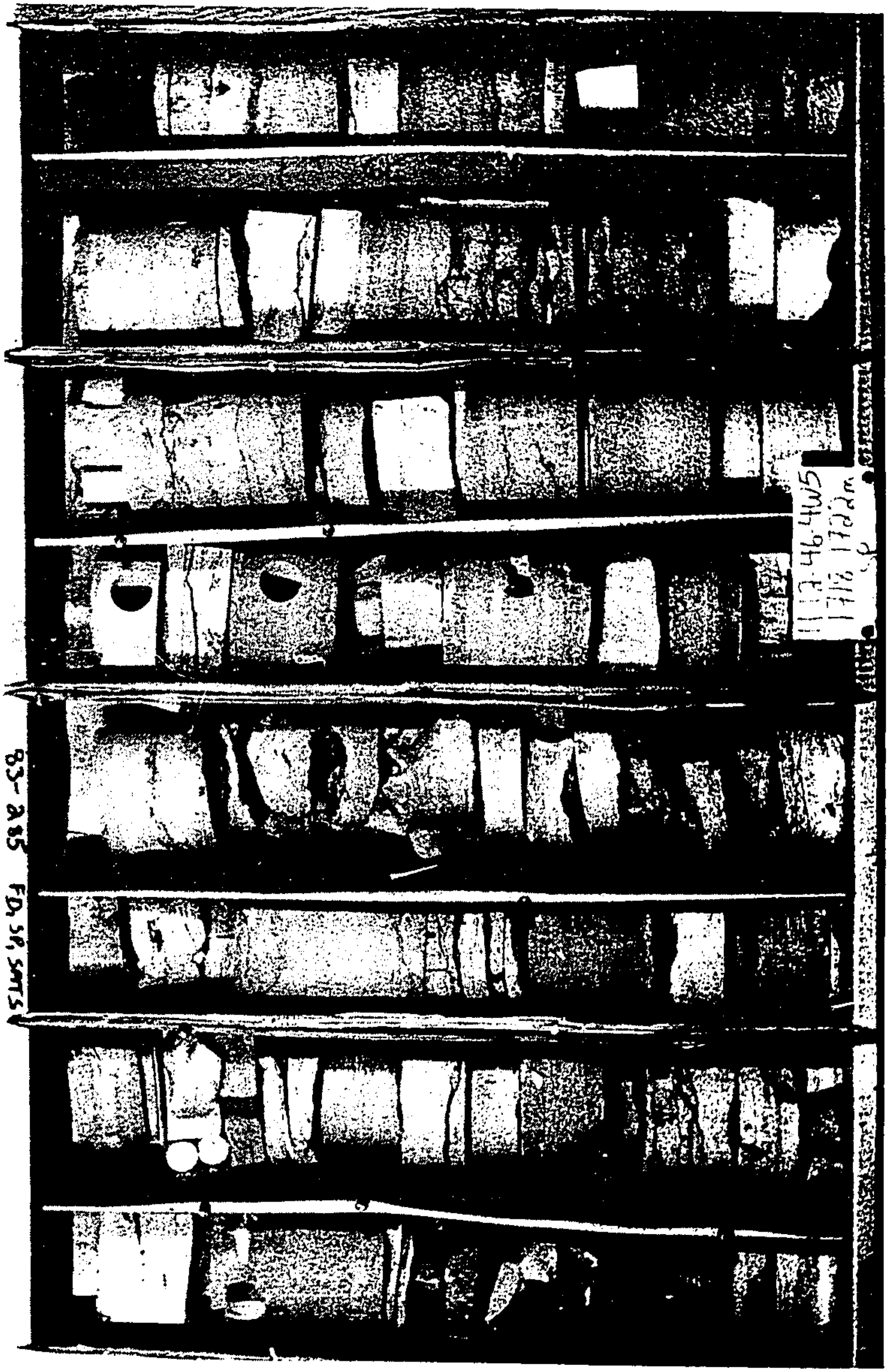
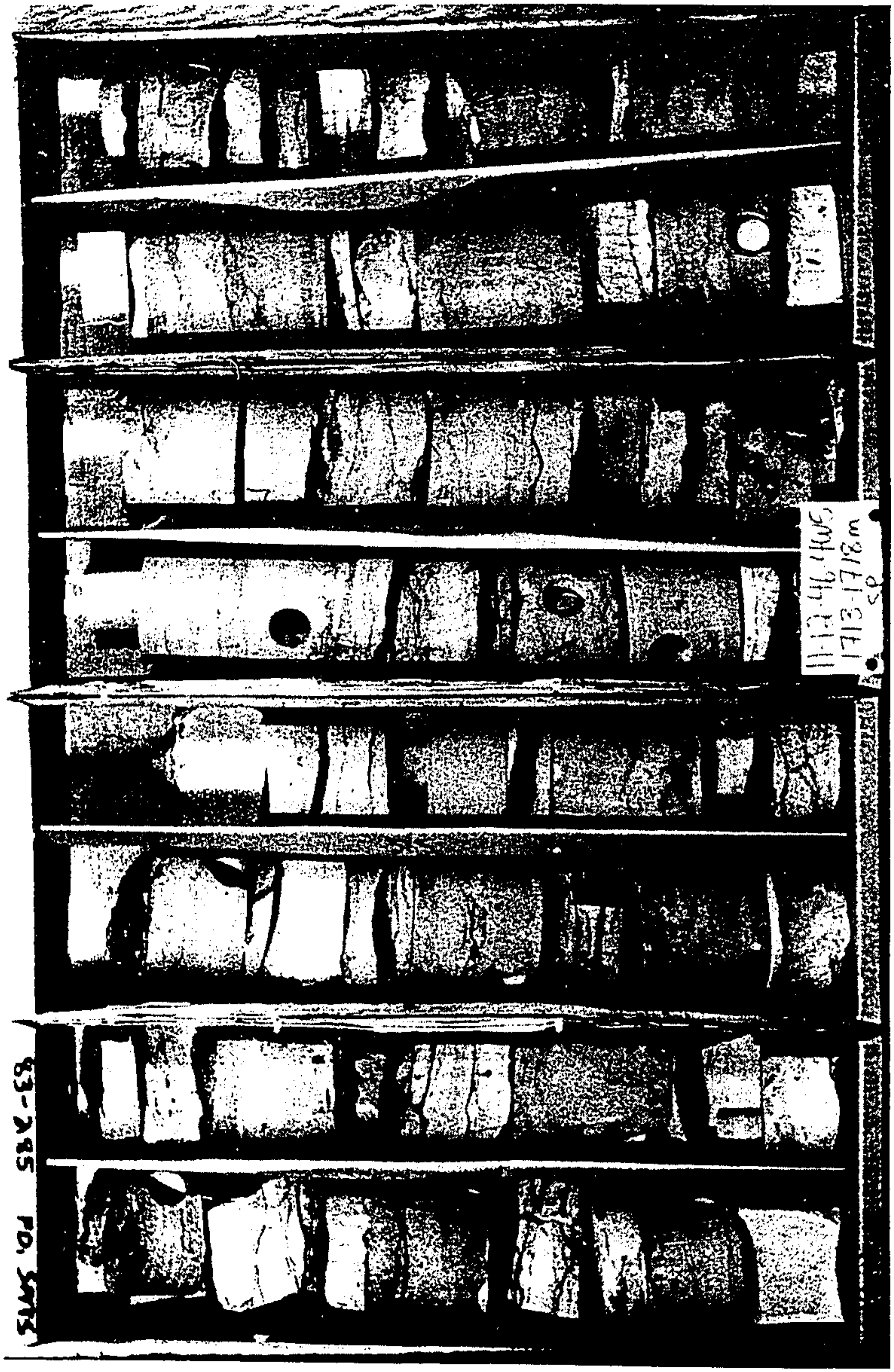


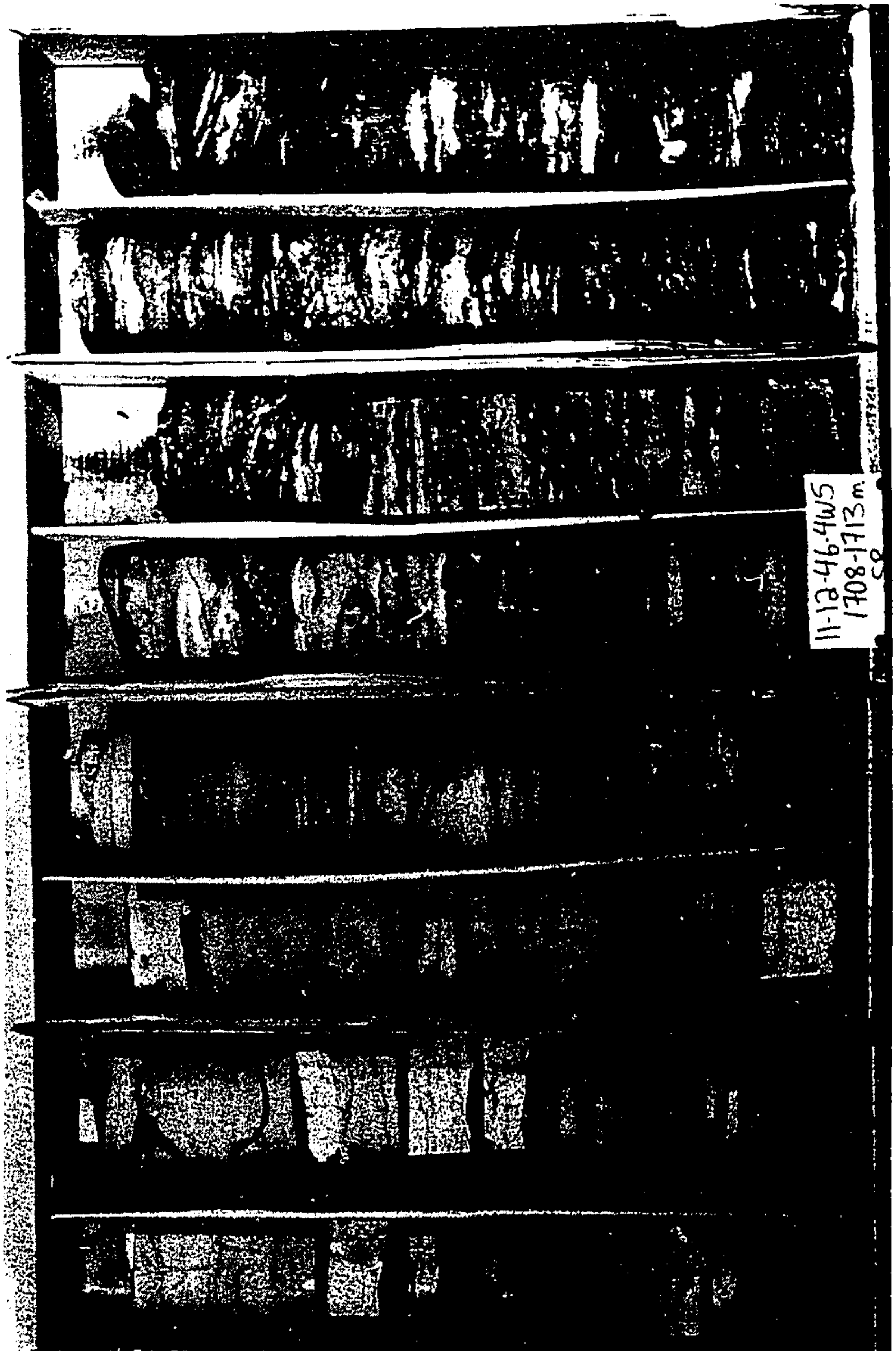
Figure 4.15. The following five pages contain a complete set of core photographs for the type well (11-12-46-4W5) of facies association 5. Each core sleeve is approximately 60 cm long and the stratigraphic top is located in the upper right corner of each photograph.


VE2


11-12-46-4W5
1722-1725m
SP


83-285 FD, SP, SMTS


11-13-46-14W5
1713-1718m
SP


11-12-46-4W5
1708-1713m

cross bedded sandstone, ripple cross laminated sandstone, planar laminated sandstone, massive sandstone, muddy sandstone and muddy conglomerate. The sediments of this association become finer grained upward, are 3-18 m thick and are only observed in the Crystal valley-fill.

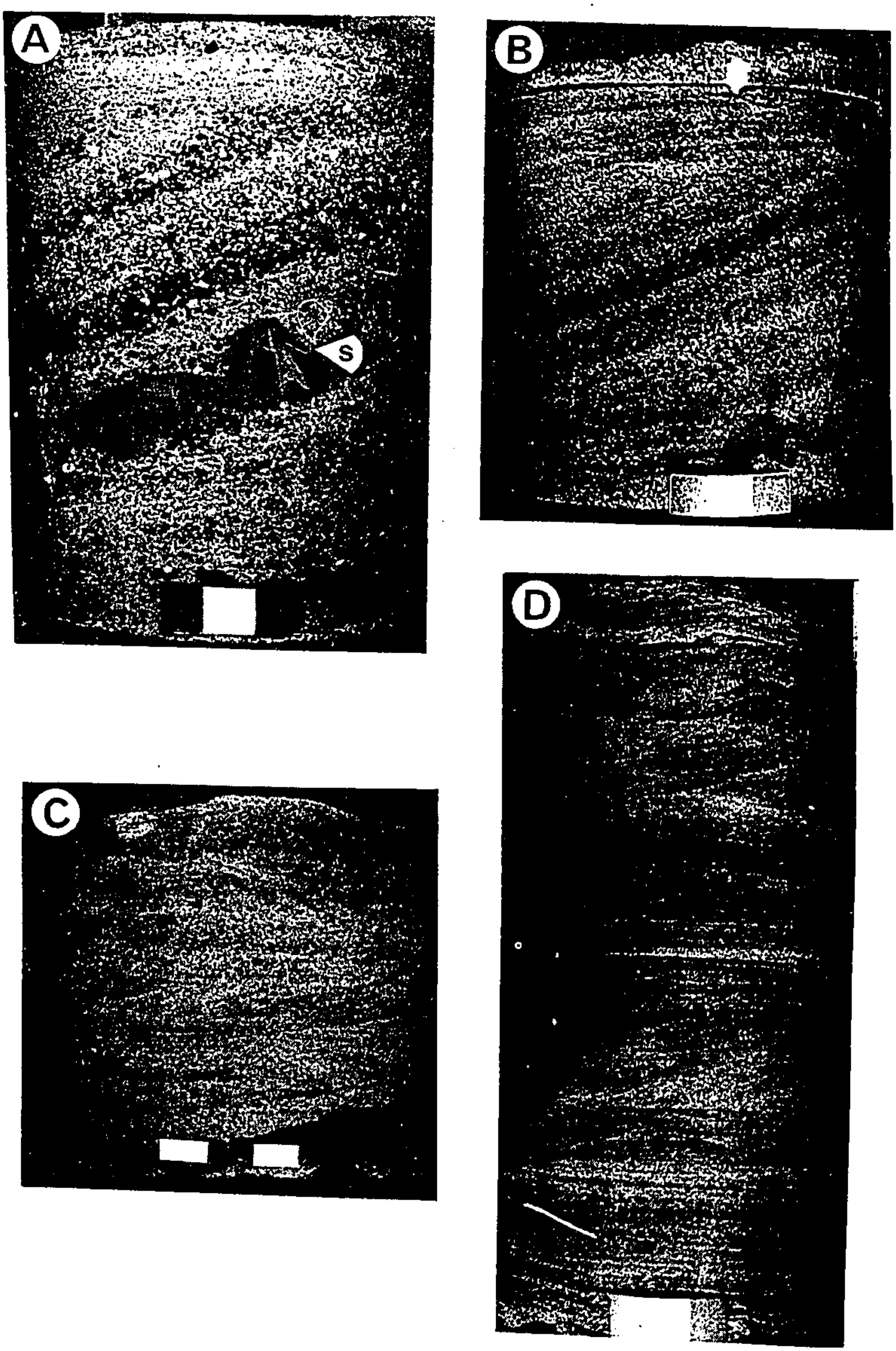
In general, the lower part of facies association 5 is dominated by FU successions, while the upper part is dominated by muddy sandstone. The FU successions are sharp based, 0.4-3.5 m thick and have a basal lag of mudstone clasts, coarse-grained sand and granules (Figs 4.14 & 4.16A). Cross bedded (Fig. 4.16B) or massive sandstone occurs at the base of most successions, planar or ripple cross laminated sandstones occur in the central part and muddy sandstones occur at the top. Grain size decreases upward from medium- to coarse-grained sandstone at the base, to very fine- or fine-grained sandstone at the top. Trace fossils are rare.

The coarsest and thickest FU successions are located towards the base of facies association 5. In the central part of the association the FU successions are relatively fine-grained, thin and contain no cross beds at the base.

Contacts between adjacent FU successions are sharp, while the contacts between the facies within a single FU succession are gradational. The number of FU successions in facies association 5 varies from 1 to 8, with an average of 3.

The upper part of this association consists mainly of

Figure 4.16. Sediments of facies association 5. Scale bars are 3 cm long. (A). Coarse-grained, cross bedded sandstone from 11-12-46-4W5 (1727 m). Note the sideritized (s) mudstone clasts and the scattered pebbles. (B). Medium-grained, cross bedded sandstone from 10-6-46-3W5 (1744 m). (C). Fine-grained, ripple cross laminated sandstone from 12-1-46-4W5 (1753 m). (D). Planar to ripple cross laminated sandstone beds from 8-26-45-4W5 (1822 m). Mudstone laminae drape the ripple cross laminated sandstone in the upper part of the photograph.


A
S
B
C
D

muddy sandstone that is interbedded with minor amounts of planar laminated and ripple cross laminated sandstone. These sediments are moderately bioturbated and show an increase in the degree of bioturbation and the percentage of mud upward. The muddy sandstone beds contain about five percent mudstone which occurs as thin, undulating laminae that drapes sandstone beds, outlines Ophiomorpha burrows (Figs 4.13 C & D) or is randomly distributed. Other trace fossils observed include Skolithos, Planolites, Paleophycos, Teichichnus, Arenicolites, Conichnus and Macaronichnus. These traces are typical of the Cruziana and Skolithos ichnofacies (Frey & Pemberton, 1984).

The planar and ripple cross laminated sandstone ("PR") occur in beds that are 4-15 cm thick, sharp based with bioturbated tops and are very fine- to fine-grained (Fig. 4.16C). Ripple cross laminae commonly overlie planar laminae in individual ("PR") beds which are capped by thin mudstone laminae (Fig. 4.16D). The "PR" beds were previously described in facies associations 2, 3 and 4 (Figs 4.7D, 4.10C & 4.13A).

In the extreme upper part of facies association 5, pebble stringers and muddy conglomerate beds are interbedded with the muddy sandstone. The conglomerate beds are sharp based, massive or cross bedded, 1-25 cm thick, matrix-supported (mudstone) and contain mudstone intra-clasts. The interbedded horizon is 5-200 cm thick and forms a gradational upper contact with the overlying dark mudstones of facies association 2.

Interpretation

The low to moderate degree of bioturbation, low number of individual traces in the lower part of the association, presence of Skolithos and Cruziana ichnofacies in the upper part and the abundance of sand suggest deposition in a moderate to high energy, marginal marine environment. Overall, the sediments become finer grained and more bioturbated upward which suggests a relative deepening of the water column.

4.6 Facies Association 6 - Cross Bedded Sandstone

Facies association 6 consists of cross bedded sandstone which is interbedded with planar laminated, massive and muddy sandstone. Trace amounts of matrix-supported, massive conglomerate are also observed. The type well is located in the central part of the Crystal valley at 12-20-46-3W5 (Figs 4.17 & 4.18).

In general, facies association 6 becomes finer grained upward and varies in thickness from 2-16 m. Vertical contacts between the facies are gradational.

Cross bedded sandstones constitute about sixty to seventy percent of the volume of this association. They are fine- to very coarse-grained, poorly to well sorted, 0.1-3.0 m thick and the laminae dip from 5-30°. Some beds contain granules, pebbles and mudstone clasts. The mudstone clasts are angular to well rounded, 1-60 mm in diameter and consist of dark bioturbated mudstone; some are sideritized.

Figure 4.17. Type well for facies association 6 from 12-20-46-3W5 (1717-1735 m) showing the vertical facies succession. The corresponding resistivity and gamma-ray well logs, and the position of the core (black bar) are also shown. A complete set of core photographs is presented in Figure 4.18, while individual facies photographs are shown in Figure 4.19. R - Rosselia, S - Skolithos, O - Ophiomorpha, P - Planolites

Facies Association 6

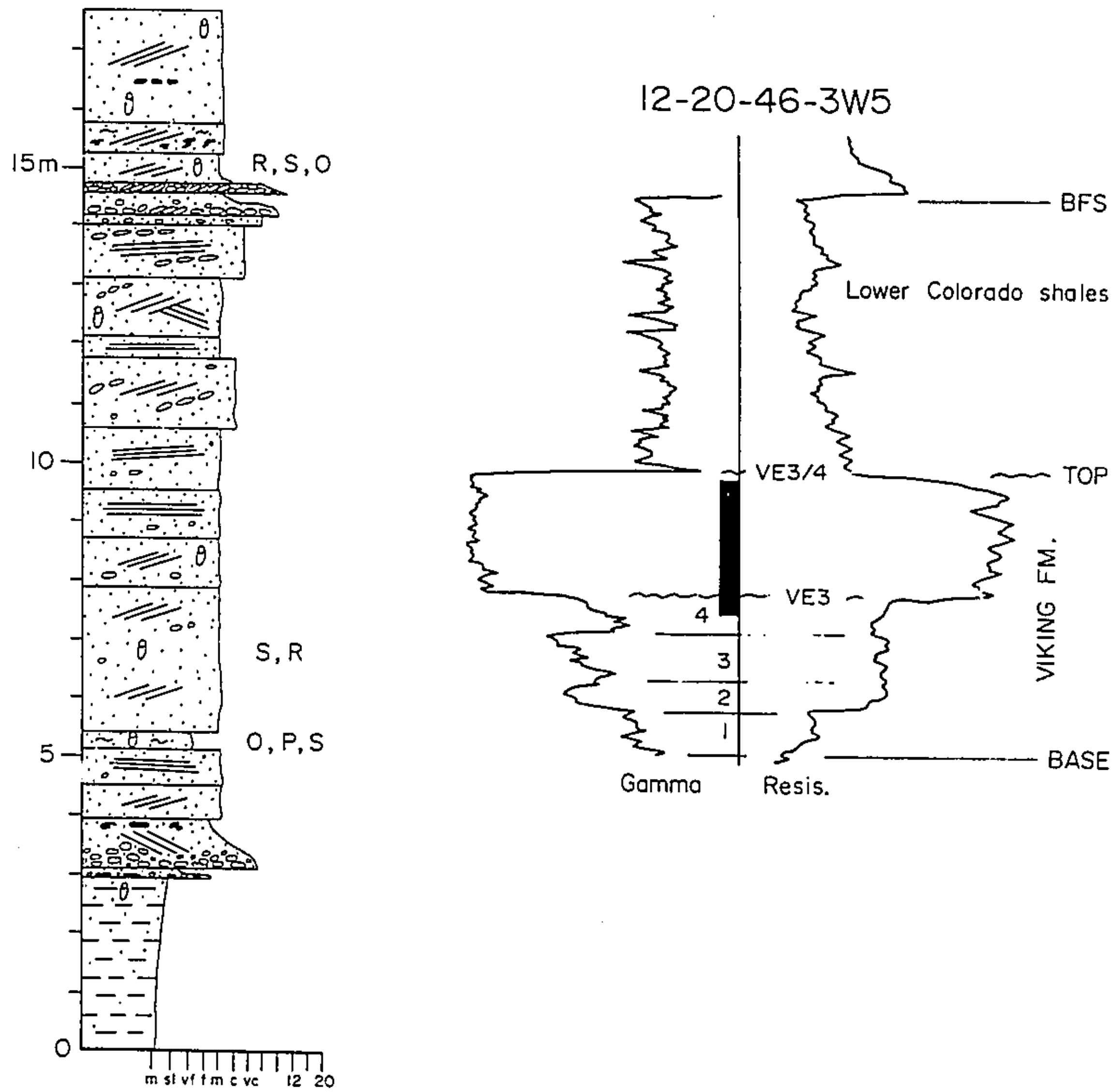
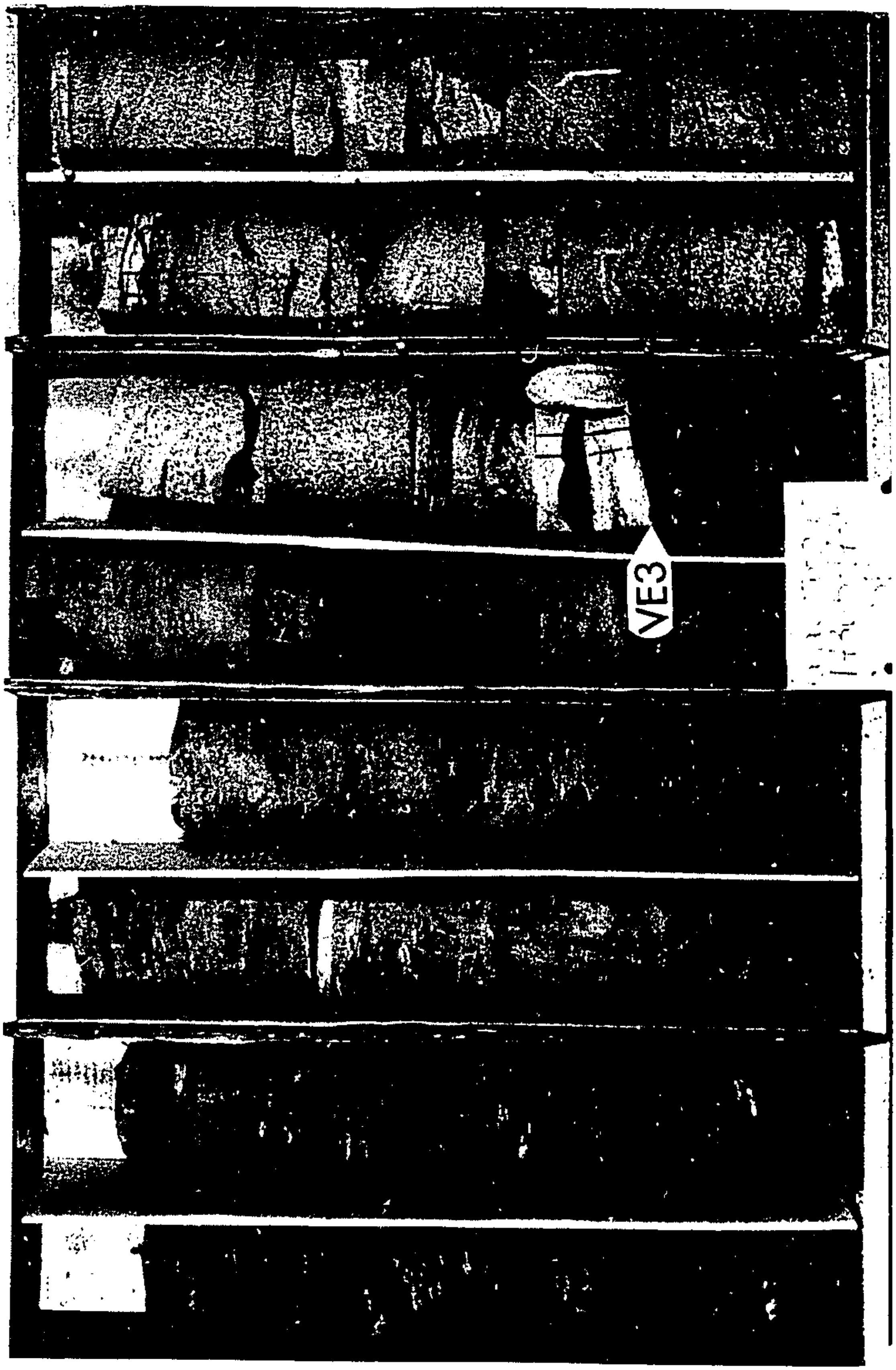
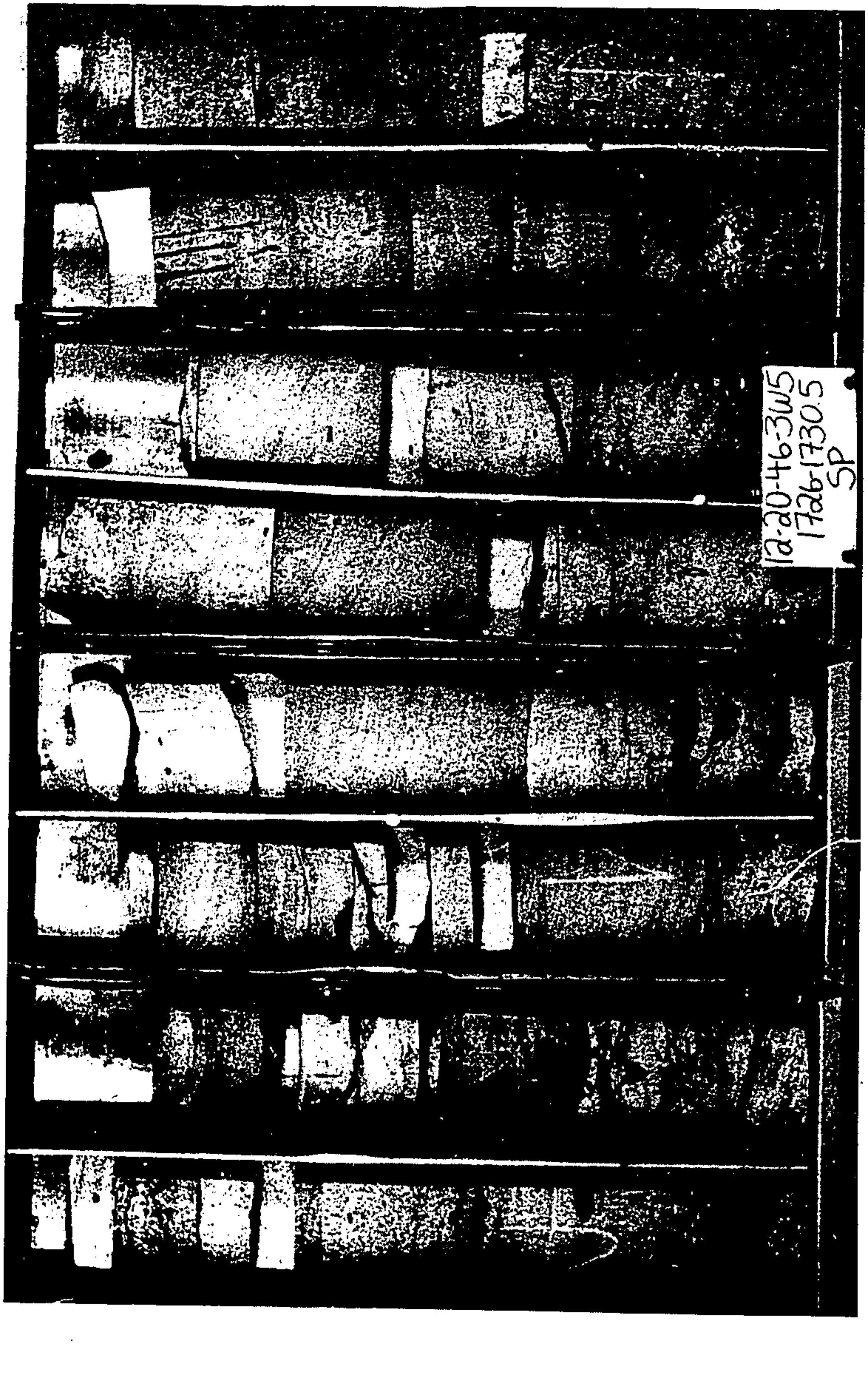
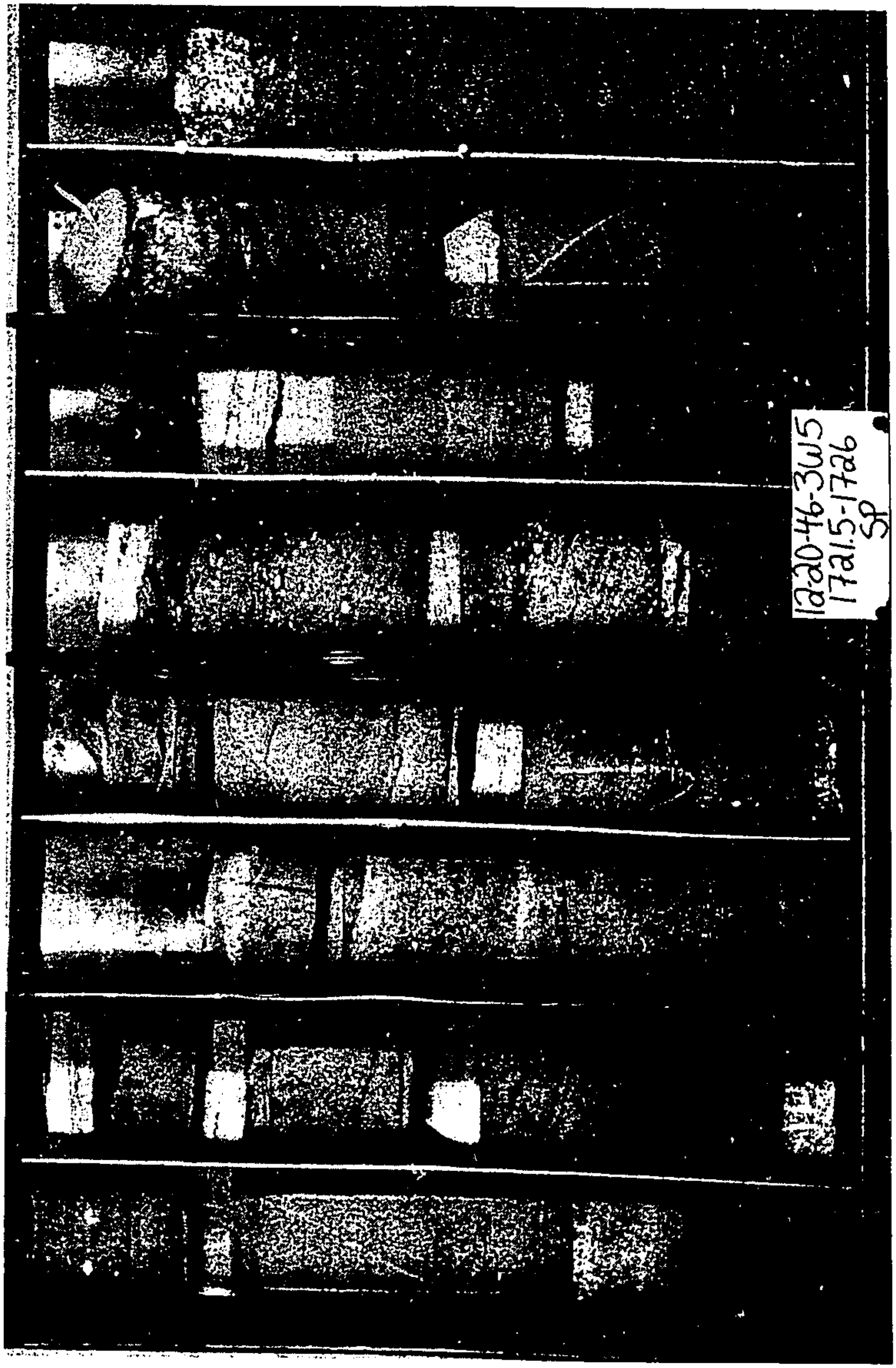
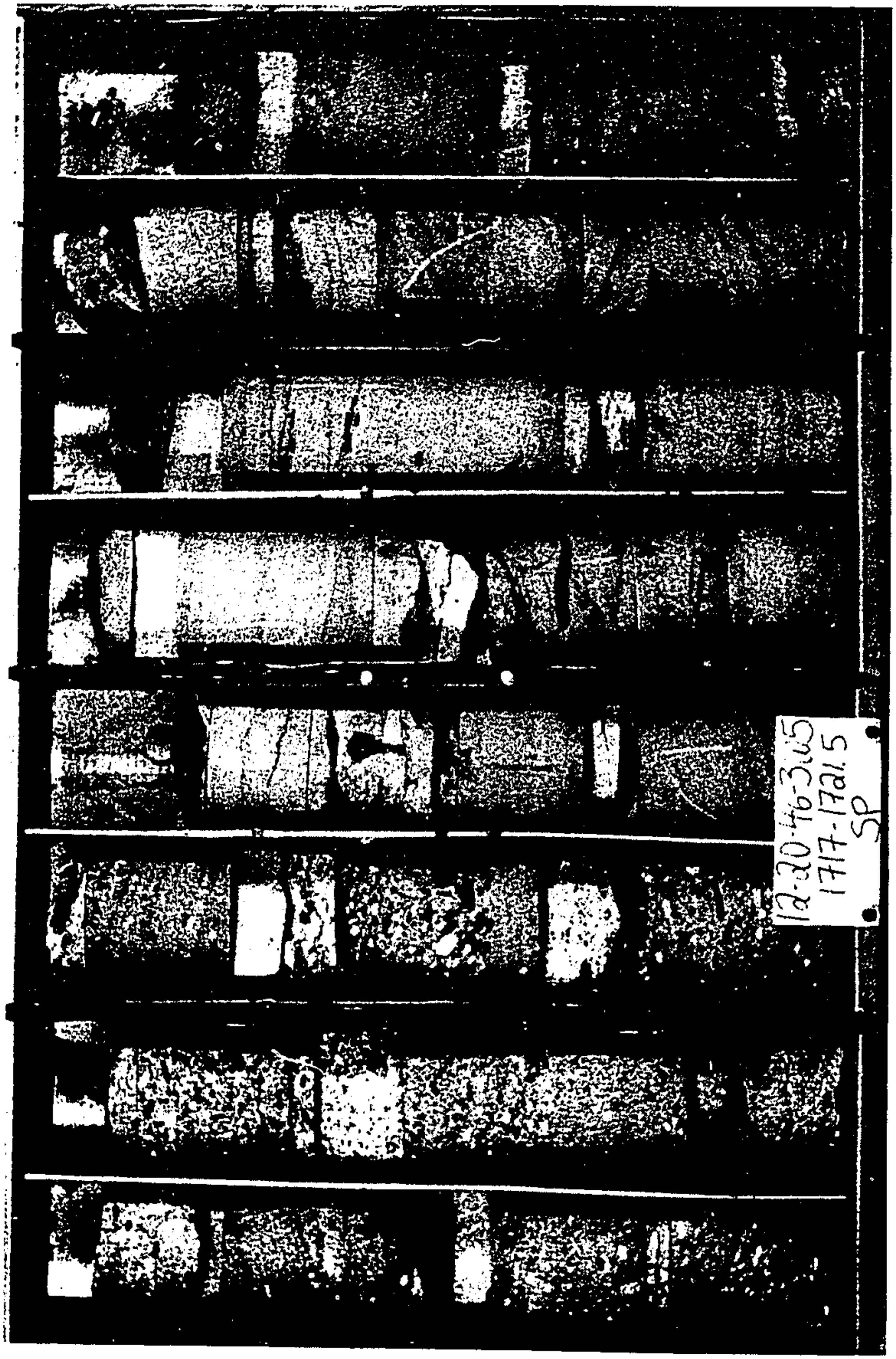


Figure 4.18. The following four pages contain a complete set of core photographs for the type well (12-20-46-3W5) of facies association 6. Each core sleeve is approximately 60 cm long and the stratigraphic top is in the upper right corner of each photograph.


VE3


12-20-46-3W5
1726-1730.5
SP


1220-46-3W5
1721.5-1726
SP


12-20-46-3W5
1717-1721.5
SP

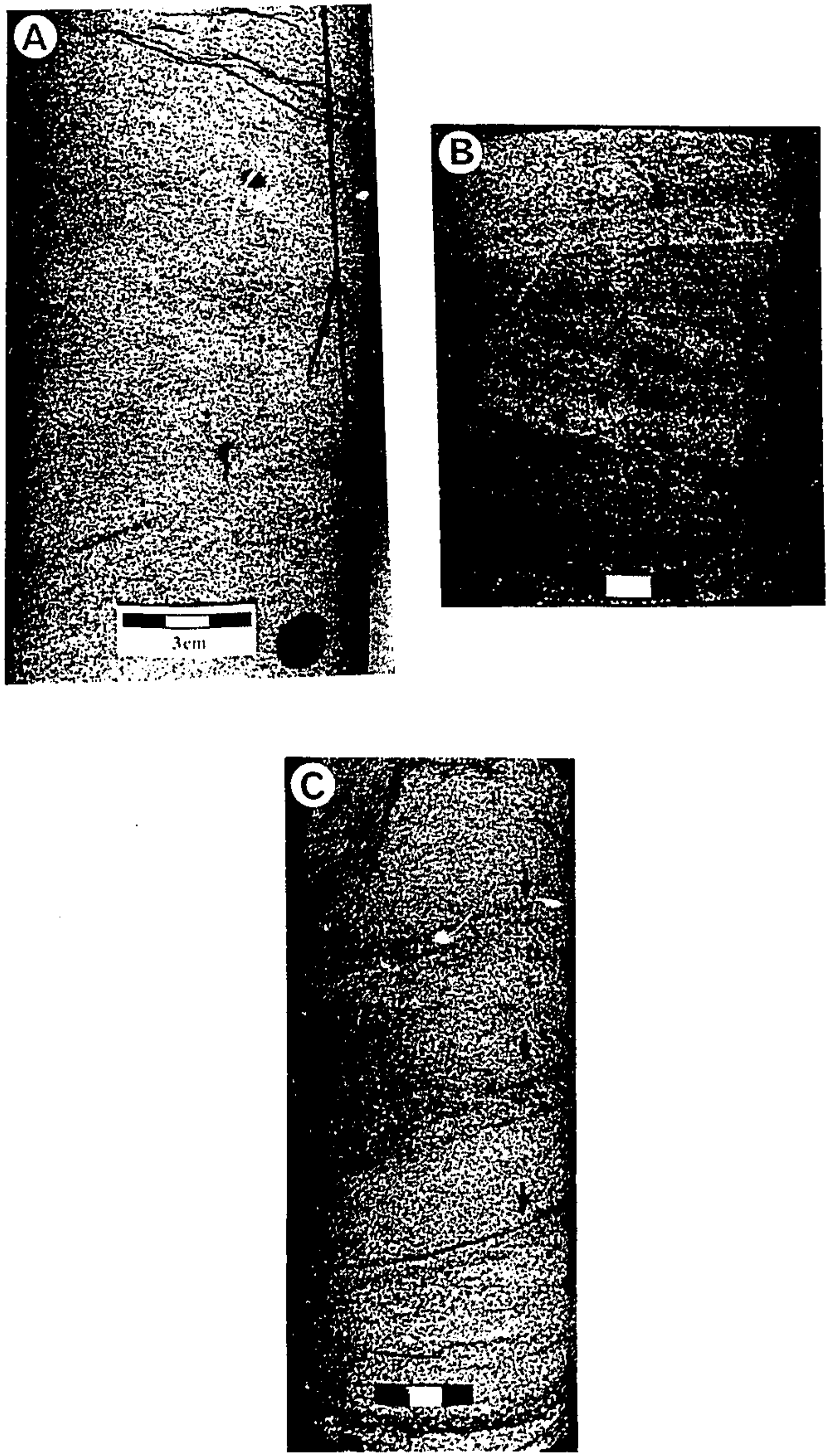
Individual cross bed sets are 10-30 cm thick. Reactivation surfaces and scours highlight the set boundaries. Most of the cross beds are uni-directional, but some are bi- and multi-directional (Fig. 4.19A).

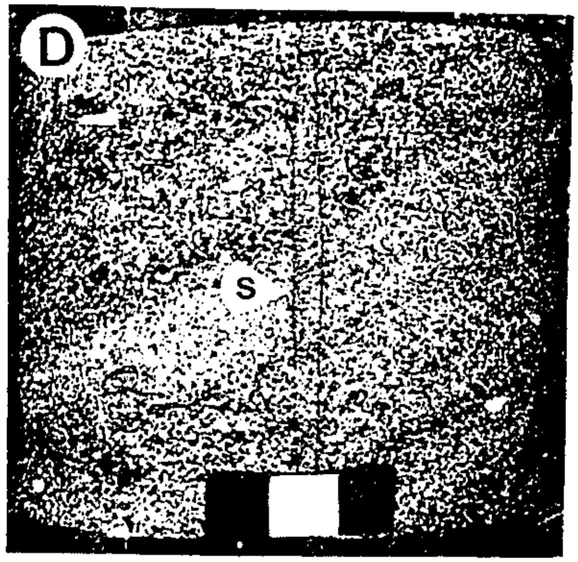
The cross bedded sandstones are often interlaminated with mudstone or carbonaceous material, which constitutes approximately one to five percent of the facies volume. The mudstone or carbonaceous material occurs as thin laminae that drape the cross bed sets at irregular intervals (Fig. 4.19B). The spacing between adjacent mudstone laminae, measured perpendicular to the foreset, can vary from 0.1-8.0 cm. In some cores, the mudstone laminae are grouped in pairs or couplets (Fig. 4.19C). The spacing between the laminae in a pair, measured perpendicular to the foreset, is 0.5-1.0 cm, while between adjacent pairs, the spacing is 3.0-6.0 cm. However, most laminae appear to be randomly spaced.

The remainder of the sediments in facies association 6 consist of fine- to medium-grained, moderately sorted, planar laminated, massive and muddy sandstone, with a minor amount of massive conglomerate. These facies are more abundant in the upper part of this facies association where they occur in beds that are 10-80 cm thick.

The cross bedded sandstones in this facies association are mildly to moderately bioturbated. The most abundant trace fossils are long (5-25 cm), vertical, mud-lined Skolithos burrows (Fig. 4.19D). Other trace fossils include

Figure 4.19. The following two pages show core photographs of the sediments of facies association 6. Scale bars are 3 cm long. (A). Bi-directional, cross bedded sandstone from 6-12-51-11W5 (1954 m). (B). Irregular spacing of carbonaceous laminae in a cross bedded sandstone from 14-19-46-3W5 (1716 m). (C). Regular spacing of paired mudstone laminae (arrows) from 12-20-46-3W5 (1726 m). These are interpreted as mudstone couplets that are produced during the two slack water periods of the tidal cycle. (D). Mud-lined *Skolithos* (s) burrow cutting through coarse-grained cross bedded sandstone from 5-18-46-3W5 (1697 m). (E). *Rosselia* (r) trace fossil in a weakly cross bedded sandstone from 12-20-46-3W5 (1727 m).


A
3cm
B
C


D
s


E
r

Rosselia (Fig. 4.19E), Ophiomorpha, Planolites and Diplocraterion, typical of the Skolithos ichnofacies (Frey & Pemberton, 1984). The degree of bioturbation increases upward and corresponds to an upward increase in the proportion of mudstone. However, the degree of bioturbation is still relatively mild compared to other facies associations.

The sediments of facies association 6 often form FU successions that are 0.3-4.0 m thick. The FU successions, from bottom to top, consist of massive conglomerate, cross bedded sandstone, planar laminated or massive sandstone, and muddy sandstone. The type well has at least 2 of these FU successions (Figs 4.17 & 4.18).

Interpretation

The coarse-grained nature, presence of mudstone intra-clasts, abundance of cross bedded sandstones and FU successions, and mild bioturbation imply deposition in a relatively high energy, non-marine to marginal marine environment. The wide range of grain size and sorting, and the wide variety of sedimentary structures suggest that the energy levels were constantly fluctuating during the deposition of these sediments.

The carbonaceous or mudstone laminae resemble the mud couplets described by Visser (1980) and are interpreted as tide-generated structures. The carbonaceous laminae would be deposited during the two slack water periods of the tidal cycle, and the corresponding sandstone laminae or beds would

be deposited during the dominant and subordinate tidal currents. These structures are observed in many channelized, subtidal environments, including those in the Oosterschelde tidal basin (Visser, 1980; Nio et al., 1983; Mowbray & Visser, 1984; Yang & Nio, 1985).

4.7 Facies Association 7 - Massive Sandstone

Facies association 7 consists of massive sandstone deposits which form FU facies successions, 2-12 m thick. These FU successions are only observed in a few wells and are usually found in stacks of 1-3 successions. The best examples of this association occur in the Crystal valley at 10-36-45-4W5, 14-36-45-4W5 and 2-1-46-4W5. The type well is located at 10-36-45-4W5 (Figs 4.20 & 4.21).

The lower part of each FU succession is sharp based, has a basal lag of granules, pebbles and mudstone clasts, and consists of medium- to coarse-grained, poorly sorted, massive sandstone with approximately 10-30% granules and pebbles (Fig. 4.22A). The granules and pebbles are well rounded quartz and chert grains, and many of these are a cream to buff white colour. In thin section, these clasts are identified as sericitized chert grains that are leached or corroded, and partially replaced with sericite and carbonate minerals. These sandstones have up to 10% secondary porosity.

In the central part of each FU succession, the massive sands are fine-grained, moderately to well sorted, and contain fewer granules and pebbles. White, sericitized

Figure 4.20. Type well for facies association 7 from 10-36-45-4W5 (1789-1812 m) which shows a stack of two fining-upward, massive sandstone successions. The corresponding resistivity and gamma-ray well logs, and the position of the core (black bar) are also shown. A complete set of core photographs are presented in Figure 4.21, while individual facies photographs are presented in Figure 4.22. O - *Ophiomorpha*, P - *Planolites*, S - *Skolithos*

Facies Association 7

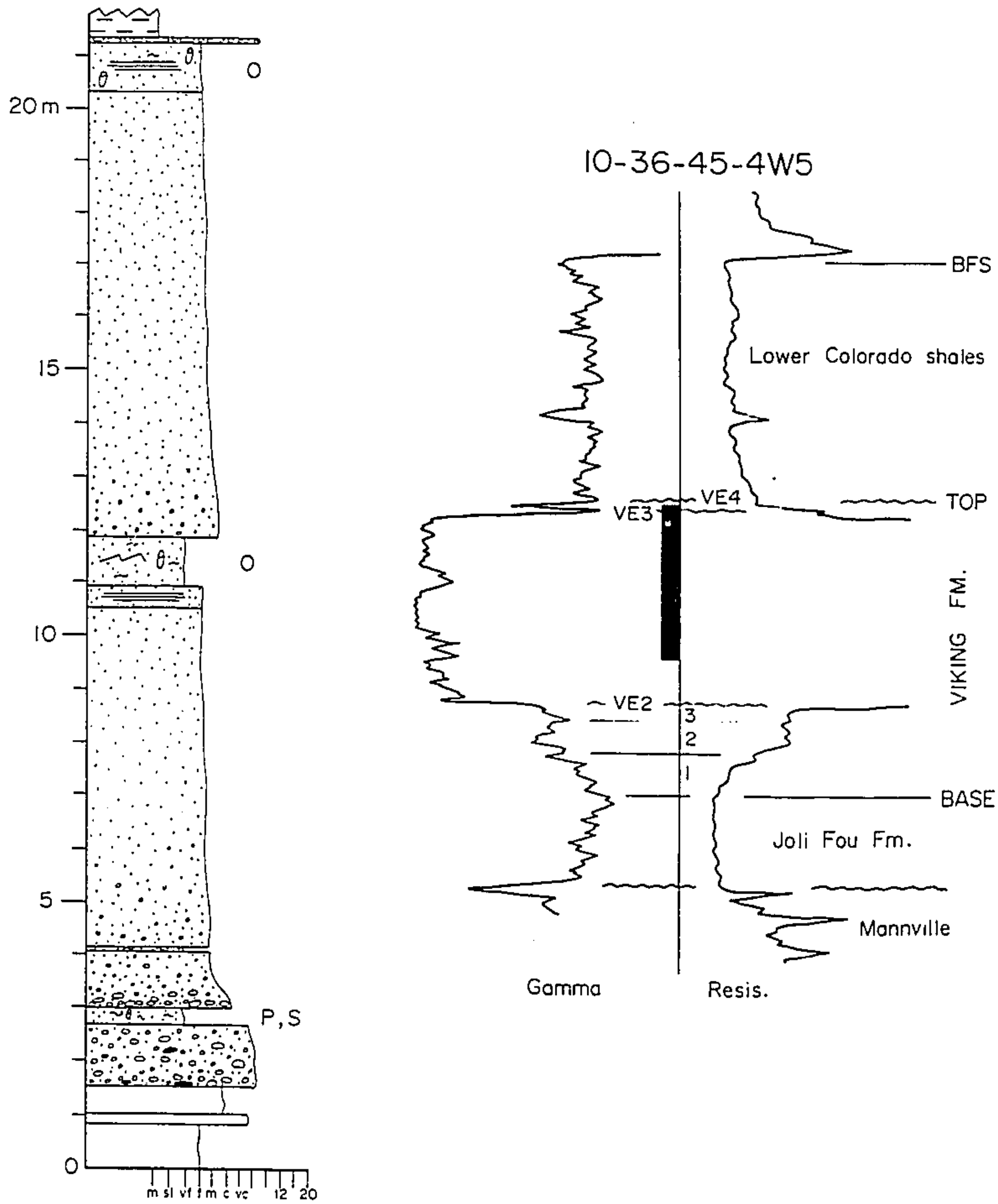
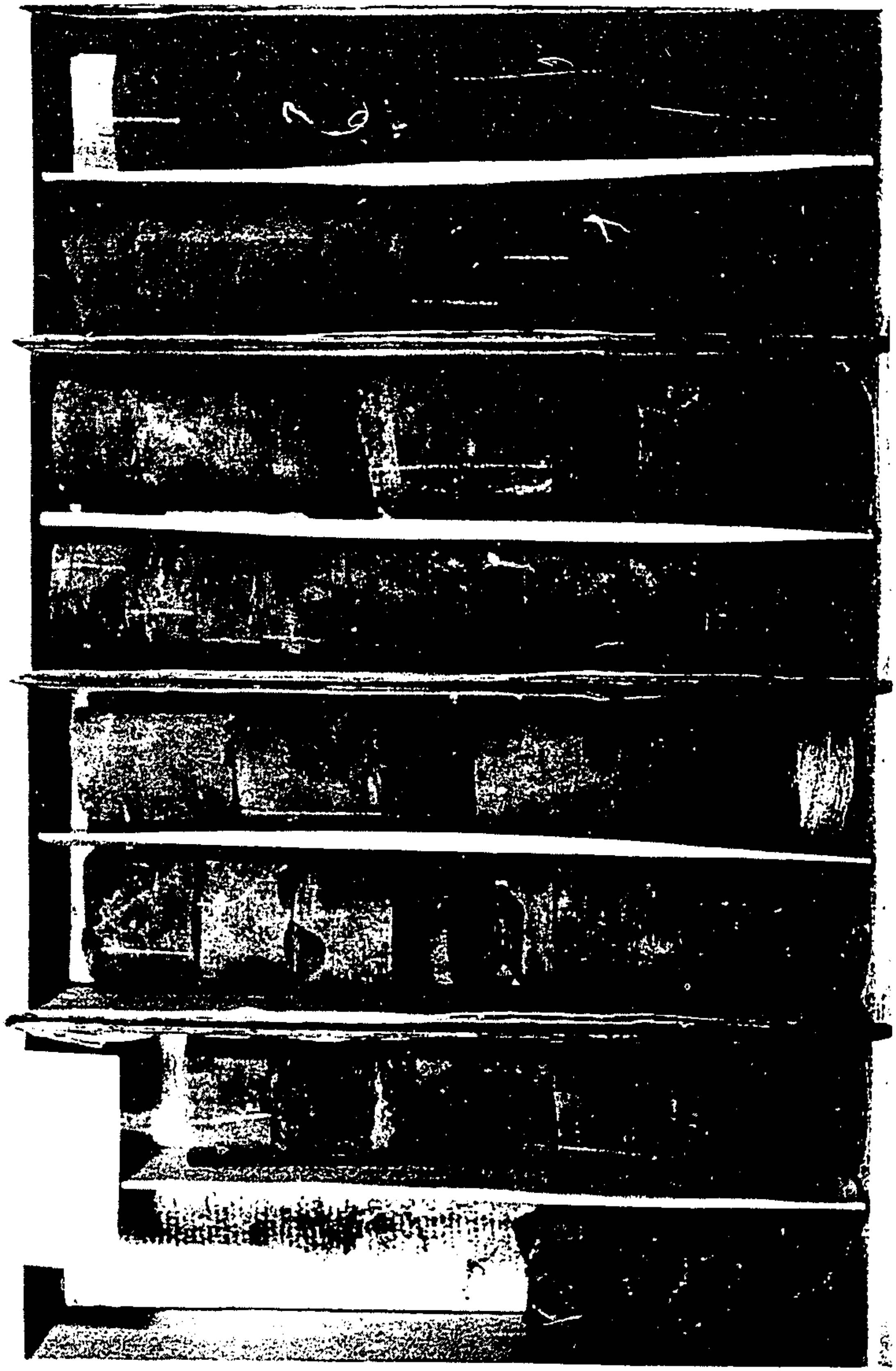
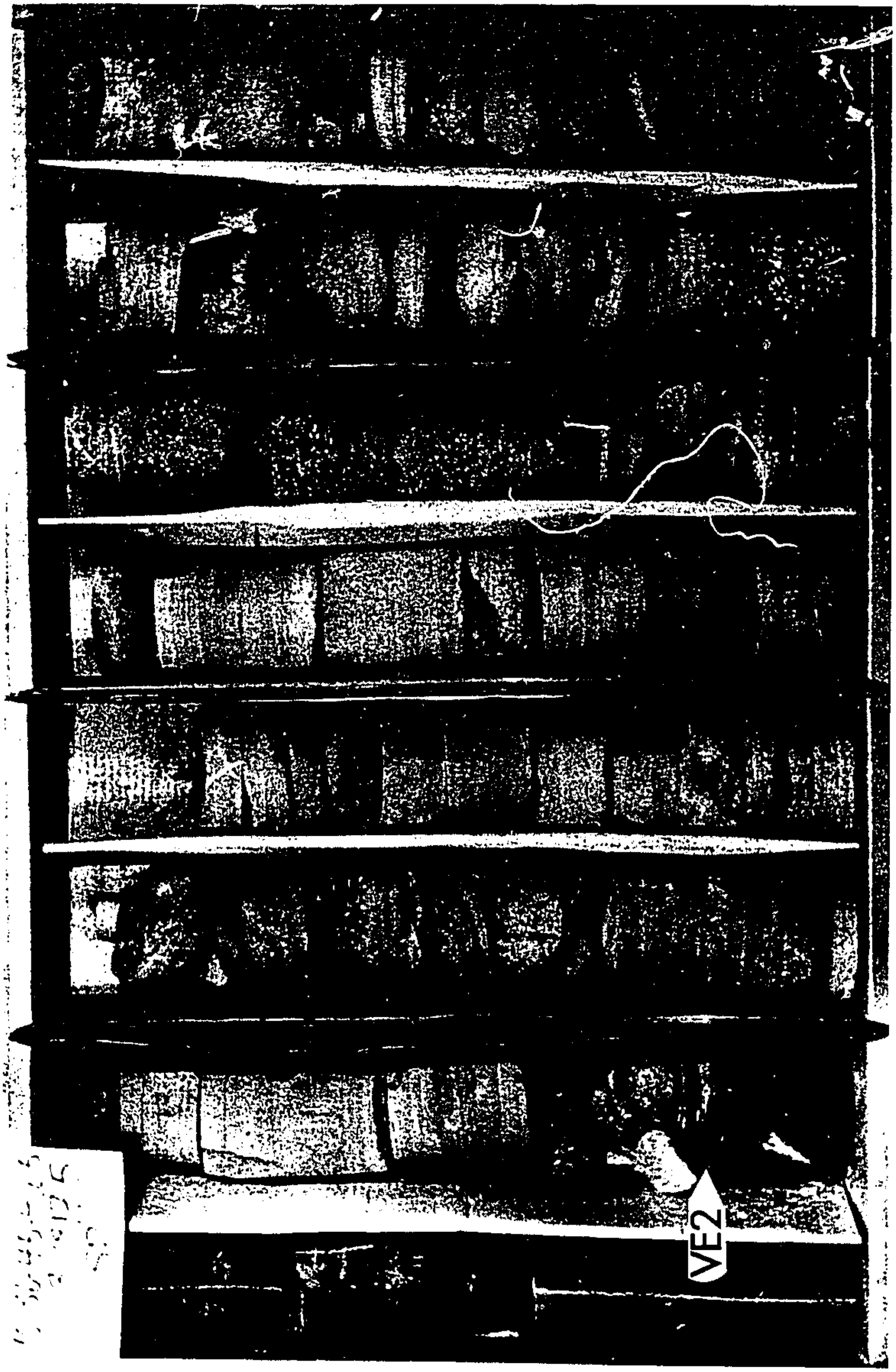
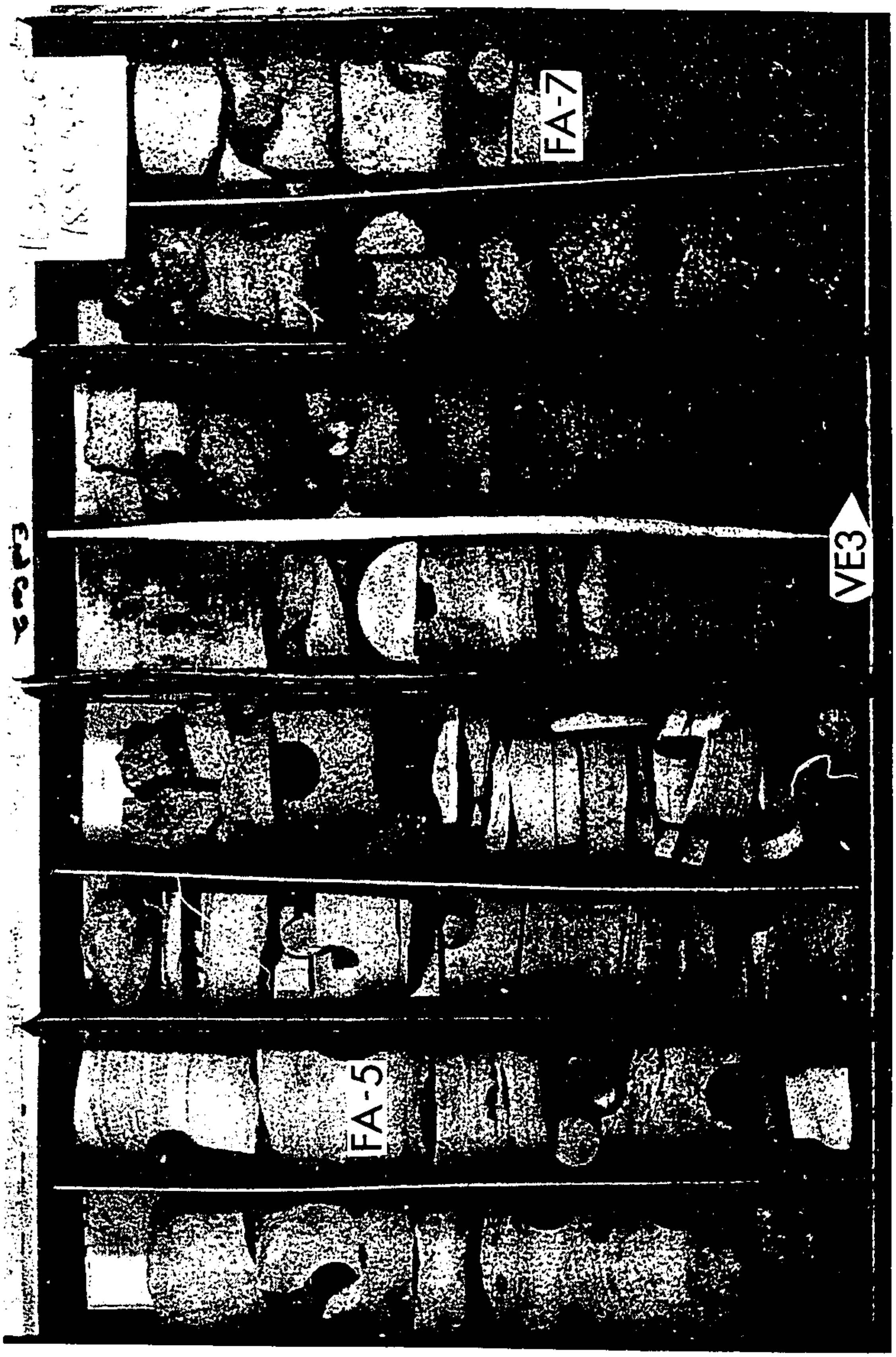
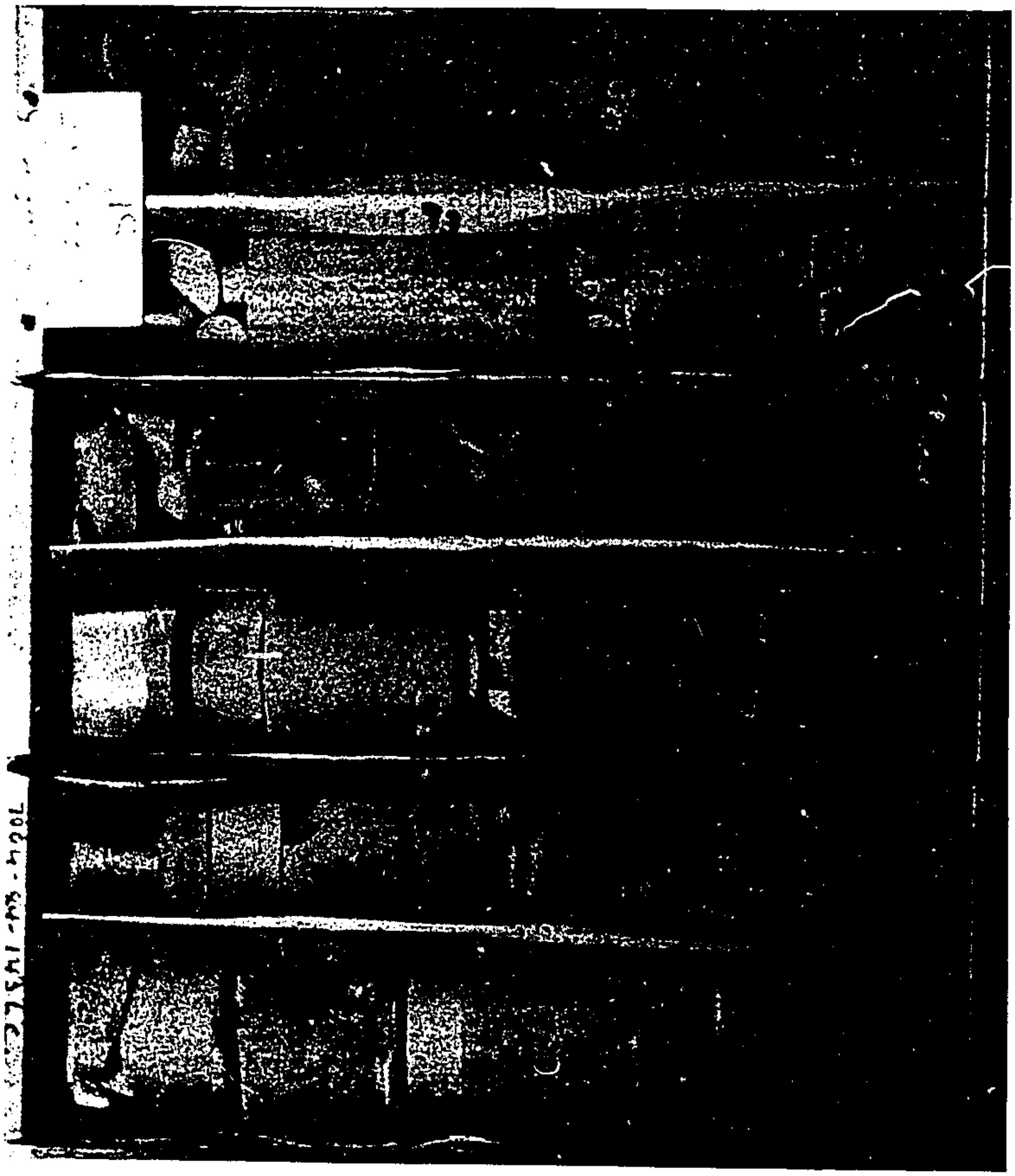


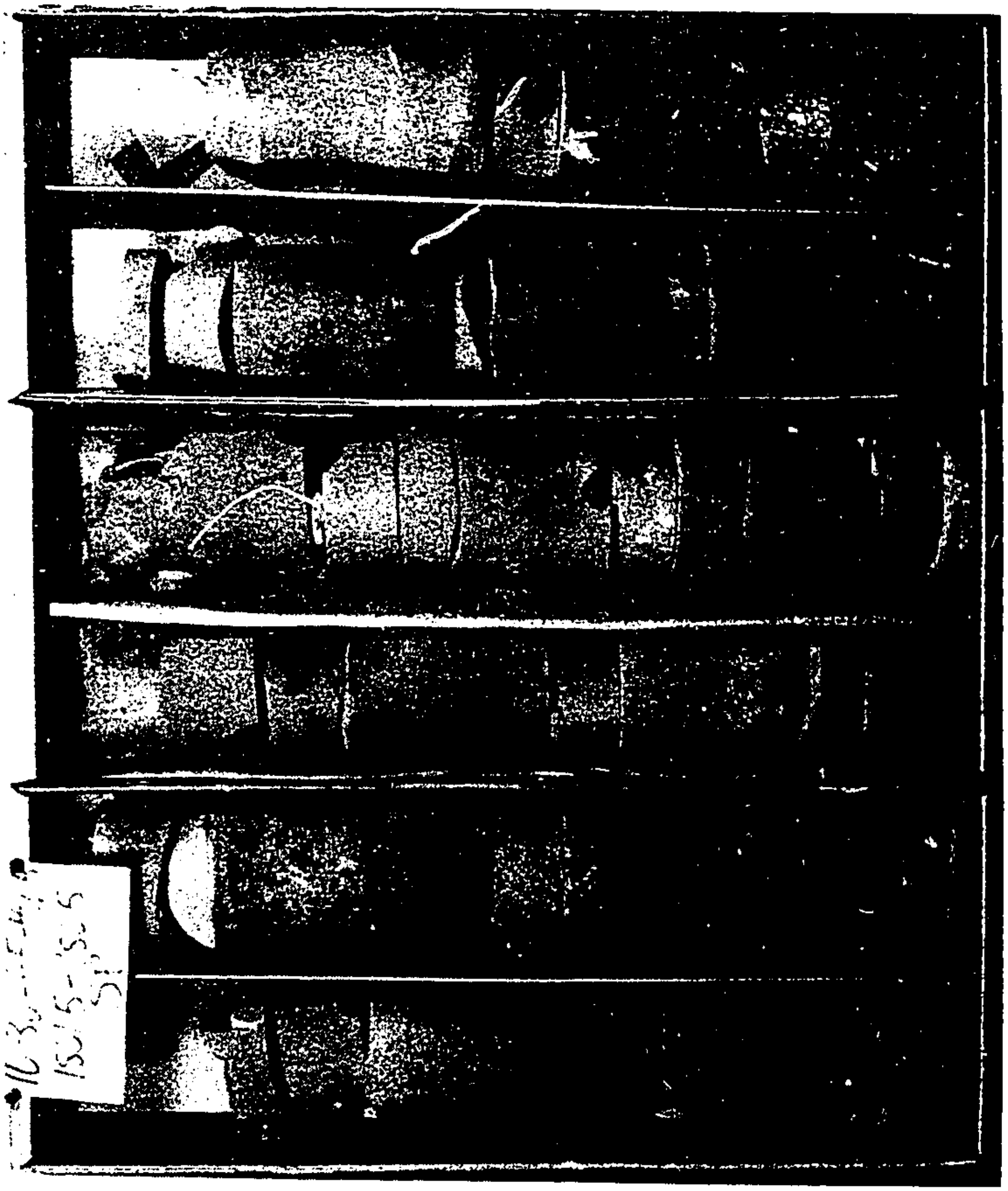
Figure 4.21. The following eight pages contain a complete set of core photographs for the type well (10-36-45-4W5) of facies association 7. Each core sleeve is approximately 60 cm long and the stratigraphic top is in the upper right corner of each photograph.

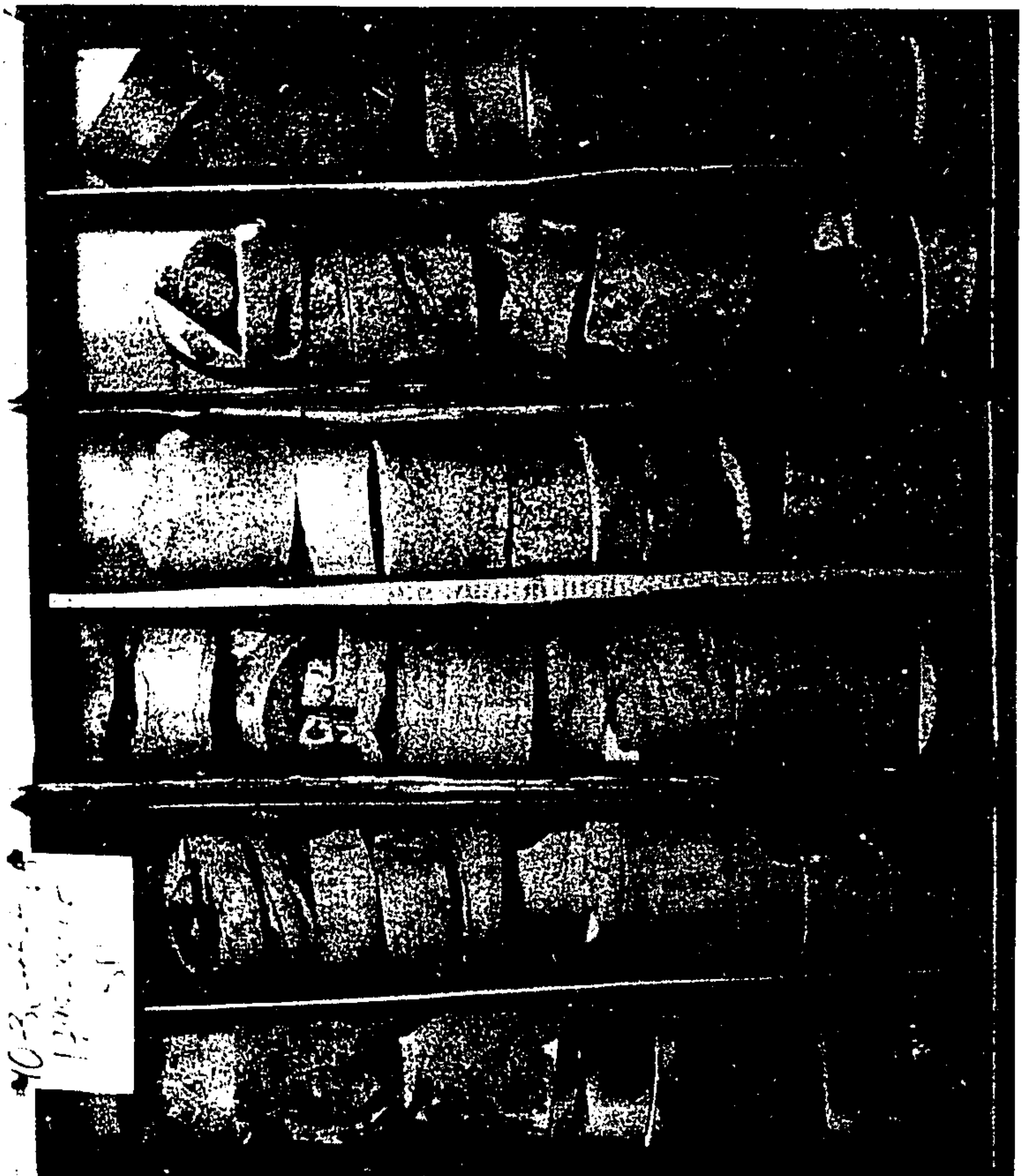


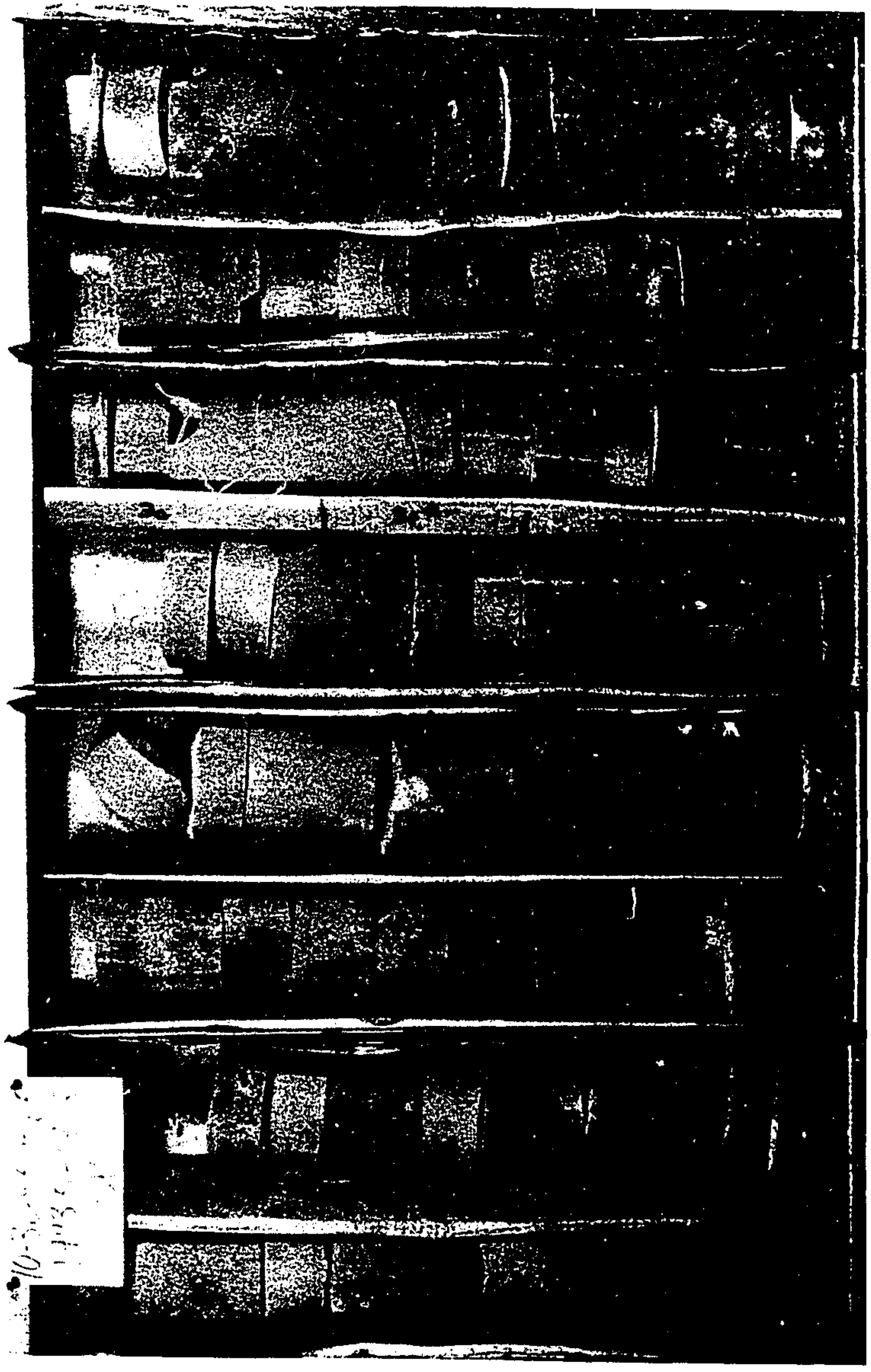

VE2


FA-7
VE3
FA-5









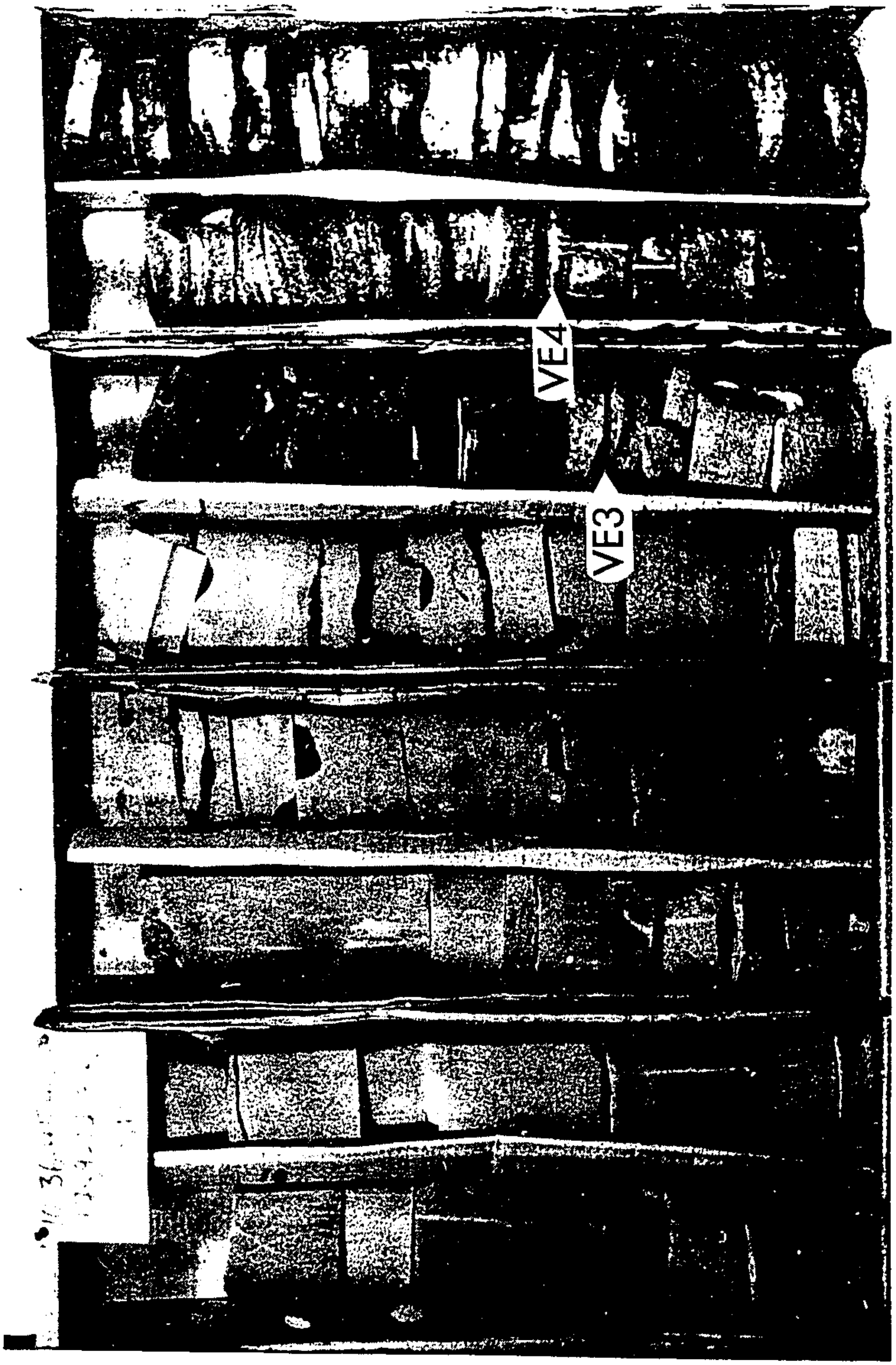
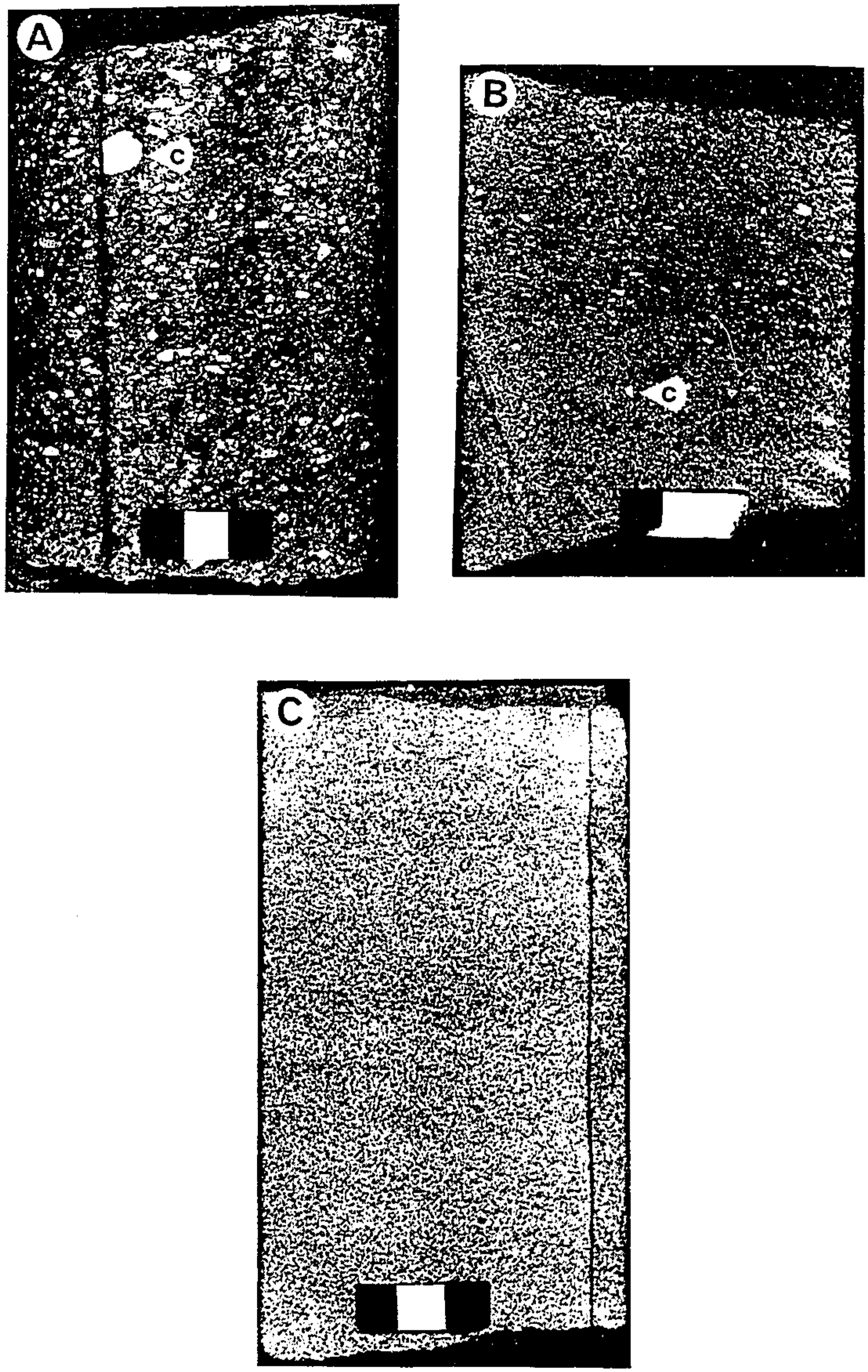

VE4
VE3

Figure 4.22. Sediments of facies association 7. Scale bars are 3 cm long. (A). Granular, medium- to coarse-grained massive sandstone from 14-36-45-4W5 (1794 m). Note the light coloured chert grains (c) which are partially altered to sericite. (B). Fine- to medium-grained massive sandstone from 14-36-45-4W5 (1791 m). Light coloured chert grains (c) are also observed. (C). Very well sorted, fine-grained massive sandstone from 8-12-46-4W5 (1736 m).


A
c
B
c
C

chert grains are still observed (Fig. 4.22B). Very thin, rare mudstone laminae also occur in the central part of some successions. These mudstone laminae break up the continuous succession of massive, mud free sandstones, but do not interrupt the overall fining-upward grain size succession.

At the top of each succession, the massive sandstones are very fine- to fine-grained, very well sorted and contain no granules or pebbles (Fig. 4.22C). The massive sandstones are overlain by very fine-grained, horizontal to low angle inclined (2-6°) sandstone beds or by muddy, very fine-grained, wave topped, ripple cross laminated sandstone beds. These beds are 0.2-1.5 m thick and are well sorted. Small Ophiomorpha, Skolithos and Planolites traces, typical of the Skolithos and Cruziana ichnofacies occur throughout these deposits, as do thin, convolute mudstone laminae. The mudstone laminae constitute 1-2% of the facies volume of the ripple cross laminated and horizontally laminated sandstone beds.

Interpretation

The sharp base, lack of sedimentary structures, normal grading and fining-upward grain size trend suggest rapid deposition of sand out of suspension from a subaqueous current. The fining-upward grain size trend also implies that the current velocity was waning.

4.8 Facies Association 8 - Interbedded Conglomerate

Facies association 8 consists of massive, cross bedded, planar bedded, imbricated and chaotically bedded conglomerate interbedded with massive and cross bedded sandstone. This facies association exhibits no overall grain size trend and is 6-31 m thick. The type well is located at 4-7-46-3W5 in the Crystal valley (Figs 4.23 & 4.24).

The two most abundant facies in association 8 are cross bedded and massive conglomerate. The cross bedded conglomerate beds are matrix- to clast-supported, poorly to moderately sorted and are 0.1-3.0 m thick (Fig. 4.25A). The framework clasts consist of rounded to well rounded chert and quartz pebbles that are up to 5 cm in diameter. The matrix consists of fine- to very coarse-grained sand. Rare, well rounded, sideritized mudstone clasts are also observed.

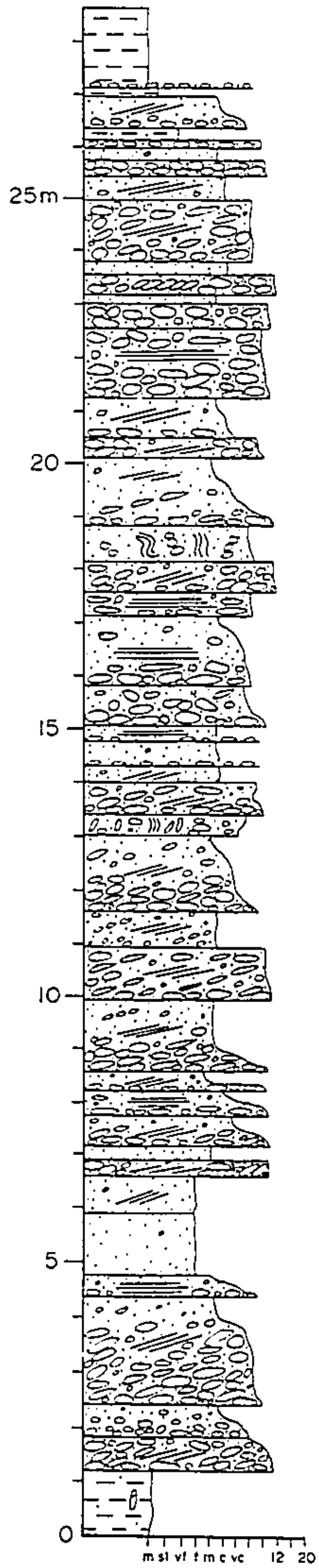
The cross beds are highlighted by textural differences between individual beds or by the preferred orientation of elongate clasts parallel to the bedding plane (Fig. 4.25A). Individual cross bed sets are 10-30 cm thick and the beds dip at 7-30°. Most of the cross bedding is uni-directional, but some is bi- and multi-directional.

The massive conglomerate beds are matrix- to clast-supported, poorly to moderately sorted and contain no physical or biogenic structures (Fig. 4.25B). The framework consists of rounded to well rounded, chert and quartz pebbles, while the matrix consists of fine- to very coarse-grained sand. Well rounded, sideritized mudstone clasts, up to 40 mm in diameter are rarely present.

The cross bedded and massive conglomerate facies are

Figure 4.23. Type well for facies association 8 from 4-7-46-3W5 (1718-1747 m). This well shows no overall grain size trend and is dominated by cross bedded conglomerate. The corresponding resistivity and gamma-ray well logs, and the position of the core (black bar) are also shown. A complete set of core photographs are presented in Figure 4.24, while individual facies photographs are shown in Figure 4.25.

Facies Association 8



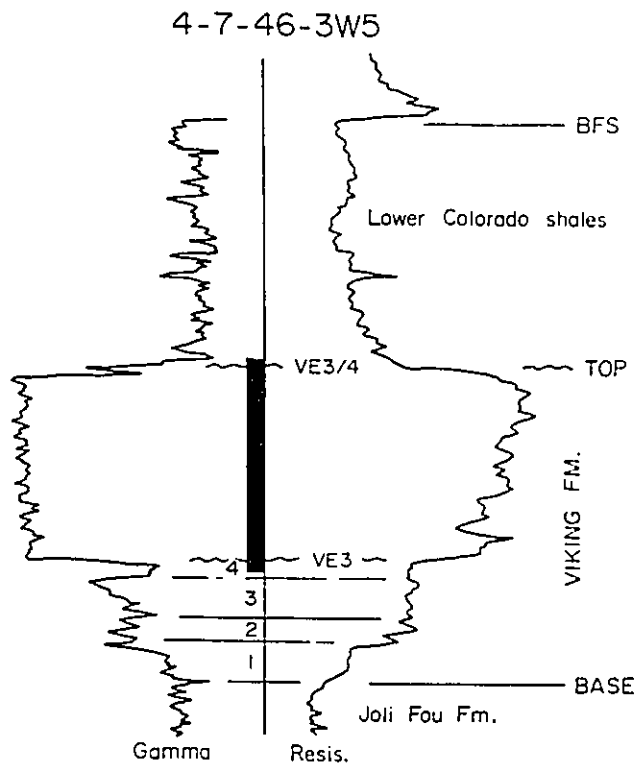
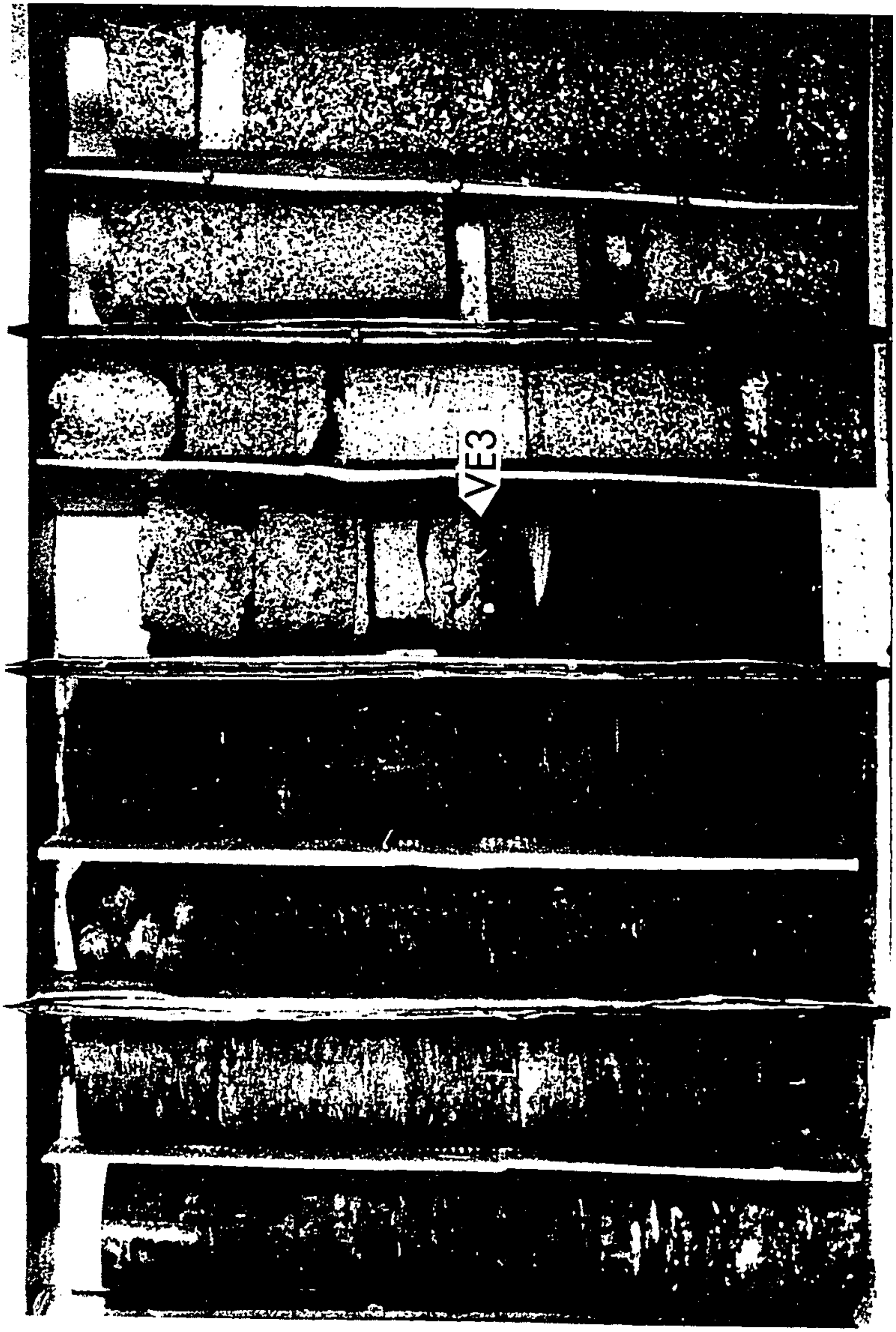
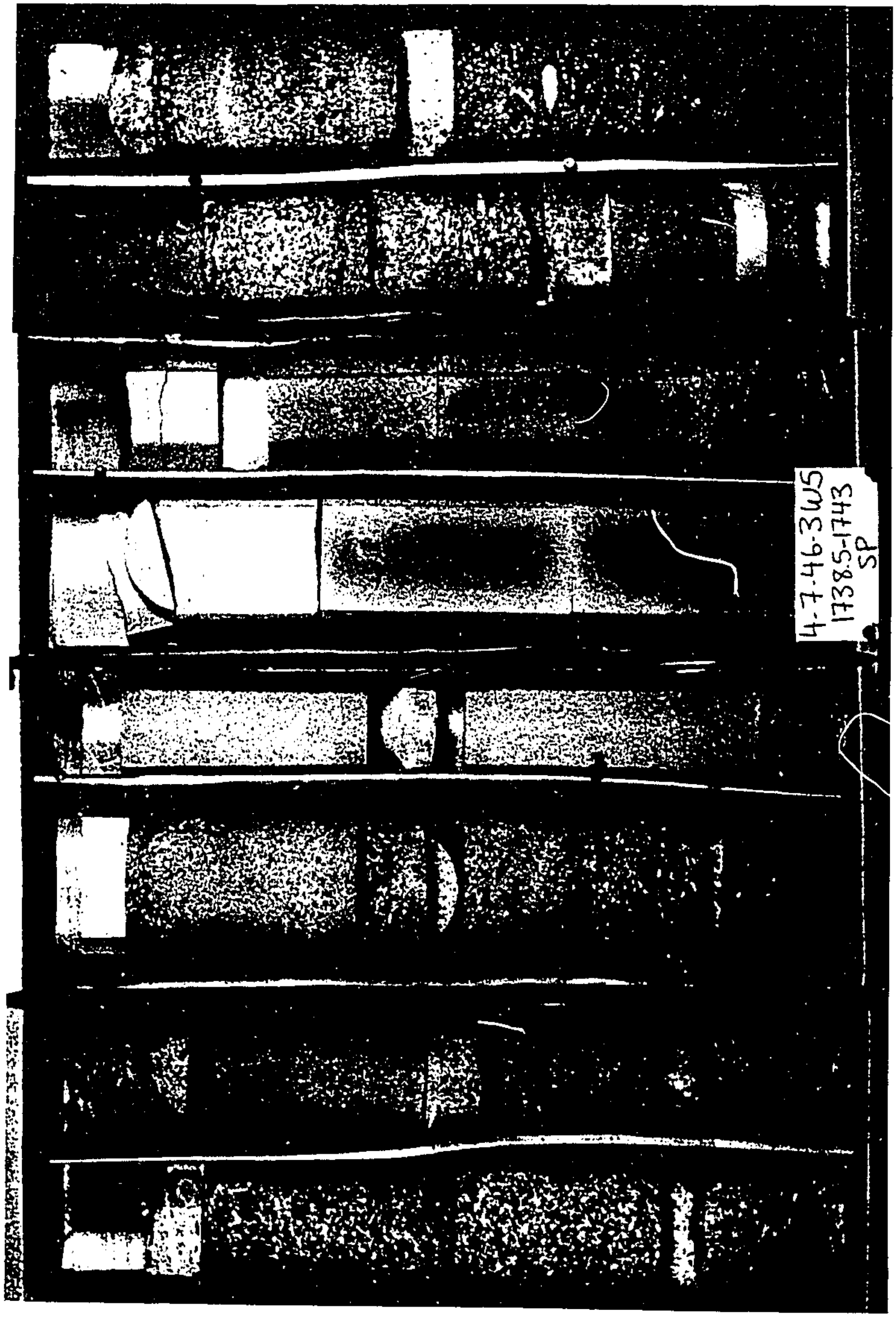
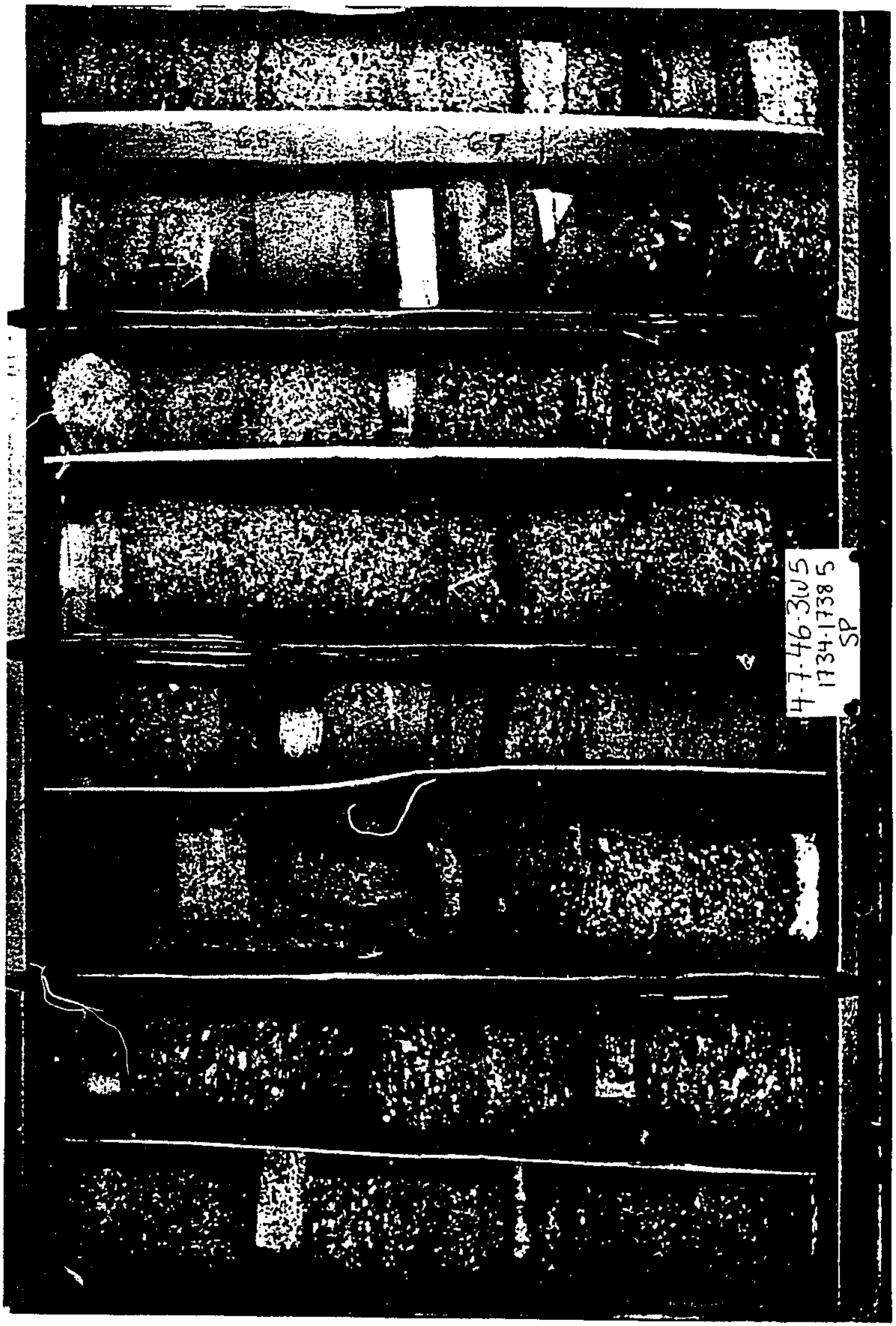
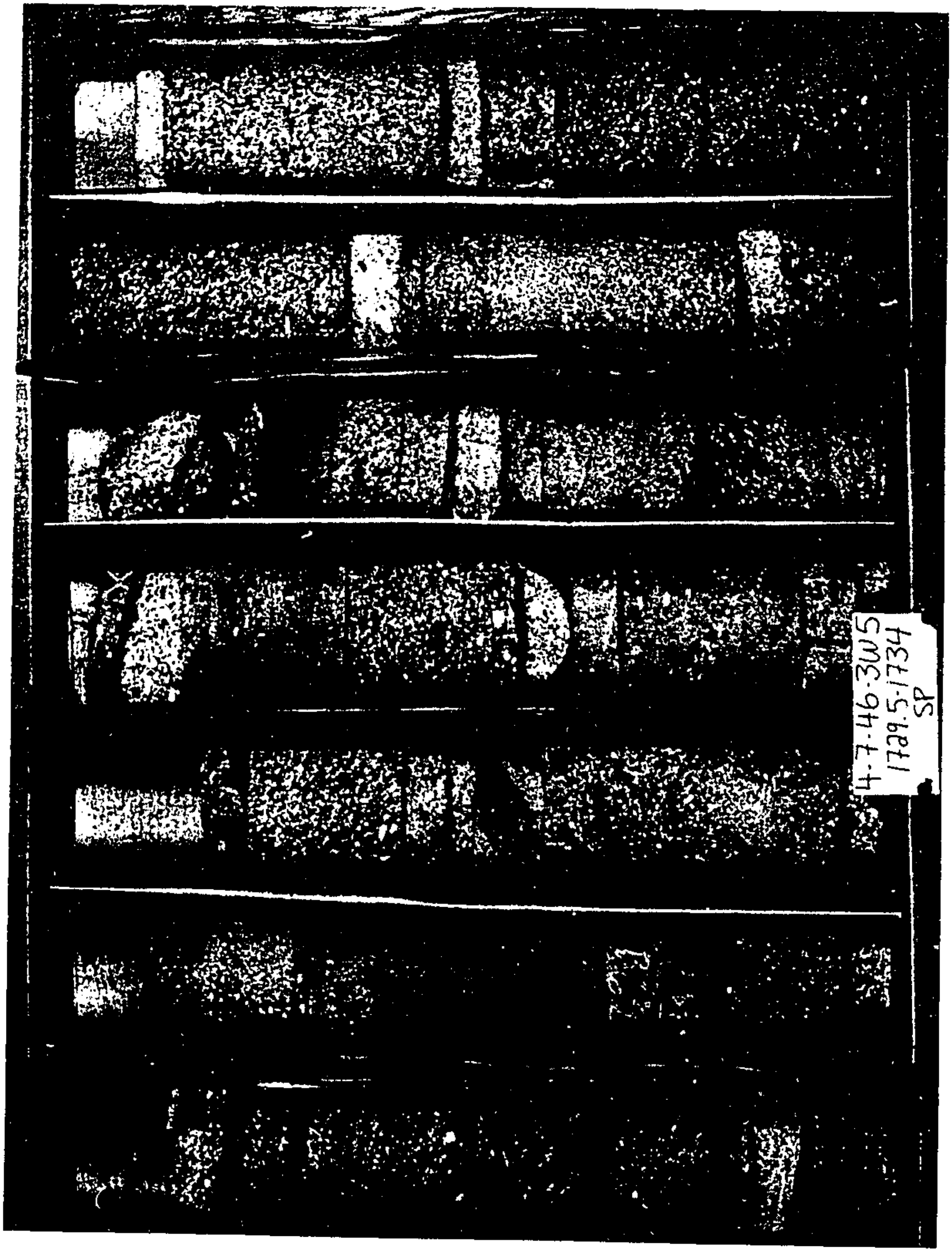


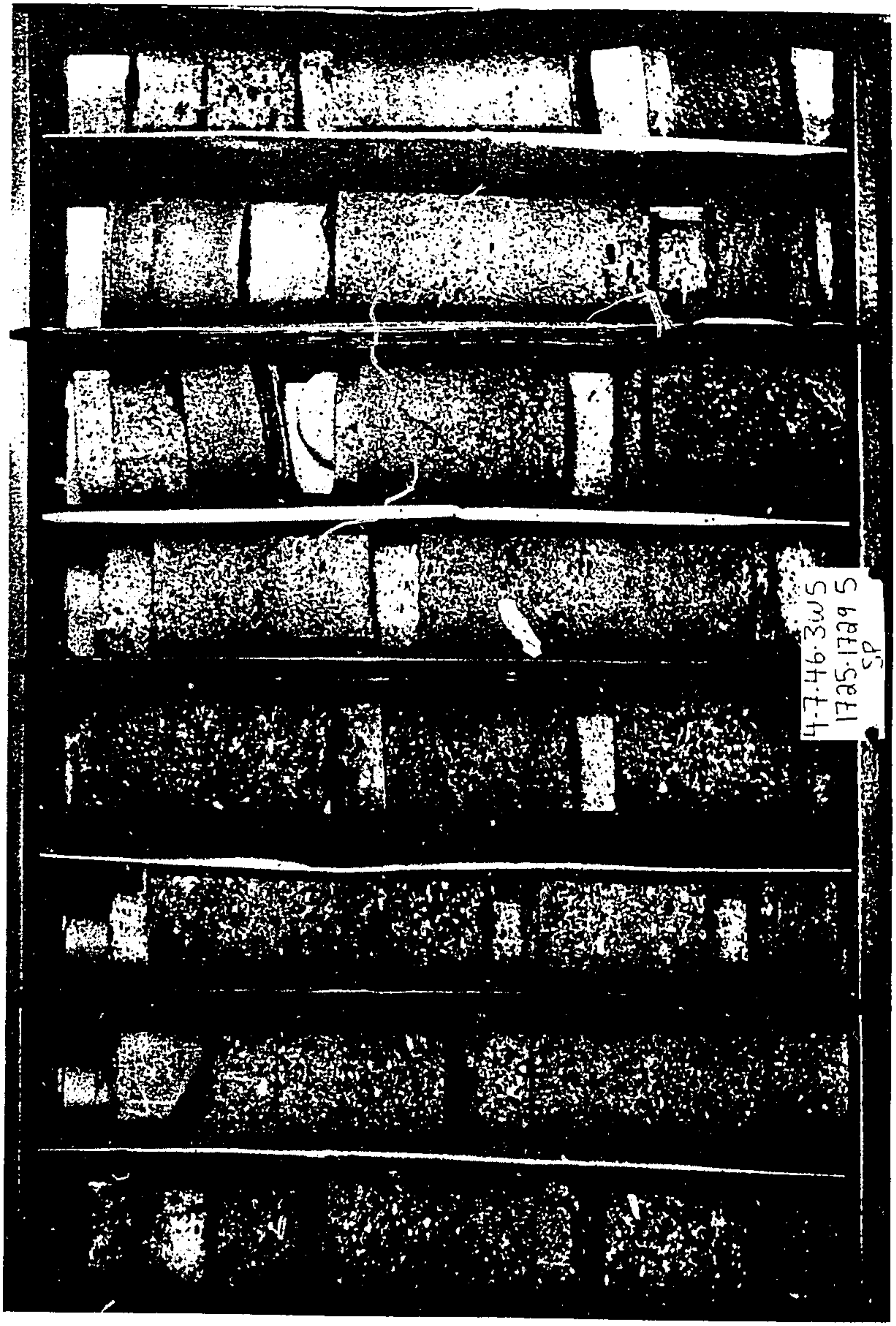
Figure 4.24. The following seven pages show a complete set of core photographs for the type well (4-7-46-3W5) of facies association 8. Each core sleeve is approximately 60 cm long and the stratigraphic top is in the upper right corner of each photograph.

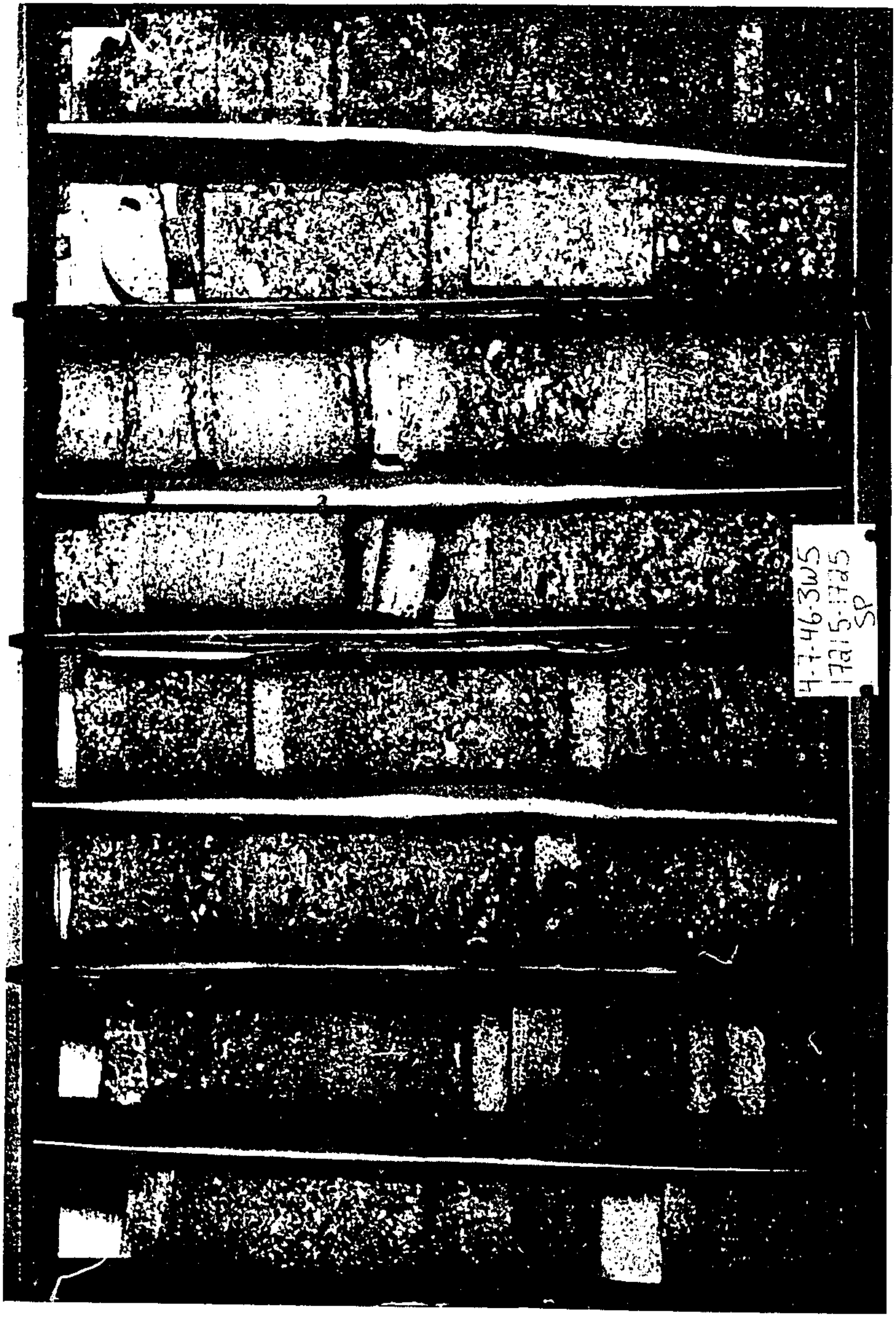

VE3


4-7-46-3W5
1738.5-1743
SP


4-7-46-3W5
1734-1738.5
SP


4-7-46-3W5
1729.5-1734
SP


4-7-46-3W5
1725-1729 5
SP


4-7-46-3W5
1721.5-1725
SP

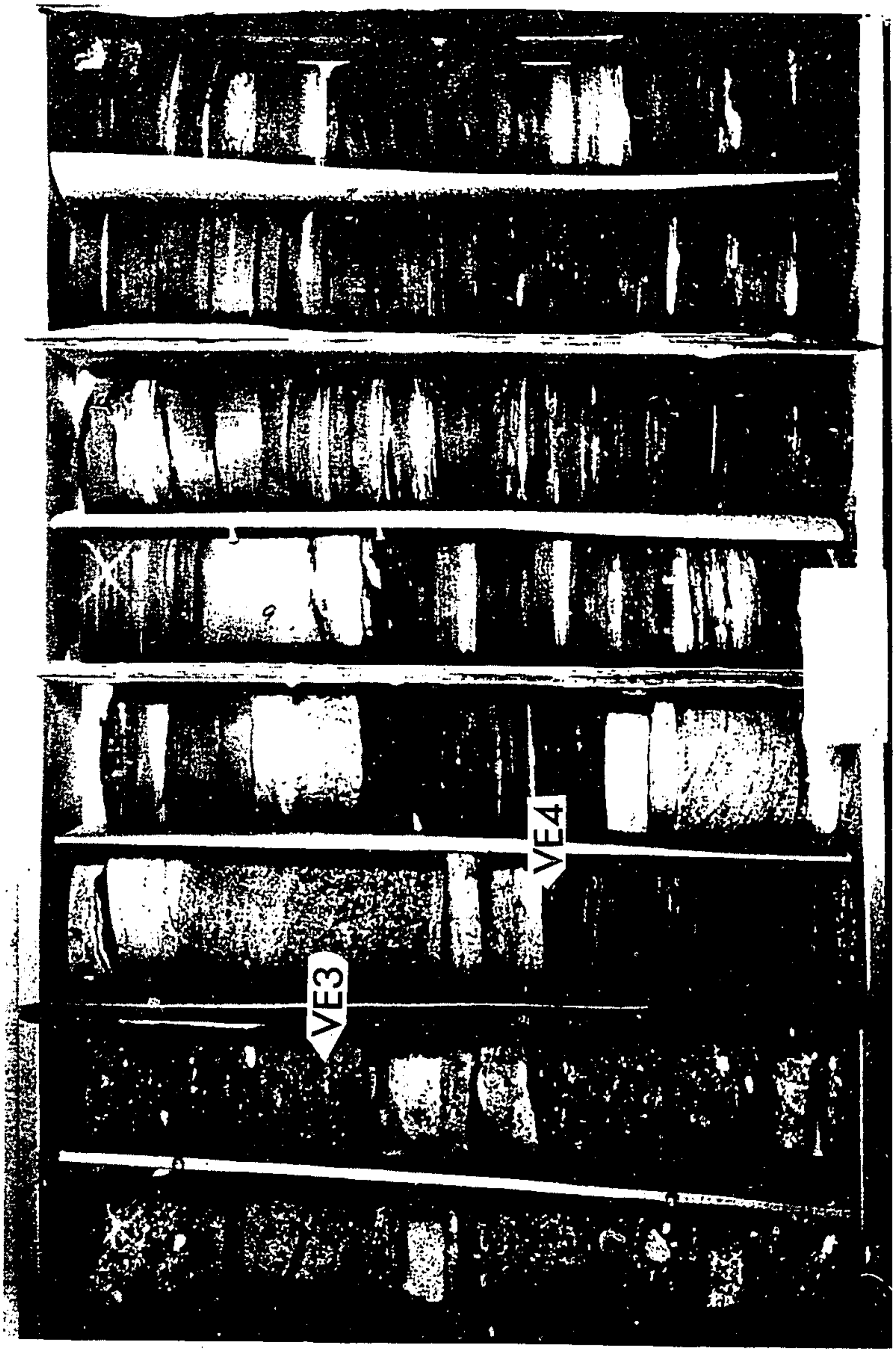
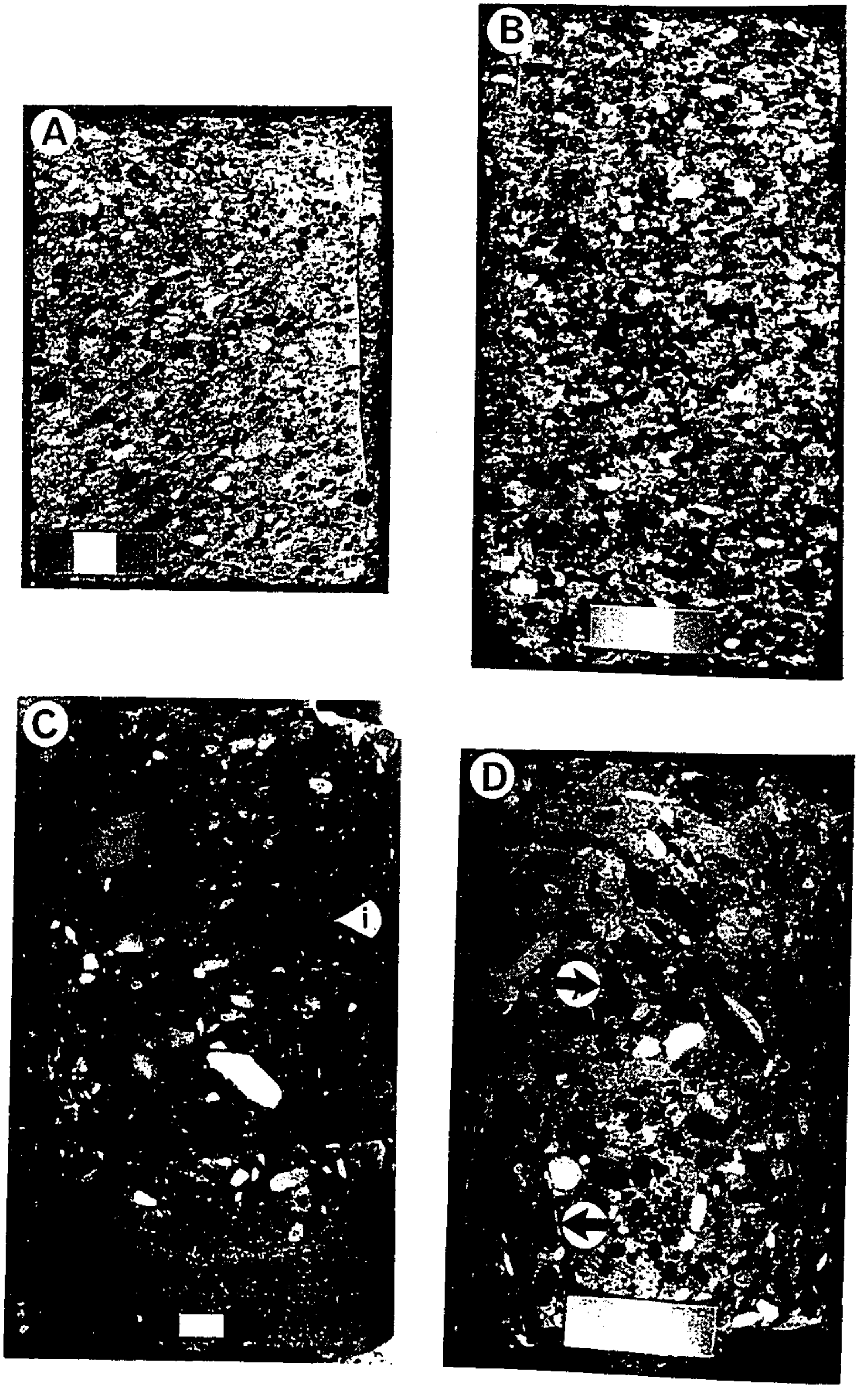

VE4
VE3

Figure 4.25. Sediments of facies association 8. Scale bars are 3 cm long. (A). Cross bedded conglomerate from 16-1-46-4W5 (1722 m). (B). Massive conglomerate from 16-1-46-4W5 (1711 m). (C). Imbricated (i) conglomerate from 4-1-46-4W5 (1786 m). Strong imbrication is highlighted by the arrow. (D). Chaotically bedded conglomerate from 16-1-46-4W5 (1731 m). Note the vertical orientation (arrows) of the long axes of many pebbles.


A
B
C
i
D

gradationally interbedded with planar bedded, imbricated (Fig. 4.25C) and chaotically bedded conglomerate (Fig. 4.25D), and massive and cross bedded sandstone. All of these facies exhibit a wide range of grain sizes and sorting, and they occur in beds 0.1-3.5 m thick. Most of these sediments are devoid of trace fossils, with the exception of rare, small Skolithos and small Ophiomorpha.

FU successions, 0.4-6.0 m thick, are often observed in facies association 8. These successions consist of cross bedded or massive conglomerate near the base and massive or cross bedded sandstone near the top. A 5 m thick FU succession occurs in the lower part of the type well (Figs 4.23 & 4.24).

Interpretation

The abundance of cross bedded conglomerate, presence of coarse grained sand, granules and pebbles, scarcity of bioturbation and trace fossils, and the paucity of mudstone laminae suggest deposition in a high energy, non-marine environment. Most of the cross beds are uni-directional, which implies that these sediments were transported and deposited by very strong, uni-directional currents, such as those that occur in a fluvial channel. The imbricated conglomerates are also indicative of a very strong, uni-directional current and their presence supports the fluvial channel interpretation.

Sedimentation rates were probably relatively high in facies association 8 as shown by the presence of chaotically

bedded conglomerate (Fig. 4.25D). Rapid deposition probably caused the beds to slump, producing severely oversteepened (60-90°) and chaotically bedded conglomerates.

4.9 Facies Association 9 - Sharp Based, Bioturbated Sandstone

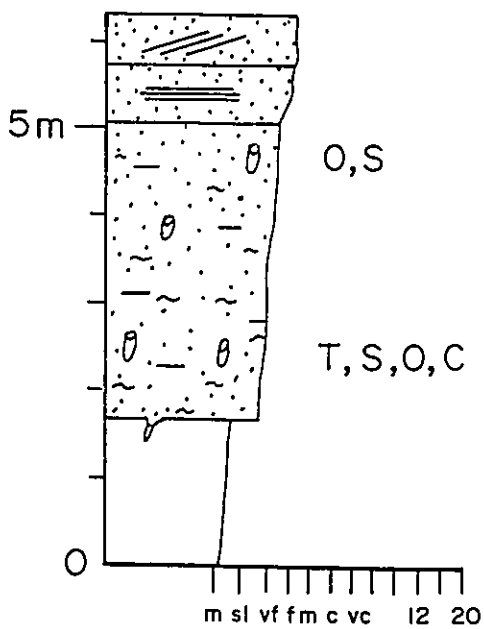
Facies association 9 consists of interbedded moderately to thoroughly bioturbated muddy sandstone, planar laminated sandstone and cross bedded sandstone. The type well is located north of Crystal at 6-9-49-2W5 (Figs 4.26 & 4.27).

The sediments of facies association 9 form a CU facies succession that has approximately forty to fifty percent sand at the base and one hundred percent sand near the top. The degree of bioturbation and the percentage of mudstone decreases upward. The thickness of this association varies from 4-15 m.

The lower part of facies association 9 consists mostly of moderately to thoroughly bioturbated muddy sandstone. Importantly, these sediments always have a sharp lower contact with the underlying bioturbated mudstone facies (Fig. 4.28A). This sharp lower contact is also observed on the resistivity well log (Fig. 4.26). Trace fossils are abundant and include Terebellina (Fig. 4.28B), Ophiomorpha (Fig. 4.28C), Chondrites and Skolithos, which are typical of the Cruziana and Skolithos ichnofacies (Frey & Pemberton, 1984). Mildly to moderately bioturbated, muddy sandstone beds, with thin, convoluted mudstone laminae are also observed in the lower to central part of this association

Figure 4.26. Type well for facies association 9 from 6-9-49-2W5 (1371.6-1378.6 m). Note the sharp lower contact with the underlying facies and the CU vertical facies succession. The corresponding resistivity well log and the position of the core (black bar) are also shown. A complete set of core photographs is presented in Figure 4.27, while individual facies photographs are presented in Figure 4.28. O - Ophiomorpha, S - Skolithos, T - Terebellina, C - Chondrites

Facies Association 9



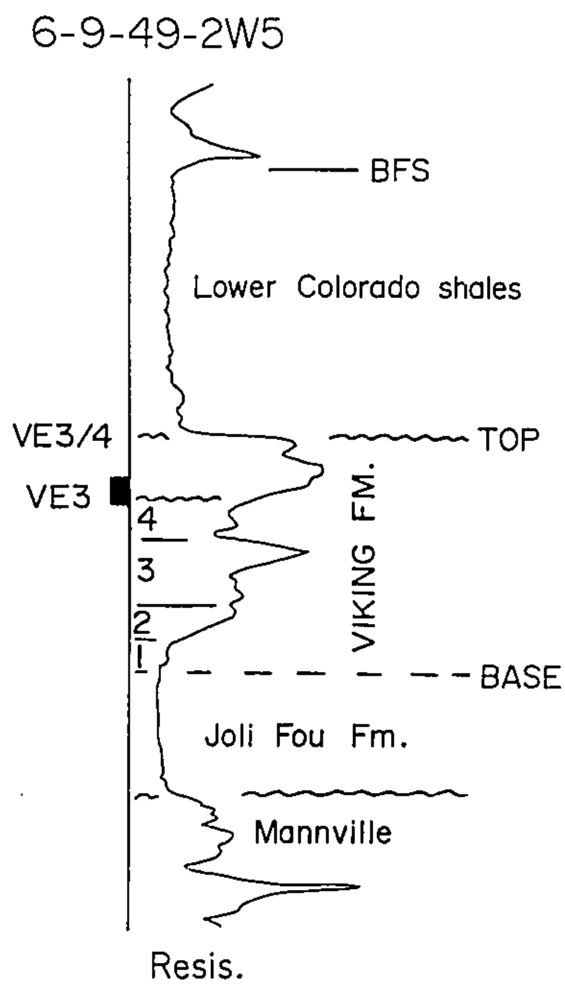
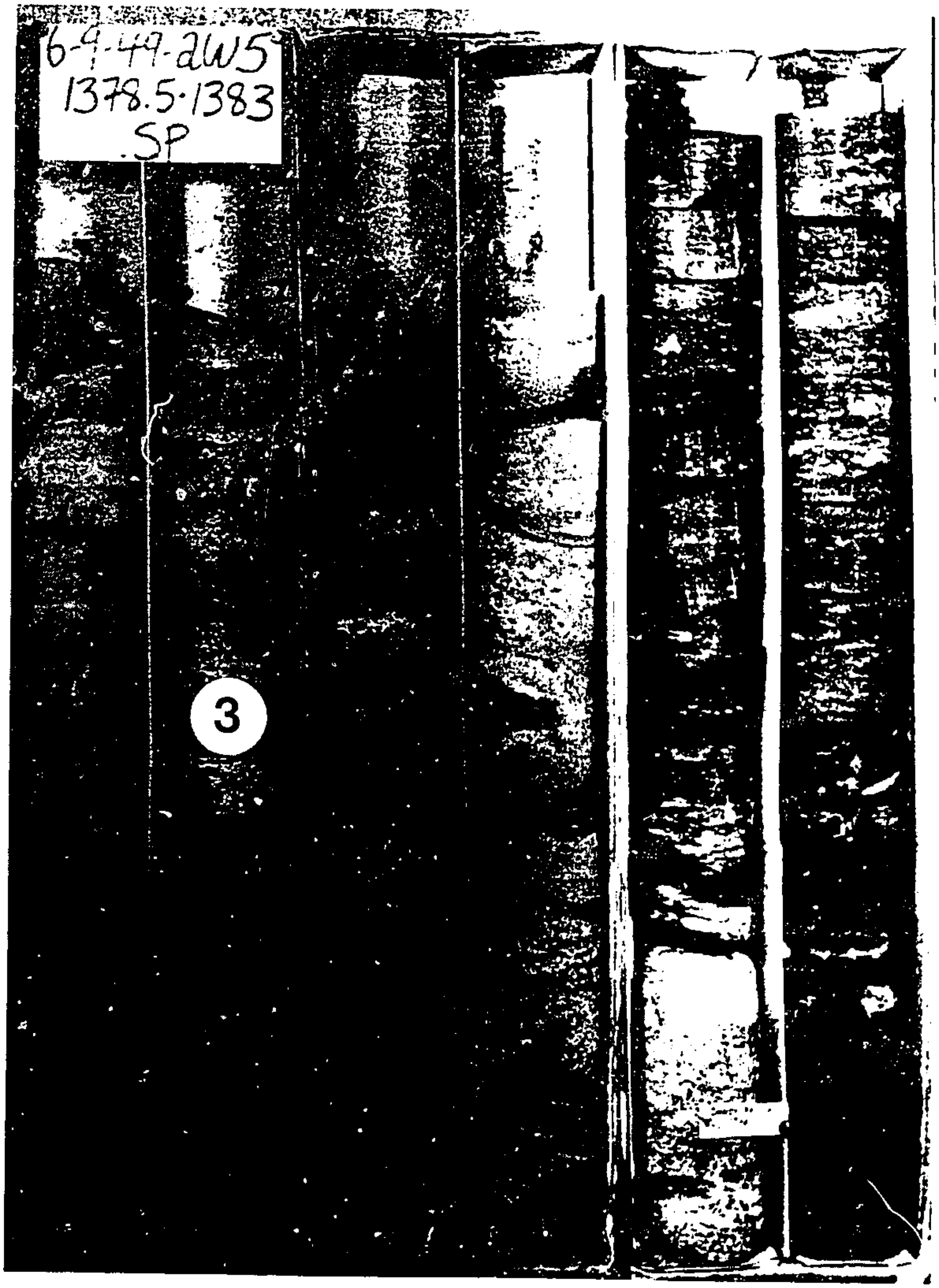
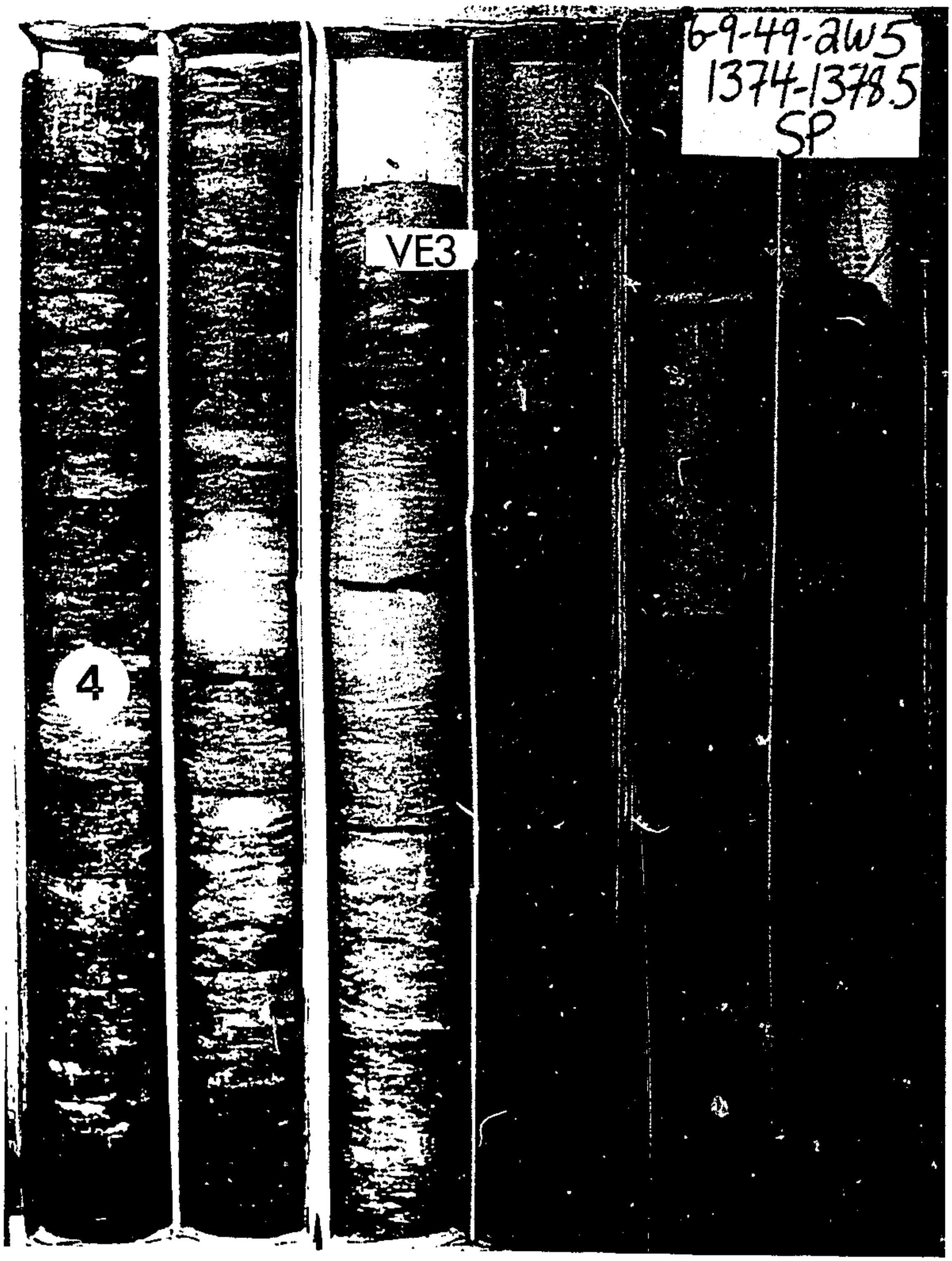


Figure 4.27. The following three pages show a complete set of core photographs for the type well (6-9-49-2W5) of facies association 9. Each core sleeve is approximately 75 cm long and the stratigraphic top is in the upper right corner of each photograph. The sandstones that are observed in the first core photograph are not part of facies association 9 but are the sandy top of a regional, CU succession (facies association 1).


6-9-49-2W5
1378.5-1383
SP
3


6-9-49-2W5
1374-1378.5
SP
VE3
4

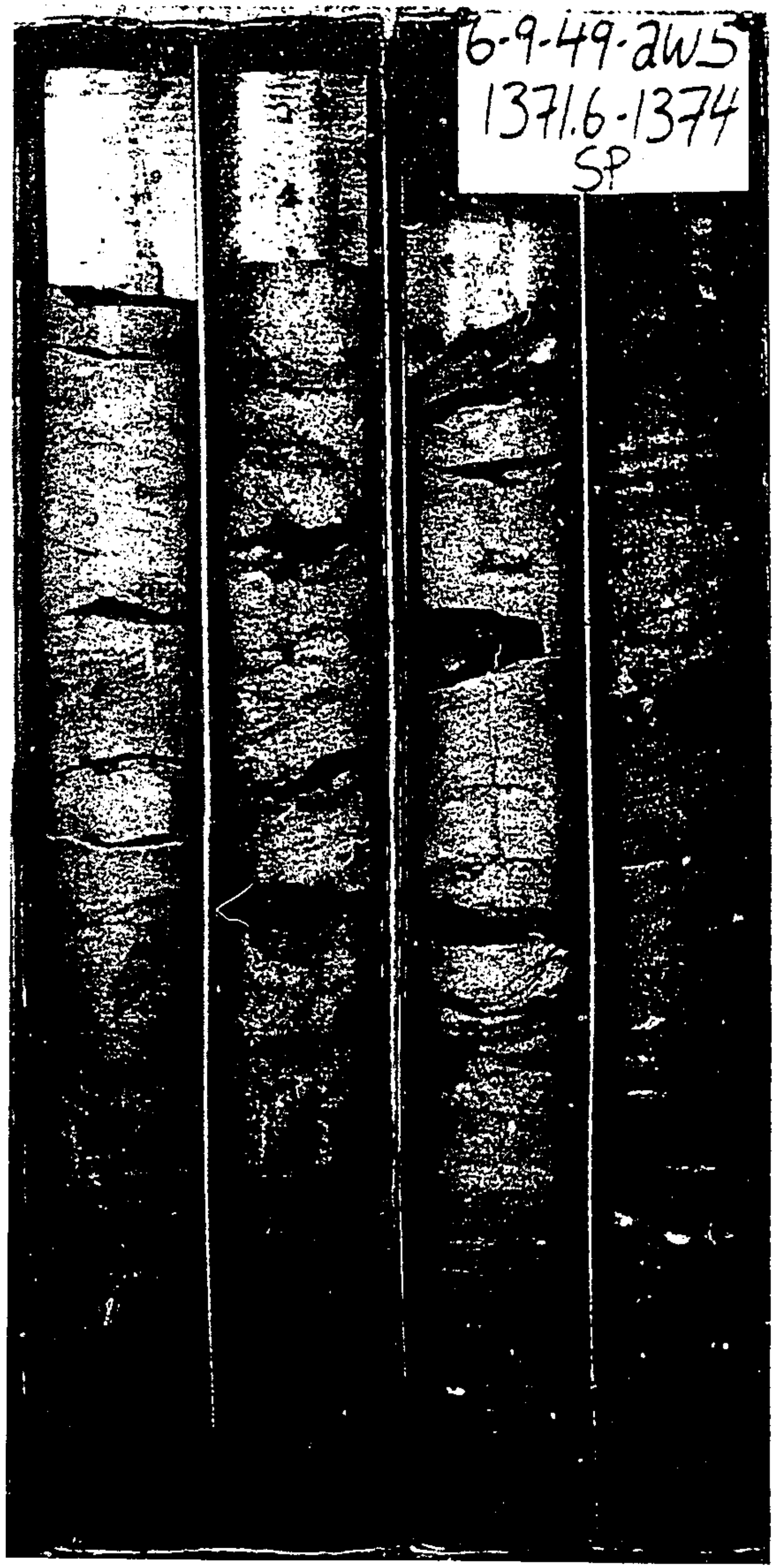
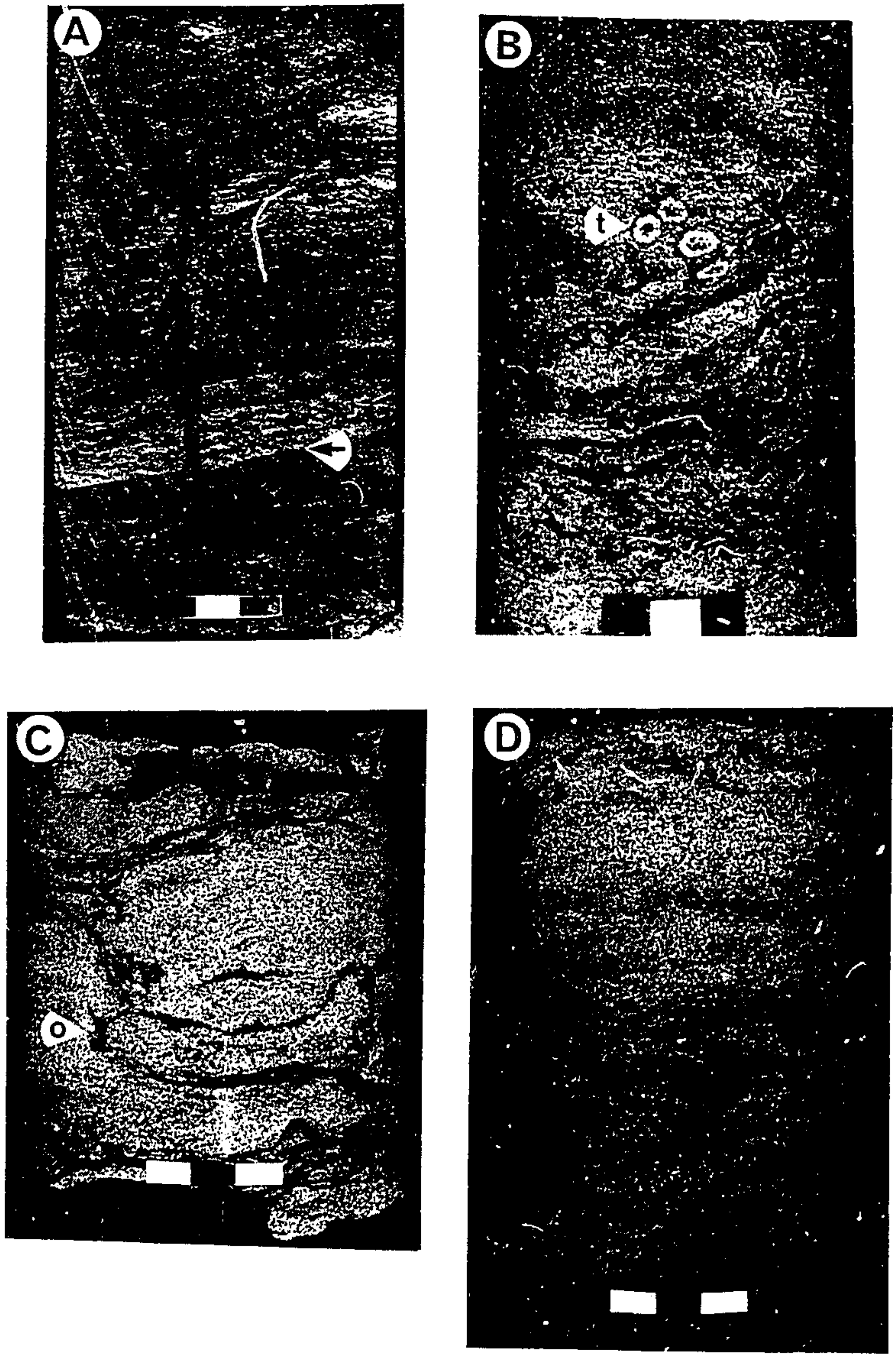

6-9-49-2W5
1371.6-1374
SP

Figure 4.28. Sediments of facies association 9. Scale bars are 3 cm long. (A). Sharp contact (arrow) between the underlying bioturbated mudstone (facies association 1) and the basal part of facies association 9. Core is from 6-9-49-2W5 at 1377 m. (B). *Terebellina* (t) trace fossils from 6-9-49-2W5 (1376 m). (C). *Ophiomorpha* (o) trace fossils from 6-9-49-2W5 (1375 m). (D). Mildly to moderately bioturbated, muddy sandstone from 6-9-49-2W5 (1373 m).


A
B
t
C
o
D

(Fig. 4.28D).

The upper part of facies association 9 consists mainly of interbedded planar laminated and cross bedded sandstone. The sand is fine- to medium-grained and is generally well sorted. Few mudstone laminae and trace fossils are observed. Cross beds are sharp based, uni-directional, 10-20 cm thick and the laminae dip at 12-15°. Contacts between the facies are gradational.

Interpretation

The moderate to thorough degree of bioturbation, abundance of traces from the Cruziana and Skolithos ichnofacies and the high percentage of sand suggest deposition in a relatively moderate to high energy, marine environment. The coarsening-upward nature of the succession suggests shallowing-upward conditions, with the highest energy deposits (cross bedded sandstone) occurring at the very top of the succession.

The CU succession of facies association 9 resembles the CU successions described in facies association 1. However, two significant differences exist - (1) the sharp base, and (2) the high percentage of sand in facies association 9. This will be discussed in more detail in chapter 9.

4.10 Facies Association 10 - Interbedded Mudstone, Sandstone & Conglomerate

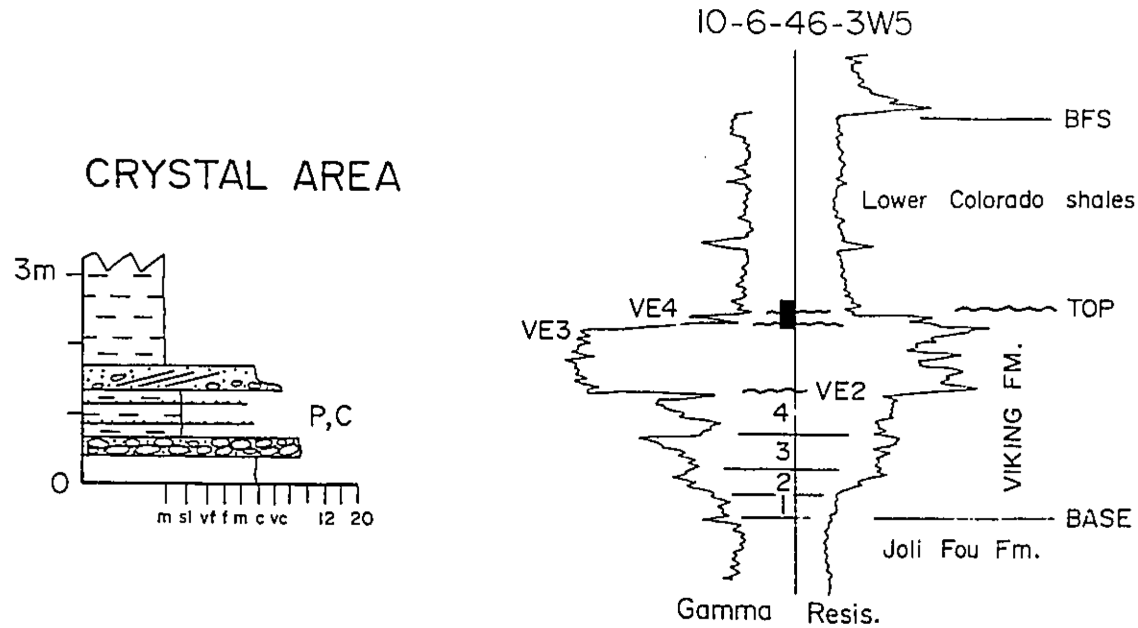
Facies association 10 consists of interbedded mudstone, sandstone and conglomerate which combine to form two types of vertical facies successions; one of which is observed in the Crystal area, the other of which is observed west of Crystal in the Cyn-Pem, Sundance and Edson (CSE) area. Although there are similarities between these two successions, they will be described separately and they will each have a corresponding type well. In the Crystal area, the type well is located at 10-6-46-3W5 (Figs 4.29 & 4.30), while in the CSE area the type well is located at 1-6-55-20W5 (Figs 4.29 & 4.31). Both of these successions rest stratigraphically on top of the regional and valley-fill sediments in the Viking Formation, and are located at the transition between the Viking Formation and the Lower Colorado shales. Facies association 10 is 0.5-2.0 m thick in the Crystal area, and 1.5-7.5 m thick in the CSE area.

In the Crystal area, facies association 10 consists, from bottom to top, of massive conglomerate, striped mudstone, cross bedded sandstone and dark shale (Figs 4.29 & 4.30). This "ideal" succession is not observed in all of the cores. Most cores in the Crystal area consist of the massive conglomerate and the dark shale facies only. The facies are 0.2-1.0 m thick and the vertical contacts between the facies are sharp.

The massive conglomerate beds are sharp based, clast-supported, and consist of well rounded chert and quartz clasts (0.2-5.0 cm in diameter) that are embedded in a coarse- to very coarse-grained sandy matrix. Sideritized mudstone clasts, 1-7 cm in diameter are commonly observed at the base of the conglomerate bed.

Figure 4.29. Type wells for facies association 10 from the Crystal area (10-6-46-3W5; 1734-1738 m) and the Cyn-Pem, Sundance and Edson (CSE) area (1-6-55-20W5; 2672-2679 m). The corresponding resistivity and gamma-ray well logs, and the position of the cores (black bars) are also shown. A core photograph for the Crystal area type well is shown in Figure 4.30, while the core photographs for the CSE area type well is presented in Figure 4.31. Individual facies photographs are shown in Figure 4.32. P - Planolites, C - Chondrites, A - Arenicolites, Z - Zoophycos, T - Terebellina, Tc - Teichichnus, H - Helminthopsis

Facies Association 10



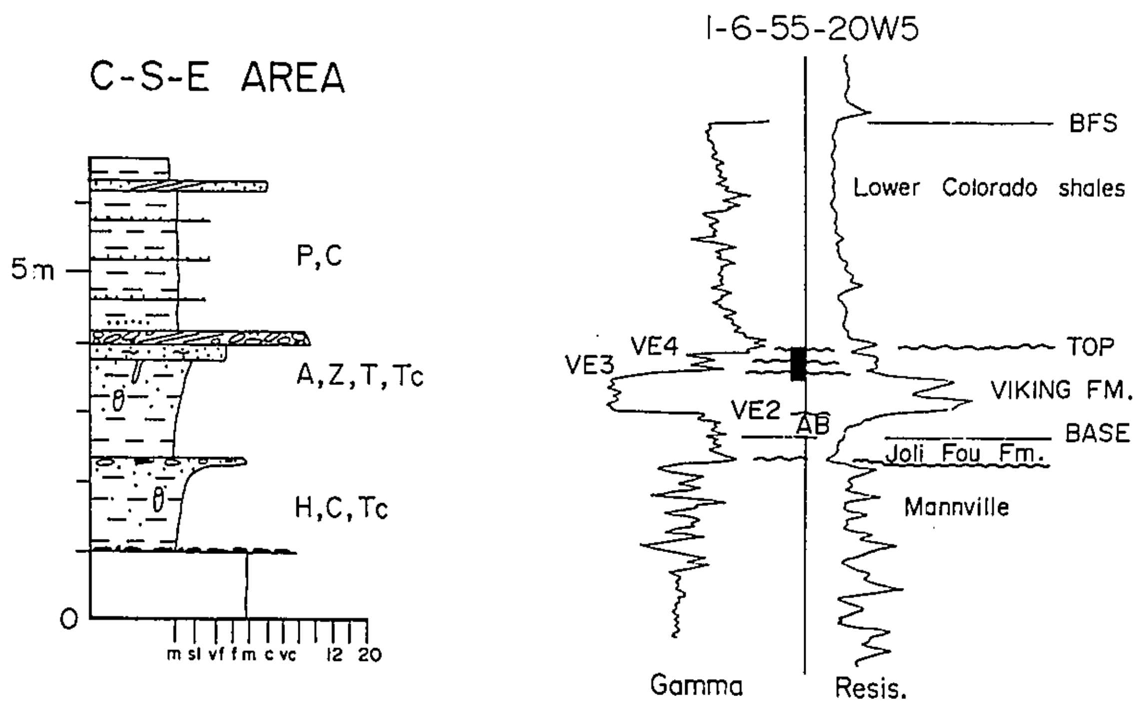
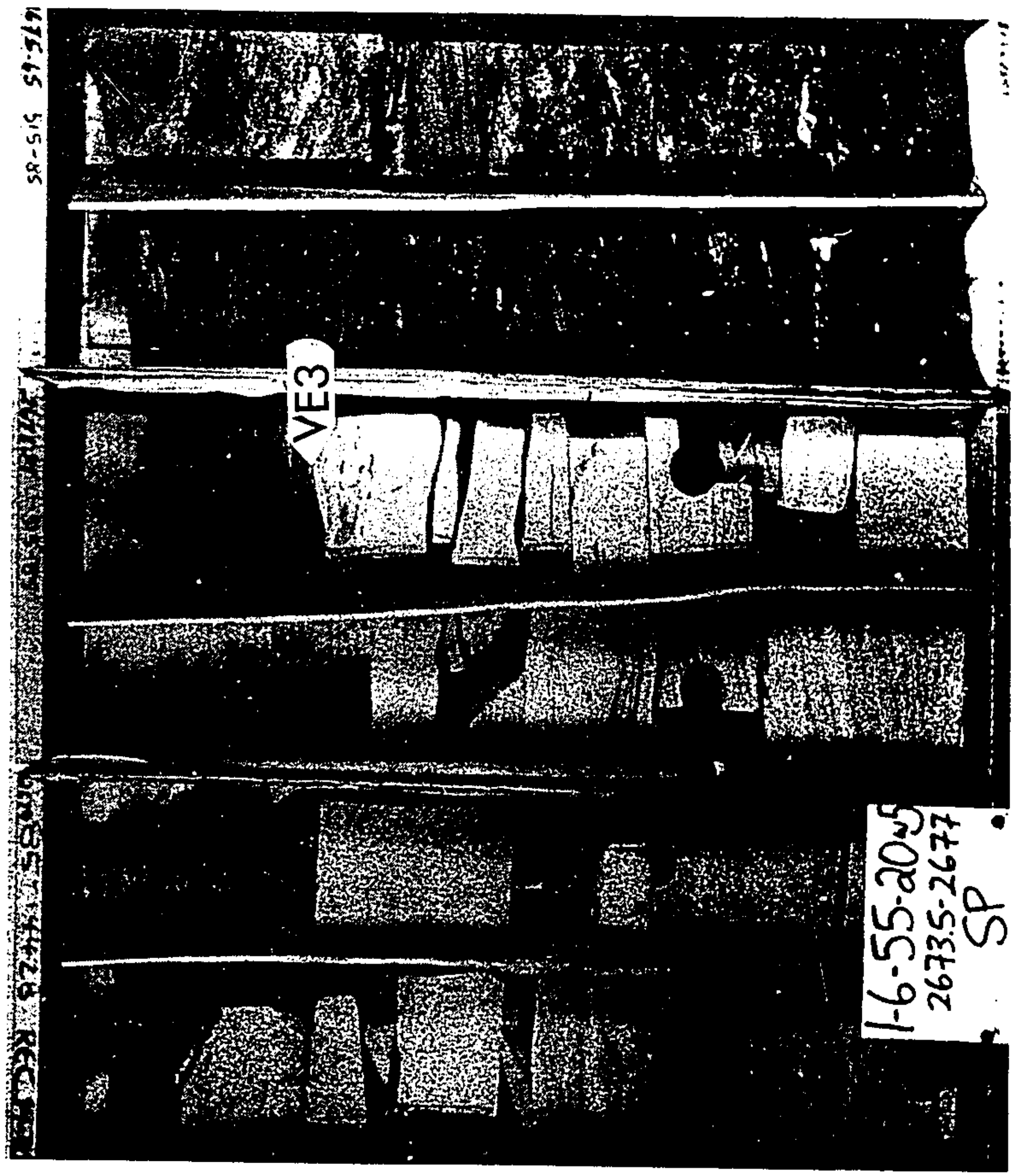
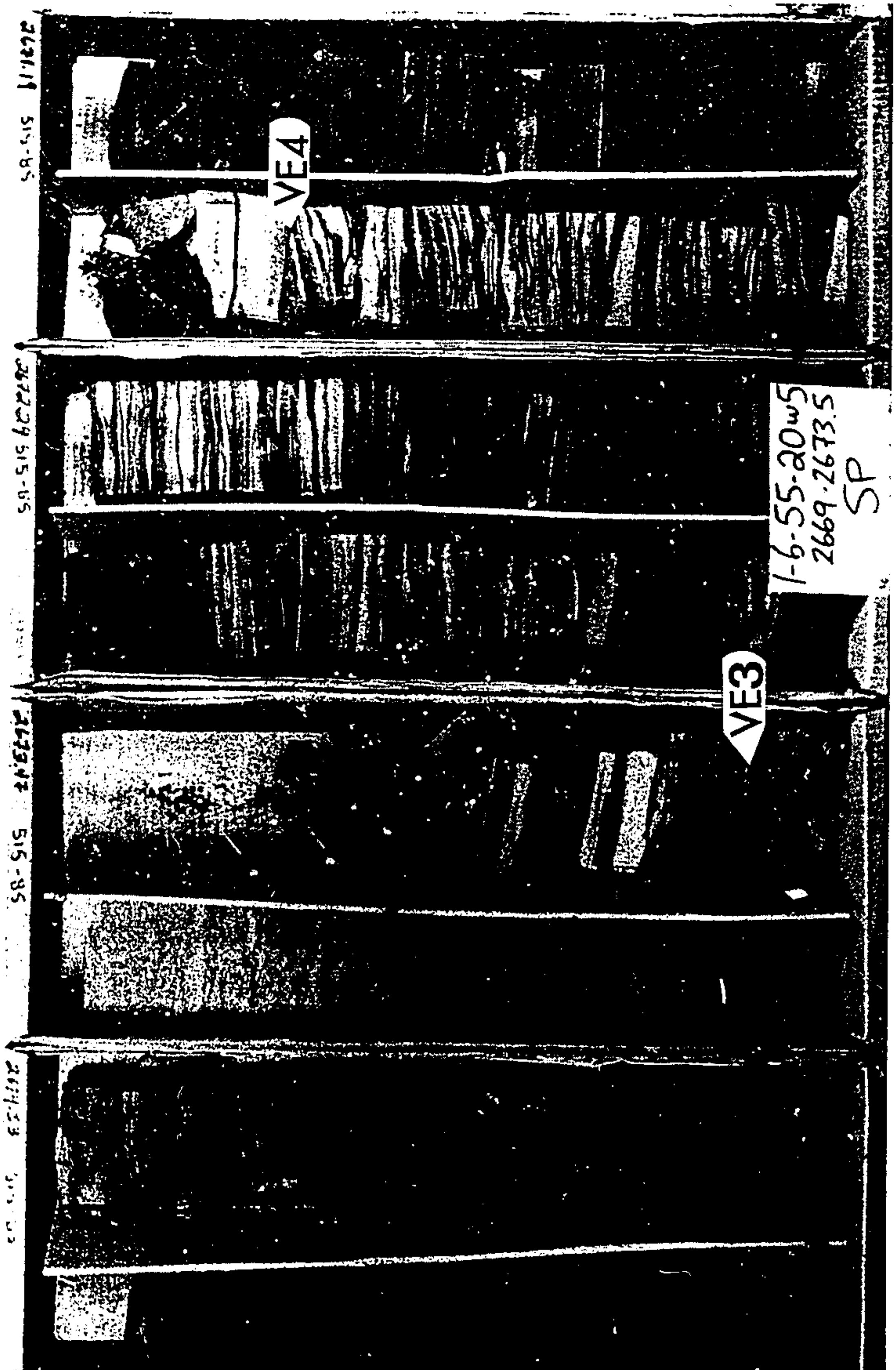


Figure 4.30. A core photograph of the type well (10-6-46-3W5) for facies association 10 from the Crystal area. The succession, from bottom to top, consists of conglomerate (C), striped mudstone (SM), cross bedded sandstone (CB) and dark mudstone (DM). Each core sleeve is approximately 60 cm long and the stratigraphic top is in the upper right corner of the photograph.


VE4
VE3

Figure 4.31. The following two pages show a complete set of core photographs for the type well (1-6-55-20W5) of facies association 10 from the CSE area. Each core sleeve is approximately 60 cm long and the stratigraphic top is in the upper right corner of each photograph.


VE3
1-6-55-20W5
2673.5-2677
SP


VE4
VE3
1-6-55-20w5
2669-2673.5
SP

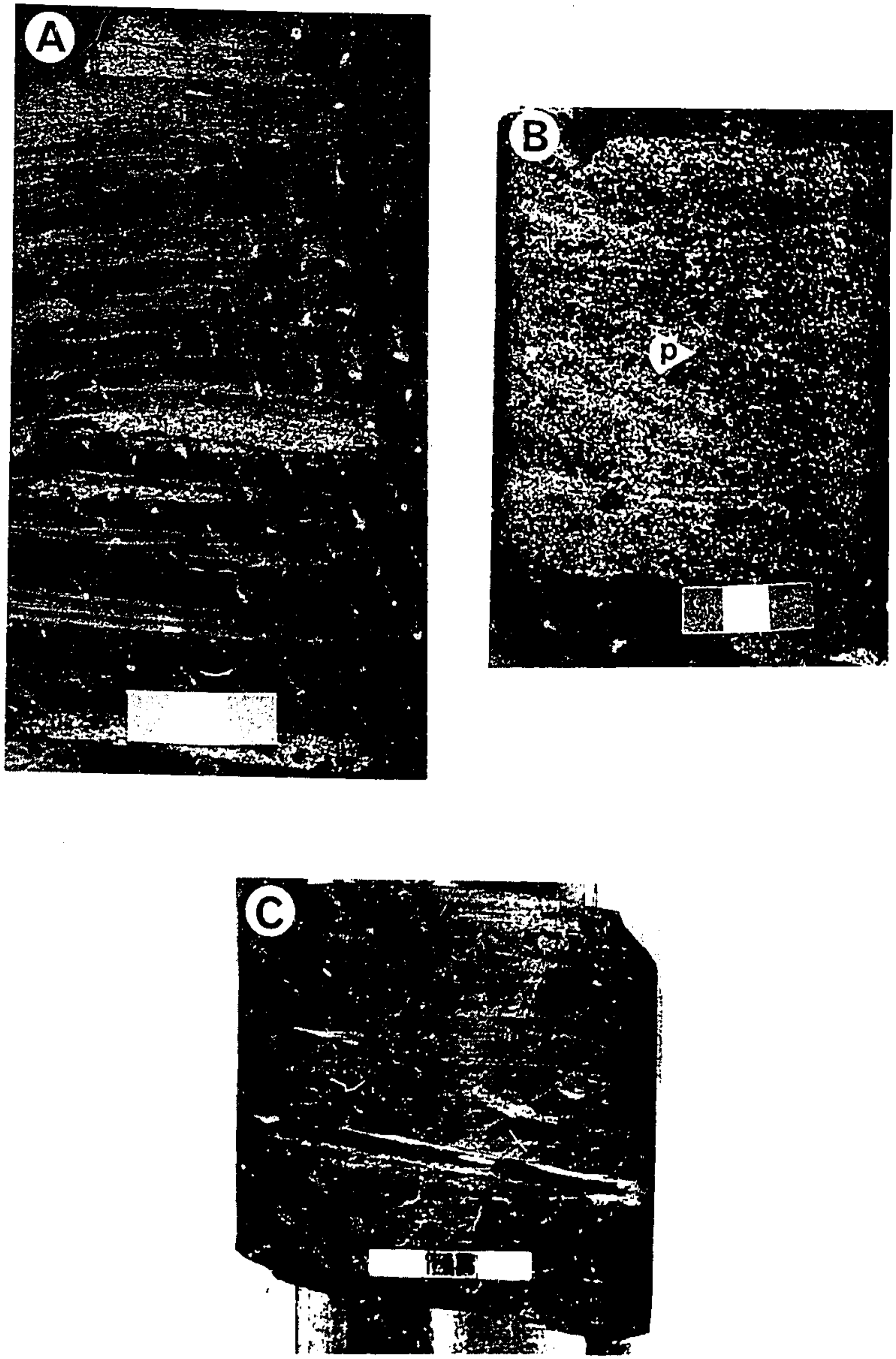
The striped mudstone facies rests stratigraphically on top of the massive conglomerate and consists of interlaminated dark mudstone and fine- to medium-grained sandstone (Fig. 4.32A). The mudstone laminae are 1-10 mm thick, while the sandstone laminae are sharp based, wave rippled and 1-30 mm thick. Some sandstone laminae are planar to ripple cross laminated, normally graded and contain scattered coarse-grained sand or granules. Recognizable trace fossils are rare and include *Planolites*, *Chondrites* and *Skolithos*.

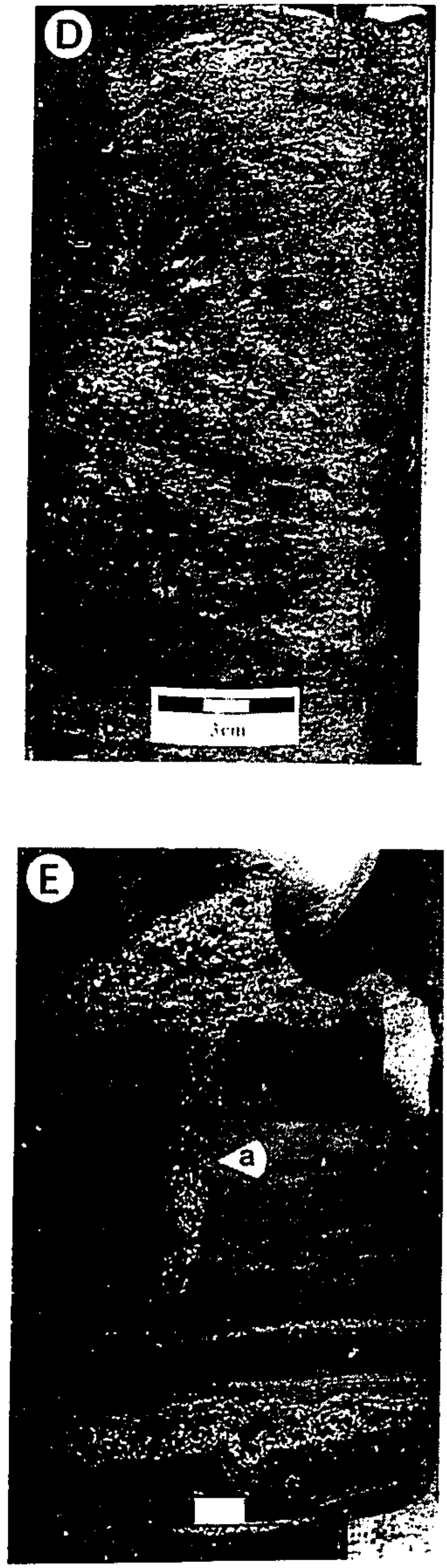
The striped mudstone facies is sharply overlain by the cross bedded sandstone facies. This facies consists of coarse- to very coarse-grained sand, with scattered granules, pebbles and mudstone intra-clasts near the base (Fig. 4.32B). Cross sets are 8-15 cm thick, the foresets dip at 7-22° and the sets are often separated by low angle (2-5°) reactivation surfaces (Fig. 4.32B). Some cross beds show an upward increase in the angle of foreset dip.

The uppermost part of facies association 10 consists of dark grey to black, fissile shale of the Lower Colorado shales. These sediments are monotonous, contain rare discontinuous lenses of wave rippled, fine-grained sandstone and have fish scales scattered throughout (Fig. 4.32C). Rare bentonite or siderite laminae and beds are also observed. The Lower Colorado shales are up to 40 m thick in the Crystal area.

In the CSE area, facies association 10 consists of

Figure 4.32. The following two pages show core photographs of the sediments of facies association 10. Scale bars are 3 cm long. (A). Interlaminated dark mudstone and fine- to medium-grained sandstone from 12-6-46-3W5 (1718 m). This is the striped mudstone facies. (B). Coarse-grained, cross bedded sandstone from 14-1-46-4W5 (1710 m). Note the reactivation surface (arrow) and the scattered pebbles (p). (C). Dark mudstone facies of the Lower Colorado from 8-2-46-4W5 (1765 m). (D). Bioturbated sandy mudstone facies from 7-8-53-13W5 (1968 m). (E). Arenicolites (a) burrow cutting into sideritized, bioturbated sandy mudstone and filled with medium- to coarse-grained sand. Core is from 6-12-51-11W5 (1945 m).


A
B
p
C


D
E
a

(bottom to top) interbedded massive to cross bedded conglomerate, bioturbated sandy mudstone, cross bedded sandstone, striped mudstone, cross bedded sandstone and dark shale (Figs 4.29 & 4.31). These facies occur in beds that are 0.2-2.5 m thick. The vertical facies succession is very similar to that described for the Crystal area. The main difference is the presence of bioturbated sandy mudstone and cross bedded sandstone facies which occur between the conglomerate and striped mudstone facies. The vertical contacts between the facies are sharp.

The bioturbated sandy mudstone beds are 0.3-1.8 m thick, consist of very fine- to fine-grained sand, become sandier and coarser grained upward and are thoroughly bioturbated (Fig. 4.32D). Trace fossils are abundant in these sediments and include <u>Helminthopsis</u>, <u>Chondrites</u>, <u>Teichichnus</u>, <u>Terebellina</u> and <u>Zoophycos</u>. These trace fossils are typical of the <u>Cruziana</u> ichnofacies (Frey & Pemberton, 1984). Bentonite layers, up to 4 cm thick, are also observed.

The bioturbated sandy mudstone facies occur in CU successions that have sharp, erosional tops. Most cores have 1-3 CU successions. The upper contact of these CU successions is marked by a thin lag of granules and mudstone clasts, siderite and <u>Arenicolites</u> burrows. The <u>Arenicolites</u> burrows cut into the underlying bioturbated mudstone, are 5-30 cm long and are filled with medium- to coarse-grained sand (Fig. 4.32E). These burrows are typical of the

Glossifungites ichnofacies (Frey & Pemberton, 1984).

In general, the bioturbated sandy mudstone beds are either interbedded with, or overlain by, the cross bedded sandstone facies. The cross bedded sandstone beds are medium- to coarse-grained, 0.2-2.5 m thick, contain interlaminated mudstone and have sharp lower contacts with the bioturbated sandy mudstone facies. Angular to rounded mudstone intra-clasts are also observed.

The striped mudstone deposits occur stratigraphically above the interbedded bioturbated sandy mudstone and cross bedded sandstone facies package, and are similar to those described in the Crystal area (Fig. 4.32A). A similar vertical facies succession occurs upward, as the striped mudstone facies is overlain by cross bedded sandstone, which is in turn overlain by the dark shales of the Lower Colorado shales (Fig. 4.29).

Interpretation

In the Crystal area, facies association 10 is interpreted as a transgressive-regressive-transgressive facies succession. The lowermost facies of this succession (conglomerate and striped mudstone) represent the initial transgressive phase of facies association 10. The conglomerate facies has a sharp base and consists of large pebbles and sideritized mudstone intra-clasts and is interpreted as a transgressive, erosional lag. The striped mudstone facies has little bioturbation, small traces typical of the *Cruziana* and *Skolithos* ichnofacies, and an abundance of mudstone suggesting deposition in a quiet water, marine environment.

Resting sharply on top of the striped mudstone deposits are the cross bedded sandstone beds. These sediments represent the regressive phase of the facies succession. The coarse-grained nature and the presence of mudstone intra-clasts is indicative of deposition by strong currents in a relatively high energy environment.

The uppermost facies in facies association 10 are the dark shales of the Lower Colorado shales, which represent the final transgressive phase of this facies succession. The lack of sand, presence of fish scales and abundance of very dark shale suggest deposition in a fully marine, low energy environment, below fair weather wave base. These shales are typical of the outer to inner shelf region.

In the Cyn-Pem, Sundance and Edson (CSE) area, the deposits of facies association 10 also form a transgressive-regressive-transgressive facies succession. Therefore, the interpretations of the conglomerate, striped mudstone, cross bedded sandstone and dark shale in the Crystal area can also be applied to the equivalent sediments in the CSE area. However, additional CU facies successions occur in the CSE area between the conglomerate and striped mudstone facies. The pervasive bioturbation and the abundance, diversity and type of trace fossils, along with the relatively fine-grained nature of the CU successions suggest deposition in a low to moderate energy, fully marine environment. These successions are interpreted as shallowing-upward, inner shelf to lower shoreface deposits.

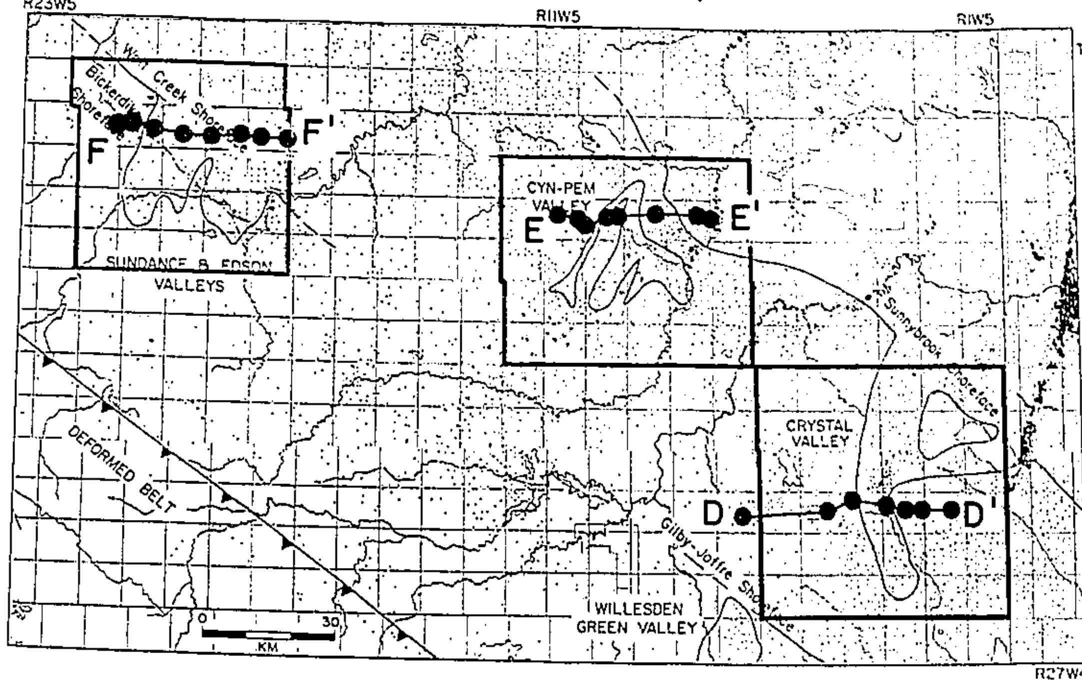
CHAPTER 5 - REGIONAL SEDIMENTS

Regional sediments occur throughout the study area and constitute the entire thickness of the Viking in areas devoid of valley-fill and shoreface deposits. The regional sediments are the oldest deposits of the Viking, and rest stratigraphically between the Joli Fou Formation mudstones (below) and the VE2, VE3 or VE4 erosion surface (above). They consist of a stack of coarsening-upward (CU) facies successions and comprise facies association 1 - bioturbated CU successions (Figs 4.2, 4.3 & 4.4). The reader is referred to section 4.1 for a complete description of the sedimentology of facies association 1.

Each regional CU succession has a sheet-like geometry and can be traced over a relatively large area (Figs 3.3, 3.5 & 3.6). Boreen (1990) has identified three regional successions, A, B1 and B2, in the Willesden Green area of south-central Alberta and has successfully correlated these over the area T39-43, R4W5-8W5. These deposits comprise allomembers A and B (Boreen & Walker, 1991; Fig. 3.1). A. D. Reynolds (pers. comm., 1989) suggests that a basinwide erosion surface, VE1, occurs between successions A and B1 in an area northeast of Willesden Green. In the Willesden Green (Boreen, 1990) and Crystal areas, VE1 cannot be identified as an erosion surface, and is presumably a correlative conformity. Strictly, the regional deposits of these areas should be re-defined as <u>one</u> allomember.

Figure 5.1. The location of cross sections DD', EE', FF', GG', and HH'. The Crystal (T43-48, R1W5-6W5), Cyn-Pem (T49-53, R7W5-12W5), and Sundance and Edson (T51-55, R18W5-22W5) areas are also shown. These areas contain the greatest density of well logs and cores used in this research (Figs 1.5 & 1.6).

CROSS SECTIONS DD', EE' & FF'



CROSS SECTIONS GG' & HH'

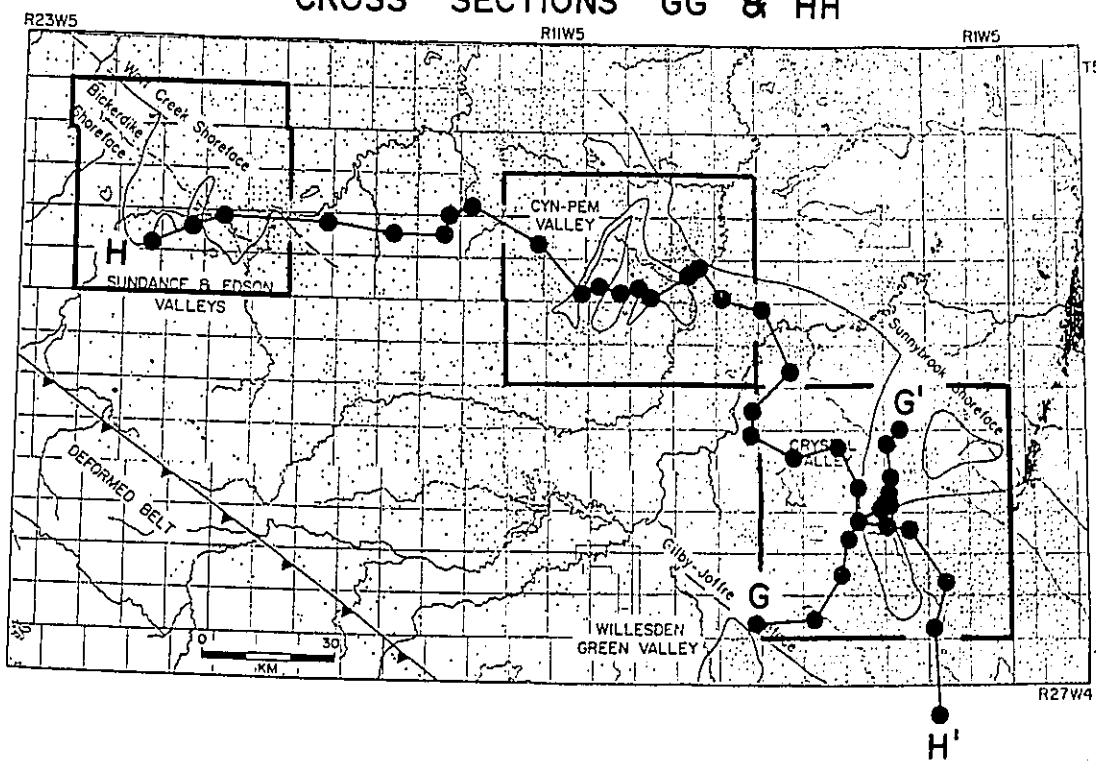
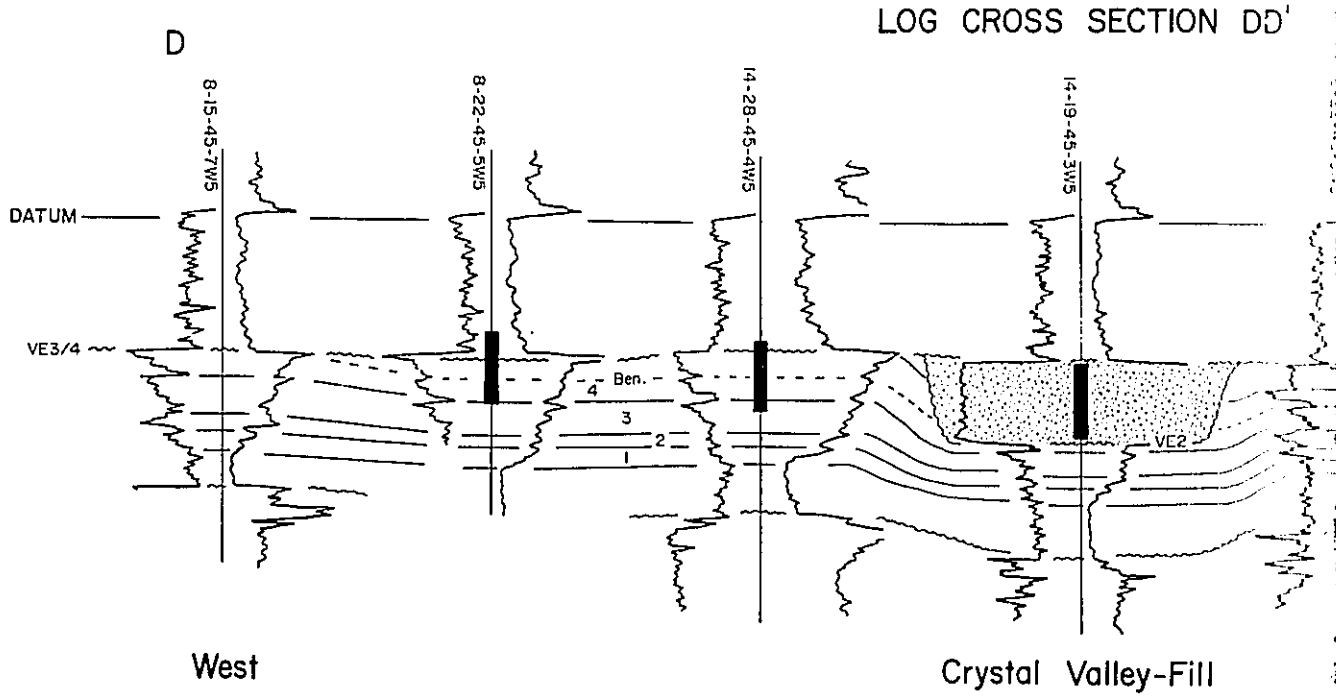
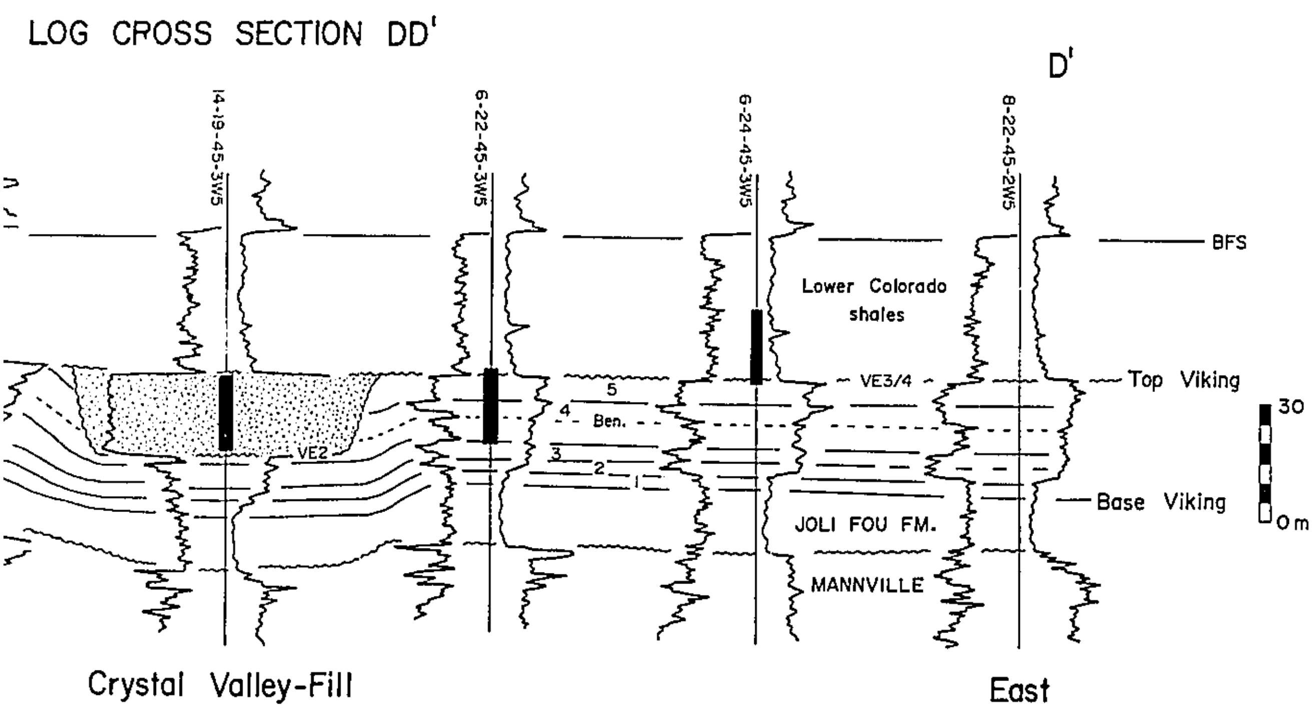


Figure 5.2. Well log cross section DD' from the Crystal area. This cross section is oriented west to east and is approximately 50 km long. Regional successions 1 to 5 occur stratigraphically between the Joli Fou mudstones (below) and the VE2 or the VE3/4 erosion surface. The Crystal valley-fill deposits (stiple) are observed in 14-19-45-3W5. The BFS log marker is the datum and the location is shown in Figure 5.1.


LOG CROSS SECTION DD'
D
8-15-45-7W5
8-22-45-5W5
14-28-45-4W5
14-19-45-3W5
DATUM
VE3/4
Ben.
4
3
2
1
VE2
West
Crystal Valley-Fill



LOG CROSS SECTION DD'
D'
14-19-45-3W5
6-22-45-3W5
6-24-45-3W5
8-22-45-2W5
BFS
Lower Colorado shales
VE3/4
Top Viking
5
4
Ben.
3
2
1
VE2
Base Viking
JOLI FOU FM.
MANNVILLE
30
0 m
Crystal Valley-Fill
East

In the Crystal area, Reinson (1985) and Reinson et al. (1988) recognize three or four regional, shelf-shoreface cycles which are used as marker beds in their log correlations. These cycles are observed in most well logs and cores in the Crystal area. However, detailed correlations and mapping of these cycles has not been attempted.

This chapter has three main objectives. The first objective is to correlate the regional CU successions across the study area, including the successions identified at Crystal (Reinson, 1985), Willesden Green (Boreen, 1990), Cyn-Pem, Sundance and Edson.

The second objective is to unravel the stacking pattern of the successions and to relate this pattern to shelf sedimentation. Specifically, the orientation of the regional shoreline trends and the relationship between shelf sedimentation and relative sea level change will be examined.

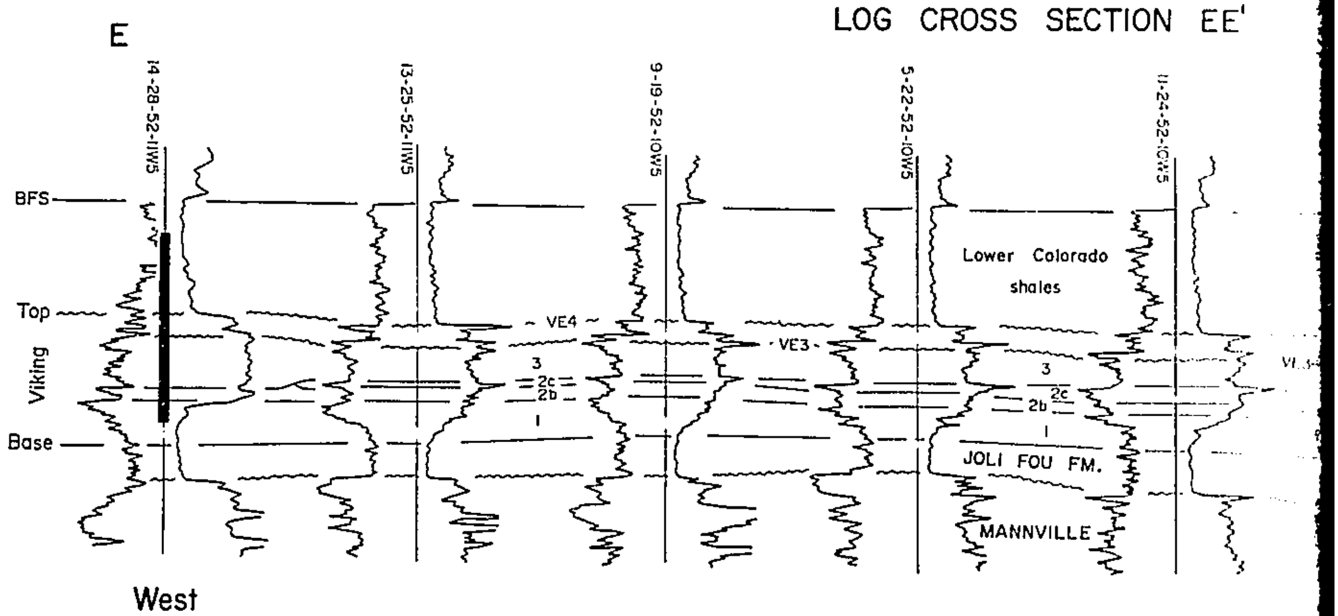
The third objective is to set up a regional stratigraphy so that the valley-fill and shoreface deposits can be confidently separated from the surrounding regional deposits. This will make it easier to determine the depth of incision of the valleys and shorefaces.

5.1 Regional Correlation

Approximately 2500 well logs, 198 cores and a grid of 52 cross sections have been used to unravel the regional stratigraphy. Originally, the stratigraphy and

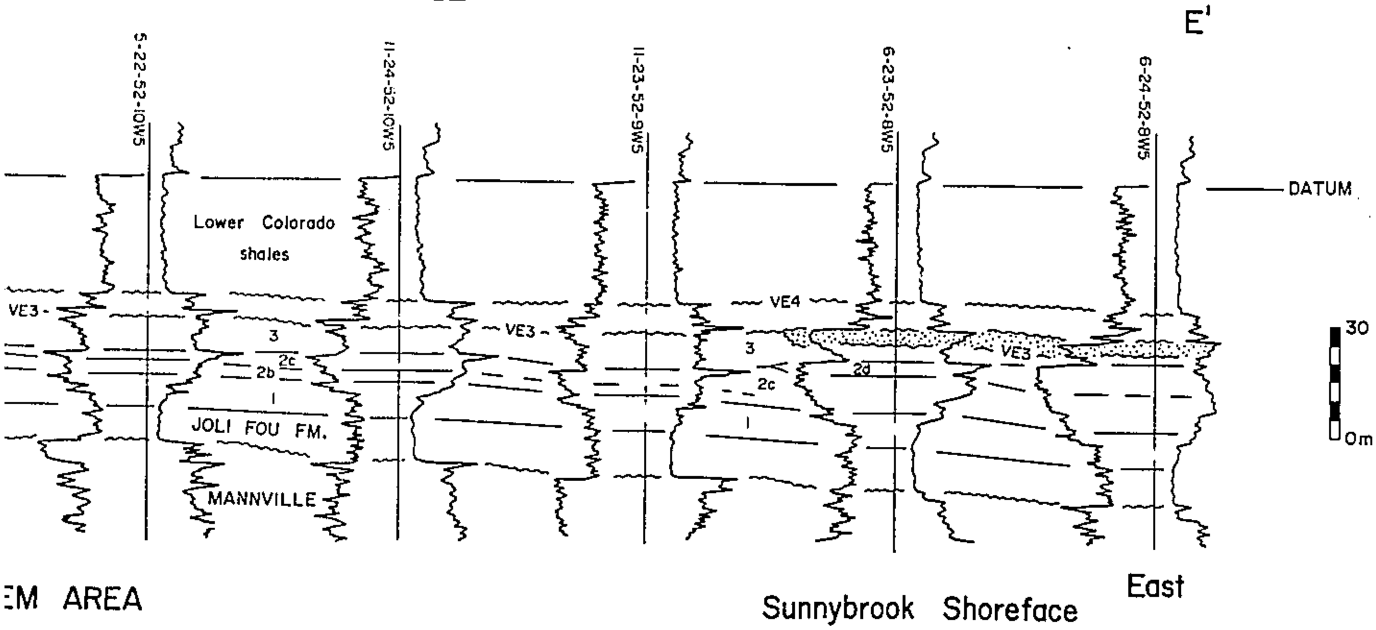
Figure 5.3. Well log cross section EE' from the Cyn-Pem area. This cross section is oriented west to east and is approximately 40 km long. Regional successions 1, 2b, 2c, 2d and 3 occur stratigraphically between the Joli Fou mudstones (below) and the VE3 erosion surface. Note the abrupt thickening of successions 2c (11-24-52-10W5) and 2d (6-23-52-8W5). The Sunnybrook shoreface deposits are encased by the VE3 erosion surface and are observed at 6-23-52-8W5 and 6-24-52-8W5. Transgressive deposits occur stratigraphically between the VE3 (below) and the VE4 erosion surfaces. The BFS log marker is the datum and the location is shown in Figure 5.1.

LOG CROSS SECTION EE'



CYN-PEM AREA

LOG CROSS SECTION EE'



sedimentology of the regional deposits were studied in three separate areas; Crystal, Cyn-Pem, and Sundance and Edson (Fig. 5.1). These results were later combined into a set of regional correlations.

The Crystal area was the first to be studied because of the superb core and well log data base (Figs 1.5 & 1.6). Five CU successions were identified and these were labelled 1 to 5 (Fig. 5.2). Further work resulted in the identification of seven CU successions in the Cyn-Pem area (Fig. 5.3), and five CU successions in the Sundance and Edson area (Fig. 5.4).

Well log and core correlations (Figs 5.2, 5.3, 5.4, 5.5 & 5.6) revealed that the original nomenclature for the regional successions in the Crystal area could also be used for the successions in the Cyn-Pem, Sundance and Edson areas. Succession 1 splits into five smaller successions in the Sundance and Edson area and these are labelled 1a to 1e (Figs 5.4 & 5.6). Succession 2 splits into four smaller successions in the Cyn-Pem area and these are labelled 2a to 2d (Figs 5.3 & 5.6). Successions 3, 4 and 5 are "single" successions and do not split into smaller successions (Fig. 5.6). Therefore, there are 12 CU successions observed in the regional deposits of the study area.

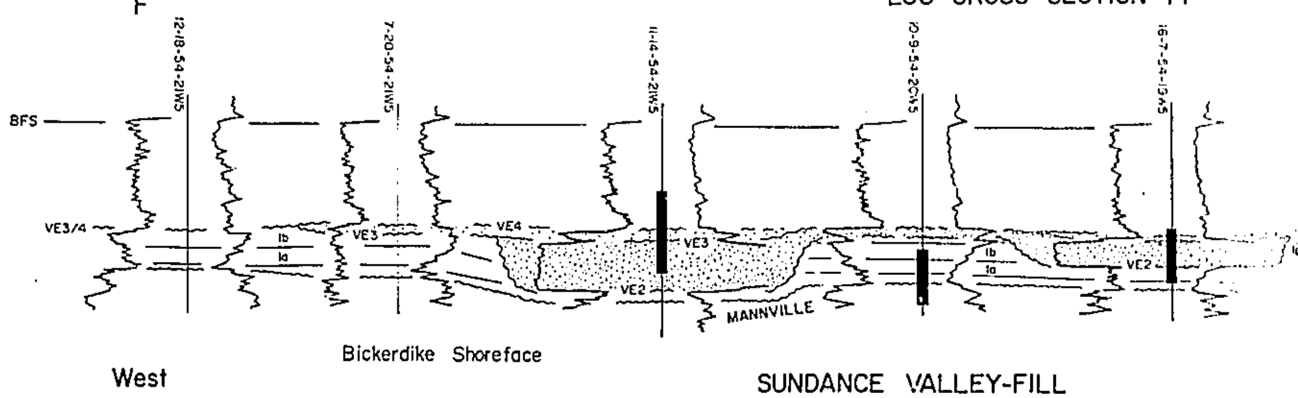
5.1.1 <u>Willesden Green to Crystal</u>

The three regional CU successions identified in the Willesden Green area (A, B1 & B2; Fig. 5.7; Boreen, 1990) are correlative with the CU successions in the Crystal area.

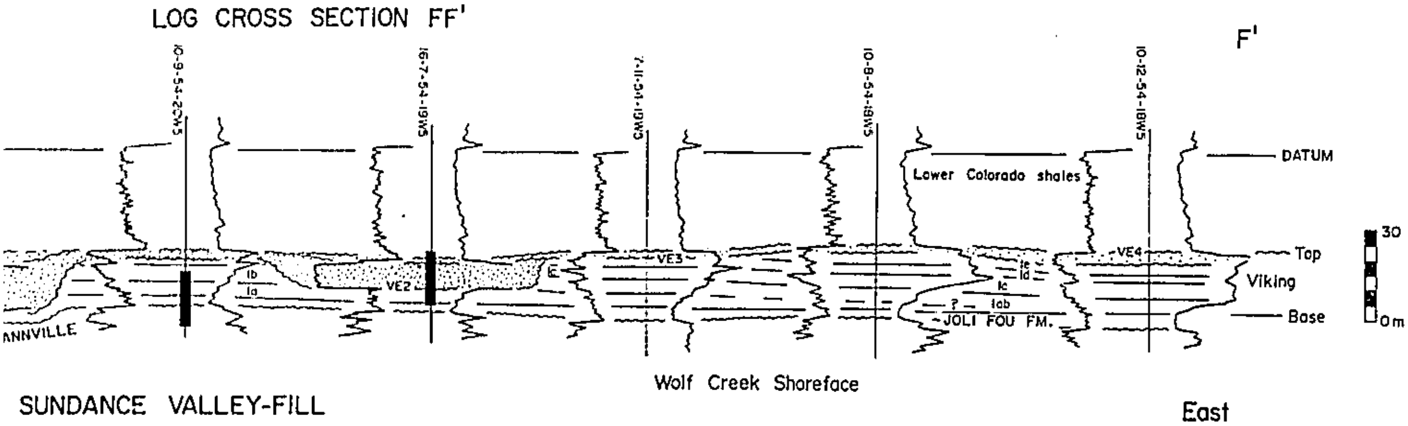
Figure 5.4. Well log cross section FF' from the Sundance and Edson area. This cross section is oriented west to east and is approximately 40 km long. Regional successions 1a to 1e occur stratigraphically between the Joli Fou mudstones (below) and the VE2, VE3 or VE3/4 erosion surface. Successions 1a and 1b amalgamate into one succession (1ab) in the east (10-8-54-18W5). Successions 1d and 1e are only observed in the east of R19W5.

The Sundance valley-fill deposits (dense stiple) are bounded by the VE2 (below) and the VE3 erosion surfaces. The Bickerdike and Wolf Creek shoreface deposits (light stiple) are also shown. The BFS log marker is used as the datum and the location of this cross section is shown in Figure 5.1.

LOG CROSS SECTION FF'



LOG CROSS SECTION FF'



The results of this well log and core correlation are shown in Figure 5.5. Succession 1 is correlative with the lower part of allomember A, succession 2 is correlative with the upper part of A, succession 3 corresponds to B1, succession 4 corresponds to B2, and succession 5 is not observed in the Willesden Green area (e.g. 6-12-43-7W5; Figs 5.5 & 5.7).

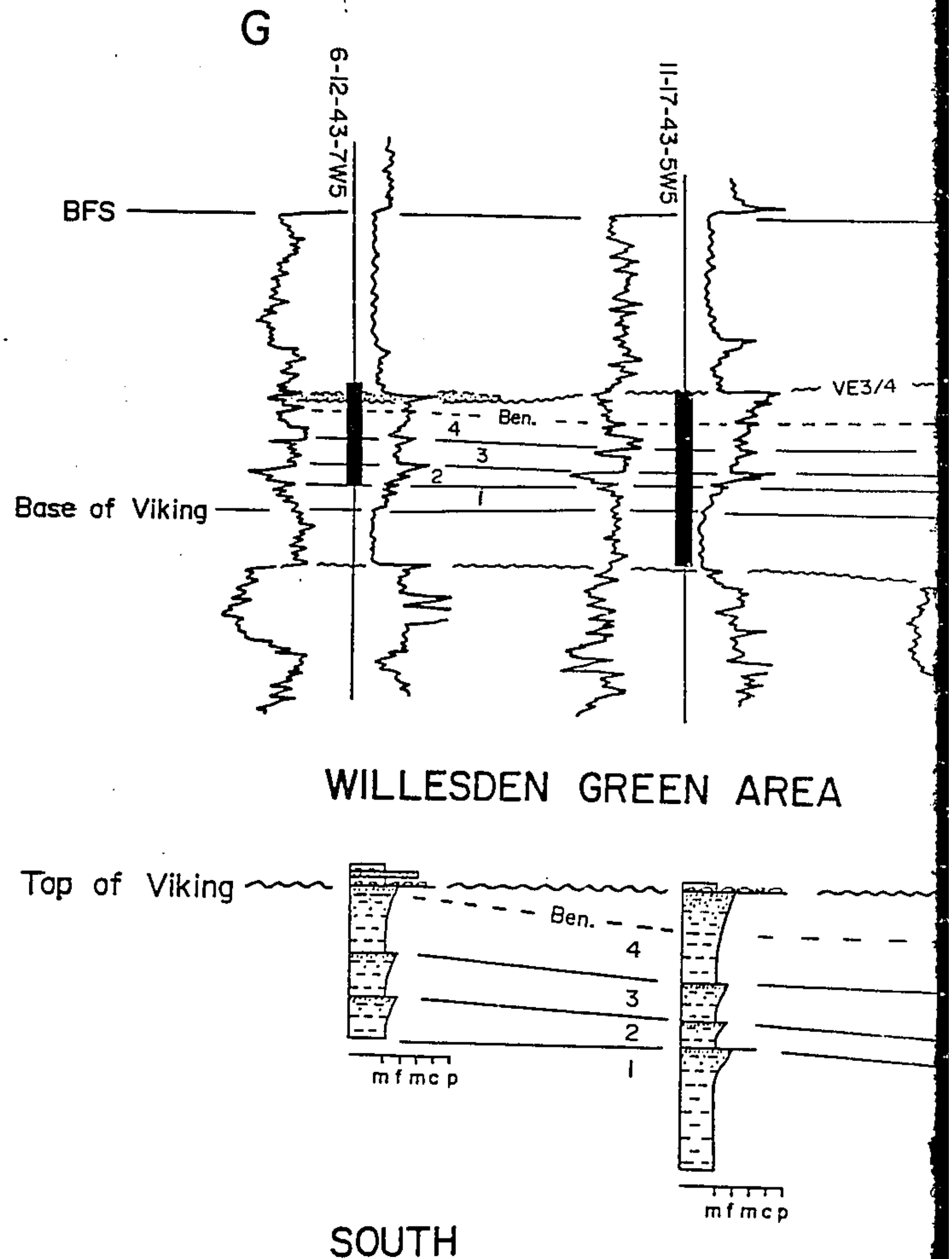
The correlation of the regional CU successions between Willesden Green and Crystal suggest that these successions have a wide lateral extent. These correlations expand and strengthen the allostratigraphy developed by Boreen and Walker (1991).

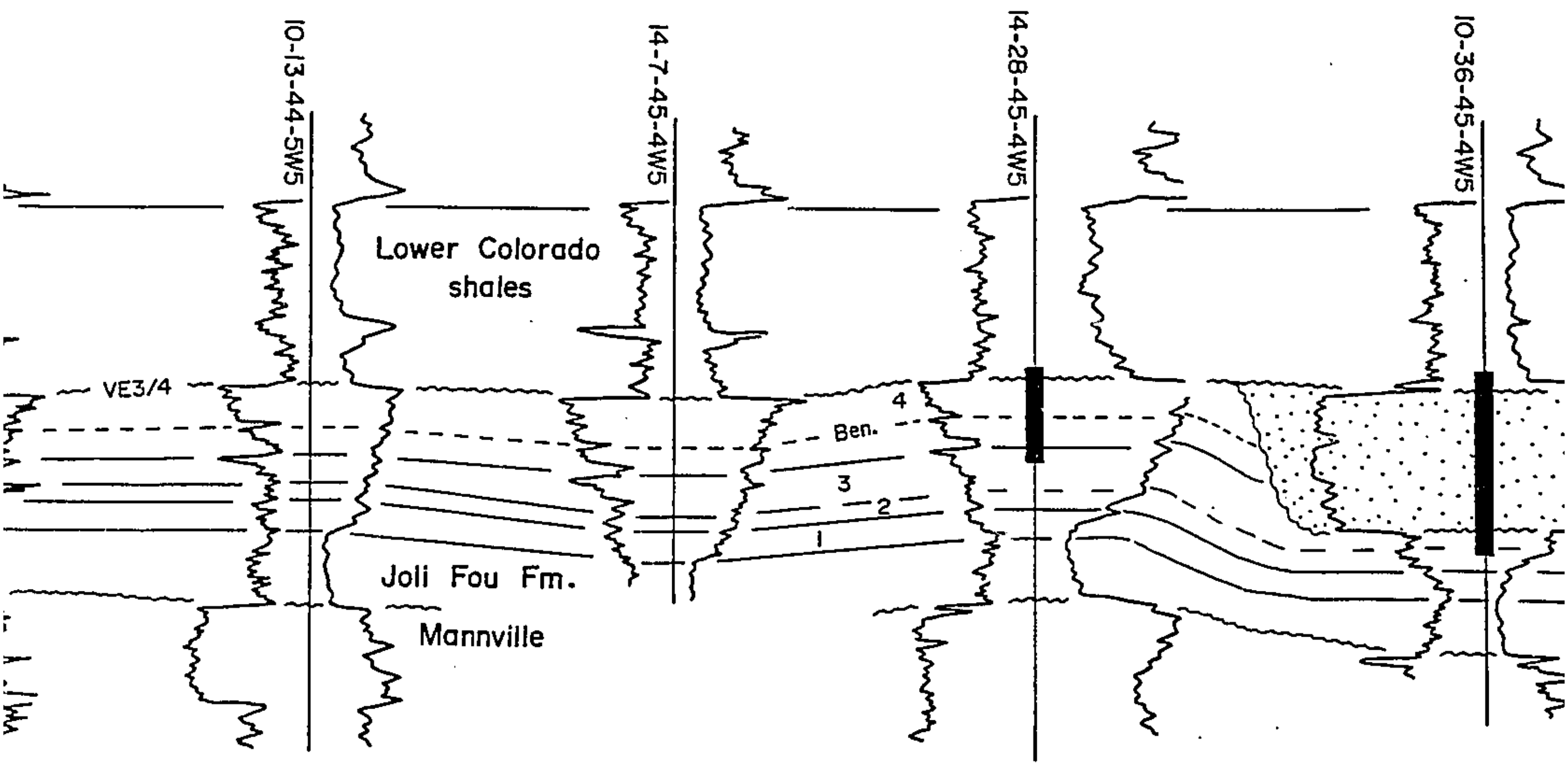
5.1.2 Sundance to Crystal

The regional stratigraphy becomes much more complex to the northwest of Crystal. Successions 1 and 2 split into smaller successions (Figs 5.3, 5.4 & 5.6), and individual successions become sandier and thicker, making it difficult to distinguish between valley-fill and regional deposits on well logs. Also, it is difficult to correlate individual successions between Cyn-Pem and Edson because the data base is relatively small (Figs 1.5, 1.6 & 5.1).

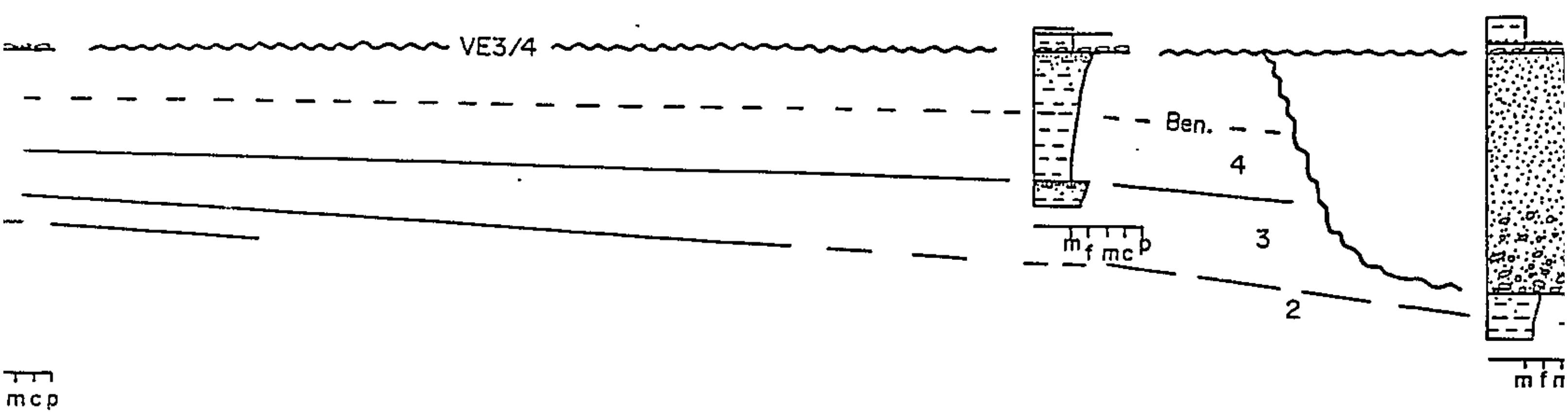
Nevertheless, regional succession 1 begins to split in the western part of the Crystal area, as shown by the three smaller successions observed in 14-19-47-3W5 (1564-1566 m). The splitting of succession 1 becomes more prominent in the Cyn-Pem area (e.g. 2 smaller successions in 15-2-52-10W5; 1756-1763.5 m), and is very pronounced in the Sundance and Edson area. The splitting of regional succession 2 is

Figure 5.5. Well log and core cross section GG' from the Willesden Green to Crystal areas. This cross section is oriented south to north, consists of 15 wells and is approximately 65 km long. Regional successions 1 to 4 can be correlated between Crystal and Willesden Green. Succession 2 is relatively muddy in some parts of the Crystal area and, therefore, merges with succession 3 in core (e.g. 10-36-45-4W5, 10-1-46-4W5, 9-1-46-4W5 & 14-17-46-3W5). Regional succession 5 is not observed west of R4W5. The datum for the well log cross section is the BFS log marker, and the black bars indicate core positions. In contrast, the datum for the core cross section is the top of the Viking or the VE3/4 erosion surface. The location of this cross section is shown in Figure 5.1.

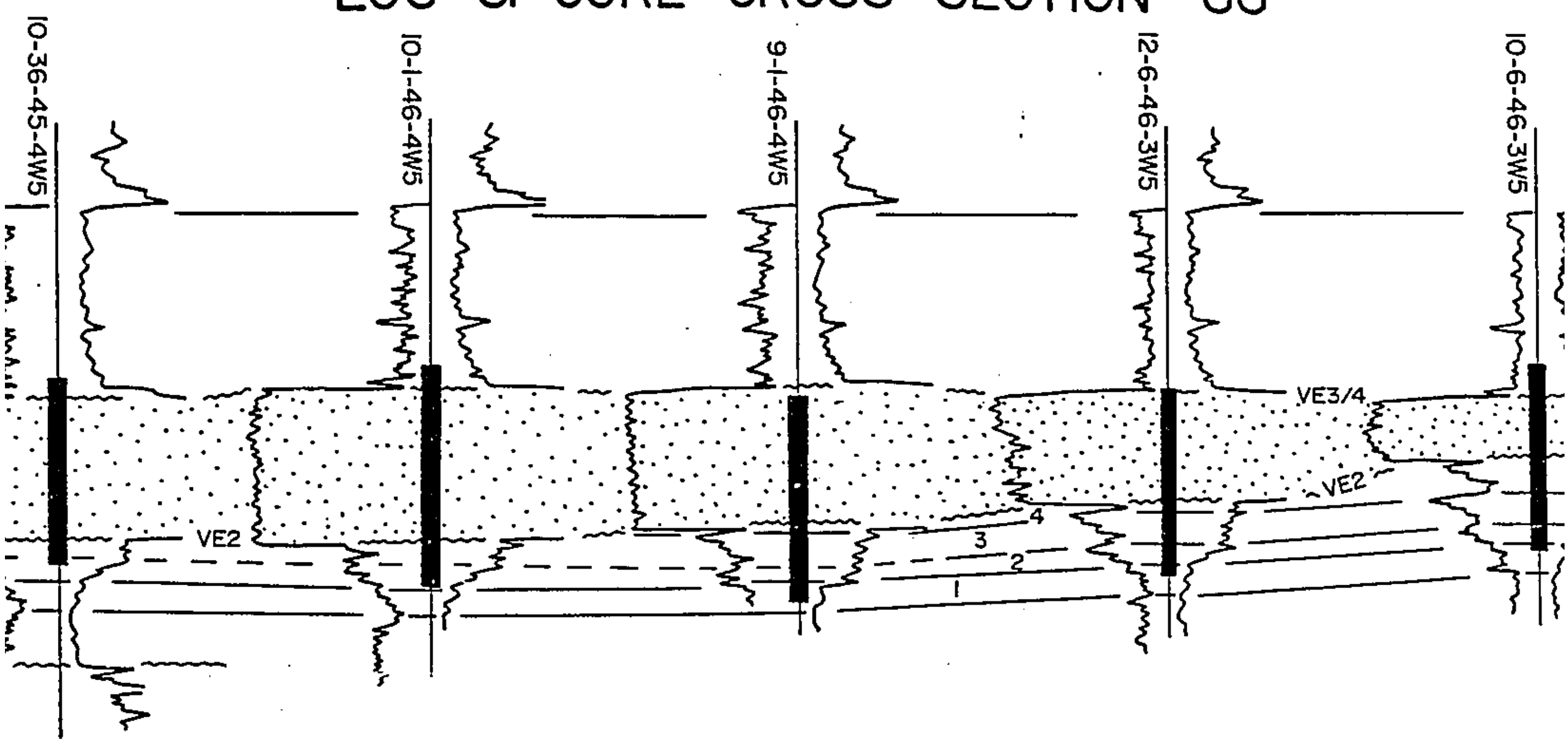

G
6-12-43-7W5
11-17-43-5W5
BFS
VE3/4
Ben.
4
3
2
1
Base of Viking
WILLESDEN GREEN AREA
Top of Viking
Ben.
4
3
2
1
m f m c p
m f m c p
SOUTH


10-13-44-5W5
14-7-45-4W5
14-28-45-4W5
10-36-45-4W5
Lower Colorado shales
VE3/4
4
Ben.
3
2
1
Joli Fou Fm.
Mannville

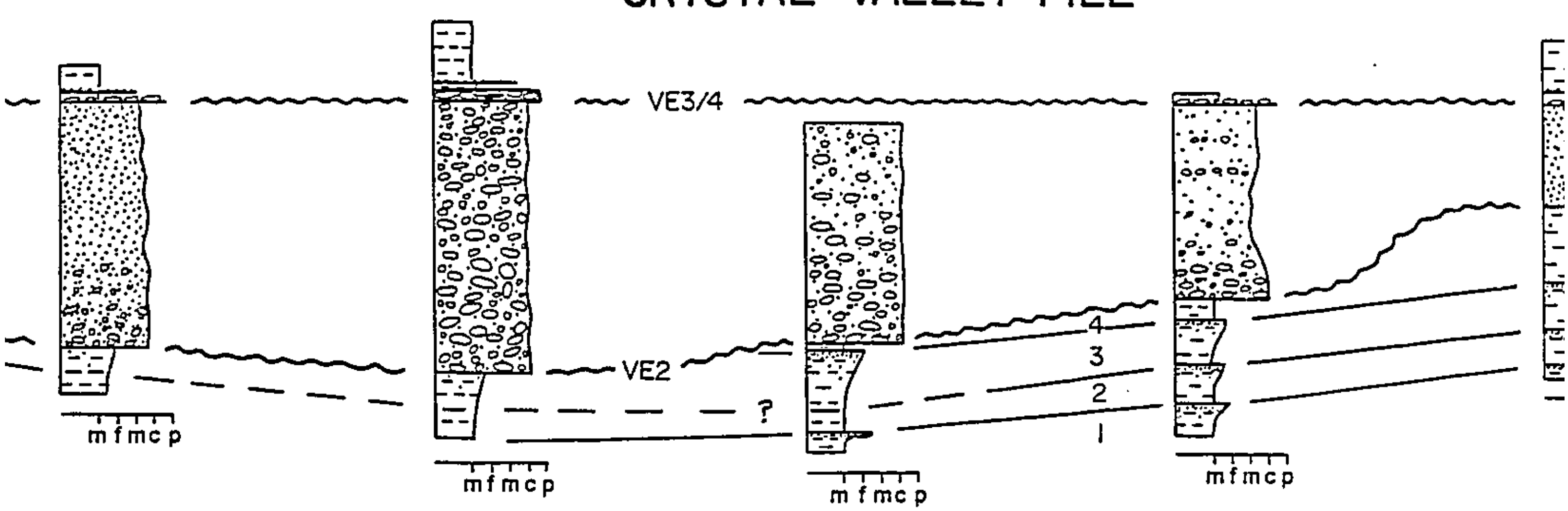
AREA

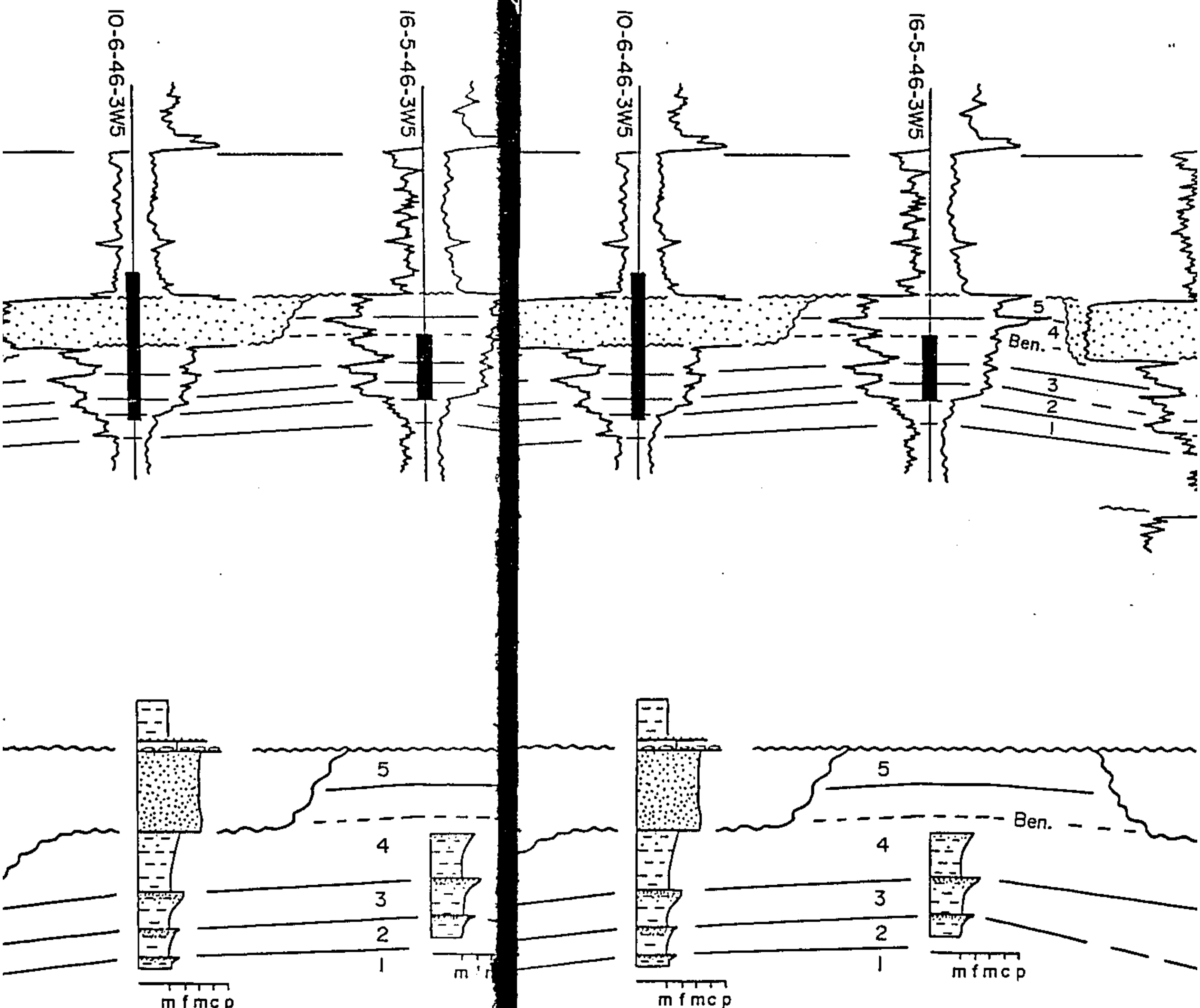

VE3/4
Ben.
4
3
2
m f m c p
m c p

LOG & CORE CROSS SECTION GG'

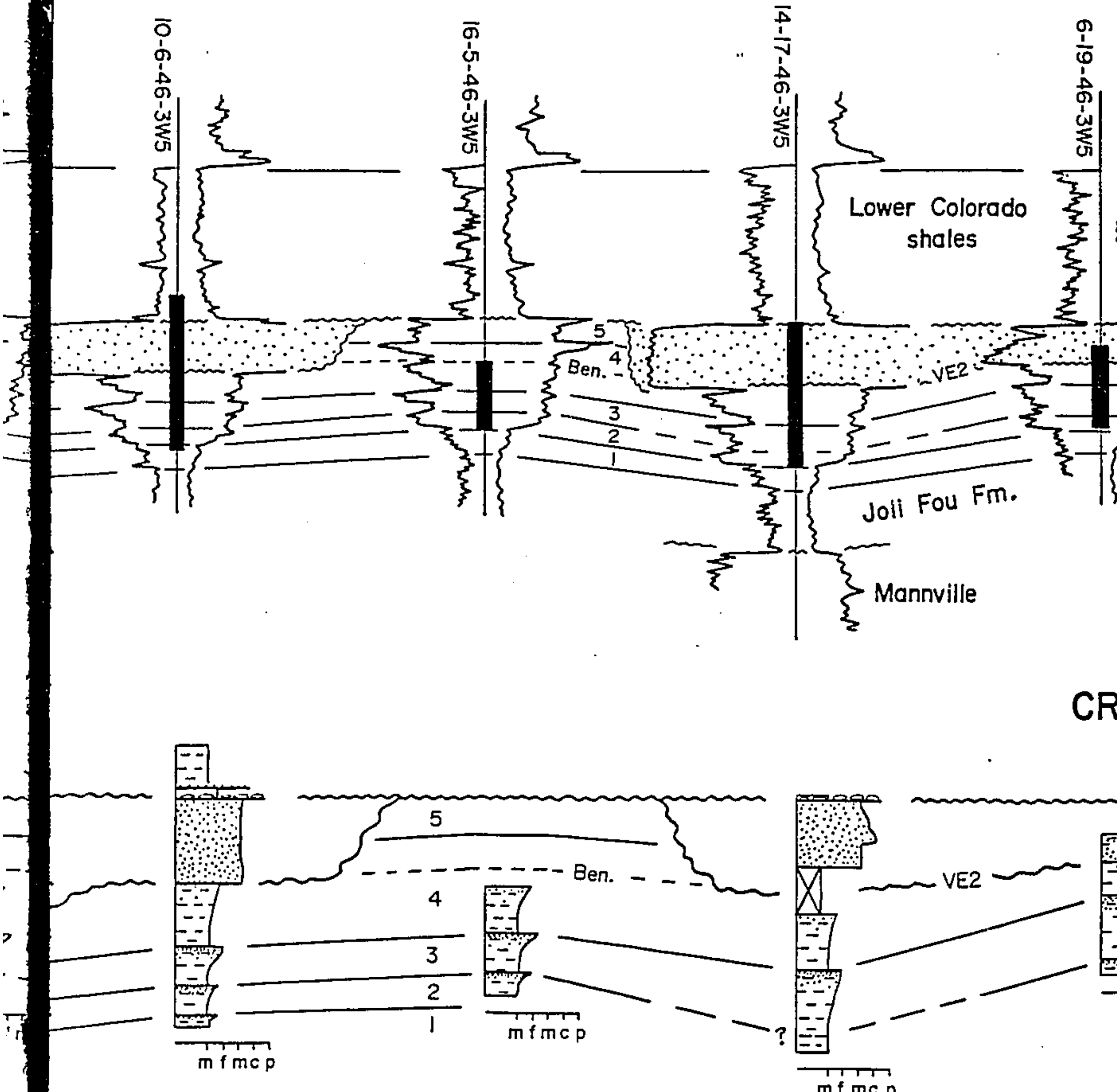


CRYSTAL VALLEY-FILL

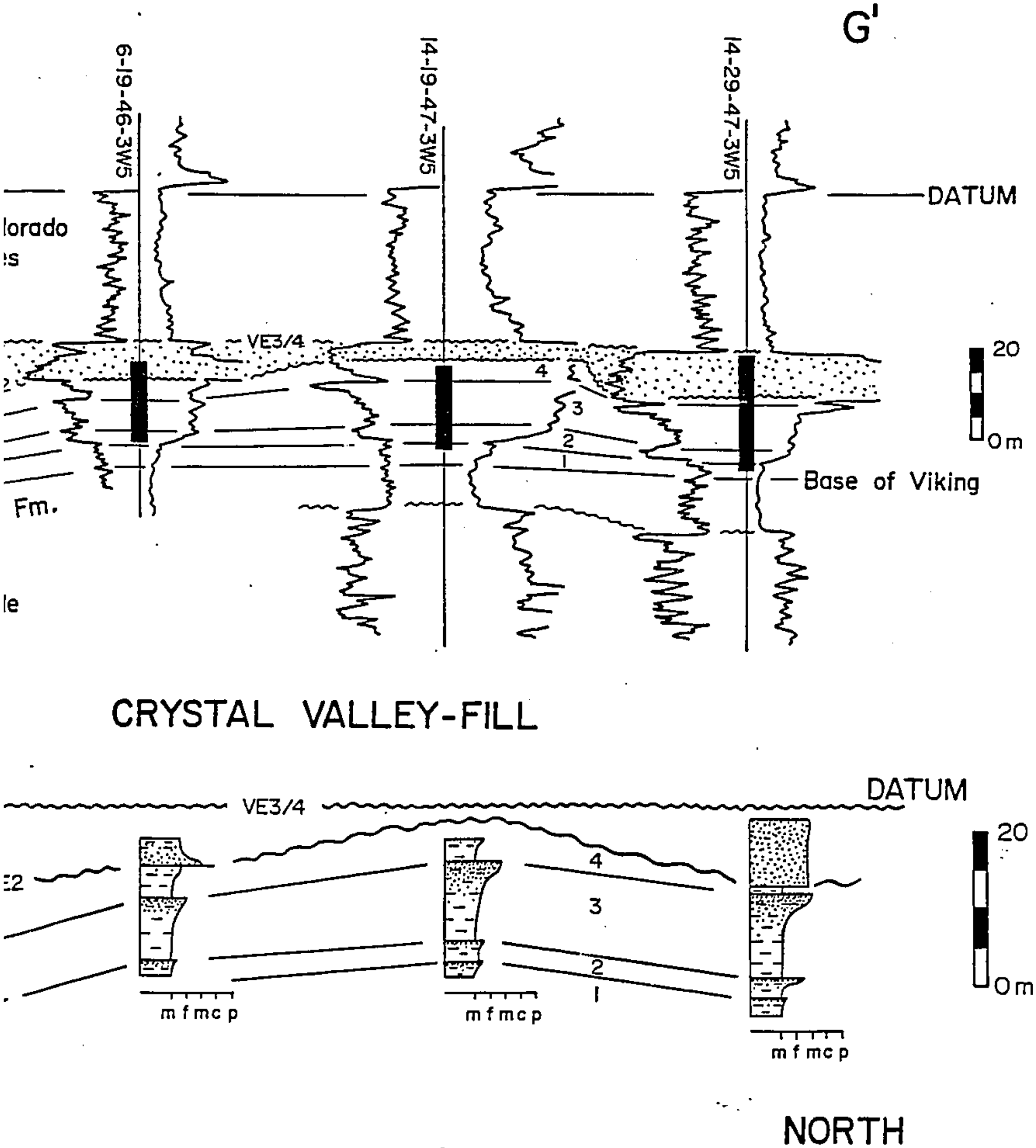




10-6-46-3W5
16-5-46-3W5
10-6-46-3W5
16-5-46-3W5
5
4
Ben.
3
2
1
5
4
3
2
1
m f mc p
5
Ben.
4
3
2
1
m f mc p
m f mc p



10-6-46-3W5
16-5-46-3W5
14-17-46-3W5
6-19-46-3W5
Lower Colorado shales
5
4
Ben.
VE2
3
2
1
Joli Fou Fm.
Mannville
CR
5
Ben.
4
VE2
3
2
1
?
m f mc p
m f mc p
m f mc p


G'
6-19-46-3W5
14-19-47-3W5
14-29-47-3W5
DATUM
lorado
es
VE3/4
4
3
2
1
20
0m
Base of Viking
Fm.
le
CRYSTAL VALLEY-FILL
DATUM
VE3/4
E2
4
3
2
1
m f mc p
m f mc p
m f mc p
20
0m
NORTH

relatively complex and it mainly occurs in the Cyn-Pem area.

5.1.3 Regional Trends

On a large-scale, both the Viking and Joli Fou Formations become thinner towards the west-northwest (Fig. 5.6). This trend is most pronounced between R14W5 to R20W5 where the Viking thins from 36 m to 10 m, and the Joli Fou thins from 15 m to 3 m (Fig. 5.6). On a smaller scale, the regional successions become sandier, thicker and split towards the west-northwest (Figs 5.2, 5.3, 5.4 & 5.6). Five major "shingles" are observed (1 to 5) and these have an offlapping geometry towards the east-southeast. The uppermost regional successions are truncated by the VE2, VE3 and/or VE4 erosion surfaces (Fig. 5.6).

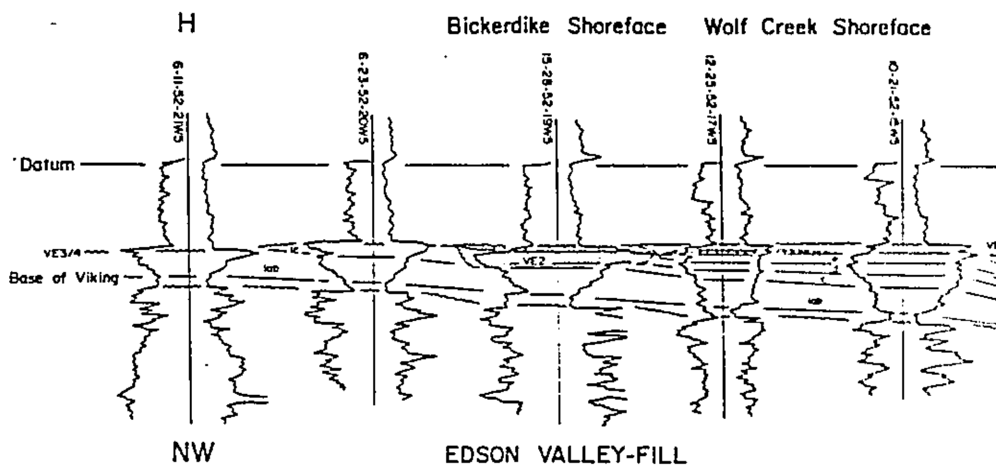
5.2 Regional Successions of the Study Area

The five "major" regional successions are labelled 1 to 5 and will be described in detail below.

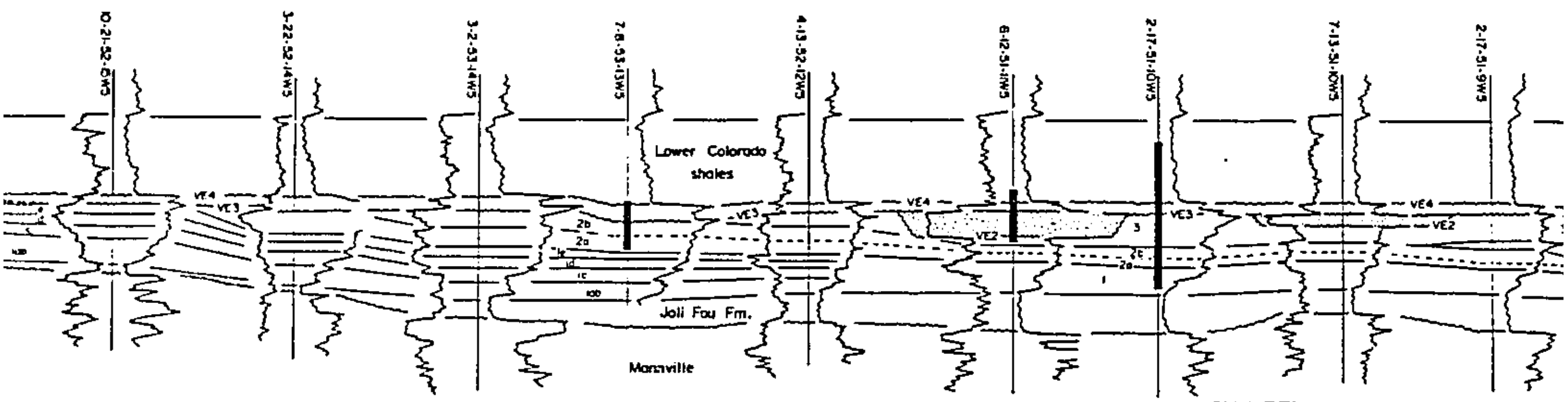
5.2.1 Succession 1

Regional succession 1 occurs at the base of the Viking Formation and gradationally overlies the mudstones of the Joli Fou Formation (Figs 5.2, 5.3, 5.4, 5.5 & 5.6). In most cores, this contact is marked by the transition from fissile, dark mudstones (Joli Fou) into silty mudstones (Viking). However, in some cores, this contact is marked by a thin lag (1-3 cm) of medium- to coarse-grained sandstone, granules and pebbles. Succession 1 is 4.0-16.1 m thick, splits into 5 smaller successions (1a to 1e) in the Sundance and Edson area, and becomes thicker and sandier towards the

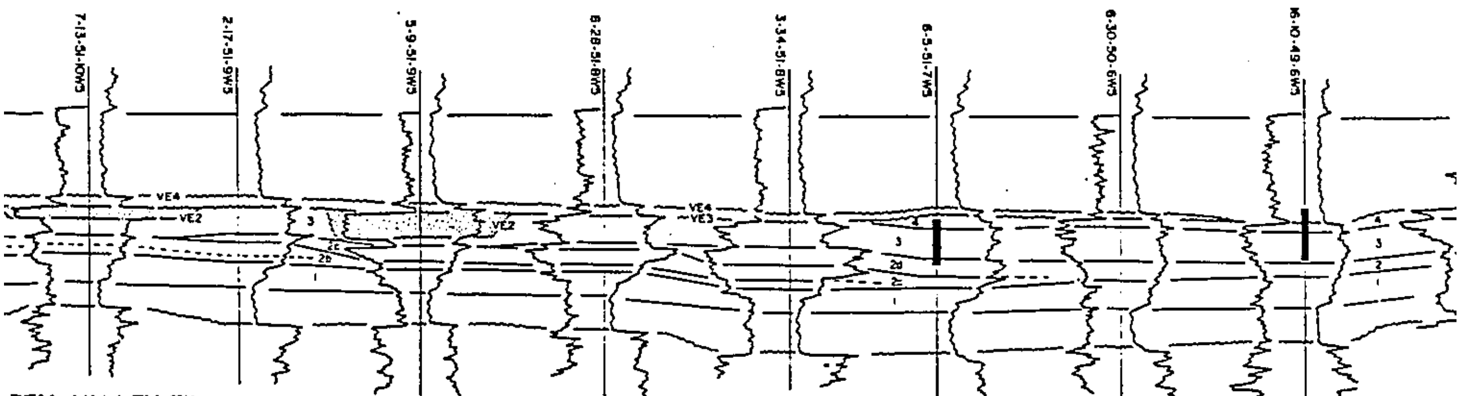
Figure 5.6. Well log cross section HH' from the Edson valley-fill to the Gilby-Joffre shoreface. This cross section is oriented northwest to southeast, consists of 30 wells and is approximately 280 km long. Regional successions 1a to 1e, 2a to 2d, 3, 4 and 5 are shown. Note the thickening of the Joli Fou and Viking Formations towards the east. The BFS log marker is used as the datum and the location of this section is shown in Figure 5.1.


H
Bickerdike Shoreface
Wolf Creek Shoreface
6-11-52-21W5
6-23-52-20W5
15-28-52-19W5
Datum
VE3/4
Base of Viking
VE2
NW
EDSON VALLEY-FILL

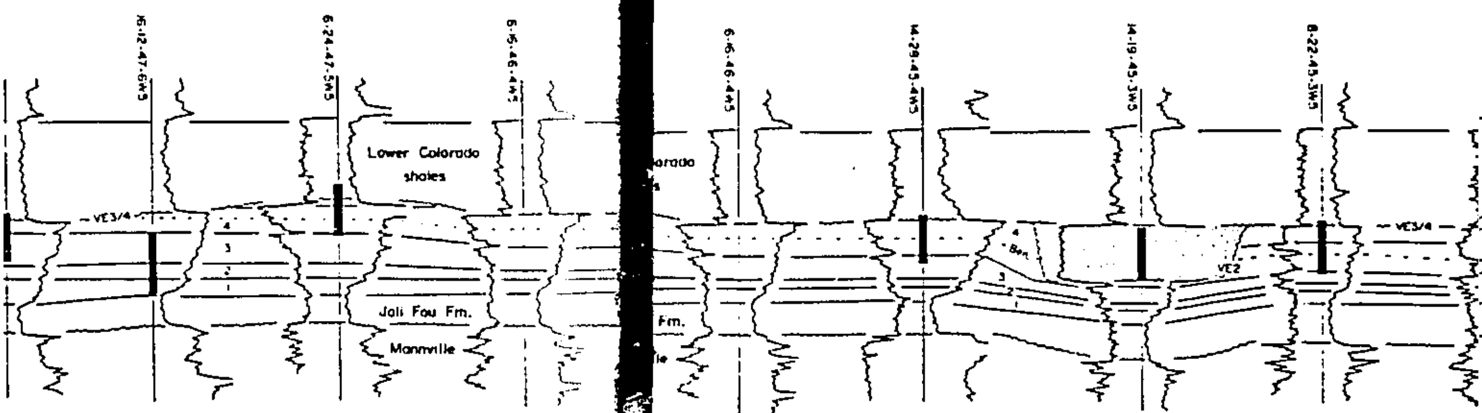
ek Shoreface LOG CROSS SECTION HH'



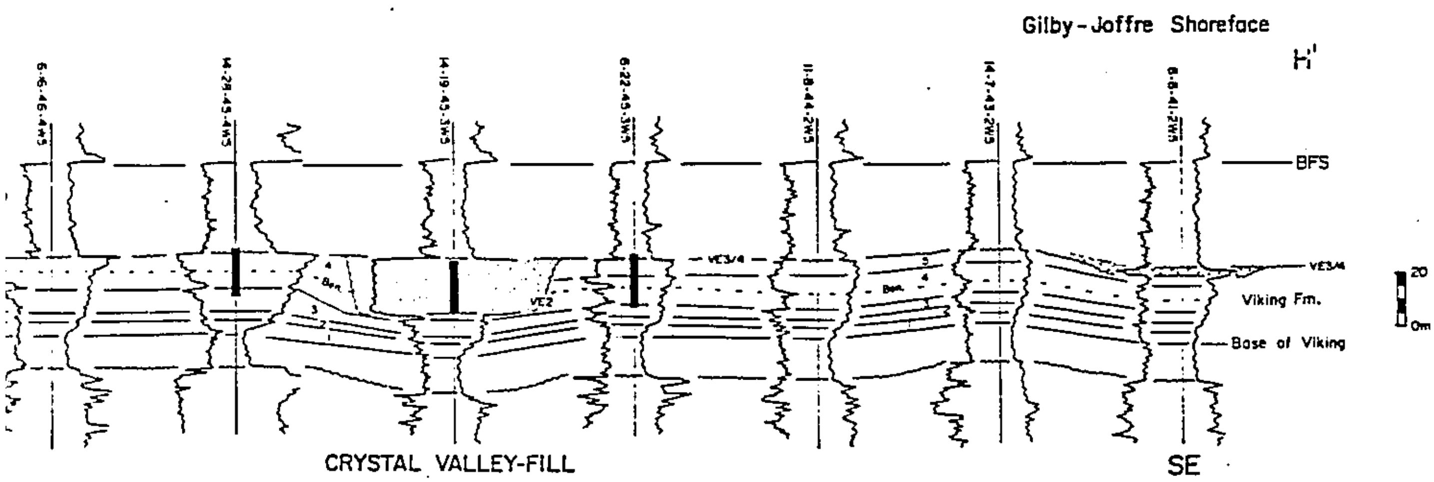
CYN-PEM VALLEY-FILL



-PEM VALLEY-FILL



CRYSTAL VALLEY-FILL


Gilby-Joffre Shoreface
H'
BFS
VE3/4
Viking Fm.
Base of Viking
VE2
20
0m
CRYSTAL VALLEY-FILL
SE

west-northwest (Figs 5.8 & 5.9).

Succession 1 is difficult to recognize in many wells because of the relatively low percentage of sandstone. In the Crystal area, this succession contains 2-5 % sandstone at the base, and 10-15 % at the top. Further west, the percentage of sandstone increases to 20-30 % in the Cyn-Pem area and 30-90 % in the Sundance and Edson area. This succession is thoroughly bioturbated and contains rare wave rippled sandstone beds. In the Sundance and Edson area, HCS sandstone beds are observed in the upper part of succession 1b.

The upper contact of succession 1 or successions 1a to 1e are relatively sharp and are usually marked by a Glossifungites ichnofacies. Some contacts are also marked by a lag of granules, pebbles, mudstone clasts and wood fragments, such as the 1b-1c contact in the Sundance and Edson area (e.g. 11-31-53-20W5; 2679 m).

5.2.2 Succession 2

Regional succession 2 is the second of five successions observed in the study area and it occurs stratigraphically between successions 1 and 3 (Figs 5.2 & 5.6). This succession splits into 4 smaller successions in the Cyn-Pem area, labelled 2a to 2d (Figs 5.3 & 5.6). The smaller successions form a shingling or an offlapping geometry towards the east. The most spectacular shingles are the 2c and 2d successions (Figs 5.3 & 5.6).

Succession 2 is 2.0-17.9 m thick, and is thickest and

Figure 5.7. Reference well (6-12-43-7W5) for Boreen's (1990) facies association 1 illustrating the stratigraphic positions of regional cycles A, B1 and B2. Compare to the stratigraphy of regional successions 1 to 4 shown in 6-12-43-7W5 (Fig. 5.5).

FACIES ASSOCIATION I

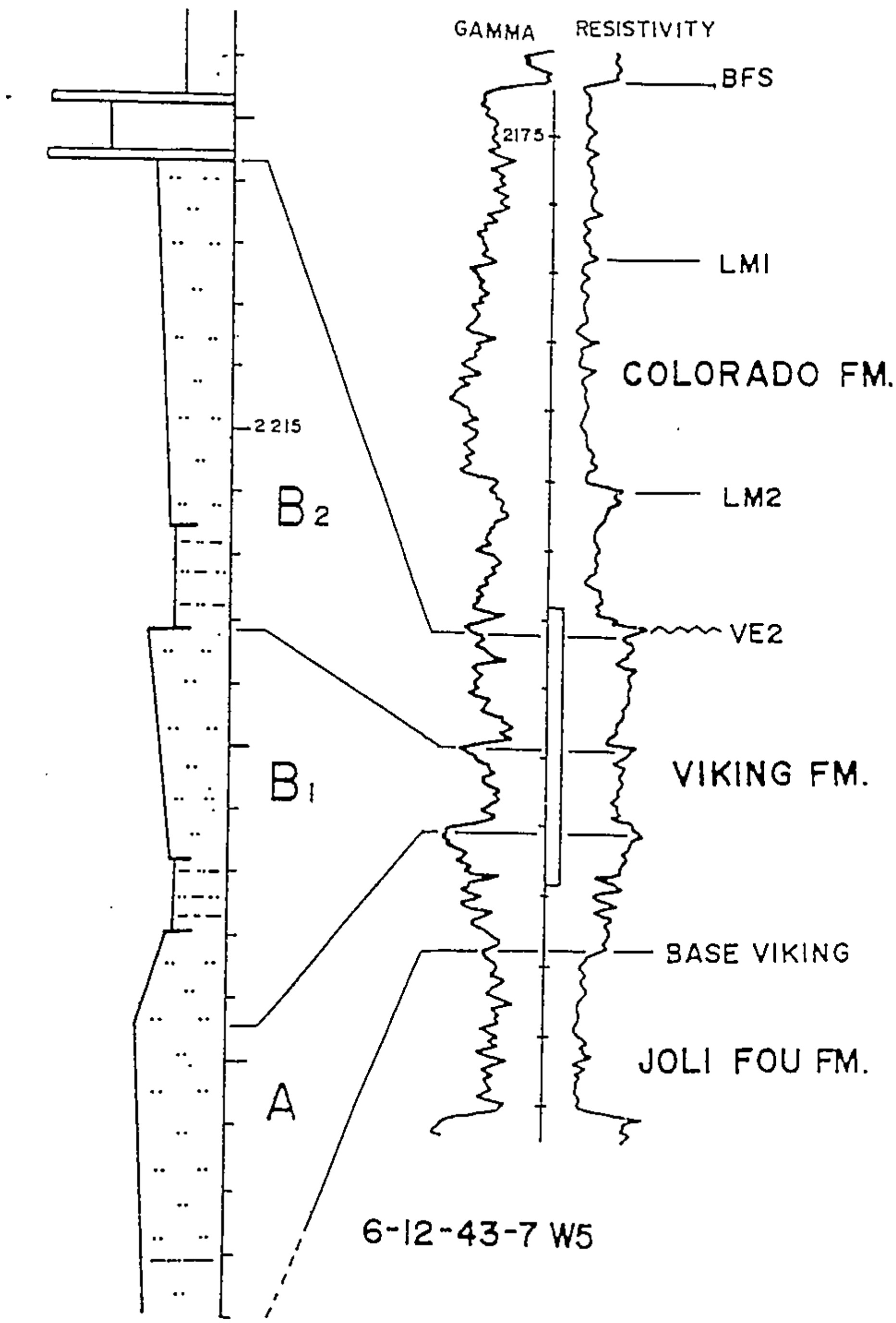


Figure 5.8. Isopach map of regional succession 1 in the Crystal area. This succession shows a subtle thickening trend towards the west (7-9 m; T46-48, R6W5). Throughout the rest of the area, succession 1 is 5-7 m thick. The distribution of data used to construct this isopach map is shown in Figures 1.5 and 1.6.

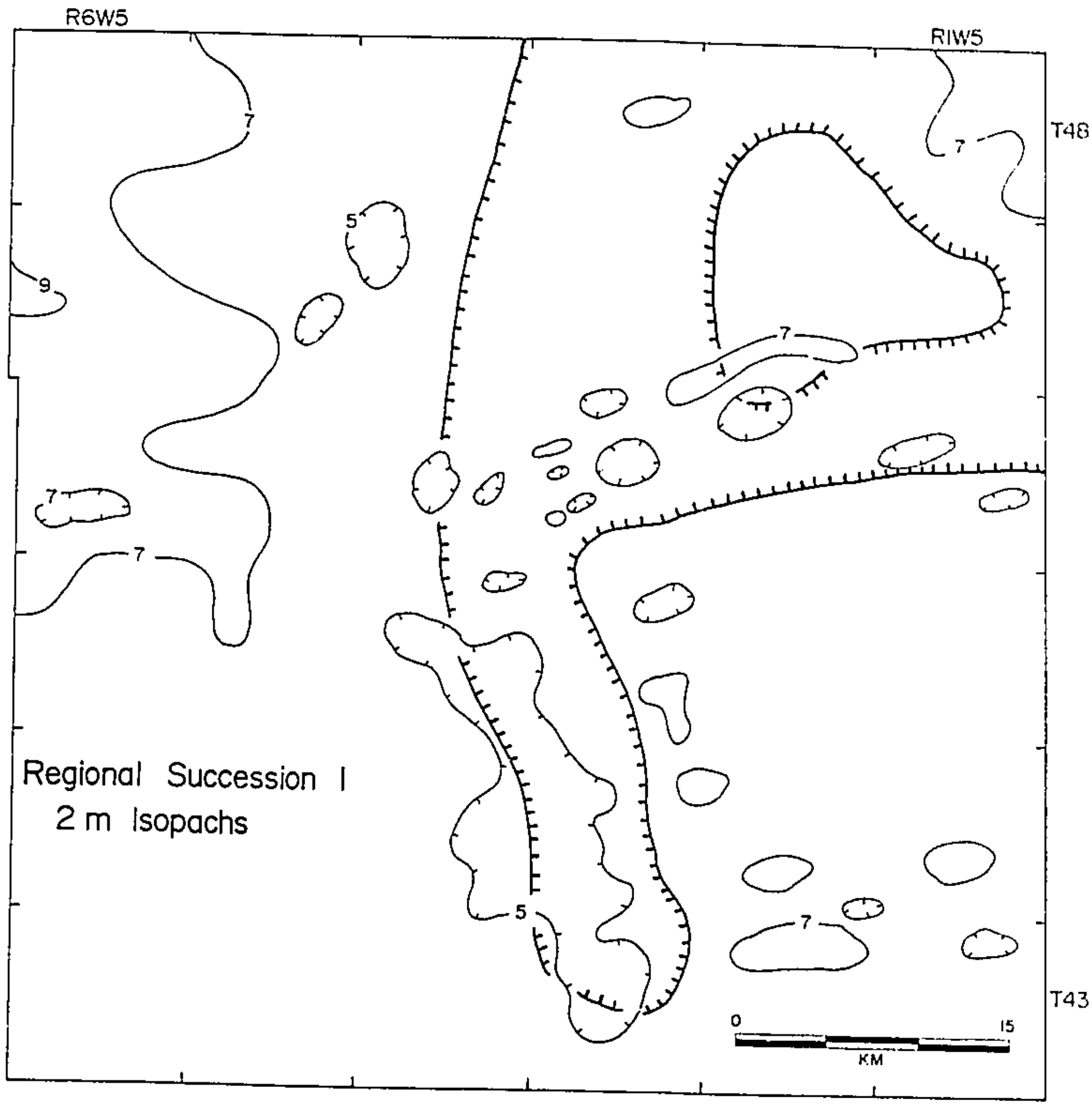

R6W5
RIW5
T48
T43
7
5
9
7
7
7
5
7
Regional Succession I
2 m Isopachs
0
15
KM

Figure 5.9. Location of cored wells which contain regional successions 1a and 1b (circles), or 1ab (crosses) in the Sundance and Edson area. Successions 1a and 1b merge to the southeast forming a single succession, labelled 1ab. The "shale-out line" of succession 1a is oriented southwest to northeast defining the orientation of the "regional" shoreline trend.

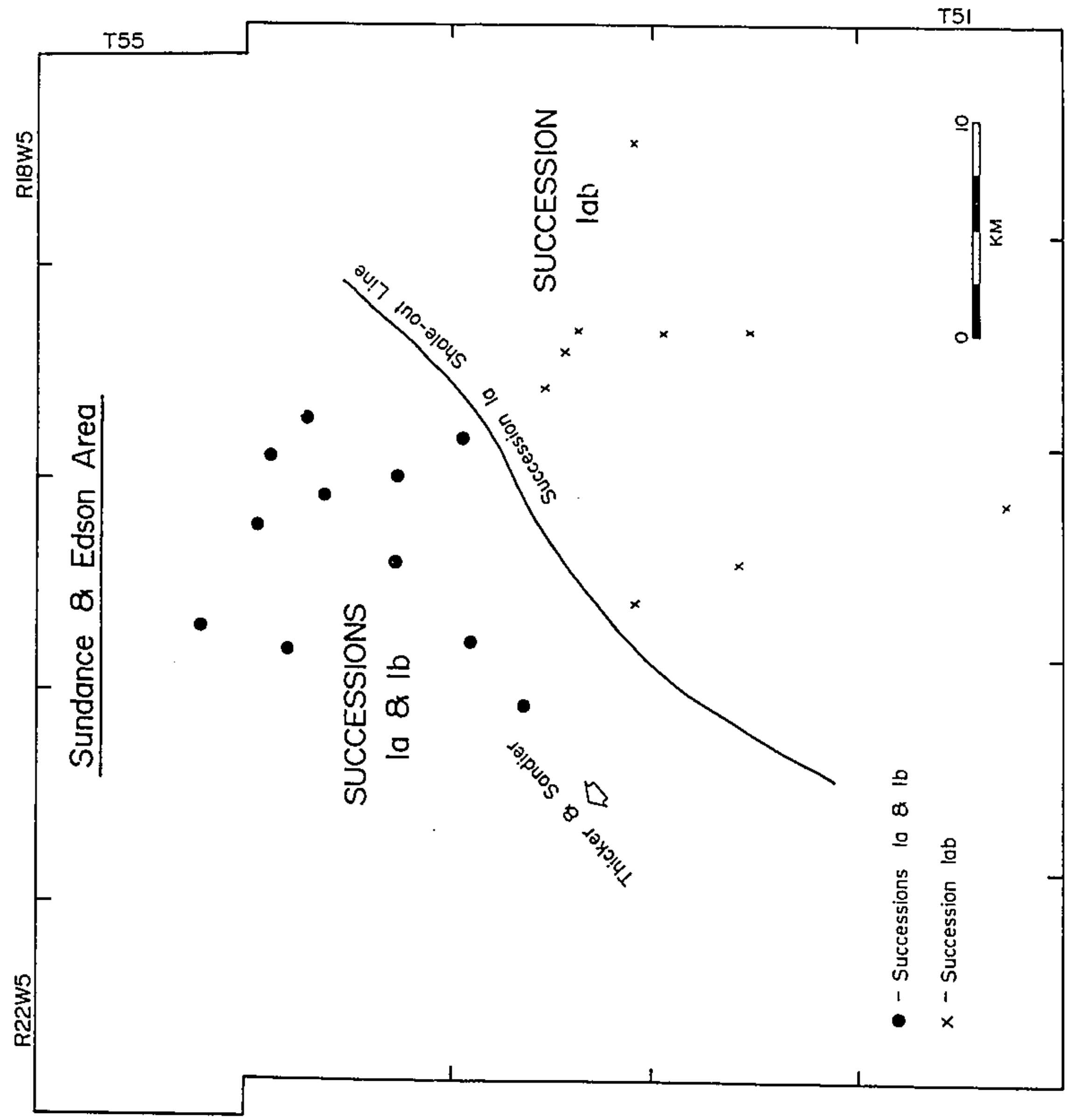
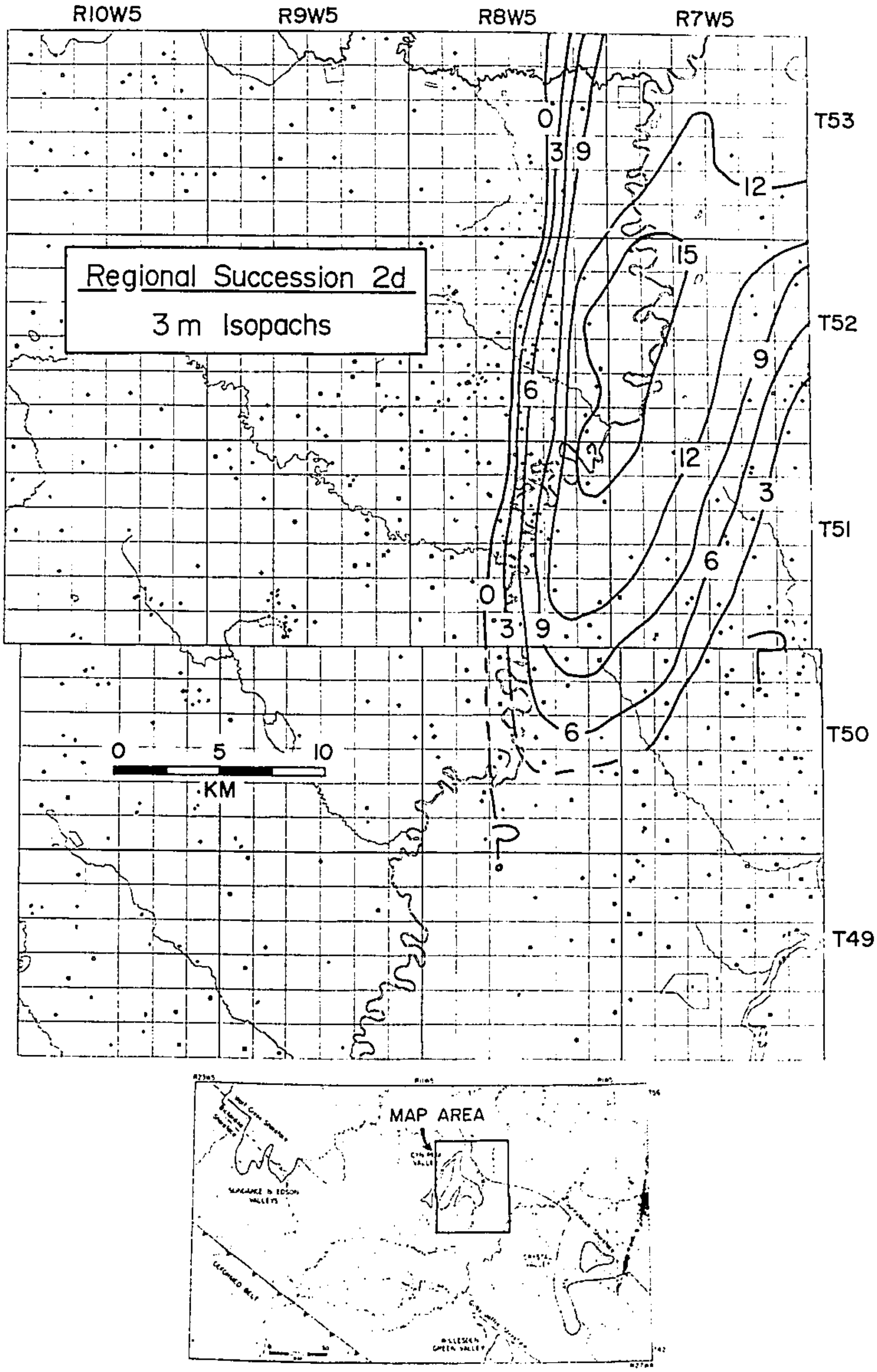

T55
T51
R18W5
R22W5
Sundance & Edson Area
SUCCESSION
Iab
SUCCESSIONS
Ia & Ib
Succession Ia
Shale-out Line
Thicker & Sandier
0
10
KM
● - Successions Ia & Ib
x - Succession Iab

Figure 5.10. Isopach map of succession 2d in the Cyn-Pem area. The isopachs are superimposed onto a map which shows the distribution of the well log data used to construct this figure. Succession 2d is difficult to separate from succession 2c in the eastern part of R8W5 and in R7W5. As a result, the isopach map represents a composite thickness of successions 2c and 2d in these areas. Note the abrupt shale-out of these successions in the eastern part of R7W5.


R10W5
R9W5
R8W5
R7W5
T53
T52
T51
T50
T49
Regional Succession 2d
3 m Isopachs
0
3
6
9
12
15
0 5 10
KM
MAP AREA

sandiest in T51-53/R7W5-8W5, which corresponds to the location of succession 2d (Fig. 5.10). Succession 2 becomes significantly thinner towards the west and east of this area (Fig. 5.6).

In the Crystal area, succession 2 is relatively muddy (10-30 % sandstone at the top), and is very difficult to distinguish from succession 3. In contrast, succession 2 is very sandy in the Cyn-Pem area and may contain up to 90% sandstone at the top.

The upper contact is generally sharp and may be marked by a Glossifungites ichnofacies, cross bedded sandstone beds or a thin lag (1-4 cm) of granules and pebbles.

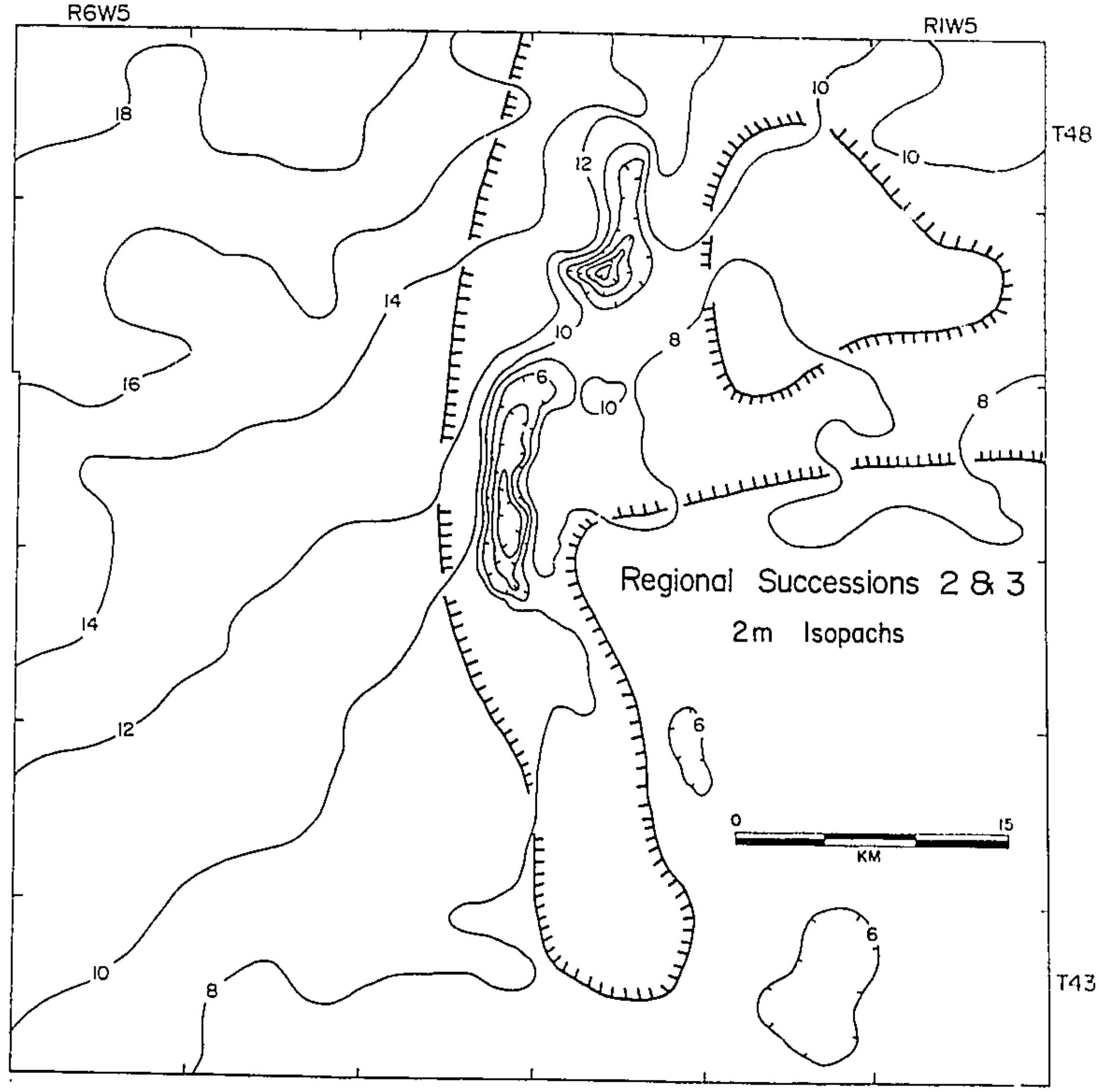
5.2.3 Succession 3

Regional succession 3 is one of the most prominent successions in the study area and is underlain by succession 2 and is overlain by succession 4 or by the VE3 erosion surface (Figs 5.2, 5.3, 5.5 & 5.6). It varies in thickness from 3-6 m in the extreme southeastern part of the Crystal area (T43, R1W5; Figs 5.2 & 5.11), up to 17 m in the Cyn-Pem area (Figs 5.3 & 5.6).

Succession 3 coarsens upwards from 10-15 % siltstone and sandstone at the base, up to 80-95 % sandstone at the top. This succession also becomes less bioturbated upward.

In the Crystal area, cross bedded sandstone beds are observed at the top of regional succession 3 in 14-19-47-3W5 (1551 m), 14-29-47-3W5 (1615 m), 8-32-47-3W5 (1575 m), 14-29-48-6W5 (1700 m) and 6-9-49-2W5 (1378 m). These beds are

Figure 5.11. Isopach map of regional successions 2 and 3 in the Crystal area. Regional succession 2 is relatively muddy in the Crystal area and is difficult to distinguish from succession 3. However, where observed, succession 2 has a consistent thickness of 2-6 m. Therefore, the strong trend of thickening towards the northwest probably results from the thickening of succession 3 rather than succession 2. This thickening trend also corresponds with a northwestern sandying trend for the sediments of succession 3. Note the erosion of successions 2 and 3 in the central part of the Crystal valley. The distribution of data used to construct this isopach map is shown in Figures 1.5 and 1.6.


R6W5
RIW5
T48
T43
18
16
14
12
10
8
6
Regional Successions 2 & 3
2m Isopachs
0
15
KM

10-15 cm thick, consist of well sorted, medium-grained sandstone and have abundant glauconite scattered throughout. The cross bedded sandstones are interbedded with thoroughly bioturbated muddy sandstones in the upper 1-2 m of succession 3. Some planar and ripple cross laminated sandstone beds are also observed.

HCS sandstone beds are the most diagnostic feature of succession 3 in the Cyn-Pem area. These beds are sharp based, 5-45 cm thick, normally graded, consist of very fine- to medium-grained sandstone and are interlaminated with dark mudstones. The HCS sandstone beds are interbedded with planar laminated, wave rippled and cross bedded sandstones, and mildly bioturbated sandy mudstones. Glauconitic grains are observed in trace amounts (1-2 %) in both the planar laminated and cross bedded sandstones.

The upper part of succession 3 is often marked by a Glossifungites ichnofacies, which consists of Arenicolites and Skolithos burrows. Thin lags (1-5 cm) of granules, pebbles and mudstone clasts are also observed at the contact between successions 3 and 4.

Regional succession 3 becomes sandier and thicker towards the northwest (Figs 5.2, 5.6 & 5.11). Succession 3 thins in the western part of the Cyn-Pem area (Figs 5.1, 5.3 & 5.6), because of erosive truncation by the VE3 erosion surface.

The increase in sand content can be observed by comparing the gamma-ray well log signatures of succession 3 at 8-15-45-7W5 and at 6-24-45-3W5 (Fig. 5.2). Succession 3 has a very subdued gamma-ray response at 8-15-45-7W5 (Fig. 5.2), and a prominent response at 6-24-45-3W5 (Fig. 5.2), suggesting that the western well (8-15-45-7W5) is much sandier than the eastern well. This difference becomes more pronounced in a northwest to southeast direction.

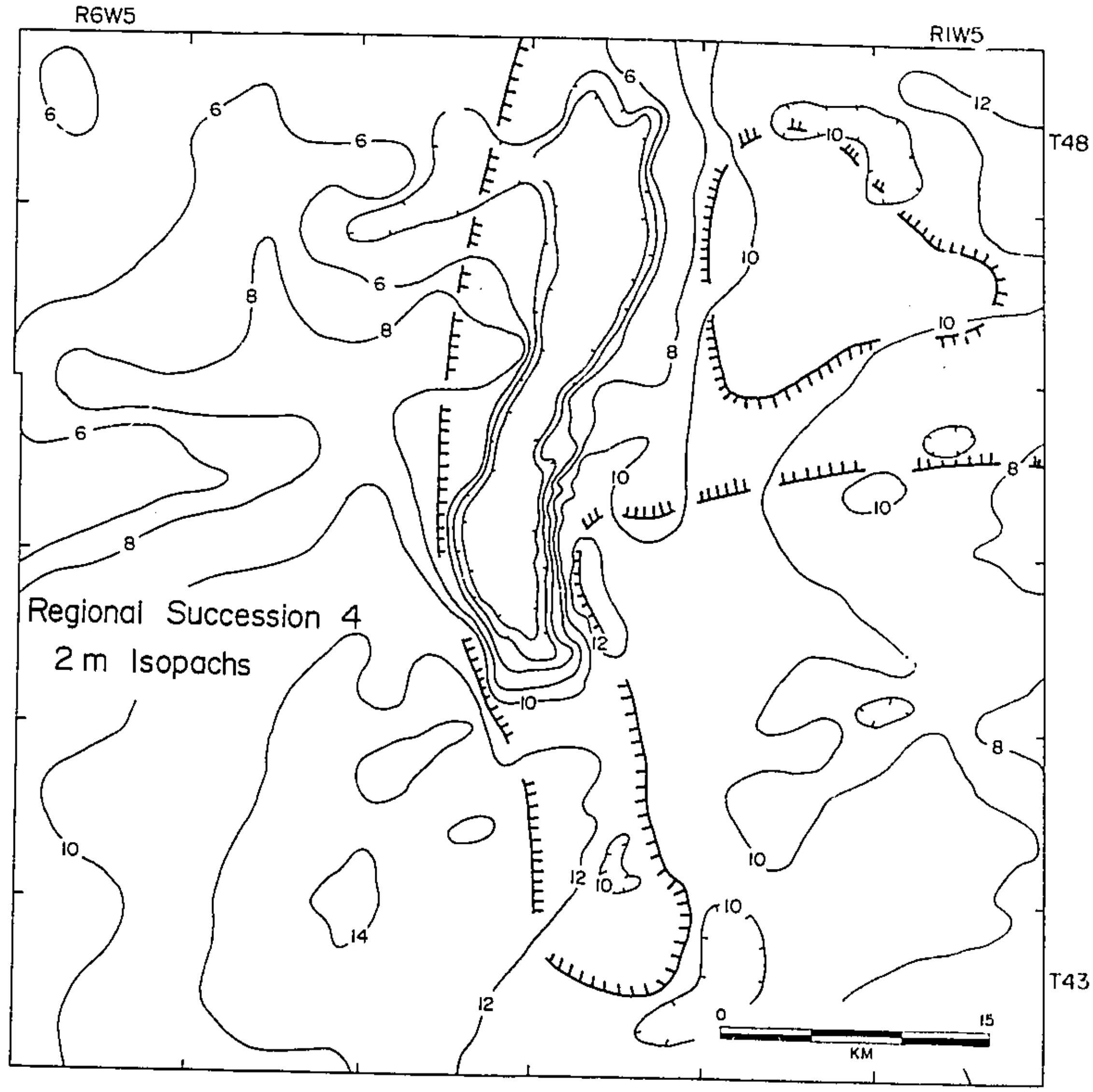
5.2.4 Succession 4

Succession 4 is underlain by the sandy top of succession 3 and is overlain by the muddy deposits of succession 5, or by the VE3/4 erosion surface (Figs 5.2, 5.5 & 5.6). These deposits are 0.1-14.3 m thick (Fig. 5.12). Regional succession 4 is only observed southeast of a line that passes through T49/R10W5 and T51/R7W5 (Fig. 5.13).

The basal part of succession 4 contains 10-15 % sandstone, and the upper part contains 40-90 % sandstone. In some wells, glauconitic, medium-grained, cross bedded sandstone beds (10-15 cm thick) are observed in the upper 1-2 m of succession 4. The cross bedded sandstones are usually capped by a lag of granules, pebbles and mudstone clasts (Fig. 4.4C; 6-29-45-3W5, 1780 m). Sandy tops also occur at 6-32-45-3W5 (1767 m), 7-32-45-3W5 (1762 m), 12-5-46-3W5 (1760 m), 2-6-47-4W5 (1710 m) and 6-5-51-7W5 (1659 m). *Arenicolites* and *Skolithos* burrows are also observed in the upper part of succession 4 and these are typical of the *Glossifungites* ichnofacies (Frey & Pemberton, 1984).

A prominent pair of bentonite beds are observed in the central part of succession 4. These beds show up as a

Figure 5.12. Isopach map of regional succession 4 in the Crystal area. This succession thickens from 8-10 m in the southeastern corner to 10-14 m along a line passing through T43/R5W5 and T48/R1W5. Northwest of this line, succession 4 becomes thinner because of its erosive contact with the top of the Viking (VE3 or VE3/4 erosion surface). Note the extensive removal of succession 4 by the Crystal valley scour (VE2 erosion surface). The distribution of data used to construct this isopach map is shown in Figures 1.5 and 1.6.


R6W5
R1W5
T48
T43
Regional Succession 4
2 m Isopachs
0
15
KM
6
8
10
12
14

"double" or a "single" spike on both the resistivity and gamma-ray well logs (Figs 5.2, 5.5 & 5.6), and are represented by a dashed line on cross sections DD', GG' and HH' (Figs 5.2, 5.5 & 5.6). The bentonites are 0.1-4.0 cm thick and are identified on well logs by a low resistivity (left deflection - resistivity log) and a high radioactivity (right deflection - gamma-ray log). The VE3 or VE3/4 erosion surface truncates or cuts out the bentonites west of R7W5.

The maximum thickness and sandiness of succession 4 occurs along a line that passes from T43/R5W5 to T48/R1W5 (Fig. 5.12). To the southeast of this line, succession 4 is represented by its "true" thickness and it becomes thicker and sandier towards the northwest (Figs 5.2 & 5.6). To the northwest of this line, succession 4 becomes thinner because of erosive truncation by the VE3 or VE3/4 erosion surface (e.g. 8-15-45-7W5, 8-22-45-5W5 & 14-28-45-4W5; Fig. 5.2). Most of succession 4 is cut out by the Crystal valley in an area between T45/R4W5 and T48/R3W5 (Fig. 5.12).

5.2.5 Succession 5

Regional succession 5 is the uppermost CU succession and is only observed in the Crystal area (Fig. 5.2; 6-22-45-3W5, 6-24-45-3W5 & 8-22-45-2W5). This succession is underlain by the sandy top of regional succession 4, is sharply overlain by the VE3 or VE3/4 erosion surface and is 0.1-10.2 m thick (Fig. 5.14). Regional succession 5 is not observed west or northwest of a line that passes from

Figure 5.13. The erosional edge of regional successions 4 and 5. Succession 5 is not observed northwest of a line that passes through T43/R4W5 and T48/R2W5, and succession 4 is not observed northwest of a line that passes through T49/R10W5 and T51/R7W5.

Erosional Edge of Successions 4 & 5

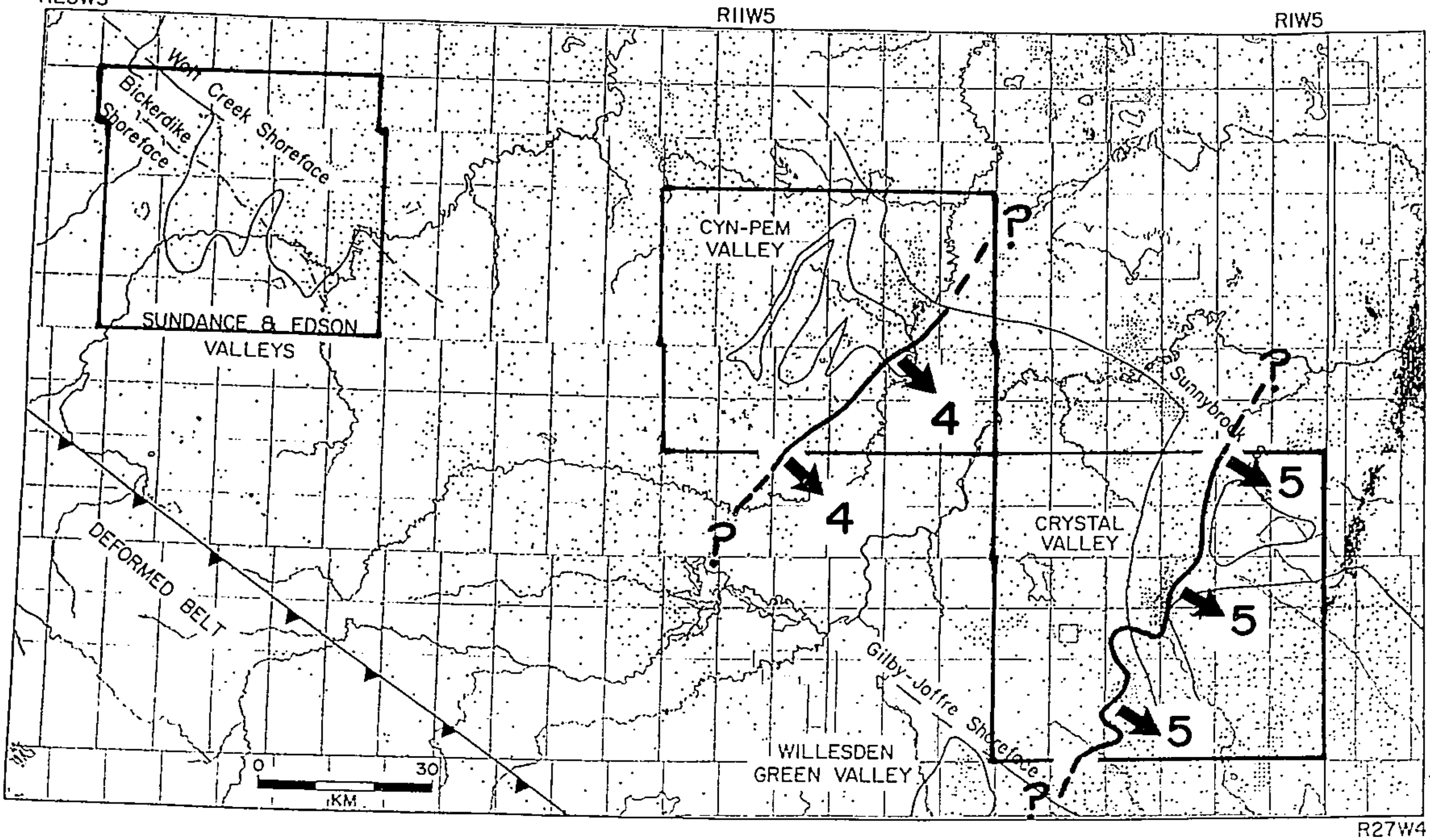
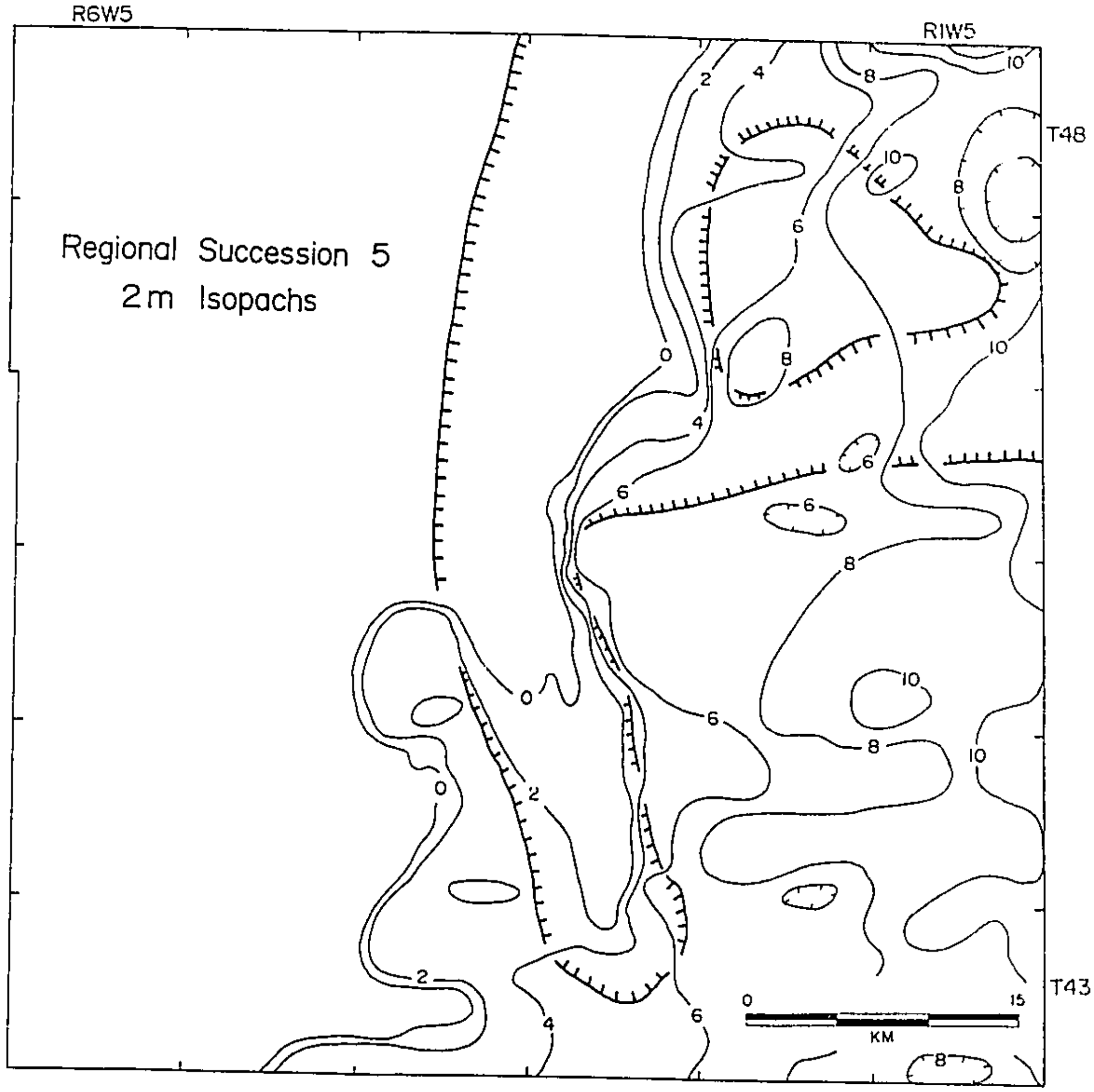


Figure 5.14. Isopach map of regional succession 5 in the Crystal area. This succession becomes progressive thinner towards the northwest because of its erosive upper contact with the VE3 or VE3/4 erosion surface. The distribution of the well log and core data used to construct this isopach map is shown in Figures 1.5 and 1.6.


R6W5
R1W5
T48
T43
Regional Succession 5
2 m Isopachs
0
15
KM

T43/R5W5 to T48/R2W5 (Figs 5.13 & 5.14).

Succession 5 is relatively muddy throughout the Crystal area and contains a maximum of 20-30 % siltstone and sandstone in the upper part of the succession. Arenicolites and Skolithos burrows, 5-15 cm long, are observed near the top of some successions and they are filled with medium- to coarse-grained sandstone.

Thickness and sandiness trends are impossible to determine because the upper part of this succession is extensively eroded by the VE3 or VE3/4 erosion surface.

5.2.6 Summary

(1) Five major "shingles" are observed in the regional deposits and these are labelled 1 to 5. These shingles or successions have an offlapping geometry towards the east-southeast.

(2) At least 12 CU successions have been recognized and are labelled 1a to 1e, 2a to 2d, 3, 4 and 5 (Fig. 5.6). Some successions merge basinward, including 1a and 1b (1ab; Figs 5.4, 5.6 & 5.9), 2a to 2d (2; Fig. 5.6), 2 and 3 (2/3; Figs 5.2 & 5.5).

(3) Most successions become thicker and sandier towards the west-northwest (Figs 5.2, 5.3, 5.4 & 5.6). Isopach maps of individual CU successions confirm the thickening trend (Figs 5.8, 5.9, 5.10, 5.11 & 5.12).

5.3 Interpretation

The following represents an interpretation of various aspects of the regional deposits, including (1) the facies association, (2) the upper contact, (3) the vertical stack of successions, (4) lateral trends or stacking patterns, and (5) the orientation of the regional shorelines.

5.3.1 Facies Association

A preliminary interpretation of the regional CU successions (facies association 1) was presented in section 4.1. The muddier successions were interpreted as the deposits of an open-marine, quiet-water environment, and were probably deposited below fair weather wave base. The sandier successions, such as those which contain HCS or cross bedded sandstones, were interpreted as the deposits of a marine environment which was considerably shallower than the environment of deposition for the muddy successions. The HCS and wave rippled sandstones are interpreted as the deposits of waning currents, such as those which are deposited by storms.

In some wells, the HCS sandstone beds constitute approximately 80-90 % of the volume of sediments in the upper part of the succession, and may suggest deposition in a lower shoreface environment. Also, the presence of cross bedded sandstones and a Skolithos ichnofacies indicate that the environment had relatively high energy levels, possibly above fair weather wave base in the lower to middle shoreface.

However, most regional successions are relatively muddy and contain approximately 40-50 % sandstone at the top. The abundance of mudstone and lack of primary sedimentary structures are indicative of deposition below fair weather wave base, in a relatively quiet-water environment.

The CU regional successions of the Viking Formation are typical of the deposits of a prograding, wave-dominated, shelf to shoreface environment (Reinson, 1985; Downing & Walker, 1988; Reinson et al., 1988; Boreen, 1990). The lower or muddier part of each succession is consistent with deposition in an outer to middle shelf environment, and the upper or sandier part of each succession is consistent with deposition in an inner shelf to lower shoreface environment.

5.3.2 Upper Contact

Most CU successions have a very sharp upper contact. Some of these contacts are marked by a lag deposit of granules, pebbles and mudstone clasts, and by a *Glossifungites* ichnofacies. The lag was probably produced during the wave and current winnowing of the upper part of the succession, and is interpreted as erosional in origin.

The upper part of each CU succession is capped by a marine flooding surface which is defined as "a surface that separates younger from older strata, across which there is evidence of an abrupt increase in water depth" (Van Wagoner et al., 1988; p.39). These surfaces are commonly associated with subaqueous erosion and a minor hiatus (Van Wagoner et al., 1988).

5.3.3 Lateral Stacking Pattern

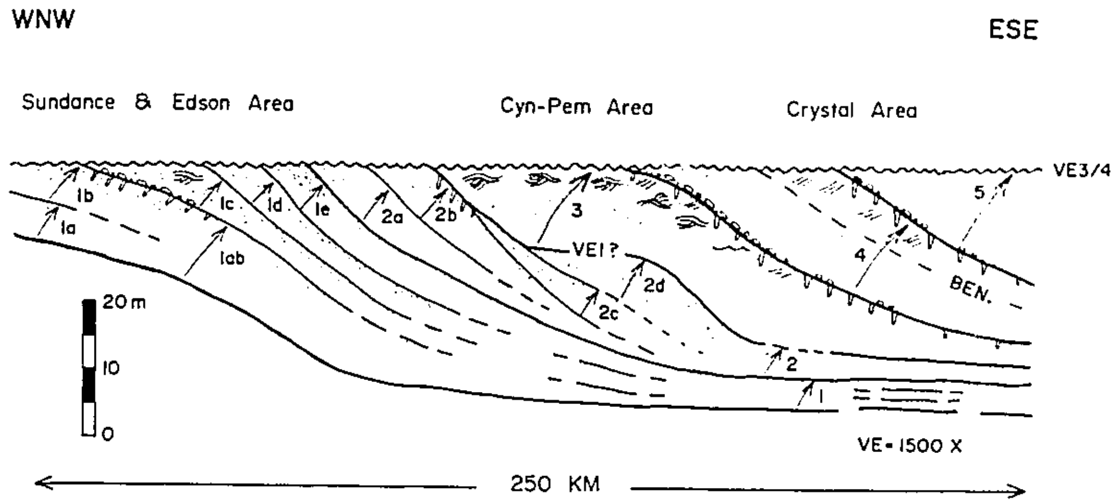
The regional CU successions form a progradational stacking pattern. This is defined by the increase in sandstone content from succession 1 to succession 4 in any given stack (Fig. 5.15). For example, in the Crystal area, succession 4 is sandier than succession 3, and succession 3 is sandier than successions 1 and 2 (Fig. 5.15). This indicates that succession 4 progrades out over top of succession 3, forming an offlapping or shingling geometry towards the east.

The only exception to the progradational stacking pattern is observed between successions 2 and 3 in the Cyn-Pem area (Fig. 5.15). These successions form a retrogradational stacking pattern in parts of the Cyn-Pem area, especially when one compares the sandiness of successions 2c and 2d, to the overlying deposits of succession 3.

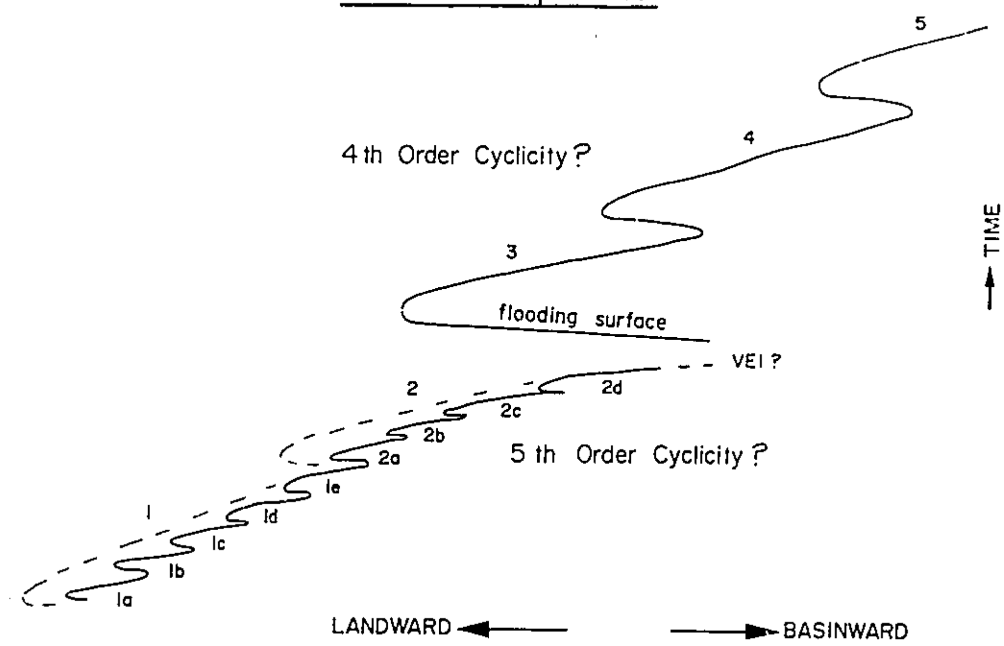
The abrupt increase in sand content of regional succession 2 can be explained in one of two ways, including; (1) successions 2c and 2d represent inner- to mid-shelf "banks" or "bars" of sandstone, or (2) the sediments of successions 2c and 2d are the deposits of a lowstand shoreline. Unfortunately, the lack of cores through these deposits precludes a confident interpretation of successions 2c and 2d. Based on the sigmoidal sand body geometry of these successions and the possible correlation of the upper contact of succession 2 with the VE1 erosion surface described by A.D. Reynolds (pers. comm., 1989), I would tend to favour a lowstand shoreline interpretation. If this interpretation is correct, a significant relative rise in

Figure 5.15. Schematic cross section and coastal onlap curve of the regional successions. The thickening and sandying trends, and stacking pattern of the regional successions are shown. Note the erosional lag at the top of successions 1b (Sundance & Edson area), 3 and 4 (Cyn-Pem to Crystal area).

REGIONAL STRATIGRAPHY



Coastal Onlap Curve



sea level would have "drowned" the deposits of succession 2 and the shoreline would have moved westward from R7W5-8W5 to at least R13W5 (succession 3), a distance of over 50 km.

5.3.4 Vertical Stack of Successions

The cyclic and stacked nature of the regional CU successions provides a record of coastal onlap (Fig. 5.15). The CU nature of each succession may be caused by progradation during stillstand, an increase in the rate of sediment supply, a minor relative fall in sea level or any combination of the above. In contrast, the marine flooding surface developed during a minor relative rise in sea level (Van Wagoner et al., 1988, 1990).

The shelf to shoreface sandying-upward successions, progradational stacking pattern, marine flooding surfaces, lack of subaerial erosion and absence of a basinward shift of facies suggest that the regional sediments were deposited during highstand conditions. The regional successions form a highstand systems tract which consists of a progradational parasequence set (Van Wagoner et al., 1990).

Van Wagoner et al. (1990) and Plint (in press) describe parasequences of similar thickness, geometry and stacking pattern to those observed in the Viking Formation, which form fourth- or fifth-order depositional cycles (50,000 to 200,000 yrs). It is probable that the regional successions of the Viking are also fourth- or fifth-order cycles (Fig. 5.15).

The controlling mechanism(s) for the cyclicity of the regional successions may include eustatic sea level change, local or regional tectonics, autocyclic processes (e.g. rate of sediment supply) or any combination of the above. Both the cyclicity and controllling mechanism(s) of these successions will be discussed in more detail in chapter 10.

5.3.5 Orientation of the Regional Shorelines

The thickening and increase in sand content of the regional successions to the west-northwest (Figs 5.2, 5.3, 5.4, 5.6, 5.8, 5.9, 5.10, 5.11 & 5.12), the independent confirmation of these trends by Boreen (1990) in the Willesden Green area, and the NNE-SSW orientation of the isopach lines suggest that the regional shorelines were oriented approximately NNE-SSW. This orientation is roughly perpendicular to the WNW-ESE orientation of the Gilby-Joffre shoreface trend (Downing & Walker, 1988).

The Gilby-Joffre shoreface deposits rest stratigraphically on top of the VE3 erosion surface (Boreen & Walker, 1991), and the regional shelf to shoreface successions occur stratigraphically below this surface. Therefore, the regional shoreline trends represent an "early" orientation of the Viking shorelines, and the Gilby-Joffre shoreline trend represents a "late" orientation of the Viking shoreline.

A large time gap must occur between the development of these two shoreline trends, which is coincident with the timing of the VE2 lowstand incision (base of Viking valleys). It is probable that the shape of the basin changed during this lowstand time interval. Uplift in the southwest, subsidence in the northwest (Peace River Arch area), or a combination of both would result in the re-orientation of the shoreline from NNE-SSW (regional) to NW-SE (Gilby-Joffre & Joarcam).

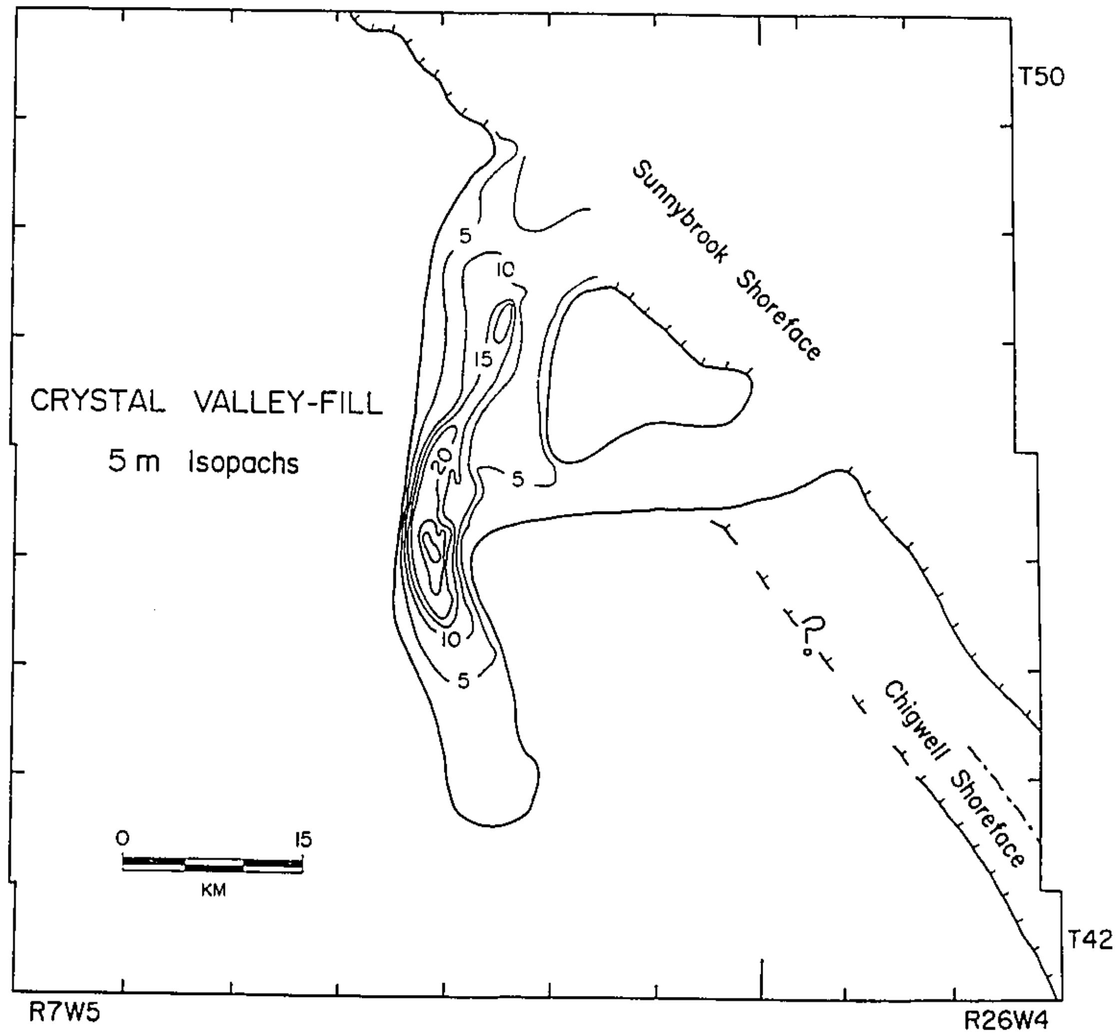
CHAPTER 6 - CRYSTAL VALLEY-FILL

The Crystal valley-fill occurs in T43-49 and R28W4-4W5, and is approximately 55 km long, 7-12 km wide and has a maximum depth of 32 m (Fig. 6.1). It is oriented north to south, oblique to the regional Viking paleoshoreline trends identified at Joffre (Downing & Walker, 1988), Chigwell (Raychaudhuri, 1989) and Joarcam (Posamentier & Chamberlain, 1989).

The Crystal valley has a forked appearance; one arm trends north-south (main) and the other arm trends west-east (secondary). These arms are separated by an "island" of regional deposits which occur in T47-48, R1W5-2W5 (Fig. 6.1). The thickest valley-fill deposits occur in the main arm (T45-46) and become progressively thinner towards the north and south (Fig. 6.1). In the north, the valley-fill sediments merge with the deposits of the Sunnybrook shoreface.

Oil was first discovered in the Crystal valley-fill deposits in 1978 at 6-7-46-3W5 (Reinson, 1985). Since then, two separate oil reservoirs, the "A" and "H" pools have been identified (Reinson, 1985; Reinson et al., 1988). Both of these reservoirs are centrally located (T45-46, R3W5-4W5; Fig. 1.1), and they extend 10-12 km down the length of the valley. The total production of the Crystal pools, up to March 1990, is 2.14×10^6 m^3 (13484.2 MSTB) of oil and 5.98×10^8 m^3 (21.1 BCF) of gas (Alberta Production Report,

Figure 6.1. Isopach map of the valley-fill sediments at Crystal. Isopachs are in 5 m intervals. Note the position of the secondary (eastern) arm of the Crystal valley, relative to the main (north-south trending) arm.



T50
Sunnybrook Shoreface
CRYSTAL VALLEY-FILL
5 m Isopachs
5
10
15
20
5
10
5
?
Chigwell Shoreface
0
15
KM
T42
R7W5
R26W4

1990).

An extensive core (104) and well log data base is available in the Crystal area (Figs 1.5 & 1.6). This allows for a detailed reconstruction of the sedimentology and stratigraphy of the Viking in this area.

6.1 Previous Work

Reinson (1985) and Reinson et al. (1988) interpreted the Crystal sediments as a "multistage tidal channel-fill deposit within a larger estuarine channel-bay complex". Their interpretations are based on a study of the sedimentology and reservoir geology in a small area of the Crystal valley (T45-46, R3W5-4W5), and are best considered as local interpretations.

Reinson (1985) and Reinson et al. (1988) recognized two major facies associations in the valley, including tidal-channel and estuary bay-fill sediments, and combined these sediments into five depositional units; four channel stages (A, B, C & H), and subtidal estuarine bay-fill mudstones. Channel stages A, B and C form three successive and partly superimposed tidal-channel stages in the central part of the valley, and constitute the main reservoir sandstones ("A" pool) at Crystal (Reinson, 1985; Reinson et al., 1988). The western margins of these stages are gradationally interbedded with the subtidal estuarine bay-fill mudstones (Reinson et al., 1988).

In contrast, channel stage H is a shallow channel-bar complex which is restricted to the western part of the valley, and forms the upper reservoir or "H" pool at Crystal (Reinson, 1985; Reinson et al., 1988). Both gradational and sharp contacts are observed between the channel stage H sandstones and the underlying estuarine mudstones (Reinson et al., 1988).

The work of Reinson (1985) and Reinson et al. (1988) has opened up some interesting problems with respect to the valley-fill sediments at Crystal. These problems include;

(1) How can the rapid lateral facies changes described by Reinson (1985) and Reinson et al. (1988) be interpreted? These facies changes include conglomeratic "tidal channel" facies passing into muddy "subtidal estuarine bay-fill" over a distance of less than 500 m. No transitional deposits (e.g. interbedded conglomerate and mudstone) were recognized by Reinson (1985) and Reinson et al. (1988).

(2) How can the three tidal channel stages (A, B & C) described by Reinson (1985) and Reinson et al. (1988) be recognized and correlated? In many wells, the contacts between these stages appear arbitrary. A good example of this occurs in 16-24-45-4W5 where the three channel stage breaks are placed at subtle grain size or sedimentary structure changes; however, these changes occur repetitively throughout the entire core.

(3) How can the regional context of the tidal channels described by Reinson (1985) and Reinson et al. (1988) be understood? Where are the associated barrier island sediments and how does 30 m of interbedded sandstone and

conglomerate accumulate in a tidal channel?

(4) How can the absence of facies assemblages, which are commonly observed in other valley-fill or estuarine complexes, be explained? These include fluvial sediments at the head of the valley and transgressive shoreline or shoreface sediments at the mouth of the valley.

(5) How can the northern and southern margins of the valley-fill be delineated? Only the western and eastern edges of the valley-fill were identified by Reinson (1985) and Reinson et al. (1988).

(6) How can the stratigraphic and paleogeographic relationships between the Crystal valley-fill and other valley-fill (e.g. Cyn-Pem) and shoreface deposits (e.g. Sunnybrook) be explained?

Two main problems exist with the interpretations of Reinson (1985) and Reinson et al. (1988); (1) they do not explain the abrupt lateral facies changes between the conglomerates (FA-8), and the mudstones (FA-2) and fine-grained sandstones (FA-4), and (2) there are difficulties in recognizing and correlating the three tidal channel stages. If these sediments were deposited in laterally adjacent, coeval channels and bays as Reinson (1985) and Reinson et al. (1988) suggest, one would expect to find transitional deposits in the bay sediments close to the channel. The transitional deposits might consist of interbedded conglomerates and dark mudstones. However, these interbedded deposits are not observed in the valley-fill sediments at Crystal. Therefore, it is unlikely that the dark mudstones (FA-2) co-existed with, and were laterally adjacent to, the conglomerates (FA-8).

Furthermore, there are many examples in the Crystal valley where laterally adjacent cores, less than 1 km apart, have completely different facies associations. For example, at 10-1-46-4W5 the valley-fill sediments consist entirely of interbedded coarse-grained sandstones (FA-6 & FA-7) and conglomerates (FA-8). Approximately 800 meters to the west (8-2-46-4W5), the valley-fill sediments consist entirely of interbedded fine-grained sandstones (FA-4) and dark mudstones (FA-2). No evidence of interbedding or interfingering exists between these cores. This example highlights the abrupt lateral contact between these facies assemblages.

Sharp and abrupt lateral and vertical contacts exist between the coarse-grained sandstones (FA-6 & FA-7) and conglomerates (FA-8), and the fine-grained sandstones (FA-4) and dark mudstones (FA-2) throughout the Crystal valley. These contacts divide the valley-fill sediments into two separate deposits; a smaller channel-like deposit of conglomerates and coarse-grained sandstones in the central part of the valley, and a much larger, laterally extensive deposit of dark mudstones and fine-grained sandstones throughout the rest of the valley.

Based on the sharp and well defined lateral contacts, and the sharp and erosive vertical contacts between the coarse-grained channel-like deposit and the finer grained laterally extensive deposit, the Crystal valley-fill is subdivided into two discrete fills; fill 1 and fill 2. Fill 1 consists of fine-grained sandstones and dark mudstones, while fill 2 consists of coarse-grained sandstones and conglomerates. Both the lateral and vertical contacts between fills 1 and 2 are easily recognized in the Crystal valley.

6.2 Preliminary Interpretation

The valley-fill deposits cut into five regional CU successions, labelled 1 to 5, forming sharp and erosive contacts (Figs 3.3, 3.4, 3.5 & 3.7). The contact between the valley-fill and regional deposits is defined as the VE2 erosion surface (chapter 3). This surface was fluvially cut during lowstand incision and is observed at the base of all of the Viking valley-fill deposits. The VE2 scour was modified by wave and/or tidal action during the ensuing "VE3" transgression, creating the VE3-1 erosion surface. From this point on in the thesis, the base of fill 1, in the absence of a lag deposit, will be defined as the VE2 + VE3-1 erosion surface; VE2 represents lowstand incision and VE3-1 represents transgressive modification.

The Crystal valley-fill has been subdivided into two separate deposits which are labelled fills 1 and 2 (Figs 3.3 & 3.4; Pattison, 1990; Pattison & Walker, 1990). The sediments of fill 1 form a tripartite facies zonation that is sandstone-rich in the north and south, and mudstone-rich

in the central part of the valley.

These fills consist of facies associations (FA) 2 to 8 which have been described and interpreted in chapter 4. Most of these associations contain restricted trace fossil assemblages and have been interpreted as the deposits of a marginal marine environment.

A sharp based, CU succession of thoroughly bioturbated mudstones and sandstones occurs at the mouth of the Crystal valley-fill. These deposits are laterally extensive, oriented NW-SE and are interpreted as shoreface deposits. They are labelled the Sunnybrook shoreface deposits (Fig. 6.1) and are discussed in more detail in chapter 9.

The valley incision, location of the shoreface deposits to the northeast, tripartite facies zonation of fill 1, restricted trace fossil assemblages and marginal marine interpretation of most facies associations suggest a transgressive estuarine setting for the Crystal valley-fill deposits. The remainder of this chapter will expand on this preliminary interpretation by providing detailed descriptions and interpretations of fills 1 and 2.

6.3 Fill 1

Fill 1 forms the bulk of the sediments in the Crystal valley and is the only fill observed south of T46 (Fig. 6.2). The maximum thickness of fill 1 occurs in 16-2-46-4W5 where it is 31.8 m thick (Fig. 6.2).

The geometry and lateral extent of the sediments in fill 1 are shown in Figures 6.3, 6.4 and 6.5. Fill 1 is

Figure 6.2. Isopach map of fill 1. Isopachs are in 5 m intervals. The deposits of fill 1 are cut out by the fill 2 incision which is shown as a narrow channel-like feature in the central part of the Crystal valley.

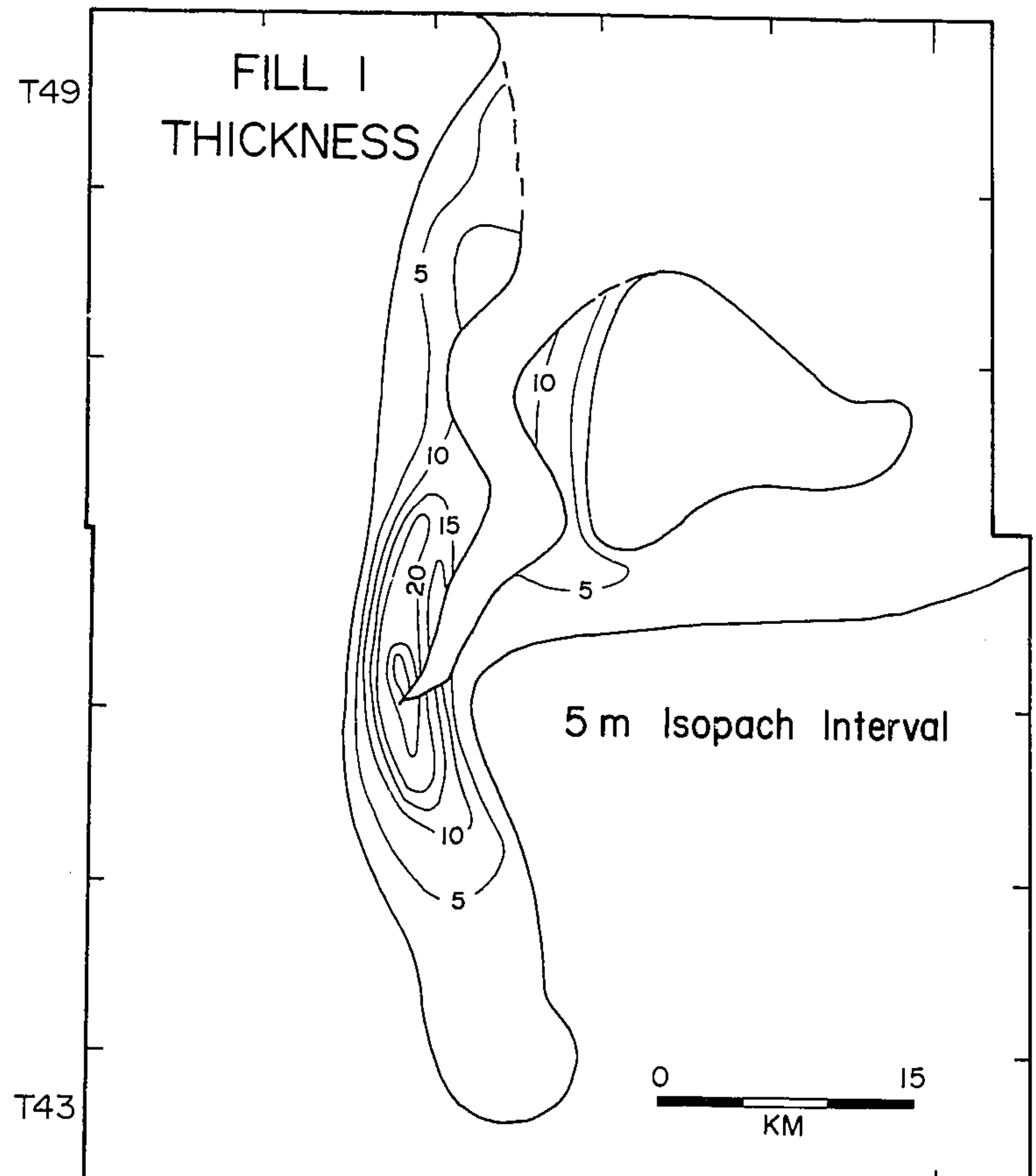

FILL I
THICKNESS
T49
T43
5
10
15
20
10
5
10
5
5 m Isopach Interval
0
15
KM
R5W5
R1W5

Figure 6.3. The location of the four main facies associations of fill 1 and cross sections II' and JJ'. Dark Mudstone (FA-2), Bioturbated Muddy Sandstone (FA-3), Fine-Grained Sandstone (FA-4) & Interbedded Sandstones (FA-5).

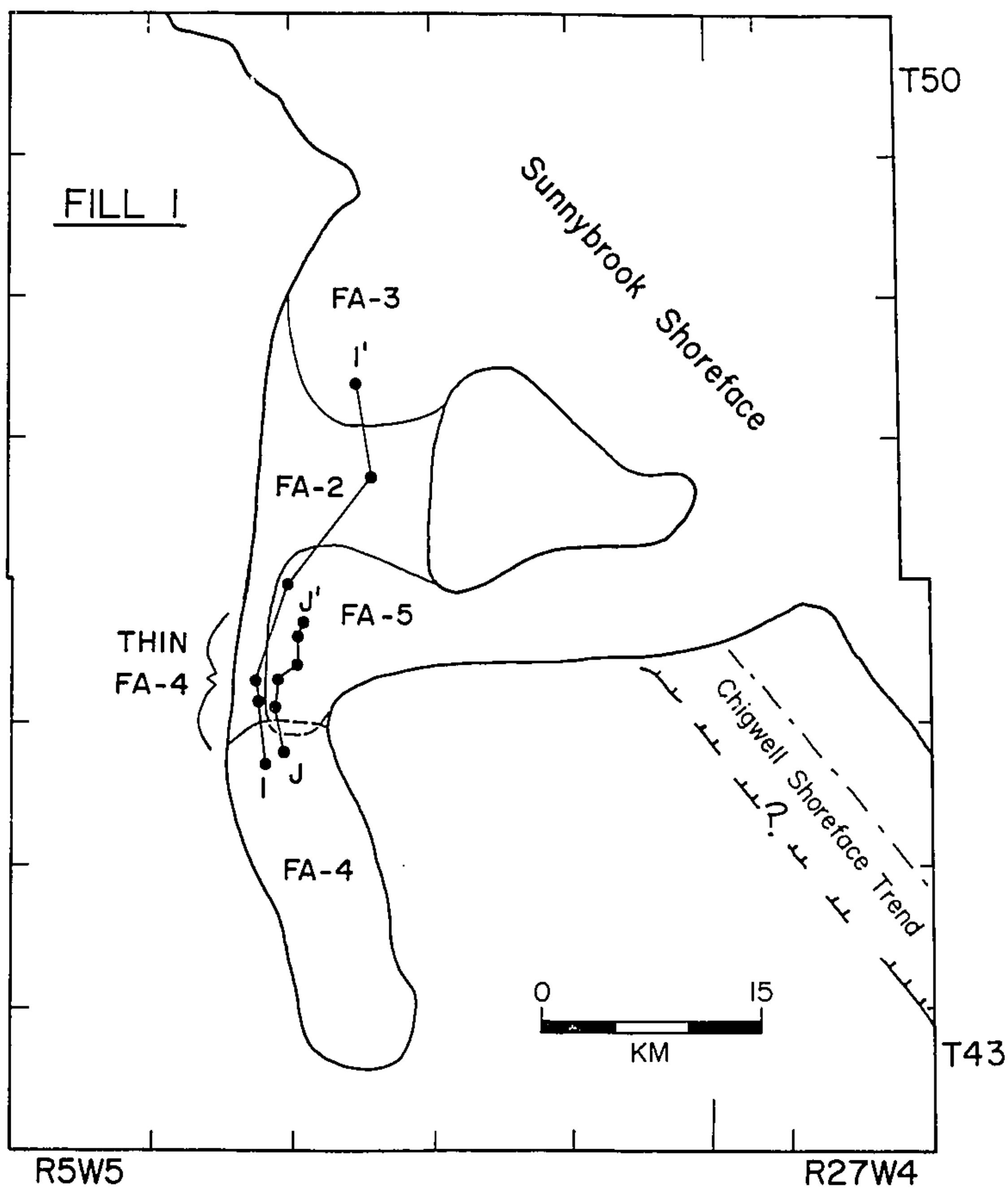
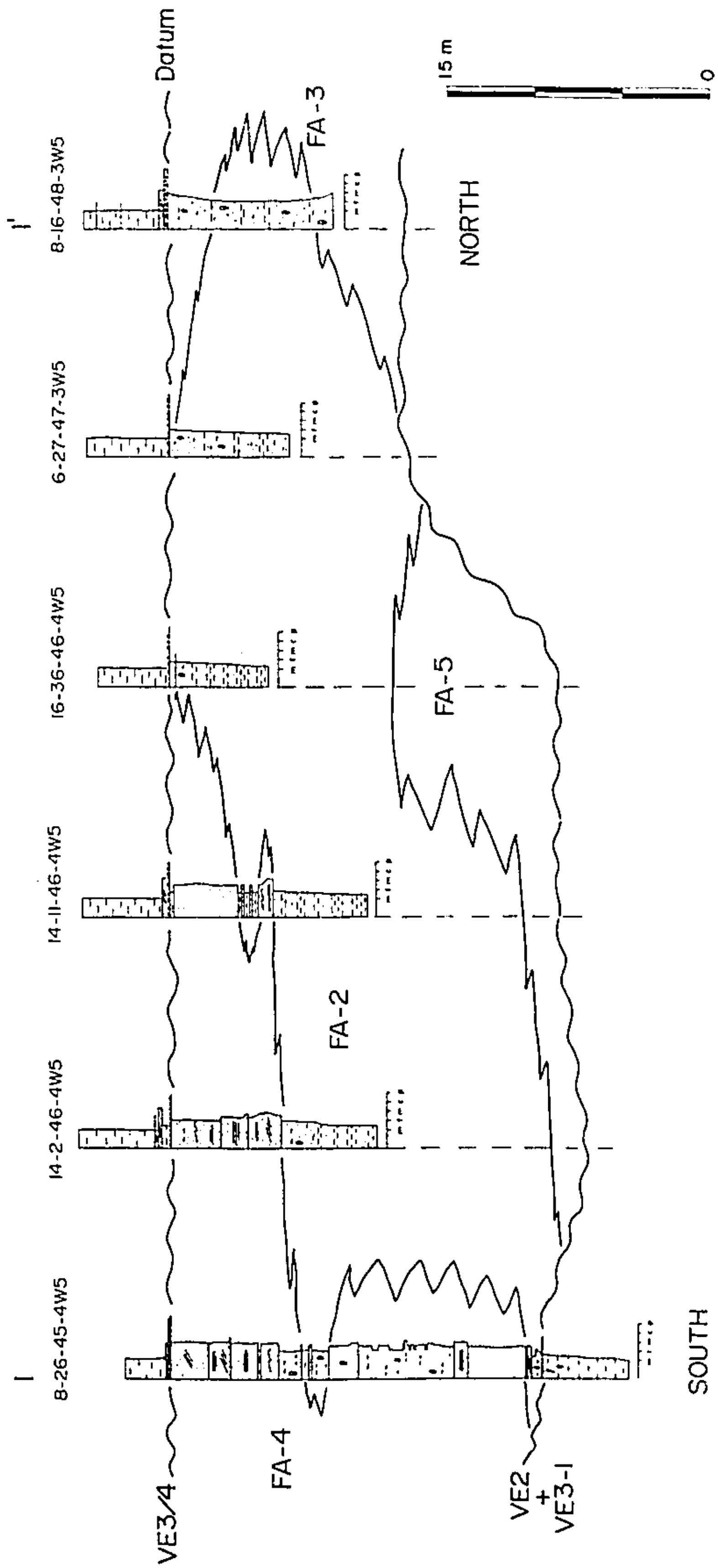

T50
FILL I
Sunnybrook Shoreface
FA-3
I'
FA-2
J'
FA-5
THIN
FA-4
I
J
FA-4
Chigwell Shoreface Trend
?
0
15
KM
T43
R5W5
R27W4

Figure 6.4. The following two pages show core and well log cross section II'. The four main facies associations of fill 1 (FA-2, FA-3, FA-4 & FA-5), two Viking erosion surfaces (VE2+VE3-1 & VE3/4), and three regional CU successions (1 to 3) are shown. Black bars on the well log cross section indicate core positions. Location shown in Figure 6.3.


I
I'
8-26-45-4W5
14-2-46-4W5
14-11-46-4W5
16-36-46-4W5
6-27-47-3W5
8-16-48-3W5
Datum
VE3/4
FA-4
FA-2
FA-3
FA-5
VE2
+
VE3-1
15 m
0
NORTH
SOUTH

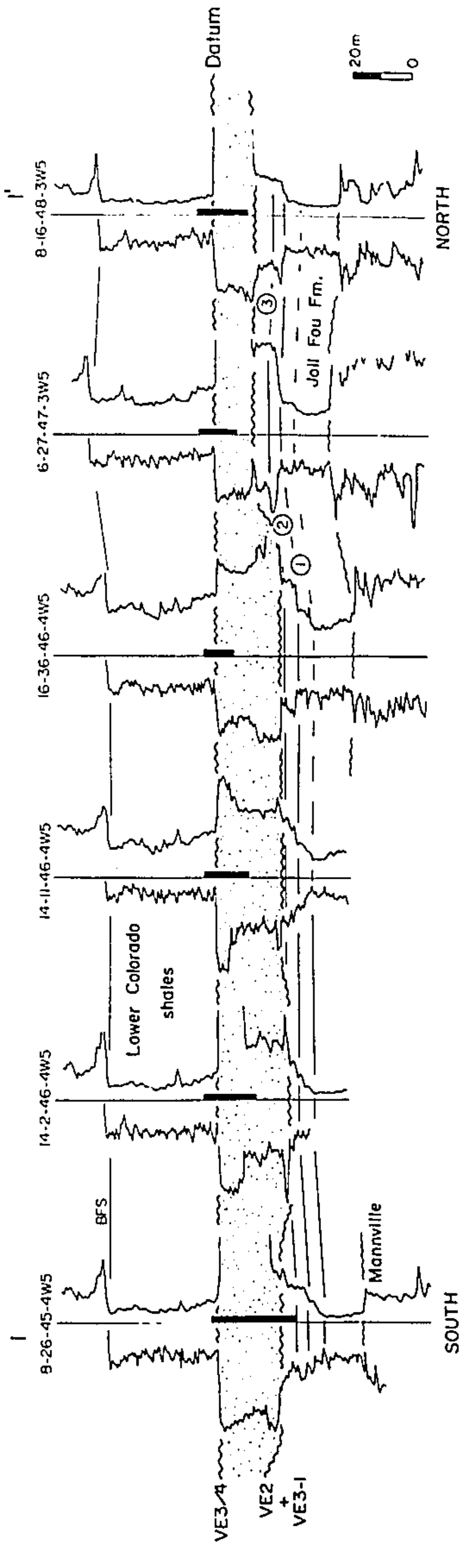
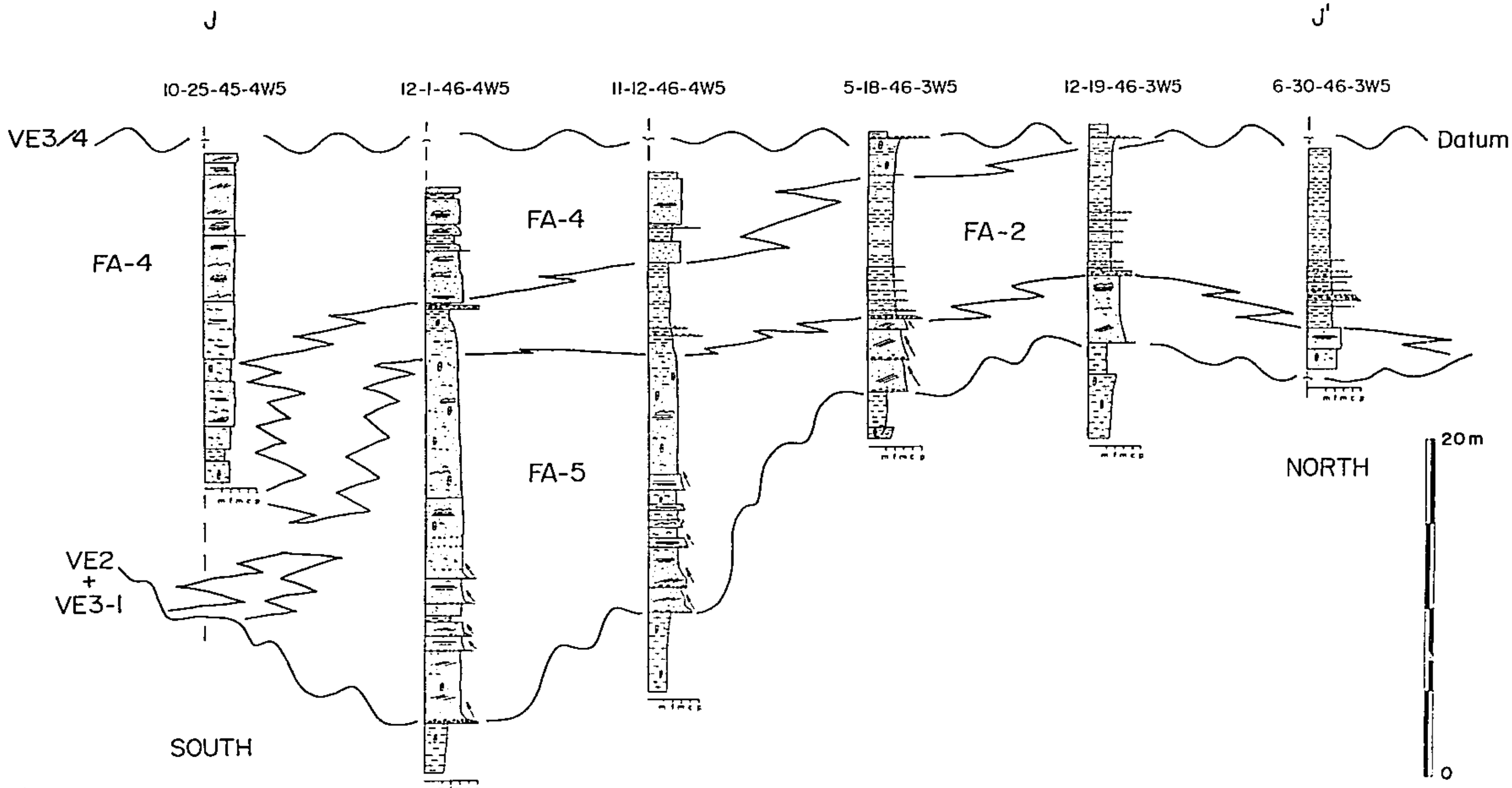
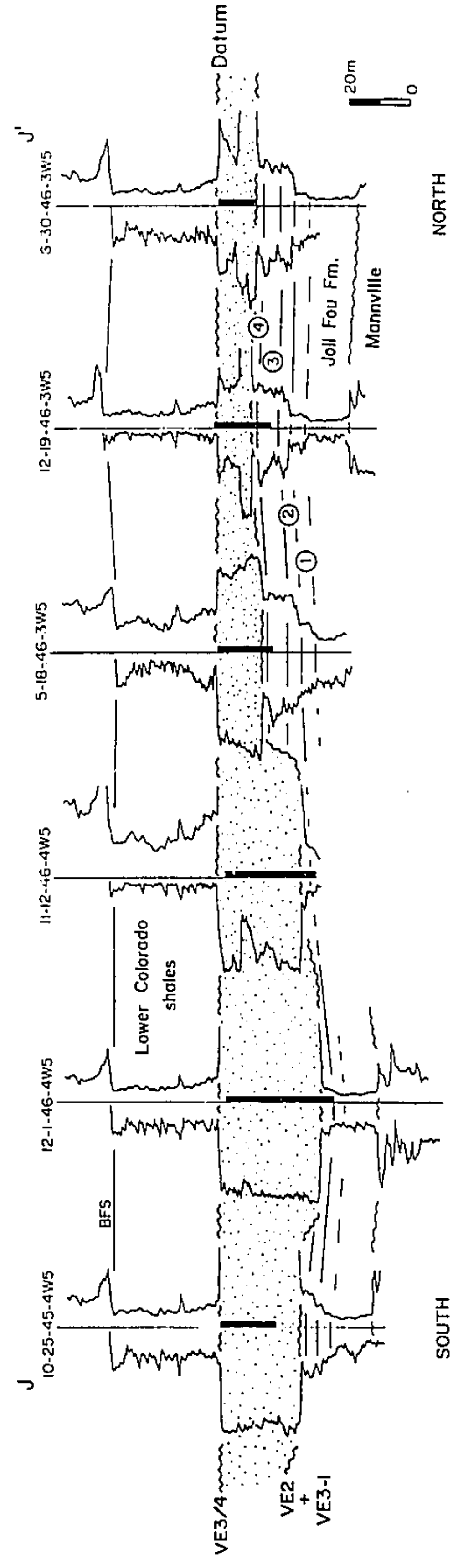

Datum
20m
0
I'
8-16-48-3W5
NORTH
3
Joli Fou Fm.
6-27-47-3W5
2
1
16-36-46-4W5
14-11-46-4W5
Lower Colorado
shales
14-2-46-4W5
BFS
Mannville
I
8-26-45-4W5
SOUTH
VE3/4
VE2
+
VE3-1

Figure 6.5. The following two pages show core and well log cross section JJ'. Three facies associations (FA-2, FA-4 & FA-5), two Viking erosion surfaces (VE2+VE3-1 & VE3/4) and four regional CU successions (1 to 4) are shown. Black bars on the well log cross section indicate core positions. Location shown in Figure 6.3.


J
J'
10-25-45-4W5
12-1-46-4W5
11-12-46-4W5
5-18-46-3W5
12-19-46-3W5
6-30-46-3W5
VE3/4
Datum
FA-4
FA-4
FA-2
FA-5
VE2
+
VE3-1
SOUTH
NORTH
20m
0



J
J'
10-25-45-4W5
12-1-46-4W5
11-12-46-4W5
5-18-46-3W5
12-19-46-3W5
6-30-46-3W5
Datum
20m
0
SOUTH
NORTH
BFS
Lower Colorado shales
Joli Fou Fm.
Mannville
VE3/4
VE2 + VE3-1

bounded by the VE2 or VE3-1 erosion surface below and by the VE3 or VE4 erosion surface above (Figs 6.4 & 6.5).

Fill 1 is subdivided into four facies associations (FA) which occupy specific areal and/or stratigraphic positions in the valley (Fig. 6.3). They include; (i) dark mudstone (FA-2), (ii) bioturbated muddy sandstone (FA-3), (iii) fine-grained sandstone (FA-4), and (iv) interbedded sandstone (FA-5). Also, basal lags consisting of cross bedded sandstones (FA-6) and interbedded conglomerates (FA-8) are observed in a few wells. Isopach maps of these associations are shown in Figure 6.6.

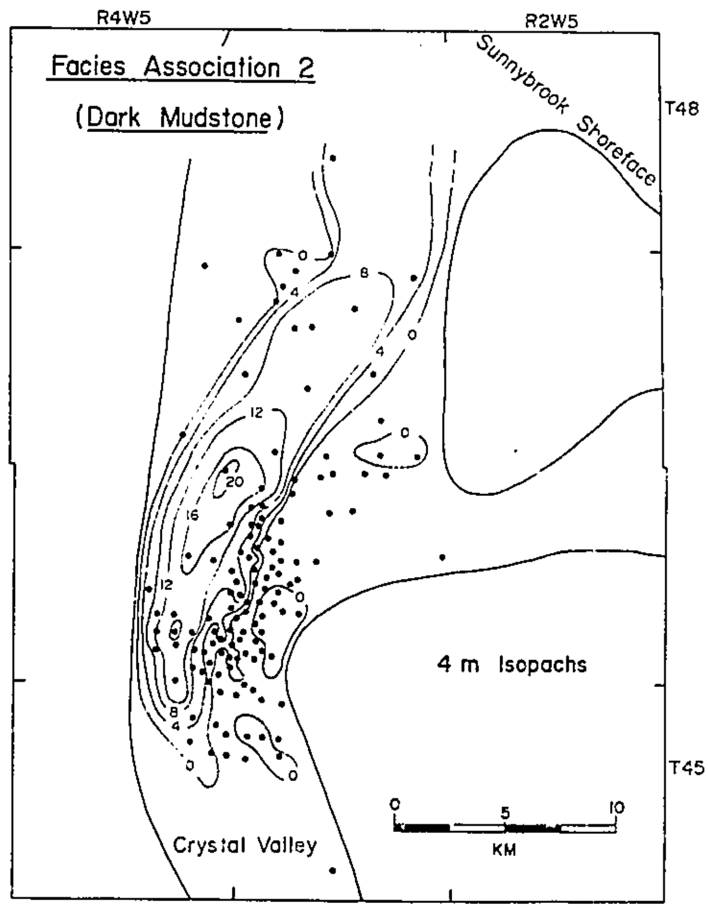
6.3.1 Basal Lag Deposits (FA-6 & FA-8)

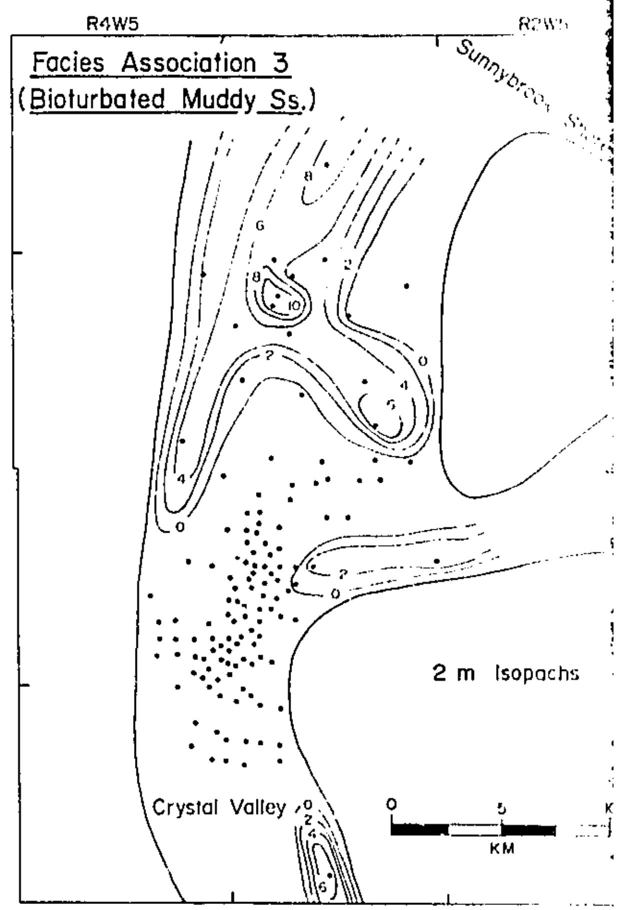
Basal lag deposits are observed in four locations in fill 1, including 14-20-45-3W5, 6-29-45-3W5, 8-31-45-3W5 and 14-1-46-4W5. These lags occur stratigraphically on top of the VE2 erosion surface, consist of coarse-grained cross bedded sandstones, conglomerates and mudstone clasts, are 0.1-0.5 m thick and are sharply overlain by the deposits of FA-2 or FA-4. They represent the oldest deposits of fill 1 and they have a very restricted lateral extent.

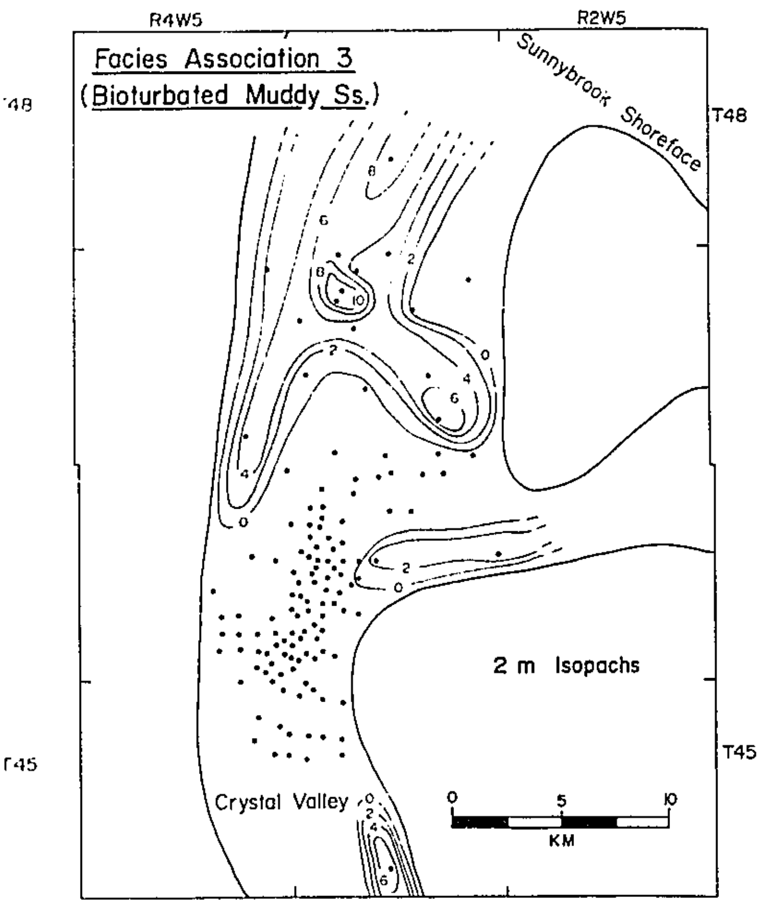
Interpretation

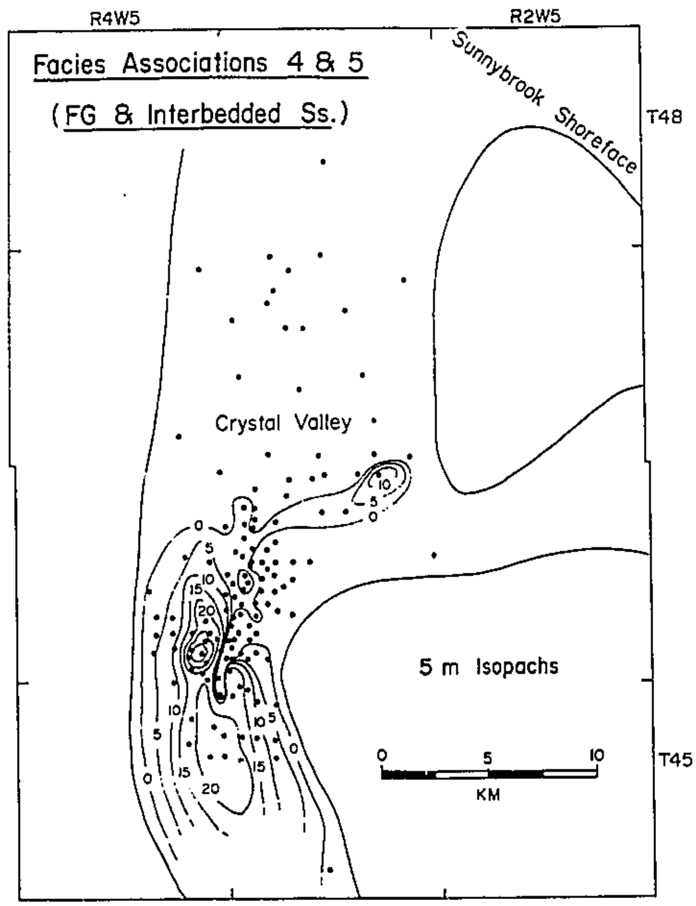
The presence of coarse-grained sandstones, conglomerates and mudstone clasts, and the absence of mudstone and bioturbation suggest deposition in a high energy environment. The sedimentology, location in the Crystal valley, patchy distribution, and sharp lower contact with the regional deposits may suggest deposition as a

Figure 6.6. Isopach maps of FA-2, FA-3 and FA-4/FA-5. Data are shown by black dots (103 cores & 25 well logs). FA-2 is concentrated in the central part of the valley, FA-3 is concentrated in the north and FA-4/FA-5 is concentrated in the south. The isopach map for FA-3 combines the deposits of fills 1 and 2. FA-4 and FA-5 are isopached together because they are difficult to distinguish in many cores. Isopach intervals differ for each map.


R4W5
R2W5
Facies Association 2
(Dark Mudstone)
Sunnybrook Shoreface
T48
T45
4 m Isopachs
Crystal Valley
KM


R4W5
Facies Association 3
(Bioturbated Muddy Ss.)
2 m Isopachs
Crystal Valley
KM


R4W5
R2W5
T48
T45
Facies Association 3
(Bioturbated Muddy Ss.)
Sunnybrook Shoreface
Crystal Valley
2 m Isopachs
KM


R4W5
R2W5
T48
T45
Facies Associations 4 & 5
(FG & Interbedded Ss.)
Sunnybrook Shoreface
Crystal Valley
5 m Isopachs
KM

fluvial or a transgressive lag. These lags are tentatively interpreted as fluvial in origin and their contact with the overlying estuarine mudstones is defined as the VE3-1 (transgressive modification) erosion surface.

In areas of basal lag deposits, the base of fill 1 is defined as the VE2 erosion surface (Fig. 6.7). In other areas, VE2 and VE3-1 are coplanar and the base of fill 1 is defined as the VE2 + VE3-1 erosion surface (Fig. 6.7).

6.3.2 Dark Mudstone (FA-2)

The dark mudstone deposits extend over a very wide area in the central part of the Crystal valley and are observed from T45-48 (Figs 6.3 & 6.6). The darkest or muddiest FA-2 deposits are located in the northern part of T46 and the southern half of T47 (Figs 6.4 & 6.5). They reach a maximum thickness of 21.8 m in 16-36-46-4W5 (Fig. 6.6).

The sediments of FA-2 rest stratigraphically on top of the VE2 erosion surface and are the most basal sediments of fill 1 throughout a large area of the Crystal valley (e.g. 6-27-47-3W5; Fig. 6.4). From bottom to top, they form a FU to CU facies succession. The dark mudstones have gradational lateral and vertical contacts with FA-4 to the south (8-26-45-4W5; Fig. 6.4), FA-5 to the southeast (12-1-46-4W5; Fig. 6.5) and FA-3 to the north (8-16-48-3W5; Figs 6.4).

Interpretation

The low to moderate degree of bioturbation, *Cruziana* ichnofacies, low diversity of traces, small size of individual traces, abundance of mudstone, gradational lateral contacts with FA-4 (south) and FA-3 (north), central location in the valley and wide lateral extent of FA-2 suggest deposition in a laterally extensive, quiet-water, estuarine environment. The dark mudstones of FA-2 are similar to the estuarine mudstones observed in the central part of many modern and ancient estuaries, including the Gironde, France (Allen, 1971; Allen et al., 1980; Allen & Truilhe, 1988; Allen, 1989; Allen, in press), Georgia coast, U.S.A. (Dorjes & Howard, 1975; Greer, 1975; Frey & Howard, 1986), James Estuary, Virginia, U.S.A. (Johnson et al., 1989; Nichols et al., 1989), Haringvliet, The Netherlands (Oomkens & Terwindt, 1960), Late Cretaceous, Drumheller, Alberta, Canada (Rahmani, 1988), Glauconitic Member, Alberta (Strobl, 1988; Wood & Hopkins, 1989) and Paddy Member, Alberta (Leckie, 1989b).

The wide lateral extent of the estuarine mudstones suggests that most of the Crystal valley was inundated during the early stages of fill 1 deposition and, therefore, the sediments in the lower part of fill 1 are transgressive. This interpretation is also supported by the FU succession observed in the lower half of the estuarine mudstones.

The upper half of the estuarine mudstones exhibits a CU succession which may be interpreted in one of the following ways; (1) an increase in the rate of sediment supply, (2) progradation during stillstand, (3) a relative fall in sea level, or (4) any combination of the above.

6.3.3 Bioturbated Muddy Sandstone (FA-3)

The sediments of FA-3 are mainly observed north of T46 (Figs 6.3 & 6.6). These sediments reach a maximum thickness of 5.8 m in 14-21-47-3W5 (Fig. 6.6).

The bioturbated muddy sandstone deposits are the most thoroughly bioturbated sediments observed in fill 1. They form gradational lateral and vertical contacts with the dark mudstone (FA-2) deposits to the south (Fig. 6.4).

FA-3 is also observed in the northern part of fill 2 and, therefore, the distinction between fills 1 and 2 becomes blurred in T48. However, the FA-3 deposits of fill 1 are finer grained, more bioturbated and are thinner than the FA-3 deposits in fill 2.

Interpretation

The sediments of FA-3 have been initially interpreted as the deposits of a moderate to high energy, marginal marine environment (section 4.3). The location at the mouth of the valley, proximity to the Sunnybrook shoreface deposits, and the gradational lateral and vertical contacts with the estuarine mudstones to the south suggest deposition in an estuarine-marine environment. The sandstones of FA-3 were probably reworked from the Sunnybrook shoreface into the Crystal valley during the "VE3-1" transgression. Similar deposits are observed at the mouths of many modern estuaries, including the eastern shore, Nova Scotia, Canada (Boyd et al., 1987), Georgia coast, U.S.A. (Dorjes & Howard, 1975; Greer, 1975; Frey & Howard, 1986), James Estuary, Virginia, U.S.A. (Johnson et al., 1989; Nichols et al., 1989), Willapa Bay, U.S.A. (Clifton, 1983), Gironde, France (Allen, 1989; Allen, in press), Haringvliet, The Netherlands (Oomkens & Terwindt, 1960), and New South Wales, Australia (Roy, 1984; Nichol, 1989) estuaries. Most of these modern estuaries exhibit a tripartite facies zonation that is similar to the tripartite zonation of fill 1.

6.3.4 Fine-Grained Sandstone (FA-4)

The deposits of FA-4 extend from the southern margin of the Crystal valley (T43) to the northern part of T46 (Figs 6.3 & 6.6), forming a northward thinning wedge of sediments that rest on top of FA-2 (Figs 6.3, 6.4 & 6.5). The maximum thickness of FA-4 is 27.4 m (10-25-45-4W5; Fig. 6.5).

The sediments of FA-4 form a sandying- or coarsening-upward facies succession. This trend is most prominent in the upper 5-10 m of the association (10-25-45-4W5; Fig. 6.5), which is dominated by fine- to medium-grained cross bedded sandstones. Laterally, FA-4 becomes thinner and muddier northward (Figs 6.4 & 6.5). This northward thinning wedge of sediments forms the "H" oil pool (Reinson, 1985; Reinson et al., 1988).

The sediments of FA-4 have gradational contacts with the dark mudstones of FA-2 to the north (Figs 6.4 & 6.5) and the sandstones of FA-5 to the northeast (Fig. 6.5). The contact with FA-5 is often "blurred" because these two associations have similar facies (Fig. 6.5). Therefore, the sediments of FA-4 and FA-5 are isopached together (Fig.

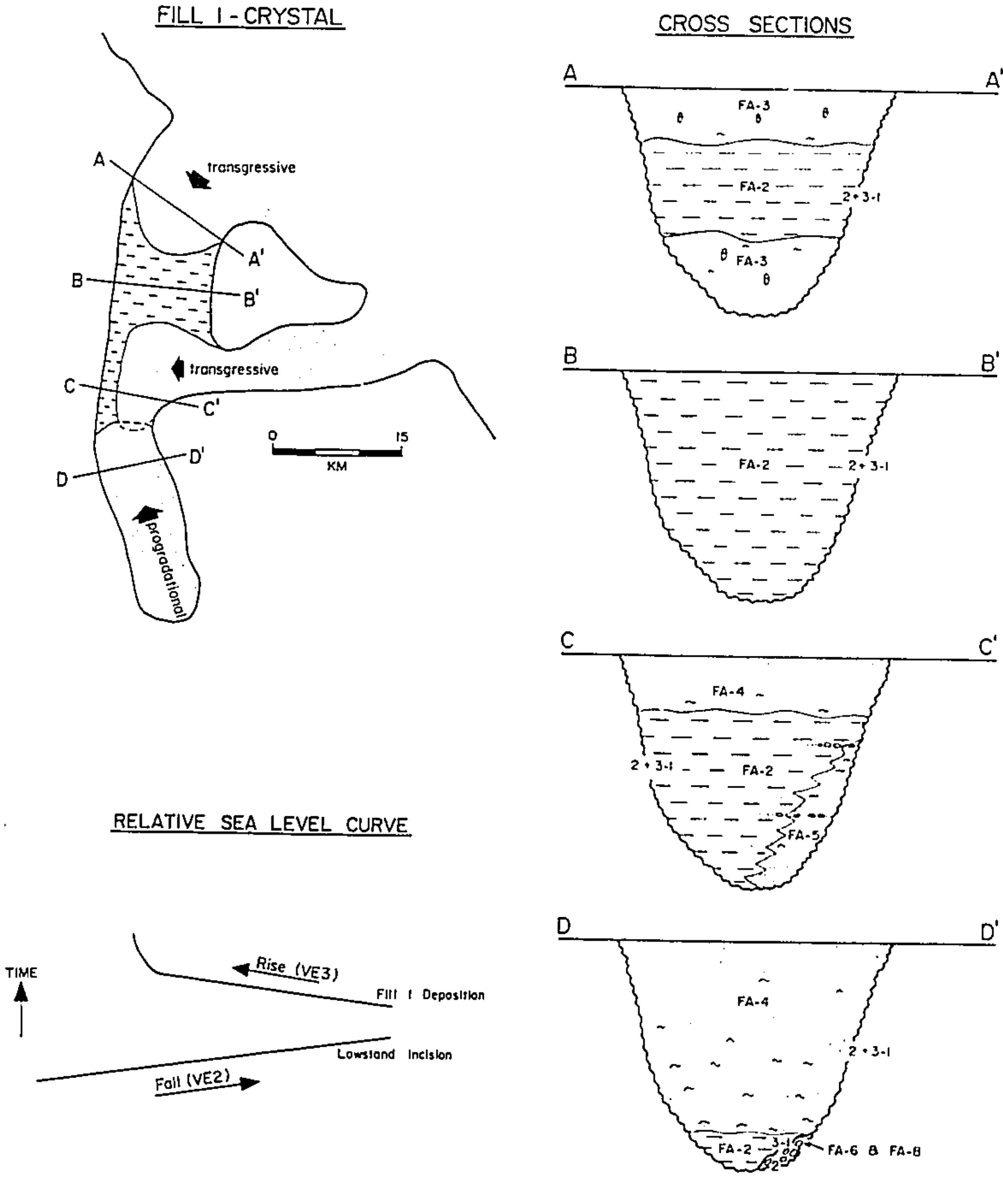
6.6).

Interpretation

The fine-grained sandstones have been initially interpreted as the deposits of a moderate energy, marginal marine environment (section 4.4). In the context of the tripartite facies zonation of fill 1 and the interpretation of the estuarine mudstones (FA-2) and marine sandstones (FA-3), the sediments of FA-4 occupy a more "terrestrial" position in the valley similar to the upper estuary sandstones of the Gironde (Allen, in press) or the bay-head delta sandstones of the eastern shore estuaries, Nova Scotia (B. Zaitlin, pers. comm., 1990). The abundance of well sorted, planar laminated and cross bedded sandstones, abundance of mudstone laminae, CU facies succession, low to moderate degree of bioturbation, "terrestrial" position in the valley and gradational contact with the estuarine mudstones to the north suggest deposition in a delta front or bay-head delta environment.

The CU nature of the delta front sandstones, the northward thinning wedge-shaped geometry and the lower contact with the estuarine mudstones suggest progradation of the bay-head delta during the latter stages of fill 1 deposition (Fig. 6.7). This progradation may occur during a stillstand, a relative fall in sea level, an increase in the rate of sediment supply or any combination of the above. The CU nature of the FA-4 sandstones coincides with the CU nature of the upper estuarine mudstones, and may record the

Figure 6.7. Four schematic cross sections (A to D) showing the internal sedimentology and stratigraphy of fill 1. Location shown in upper left and relative sea level curve shown in lower left. FA-2 - Dark Mudstone, FA-3 - Bioturbated Muddy Sandstone, FA-4 - Fine-Grained Sandstone, FA-5 - Interbedded Sandstones, FA-6 - Cross Bedded Sandstone, FA-8 - Interbedded Conglomerate, VE2 - "earliest" Viking lowstand incision, & VE3-1 - transgressive modification surface.


FILL I - CRYSTAL
A
transgressive
A'
B
B'
transgressive
C
C'
D
D'
0
15
KM
progradational
RELATIVE SEA LEVEL CURVE
TIME
Rise (VE3)
Fill I Deposition
Lowstand Incision
Fall (VE2)
CROSS SECTIONS
A
A'
FA-3
FA-2
2+3-1
FA-3
B
B'
FA-2
2+3-1
C
C'
FA-4
2+3-1
FA-2
FA-5
D
D'
FA-4
2+3-1
FA-2
3-1
FA-6 & FA-8
2

"slowing" or the end of the "VE3-1" transgression (Fig. 6.7).

6.3.5 Interbedded Sandstones (FA-5)

The sediments of FA-5 are located in T46/R3W5 and in the northern part of T45/R3W5 (Fig. 6.3). They form a "fan-shaped" wedge of sediments that extends westward into the main arm of the Crystal valley from the eastern arm (Fig. 6.3). These deposits are concentrated in the lower part of fill 1 and reach a maximum thickness of 21.7 m in 12-1-46-4W5 (Figs 6.5 & 6.6).

Overall, FA-5 forms a FU succession that is usually capped by thin (1-25 cm), muddy conglomerate beds (Fig. 6.5). These beds are best developed in sections 18, 19 and 30 (T46/R3W5). The sandstones of FA-5 have gradational lateral and vertical contacts with the fine-grained sandstones of FA-4 to the southwest and with the dark mudstones of FA-2 to the west-northwest.

Interpretation

The interbedded sandstones have been initially interpreted as the deposits of a moderate to high energy, marginal marine environment (section 4.5). The fan-like geometry, FU succession, proximity to the eastern arm of the Crystal valley and thinning of these sandstones to the west suggest deposition through the eastern arm of the Crystal valley, probably during the early phases of the "VE3-1" transgression (Fig. 6.7). Sandstones (FA-3) were also deposited through the main arm of the valley during this transgression.

The sandstones of FA-5 are interbedded with the lower, FU half of the estuarine mudstones suggesting deposition during transgressive conditions. Therefore, the sediments of FA-5 are interpreted as transgressive sandstones.

6.3.6 Summary

The sediments of fill 1, from south to north, consist of delta front sandstones (FA-4), transgressive sandstones (FA-5), estuarine mudstones (FA-2), and estuarine-marine sandstones (FA-3). Thin, basal fluvial lags (FA-6 & FA-8) are preserved in scattered locations. These deposits form an excellent tripartite facies zonation and can be described as transgressive to progradational in origin.

Three Viking erosion surfaces are associated with the deposits of fill 1, including VE2 (lowstand incision), VE3-1 (transgressive modification), and VE3/4 (transgressive ravinement; Figs 6.4 & 6.5).

6.4 Fill 2

The deposits of fill 2 are concentrated in a relatively small channel, approximately 30 km long and 0.4-4.5 km wide, in the central part of the Crystal valley (Fig. 6.8). Fill 2 reaches a maximum thickness of 30.2 m in 2-1-46-4W5 (Fig. 6.8).

The geometry and lateral extent of the sediments in fill 2 are shown in Figures 6.9 and 6.10. The deposits of fill 2 rest in a "VE3" lowstand scour that postdates and cuts into the VE2 + VE3-1 erosion surface (e.g. 4-7-46-3W5;

Figure 6.8. Isopach map of fill 2. Isopachs are in 10 m intervals. The outline of the Crystal valley is also shown.

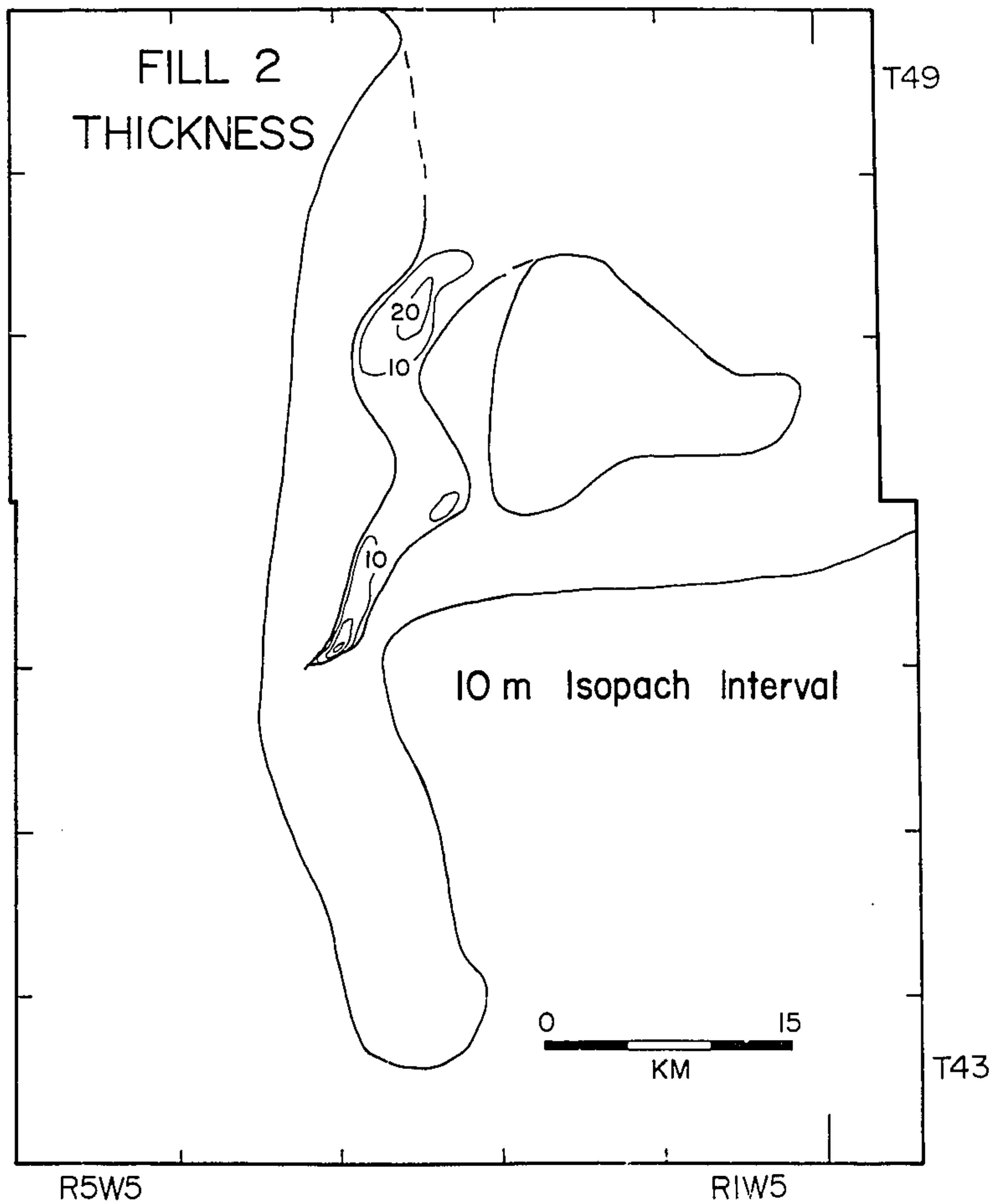

FILL 2
THICKNESS
T49
20
10
10
10 m Isopach Interval
0
15
KM
T43
R5W5
R1W5

Figure 6.9. The location of the three main facies associations of fill 2 (FA-3, FA-6 & FA-8), cross section KK' and the Sunnybrook shoreface. FA-3 - Bioturbated Muddy Sandstone, FA-6 - Cross Bedded Sandstone & FA-8 - Interbedded Conglomerate. The location of FA-7 (Massive Sandstone) coincides with the position of FA-8.

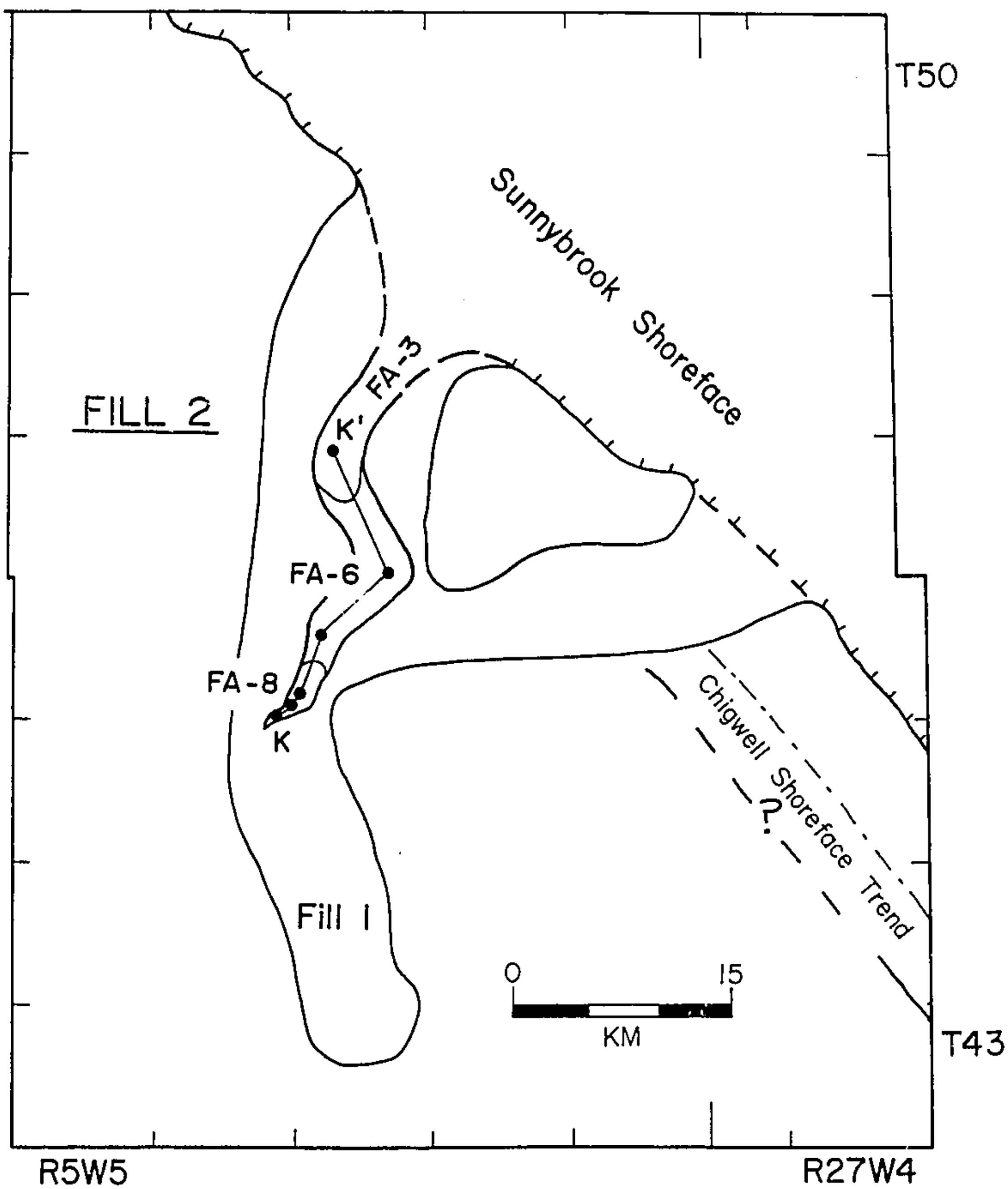
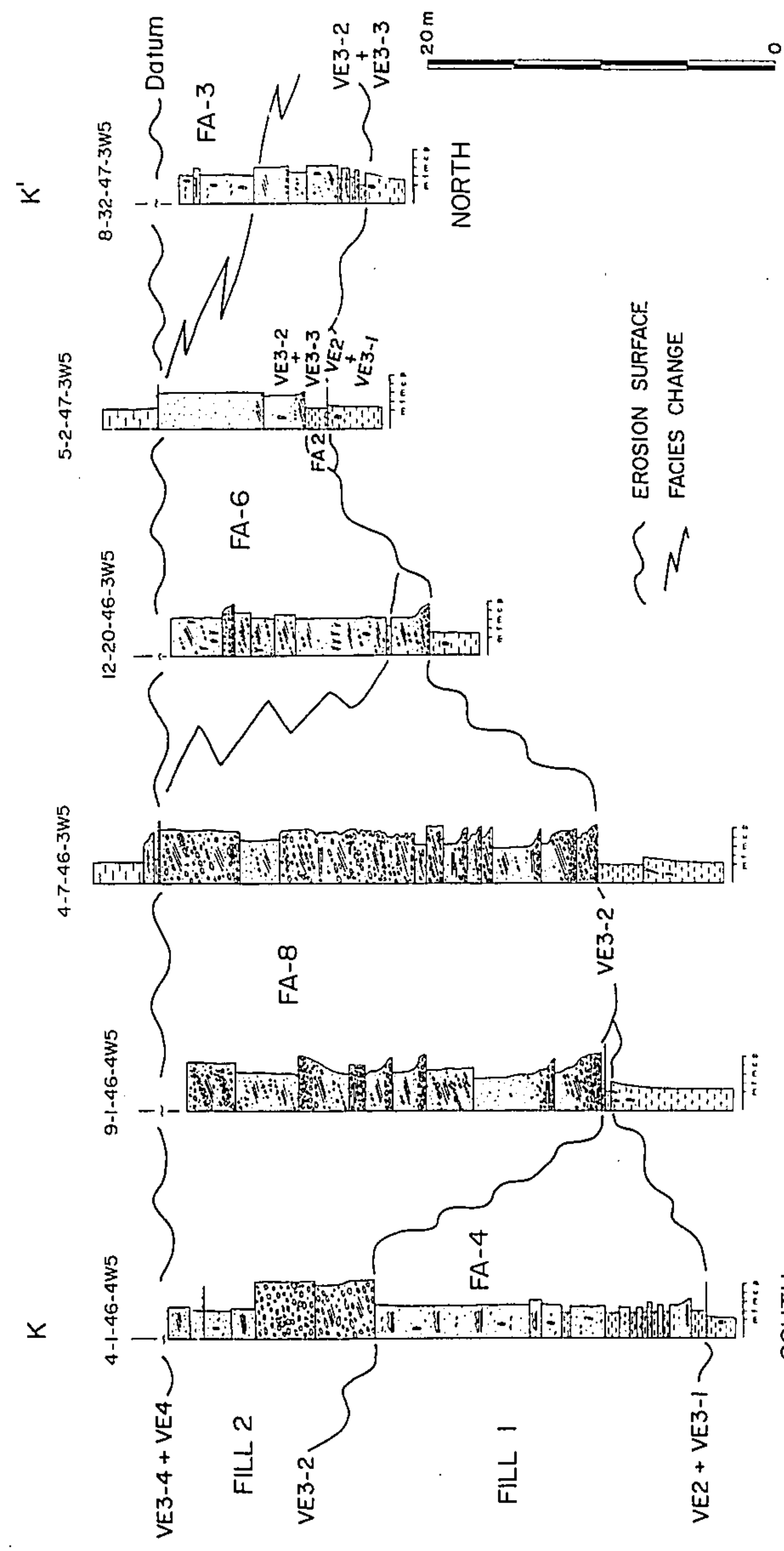

T50
Sunnybrook Shoreface
FILL 2
K'
FA-3
FA-6
FA-8
K
Chigwell Shoreface Trend
?
Fill 1
0
15
KM
T43
R5W5
R27W4

Figure 6.10. The following two pages show core and well log cross section KK'. The three main facies associations of fill 2 (FA-3, FA-6 & FA-8), four Viking erosion surfaces (VE2 + VE3-1, VE3-2, VE3-3 & VE3-4 + VE4), and four regional CU successions (1 to 4) are shown. Note the fill 1 deposits in the lower parts of 4-1-46-4W5 (FA-4) and 5-2-47-3W5 (FA-2). Black bars on the well log cross section indicate core positions. Location shown in Figure 6.9.


K
K'
4-1-46-4W5
9-1-46-4W5
4-7-46-3W5
12-20-46-3W5
5-2-47-3W5
8-32-47-3W5
Datum
FA-3
FA-6
FA-8
FA-4
FA2
VE3-2 + VE3-3
VE2 + VE3-1
VE3-2 + VE3-3
VE3-2
VE3-4 + VE4
FILL 2
VE3-2
FILL 1
VE2 + VE3-1
SOUTH
NORTH
EROSION SURFACE
FACIES CHANGE
20 m
0

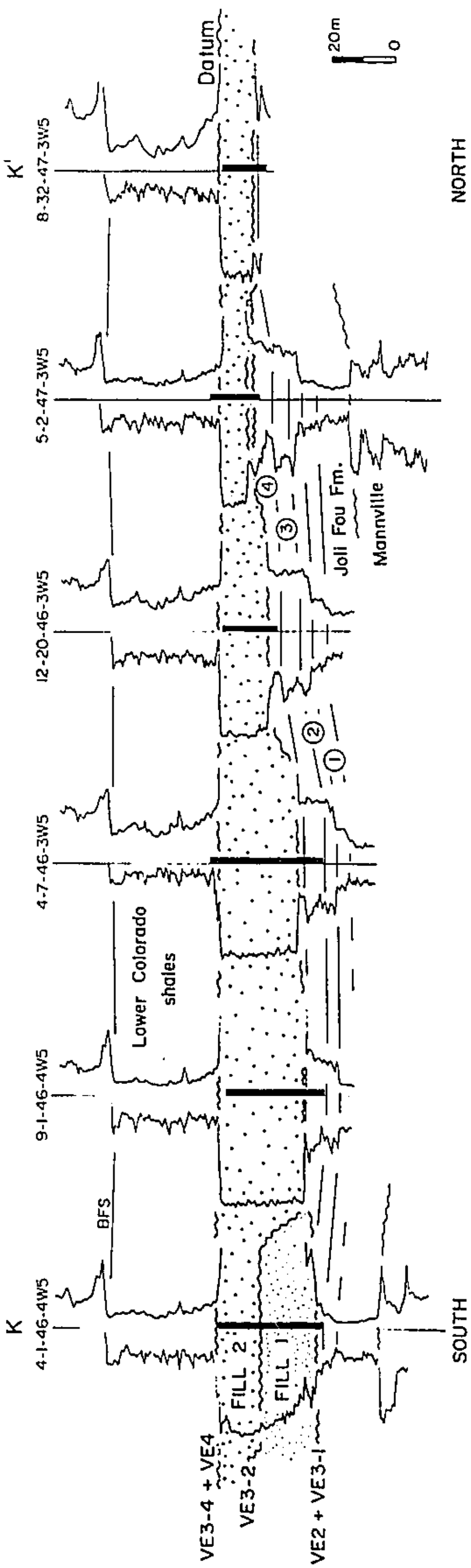

K
K'
4-1-46-4W5
9-1-46-4W5
4-7-46-3W5
12-20-46-3W5
5-2-47-3W5
8-32-47-3W5
Datum
20m
0
NORTH
SOUTH
BFS
Lower Colorado shales
Joli Fou Fm.
Mannville
1
2
3
4
FILL 2
FILL 1
VE3-4 + VE4
VE3-2
VE2 + VE3-1

Fig. 6.10). This scour represents the second erosion surface that has been cut during "VE3" time and, therefore, is labelled VE3-2. The VE3-2 erosion surface is the second lowstand incision in the Crystal valley; VE2 was the first (Fig. 6.7).

The sediments of fill 2 can be subdivided into four FA's which occupy specific areal and/or stratigraphic positions in the valley (Fig. 6.9). From south to north, they include (i) interbedded conglomerate (FA-8), (ii) massive sandstone (FA-7), (iii) cross bedded sandstone (FA-6), and (iv) bioturbated muddy sandstone (FA-3). Isopach maps of these associations are shown in Figures 6.6 and 6.11.

6.4.1 Interbedded Conglomerate (FA-8)

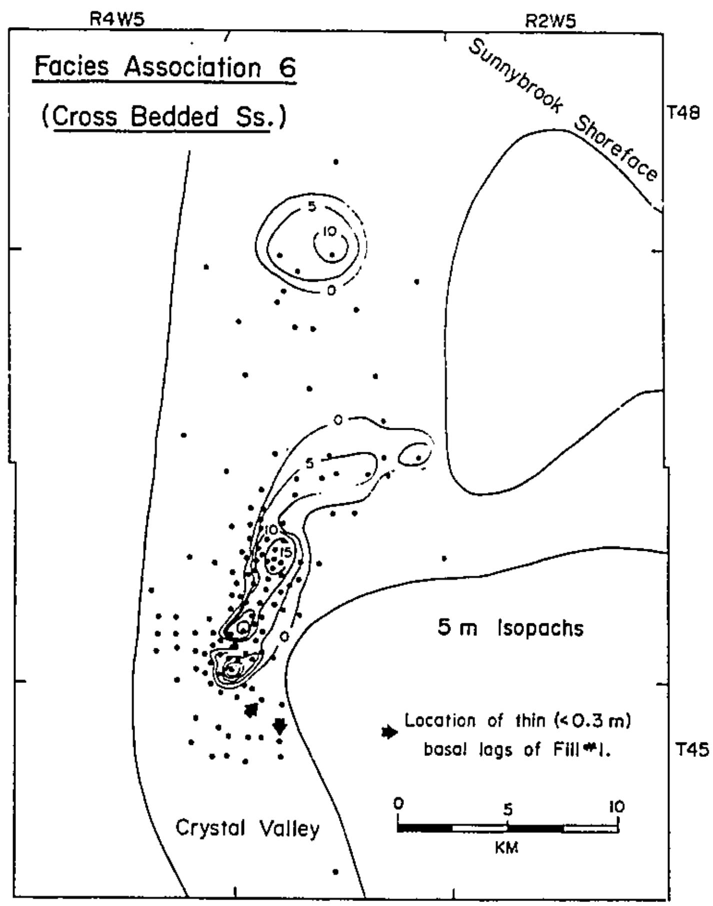
The interbedded conglomerates are the thickest facies association observed in fill 2. These deposits reach a maximum thickness of 28.4 m in 16-1-46-4W5 (Fig. 6.11). The interbedded conglomerates mainly occur in the southern part of fill 2 (Figs 6.9 & 6.11). Thin deposits of FA-8 also occur in the central and northern parts of T46 (Fig. 6.11).

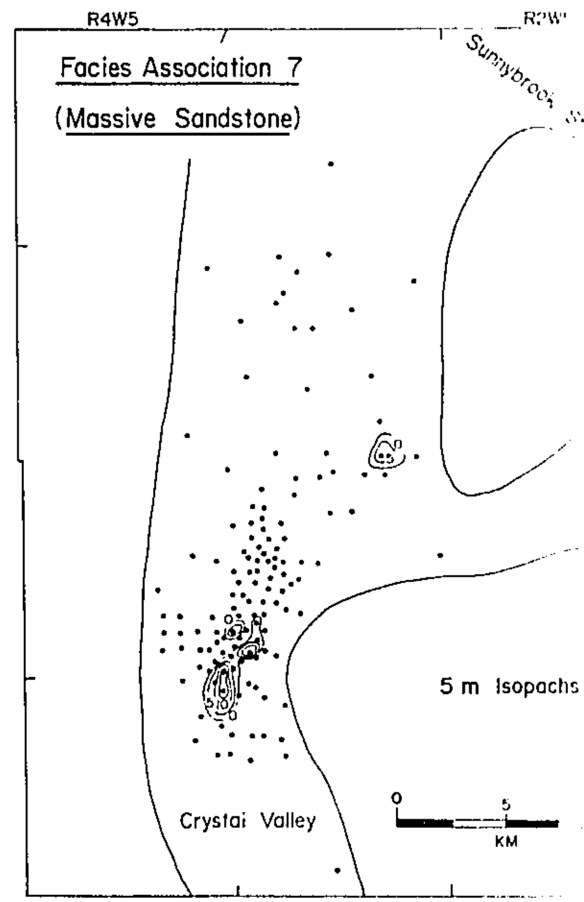
The conglomerates of FA-8 become thinner and finer grained towards the north (Figs 6.10 & 6.11). They are gradationally interbedded to the north with the cross bedded sandstones of FA-6 and the massive sandstones of FA-7.

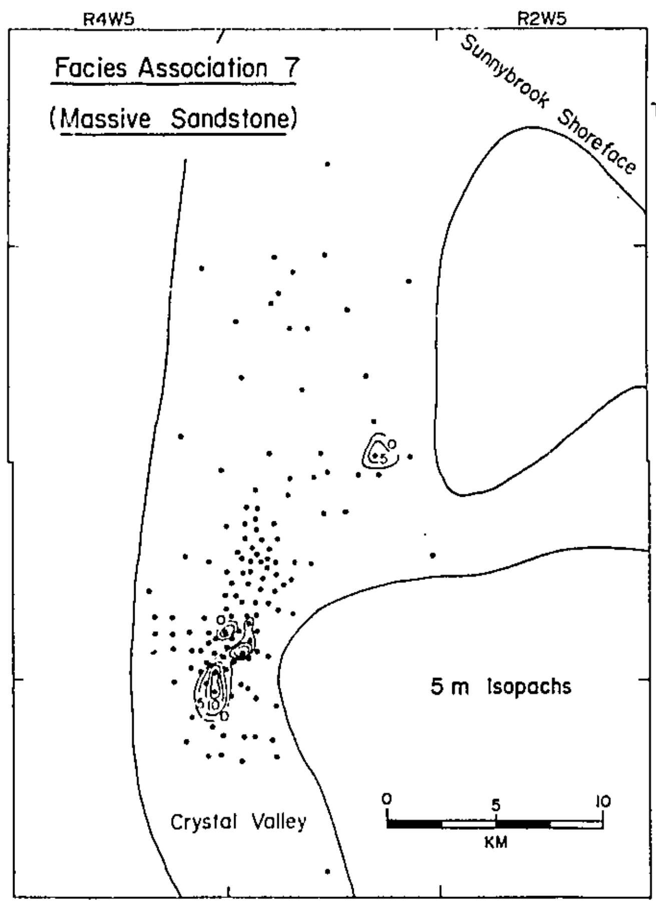
Interpretation

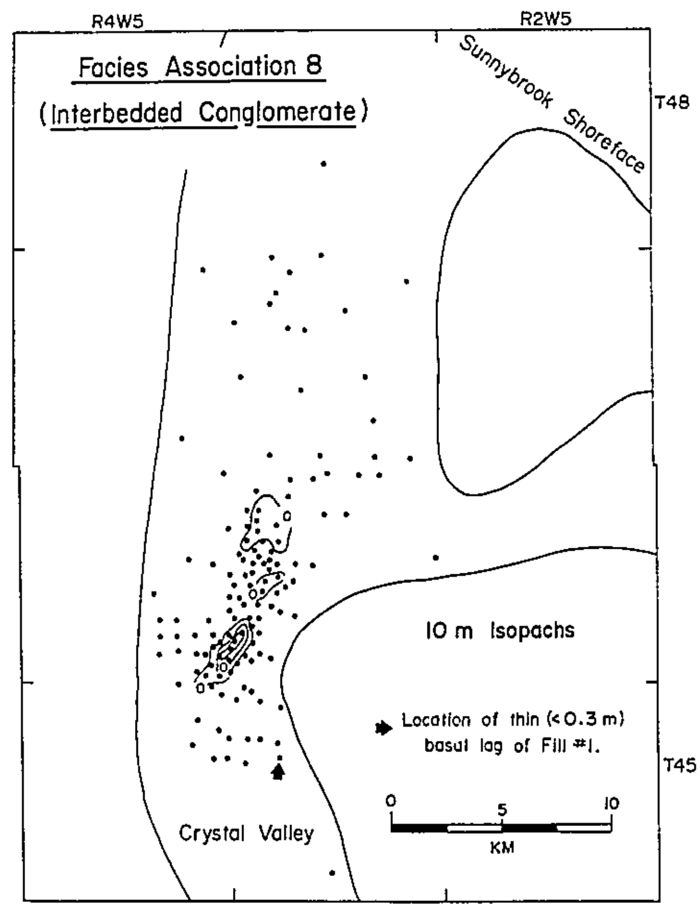
The abundance of cross beds, presence of pebbles, granules and coarse-grained sand, paucity of bioturbation

Figure 6.11. Isopach maps of FA-6, FA-7 and FA-8. Data are shown by black dots (103 cores & 25 well logs). These facies associations have a very limited lateral extent in comparison to the associations observed in fill 1 (Fig. 6.6). Isopach intervals are 5 m for FA-6 and FA-7, and 10 m for FA-8. The location of three basal lags (FA-6 & FA-8) deposits from fill 1 are highlighted by arrows.


R4W5
R2W5
Facies Association 6
(Cross Bedded Ss.)
Sunnybrook Shoreface
T48
T45
5 m Isopachs
Location of thin (<0.3 m) basal lags of Fill #1.
Crystal Valley
0 5 10
KM


R4W5
Facies Association 7
(Massive Sandstone)
5 m Isopachs
Crystal Valley
KM


R4W5
R2W5
Facies Association 7
(Massive Sandstone)
Sunnybrook Shoreface
T48
5 m Isopachs
T45
Crystal Valley
0 5 10
KM


R4W5
R2W5
Facies Association 8
(Interbedded Conglomerate)
Sunnybrook Shoreface
T48
10 m Isopachs
Location of thin (< 0.3 m) basal lag of Fill #1.
T45
Crystal Valley
0 5 10
KM

and mudstone laminae, channel-like geometry, frequent vertical changes in grain size, sorting and type of sedimentary structures, and presence of FU successions suggest deposition in a high energy, fluvial channel. The uni-directional, cross bedded conglomerates and imbricated conglomerates are indicative of strong uni-directional currents. The chaotically bedded conglomerate (Fig. 4.25D) and oversteepened sandstone beds (60-90°) suggest relatively high sedimentation rates. These characteristics are very similar to the facies and successions decribed for modern and ancient, gravelly braided river deposits (Miall, 1977, 1978; Rust, 1978; Rust & Koster, 1984). Therefore, the interbedded conglomerates of fill 2 are interpreted as the deposits of a coarse-grained, braided river.

6.4.2 Massive Sandstone (FA-7)

The massive sandstones are the thinnest and the least extensive deposits of fill 2. FA-7 occurs in the southern (T45-46) and central (T46-47) parts of fill 2, and reaches a maximum thickness of 19.8 m in 10-36-45-4W5 (Fig. 6.11).

In general, the sediments of FA-7 become finer grained and thinner to the north (Fig. 6.11). These deposits are gradationally interbedded with the sediments of FA-6 and FA-8.

Interpretation

The massive sandstones have been initially interpreted as subaqueous, waning flow deposits that were rapidly deposited out of suspension (section 4.7). Miall (1984) suggests that high sedimentation rates in a fluvio-deltaic setting would lead to the oversteepening and under compaction of beds, which could result in large-scale slope failure. This process is well documented in the Mississippi delta (Coleman et al., 1974; Prior & Coleman, 1978, 1982; Coleman et al., 1983), and it may lead to the deposition of massive sandstones, such as those observed in the delta front sediments of the Lower Cretaceous, Spitsbergen (Nemec et al., 1988).

The proximity of the massive sandstones to the southern end of the "VE3-2 incision", the gradational lateral and vertical contacts with the deposits of FA-8 and FA-6, and the channelized geometry suggest deposition as subaqueous slumps caused by high rates of fluvial sedimentation. These slumps may consist of re-deposited delta front sandstones of FA-4 (fill 1) and/or fluvial conglomerates of FA-8 (fill 2).

6.4.3 Cross Bedded Sandstone (FA-6)

The cross bedded sandstones are the most laterally extensive deposits of fill 2 and are observed as a continuous "ribbon" in T46 and as a smaller "patch" in T47/48 (Figs 6.9 & 6.11). FA-6 reaches a maximum thickness of 20.2 m in 12-6-46-3W5 (Fig. 6.11).

The sediments of FA-6 become finer grained, more bioturbated and thinner towards the north (Fig. 6.10). These deposits also become finer grained and more bioturbated upward. The cross bedded sandstones are gradationally interbedded with the conglomerates (FA-8) and massive sandstones (FA-7) in the south, and with the bioturbated muddy sandstones (FA-3) in the north (Fig. 6.10). They are less conglomeratic, muddier and more thoroughly bioturbated than the deposits of FA-8 and FA-7 to the south.

Interpretation

The cross bedded sandstones have been initially interpreted as the deposits of a relatively high energy, non-marine to marginal marine environment (section 4.6). Most of the cross bedded sandstone beds contain carbonaceous or mudstone laminae which often occur in pairs or couplets (Figs 4.18 & 4.19C), and are interpreted as tide-generated structures.

The channelized geometry, gradational lateral and vertical contacts with the fluvial (FA-8) and slump (FA-7) deposits to the south, and the abundance of tide-generated cross bedding suggest deposition in a tidal-fluvial channel. The presence of bi- and multi-directional cross bed sets, a Skolithos ichnofacies and FU successions are also consistent with deposition in a tidal-fluvial channel. These deposits are very similar to the tidal/estuarine point bar facies which occur in the "funnel" part of the Gironde estuary (Allen, in press).

The tidal-fluvial deposits of FA-6 often rest stratigraphically on top of the fluvial deposits (e.g. 12-20-46-3W5; Fig. 6.10). This vertical facies succession is interpreted as transgressive and it heralds the initial

stages of the "fill 2 transgression" (Fig. 6.12). It is probable that the morphology and geometry of the VE3-2 scour was modified by tidal currents or wave action during this transgression. Therefore, the contact between the fluvial conglomerates and the tidal-fluvial cross bedded sandstones has tentatively been defined as the VE3-3 transgressive erosion surface (Fig. 6.12). Because this contact is gradational in most wells, the "true" position of the VE3-3 erosion surface may never be known. However, it is important to recognize the significance of transgressive modification and, therefore, the VE3-3 erosion surface is shown as a dashed surface in Figure 6.12.

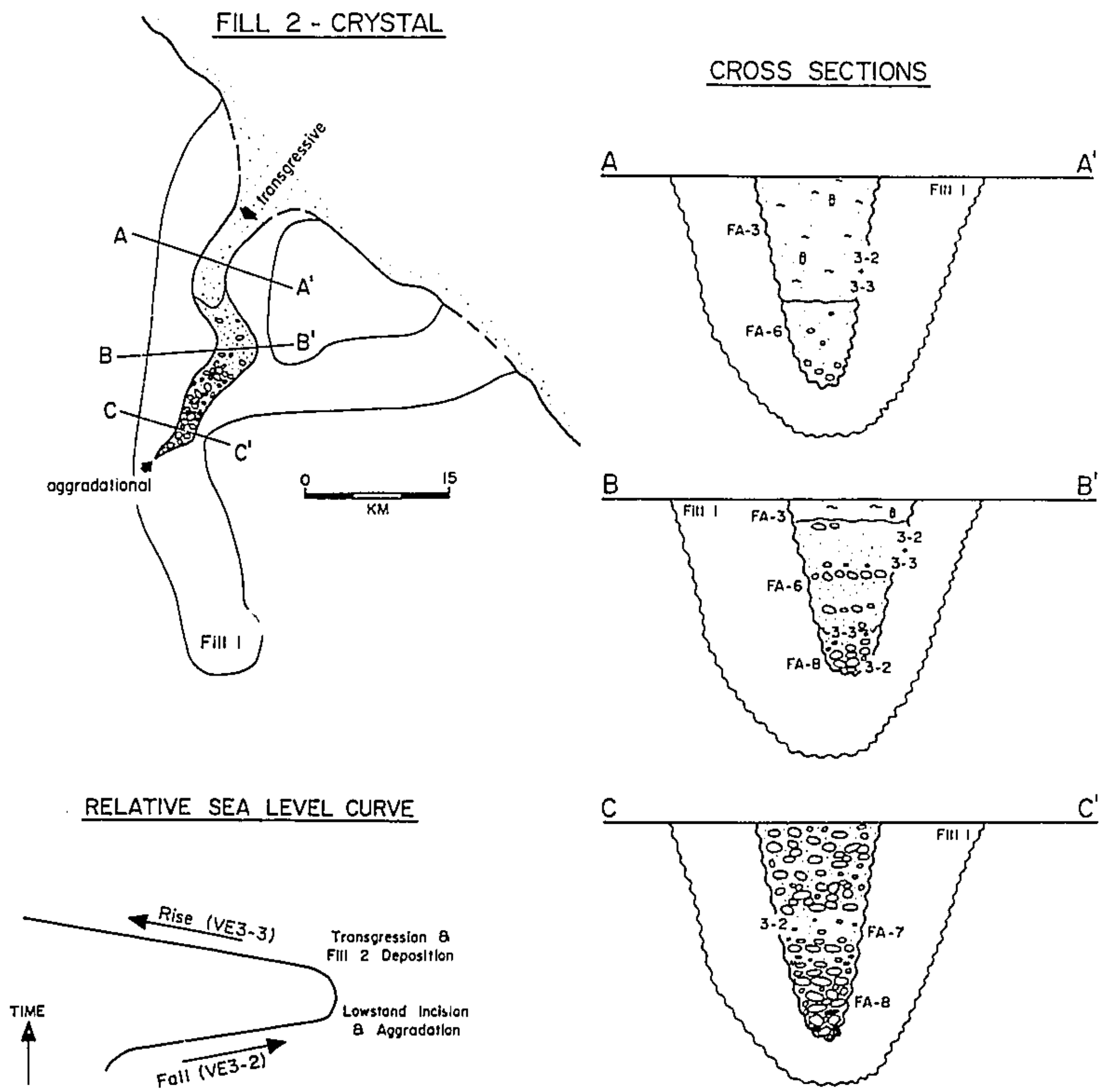
In most areas, the VE3-2 and VE3-3 erosion surfaces are coplanar (Fig. 6.12). Separation between these two surfaces is only inferred in wells that contain the fluvial conglomerates and the tidal-fluvial cross bedded sandstones (eg. southern part of fill 2; Fig. 6.12).

6.4.4 Bioturbated Muddy Sandstone (FA-3)

The sediments of FA-3 occur in the northern part of fill 2 (Figs 6.9 & 6.10). These deposits are difficult to map and correlate in this area because of the poor core control (Fig. 2.6). The maximum thickness of FA-3 occurs in 6-29-47-3W5 where they are 10.4 m thick (Fig. 6.6).

The bioturbated muddy sandstones have gradational lateral and vertical (e.g. 8-32-47-3W5; Fig. 6.10) contacts with the cross bedded sandstones (FA-6) to the south. To the north, the sediments of FA-3 grade into the Sunnybrook

Figure 6.12. Three schematic cross sections (A to C) showing the internal sedimentology and stratigraphy of fill 2. Location shown in upper left and relative sea level curve shown in lower left. FA-3 - Bioturbated Muddy Sandstone, FA-6 - Cross Bedded Sandstone, FA-7 - Massive Sandstone, FA-8 - Interbedded Conglomerate, VE3-2 - "second" lowstand incision at Crystal, & VE3-3 - transgressive modification surface.


FILL 2 - CRYSTAL
transgressive
A
A'
B
B'
C
C'
aggradational
0
15
KM
Fill I
CROSS SECTIONS
A
A'
Fill I
FA-3
3-2
3-3
FA-6
B
B'
Fill I
FA-3
3-2
3-3
FA-6
3-3
FA-8
3-2
C
C'
Fill I
3-2
FA-7
FA-8
RELATIVE SEA LEVEL CURVE
Rise (VE3-3)
Transgression & Fill 2 Deposition
Lowstand Incision & Aggradation
TIME
Fall (VE3-2)

shoreface deposits (Fig. 6.9).

FA-3 is also observed in the northern part of fill 1. However, the FA-3 sandstones of fill 2 are coarser, thicker and less bioturbated than those in fill 1.

Interpretation

The bioturbated muddy sandstones have been interpreted as the deposits of a marginal marine environment (section 4.3). The wavy and lenticular bedding, carbonaceous mudstone drapes on cross beds, channelized geometry, bi-directional cross beds, Skolithos ichnofacies, and thoroughly bioturbated sandstone beds indicate deposition in a tidally-influenced, marginal-marine channel. These deposits occur at the mouth of the Crystal valley and they form a southward thinning wedge of sediments that rest stratigraphically on top of the tidal-fluvial cross bedded sandstones (Fig. 6.12). The bioturbated muddy sandstones were probably reworked into the mouth of the Crystal valley during the "VE3-3" transgression.

6.4.5 Summary

The sediments of fill 2, from south to north, consist of fluvial conglomerates (FA-8) and slump deposits (FA-7), tidal-fluvial sandstones (FA-6), and tidal-marine sandstones (FA-3). These deposits become finer grained and more bioturbated towards the north, but do not exhibit a tripartite facies zonation (Fig. 6.12). These deposits can be described as aggradational (FA-8) to transgressive (FA-3 & FA-6) in origin. Four Viking erosion surfaces are associated with the deposits of fill 2, including VE3-2 (lowstand incision), VE3-3 (transgressive modification), VE3-4 (transgressive ravinement; Fig. 6.10), and VE4.

6.5 <u>Sequence of Events</u>

Ten different erosional or depositional events are recognized in the deposits of the Crystal valley-fill:

(1) A major relative fall in sea level resulted in the cutting of the Crystal valley and, hence, the development of the VE2 erosion surface (Figs 6.13 & 6.14).

(2) During the relative fall in sea level, thin fluvial deposits aggraded in the Crystal valley. These are the basal lags of fill 1 (Figs 6.13 & 6.14).

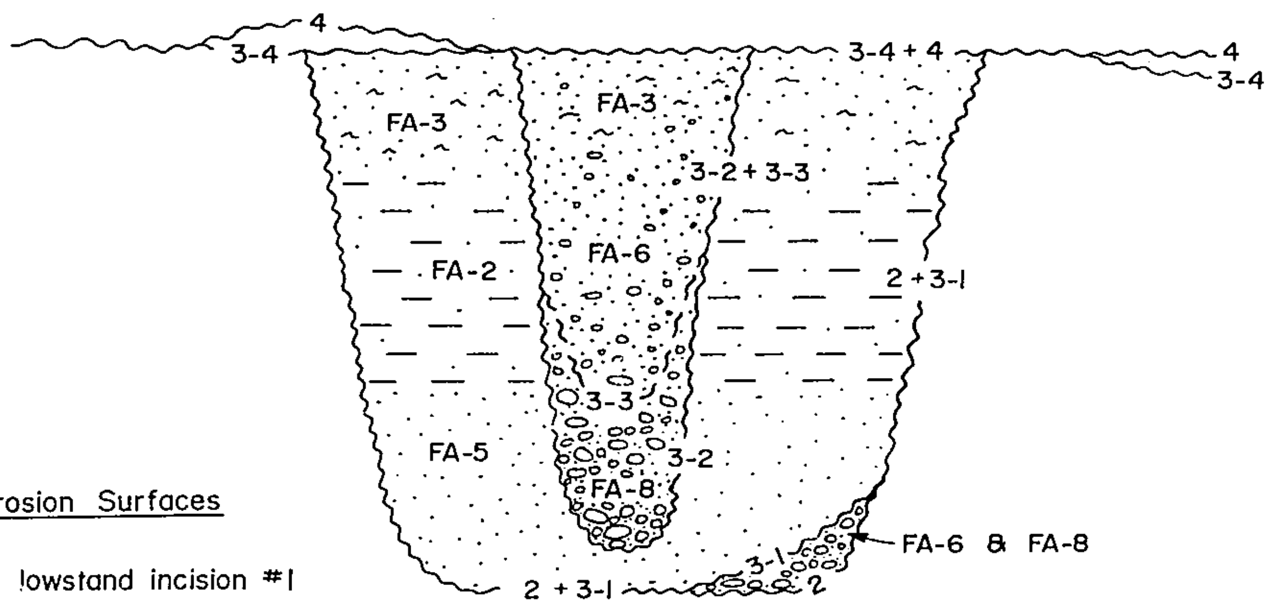
(3) A subsequent relative rise in sea level flooded the Crystal valley and modified the geometry and depth of the VE2 scour. This coincides with the development of the VE3-1 erosion surface and the deposition of fill 1 (Figs 6.13 & 6.14).

(4) During the latter stages of fill 1 deposition, the fluvio-deltaic system prograded northward over top of the estuarine mudstones (FA-2). A relative fall in sea level may have caused the progradation of the fluvio-deltaic system. This fall may "herald" the much larger relative fall in sea level that is associated with the "VE3-2" lowstand incision.

(5) A large relative fall in sea level resulted in the cutting of the second lowstand incision at Crystal. This scour has a small, channel-like geometry relative to the

Figure 6.13. Schematic cross section of the sedimentology and internal stratigraphy of the Crystal valley. The deposits of fill 1 (FA-2, FA-3, FA-4, FA-5 & FA-6/FA-8 basal lags), the deposits of fill 2 (FA-3, FA-6 & FA-8), and five Viking erosion surfaces (VE2, VE3-1, VE3-2, VE3-3, VE3-4 & VE4) are shown. Depth of the valley is approximately 30 m and the width is approximately 10 km. Compare to the "earlier" version of the Crystal allostratigraphy (Fig. 3.4). FA-2 - Dark Mudstone, FA-3 - Bioturbated Muddy Sandstone, FA-4 - Fine-Grained Sandstone, FA-5 - Interbedded Sandstones, FA-6 - Cross Bedded Sandstone, FA-7 - Massive Sandstone, & FA-8 - Interbedded Conglomerate.

Crystal Valley-Fill



Erosion Surfaces

2. lowstand incision #1

3-1. transgressive "modification" surface #1

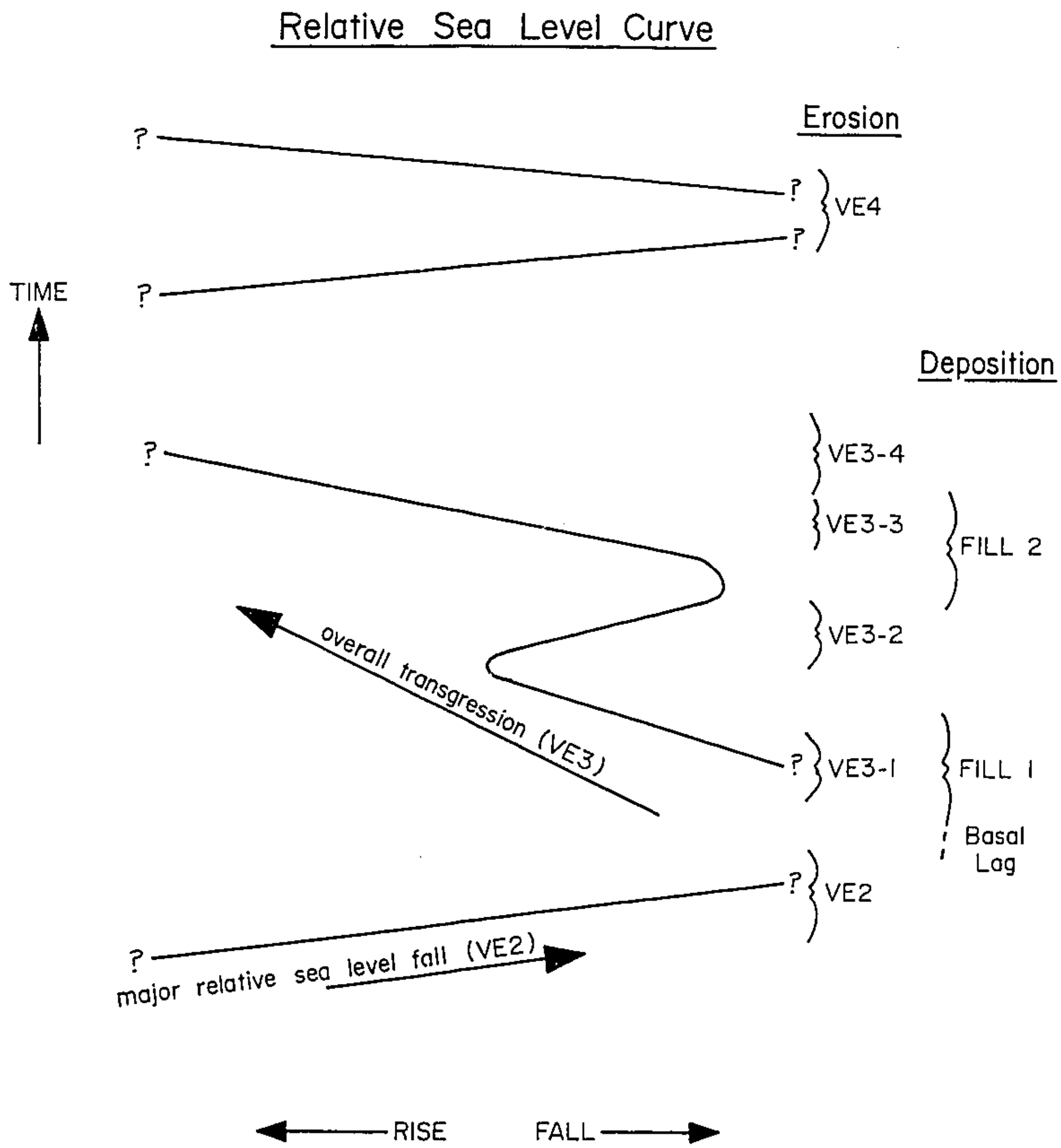
3-2. lowstand incision #2

3-3. transgressive "modification" surface #2

3-4. transgressive ravinement surface

4. basinwide erosion

Figure 6.14. Relative sea level curve inferred from the study of the Crystal valley-fill deposits. The timing of erosional and depositional events are shown. A major fall in relative sea level (VE2) is followed by an ensuing transgression (VE3) that is punctuated by stillstands and minor regressions (VE3-2). The VE3 "transgression" is followed by the VE4 lowstand/transgressive event.


Relative Sea Level Curve
Erosion
?
?
VE4
?
TIME
?
Deposition
?
VE3-4
VE3-3
FILL 2
VE3-2
overall transgression (VE3)
?
VE3-1
FILL 1
Basal
Lag
?
VE2
?
major relative sea level fall (VE2)
RISE
FALL

much larger VE2 + VE3-1 incision; and is labelled the VE3-2 erosion surface (Figs 6.13 & 6.14).

(6) During the latter stages of the relative fall in sea level, the fluvial conglomerates aggraded in the southern part of the VE3-2 scour.

(7) A subsequent relative rise in sea level flooded the Crystal valley and modified the geometry and depth of the VE3-2 scour. This coincides with the development of the VE3-3 erosion surface (Figs 6.13 & 6.14), and the deposition of the tidal-fluvial cross bedded sandstones (FA-6) and the tidal-marine sandstones (FA-3).

(8) During the continued relative rise in sea level, the shoreline moves to the southwest of the Crystal area and the upper part of the valley-fill deposits are truncated and reworked during transgressive ravinement. This produces the VE3-4 erosion surface at the top of fills 1 and 2 (Figs 6.13 & 6.14).

(9) A thin transgressive package of mudstones, sandstones and conglomerates are deposited on top of the VE3-4 erosion surface.

(10) It will be shown later (chapter 9) that a relative fall in sea level followed by a subsequent relative rise resulted in the development of the VE4 erosion surface (Figs 6.13 & 6.14).

6.6 VE3 Nomenclature

From this point on in the thesis, the VE3 erosion surface will be described using the nomenclature introduced in this chapter (VE3-1, VE3-2, VE3-3 & VE3-4). Three other VE3 surfaces have been identified in the Cyn-Pem, Sundance and Edson area, and these are labelled VE3-5, VE3-6 and VE3-7 (chapters 7 & 8). This nomenclature provides a convenient and simple method for recording the sequence of erosive events that are associated with the overall "VE3" transgression. The reader is referred to chapters 9 and 10 for a thorough documentation of the VE3 erosion surface nomenclature.

CHAPTER 7 - CYN-PEM VALLEY-FILL

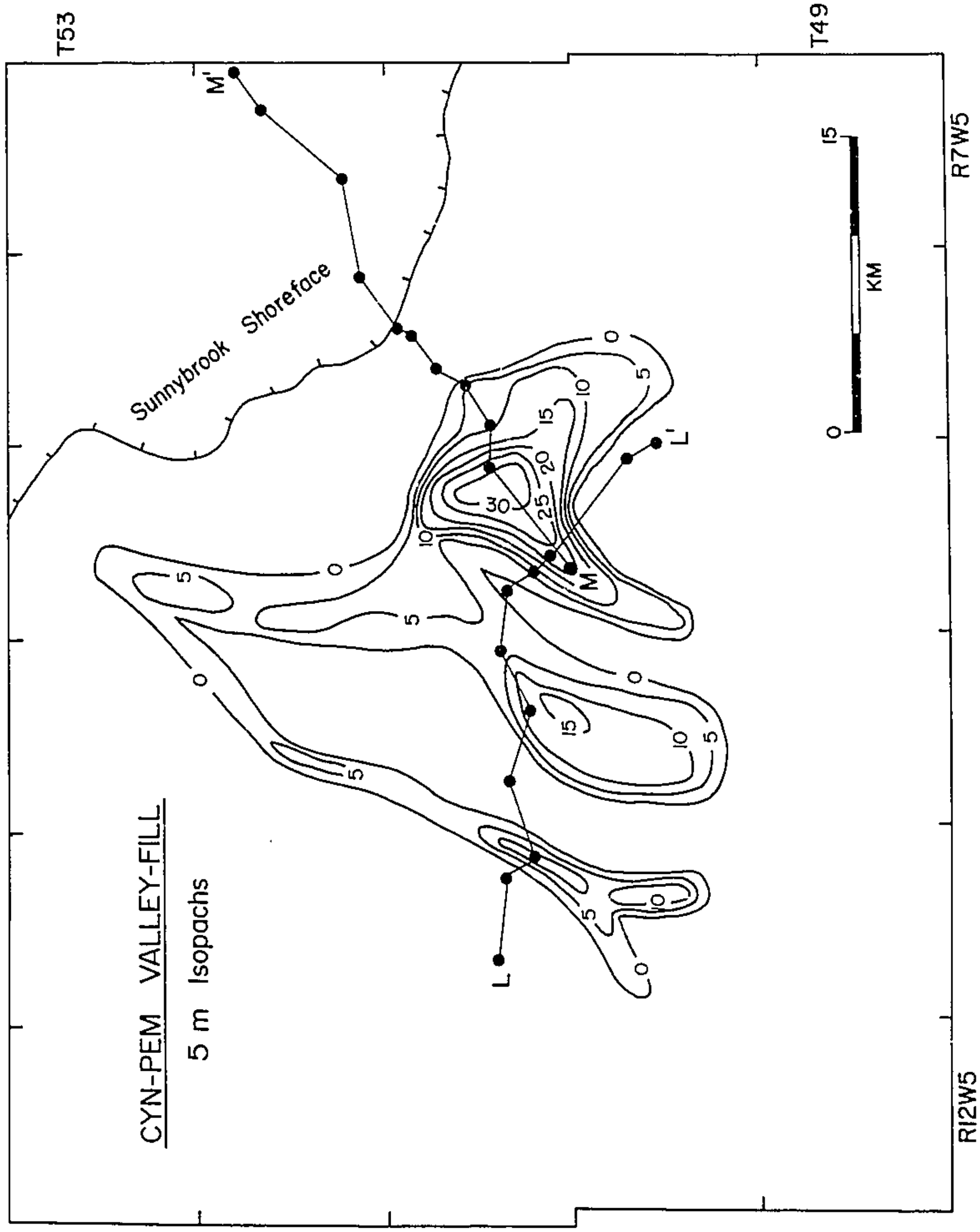
The Cyn-Pem valley-fill complex occurs in T50-53, R8W5-11W5 and it consists of three main valley arms; west, central and east (Fig. 7.1). All three valley arms merge in the northwest forming a much wider valley-fill complex. The western arm is the longest (36 km) and narrowest (1-5 km), but the thickest deposits occur in the eastern arm (Fig. 7.1). The maximum thickness of the valley-fill is 34.4 m in 7-23-51-9W5.

The valley-fill complex is oriented NNE-SSW, perpendicular to the orientation of the regional shoreline trend at Gilby-Joffre (Downing & Walker, 1988). It is located 4.2-9.7 km southwest of the Sunnybrook shoreface but is not directly connected to the shoreface (Fig. 7.1). The Cyn-Pem valley-fill complex has a similar maximum thickness and orientation to the Crystal valley-fill, and is located on the same shoreline trend (Sunnybrook).

Only two wells in the Cyn-Pem valley-fill complex produce oil and gas, and they are located in the western arm of the valley (8-13-51-11W5 & 16-13-51-11W5). The total production from these wells, up to March 1990, is 7.52×10^3 m^3 (47.3 MSTB) of oil and 1.70×10^7 m^3 (0.6 BCF) of gas (Alberta Production Report, 1990).

An extensive well log data base is available in the Cyn-Pem area and this has been used to delineate the valley-fill deposits (Figs 1.5 & 7.1). Unfortunately, only two

Figure 7.1. Isopach map of the Cyn-Pem valley-fill complex. This complex consists of a western, central and eastern arm, and is located approximately 4.2 to 9.7 km southwest of the Sunnybrook shoreface. Note the location of cross sections LL' and MM'. Isopachs are in 5 m intervals.


CYN-PEM VALLEY-FILL
5 m Isopachs
Sunnybrook Shoreface
T53
T49
R7W5
RI2W5
0
15
KM
L
L'
M
M'

cores penetrate the valley-fill deposits (6-12-51-11W5 & 4-16-53-9W5; Fig. 1.6), and it is difficult if not impossible to provide detailed reconstructions of the stratigraphy and sedimentology of these deposits.

7.1 Stratigraphic Packages

Four different stratigraphic packages (regional, valley-fill, shoreface and transgressive) and six bounding erosion surfaces (VE2/3, VE3-1a, VE3-3, VE3-4, VE3-5 & VE4) are recognized in the Cyn-Pem area (Figs 7.2 & 7.3). The subdivision of the VE3 erosion surface into smaller surfaces has been described in chapters 3 and 6. The VE3 nomenclature records a sequence of erosive events with the oldest being the VE3-1 surface. The VE3 nomenclature used in this chapter is consistent with those provided elsewhere in this thesis.

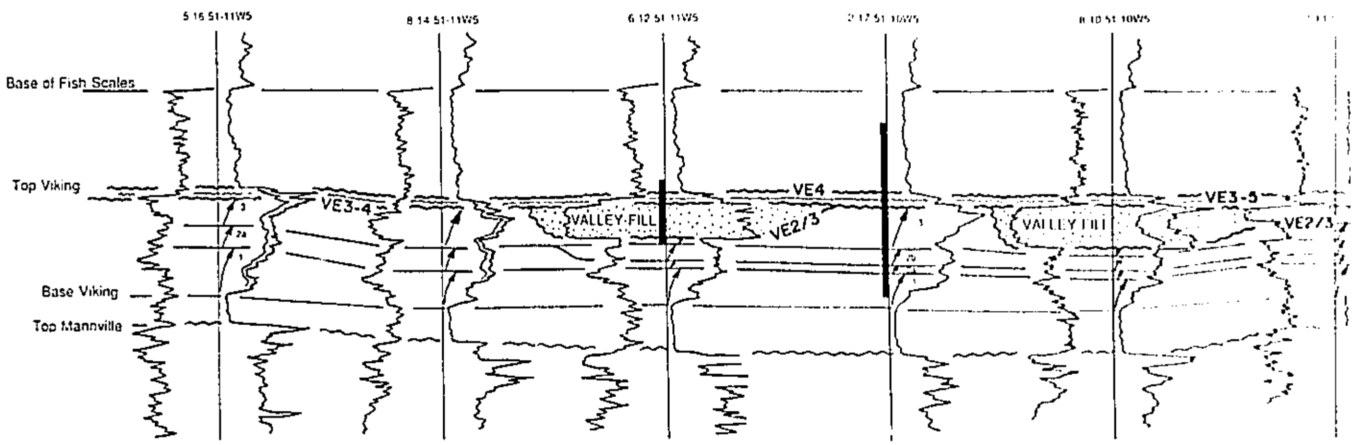
The regional deposits consist of six CU successions, labelled 1, 2a, 2b, 2c, 2d and 3. They have a sheet-like geometry and were discussed in detail in chapter 5.

The regional deposits are cut by a major unconformity, labelled VE2/3 (VE2 + VE3), which outlines the Cyn-Pem valley-fill complex (Figs 7.2 & 7.3). The VE2 scour was cut during lowstand incision and is time equivalent to the VE2 erosion surface at Crystal (chapter 3). The VE3 scour was cut during the ensuing transgression, thereby modifying the geometry of the initial VE2 scour. Due to the limited core control, it is impossible to determine which VE3 erosional surface (VE3-1, VE3-2 and/or VE3-3) occurs at the base of

Figure 7.2. Well log cross section LL'. This section is oriented west to east through the three arms of the Cyn-Pem valley-fill complex, and is approximately 31 km long (Fig. 7.1). Regional successions 1, 2a, 2b, 2c and 3, valley-fill deposits (stippled), and four Viking erosion surfaces (VE2/3, VE3-4, VE3-5 and VE4) are shown. Datum is the BFS log marker and black bars show core positions.

L

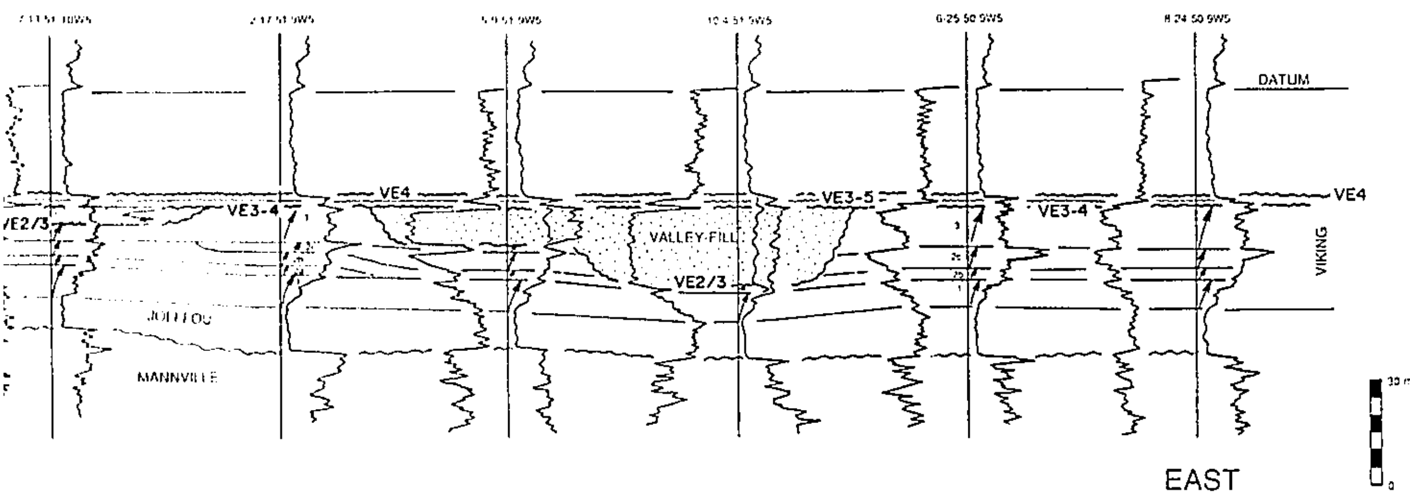
CYN-PEM V
(STRIKE S



WEST

M VALLEY-FILL
KE SECTION)

L'



the Cyn-Pem valley. Valley-fill deposits rest stratigraphically on top of the VE2/3 erosion surface and are bounded above by the VE3-4 erosion surface (transgressive ravinement; Figs 7.2 & 7.3). No internal erosion surfaces have been identified in the Cyn-Pem valley-fill deposits and, as a result, these sediments appear to represent one fill event.

Two shoreface deposits are recognized in this area, including the Sunnybrook shoreface (Fig. 7.3) and a thin shoreface package which rests stratigraphically on top of the regional and valley-fill deposits (Figs 7.2 & 7.3). The Sunnybrook shoreface is bounded by the VE3-1a erosion surface below and by the VE3-3 erosion surface above (Fig. 7.3). The thin shoreface package is bounded by the VE3-4 erosion surface below and by the VE3-5 erosion surface above (Figs 7.2 & 7.3). These deposits are the distal sediments of the Wolf Creek/Gilby-Joffre shoreface (chapter 9).

Transgressive deposits rest stratigraphically between the VE3-5 and VE4 erosion surfaces, and are very thin (0.1-2.0 m; Figs 7.2 & 7.3). A thorough discussion of the shoreface and transgressive deposits, and a complete documentation and justification of the VE3 erosion surface nomenclature will be presented in chapters 9 and 10.

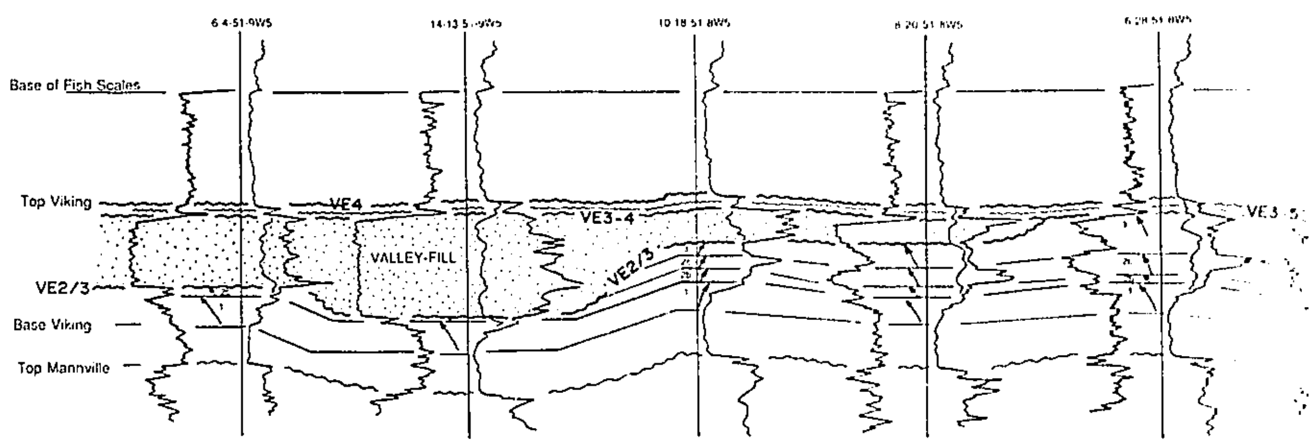
7.2 Sedimentology

The sedimentology of the valley-fill deposits is difficult to determine because of the limited core control. Most well logs suggest that the dominant lithology is

Figure 7.3. Well log cross section MM'. This section is oriented southwest to northeast through the eastern arm of the Cyn-Pem valley-fill complex and the Sunnybrook shoreface, and is approximately 32 km long (Fig. 7.1). Regional successions 1, 2b, 2c, 2d and 3, valley-fill deposits (heavy stipple), Sunnybrook shoreface deposits (light stipple), and six Viking erosion surfaces (VE2/3, VE3-1a, VE3-3, VE3-4, VE3-5 & VE4) are shown. Datum is the BFS log marker.

M

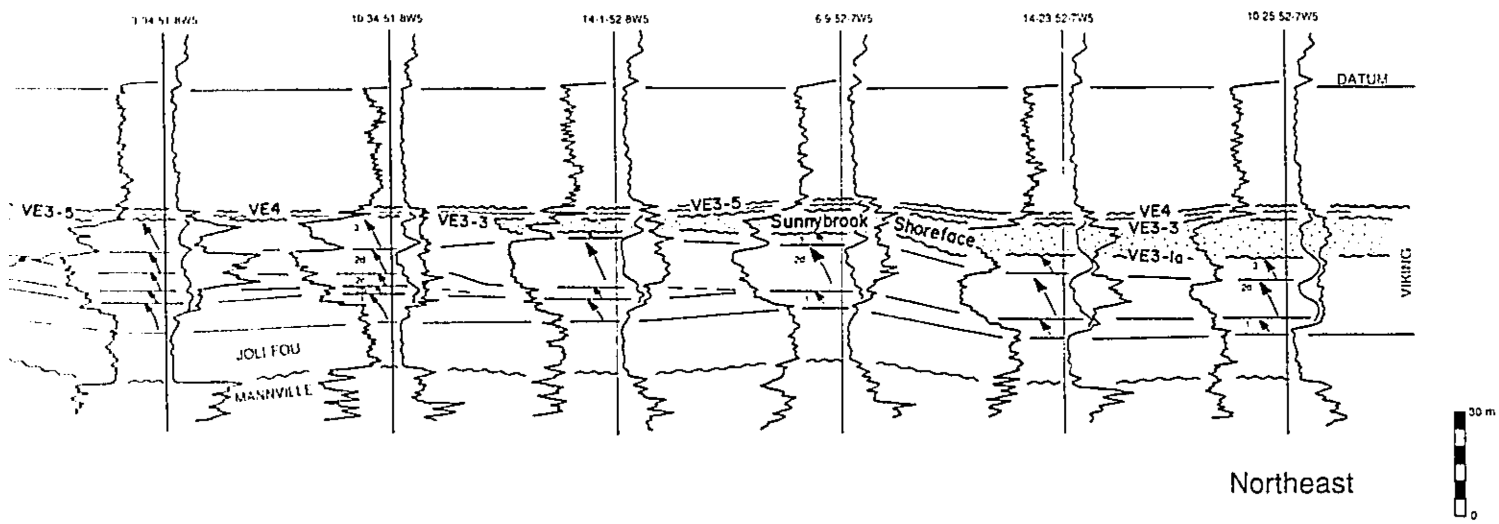
CYN



Southwest

CYN-PEM VALLEY-FILL
(DIP SECTION)

M'



Northeast

sandstone, with minor concentrations of valley-fill mudstones (FA-2). The two cores from the Cyn-Pem valley-fill consist of cross bedded sandstones (FA-6; Fig. 7.4). A full description and a preliminary interpretation of FA-2 and FA-6 are presented in chapter 4.

7.2.1 Dark Mudstone (FA-2)

Dark mudstones have been identified on four well logs in the valley-fill, forming a thin sliver in T52/R9W5 (Fig. 7.5). These deposits are 1.8-5.7 m thick and are located in the northeastern part of the complex.

Interpretation

The sediments of FA-2 have been interpreted as the deposits of a low to moderate energy, restricted marine environment. Their proximity to the Sunnybrook shoreface and channelized geometry suggest deposition in an estuarine or bay environment.

7.2.2 Cross Bedded Sandstone (FA-6)

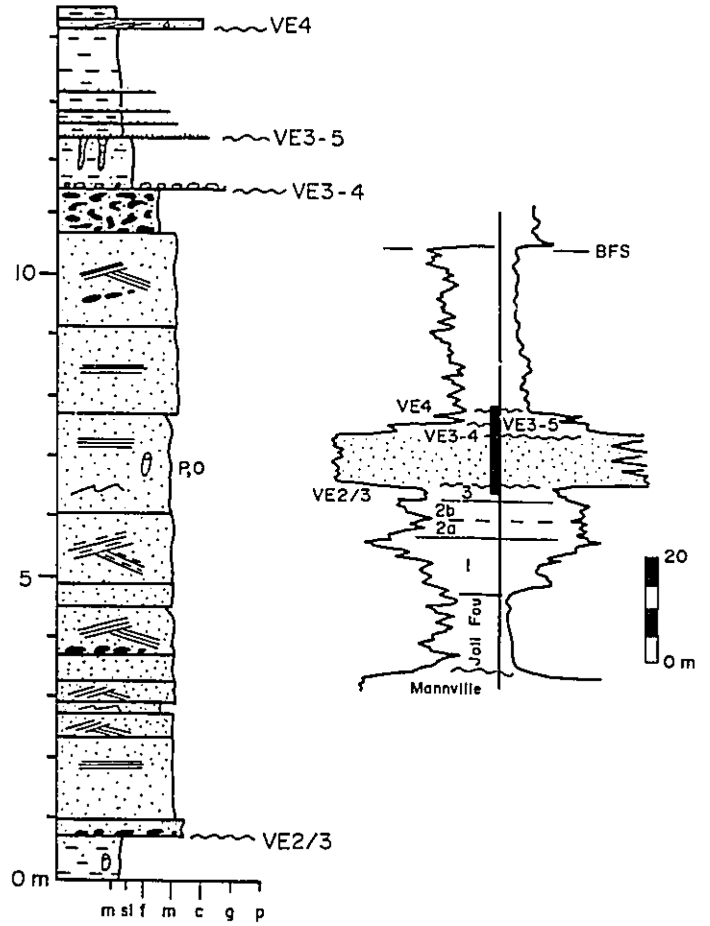
Cross bedded sandstones are observed in 6-12-51-11W5 and 4-16-53-9W5 (Fig. 7.4). These deposits are 4.2-10.0 m thick and they occur at the southern and northern ends of the western arm of the Cyn-Pem valley (Figs 7.1 & 7.4). The occurrence of FA-6 at both ends of the valley-fill complex and the identification of sandstones throughout most of the complex suggest that FA-6 may be the dominant facies association at Cyn-Pem.

Interpretation

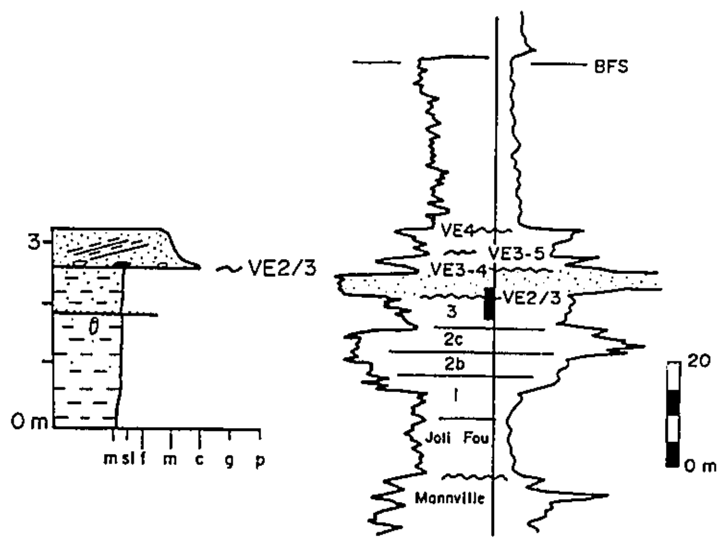
The abundance of cross beds, presence of mudstone

Figure 7.4. Litho-logs of the two cored wells from 6-12-51-11W5 (1942.5-1957 m) and 4-16-53-9W5 (1619-1622 m) in the Cyn-Pem valley-fill. The corresponding resistivity and gamma-ray well logs, and the position of the core (black bar) are also shown. These sediments consist of FA-6 and are bounded by the VE2/3 erosion surface below and by the VE3-4 erosion surface above. Figure 4.1 explains the symbols used in the litho-logs. The VE3-5 and VE4 erosion surfaces are also shown.

6-12-51-11W5



4-16-53-9W5



intra-clasts, fining-upward successions, mudstone couplets and trace fossils, and channelized geometry suggest deposition in a relatively high energy, tidal channel. Therefore, the western arm of the Cyn-Pem valley-fill complex may be dominated by tidal channel deposits.

7.3 Interpretation & Comparison to Crystal

The proximity to the Sunnybrook shoreface, channelized geometry, abundance of sandstones, presence of estuarine mudstones (FA-2) and tidal channel sandstones (FA-6) suggest deposition in an estuarine valley-fill system. These sediments do not exhibit a tripartite facies zonation. It is probable that the Cyn-Pem valley-fill deposits were physically connected to the Sunnybrook shoreface during the early stages of the Viking time interval. This "connection' was probably thin and was likely ravined or eroded during the ensuing VE3 transgression.

The Cyn-Pem and Crystal valley-fill deposits have both similarities and differences. The similarities include; (1) a VE2/3 lower bounding erosion surface, (2) a VE3-4 upper bounding erosion surface, (3) a NNE-SSW orientation, (4) a maximum thickness of 32-34 m, and (5) the Sunnybrook shoreface deposits to the northeast.

The differences between the Cyn-Pem and Crystal valley-fill deposits include; (1) a uni- or bi-partite (Cyn-Pem) versus tripartite (Crystal) facies zonation, (2) a lack of conglomerates versus an abundance of conglomerates, (3) bifurcating upstream versus bifurcating downstream, and (4) no connection with Sunnybrook versus a connection with Sunnybrook.

7.4 Sequence of Events

The geological history of the Cyn-Pem valley-fill and overlying deposits can be summarized in seven stages.

(1) A large relative drop in sea level resulted in the cutting of the Cyn-Pem valley and, hence, the development of the VE2 erosion surface (Fig. 7.5).

(2) A subsequent relative rise in sea level flooded the Cyn-Pem valley and modified the geometry and depth of the VE2 scour. This coincides with the development of the VE3 erosion surface (VE3-1, VE3-2 and/or VE3-3) at the base of the valley (Fig. 7.5) and with the deposition of the Cyn-Pem valley-fill deposits (FA-2 & FA-6).

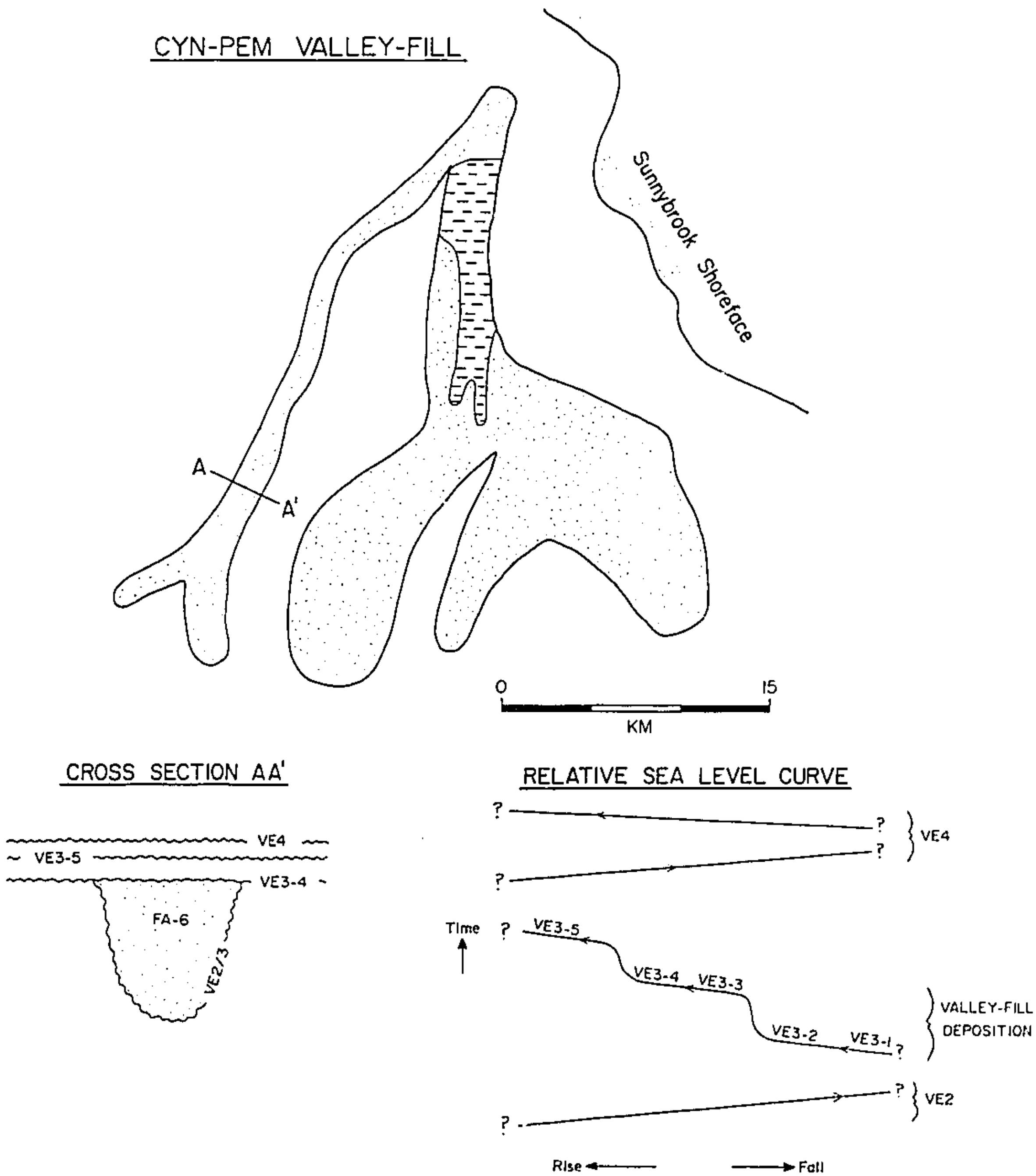
(3) The relative rise in sea level continued and the Cyn-Pem valley-fill deposits were truncated and reworked during transgressive ravinement. This produced the VE3-4 erosion surface at the top of the valley (Fig. 7.5).

(4) An ensuing stillstand lead to the development of a shoreline trend to the southwest of the Cyn-Pem area (Wolf Creek/Gilby-Joffre), and the deposition of distal shoreface deposits across the Cyn-Pem area.

(5) A subsequent relative rise in sea level moved the shoreline further to the southwest and resulted in the development of the VE3-5 erosion surface (Fig. 7.5).

(6) A thin package of transgressive sediments were deposited.

Figure 7.5. Gross lithology map, schematic cross section and relative sea level curve for the Cyn-Pem valley-fill deposits. The relative timing of the VE2, VE3-1, VE3-2, VE3-3, VE3-4, VE3-5 and VE4 erosion surfaces are shown on the relative sea level curve. The nature of the curve between VE2 and VE3-3 "time" (VE2/3) is difficult to determine in the Cyn-Pem area bacause of the lack of core data. Compare with the relative sea level curve for the Crystal valley-fill (Fig. 6.14).


CYN-PEM VALLEY-FILL
Sunnybrook Shoreface
A
A'
0
15
KM
CROSS SECTION AA'
VE4
VE3-5
VE3-4
FA-6
VE2/3
RELATIVE SEA LEVEL CURVE
VE4
Time
VE3-5
VE3-4
VE3-3
VE3-2
VE3-1
VALLEY-FILL DEPOSITION
VE2
Rise
Fall

(7) The VE4 erosion surface was cut.

CHAPTER 8 - SUNDANCE & EDSON VALLEY-FILL COMPLEX

The Sundance and Edson valley-fill complex is located in T51-55, R18W5-21W5 (Fig. 8.1). This complex is oriented NNE-SSW and is connected to the Wolf Creek shoreface in the northeast (Fig. 8.1). The Sundance valley is approximately 36 km long and 14 km wide, and the Edson valley is approximately 24 km long and 15 km wide.

The valley-fill reaches a maximum thickness of 16.3 m in the northwestern corner of the Sundance valley (11-14-54-21W5; Fig. 8.1). A second shoreface trend, oriented parallel to the Wolf Creek shoreface, is observed on top of the central valley-fill deposits and is labelled the Bickerdike shoreface (Fig. 8.1).

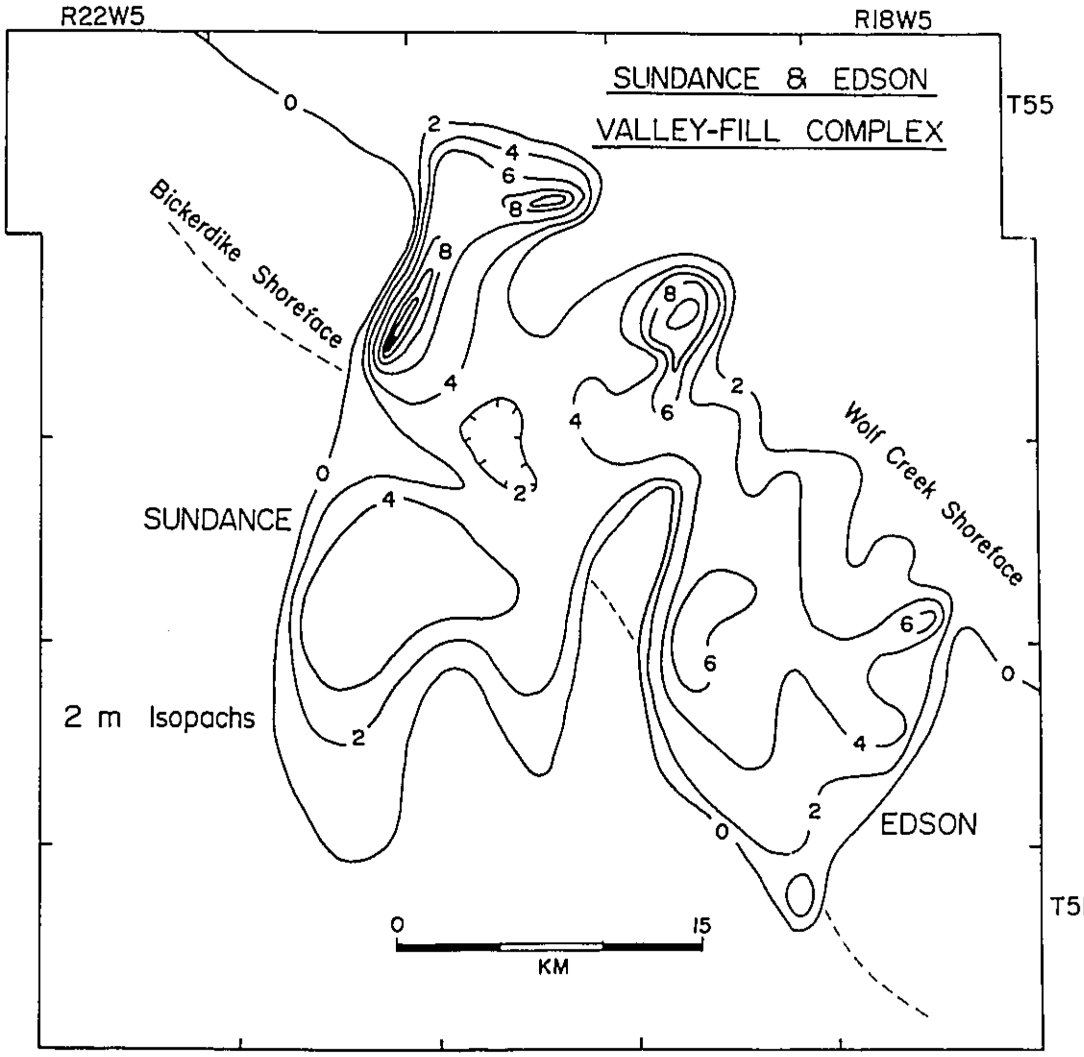
Oil and gas reservoirs occur between the Bickerdike and Wolf Creek shoreface trends. The cumulative production from these reservoirs includes 2.06×10^9 m^3 (72.7 BCF) of gas and 4.29×10^2 m^3 (2.7 MSTB) of oil at Sundance, and 2.91×10^9 m^3 (102.8 BCF) of gas and 2.91×10^3 m^3 of oil at Edson (Alberta Production Report, 1990).

An extensive core (34) and well log data base exists in the Sundance and Edson area (Figs 1.5 & 1.6). This allows for a detailed reconstruction of the stratigraphy and sedimentology of the valley-fill deposits.

8.1 Stratigraphic Packages & Bounding Erosion Surfaces

The Viking and Joli Fou Formations are significantly thinner in the Sundance and Edson area than in the Crystal

Figure 8.1. Isopach map of the Sundance and Edson valley-fill complex. The Wolf Creek and Bickerdike shoreface trends are also shown. Isopachs are in 2 m intervals.


R22W5
R18W5
T55
T51
SUNDANCE & EDSON
VALLEY-FILL COMPLEX
Bickerdike Shoreface
Wolf Creek Shoreface
SUNDANCE
EDSON
2 m Isopachs
0
2
4
6
8
0
15
KM

and Cyn-Pem area (section 5.1.3). However, similar sedimentary rock packages and bounding erosion surfaces are observed in both areas including regional, valley-fill, shoreface and transgressive deposits and the VE2, VE3 and VE4 erosion surfaces (section 3.2.3). Core and well log cross sections NN', OO' and PP' highlight these deposits and their bounding erosion surfaces (Figs 8.2, 8.3, 8.4 & 8.5).

Five regional successions, labelled 1a to 1e, are recognized in the Sundance and Edson area and these are cut by the valley-fill deposits (Figs 8.3, 8.4 & 8.5). The valley-fill consists of sandstones (FA-3, FA-4 & FA-6) and mudstones (FA-2), and their lateral distribution is shown in Figure 8.2. In comparison to the Crystal valley (Figs 6.3 & 6.9), the lateral distribution of the facies associations at Sundance and Edson is very complex. The valley-fill deposits form a "double" tripartite facies geometry that is identified by two zones of dark mudstones (FA-2); one along the southwestern edge of the Wolf Creek shoreface, and the other along the southwestern edge of the Bickerdike shoreface (Fig. 8.2). This outlines a sand-mud-sand-mud-sand facies geometry down the length of the valley (SW-NE), and defines the "double" tripartite geometry of the valley-fill deposits.

The basal erosion surface of the valley complex has been defined as VE2 and is equivalent to the lowstand incision in the Crystal and Cyn-Pem valleys (chapter 3; Figs 8.3, 8.4 & 8.5). Four different erosion surfaces were cut

Figure 8.2. Location of the facies associations in the Sundance and Edson valley-fill complex. Note the two separate bands of dark mudstones (FA-2); one along the SW margin of the Wolf Creek shoreface and the other along the SW margin of the Bickerdike shoreface. This defines a "double" tripartite facies geometry. Also note the three linear trends of cross bedded sandstones (FA-6) between the two shorefaces. Location of cross sections NN', OO' and PP' are shown. FA-3 - Bioturbated Muddy Sandstone, FA-4 - Fine-Grained Sandstone, FA-9 - Sharp Based, Bioturbated Sandstone.

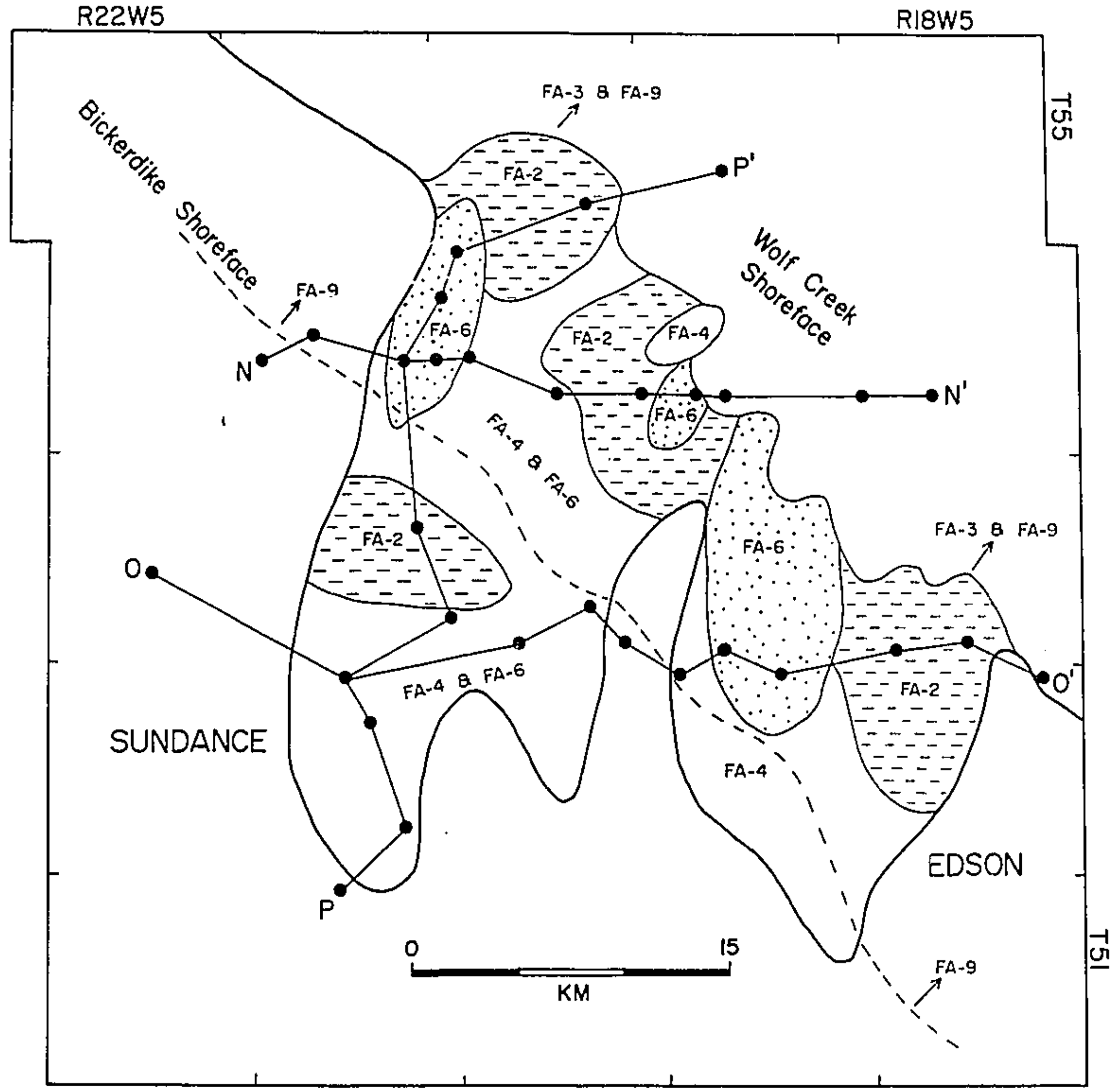
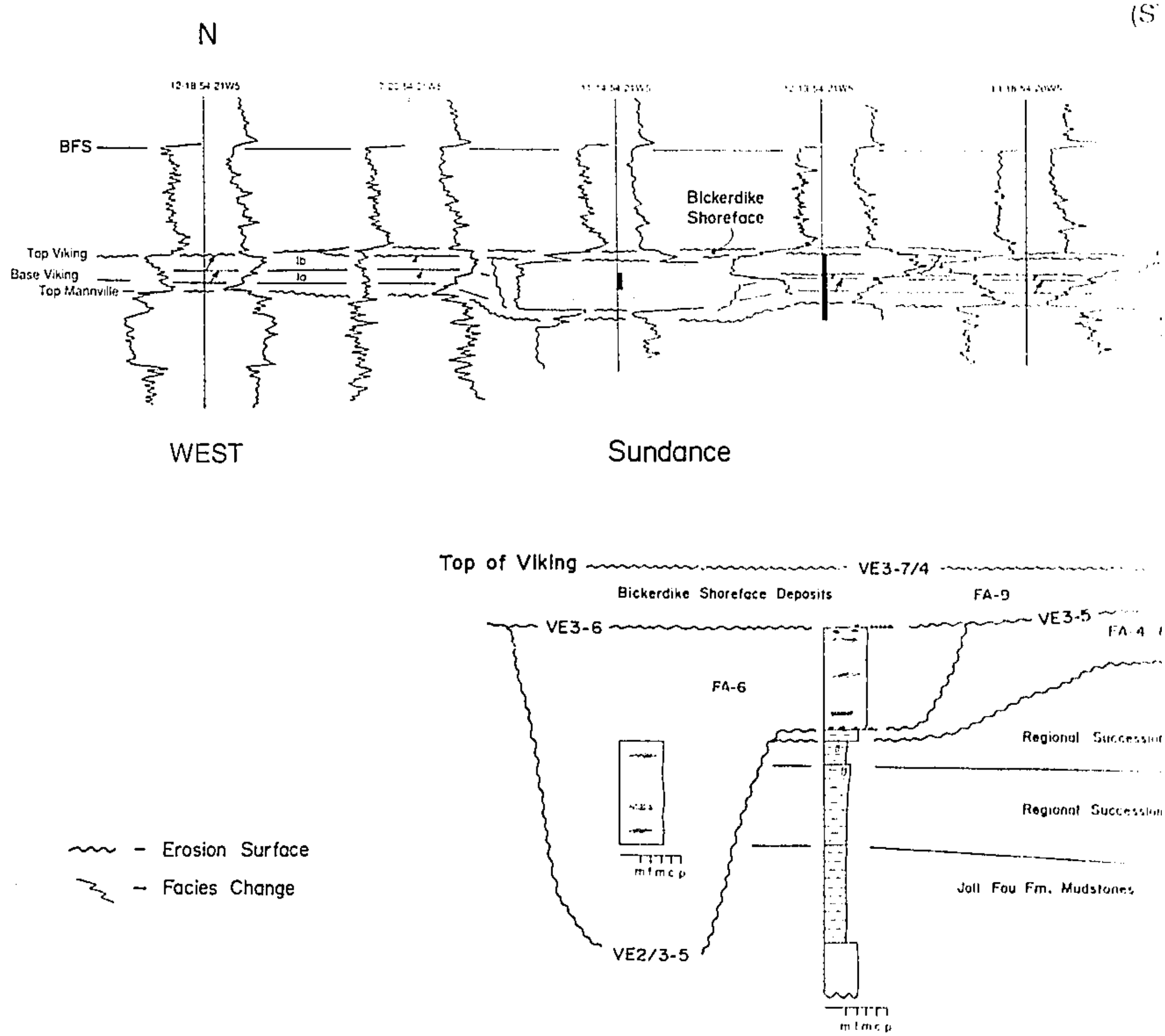

R22W5
R18W5
T55
T51
FA-3 & FA-9
FA-2
P'
Bickerdike Shoreface
Wolf Creek Shoreface
FA-9
FA-6
FA-2
FA-4
N
N'
FA-6
FA-4 & FA-6
FA-2
FA-6
FA-3 & FA-9
O
O'
FA-4 & FA-6
FA-2
SUNDANCE
FA-4
EDSON
P
0
15
KM
FA-9

Figure 8.3. Well log and core cross section NN'. This cross section consists of 11 wells and is oriented west to east through the northern part of Sundance (Fig. 8.2). Two linear trends of cross bedded sandstones (FA-6), the NE tripartite fill (FA-4 & FA-6 - FA-2 - FA-3; sand-mud-sand), Bickerdike shoreface, Wolf Creek shoreface and transgressive deposits are shown. The valley and shorefaces cut into regional successions 1a to 1e. Six Viking erosion surfaces (VE2, VE3-4, VE3-5, VE3-6, VE3-7 & VE4) are recognized. FA-2 - Dark Mudstone, FA-3 - Bioturbated Muddy Sandstone, FA-4 - Fine-Grained Sandstone, FA-9 - Sharp Based, Bioturbated Sandstone.

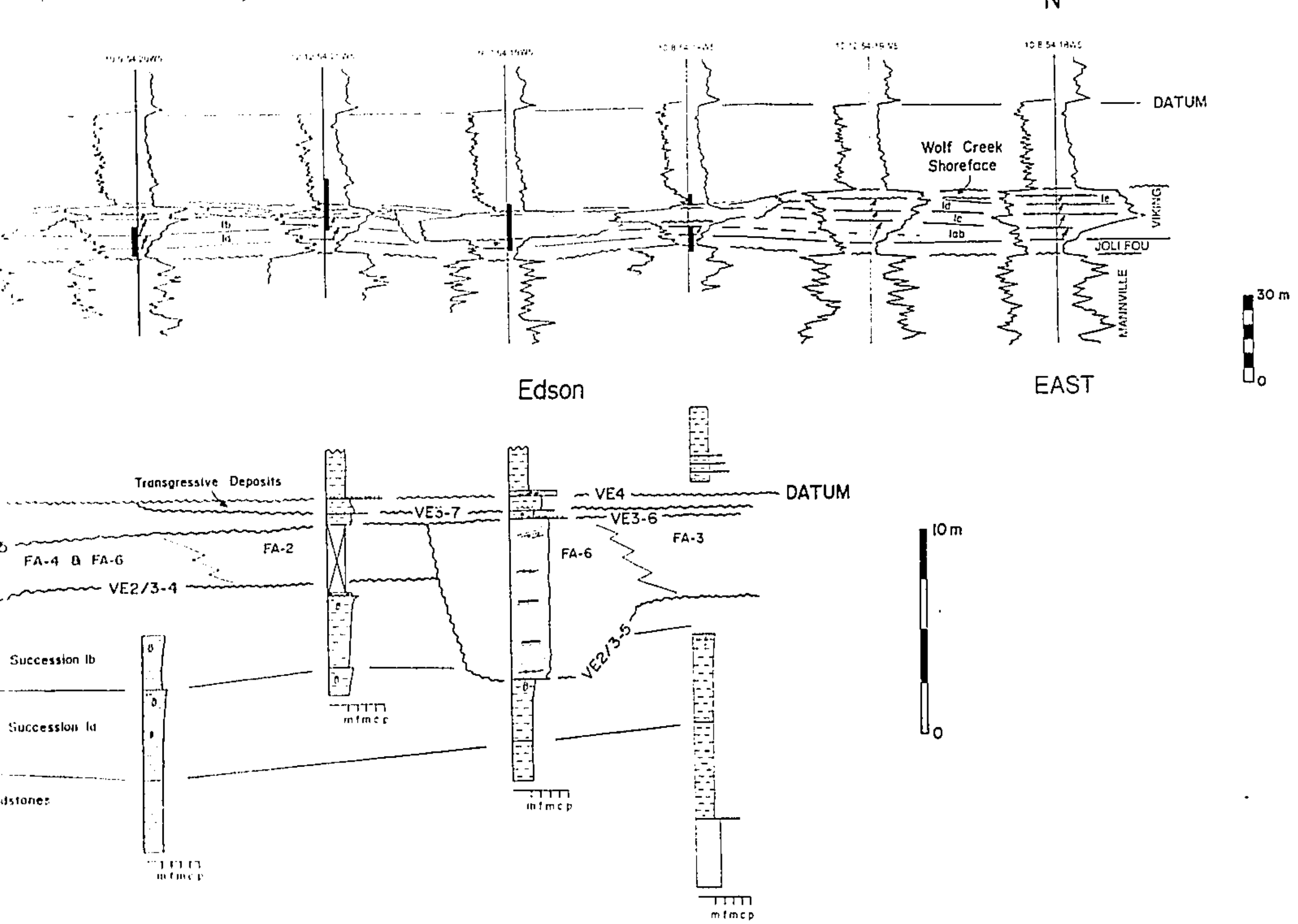
The well log cross section is hung on the BFS log marker and the core cross section is hung on the top of the Viking. Black bars on the well logs indicate core positions.

SUNDANCE



N
BFS
Top Viking
Base Viking
Top Mannville
Ib
Ia
Bickerdike
Shoreface
WEST
Sundance
Top of Viking
VE3-7/4
Bickerdike Shoreface Deposits
FA-9
VE3-6
VE3-5
FA-6
Joli Fou Fm. Mudstones
VE2/3-5
m f m c p
Erosion Surface
Facies Change

NCE & EDSON VALLEY-FILLS
(STRIKE SECTION)



during the ensuing transgression and these are labelled VE3-4 (oldest) to VE3-7 (Figs 8.3, 8.4 & 8.5).

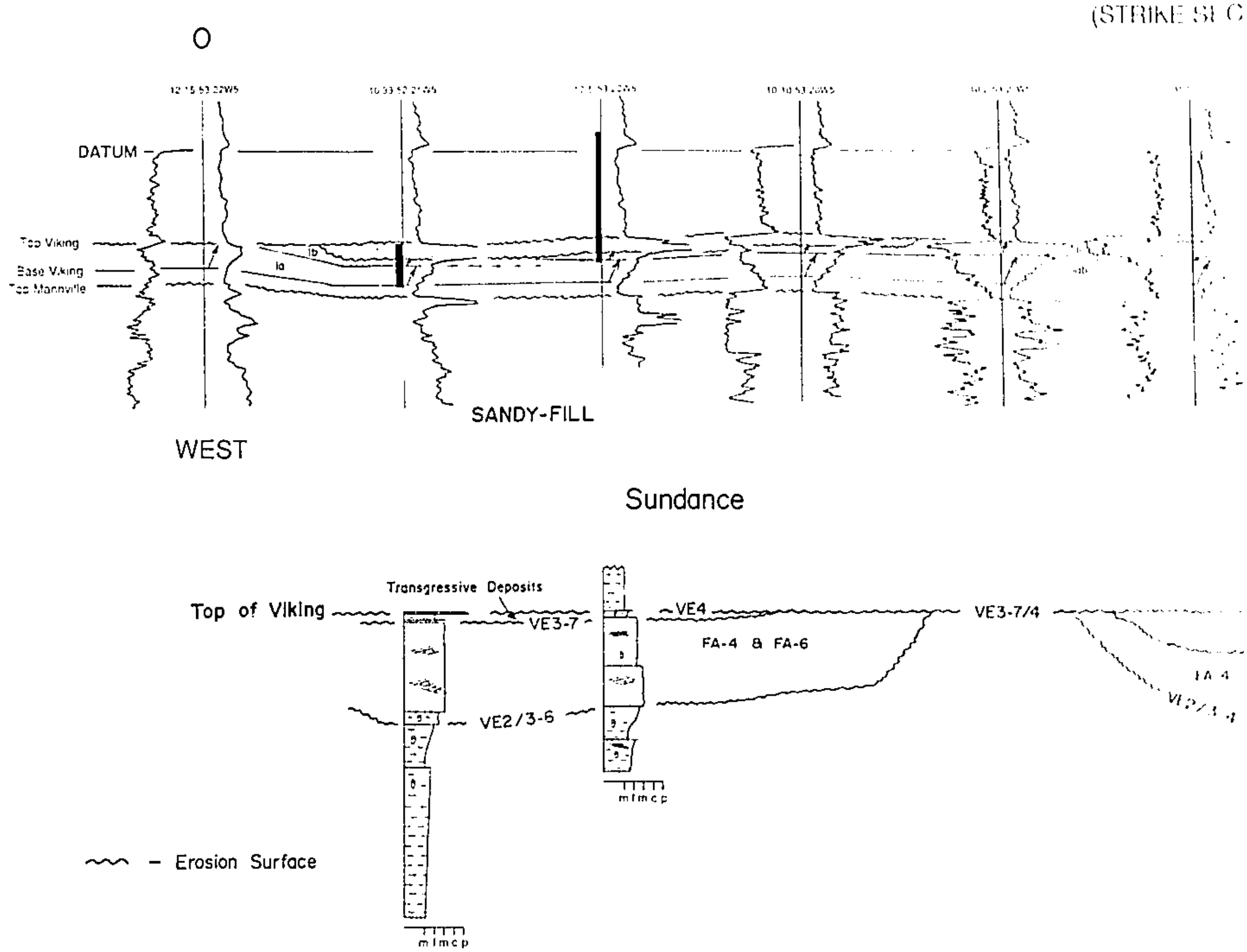
The VE3-4 erosion surface is defined as the Wolf Creek shoreface scour and is also associated with transgressive modification in the entire valley complex (Figs 8.3, 8.4 & 8.5). The VE3-5 erosion surface is defined as the transgressive ravinement surface on top of the Wolf Creek shoreface deposits, and is also observed as smaller channel-like features within the confines of the much larger valley complex (Figs 8.3, 8.4 & 8.5). The VE3-6 erosion surface is defined as the Bickerdike shoreface scour and is also associated with transgressive modification in the southwestern half of the valley complex (Figs 8.3, 8.4 & 8.5). The VE3-7 erosion surface is defined as the transgressive ravinement surface on top of the Bickerdike shoreface deposits (Figs 8.3, 8.4 & 8.5). Further justification and explanation of this nomenclature will occur throughout this chapter.

Both the Wolf Creek and Bickerdike shoreface deposits are sharp based and consist of bioturbated sandstone (FA-9) with minor amounts of bioturbated muddy sandstone (FA-3). The Wolf Creek shoreface deposits are bounded by the VE3-4 erosion surface below and by the VE3-5 or VE3-5/4 erosion surface above (Figs 8.3, 8.4 & 8.5). The Bickerdike shoreface deposits are bounded by the VE3-6 erosion surface below and by the VE3-7 or VE3-7/4 erosion surface above (Figs 8.3, 8.4 & 8.5).

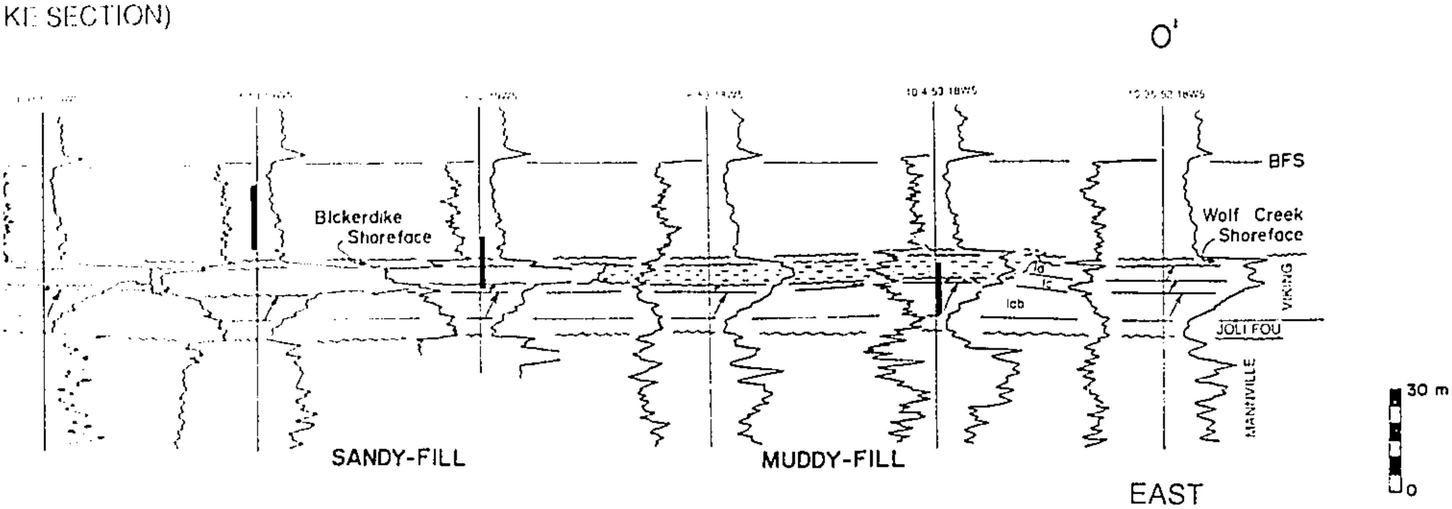
Figure 8.4. Well log and core cross section OO'. This cross section consists of 11 wells and is oriented west to east through the southern part of Sundance and the central to northern part of Edson (Fig. 8.2). Regional successions 1a to 1d, NE and SW tripartite fills, one linear trend of cross bedded sandstones (FA-6), Bickerdike shoreface, Wolf Creek shoreface and transgressive deposits are shown. Viking erosion surfaces VE2, VE3-4, VE3-5, VE3-6, VE3-7 and VE4 are recognized. FA-2 - Dark Mudstone, FA-3 - Bioturbated Muddy Sandstone, FA-4 - Fine-Grained Sandstone.

The well log cross section is hung on the BFS log marker and the core cross section is hung on the top of the Viking. Black bars on the well logs indicate core positions.

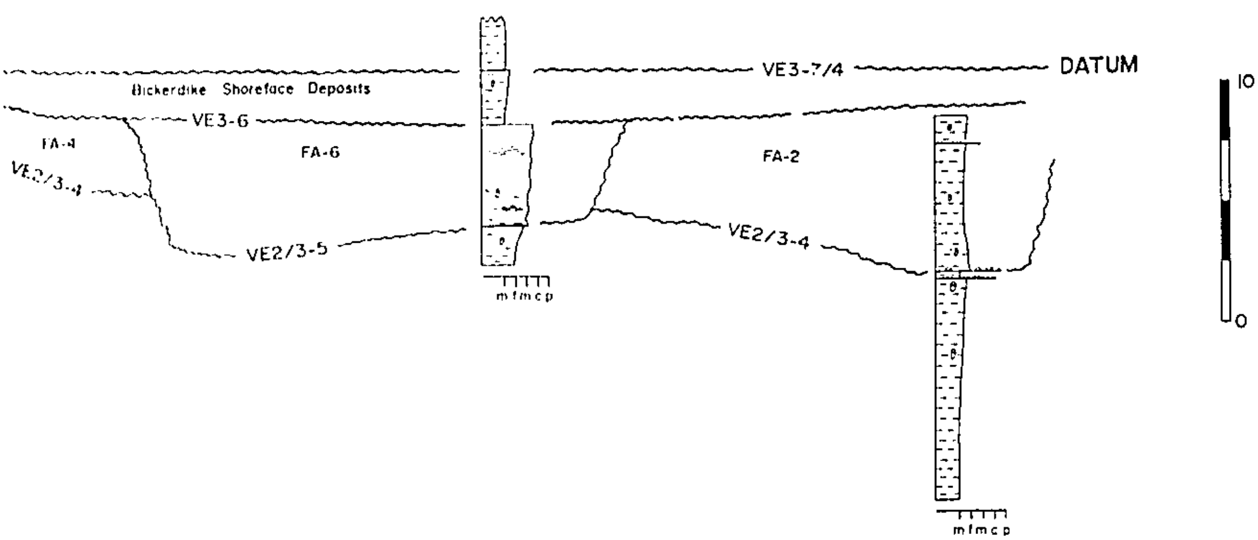
SUNDANCE & EDSON \
(STRIKE SEC



DSON VALLEY-FILLS
KE SECTION)



Edson



Transgressive deposits rest stratigraphically on top of the shoreface and valley-fill deposits and are bounded by the VE3-5, VE3-6 or VE3-7 erosion surface below and by the VE4 erosion surface above (Figs 8.3, 8.4 & 8.5). The reader is referred to chapter 9 for a thorough discussion of the shoreface and transgressive deposits.

In summary, the stratigraphy (rock packages and erosion surfaces) of the Viking Formation in the Sundance and Edson area is similar to that of the Crystal and Cyn-Pem areas. The sedimentology of the Sundance and Edson valley-fill complex is also very similar to the sedimentology of fill 1 at Crystal, and includes the presence of FA-2, FA-3, FA-4 and a tripartite facies geometry.

8.2 Preliminary Interpretation

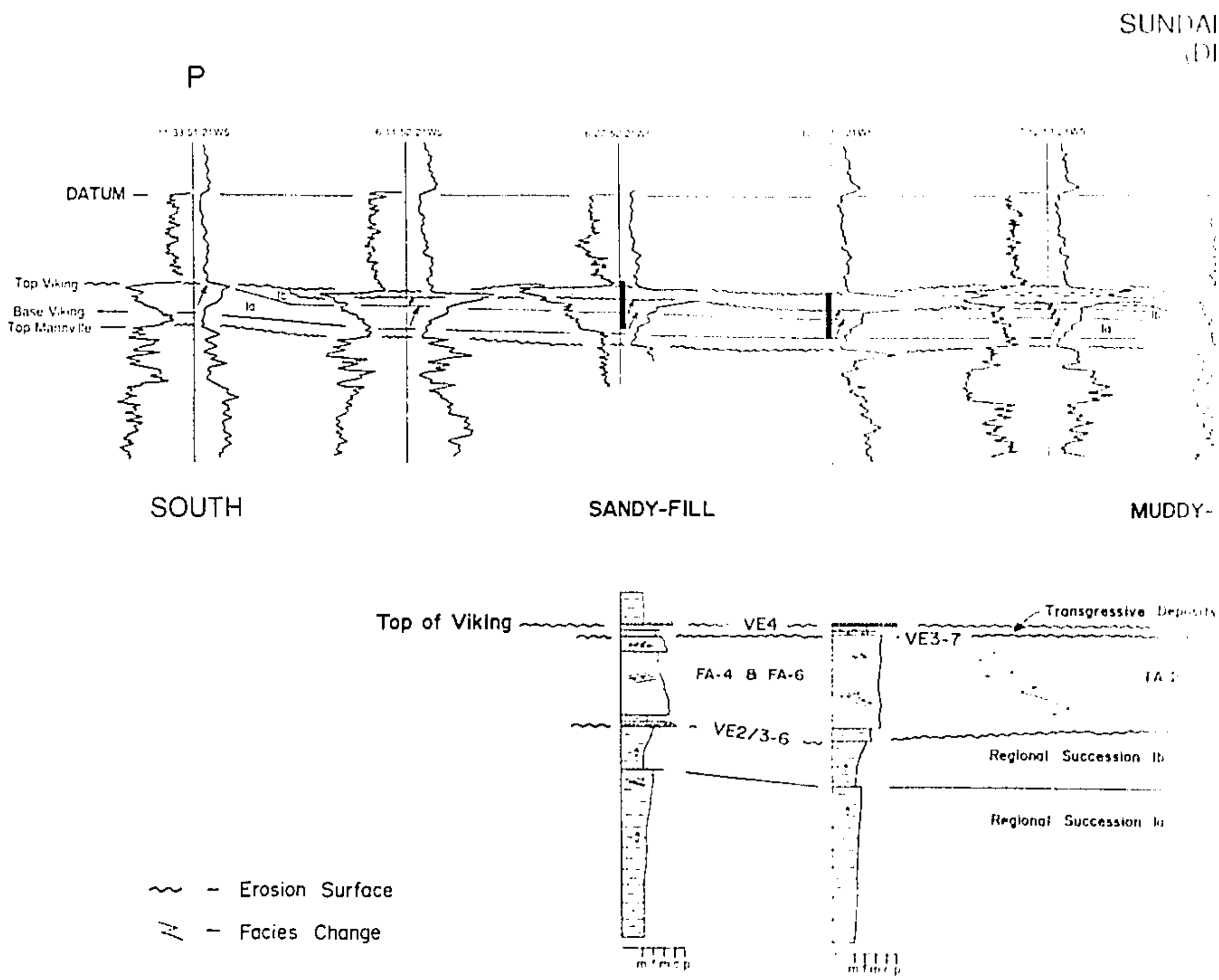
The restricted to marginal marine interpretation of FA-2, FA-3, FA-4 and FA-6 (chapter 4), location in a valley, tripartite facies geometry, proximity of the Wolf Creek and Bickerdike shoreface deposits, and similarities with fill 1 at Crystal suggest deposition in an estuarine valley-fill environment. The "double" tripartite geometry at Sundance and Edson is directly linked to the position of the two shoreface trends. The relationship between the valley-fill and shoreface deposits, and the detailed reconstruction of the sedimentology and geologic history of the valley-fill complex will be expanded on below.

8.3 Sedimentology

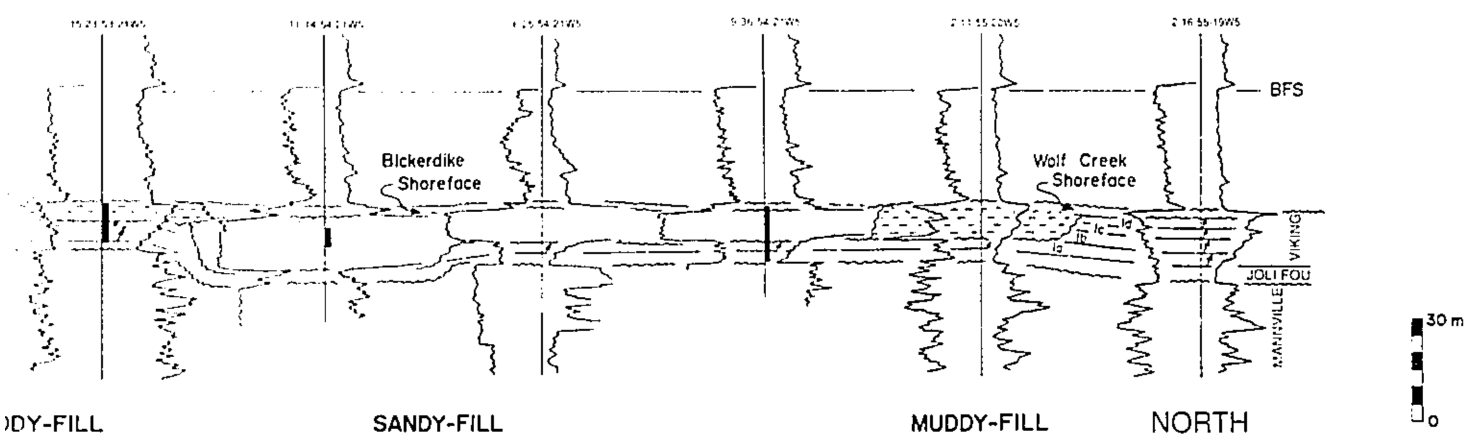
Four facies associations are observed in the Sundance

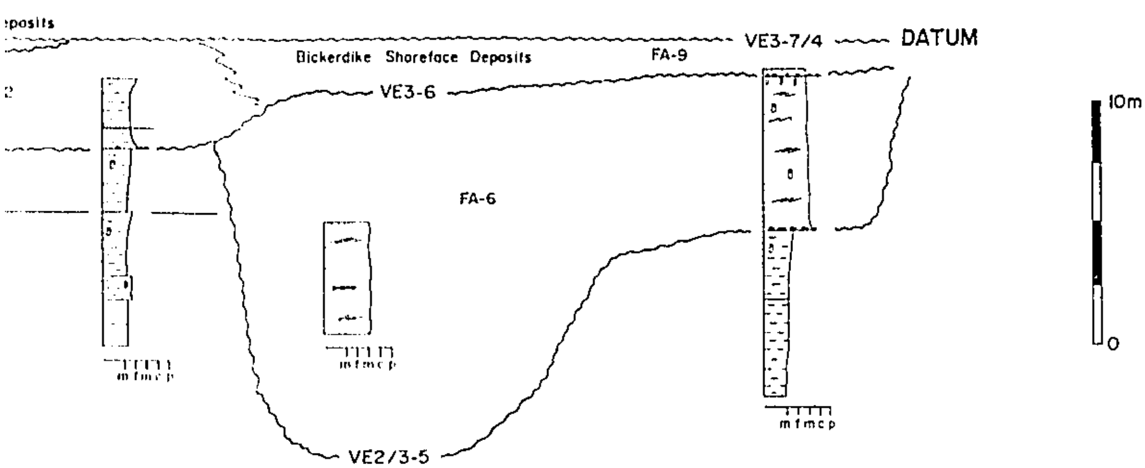
Figure 8.5. Well log and core cross section PP'. This cross section consists of 11 wells and is oriented south to north through the Sundance valley (Fig. 8.2). The "double" tripartite geometry of the valley-fill is highlighted by two separate deposits of dark mudstones (FA-2) which are surrounded by sandstones of FA-3, FA-4 and FA-6. Regional successions 1a to 1d, one linear trend of cross bedded sandstone (FA-6), Bickerdike shoreface, Wolf Creek shoreface and transgressive deposits are also shown. Viking erosion surfaces VE2, VE3-4, VE3-5, VE3-6, VE3-7 and VE4 are recognized. FA-3 - Bioturbated Muddy Sandstone, FA-4 - Fine-Grained Sandstone, FA-9 - Sharp Based Bioturbated Sandstone.

The well log cross section is hung on the BFS log marker and the core cross section is hung on the top of the Viking. Black bars on the well logs indicate core positions.


SUNDAI
P
DATUM
Top Viking
Base Viking
Top Mannville
Ia
Ib
SOUTH
SANDY-FILL
MUDDY-
Top of Viking
VE4
VE3-7
Transgressive
FA-4 & FA-6
VE2/3-6
Regional Succession Ib
Regional Succession Ia
Erosion Surface
Facies Change

IDANCE VALLEY-FILL
(DIP SECTION)





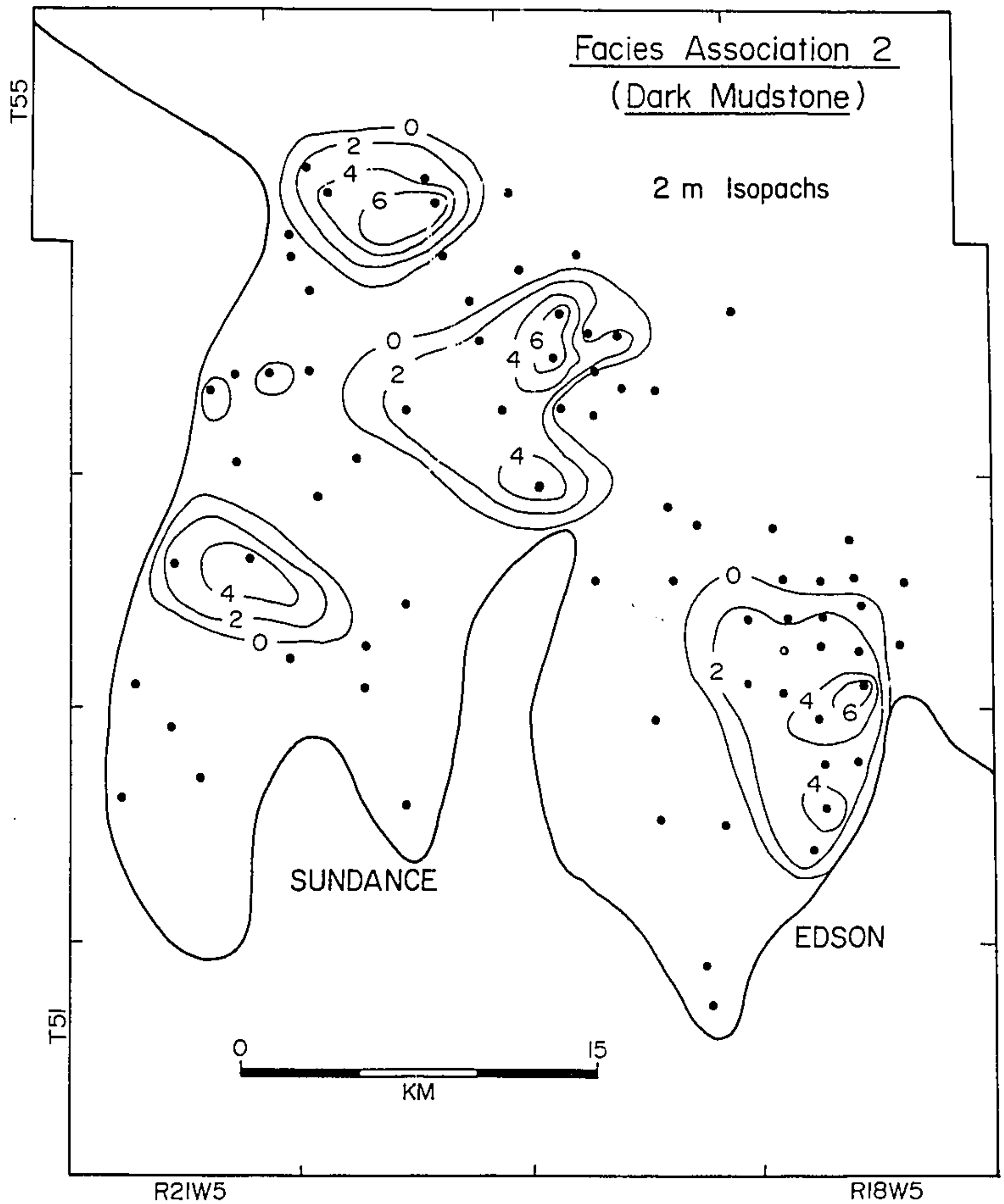
and Edson valley-fill complex, including dark mudstone (FA-2), bioturbated muddy sandstone (FA-3), fine-grained sandstone (FA-4), and cross bedded sandstone (FA-6). A description, preliminary interpretation and photographic record of these associations was presented in chapter 4.

8.3.1 Dark Mudstone (FA-2)

The dark mudstones are located in four separate pods in the Sundance and Edson valley-fill complex (Figs 8.2 & 8.6). Three pods occur along the southwestern margin of the Wolf Creek shoreface and a single pod occurs along the southwestern margin of the Bickerdike shoreface (Figs 8.2 & 8.6). These pods line up to form two distinct bands of FA-2 which are encased by the sandstones of FA-3, FA-4 and FA-6. This forms the "double" tripartite facies geometry of the valley-fill complex. The sediments of FA-2 are up to 7.9 m thick (2-11-55-20W5; Fig. 8.6), and are thicker along the SW margin of the Wolf Creek shoreface rather than along the SW margin of the Bickerdike shoreface.

The dark mudstones form a fining-upward followed by a coarsening-upward facies succession (e.g. 10-4-53-18W5, Fig. 8.4; 15-23-53-21W5 & 2-11-55-20W5, Fig. 8.5), which is similar to the fining-upward to coarsening-upward succession observed in FA-2 of the Crystal valley-fill. The sediments of FA-2 have gradational vertical and lateral contacts with FA-3 to the northeast, and FA-4 to the southwest (Figs 8.2, 8.3, 8.4 & 8.5). Sharp vertical and lateral contacts are observed between the sediments of FA-2 and the sediments of

Figure 8.6. Isopach map of facies association 2 (dark mudstone). These sediments are located in four separate pods which form two distinct bands; one along the SW margin of the Wolf Creek shoreface and the other along the SW margin of the Bickerdike shoreface. Black dots indicate core and well log data points, and the isopachs are in 2 m intervals.


Facies Association 2
(Dark Mudstone)
2 m Isopachs
T55
T51
SUNDANCE
EDSON
0
15
KM
R21W5
R18W5

FA-6 in the northern part of the valley complex (Figs 8.2, 8.3, 8.4 & 8.5).

Interpretation

The dark mudstones of FA-2 have been initially interpreted as the deposits of a restricted marine environment (section 4.2). The similarities with the dark mudstones at Crystal, location in a valley, tripartite geometry, gradational interbedding with transgressive shoreface deposits (FA-3), and the gradational contact with the sandstones of FA-4 suggest deposition in an estuarine environment. The sedimentology, lateral extent and valley position of the dark mudstones are similar to the estuarine mudstones observed in many modern estuaries (Allen, 1989, in press; Boyd et al., 1987; Clifton, 1983; Dorjes & Howard, 1975; Frey & Howard, 1986; Greer, 1975; Johnson et al., 1989; Nichol, 1989; Nichols et al., 1989; Roy, 1984).

The concentration of the estuarine mudstones in two separate bands in the valley-fill complex (Fig. 8.2), and their proximity to the two shoreface trends suggest deposition during two different time intervals. These time intervals correspond to the development of the Wolf Creek shoreface trend (VE3-4; Figs 8.3, 8.4 & 8.5), and the development of the Bickerdike shoreface trend (VE3-6; Figs 8.3, 8.4 & 8.5), and hence, the valley-fill can be divided into at least two separate fill events.

The presence of dark mudstones at the base of the valley in many wells (e.g. 15-23-53-21W5; Fig. 8.5) implies that the valley complex was inundated during the early stages of each fill event and that most of the fill is transgressive. The base of the valley, or the VE2 erosion surface, would have been transgressively modified (VE3) before each fill event and therefore this surface is a composite erosion surface (VE2/3-4 or VE2/3-6; Figs 8.3, 8.4 & 8.5).

8.3.2 Bioturbated Muddy Sandstone (FA-3)

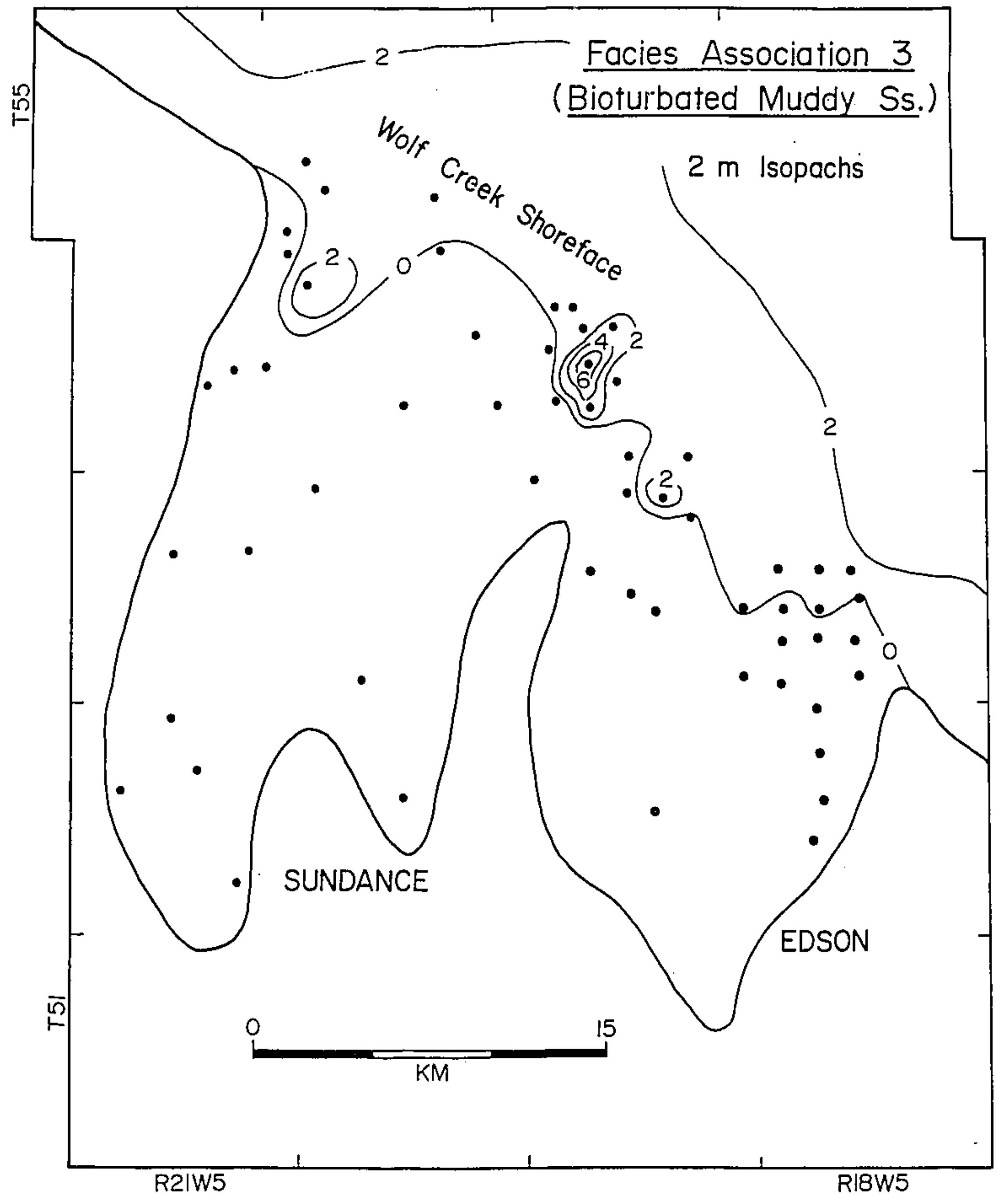
The sediments of FA-3 are concentrated in a narrow zone in the northeastern corner of the valley-fill complex (Figs 8.2 & 8.7). These sediments are relatively thin and are the least widespread of all of the facies associations observed in the complex. The maximum thickness of FA-3 is 8.0 m in 10-17-54-19W5 (Fig. 8.7).

Gradational lateral contacts are inferred between the bioturbated muddy sandstones and the Wolf Creek shoreface deposits (FA-9), dark mudstones (FA-2) and cross bedded sandstones (FA-6; e.g. 10-8-54-19W5, Fig. 8.3). The sediments of FA-3 are underlain by the VE2/3-4 erosion surface and are overlain by the VE3-5 transgressive ravinement surface (Fig. 8.3). These deposits exhibit a coarsening-upward facies succession.

Interpretation

The moderate to thorough degree of bioturbation, presence of wavy and lenticular bedding, mudstone drapes on cross beds, bi-directional cross beds, synaeresis cracks and restricted trace fossil assemblage suggest deposition in a

Figure 8.7. Isopach map of facies association 3 (bioturbated muddy sandstone). These sediments are located in the extreme northeastern part of the Sundance and Edson valley-fill complex, and are adjacent to and interbedded with the Wolf Creek shoreface deposits. Black dots indicate core and well log data points, and the isopachs are in 2 m intervals.


Facies Association 3
(Bioturbated Muddy Ss.)
2 m Isopachs
Wolf Creek Shoreface
2
0
2
4
6
2
2
2
0
SUNDANCE
EDSON
T55
T51
0
15
KM
R21W5
R18W5

marginal marine environment (section 4.3). Furthermore, the proximity to the Wolf Creek shoreface, gradational lateral contact with the estuarine mudstones to the southwest, and location in a valley suggest deposition at the marine end of an estuarine valley-fill complex. The bioturbated muddy sandstones (FA-3) are interpreted as transgressive shoreface deposits that were reworked into the Sundance and Edson valley-fill complex during the VE3 transgression.

8.3.3 <u>Fine-Grained Sandstone (FA-4)</u>

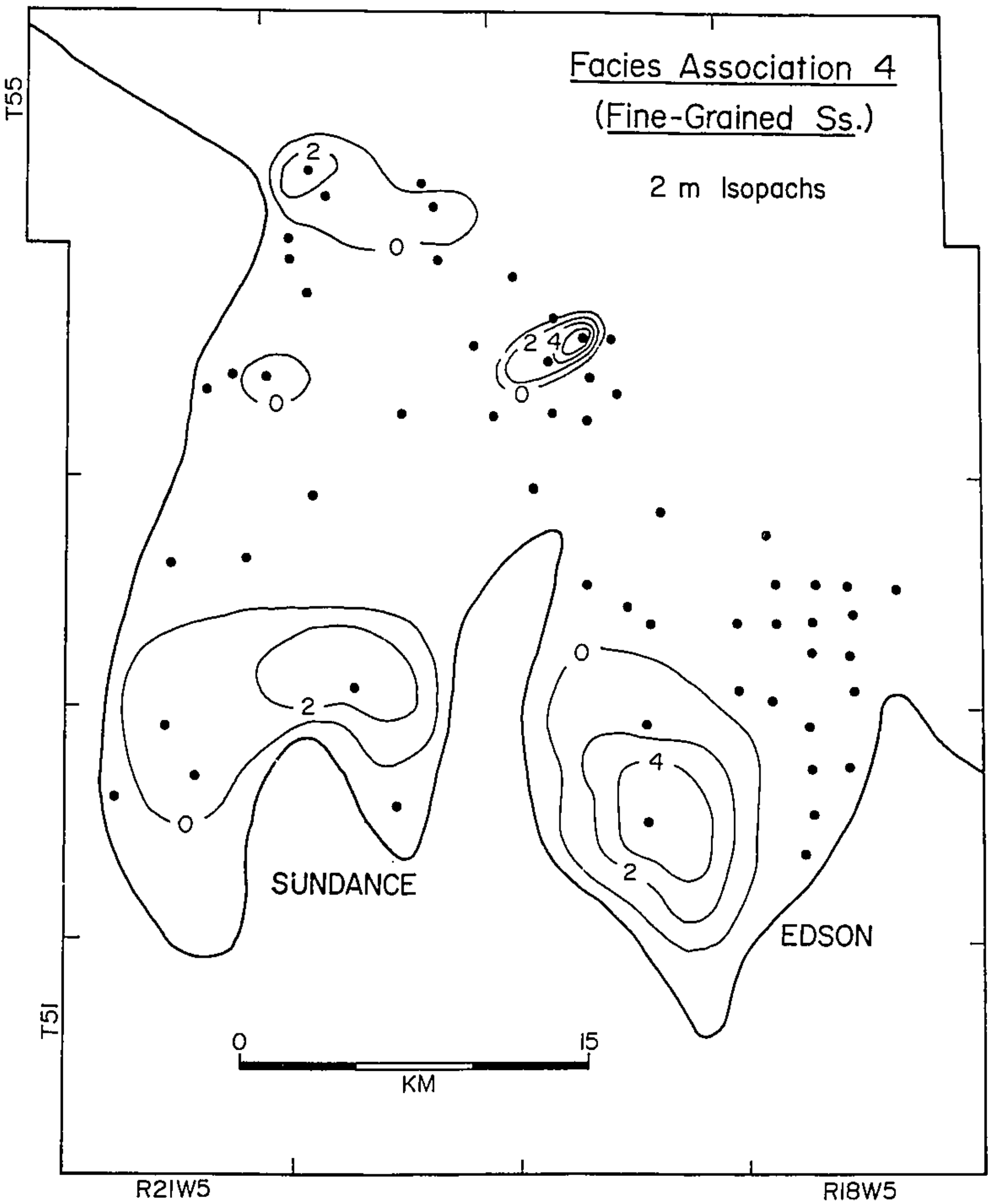
The sandstones of FA-4 are concentrated in three separate locations including, (1) scattered basal pods in the northern part of Sundance, (2) the southern part of Sundance, and (3) the southern part of Edson (Figs 8.2 & 8.8). This association is interbedded with the sediments of FA-6 in the southern part of the Sundance valley (Figs 8.2, 8.3, 8.4 & 8.5). The fine-grained sandstones reach a maximum thickness of 7.5 m in 10-20-54-19W5 (Fig. 8.8).

The sandstones of FA-4 are very fine- to fine-grained and do not exhibit a vertical grain size trend. Gradational lateral and vertical contacts are observed between the sandstones of FA-4 and the estuarine mudstones of FA-2. Sharp vertical contacts exist between the cross bedded sandstones (FA-6) and the underlying fine-grained sandstones (FA-4) in the area between the Bickerdike and Wolf Creek shorefaces (e.g. 12-13-54-21W5; Figs 8.2 & 8.3).

<u>Interpretation</u>

The fine-grained sandstones have been initially

Figure 8.8. Isopach map of facies association 4 (fine-grained sandstone). These sediments are concentrated in the southern and northern parts of the Sundance valley, and in the southern part of the Edson valley. Black dots indicate core and well log data points, and the isopachs are in 2 m intervals.


Facies Association 4
(Fine-Grained Ss.)
2 m Isopachs
T55
T51
R21W5
R18W5
SUNDANCE
EDSON
0
15
KM
0
2
4

interpreted as the deposits of a marginal marine, moderate energy environment (section 4.4). The FA-4 sandstones at Crystal were interpreted as delta front or bay head delta sediments that were deposited within an estuarine valley (chapter 6).

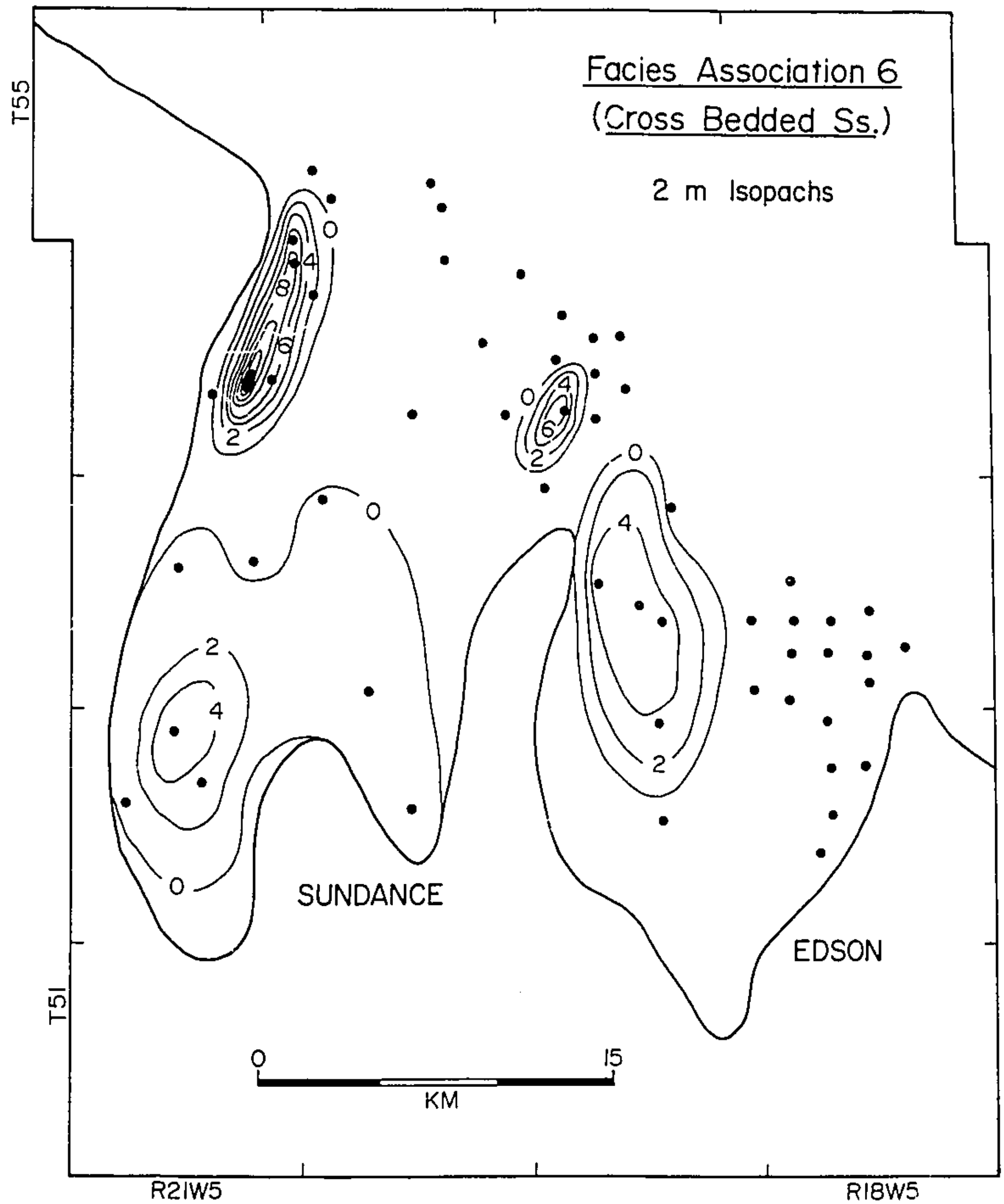
The tripartite geometry, gradational lateral and vertical contacts with the estuarine mudstones (FA-2), similarities with the fine-grained sandstones at Crystal, and location in a valley suggest deposition in a delta front or bay head delta environment. Furthermore, the location of these sediments in the extreme northern part of the valley and the gradational contact with the overlying estuarine mudstones suggest deposition during a transgression.

8.3.4 Cross Bedded Sandstone (FA-6)

The cross bedded sandstones are located in four separate zones, including (1) a linear trend in northwest Sundance, (2) a linear trend in northeast Sundance, (3) a linear trend in northwest Edson, and (4) interbedded with FA-4 in south Sundance (Figs 8.2 & 8.9). The three linear trends are oriented NNE-SSW, which is parallel to the orientation of the valley (Fig. 8.2). The sediments of FA-6 reach a maximum thickness of 16.3 m in 11-14-54-21W5 (Fig. 8.9). Most oil and gas production comes from wells that penetrate the cross bedded sandstone facies association.

The sandstones of FA-6 show no apparent vertical grain size trend and consist of medium-grained sandstone. Ripped up mudstone clasts and a lag of coarse-grained sandstone

Figure 8.9. Isopach map of facies association 6 (cross bedded sandstone). These deposits occur as three linear trends between the Wolf Creek and Bickerdike shoreface, and in the southern part of the Sundance valley, interbedded with the sediments of FA-4. Black dots indicate core and well log data points, and the isopachs are in 2 m intervals.


Facies Association 6
(Cross Bedded Ss.)
2 m Isopachs
T55
T51
SUNDANCE
EDSON
0
15
KM
R21W5
R18W5

commonly occur at the base of this facies association (e.g. 12-13-54-21W5, Fig. 8.3; 9-36-54-21W5, Fig. 8.5). This lag is interpreted as erosional in origin.

In the three linear trends (Figs 8.2 & 8.9), the base of FA-6 is defined as the VE3-5 erosion surface (Figs 8.3, 8.4 & 8.5). Sharp vertical contacts exist between the cross bedded sandstones and the underlying sediments of FA-2 or FA-4 (e.g. 12-13-54-21W5; Fig. 8.3). Sharp lateral contacts are also inferred from the juxtaposition of the estuarine mudstones and the cross bedded sandstones (Figs 8.2, 8.3, 8.4 & 8.5). The two linear trends at Sundance have channel-like morphologies and are thicker than the linear trend at Edson (Figs 8.2 & 8.9). The most prominent trend is observed in the extreme northwestern corner of Sundance, and is approximately 3 km wide, 12 km long and 16 m deep (Fig. 8.9).

Interpretation

The cross bedded sandstones have been initially interpreted as the deposits of a relatively high energy, marginal marine environment (section 4.6). The basal lag, sharp vertical and lateral contacts with the sediments of FA-2 and FA-4, channelized geometry, NNE-SSW orientation, lateral extent or scale, proximity to the shoreface deposits, abundance of bi-directional cross bedding and mudstone drapes on the foresets, and restricted trace fossil assemblage in the two linear trends of FA-6 in north Sundance suggest deposition in a tidal inlet or channel.

These deposits have a similar sedimentology, geometry and scale to many modern and ancient tidal inlet deposits (Kumar & Sanders, 1974; Moslow & Heron, 1978; Tye, 1984; Boothroyd, 1985; Moslow & Tye, 1985; Cheel & Leckie, 1990). Furthermore, the sharp lateral and vertical contacts with the NE tripartite deposits (FA-2 & FA-4) and hence the Wolf Creek shoreface deposits (FA-3), and the sharp vertical contact with the overlying Bickerdike shoreface deposits suggests that the tidal inlets were cut and filled after the development of the VE3-4 erosion surface (Wolf Creek) but before the development of the VE3-6 erosion surface (Bickerdike).

The VE3-5 scours could have been cut during lowstand incision or during transgression. The abrupt terminus of these scours to the northeast, presence of estuarine mudstones (FA-2) to the northeast, absence of fluvial deposits, and abundance of tidal cross bedding suggest that the VE3-5 scours were cut during transgression. It is probable that this transgression moved the shoreface from the Wolf Creek to the Bickerdike area, and the main sedimentological record of this event is the channelized, cross bedded sandstone. This interpretation is supported by the work of Kumar and Sanders (1974) which suggests that tidal inlet sequences have an extremely high preservation potential and could be the only entry into the geological record during erosive shoreface retreat (i.e. transgression).

The easternmost (Edson) linear trend of FA-6 and the scattered FA-6 deposits to the southwest of the Bickerdike shoreface trend are more difficult to interpret. It is possible that these sediments were deposited in tidal channel or tidal delta environments, or were reworked during transgression. These deposits are more widespread and much thinner than the tidal inlet deposits in the northern part of Sundance, and therefore are not interpreted as tidal inlet deposits.

8.3.5 Summary

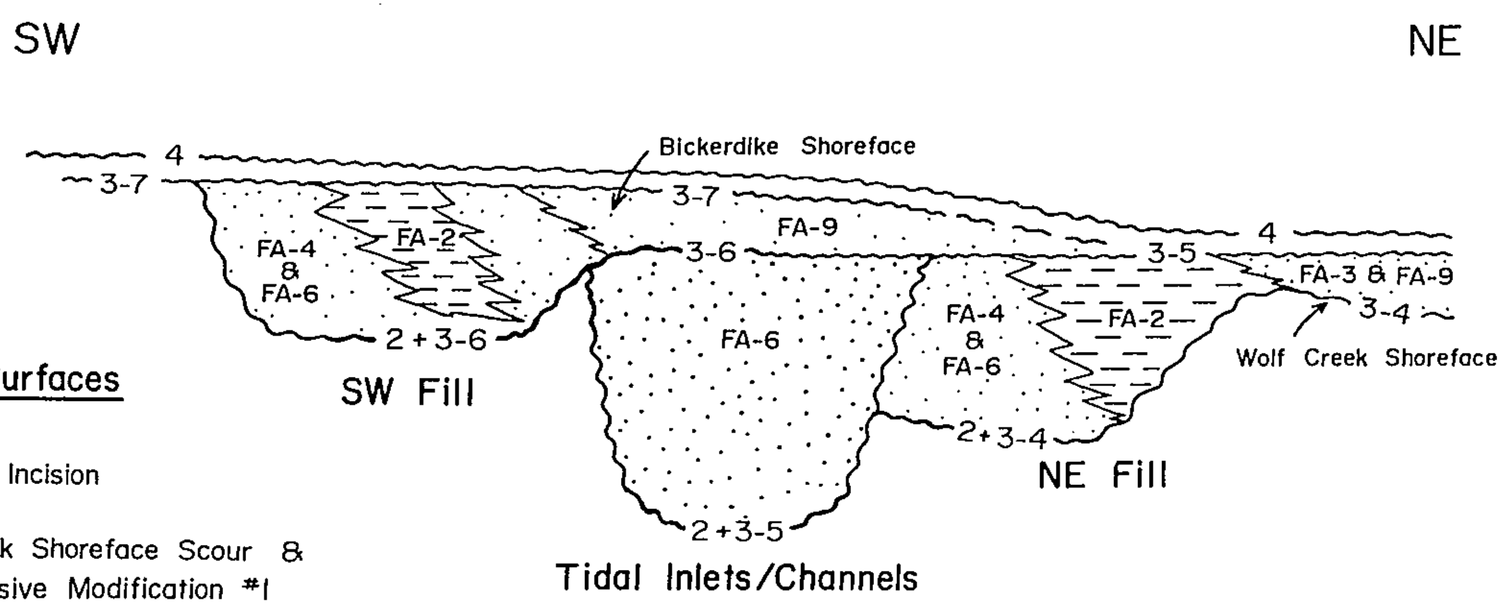
Four facies associations are observed in the sediments of the Sundance and Edson valley-fill complex and they are interpreted as estuarine mudstones (FA-2), transgressive shoreface sandstones (FA-3), delta front or bay head delta sandstones (FA-4), and tidal inlet, tidal channel, tidal delta or transgressively reworked sandstones (FA-6). These deposits combine to form a "double" tripartite facies geometry (sand-mud-sand-mud-sand), which subdivides the valley-fill complex into a NE fill and a SW fill (Fig. 8.10). The Wolf Creek shoreface is time equivalent to the NE fill and the Bickerdike shoreface is time equivalent to the SW fill (Fig. 8.10). Tidal inlets or channels cut into the deposits of the NE fill, and they are the main record of the transgression that moved the shoreface from the Wolf Creek to the Bickerdike trend.

8.4 Sequence of Events

The schematic cross section (Fig. 8.10), reconstructed

Figure 8.10. Schematic cross section summarizing the sedimentology and stratigraphy of the Sundance and Edson valley-fill complex, Bickerdike shoreface and Wolf Creek shoreface. Note the "double" tripartite geometry of the valley-fill deposits and the deep tidal inlets or channels, which are filled with cross bedded sandstones. Erosion surfaces VE3-5 and VE3-6 were both formed during a transgression which moved the shoreface from Wolf Creek to Bickerdike.

SUNDANCE & EDSON VALLEY-FILL COMPLEX



Erosion Surfaces

2. Lowstand Incision

3-4. Wolf Creek Shoreface Scour &
Transgressive Modification #1

3-5. Transgressive Ravinement #1 &
Tidal Inlet/Channel Scour

3-6. Bickerdike Shoreface Scour &
Transgressive Modification #2
&
Transgressive Ravinement #2

3-7. Transgressive Ravinement #3

4. Basinwide Erosion

Facies Associations

FA-2 Dark Mudstone

FA-3 Bioturbated Muddy Sandstone

FA-4 Fine-Grained Sandstone

FA-6 Cross Bedded Sandstone

FA-9 Sharp Based, Bioturbated Sandstone

paleogeography maps (Fig. 8.11), and relative sea level curve (Fig. 8.11) provide a summary of the depositional and erosional events inferred from a study of the Sundance and Edson valley-fill complex. Seven erosional and/or depositional events are recorded in the sediments of this valley complex, and these are described below.

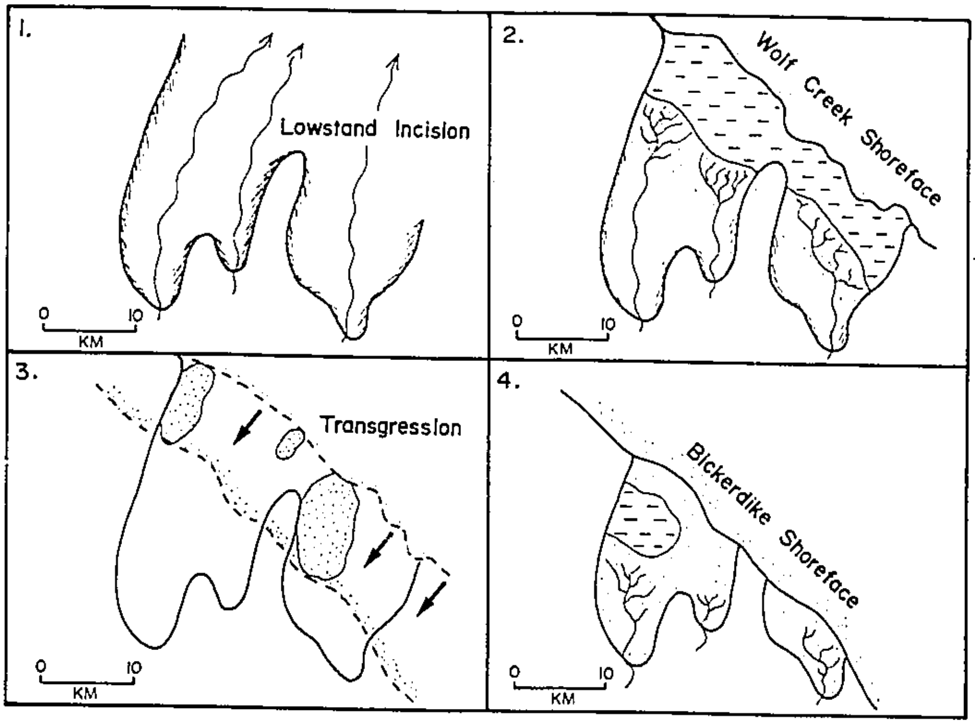
(1) A large relative drop in sea level resulted in the cutting of the Sundance and Edson valley complex, producing the VE2 erosion surface (Figs 8.10 & 8.11).

(2) A subsequent relative rise in sea level, followed by a stillstand resulted in the cutting of the VE3-4 erosion surface at the base of the Wolf Creek shoreface (incised shoreface scour) and at the base of the valley (transgressive modification surface; Figs 8.10 & 8.11). During the stillstand, sediments were deposited into the NE part of the valley-fill complex and along the Wolf Creek shoreface forming the first of two tripartite facies geometries.

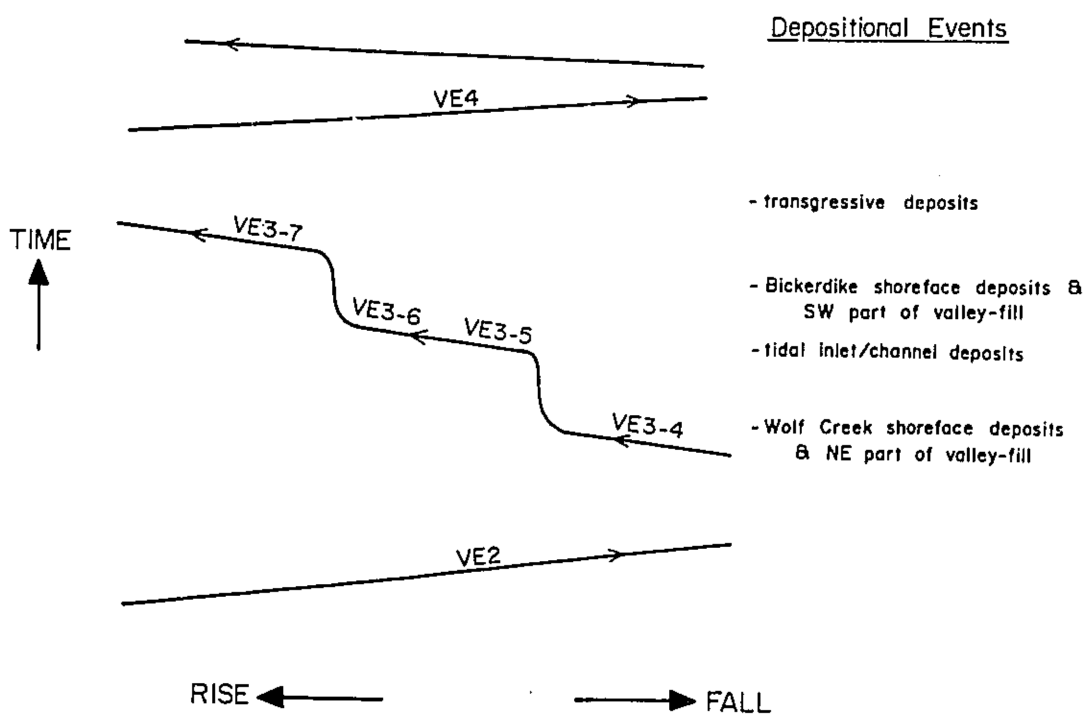
(3) A subsequent relative rise in sea level moved the shoreface from the Wolf Creek to Bickerdike trend. During the transgression, tidal scours and a ravinement surface were cut, forming the VE3-5 erosion surface (Figs 8.10 & 8.11). The tidal scours or inlets were filled with cross bedded sandstones (FA-6) and were ravined during the latter stages of this transgression. This ravinement resulted in the formation of the VE3-6 erosion surface (Figs 8.10 & 8.11). The VE3-5 and VE3-6 erosion surfaces have a close

Figure 8.11. Reconstructed paleogeography and relative sea level curve for the valley-fill, shoreface and transgressive deposits in the Sundance and Edson area. The four paleogeographic maps correspond to the development of the VE2, VE3-4, VE3-5 and VE3-6 erosion surfaces. The "double" tripartite geometry of the Sundance and Edson valley-fill complex is clearly related to the two separate positions of the shoreline (Wolf Creek & Bickerdike).

Reconstructed Paleogeography



Relative Sea Level Curve



genetic and temporal link.

(4) An ensuing stillstand led to the development of the Bickerdike shoreface scour (VE3-6), and to the deposition of the Bickerdike shoreface and the SW valley-fill complex sediments. This formed the second tripartite facies geometry in the Sundance and Edson valley-fill complex (Figs 8.10 & 8.11).

(5) A subsequent relative rise in sea level moved the shoreface southwest of Bickerdike and resulted in the development of the VE3-7 erosion surface (transgressive ravinement) on top of the Bickerdike and SW valley-fill deposits (Figs 8.10 & 8.11).

(6) A thin package of distal shoreface and transgressive sediments were deposited.

(7) The VE4 erosion surface was cut.

CHAPTER 9 - SHOREFACE AND TRANSGRESSIVE DEPOSITS

Most of this chapter will concentrate on describing the regional extent, stratigraphy, sedimentology and geological history of the shoreface deposits. The transgressive deposits are thin (0.1-8.0 m), patchy, and are difficult to correlate. Therefore, the transgressive deposits will be briefly discussed at the end of this chapter.

Shoreface deposits occur as isolated sand bodies and are observed throughout the study area. These sand bodies line up to form seven paleoshoreline trends including Joarcam, Sunnybrook "B", Sunnybrook "A", Chigwell, Wolf Creek/Gilby-Joffre, Bickerdike, and Caroline-Garrington (Allomember D; Boreen & Walker, 1991; Fig. 9.1). The shoreface deposits form coarsening-upward successions that consist of sharp based, bioturbated sandstones (FA-9) at the base, and cross bedded sandstones (FA-6) at the top. These deposits are bounded by a VE3 erosion surface below, thus removing any genetic link between the sand bodies and the underlying marine mudstones. The VE3 erosion surface has been subdivided into nine smaller surfaces (Fig. 9.2) which are labelled VE3-1a (Sunnybrook "A"), VE3-1b (Chigwell), VE3-2a (Sunnybrook "B"), VE3-2b (Joarcam), VE3-3 (transgressive ravinement), VE3-4 (Wolf Creek/Gilby-Joffre), VE3-5 (transgressive ravinement & Sundance and Edson tidal inlets), VE3-6 (Bickerdike), and VE3-7 (Caroline-Garrington, base of Allomember D). Some shoreface deposits are prolific

Figure 9.1. Location of the seven paleoshoreline trends, including Joarcam, Sunnybrook "B", Sunnybrook "A", Chigwell, Wolf Creek/Gilby-Joffre, Bickerdike, and Caroline-Garrington. The location of the Sundance, Edson, Cyn-Pem, Crystal and Willesden Green valley-fill deposits are also shown. Oil and gas reservoirs (solid black) occur in the shoreface and valley-fill deposits. The location of cross sections VV', WW', XX' and YY' are shown. Ca - Caroline, G - Garrington, H - Harmattan East, M - Mikwan, F - Fenn.

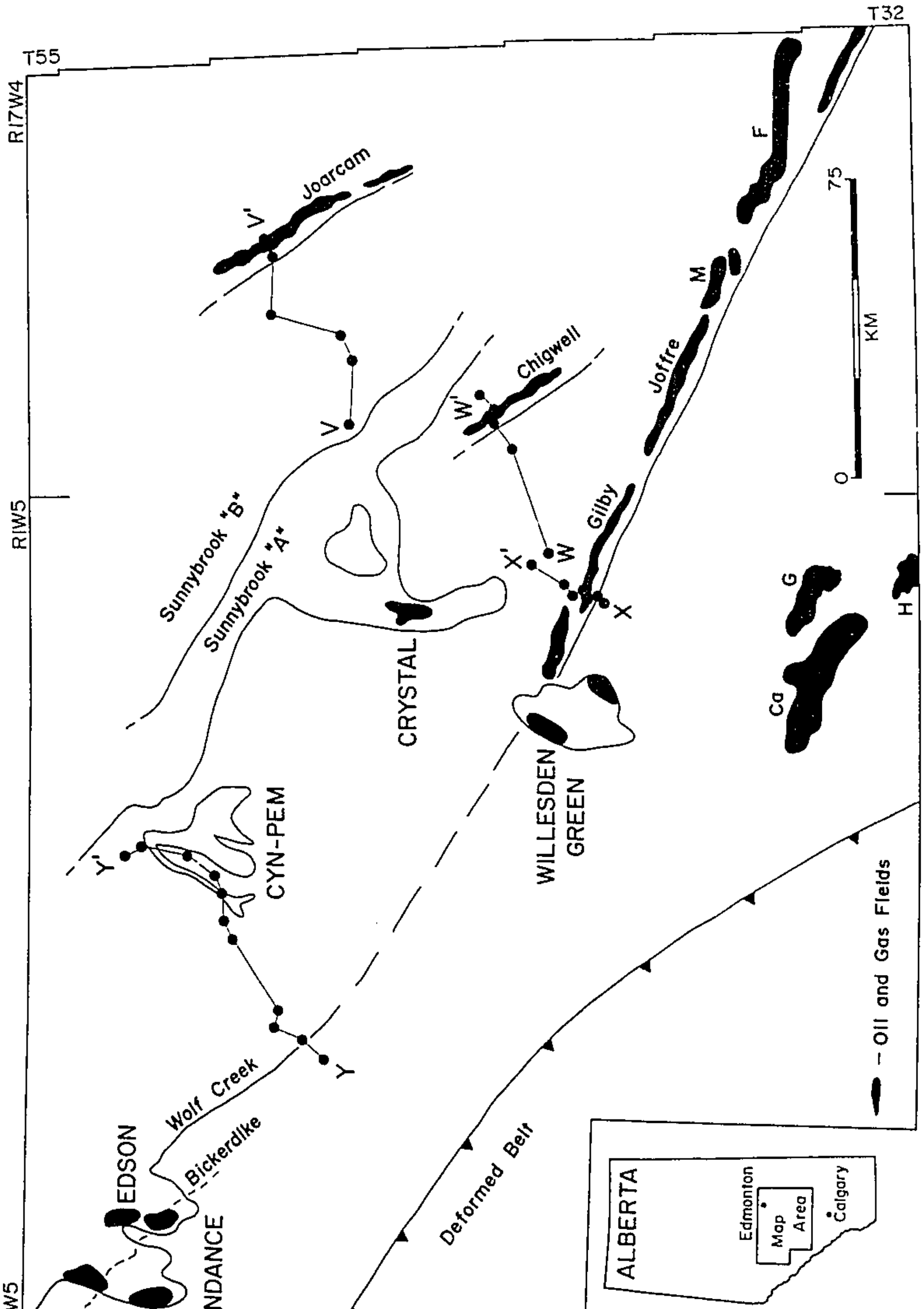
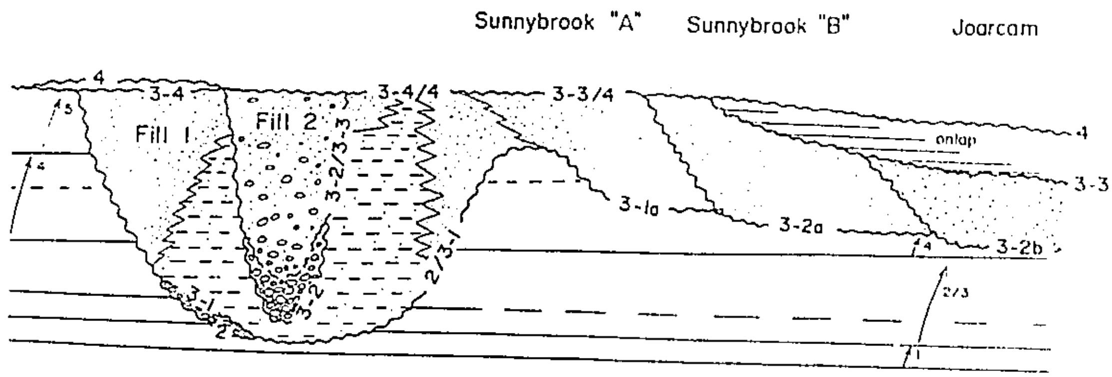
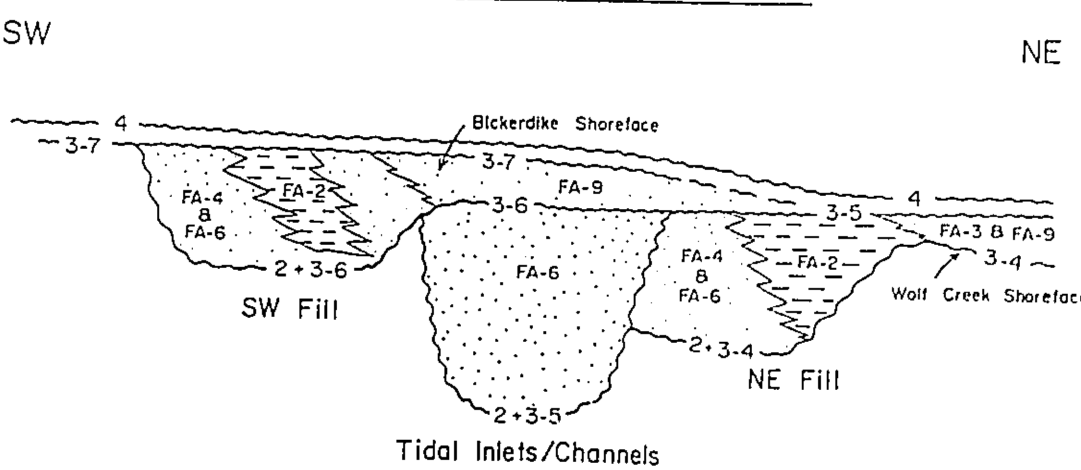

T55
R17W4
T32
Joarcam
V'
V
Chigwell
W'
W
Joffre
M
F
75
KM
0
R1W5
Sunnybrook "B"
Sunnybrook "A"
CRYSTAL
Gilby
X'
X
G
H
Ca
WILLESDEN GREEN
CYN-PEM
Y'
Y
Wolf Creek
Bickerdike
EDSON
SUNDANCE
R22W5
Deformed Belt
ALBERTA
Edmonton
Map Area
Calgary
- Oil and Gas Fields

Figure 9.2. Summary of the VE3 erosion surface nomenclature in the Crystal, and Sundance and Edson areas. Nine smaller surfaces are identified, including VE3-1a (Sunnybrook "A"), VE3-1b (Chigwell), VE3-2a (Sunnybrook "B"), VE3-2b (Joarcam), VE3-3 (transgressive ravinement NE of Crystal & transgressive modification within Fill 2 at Crystal), VE3-4 (Wolf Creek/Gilby-Joffre), VE3-5 (Sundance & Edson tidal inlets), VE3-6 (Bickerdike), and VE3-7 (Caroline-Garrington).

CRYSTAL AREA



SUNDANCE & EDSON VALLEY-FILL COMPLEX



oil and gas producers (Joarcam, Chigwell, Gilby & Joffre), while others are saturated in water (Sunnybrook "A" and "B", Wolf Creek).

9.1 Sunnybrook Shoreface

The Sunnybrook shoreface is located northeast of the Cyn-Pem and Crystal valleys (Figs 9.1, 9.2 & 9.3). It is oriented NW-SE, has a maximum thickness of 18.2 m (11-20-47-25W4) and can be traced basinwards (NE) for up to 75 km, and along strike for up to 195 km (Figs 9.1 & 9.3). The thickest deposits occur northeast of the Crystal valley (Fig. 9.3). Cross sections QQ', RR' and SS' summarize the stratigraphy and sedimentology of these deposits (Figs 9.4, 9.5 & 9.6).

The Sunnybrook shoreface is named after the small town of Sunnybrook, Alberta which is located at 2-3-49-2W5. Pattison (1990) and Pattison and Walker (1990) previously called this shoreface the Crystal shoreface. The type well for facies association 9 (sharp based, bioturbated sandstone) is located approximately 3 km northwest of Sunnybrook (6-9-49-2W5; Figs 4.26, 4.27 & 4.28). The Sunnybrook shoreface is subdivided into two shorefaces labelled "A" and "B" (Figs 9.1, 9.2, 9.3, 9.4 & 9.6).

9.1.1 Sunnybrook "A"

The Sunnybrook "A" shoreface is the more southerly and older of the two (Figs 9.2, 9.3, 9.4, 9.5 & 9.6). It is oriented NW-SE, has a maximum thickness of 17.1 m (6-27-47-26W4) and can be traced basinwards for approximately 30 km

Figure 9.3. Isopach map of the Sunnybrook shoreface deposits (5 m isopach interval). Location of cross sections QQ', RR' and SS' are also shown. Note the lateral "connection" between the Sunnybrook and Crystal deposits versus the "gap" between the Sunnybrook and Cyn-Pem deposits.

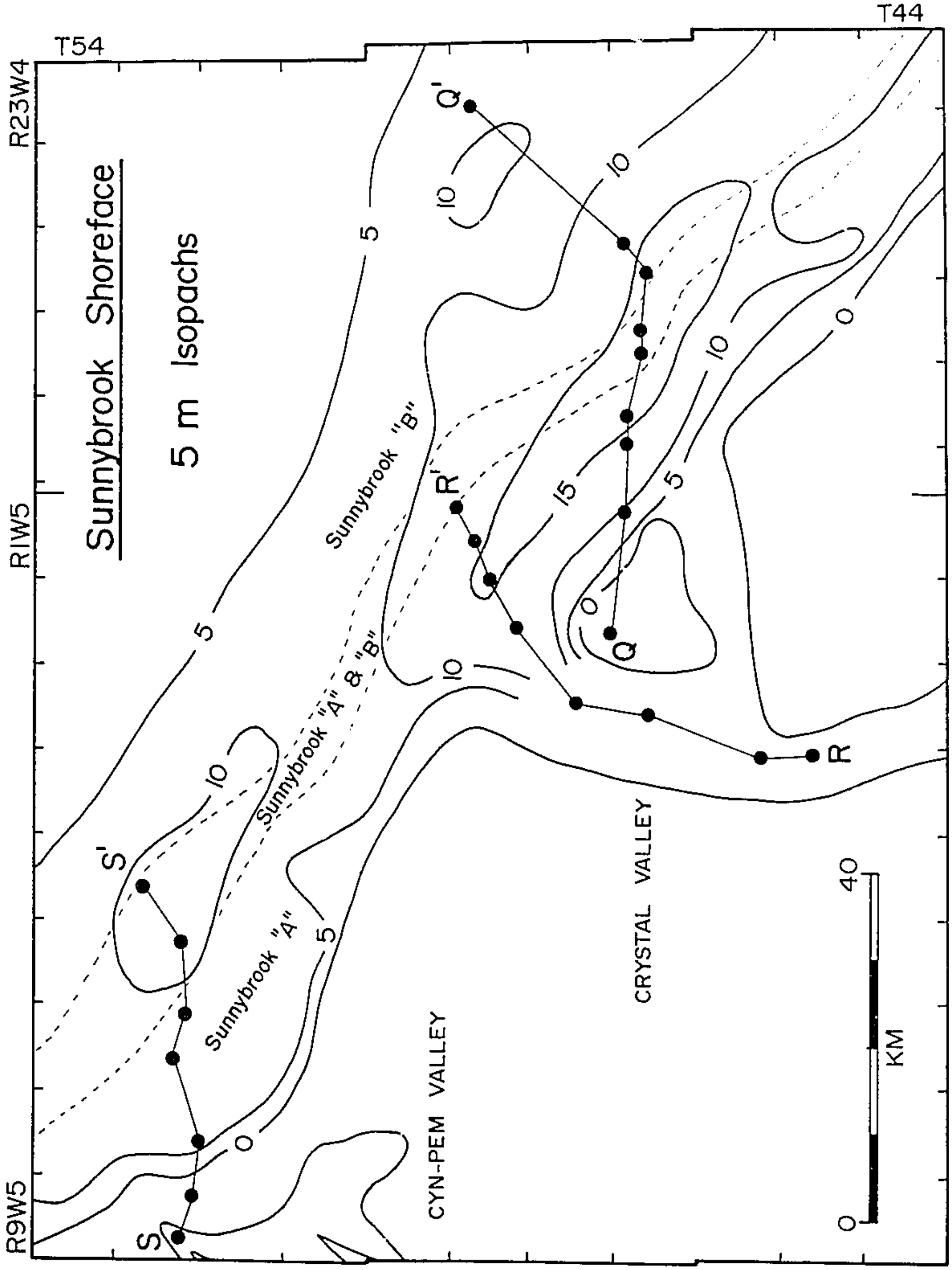
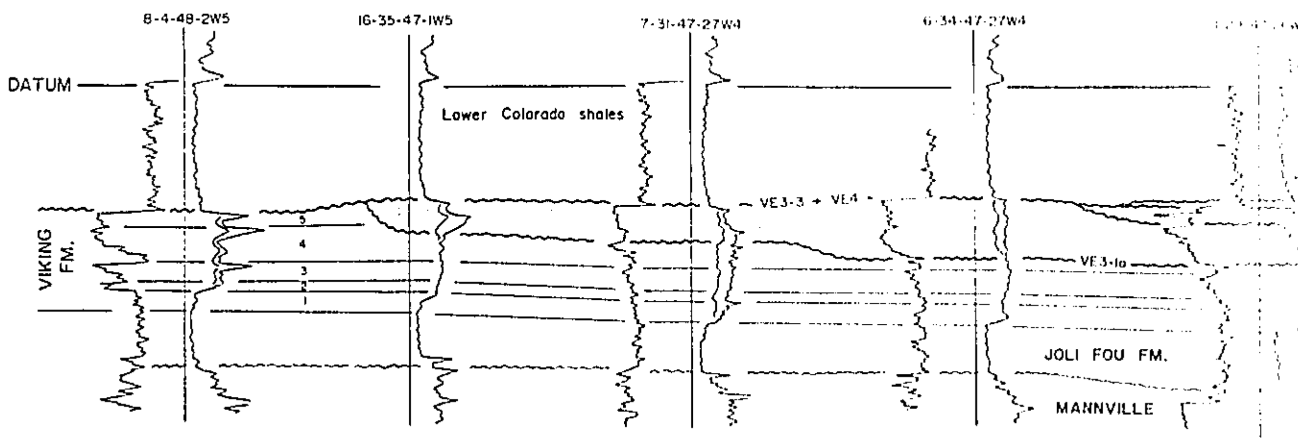

Sunnybrook Shoreface
5 m Isopachs
T54
T44
R23W4
R1W5
R9W5
Sunnybrook "B"
Sunnybrook "A" & "B"
Sunnybrook "A"
CRYSTAL VALLEY
CYN-PEM VALLEY
Q'
Q
R'
R
S'
S
KM
0
40

Figure 9.4. Well log cross section QQ'. This cross section consists of nine wells and is oriented west to east across the Sunnybrook "A" (heavy stipple) and "B" shoreface deposits (Fig. 9.2). Four Viking erosion surfaces are recognized, including VE3-1a, VE3-2a, VE3-3 and VE4. Transgressive deposits rest stratigraphically on top of Sunnybrook "B" and onlap onto the VE3-3 erosion surface. Regional successions 1 to 5 are also shown. Datum is the BFS log marker.

Well Log Cross

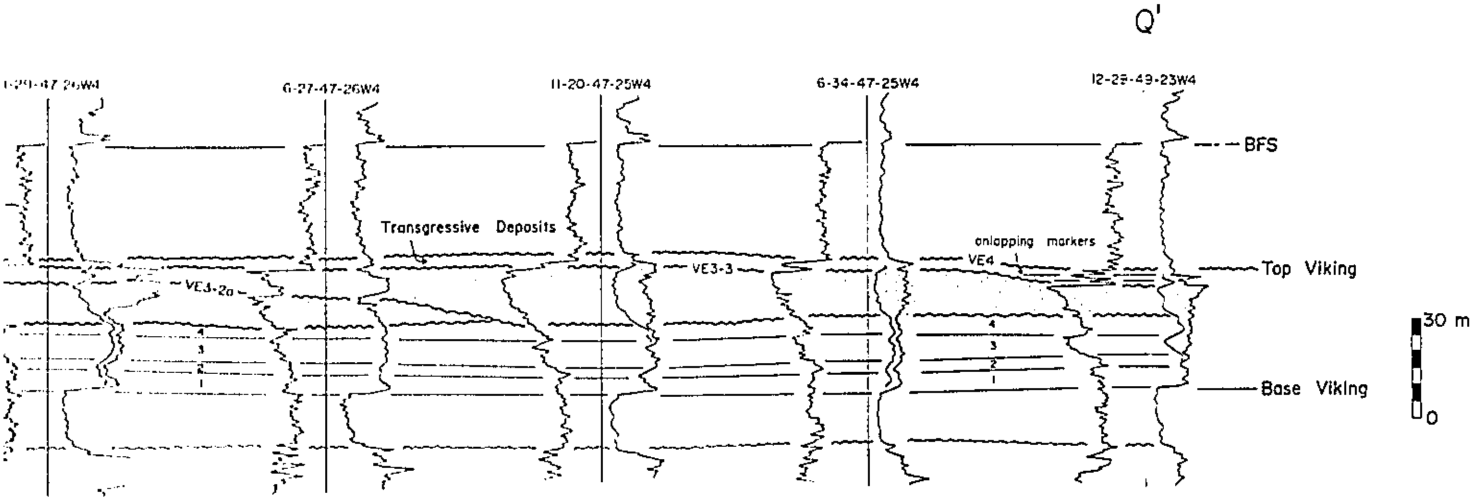
Q



WEST

Sunnybrook "A"

Cross Section QQ'



Sunnybrook "B"

EAST

(Fig. 9.3).

The deposits of the Sunnybrook "A" shoreface are underlain by the VE3-1a erosion surface and overlain by the VE3-2a (Figs 9.4 & 9.6), VE3-3 (Figs 9.5 & 9.6), or VE3-3/VE4 (Figs 9.4 & 9.5) erosion surface. The VE3-1a surface forms an asymmetrical scour which is "open" towards the northeast (Figs 9.4, 9.5 & 9.6). Most of regional succession 4 and all of succession 5 are truncated or cut out by the VE3-1a scour in the Crystal area (Figs 9.4 & 9.5). In the Cyn-Pem area, most of regional succession 3 is cut out by this scour (Fig. 9.6). The maximum depth of incision is approximately 14 m.

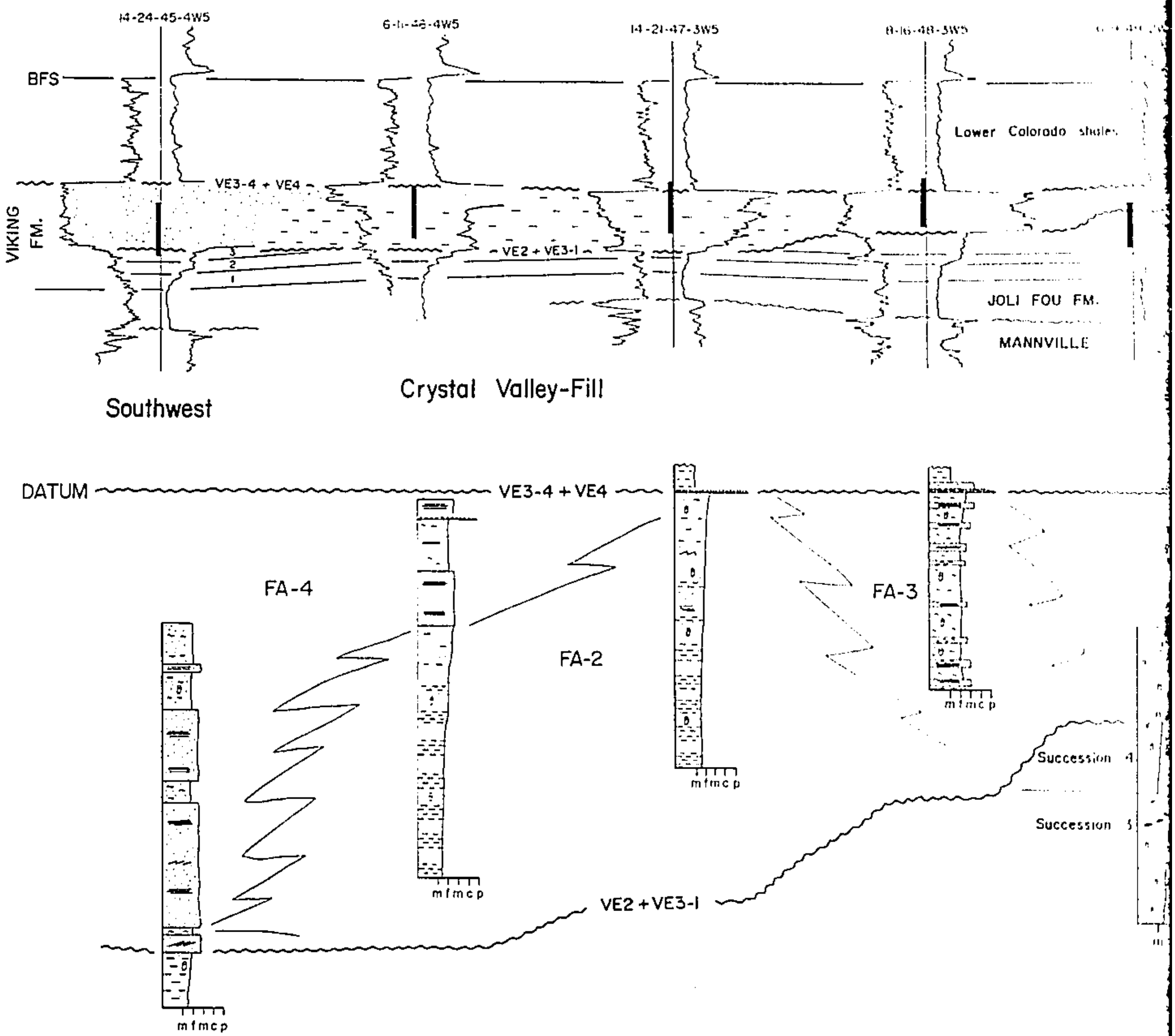
To the northeast, the Sunnybrook "A" shoreface is truncated by the VE3-2a erosion surface, which defines the base of the Sunnybrook "B" shoreface (Figs 9.4 & 9.6). To the northwest and southeast, Sunnybrook "A" shales-out and is difficult to recognize.

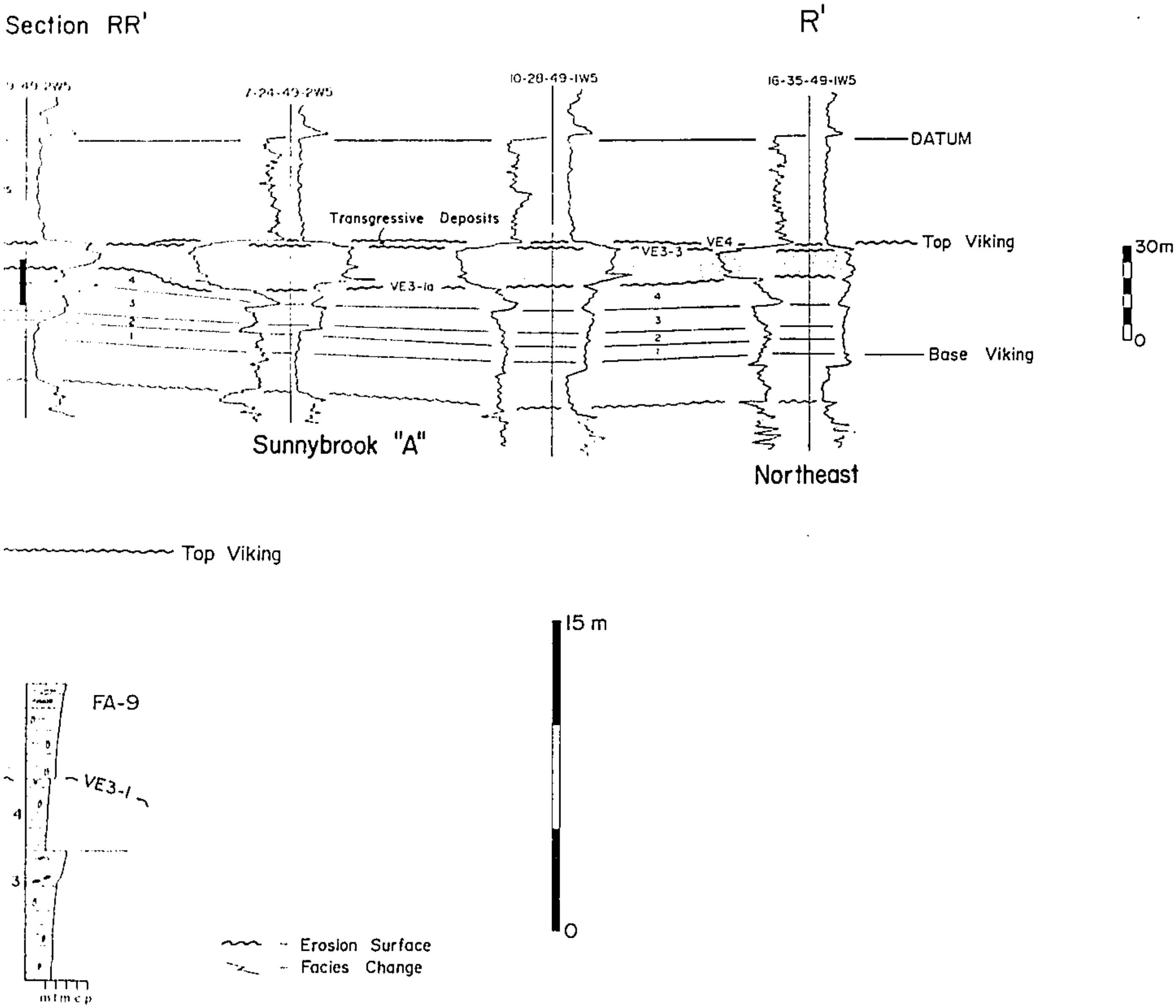
Only three cores penetrate the Sunnybrook "A" shoreface deposits (Fig. 1.6). An examination of the available cores, gamma ray well logs and drill cuttings from four wells suggests that Sunnybrook "A" consists of sharp based, bioturbated sandstones (FA-9), becomes sandier, coarser and less bioturbated upward, and has a maximum grain size of medium-grained sand. Gradational lateral contacts are inferred between the sediments of Sunnybrook "A" and the bioturbated muddy sandstones (FA-3) in the northern part of fill 1 at Crystal (Figs 9.2 & 9.5). Therefore, the VE3-1

Figure 9.5. Well log and core cross section RR'. This section consists of 8 wells and is oriented southwest to northeast through the Crystal valley (fill 1) and Sunnybrook "A" shoreface (Fig. 9.2). Five Viking erosion surfaces are recognized, including VE2, VE3-1(a), VE3-3, VE3-4 and VE4. Transgressive deposits rest stratigraphically on top of the Sunnybrook "A" shoreface. Regional successions 1 to 4 are also shown. Datum for the well log section is the BFS log marker, and for the core section is the top of the Viking. Black bars on the well logs indicate core positions. FA-2 - Dark Mudstone, FA-3 - Bioturbated Muddy Sandstone, FA-4 - Fine-Grained Sandstone, FA-9 - Sharp Based, Bioturbated Sandstone.

R

Core & Well Log Cross Sect





Section RR'
R'
7-24-49-2W5
10-28-49-1W5
16-35-49-1W5
DATUM
Transgressive Deposits
VE4
VE3-3
VE3-1a
Top Viking
Base Viking
30m
0
4
3
2
1
Sunnybrook "A"
Northeast
Top Viking
15 m
0
FA-9
VE3-1
4
3
Erosion Surface
Facies Change

erosion surface at the base of fill 1 is correlative with the VE3-1a erosion surface at the base of Sunnybrook "A". This creates a temporal and genetic link between the sediments of fill 1 and those of the Sunnybrook "A" shoreface.

9.1.2 <u>Sunnybrook "B"</u>

The Sunnybrook "B" shoreface is located basinwards (NE) of Sunnybrook "A", and is the younger of the Sunnybrook shorefaces (Figs 9.2 & 9.3). It is oriented NW-SE, has a maximum thickness of 18.2 m (11-20-47-25W4) and can be traced basinwards for up to 45 km (Fig. 9.3).

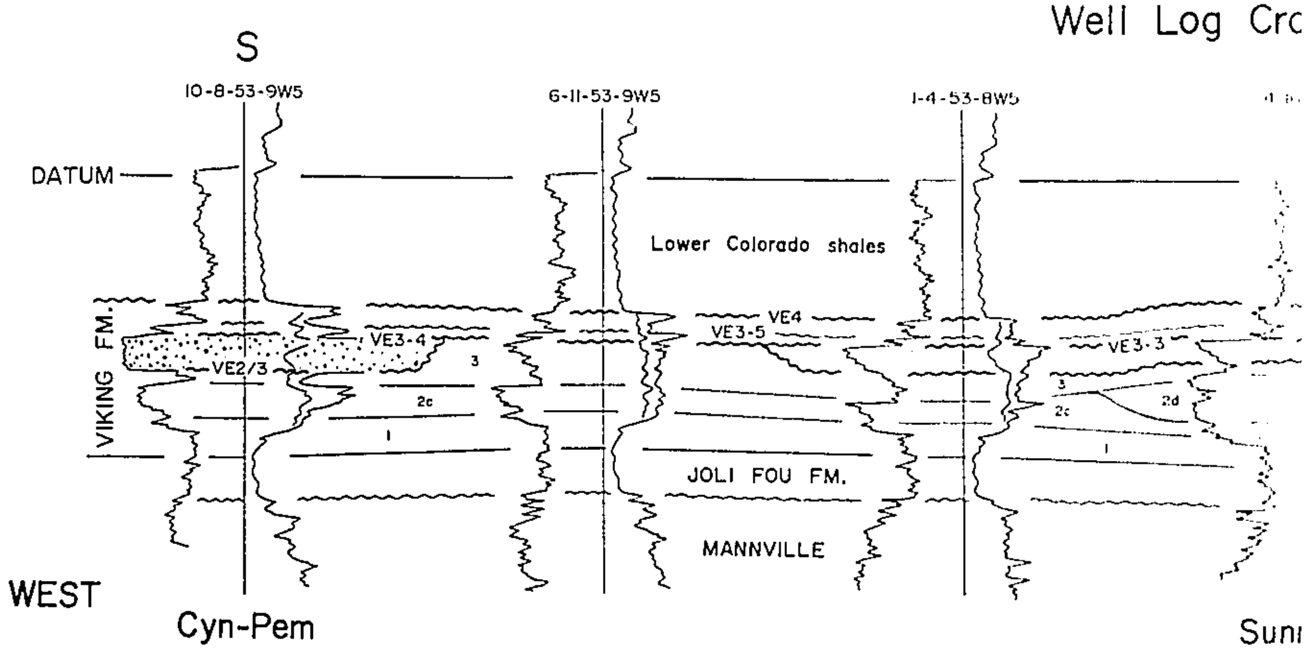
These deposits are underlain by the VE3-2a erosion surface (Figs 9.4 & 9.6), and are overlain by the VE3-3 (Figs 9.4 & 9.6) or the VE3-2b (Joarcam; section 9.4) erosion surface. The VE3-2a surface forms an asymmetrical scour which is "open" towards the northeast. This surface cuts into the sediments of Sunnybrook "A" and regional succession 4 (Figs 9.4 & 9.6). The maximum depth of incision is approximately 13 m.

Onlapping transgressive deposits overlie the Sunnybrook "B" shoreface in the Crystal area (Figs 9.2 & 9.4). Distal shoreface deposits (Wolf Creek/Gilby-Joffre; section 9.6) overlie the Sunnybrook "B" shoreface in the Cyn-Pem area (Fig. 9.6).

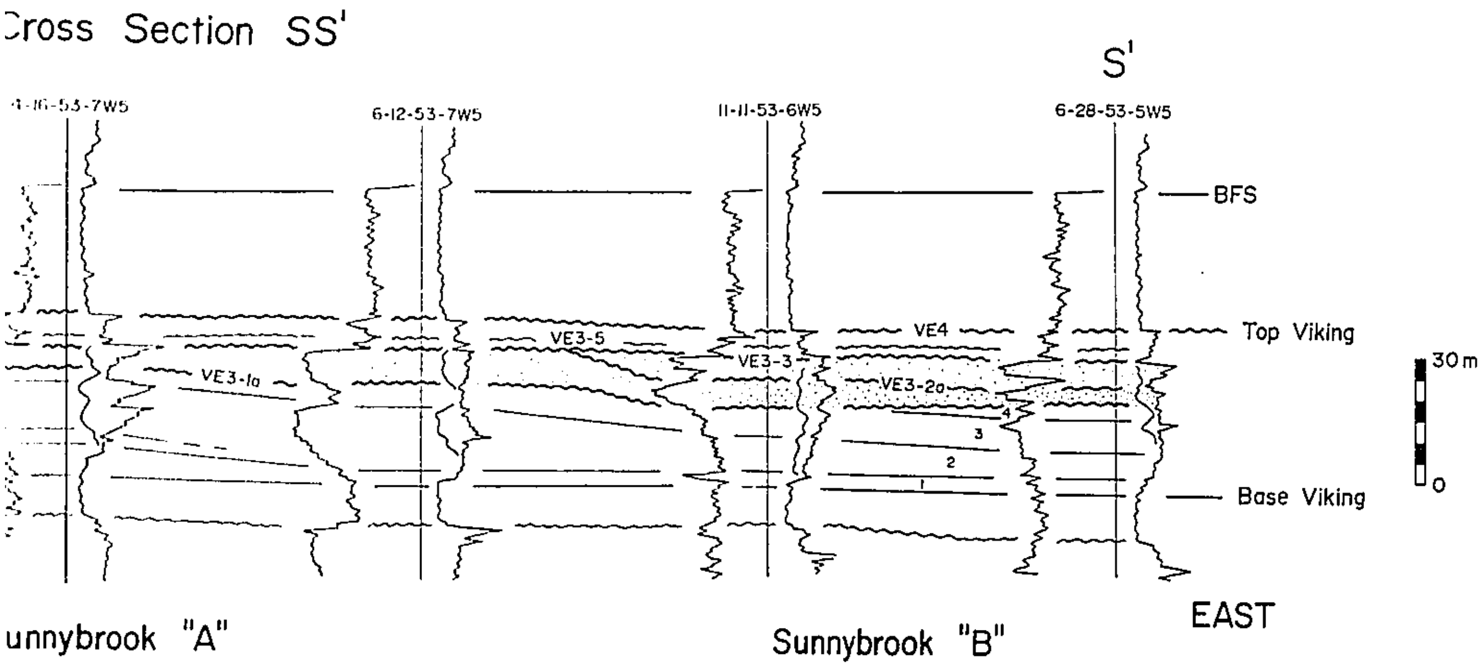
Very little information is available on the sedimentology of the Sunnybrook "B" shoreface deposits. An examination of drill cuttings from three wells indicates

Figure 9.6. Well log cross section SS'. This cross section consists of 7 wells and is oriented west to east across the Cyn-Pem valley-fill (coarse stipple) and the Sunnybrook "A" (dense stipple) and "B" (light stipple) shorefaces (Fig. 9.2). Seven Viking erosion surfaces are recognized, including VE2/3, VE3-1a, VE3-2a, VE3-3, VE3-4, VE3-5 and VE4. Distal shoreface deposits (Wolf Creek/Gilby-Joffre) are observed between the VE3-3/VE3-4 and VE3-5 erosion surfaces. Transgressive deposits occur between the VE3-5 and VE4 erosion surfaces. Regional successions 1, 2, 2c, 2d and 3 are also shown. Datum is the BFS log marker.

Well Log Cro



S
10-8-53-9W5
6-11-53-9W5
1-4-53-8W5
DATUM
Lower Colorado shales
VIKING FM.
VE4
VE3-5
VE3-4
VE3-3
VE2/3
3
2c
2d
1
JOLI FOU FM.
MANNVILLE
WEST
Cyn-Pem
Sunı


Cross Section SS'
S'
4-16-53-7W5
6-12-53-7W5
11-11-53-6W5
6-28-53-5W5
BFS
Top Viking
Base Viking
VE4
VE3-5
VE3-3
VE3-1a
VE3-2a
4
3
2
1
30 m
0
Sunnybrook "A"
Sunnybrook "B"
EAST

that the maximum grain size is medium-grained sand. The gamma-ray well log signatures indicate that these deposits become sandier upwards (e.g. 11-20-47-25W4; Fig. 9.4). The sharp, erosive base and similar well log signature to the deposits of Sunnybrook "A" suggest that the Sunnybrook "B" deposits may consist of sharp based, bioturbated sandstones (FA-9; Figs 4.26, 4.27 & 4.28).

9.2 Wolf Creek Shoreface

The Wolf Creek shoreface is located northeast of the Sundance and Edson valley-fill complex (Figs 9.1, 9.2 & 9.7). It is named after the small town of Wolf Creek (located at 14-2-54-16W5) which is approximately 13 km northeast of Edson, Alberta.

This shoreface is oriented NW-SE, has a maximum thickness of 5.8 m (Fig. 9.7), and can be traced basinward for at least 70 km. The distal equivalents of this shoreface rest stratigraphically on top of the Cyn-Pem valley-fill and Sunnybrook shoreface (section 9.6). Cross section TT' summarizes the stratigraphy and sedimentology of these deposits (Fig. 9.8).

The Wolf Creek shoreface can be traced towards the southeast where it merges with the well-established Gilby-Joffre shoreface trend (Downing & Walker, 1988; Raddysh, 1988; Boreen, 1990; Fig. 9.1). The Wolf Creek/Gilby-Joffre shoreface trend is approximately 400 km long, and is the most extensive shoreface recognized in the study area.

The shoreface is bounded by the VE3-4 erosion surface

Figure 9.7. Isopach map of the Wolf Creek shoreface deposits (1 m isopach interval). Location of well log cross section TT', and the Sundance and Edson valleys are also shown.

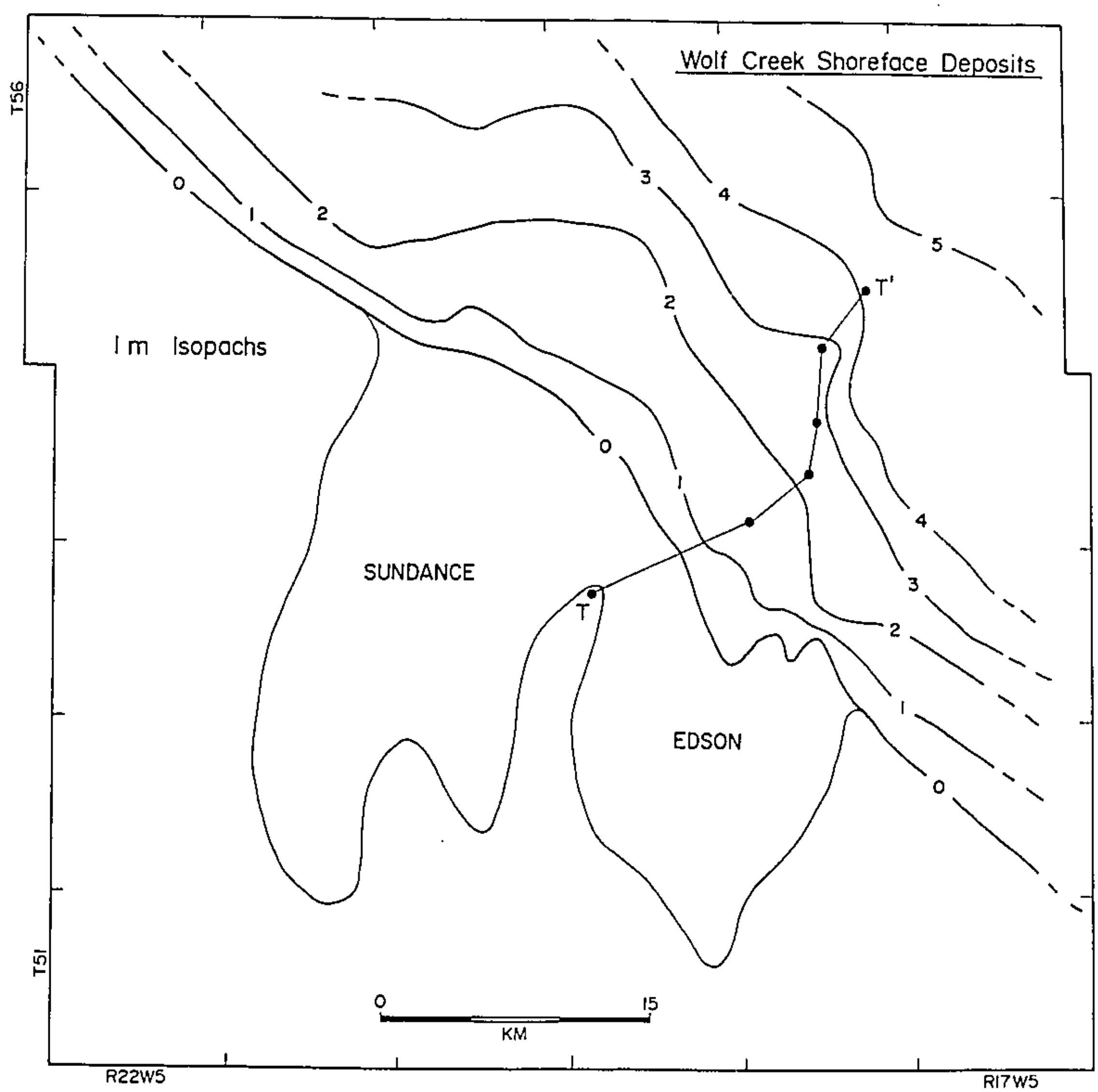
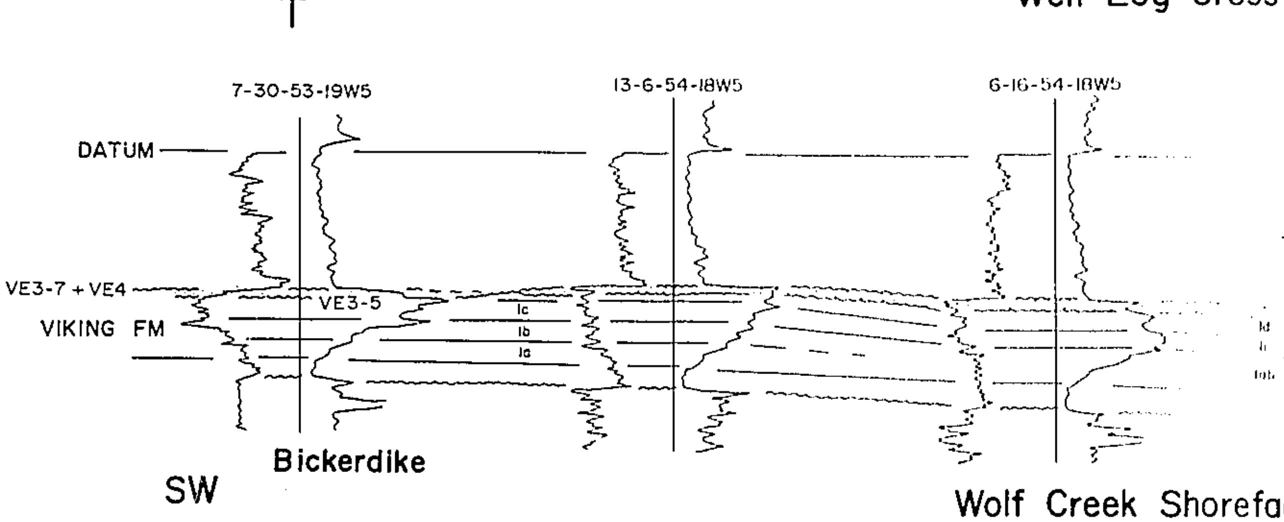
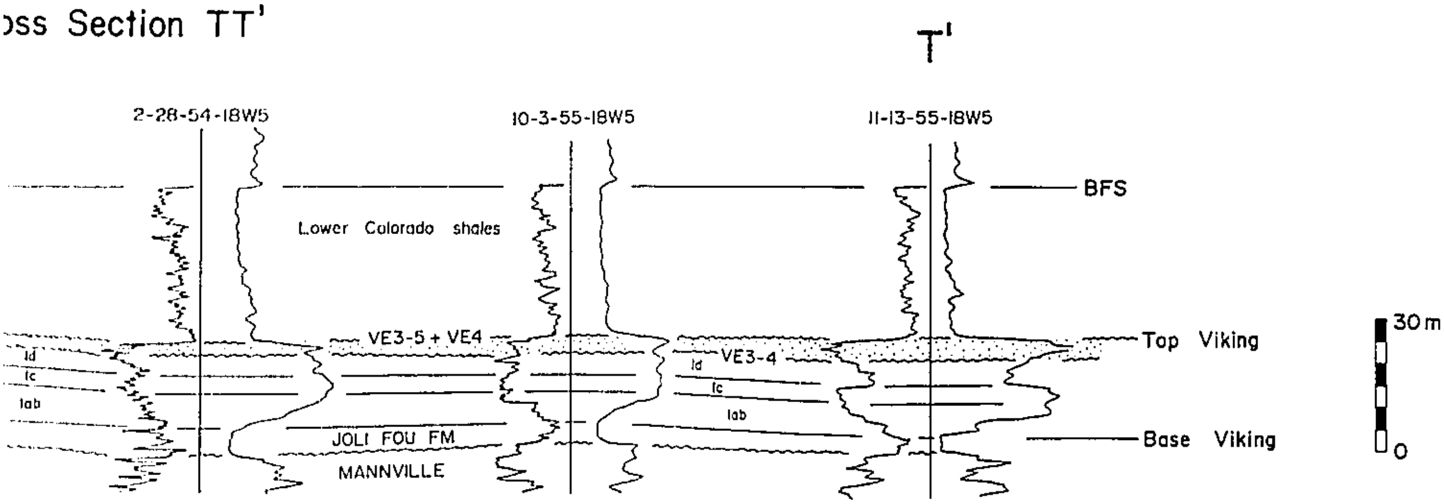

Wolf Creek Shoreface Deposits
1 m Isopachs
0
1
2
3
4
5
T'
T
SUNDANCE
EDSON
0
15
KM
T56
T51
R22W5
R17W5

Figure 9.8. Well log cross section TT'. This cross section consists of 6 wells and is oriented southwest to northeast (Fig. 9.6) through the Wolf Creek shoreface deposits (dense stipple). These deposits are bounded below by the VE3-4 erosion surface and above by the VE3-5 + VE4 erosion surface. The Bickerdike shoreface deposits (light stipple) are shown in the extreme southwestern well, and are bounded below by the VE3-5 erosion surface and above by the VE3-7 + VE4 erosion surface. Regional successions 1a, 1b, 1ab, 1c and 1d are also shown. Datum is the BFS log marker.

Well Log Cross



ɔss Section TT'



ɘface

below and by the VE3-5 or VE4 erosion surface above (Fig. 9.8). The VE3-4 surface forms an asymmetrical scour which is "open" towards the northeast. Regional successions 1d, 1e, 2 and 3 are truncated or completely cut out beneath this surface (Fig. 9.8). The maximum depth of incision is approximately 5 m.

Gradational lateral contacts are inferred between the Wolf Creek shoreface deposits and the Sundance and Edson valley-fill deposits (Figs 8.3, 8.4 & 8.5). The sandstones and mudstones of the NE part of the valley-fill complex, and the sandstones of the Wolf Creek shoreface combine to form a tripartite facies geometry. These deposits are underlain by the VE3-4 erosion surface, and are overlain by distal Bickerdike shoreface deposits (Fig. 8.4) or a thin package of transgressive sediments (Fig. 8.10).

It is difficult, if not impossible to determine the sedimentology of the Wolf Creek shoreface deposits because of the absence of core data (Fig. 1.6). The sharp, erosive base and the sandier-upward well log signature may suggest that these deposits consist of FA-9 (sharp based, bioturbated sandstone).

9.3 Bickerdike Shoreface

The Bickerdike shoreface is located approximately 10-12 km southwest of the Wolf Creek shoreface trend (Figs 9.1 & 9.2). It is named after the small town of Bickerdike (located at 1-6-53-18W5) which is 15 km west of Edson, Alberta. This shoreface has a limited lateral extent and is

only observed in the Sundance and Edson area (Fig. 9.1). The Bickerdike shoreface roughly divides the Sundance valley into two equal areas, and it marks the dividing line between the two tripartite facies zones within the valley-fill complex (chapter 8).

The Bickerdike shoreface is oriented NW-SE, parallel to the Wolf Creek shoreface (Fig. 9.1) and has a maximum thickness of 3.5 m (Fig. 9.9). It is thickest on top of the valley-fill complex and becomes thinner towards the northeast where it rests stratigraphically on top of the Wolf Creek shoreface deposits (Fig. 8.4). Cross section UU' summarizes the stratigraphy and sedimentology of these shoreface deposits (Fig. 9.10).

The Bickerdike shoreface is bounded by the VE3-5 or VE3-6 erosion surface below, and by the VE3-7 or VE4 erosion surface above (Fig. 9.10). The VE3-5 and VE3-6 erosion surfaces cut into the underlying regional and valley-fill deposits (NE tripartite fill; Fig. 8.10), and they form an asymmetrical scour which is "open" towards the northeast (Fig. 9.10). The maximum depth of incision is approximately 3 m. A thin (0.1-1.0 m) package of transgressive deposits rests stratigraphically on top of the Bickerdike shoreface (Fig. 8.3).

Gradational lateral contacts are inferred between the Bickerdike shoreface deposits and the valley-fill deposits in the southwestern part of the valley complex (Figs 8.5 & 8.10). These deposits combine to form the second tripartite

Figure 9.9. Isopach map of the Bickerdike shoreface deposits (1 m isopach interval). Location of well log cross section UU', and the Sundance and Edson valleys are also shown.

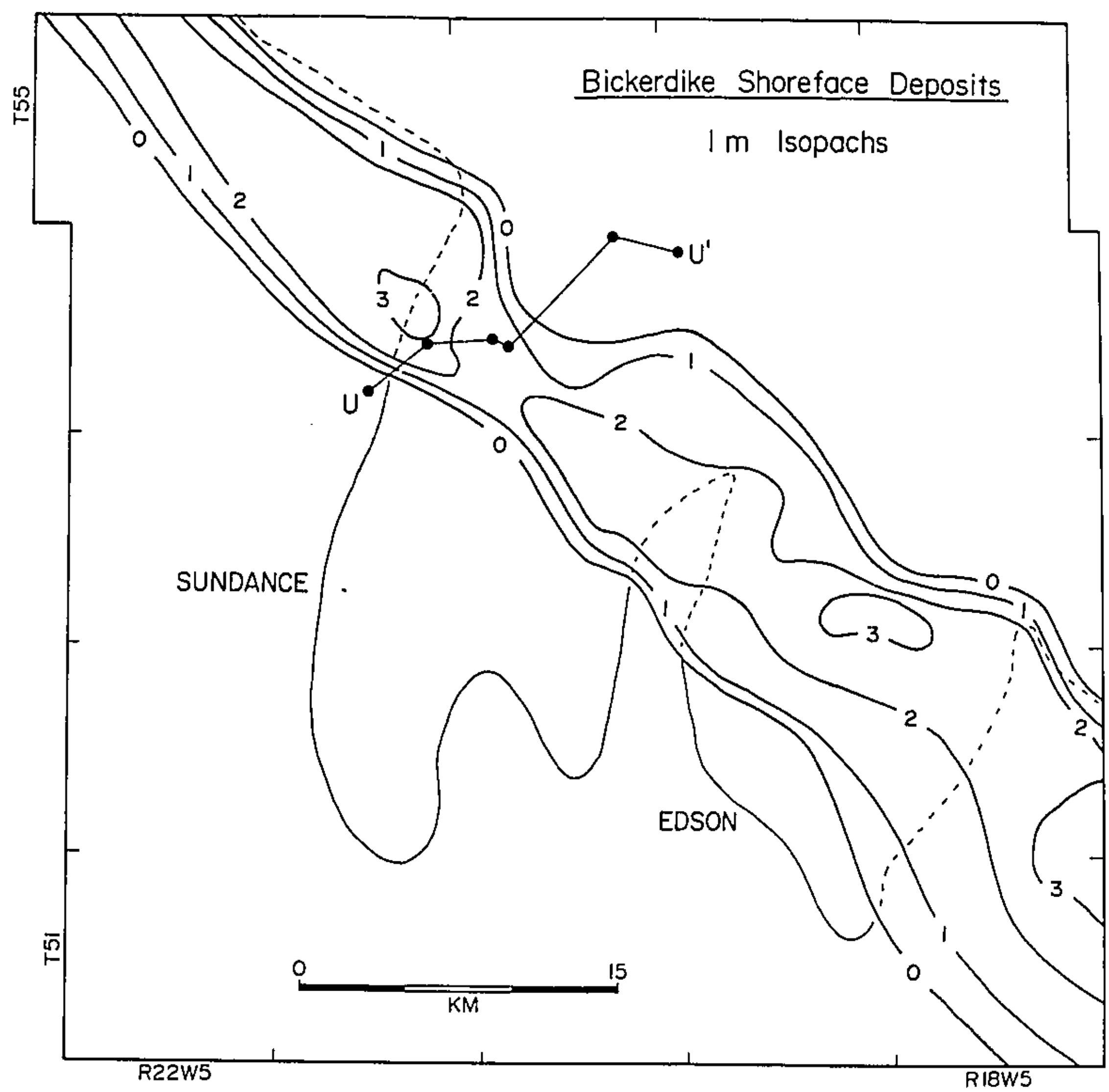
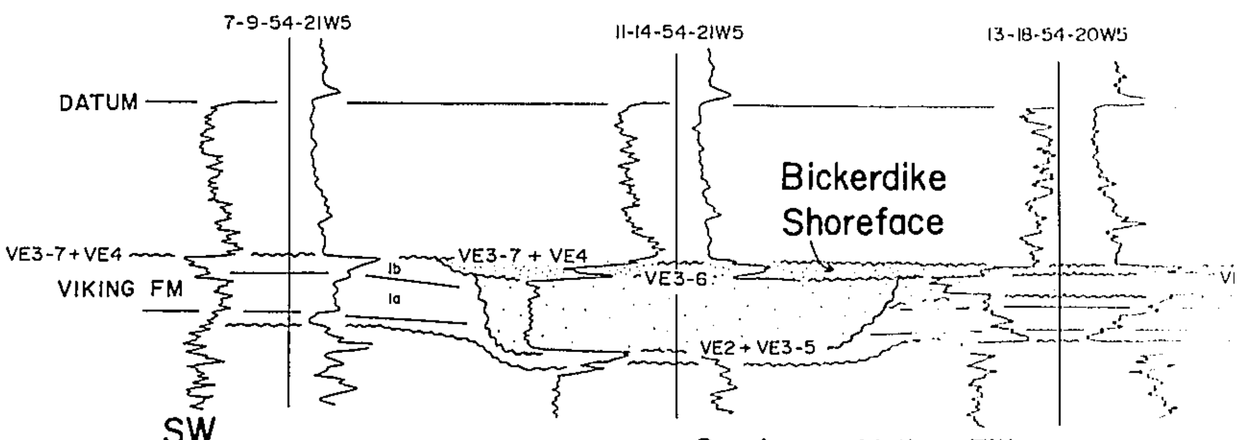
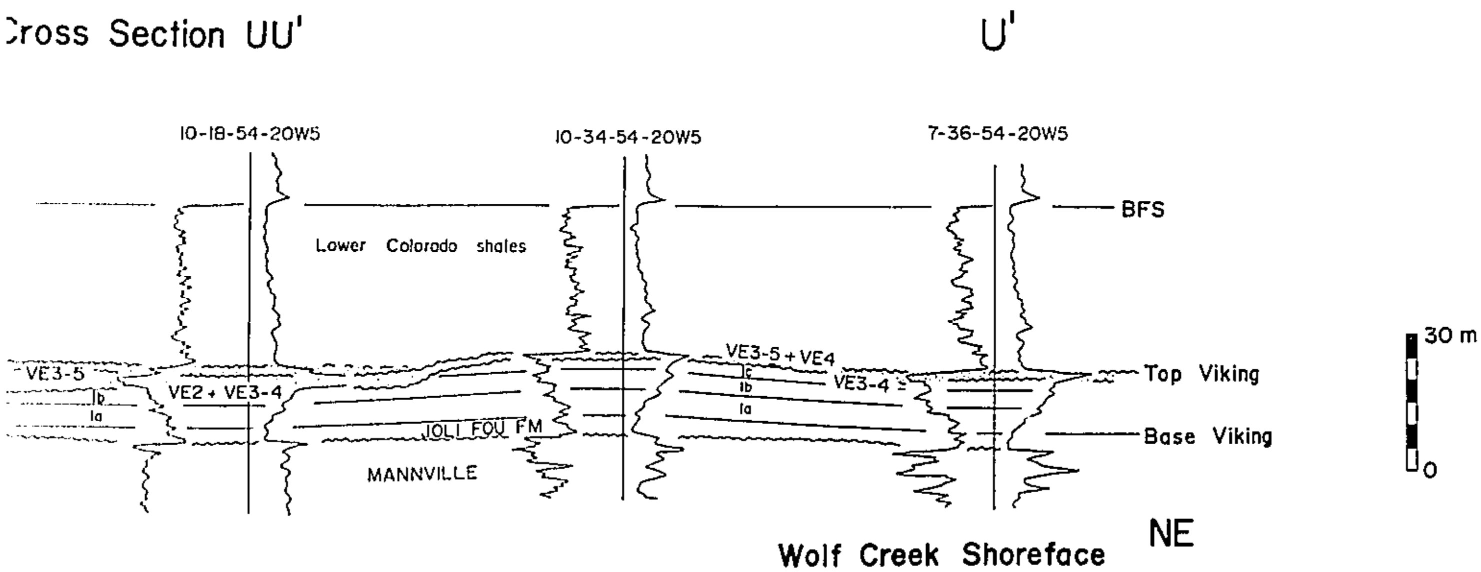

Bickerdike Shoreface Deposits
1 m Isopachs
T55
T51
R22W5
R18W5
SUNDANCE
EDSON
U
U'
0
15
KM

Figure 9.10. Well log cross section UU'. This cross section consists of 6 wells and is oriented southwest to northeast through the Bickerdike shoreface, Sundance valley (light stipple) and Wolf Creek shoreface (Fig. 9.8). Six Viking erosion surfaces are recognized, including VE2, VE3-4, VE3-5, VE3-6, VE3-7 and VE4. Regional successions 1a, 1b and 1c are also shown. Datum is the BFS log marker.

U

Well Log Crc




Cross Section UU'
U'
10-18-54-20W5
10-34-54-20W5
7-36-54-20W5
BFS
Lower Colorado shales
VE3-5
VE2 + VE3-4
VE3-5 + VE4
VE3-4
Ib
Ia
Ic
JOLI FOU FM
MANNVILLE
Top Viking
Base Viking
30 m
0
Wolf Creek Shoreface
NE

facies geometry observed at Sundance and Edson (Fig. 8.10).

Numerous cores penetrate the Bickerdike shoreface deposits (Fig. 1.6). These sediments consist of relatively muddy, sharp based bioturbated sandstones (FA-9), which are thoroughly bioturbated and become sandier upwards. The amount of sandstone increases from 1-5% near the base, up to 25-40% near the top. These deposits become muddier towards the northeast.

9.4 Joarcam Shoreface

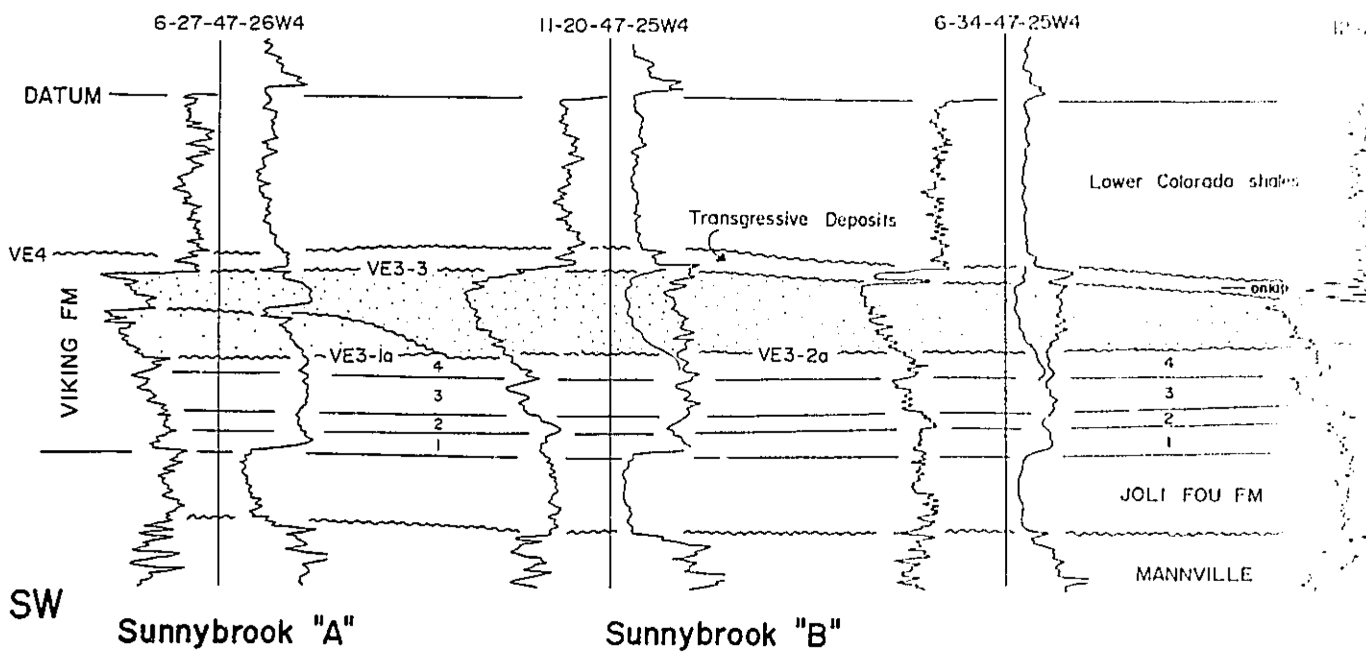
The Joarcam shoreface occurs in the northeastern corner of the study area and is located in T46-51, R20W4-23W4 (Figs 9.1 & 9.2). It can be traced along strike (NW-SE) for up to 45 km and basinward (NE) for at least 6 km. Cross section VV' (Fig. 9.11) speculates on the stratigraphy and sedimentology of the deposits, and Figure 9.12 shows a possible re-interpretation of Power (1987) based on regional correlations between Sunnybrook and Joarcam.

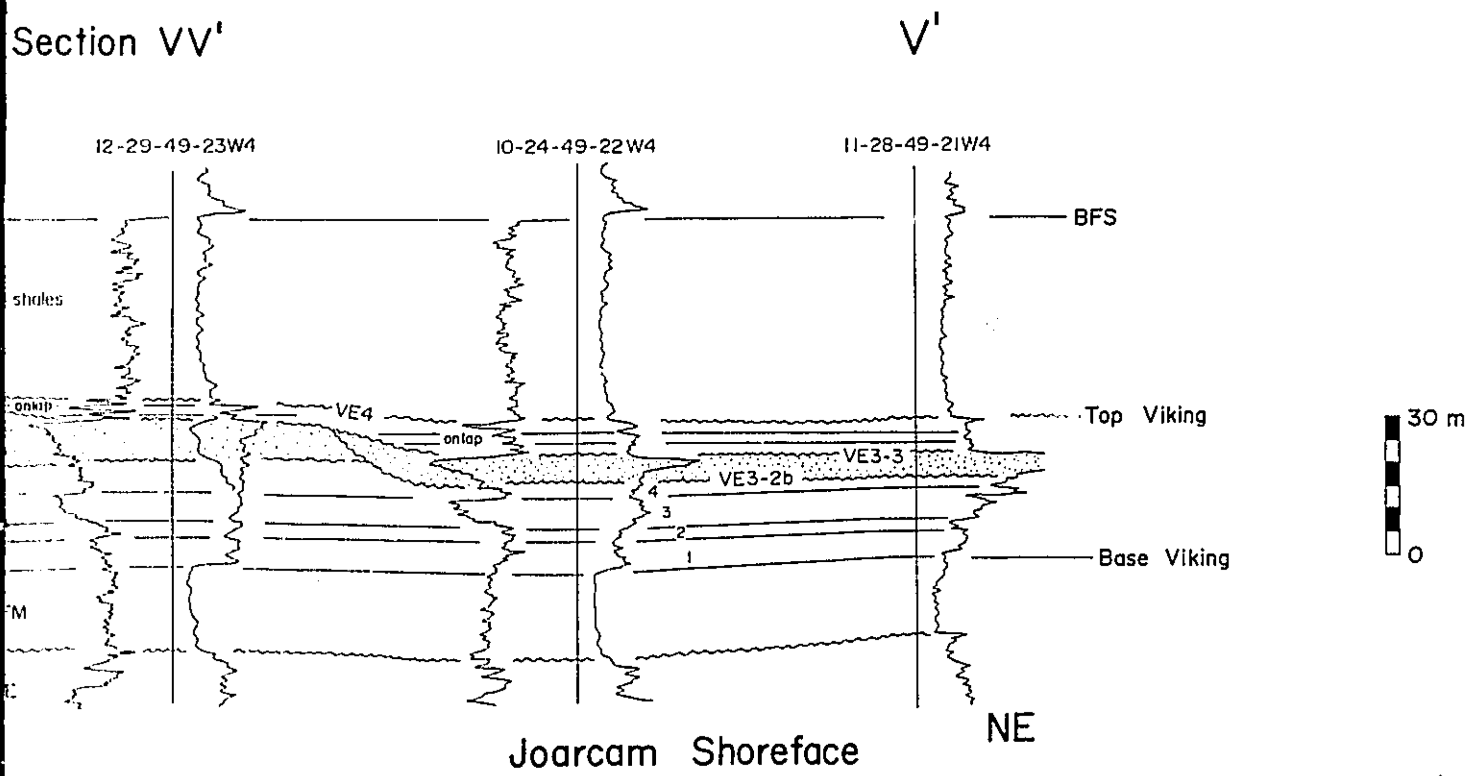
The Joarcam field has produced 1.67×10^7 m^3 (105000 MSTB) of oil and 2.65×10^9 m^3 (93.4 BCF) of gas, up to March 1990 (Alberta Production Report, 1990). Three separate oil and gas reservoirs or sandstones occur at Joarcam, including the Third (base), Main and Upper sandstones (Posamentier & Chamberlain, 1989). Regional correlations show that the Third sandstones are regional succession 2/3 and they consist of thoroughly bioturbated sandy mudstones and muddy sandstones (Figs 9.11 & 9.12). These correlations also show that the Upper sandstones

Figure 9.11. Well log cross section VV'. This cross section is oriented southwest to northeast through the Sunnybrook "A" (light stipple) and "B", and Joarcam (dense stipple) shorefaces (Fig. 9.1). Five Viking erosion surfaces are recognized, including VE3-1a, VE3-2a, VE3-2b, VE3-3 and VE4. Transgressive deposits occur between VE3-3 and VE4, and they onlap towards the southwest onto the VE3-3 erosion surface. Regional successions 1 to 4 are also shown. Datum is the BFS log marker.

V

Well Log Cross Section





Section VV'
V'
12-29-49-23W4
10-24-49-22W4
11-28-49-21W4
BFS
shales
onlap
VE4
onlap
VE3-3
VE3-2b
4
3
2
1
Top Viking
Base Viking
FM
30 m
0
NE
Joarcam Shoreface

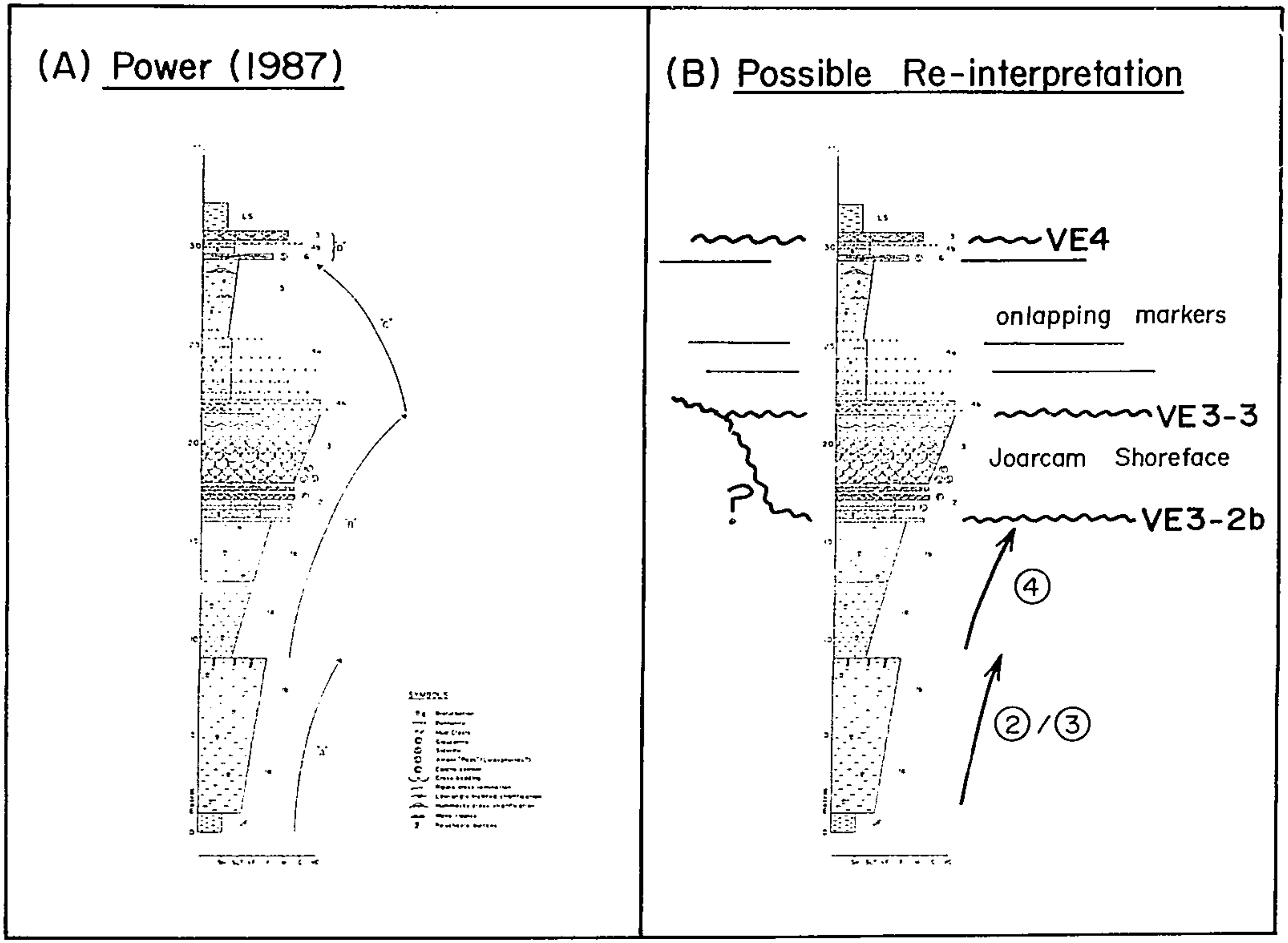
consist of transgressive deposits which onlap onto the VE3-3 erosion surface (top of Joarcam shoreface; Fig. 9.11).

The Main sandstones form a coarsening-upward succession that consists of cross bedded, medium- to coarse-grained pebbly sandstone, interbedded with bioturbated muddy sandstone (Power, 1987, 1988). They are the coarsest sediments observed in the Joarcam field and are 3.0-5.5 m thick (Power, 1987). Regional successions 1, 2/3 and 4 underlie the Main sandstones at Joarcam, and succession 4 is truncated or partly cut out beneath these deposits (Fig. 9.11). The depth of erosion increases basinwards (NE) and is approximately 4-5 m (Fig. 9.11).

Various interpretations have been proposed for the Main sandstones at Joarcam. J.J. Bartlett (pers. comm., 1990) suggests that the coarse deposits might have been transported from a northwestern source by shelf currents and this succession could be a regional coarsening-upward succession. Power (1988) suggests that the Main sandstones are part of a continuous progradational sand wedge that extends from Joffre to Joarcam. Posamentier and Chamberlain (1989) suggest that the Main sandstones represent a lowstand shoreface deposit. The latter two interpretations imply that the shoreline was oriented roughly parallel to the trend of the Joarcam field.

One of the most significant problems in interpreting the Joarcam shoreface deposits is the apparent gradational contact at the base of the Main sandstones. Most of the

Figure 9.12. (A). An idealized facies succession for the Joarcam deposits (Power, 1987). Power (1987) recognized four depositional units labelled "A" to "D". Vertical scale is in meters, grain size scale is shown at the base, and a list of symbols is provided in the bottom right corner. (B). A possible re-interpretation of the Joarcam succession based on a regional correlation of sedimentary rock packages and their bounding erosion surfaces. From top to bottom, the Upper, Main and Third sandstones consist of transgressive, shoreface and regional deposits (successions 2/3 & 4). Three Viking erosion surfaces are recognized, including VE3-2b, VE3-3 and VE4.


(A) Power (1987)
(B) Possible Re-interpretation
VE4
onlapping markers
VE3-3
Joarcam Shoreface
VE3-2b
?
④
②/③

cores studied by Power (1987) show a gradational contact between the underlying sediments of regional succession 4 and the overlying sandstones of the Joarcam shoreface (Power pers. comm, 1989). However, some of the contacts in the western part of the field are relatively sharp in core, and one is also marked by a pebble (Power pers. comm., 1989). A re-examination of some Joarcam shoreface cores will be necessary in order to determine the sharp versus gradational nature of the contact between the Main sandstones and the underlying deposits of regional succession 4.

Posamentier and Chamberlain's (1989) interpretation of the Main sandstones (Joarcam shoreface) is favoured, because (1) the Joarcam shoreface deposits do not correlate with the deposits of a regional coarsening-upward succession (Figs 9.11 & 9.12), and are too coarse-grained to be included in the regional sedimentary package, (2) the abrupt westward pinch-out of the Joarcam shoreface deposits (Fig. 9.11) rules out the continuous sand sheet interpretation of Power (1987, 1988), and (3) sediments of regional succession 4 are partly cut out beneath the Joarcam shoreface (Fig. 9.11).

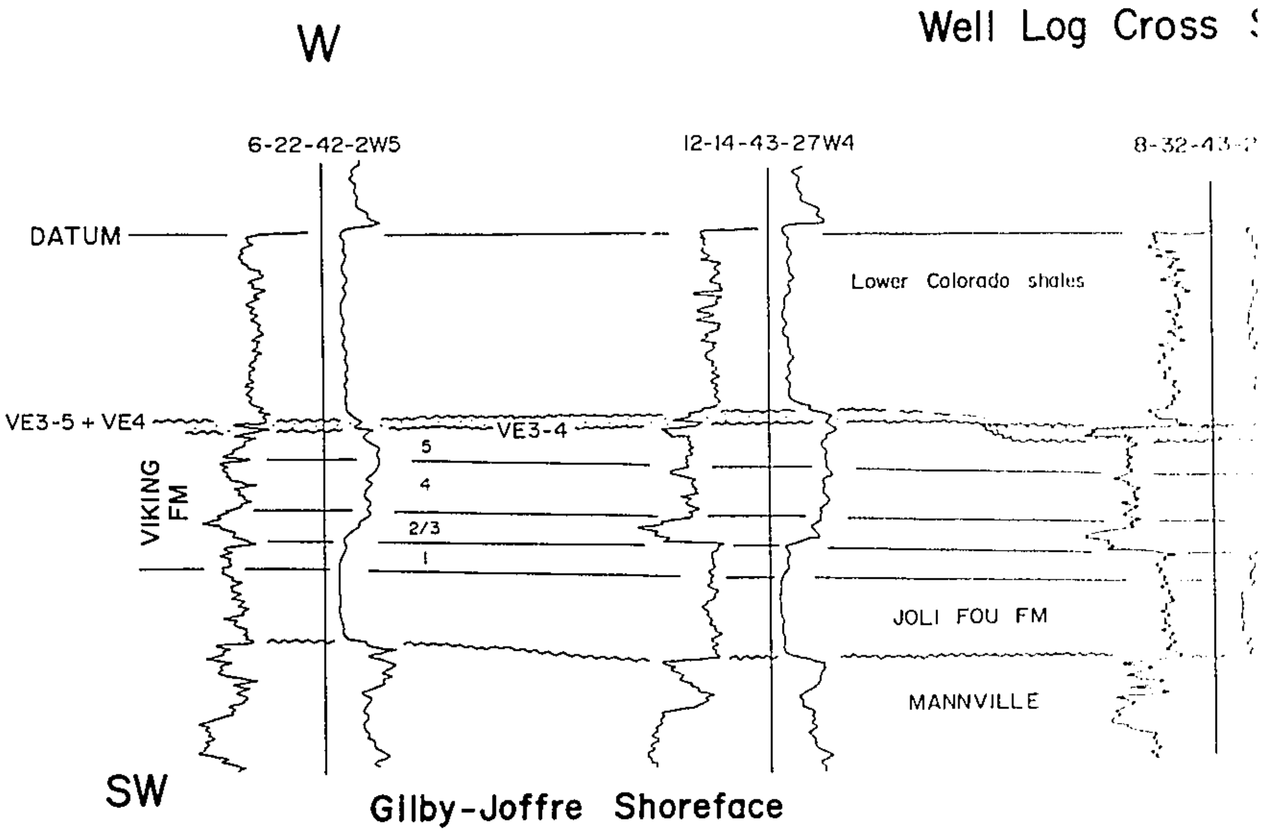
Pattison (1990) previously suggested that the distal deposits of the Sunnybrook (previously named Crystal) shoreface rested stratigraphically on top of the Joarcam shoreface. Pattison (1990) also implied that the Joarcam shoreface deposits were the earliest "VE3" shoreface in the study area. A re-examination of Pattison's (1990) correlations, the construction of a new and expanded set of cross sections, and extensive discussions with H. Posamentier (pers. comm., 1990) suggest that the Joarcam shoreface deposits cut into and are younger than the Sunnybrook shoreface deposits. The Joarcam shoreface deposits have been re-interpreted as lowstand shoreline deposits that are associated with the VE3-2 falling stage incision at Crystal (Fill 2, Figs 6.12 & 6.14; VE3-2b, Figs 9.11 & 9.12). The Sunnybrook "B" shoreface sediments were also deposited during this lowstand (VE3-2a; Figs 9.4 & 9.6). The Joarcam shoreface deposits are coarser than the Sunnybrook "B" deposits, and have a similar grain size to the cross bedded sandstones (FA-6) in fill 2 (Crystal valley; chapter 6).

The base of the Joarcam shoreface is defined as the VE3-2b erosion surface, and the top is defined as the VE3-3 erosion surface (Figs 9.11 & 9.12). Up to 8 m of transgressive deposits rest sharply on top of the Joarcam shoreface, and these deposits onlap landwards (SW) onto the VE3-3 surface (Fig. 9.11).

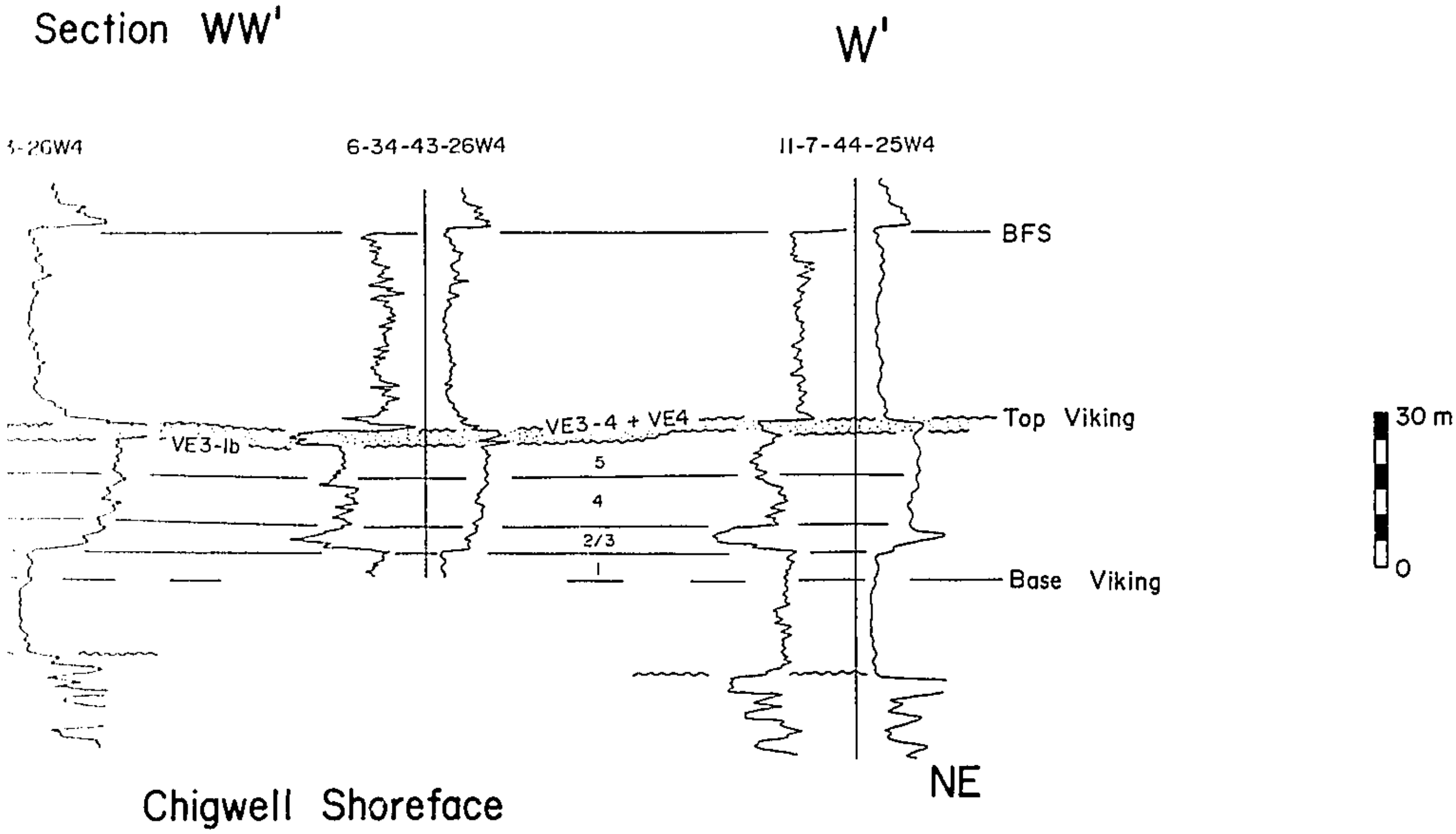
9.5 Chigwell Shoreface

The Chigwell shoreface is located in T41-44/R25W4-27W4, is oriented NW-SE and can be traced along strike for approximately 40 km and basinwards (NE) for approximately 5 km (Fig. 9.1). The maximum thickness of this shoreface is 8 m (Raychaudhuri, 1989), with the thickest deposits occurring in T42. Cross section WW' summarizes the stratigraphy and sedimentology of these deposits (Fig. 9.13). The Chigwell

Figure 9.13. Well log cross section WW'. This cross section consists of five wells and is oriented southwest to northeast through the Gilby-Joffre (light stipple) and Chigwell (dense stipple) shorefaces (Fig. 9.1). Four Viking erosion surfaces are recognized, including VE3-1b, VE3-4, VE3-5 and VE4. Regional successions 1, 2/3, 4 and 5 are also shown. Datum is the BFS log marker.



W
Well Log Cross
6-22-42-2W5
12-14-43-27W4
DATUM
Lower Colorado shales
VE3-5 + VE4
VE3-4
5
4
2/3
1
VIKING FM
JOLI FOU FM
MANNVILLE
SW
Gilby-Joffre Shoreface



Section WW'
W'
-26W4
6-34-43-26W4
11-7-44-25W4
BFS
VE3-4 + VE4
Top Viking
VE3-Ib
5
4
2/3
1
Base Viking
30 m
0
NE
Chigwell Shoreface

field, up to March 1990, has produced 5.14 x 10^5 m^3 (3230 MSTB) of oil and 1.64 x 10^8 m^3 (5.8 BCF) of gas (Alberta Production Report, 1990).

Raychaudhuri (1989) described the Chigwell shoreface deposits as a coarsening-upward succession that passes up from pale sandstones at the base to cross bedded and structureless sandstones at the top. These deposits have a sharp and erosive base, which Raychaudhuri (1989) originally defined as the VE2 erosion surface.

It is extremely difficult to place the Chigwell shoreface deposits in a regional stratigraphic framework. These deposits shale-out towards the E-NE and can not be identified along the western margin of the Sunnybrook "A" shoreface. Also, the Chigwell shoreface deposits are not observed in the Crystal area and therefore can not be placed into a stratigraphic context with the Crystal valley-fill deposits.

The distal deposits of the Gilby-Joffre shoreface rest stratigraphically on top of the Chigwell shoreface which suggests that the Chigwell shoreface is older than Gilby-Joffre shoreface (Fig. 9.13). Therefore, the Chigwell shoreface must have been cut prior to the development of the VE3-4 erosion surface (Gilby-Joffre shoreface scour; section 9.6).

The NW-SE orientation of the Chigwell shoreface suggests that these sediments were deposited during the "VE3" transgression rather than during the "VE2" lowstand.

Prior to the "VE2" lowstand, regional shoreline trends were oriented N-S or NNE-SSW (regional successions 1a, 1b, 2d, 3 & 4; chapter 5). After the "VE2" lowstand, the regional shoreline trends were oriented NW-SE (e.g. Sunnybrook & Joarcam). This suggests that the Chigwell shoreface was deposited during the "VE3" transgression, and as a result, the base of Chigwell is re-defined as a VE3 erosion surface rather than the VE2 erosion surface suggested by Raychaudhuri (1989). Two possibilities exist; either the Chigwell shoreface was deposited during the VE3-1 transgression or it was deposited during the VE3-3/VE3-4 transgression.

The sedimentology of fill 1 at Crystal suggests that the VE3-1 transgression moved the shoreface further landward than the SW margin of the Sunnybrook "A" shoreface (Pattison, 1990). A fan-shaped wedge of interbedded sandstones (FA-5) occurs along the eastern wall of the Crystal valley and these sediments are interpreted as transgressively reworked deposits that were transported through the eastern-arm of the valley during the VE3-1 transgression (Pattison, 1990). If the shoreline were along the Sunnybrook "A" trend, these sandstones would have to be transported approximately 40 km. In contrast, if the shoreline were along the Chigwell trend and this trend extended into the Crystal area, the sandstones of FA-5 would have to be transported approximately 17 km. It seems unlikely that these sediments could have been transported 40 km and, therefore, the shoreline was probably landward of the Sunnybrook "A" trend.

The Chigwell shoreface trend might be the source for the interbedded sandstones (FA-5), assuming that these shoreface deposits extended into the Crystal area during the VE3-1 time interval. Therefore, it is tentatively concluded that the base of the Chigwell shoreface was cut during the VE3-1 transgression rather than the VE3-3/VE3-4 transgression. The base of the Chigwell shoreface is labelled the VE3-1b erosion surface and the top is labelled the VE3-4 erosion surface (Fig. 9.13). The VE3-4 surface can be traced from Chigwell to Gilby-Joffre, where it becomes the base of the Gilby-Joffre shoreface (Fig. 9.13).

9.6 Gilby-Joffre Shoreface

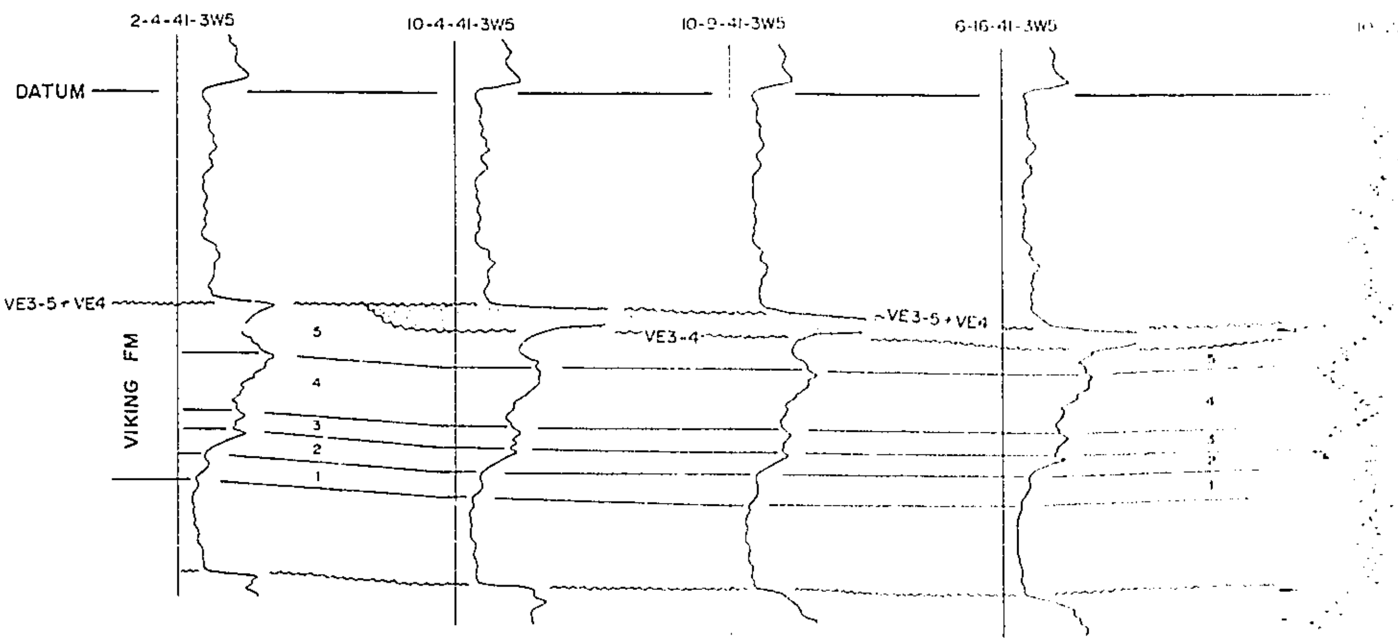
The Gilby-Joffre shoreface is one of the best developed shoreface trends in the Viking and can be recognized over a very wide area (Downing, 1986; Raddysh, 1986; Downing & Walker, 1988; Raddysh, 1988; Boreen, 1990; Boreen & Walker, 1991). It is oriented WNW-ESE, located in T32-43/R17W4-7W5 and can be traced along strike for over 185 km (Fig. 9.1). It can also be traced basinwards where it rests stratigraphically on top of the Chigwell shoreface (Figs 9.13 & 9.14). The maximum thickness of the Gilby-Joffre shoreface deposits is approximately 12 m (Downing, 1986). Cross sections XX' and YY' summarize the stratigraphy and sedimentology of these deposits (Figs 9.14 & 9.15).

The Gilby-Joffre shoreface trend includes the oil and

Figure 9.14. Well log cross section XX'. This cross section consists of 7 wells and is oriented southwest to northeast through the Gilby "A" shoreface (Fig. 9.1). Three Viking erosion surfaces are recognized, including VE3-4, VE3-5 and VE4. Regional successions 1 to 5 are also shown. Datum is the BFS log marker.

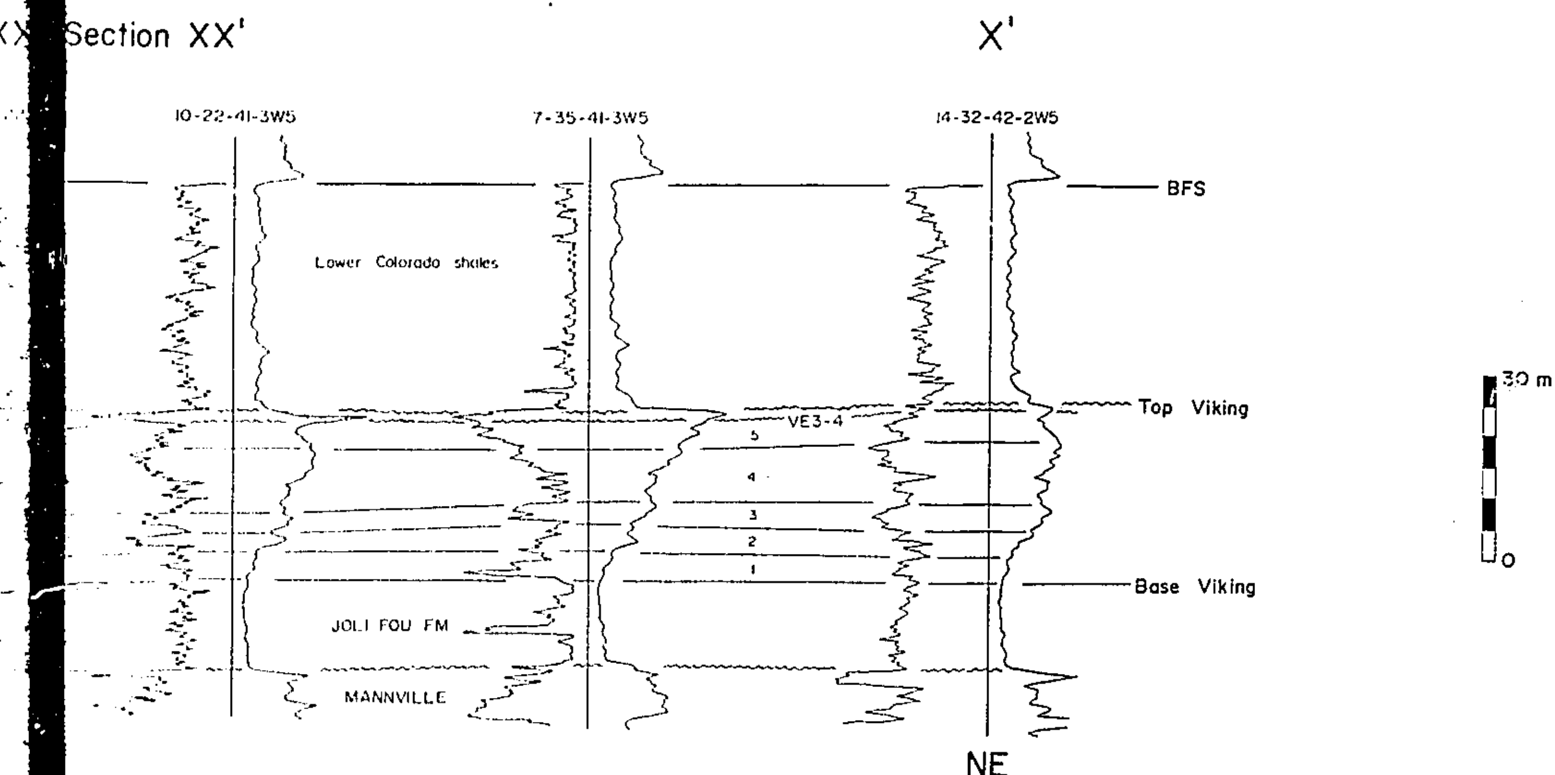
X

Well Log Cross Section XX



SW

Gilby "A" Shoreface


Section XX'
X'
10-22-41-3W5
7-35-41-3W5
14-32-42-2W5
BFS
Lower Colorado shales
Top Viking
VE3-4
5
4
3
2
1
Base Viking
JOLI FOU FM
MANNVILLE
NE
30 m
0

gas fields at Gilby "A" and "B", Joffre, Fenn and Mikwan (Fig. 9.1). These sediments have produced 9.14×10^6 m^3 (57500 MSTB) of oil and 9.95×10^8 m^3 (35.1 BCF) of gas, up to March 1990 (Alberta Production Report, 1990).

Regional well log correlation suggest that the Gilby-Joffre shoreface trend is the southeastward extension of the Wolf Creek shoreface trend (Figs 9.1 & 9.2). The Wolf Creek/Gilby-Joffre shoreface can be traced along strike for approximately 400 km (Fig. 9.1). Also, these deposits can be traced basinwards into the Cyn-Pem area where they rest stratigraphically on top of the Cyn-Pem valley-fill deposits (Figs 7.2, 7.3, 7.4, 9.6 & 9.15), and the Sunnybrook shoreface deposits (Figs 9.6 & 9.15).

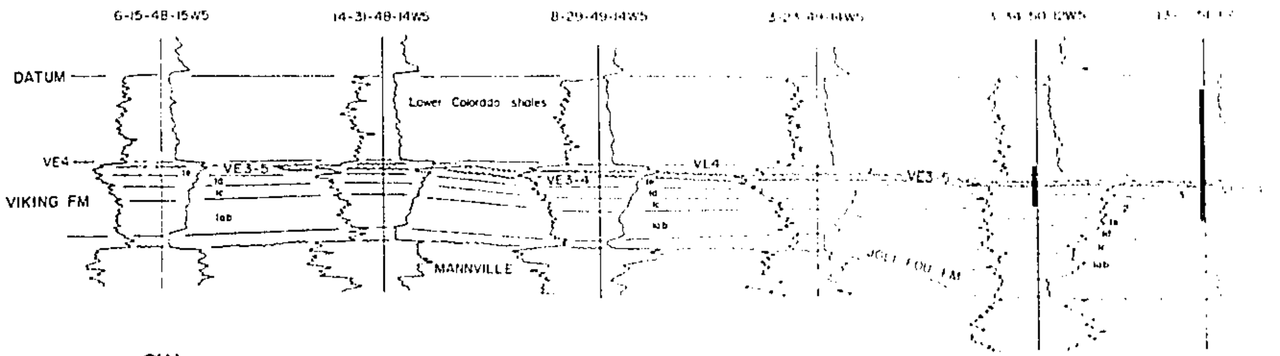
The Gilby-Joffre shoreface deposits are sharp based and consist of a coarsening-upward succession of bioturbated and cross bedded sandstones (Downing & Walker, 1988; Raddysh, 1988). An erosion surface bounds these deposits below and this surface is straight in plan view, asymetrical in cross section (perpendicular to the fields), "open" towards the northeast and has a maximum incision of 11 m (Downing & Walker, 1988). Shoreface deposits are banked up against this "one-sided" shoreface scour (Downing & Walker, 1988; Raddysh, 1988).

Downing and Walker (1988) label the Gilby-Joffre shoreface scour as the E2 bevel, Raddysh (1988) labels this scour as the C marker and Boreen (1990) labels it the VE2 erosion surface. Recent correlations by Boreen and Walker

Figure 9.15. Core and well log cross section YY'. This cross section consists of 11 wells and is oriented southwest to northeast through the Wolf Creek/Gilby-Joffre shoreface (dense stipple) and the Cyn-Pem valley-fill (Fig. 9.1). Four Viking erosion surfaces are recognized, including VE2/3, VE3-4, VE3-5 and VE4. Regional successions 1ab, 1c, 1d, 1e, 2a, 2b and 3 are also shown. Datum for the well log section is the BFS log marker and for the core section is the top of the Viking. Black bars on the well logs indicate core position. Note the thickening of the transgressive deposits towards the northeast.

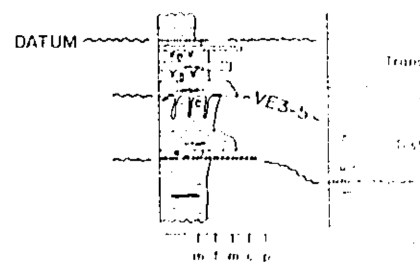
Core & Well

Y

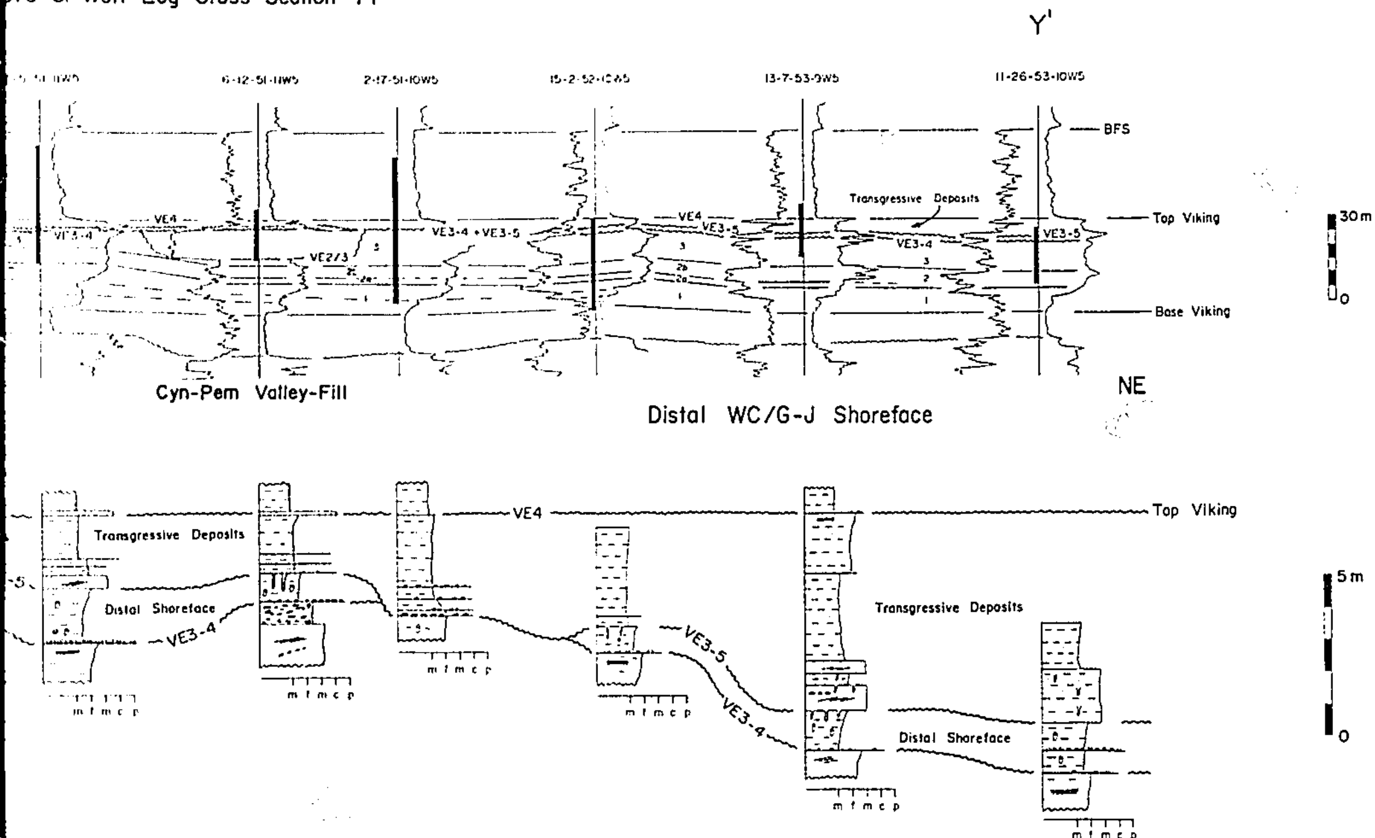


SW

Distal WC/G-J Shoreface



ore & Well Log Cross Section YY'



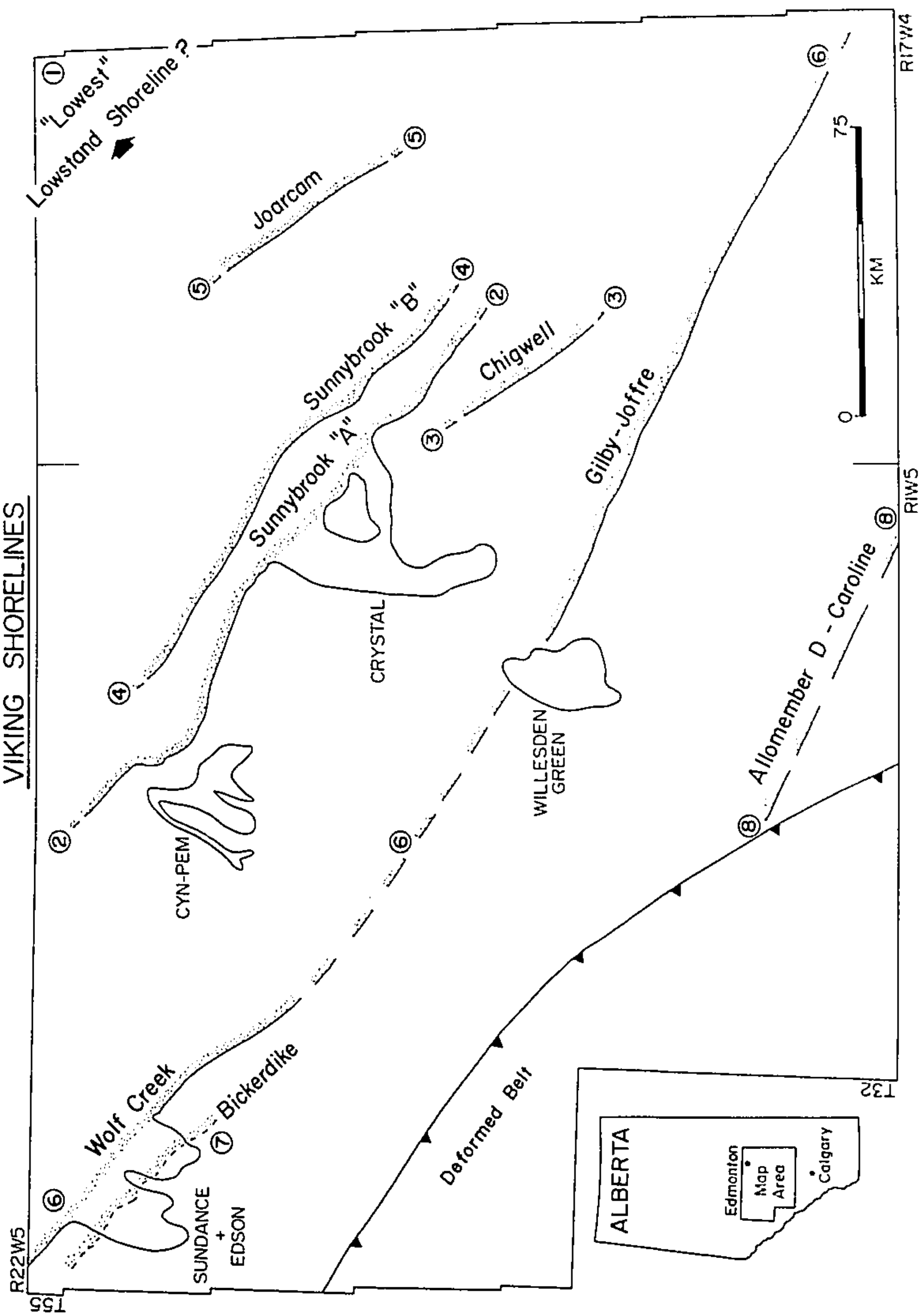
(1991; Fig. 3.1), and the correlations presented in this thesis clearly show that the base of the Gilby-Joffre shoreface was cut during the VE3 transgression and not during the VE2 lowstand. Throughout this thesis, the Gilby-Joffre shoreface scour is defined and labelled as the VE3-4 erosion surface (Figs 9.14 & 9.15). It can be traced basinwards as a transgressive ravinement surface on top of the Crystal and Cyn-Pem valley-fill deposits, and on top of the Chigwell and Sunnybrook (Cyn-Pem area) shoreface deposits (Figs 9.5, 9.13 & 9.15).

The Gilby-Joffre shoreface deposits are bounded by the VE3-5 erosion surface above (Fig. 9.15). Transgressive deposits or distal Caroline-Garrington (Allomember D; Boreen & Walker, 1991) shoreface deposits rest sharply on top of the Gilby-Joffre shoreface. Further to the southwest, these deposits become thicker (up to 18 m) and develop into the hummocky cross stratified, shoreface sandstones of the Caroline, Garrington and Harmattan East area (Davies, 1990; Boreen & Walker, 1991).

9.7 Shoreface Summary

The shoreface sand bodies are oriented NW-SE and are roughly parallel to each other. Seven paleoshoreface trends are recognized, including Joarcam, Sunnybrook "B", Sunnybrook "A", Chigwell, Wolf Creek/Gilby-Joffre, Bickerdike and Caroline-Garrington (Allomember D; Boreen & Walker, 1991; Fig. 9.16). An eighth shoreface trend probably exists basinward of the Joarcam shoreface and

Figure 9.16. Location of the seven paleoshoreface trends recognized in the study area. An eighth trend may occur basinward of Joarcam, and would represent the "lowest" lowstand shoreline. Numbers refer to the sequence of deposition with (1) being the oldest. The Sunnybrook "A" (2), Chigwell (3), Wolf Creek/Gilby-Joffre (6), Bickerdike (7) and Caroline-Garrington (8) shorefaces were deposited during stillstands superimposed onto the "VE3" transgression. The Sunnybrook "B" (4) and Joarcam (5) shorefaces were deposited during lowstand conditions superimposed onto the "VE3" transgression.


VIKING SHORELINES
① "Lowest" Lowstand Shoreline ?
⑤ Joarcam ⑤
④ Sunnybrook "B" ④
② Sunnybrook "A" ②
③ Chigwell ③
⑥ Gilby-Joffre ⑥
⑥ Wolf Creek
⑦ Bickerdike
⑧ Allomember D - Caroline ⑧
CRYSTAL
CYN-PEM
WILLESDEN GREEN
SUNDANCE + EDSON
Deformed Belt
0
75
KM
R22W5
T55
R17W4
R1W5
T32
ALBERTA
Edmonton
Map Area
Calgary

represents the "lowest" lowstand shoreface that was deposited during the VE2 lowstand (Fig. 9.16). H. Posamentier (pers. comm., 1990) suggests that most of central Alberta was subaerially exposed during the VE2 lowstand and therefore the "lowest" lowstand shoreface deposit could be a considerable distance basinward of Joarcam.

The seven paleoshoreface trends occur in three separate areas and therefore can be grouped into three zones, including (1) Chigwell-Sunnybrook-Joarcam, (2) Wolf Creek-Bickerdike-Gilby-Joffre, and (3) Caroline-Garrington. The Crystal and Cyn-Pem valleys are genetically related to the shorefaces in zone (1), and the Sundance, Edson and Willesden Green valleys are genetically related to the shorefaces in zone (2). No valley-fill deposits have been recognized in zone (3).

Regional correlations clearly indicate a transgressive, back-stepping relationship between the three shoreface zones. Zone (1) is the oldest and most basinward, and zone (3) is the youngest and most landward.

Correlations between the different shoreface deposits within zones (1) and (2) reveals further complexity. In zone (1), the four shoreface trends do not form a simple transgressive relationship with Joarcam being the oldest and Chigwell the youngest. Both the Sunnybrook "B" and Joarcam shorefaces have been interpreted as lowstand shorefaces that were deposited during a relative fall in sea level that punctuated the overall "VE3" transgression. Plint (1988) discusses the origin of similar, sharp based lowstand shorelines in the Cardium Formation of Alberta.

In contrast, the Sunnybrook "A" and Chigwell shorefaces of zone (1), and the Wolf Creek/Gilby-Joffre and Bickerdike shorefaces of zone (2) are interpreted as transgressive shoreface deposits that developed during stillstand. These stillstands were superimposed onto the overall "VE3" transgression.

Flemming (1965), McMaster and Garrison (1967), McLennen and McMaster (1971), Sanders and Kumar (1975), Swift (1975) and Carter et al. (1986) describe drowned Holocene shorefaces or shoreface scours on many modern shelves. These deposits or scours are similar to the sharp based, "transgressive" shoreface deposits of the Viking, and were deposited or cut during stillstand conditions that were superimposed on the Holocene transgression.

Similar long and linear, sharp based shoreface deposits occur in the subsurface Cardium Formation of Alberta, the most spectacular of which are the Cardium "B" or Burnstick Member shoreface sand bodies (Pattison, 1987, 1988; Pattison & Walker, 1991). These sand bodies line up to form three shoreface belts that can be traced along strike for up to 375 km (Pattison, 1988; Pattison & Walker, 1991). The three belts form a transgressive or back stepping geometry in cross section similar to the "transgressive" shoreface deposits of the Viking.

In summary, the shoreface sediments of the Viking were deposited during stillstands or minor regressions that were superimposed on the overall "VE3" transgression. Following their deposition, renewed transgression resulted in the drowning of each shoreface trend, and as a result, the upper shoreface and foreshore deposits experienced transgressive ravinement. This produced the sharp based, coarse-grained lag deposit that is observed at the top of each of the Viking shoreface deposits.

9.8 Sequence of Shoreface Deposition

At least seven paleoshoreface trends developed during the "VE2-VE3" Viking time interval. The numbers below refer to the sequence of deposition and correspond with the numbers shown in Figure 9.16.

(1) The "lowest" lowstand shoreline was deposited during the maximum VE2 lowstand. The location of this shoreline is unknown (Fig. 9.16).

(2) The "VE3" transgression began and the shoreline moved towards the southwest. During a stillstand, the Sunnybrook "A" shoreface scour was cut (VE3-1a) and the shoreface sediments were deposited.

(3) A small relative rise in sea level moved the shoreface into the Chigwell area. During an ensuing stillstand, the Chigwell shoreface scour was cut (VE3-1b) and the shoreface sediments were deposited.

(4) A subsequent relative drop in sea level moved the shoreline basinwards (NE). During a stillstand the

Sunnybrook "B" shoreface scour was cut (VE3-2a) and the shoreface sediments were deposited (Fig. 9.16).

(5) A further relative drop in sea level moved the shoreline into the Joarcam area. During a stillstand, the Joarcam shoreface scour was cut (VE3-2b) and the shoreface sediments were deposited.

(6) A subsequent relative rise in sea level moved the shoreface a considerable distance to the southwest of the Crystal valley. During a stillstand, the Wolf Creek/Gilby-Joffre shoreface scour was cut (VE3-4) and the shoreface sediments were deposited.

(7) A small relative rise in sea level moved the shoreline into the Bickerdike area. During a stillstand, the Bickerdike shoreface scour was cut (VE3-6) and the shoreface sediments were deposited (Fig. 9.16).

(8) A further relative rise in sea level moved the shoreline a considerable distance southwest of the Willesden Green valley. This produced the VE3-7 transgressive ravinement surface. During a stillstand, the Caroline-Garrington shoreface deposits (Allomember D; Boreen & Walker, 1991) prograded to the northeast, stratigraphically on top of the VE3-7 erosion surface.

9.9 Transgressive Deposits

The transgressive deposits occur at the stratigraphic top of the Viking Formation and are underlain by regional, valley-fill and shoreface deposits, and are overlain by the Lower Colorado shales. The transgressive deposits are 0.1-

8.0 m thick, discontinuous and are very difficult to correlate on a regional scale. These deposits are bounded by a VE3 erosion surface below and the VE4 erosion surface above (Figs 8.3, 8.4, 8.5, 9.4, 9.5, 9.6, 9.11, 9.12 & 9.15), and consist of interbedded mudstones, sandstones and conglomerates of facies association 10 (Figs 4.29, 4.30, 4.31 & 4.32).

In the Crystal area, the transgressive deposits are relatively thin (0.1-2.0 m) or absent, and consist of interbedded massive conglomerates and striped mudstones. They are bounded by the VE3-4 erosion surface below and by the VE4 erosion surface above (Fig. 6.13). The conglomerates are interpreted as storm deposits that were reworked from the upper part of the valley-fill deposits during the VE3-4 transgression and the mudstones are interpreted as the "background" sediments deposited below fair weather wave base. The VE4 erosion surface truncates the transgressive deposits and is identified by a sharp based, oil-stained, pebbly, coarse-grained cross bedded sandstone bed which has abundant mudstone intra-clasts in the lower 5-10 cm.

To the northeast of Crystal, the transgressive deposits become thicker and are up to 8 m thick in the Joarcam area. They can be correlated as individual markers which onlap the underlying VE3-3 erosion surface (Figs 9.2, 9.4, 9.6, 9.11 & 9.12). Power (1987, 1988) describes these deposits as interbedded mudstones, siltstones and fine- to coarse-grained sandstones. Power (1988) and Posamentier and Chamberlain (1989) interpret these sediments as transgressive, and suggest they were probably reworked from the upper part of the Joarcam shoreface.

In the Cyn-Pem area, the transgressive deposits are thin to absent in T49 but become thicker towards the northeast (T52-53) where they are 4-7 m (Figs 9.6 & 9.15). These deposits onlap the VE3-5 erosion surface (Figs 7.4, 7.5, 9.6 & 9.15) and consist of interbedded mudstones and sandstones.

In the Sundance and Edson area, the transgressive deposits are relatively thin (0.1-3.2 m), discontinuous and patchy, and are difficult to correlate between adjacent wells (Figs 8.3, 8.4 & 8.5). Part of the problem lies in the similarities between the well log signatures of a thin distal shoreface deposit (e.g. Bickerdike, 13-18-54-20W5; Fig. 8.3) and a thin package of transgressive deposits (e.g. 16-7-54-19W5; Fig. 8.3). These deposits are bounded by the VE3-7 erosion surface below and the VE4 erosion surface above.

It is possible that some of the transgressive deposits observed in the study area are distal deposits of the Caroline-Garrington shoreface (Allomember D; Boreen & Walker, 1991). Boreen (1990) has recognized distal Caroline-Garrington shoreface deposits in the Willesden Green area and he describes these sediments as interbedded silty sandstones, bioturbated shales and hummocky cross stratified sandstones. These deposits are up to 10 m thick in the southern part of the Willesden Green area and become considerably thinner towards the north.

In summary, the transgressive deposits occur as thin, discontinuous patches of sediment which rest stratigraphically on top of regional, shoreface and valley-fill deposits. They are bounded below by the VE3-3, VE3-4, VE3-5 or VE3-7 erosion surface, and above by the VE4 erosion surface. In some areas, these deposits form significant oil and gas reservoirs, such as the Upper sandstones at Joarcam (Posamentier & Chamberlain, 1989) and the pebble stringers at Harmattan East (S. Hadley, pers. comm., 1989).

CHAPTER 10 - REGIONAL GEOLOGICAL HISTORY

The bulk of this thesis has concentrated on a description and interpretation of the sedimentology and allostratigraphy of the Viking sediments. Each depositional and erosional event has been related to a relative rise or fall in sea level; thus producing a relative sea level curve for the Viking. Regional sediments were discussed in chapter 5, valley-fill sediments were discussed in chapters 6-8, and shoreface and transgressive deposits were discussed in chapter 9. Most of this chapter will describe and interpret the regional geological history by combining the results of the previous five chapters.

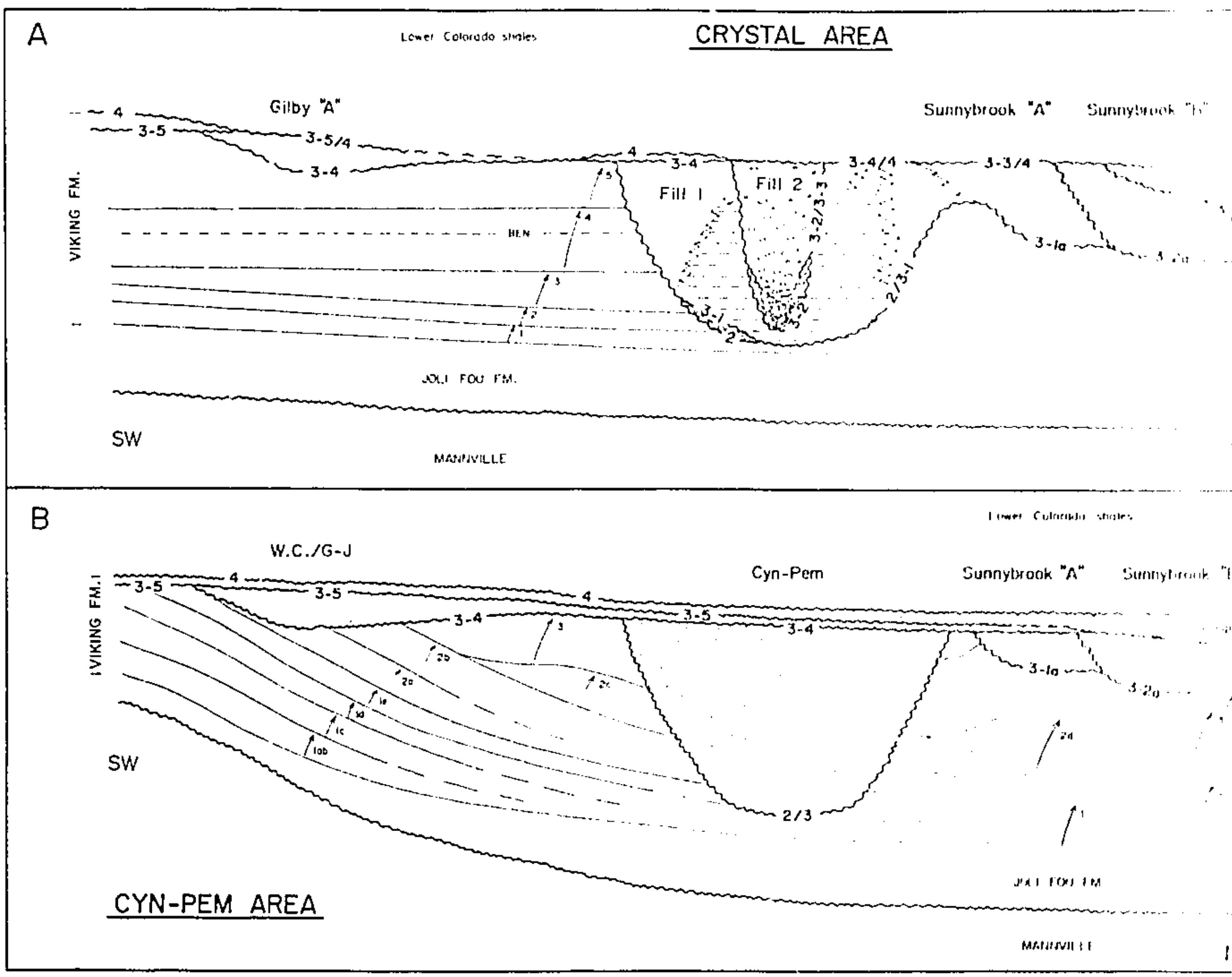
The remainder of this chapter will briefly examine the timing and magnitude of the relative fluctuations in sea level, and will also examine the possible controlling mechanisms that produced these fluctuations. The application of sequence stratigraphy will also be briefly discussed.

10.1 Regional Correlations

The allostratigraphy (Fig. 10.1) and relative sea level curve (Fig. 10.2) for the Viking Formation have been developed by studying the sedimentology and stratigraphy of these deposits from Sundance to Crystal. This work has benefitted from studies of the individual fields done by Downing and Walker (1988), Raddysh (1988), Power (1988), Raychaudhuri (1989), Boreen (1990) and Davies (1990). The

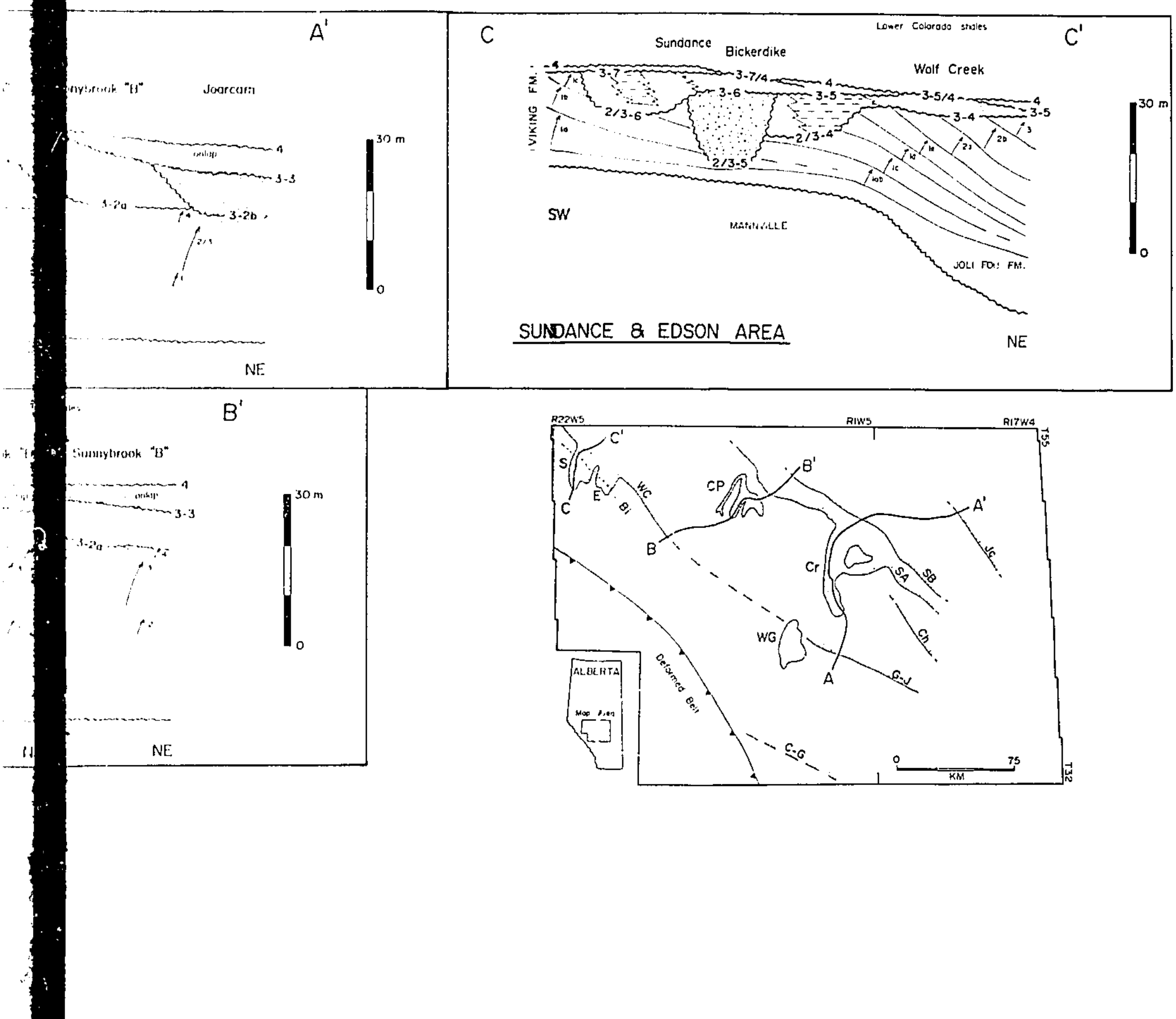
Figure 10.1. Allostratigraphy of the Viking Formation. Three schematic cross sections summarize the allostratigraphy in the Crystal (AA'), Cyn-Pem (BB'), and Sundance and Edson (CC') areas. Approximate location of the cross sections is shown in the lower right. Nine Viking erosion surfaces (VE2, VE3-1, VE3-2, VE3-3, VE3-4, VE3-5, VE3-6, VE3-7 & VE4), 12 regional parasequences (1a to 5), three valley-fill deposits, six shoreface deposits and transgressive deposits (onlap) are shown.

VIK



A
Lower Colorado shales
CRYSTAL AREA
Gilby "A"
Sunnybrook "A"
VIKING FM.
Fill 1
Fill 2
BEN
JOLI FOU FM.
SW
MANNVILLE
B
Lower Colorado shales
W.C./G-J
Cyn-Pem
Sunnybrook "A"
VIKING FM.
SW
JOLI FOU FM.
CYN-PEM AREA
MANNVILLE

VIKING FORMATION ALLOSTRATIGRAPHY



allostratigraphy is based on the preliminary Viking allostratigraphy developed by Boreen and Walker (1991; Fig. 3.1).

10.1.1 Regional CU Successions

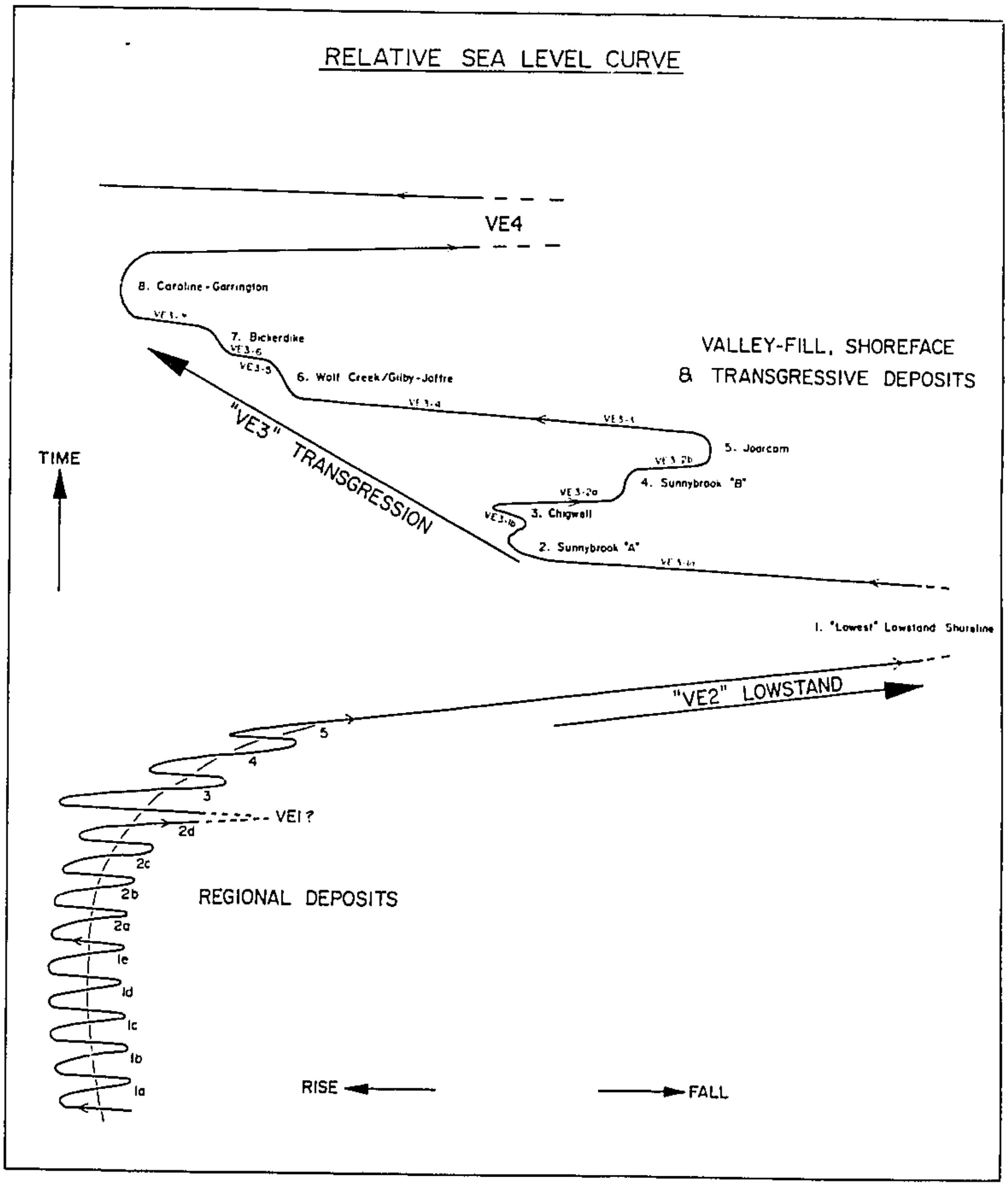
The stack of regional coarsening-upward successions forms a progradational parasequence set that has a gradational contact with the Joli Fou mudstones below, and a sharp and erosive contact with the valley-fill, shoreface or transgressive deposits above (chapter 5). This upper contact consists of the VE2, VE3 or VE4 erosion surface (Fig. 10.1).

There is little evidence of internal erosion within the parasequence set, except for the possible occurrence of the VE1 erosion surface at the top of regional succession 2 (A.D. Reynolds pers. comm., 1989). Each parasequence or coarsening-upward succession is capped by a marine flooding surface.

Most successions become thicker and sandier towards the west or northwest, implying a N-S or NNE-SSW oriented shoreline trend. This orientation is oblique to the NW-SE trending shoreface deposits that rest stratigraphically on top of the VE3 erosion surface (e.g. Gilby-Joffre shoreface; Downing & Walker, 1988).

The regional parasequences offlap towards the east and are interpreted as "highstand" deposits (Figs 10.1 & 10.2). Small relative falls in sea level may have enhanced the progradation of these deposits. These are balanced by

Figure 10.2. Relative sea level curve for the Viking. The curve can be divided into three main parts; the "early" Viking highstand, the "VE2" lowstand and the "VE3" transgression. The timing of the erosion surface development and deposition of the shoreline trends are shown. The reader is referred to Figures 6.14 (Crystal), 7.5 (Cyn-Pem) and 8.11 (Sundance & Edson) for the timing of valley-fill deposition.


RELATIVE SEA LEVEL CURVE
VE4
8. Caroline - Garrington
7. Bickerdike
VE3-6
VE3-5
6. Wolf Creek/Gilby-Joffre
VE3-4
VALLEY-FILL, SHOREFACE
& TRANSGRESSIVE DEPOSITS
5. Joarcam
VE3-2a
4. Sunnybrook "B"
3. Chigwell
2. Sunnybrook "A"
"VE3" TRANSGRESSION
TIME
1. "Lowest" Lowstand Shoreline
"VE2" LOWSTAND
5
4
3
VE1 ?
2d
2c
2b
2a
1e
1d
1c
1b
1a
REGIONAL DEPOSITS
RISE
FALL

equally small relative rises in sea level that triggered the development of the marine flooding surfaces (Fig. 10.2).

10.1.2 VE2 - Relative Fall in Sea Level

The VE2 erosion surface occurs at the base of each Viking valley-fill deposit and also forms the base of the "lowest" lowstand shoreface deposit (Figs 9.16 & 10.1). This surface was cut during a major relative fall in sea level, which is informally called the "VE2" lowstand (Fig. 10.2).

Valleys are cut during relative falls in sea level when the equilibrium profile of a stream shifts downward (Posamentier & Vail, 1988). In a basin with a shelf-break, valleys are most likely to incise at or near the position of the shelf-break. In a basin with no shelf-break, such as the Alberta Foreland basin, valley incision may occur along any point that is not in equilibrium with the "new" stream profile (Posamentier & Vail, 1988). Underlying basement topography or faulting may produce the necessary surface irregularities required to initiate the incision. This incision begins at a knickpoint and is translated landward by headward erosion (Posamentier & Vail, 1988). At Crystal, the knickpoint migrated southwards to township 43.

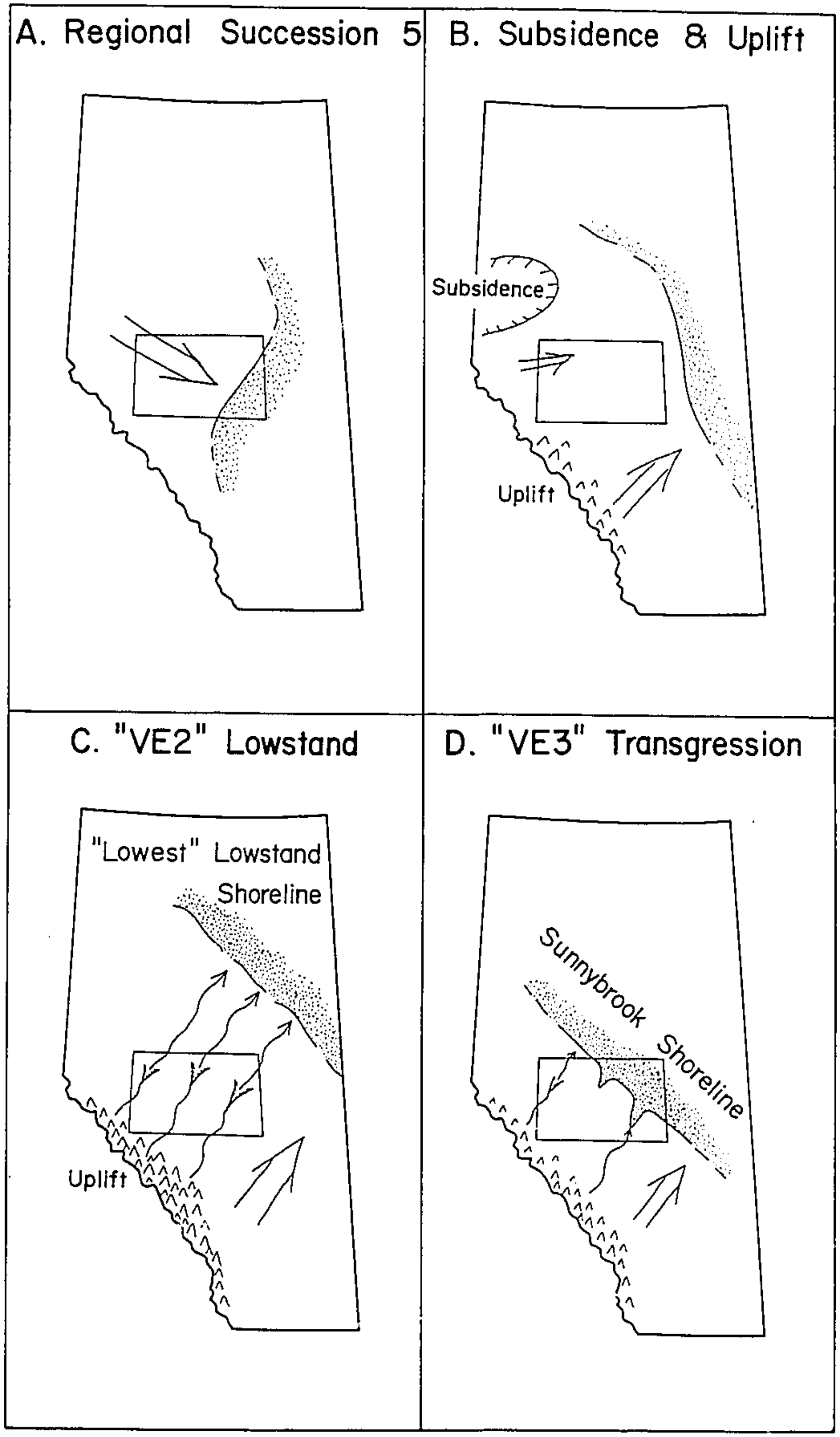
Little sedimentation occurs in an incised valley during the initial stages of lowstand because the sediments bypass the valley and are deposited as a lowstand wedge farther basinward (Posamentier & Vail, 1988; Van Wagoner et al., 1990). A thin basal lag deposit (fluvial sandstones and conglomerates) at Crystal is the only sedimentological record of the "VE2" lowstand in any of the Viking valleys.

The shape of the Alberta Foreland basin must have changed at sometime between the deposition of the regional coarsening-upward successions and the cutting of the VE2 erosion surface. Viking shoreline trends were oriented N-S or NNE-SSW (section 10.1.1) prior to the "VE2" lowstand, and NW-SE after the lowstand (Fig. 10.3).

Chamberlain et al. (1989) document a northwestward increase in the rate of subsidence in the Alberta Foreland basin during the Late Albian. In the northwest, the calculated subsidence rate was 8.5 cm/1000 yrs compared with a rate of 4.5 cm/1000 yrs in southwestern Alberta. Also, Leckie et al. (1990) and O'Connell et al. (1990) suggest that the Peace River Arch (Fig. 1.3) was subsiding during the Albian. These studies indicate that northwestern Alberta had a higher rate of subsidence than southwestern Alberta during the time of Viking deposition (Fig. 10.3). The differential subsidence of the basin may partially account for the re-orientation of the Viking shoreline trends.

Arnott (1988) discusses evidence for Late Albian tectonic activity in western Montana and southern Alberta, including bentonite-rich lithologies, extrusion of Crowsnest volcanics and intrusion of the Coast Plutonic and Idaho Batholith complexes. Arnott (1988) concludes that the tectonic activity in the Cordillera is closely related to

Figure 10.3. Paleogeography of the Alberta Foreland basin during the Late Albian. (A) Orientation (NNE-SSW) of the regional shoreline trends associated with parasequences 1a to 5. Sediment supply is mainly from the west (arrow). (B) Basinward movement of the shoreline during the early phase of the "VE2" lowstand. A greater rate of subsidence in the NW, coupled with uplift in the SW changes the orientation of the shoreline. (C) Possible "lowest" lowstand shoreline position. Continued uplift in the SW triggers the incision of the valleys and shifts the sediment supply from the west to the southwest (arrows). (D) Early stages of the "VE3" transgression. Orientation of the shoreline trend is NW-SE and the valleys begin to fill.


A. Regional Succession 5
B. Subsidence & Uplift
Subsidence
Uplift
C. "VE2" Lowstand
"Lowest" Lowstand
Shoreline
Uplift
D. "VE3" Transgression
Sunnybrook Shoreline

tectonic uplift and subsidence of the Sweetgrass Arch, and that the cyclicity of the regressive-transgressive couplets is related to these tectonic movements.

Uplift in the southwest during "early" Viking time may have enhanced the differential subsidence trend of the Alberta Foreland basin and, therefore, would contribute to the re-orientation of the Viking shorelines (Fig. 10.3).

Jordan et al. (1988) suggest that the first occurrence of conglomerates in a foreland basin may be directly linked to uplift caused by thrust sheet unloading. Coarse-grained sandstones and conglomerates are rare to absent beneath the VE2 erosion surface, but are abundant above the VE2 erosion surface. Therefore, it is possible that the re-orientation of the Viking shoreline trends, the incision of the VE2 erosion surface and the influx of conglomerates into the basin may be related to uplift in the southwest (Fig. 10.3).

It is probable that the unconformity at the base of the Crystal valley, and hence the "VE2" lowstand incision, is time correlative with the 98 Ma eustatic fall of sea level (Haq et al., 1988; Reinson et al., 1988). Incised valley-fill deposits are observed in correlative strata in the U.S., including the Muddy and J sandstones of the Denver Basin (Harms, 1966; Stone, 1972; Dresser, 1974; Weimer, 1983, 1984, 1988; Vuke, 1984; Aubrey, 1989). Reinson et al. (1988) suggest that the Viking valleys were cut at the same time as the Muddy valleys.

10.1.3 VE3 - Relative Rise in Sea Level

The VE3 erosion surface was cut during an overall transgression that followed the "VE2" lowstand. This transgression was punctuated by stillstands and a minor regression, and is informally called the "VE3" transgression (Figs 10.1 & 10.2). Regional correlations have led to the subdivision of the VE3 erosion surface into seven smaller surfaces, labelled VE3-1 to VE3-7.

VE3-1

The VE3-1 erosion surface is the oldest part of the VE3 surface recognized in the study area (Figs 10.1 & 10.2). This surface occurs at the base of the Crystal and Cyn-Pem valleys, and is usually coplanar with the VE2 erosion surface (Fig. 10.1). The VE3-1 erosion surface is a transgressive "modification" surface because it modifies the pre-existing geometry of the initial VE2 lowstand incision. This surface was probably cut by wave and/or tidal scour during the early stages of transgression. Fill 1 at Crystal was deposited after the cutting of the VE3-1 erosion surface, but before the cutting of the VE3-2 erosion surface.

The VE3-1 erosion surface also occurs at the base of the Sunnybrook "A" (VE3-1a) and Chigwell (VE3-1b) shoreface deposits (Fig. 10.1). The correlation of the VE3-1 erosion surface from Crystal to Sunnybrook "A", the inferred gradational lateral contacts between the northern sediments of fill 1 (FA-3) and the sediments of Sunnybrook "A" (FA-9), and the proximity of the Sunnybrook "A" shoreface to the mouth of the Crystal valley all suggest that the fill 1 and Sunnybrook shoreface deposits are genetically related. The Sunnybrook "A" shoreface sediments were deposited after the cutting of the VE3-1a erosion surface, but before the development of the VE3-2 erosion surface.

The VE3-1b erosion surface occurs at the base of the Chigwell shoreface and is tentatively related to the VE3-1 transgression (section 9.5). The VE3-1b surface was probably cut during the maximum landward translation of the shoreline during VE3-1 "time". Therefore, the Chigwell shoreface is younger than the Sunnybrook "A" shoreface.

VE3-2

The VE3-2 erosion surface was cut during a relative fall in sea level that punctuated the overall "VE3" transgression, and is observed at the base of fill 2 in the Crystal valley (Figs 10.1 & 10.2). Most of the fluvial conglomerates (FA-8) at Crystal were deposited during or shortly after the cutting of the VE3-2 surface.

The VE3-2 erosion surface also occurs at the base of the Sunnybrook "B" (VE3-2a) and Joarcam (VE3-2b) shorefaces (Fig. 10.1). These shoreface deposits form a regressive package of sediments and also record a basinward shift in facies. Joarcam is the younger of the two shorefaces and probably represents the maximum basinward translation of the shoreline during the VE3-2 relative fall in sea level (Figs 10.1 & 10.2).

The VE3-2 surface can not be physically traced between the Crystal valley, and the Sunnybrook "B" and Joarcam shorefaces (Fig. 10.1). However, the similar basinward shift of valley and shoreface facies, and the correlative strata above and below suggest that the erosion surface at the base of fill 2 is time equivalent to the erosion surface at the base of Sunnybrook "B" and Joarcam. If so, the sediments of fill 2 are probably genetically related to the sediments of the Joarcam and Sunnybrook "B" shorefaces (Fig. 10.1).

VE3-3 & VE3-4

The VE3-3 and VE3-4 erosion surfaces were cut during the relative rise in sea level that followed the "VE3-2" lowstand (Fig. 10.2). These erosion surfaces occur as transgressive ravinement surfaces on top of the regional, valley-fill and shoreface deposits, and as transgressive modification surfaces within the valley-fill deposits (Fig. 10.1). Technically, these two surfaces could be described as one erosion surface because they are genetically related to the same relative rise in sea level. However, they occur at two separate stratigraphic horizons in the Crystal valley and therefore define two different erosive events (Fig. 10.1).

The VE3-3 erosion surface rests stratigraphically on top of the Sunnybrook and Joarcam shoreface deposits, forming a transgressive ravinement surface basinward of Crystal (Fig. 10.1). At Crystal, this surface separates the lowstand fluvial deposits (FA-8) from the overlying transgressive deposits (FA-3 & FA-6; Fig. 10.1) in fill 2, forming a transgressive modification surface within the Crystal valley-fill deposits. The transgressive sediments of fill 2 (FA-3 & FA-6) were deposited during the time between the cutting of the VE3-3 and VE3-4 erosion surfaces.

The VE3-4 erosion surface rests stratigraphically on top of the Crystal (fills 1 & 2) and Cyn-Pem valley-fill deposits (Fig. 10.1), and can be traced southwards into the Wolf Creek/Gilby-Joffre shoreface area (Fig. 10.1). The VE3-4 erosion surface forms a transgressive ravinement surface between the distal edge of the Wolf Creek/Gilby-Joffre shoreface and the landward edge of the Sunnybrook "A" shoreface (Fig. 10.1). South of this area, the VE3-4 erosion surface forms the asymmetrical incised shoreface scour of the Wolf Creek/Gilby-Joffre trend (Fig. 10.1), and the transgressive modification surface in the northeastern part of the Sundance and Edson valley-fill complex (Fig. 10.1). The Wolf Creek/Gilby-Joffre shoreface sediments were deposited during stillstand conditions that followed the VE3-3/VE3-4 relative rise in sea level (Fig. 10.2).

VE3-5 & VE3-6

The VE3-5 and VE3-6 erosion surfaces were cut during the relative rise in sea level that moved the shoreline from Wolf Creek to Bickerdike (Figs 10.1 & 10.2). These erosion surfaces occur at two different stratigraphic horizons in the Sundance and Edson valley-fill complex.

The VE3-5 erosion surface rests stratigraphically on top of the Wolf Creek/Gilby-Joffre shoreface and northeastern Sundance and Edson valley-fill deposits, forming a transgressive ravinement surface (Fig. 10.1). This surface also forms the deep tidal scours (tidal inlets) in the Sundance and Edson valley-fill complex (Fig. 10.1). The northeastern tripartite valley-fill and Wolf Creek shoreface sediments were deposited after the cutting of the VE3-4 surface, but before the cutting of the VE3-5 surface.

The VE3-6 erosion surface rests stratigraphically on top of the tidal inlet deposits and can be traced southwards into the Bickerdike area (Fig. 10.1). This surface forms a transgressive ravinement surface on top of the tidal inlet deposits, and also forms the incised shoreface scour at the base of the Bickerdike shoreface (Fig. 10.1). Furthermore, the VE3-6 erosion surface forms a transgressive modification surface in the southwestern part of the Sundance and Edson valley-fill complex (Fig. 10.1). This erosion surface was cut during the same relative rise in sea level that lead to the cutting of the VE3-5 surface (Fig. 10.2).

The tidal inlet sediments were deposited after the cutting of the VE3-5 surface, but before the cutting of the VE3-6 surface. In contrast, the southwestern tripartite valley-fill and Bickerdike shoreface sediments were deposited after the cutting of the VE3-6 surface, but before the cutting of the VE3-7 surface.

VE3-7

The VE3-7 erosion surface is the youngest part of the VE3 surface observed in the study area and is defined as the transgressive ravinement surface which rests stratigraphically on top of the SW tripartite valley-fill and Bickerdike shoreface deposits (Fig. 10.1). It was cut during the relative rise in sea level that moved the shoreline from the Bickerdike to the Caroline-Garrington trend (Fig. 10.2).

Regional correlations suggest that the VE3-7 erosion surface forms the base of Allomember D (Fig. 3.1). This surface can be traced over a very wide area of central Alberta, forming one of the most laterally extensive transgressive ravinement surfaces of the Viking.

10.1.4 VE4 - Top of Viking

The VE4 erosion surface rests stratigraphically on top of the regional, valley-fill, shoreface and transgressive deposits, and is the uppermost erosion surface in the Viking Formation (Fig. 10.1). It has a relatively flat and smooth topography basinward of Willesden Green, but has a stepped and undulating topography landward of Willesden Green (Boreen & Walker, 1991). The VE4 erosion surface was cut during a relative fall in sea level, and was extensively modified topographically during the ensuing rise (Fig. 10.2).

10.2 Sea Level Changes - Timing, Magnitude & Controls

This section will briefly examine the timing and magnitude of the relative fluctuations in sea level that influenced the stratigraphy and sedimentology of the Viking Formation, and their possible controlling mechanisms.

The regional deposits of the Viking consist of 12 regressive-transgressive, coarsening-upward parasequences (1a to 5). The shoreface and valley-fill deposits of the Viking can be grouped into 7 regressive-transgressive successions which are loosely interpreted as "parasequences", including (from northeast to southwest) (1) Joarcam & Fill 2 (Crystal), (2) Sunnybrook "B" & Fill 2, (3) Sunnybrook "A" & Fill 1, (4) Chigwell & Fill 1, (5) Wolf Creek/Gilby-Joffre & NE Sundance/Edson, (6) Bickerdike & SW Sundance/Edson, and (7) Caroline-Garrington. Therefore, the sediments of the Viking consist of 19 regressive-transgressive parasequences.

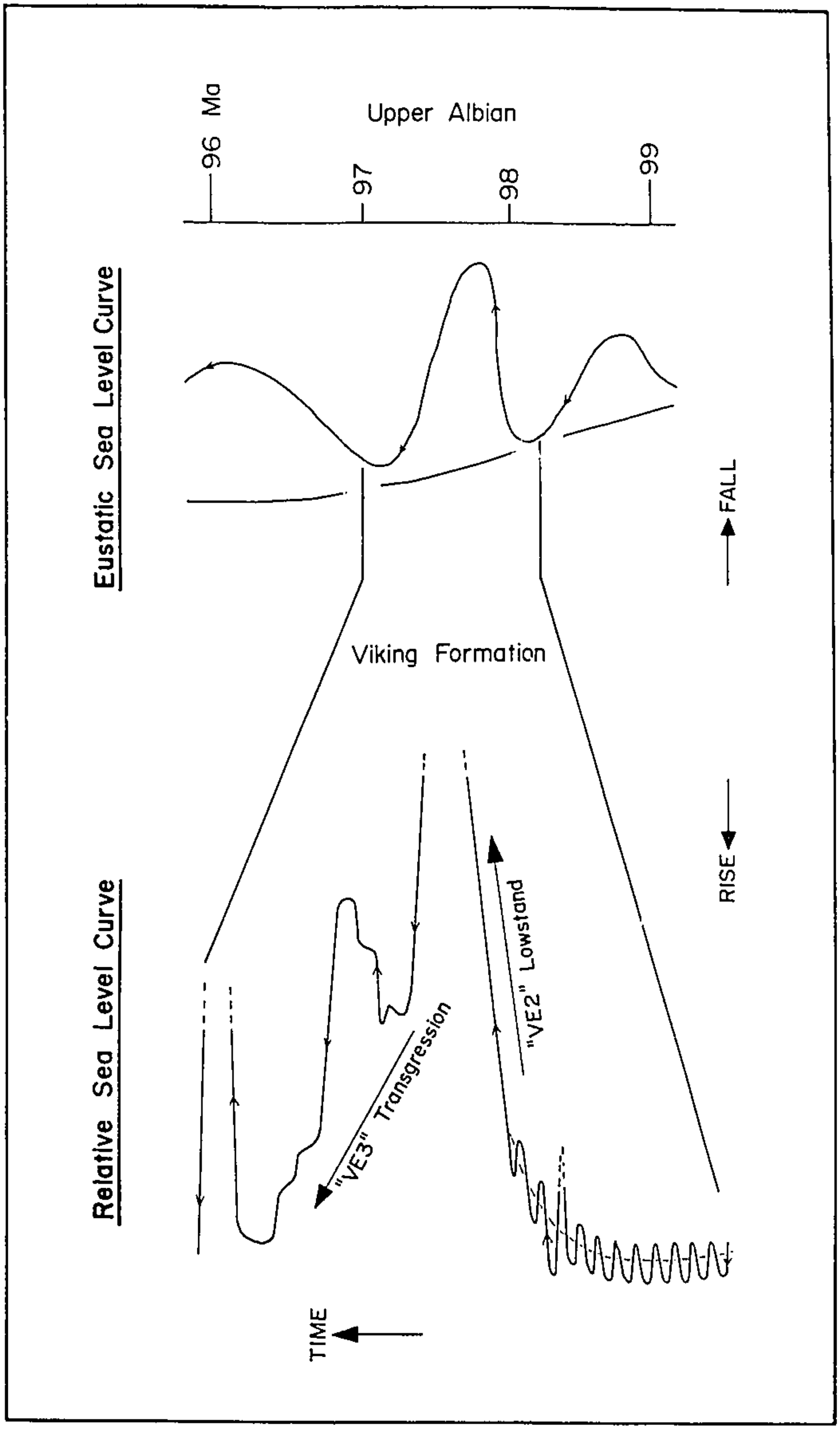
10.2.1 Timing

The first step in calculating the duration of each parasequence is to determine the absolute duration of the Viking Formation. There are three problems. First, there are no published values of the absolute duration of the Viking, except for the 1-2 million year estimate of Power (1988). Second, the biostratigraphic control in the Viking is very poor (section 1.2.2) because of a large gap in the molluscan assemblages and a lack of foraminifera (Koke & Stelck, 1985; Stelck & Koke, 1987). Third, little chronostratigraphic work has been done on the Viking. Tizzard and Lerbekmo (1975) have dated regional bentonites at 100 Ma ± 2 Ma, and provide the only published radiometric date for the Viking Formation.

The Albian - Cenomanian boundary is defined at 96 Ma (Haq et al., 1987, 1988), and is coincident with the BFS log marker or the top of the Lower Colorado shales (Stelck & Koke, 1987). The base of the Upper Albian is defined at 99 Ma (Haq et al., 1987, 1988), and is coincident with the base of the Joli Fou Formation (Stelck & Koke, 1987). Therefore, the absolute duration of the Upper Albian or the Joli Fou to Lower Colorado shales stratigraphic interval is 3 million years. This suggests that the Viking Formation is part of a third-order depositional cycle (1-5 m.y.), as defined by Van Wagoner (1990).

A simple, three-way division of the Upper Albian interval would suggest that the Viking spans a 1 million year time interval. This provides a crude estimate of the absolute age of the Viking, which can be further refined by comparing the eustatic and relative sea level curves for the Upper Albian (Fig. 10.4). The curves show a significant degree of similarity (third-order scale), including (1) the highstand preceding the 98 Ma eustatic fall and the highstand associated with regional Viking deposition, (2) the 98 Ma eustatic fall and the "VE2" lowstand, and (3) the 97-98 Ma eustatic rise and the "VE3" transgression (Fig. 10.4). Using the time scale provided by Haq et al. (1988), and the correlation of the relative and eustatic sea level curves (Fig. 10.4), the absolute duration of the Viking has

Figure 10.4. Correlation of the relative and eustatic sea level curves. The eustatic curve and absolute time scale are from Haq et al. (1988). Note the remarkable similarity between the third-order eustatic fall and rise of sea level, and the "overall" third-order relative fall and rise of sea level. Absolute duration of the Viking is estimated at 1.2 million years.


Upper Albian
96 Ma
97
98
99
Eustatic Sea Level Curve
FALL
RISE
Viking Formation
Relative Sea Level Curve
"VE3" Transgression
"VE2" Lowstand
TIME

been estimated at 1.2 million years.

The Viking Formation can be subdivided into 19 parasequences (12 regional and 7 "VE3") and one major lowstand (VE2). A significant amount of time must have elapsed between the deposition of regional succession 5 and the Sunnybrook "A" shoreface. During this time, the trend of the Viking shorelines was re-oriented, valleys were incised and a lowstand wedge was deposited basinward of Joarcam (Figs 10.2 & 10.3). The 98 Ma eustatic drop in sea level, differential subsidence and uplift in southwestern Alberta combined to trigger the aforementioned events (section 10.1.2). It is impossible to determine the duration of the "VE2" lowstand.

The 1.2 Ma duration of the Viking is loosely subdivided into 19 regressive-transgressive events (parasequences), each of which has an approximate 63,000 year duration. This assumes that each parasequence was deposited and bounded in an equal period of time. Leckie (1986b) and Plint (in press) suggest that two thirds of the time allotted to a regressive-transgressive cycle should be assigned to the regressive phase (deposition), while one third of the time should be assigned to the transgressive phase (erosion). Using this approach, each Viking parasequence must have been deposited in approximately 42,000 years.

The timing of the parasequence cyclicity in the Viking Formation is relatively consistent with the cyclicity of other parasequences or transgressive-regressive cycles in the Cretaceous Western Interior Seaway of Alberta. These include the 50,000-100,000 year cyclicity of the 18 shingles of the Dunvegan Formation (Cenomanian; Bhattacharya, 1989), the 100,000 year cyclicity of the 15 parasequences in the Muskiki-Marshybank Formations (Coniacian-Santonian; Plint, in press), and the 140,000 year cyclicity of the 7 transgressive-regressive cycles in the Bearpaw-Horseshoe Canyon Transition (Campanian-Maastrichtian; Ainsworth, 1991).

10.2.2 Magnitude

The magnitude of the relative fall in sea level responsible for triggering the incision of each valley must be greater than the maximum depth of the valley. For example, the relative fall in sea level responsible for triggering the re-incision at Crystal (fill 2) must have been greater than 30 m, because the maximum thickness of fill 2 is 30 m. This is the only direct method that can be used to estimate the magnitude of the relative fluctuations in sea level.

Two measurements are required in order to calculate the magnitude of the relative fluctuations in sea level responsible for moving the "VE3" shoreline trend across the basin: the distance between the shoreline trends and the dip of the Cretaceous shelf. The latter can not be directly measured from the stratigraphic section, and therefore must be assumed from a comparison with modern continental shelves. It is impossible to calculate the magnitude of relative fluctuations in sea level that were responsible for moving the regional parasequence shoreline trends across the basin because the shorelines are not preserved in the study area. They were likely reworked during transgressive ravinement.

Shepard (1963; p.206-259) described the topography and geometry of most modern continental shelves and reported an average gradient of 1:500. This gradient includes measurements from both passive and active continental margins. If the 1:500 gradient is applied to the Cretaceous shelf, it becomes possible to determine the magnitude of the relative fluctuations in sea level that were responsible for moving the position of the "VE3" shoreline trend (Table 10.1).

Table 10.1. Magnitude of relative fluctuations in sea level during "VE3-time". Shelf gradient is assumed to be 1:500 (Shepard, 1963).

Event	Rise (m)	Fall (m)	Distance (km)
Sunnybrook "A" to Chigwell	30		15
Chigwell to Sunnybrook "B"		54	27
Sunnybrook "B" to Joarcam		82	41
Joarcam to W.C./G-J	206		103
W.C./G-J to Bickerdike	22		11
Bickerdike to Caroline	124		62

Most of the proposed relative fluctuations in sea level are large, especially the 352 m relative rise in sea level that moved the shoreface from Joarcam to Caroline (Table 10.1).

If one assumes the dip of the Cretaceous shelf approximates the dip of modern passive continental margin shelves, then a gradient of 1:2000 (Maryland shelf, U.S.A.; Swift & Field, 1981; Swift & Niedoroda, 1985) can be used for calculating the magnitude of the relative fluctuations in sea level responsible for moving the "VE3" shorelines (Table 10.2).

Table 10.2. Magnitude of relative fluctuations in sea level during "VE3-time". Shelf gradient is assumed to be 1:2000 (Swift & Field, 1981; Swift & Niedoroda, 1985).

Event	Rise (m)	Fall (m)	Distance (km)
Sunnybrook "A" to Chigwell	7.5		15
Chigwell to Sunnbrook "B"		13.5	27
Sunnybrook "B" to Joarcam		20.5	41
Joarcam to W.C./G-J	51.5		103
W.C./G-J to Bickerdike	5.5		11
Bickerdike to Caroline	31.0		62

The magnitude of the relative fluctuations in sea level shown in Table 10.2 are four times less than those shown in Table 10.1. In reality, the magnitude of the relative fluctuations in sea level that affected Viking sedimentation are likely to fall within the range shown in Tables 10.1 and 10.2. It should be stressed that these magnitudes are only approximations, and that there is a large degree of error associated with the estimation of the dip of the Cretaceous shelf.

10.2.3 <u>Controls</u>

Most global eustatic and regional tectonic mechanisms operate on a one hundred thousand- to million-year time scale. For example, intra-plate stresses may cause 1-10 cm of eustatic sea level change over 1000 years (Cloetingh, 1986, 1988), and changes in the volume of ocean ridge systems may cause approximately 1 cm of eustatic change over 1000 years (Hays & Pitman, 1973). These global eustatic mechanisms are capable of producing cyclicity on a million-year time scale.

The timing of the collision of allochthonous terranes has been tentatively correlated to the development of major clastic wedges of the Canadian Western Interior foreland basin (Cant & Stockmal, 1989; Stockmal et al., in press). The unloading of sediments in response to these collisions may produce depositional cyclicity on a million-year time scale.

Another mechanism that may produce depositional cyclicity on a million-year time scale is thrust sheet loading as predicted by the viscoelastic (Beaumont, 1981) and elastic (Jordan, 1981) foreland basin lithospheric models. These models relate the timing of thrust sheet loading to the development of clastic wedges in the Cretaceous Western Interior Seaway of North America.

Beaumont (1981) predicts a 20-35 million year cyclicity for these events.

Jordan and Flemings (in press) have refined the elastic foreland basin lithospheric model of Jordan (1981) to account for subsidence and eustatic sea level change. They suggest that periodic thrusting events can occur on a 2 million-year time scale (Jordan & Flemings, in press).

All of the aforementioned mechanisms occur on a time scale that is at least two orders of magnitude slower than the 63,000 year cyclicity of the Viking parasequences. Therefore, one must examine other mechanisms in order to explain this cyclicity.

Glacio-eustacy

The only known eustatic mechanism that could produce the depositional cyclicity of the Viking are changes in the volume of the Earth's ice (glacio-eustacy). Glacial eustatic sea level changes are well documented for the Holocene. At the end of the last glacial period, global sea level rose approximately 100-150 m in 12,000 years (Milliman & Emery, 1968; Bloom, 1971). This works out to a rate of 8.3-12.5 m per 1000 years.

Evidence on many modern shelves indicates that the Holocene transgression was not characterized by a steady rise in sea level, but a more episodic rise that was punctuated by stillstands and minor regressions (Carter et al., 1986; Anderson & Thomas, 1991). Submerged shorelines, shoal banks and scarps are the depositional and erosional record of the episodic/punctuated Holocene rise in sea level, and these are observed on many modern shelves, including those of the Medditteranean (Flemming, 1965), United States east coast (McMaster & Garrison, 1967; McLennen & McMaster, 1971; Sanders & Kumar, 1975; Swift, 1975; Field & Duane, 1976), United States Gulf coast (Hyne & Goodell, 1967; Suter et al., 1987; Thomas & Anderson, 1988; Anderson & Thomas, 1991), Brazil (Kowsmann & Costa, 1979), and New Zealand (Carter et al, 1986).

Carter et al. (1986) recognized at least 8 submerged shorelines on the New Zealand shelf, each of which were deposited in a 1,000-2,000 year time interval. Thomas and Bentley (1978), and Anderson and Thomas (1991) suggest that marine ice-sheet decoupling caused sea level rises of a few meters within several hundred years during the Holocene. This mechanism occurred episodically during the Holocene transgression. Therefore, glacio-eustatic mechanisms are capable of producing fluctuations in eustatic sea level that would be consistent with the timing and magnitude (Tables 10.1 & 10.2) of the relative fluctuations in sea level inferred for the Viking sediments.

Mitchum and Van Wagoner (1991) and Plint (in press) invoke high frequency (fourth- or fifth-order) glacio-eustatic fluctuations in sea level to explain the cyclicity of the parasequences in the Eocene strata of Texas and in the Muskiki-Marshybank formations (Coniacian-Santonian) of Alberta, respectively. They suggest that Milankovitch-style mechanisms controlled the glacio-eustatic fluctuations in sea level.

Despite the general consensus that the Cretaceous was a relatively ice-free period (Matthews, 1984; Hallam, 1985), some evidence suggests that continental ice sheets may have existed during this period. The continents of Antarctica and Australia were located at fairly high latitudes during the Cretaceous (Barron, 1987; Frakes & Francis, 1988; Pirrie & Marshall, 1990), and therefore provide convenient locations for the development of continental ice. Frakes and Francis (1988) recognized large exotic clasts up to 3 m in diameter in some early Cretaceous mudstones of central Australia. They interpret these clasts as ice-rafted blocks that were derived from continental glaciers in central Australia. Frakes and Francis (1988) conclude that the Earth was probably not ice-free during the Cretaceous.

Therefore, one can <u>not</u> completely eliminate the possibility that glacio-eustatic mechanisms triggered eustatic sea level fluctuations during the Cretaceous. Plint (in press) concludes that glacio-eustatic fluctuations in sea level "might provide the most reasonable explanation of the relative sea level oscillations" responsible for the development of the 15 parasequences in the Muskiki-Marshybank formations of Alberta. Similarily, glacio-eustatic fluctuations in sea level may have controlled the depositional cyclicity of the Viking parasequences.

Differential Subsidence

The only regional tectonic mechanism that could have produced the depositional cyclicity of the Viking sediments is differential subsidence superimposed onto the third-order eustatic sea level fall ("VE2" lowstand). A parasequence would be deposited when the subsidence rate was less than the rate of eustatic sea level fall, while the corresponding flooding or transgressive ravinement surface would be cut when the subsidence rate exceeded the rate of eustatic sea level fall. This mechanism could explain the cyclicity of the 12 regional parasequences (successions 1a to 5), because these sediments were deposited during highstand or "early" lowstand conditions (Fig. 10.2). However, this mechanism would not explain the deposition of the 7 "VE3" parasequences because these sediments were deposited during an "overall" relative rise in sea level ("VE3" transgression; Fig. 10.2).

Sediment Supply

Autocyclic channel or delta lobe switching, and secondary responses to hinterland tectonics (allocyclic) can produce variations in the rate of sediment supply and changes in the location of the sediment point sources. These variations are capable of producing the cyclicity observed in some parasequence sets on both a local and regional scale (Van Wagoner et al., 1990).

Autocyclic mechanisms could be responsible for the development of regional parasequences 1a-1e and 2a-2d.

These parasequences are not widespread and only occur in localized areas surrounding the Sundance, Edson and Cyn-Pem valley-fill deposits. In contrast, regional parasequences 1-5 can be correlated basinward for up to 280 km, and along strike for at least 100 km. Their widespread areal extent suggests that they were not influenced by autocyclic processes, such as channel or delta lobe switching. Secondary responses to allocyclic mechanisms (tectonic uplift in the SW; Fig. 10.3), probably led to the southwestward shift of the sediment point source during the "VE2" lowstand, introduction of coarse-grained sediments and triggered the incision of the Viking valleys.

Neither a change in the rate of sediment supply nor a shift in the location of the sediment point sources are likely to have produced the depositional cyclicity of the "VE3" shoreface trends. These shorefaces shifted up to 103 km (Tables 10.1 & 10.2) in a relatively short period of time, and have not left a continuous sedimentological record across the shelf. These observations suggest that the cyclicity of the "VE3" shoreface deposits was caused by relative fluctuations in sea level, and not by variations in the rate of sediment supply nor changes in the location of the sediment point source.

<u>Summary</u>

It is impossible to suggest conclusively that one mechanism or a combination of mechanisms was responsible for developing the apparent 63,000 cyclicity of the Viking

parasequences. Various hypothetical arguments can be presented that support both eustatic and regional tectonic controls, but none of these arguments can be rigourously tested because of the lack of evidence or data (e.g. Late Albian glaciation).

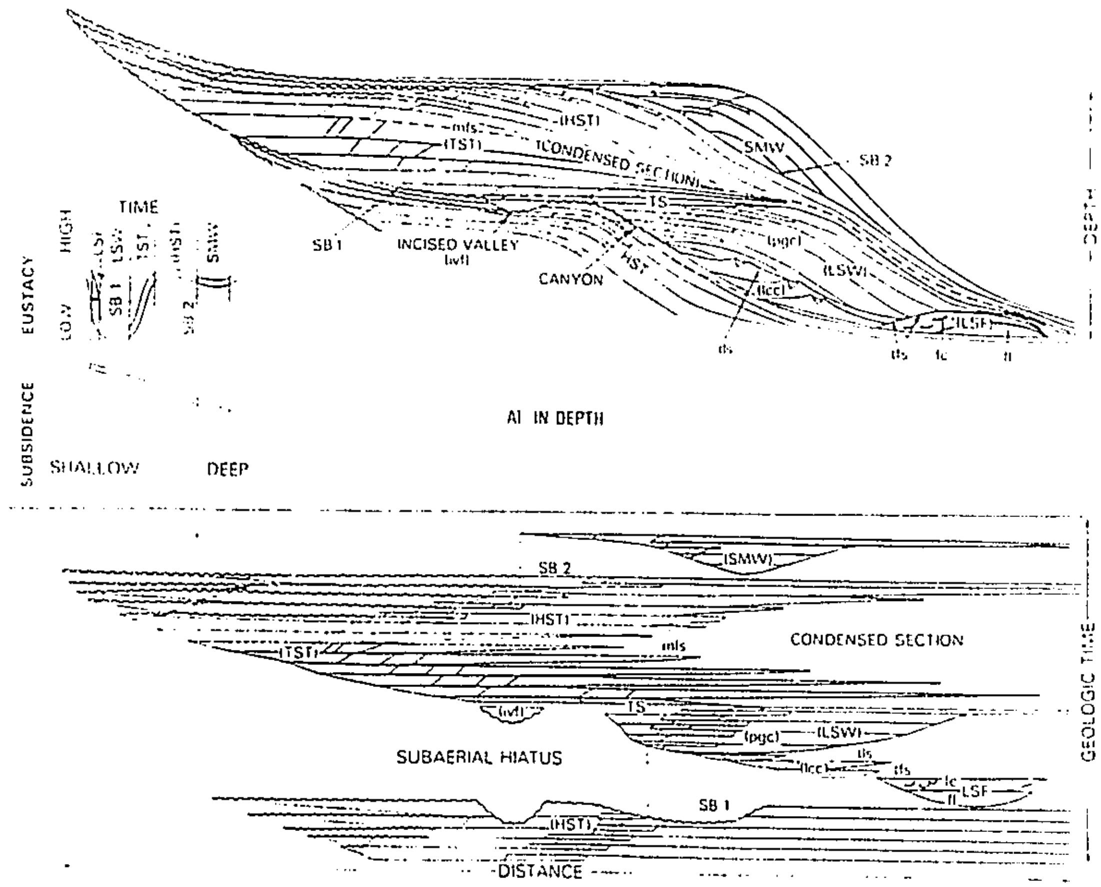
The cyclicity of regional successions 1 to 5 may be caused by glacio-eustatic or regional tectonic (differential subsidence) mechanisms, while the cyclicity of successions 1a to 1e and 2a to 2d may also be caused by changes in the rate of sediment supply or changes in the position of the sediment point sources. In contrast, the cyclicity of the 7 "VE3" parasequences might be caused by glacio-eustatic mechanisms.

10.3 Sequence Stratigraphy

Sequence stratigraphy is defined as the "study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities" (Van Wagoner et al., 1988; p.39). The fundamental unit is the sequence, which is bounded above and below by sequence boundaries (Fig. 10.5) that are cut as a response to relative falls in sea level (Van Wagoner et al., 1990). A sequence boundary is defined as an unconformity and its correlative conformity, and has evidence of subaerial erosional truncation or subaerial exposure (Van Wagoner et al., 1990).

Sequences can be subdivided into systems tracts which

Figure 10.5. A summary of the terminology used in sequence stratigraphy (Haq et al., 1987). (A) In depth. The various components as they might occur in a shelf-break setting. (B) In geologic time. A Wheeler-type diagram reflecting the relative time associated with both deposition and erosion. The following are observed in the Viking Formation: SB - Sequence Boundary, HST - Highstand Systems Tract, TST - Transgressive Systems Tract, & LST - Lowstand Systems Tract.



B) IN GEOLOGIC TIME

LEGEND

SURFACES

(SB) SEQUENCE BOUNDARIES
- (SB 1) = TYPE 1
- (SB 2) = TYPE 2

(DLS) DOWNLAP SURFACES
- (mfs) = maximum flooding surface
- (tfs) = top fan surface
- (tls) = top leveed channel surface

(TS) TRANSGRESSIVE SURFACE
- (First flooding surface above maximum regression)

SYSTEMS TRACTS

HST = HIGHSTAND SYSTEMS TRACT
TST = TRANSGRESSIVE SYSTEMS TRACT
LSW = LOWSTAND WEDGE SYSTEMS TRACT
- ivf = incised valley fill
- pgc = prograding complex
- lcc = leveed channel complex

LSF = LOWSTAND FAN SYSTEMS TRACT
- fc = fan channels
- fl = fan lobes

SMW = SHELF MARGIN WEDGE SYSTEMS TRACT

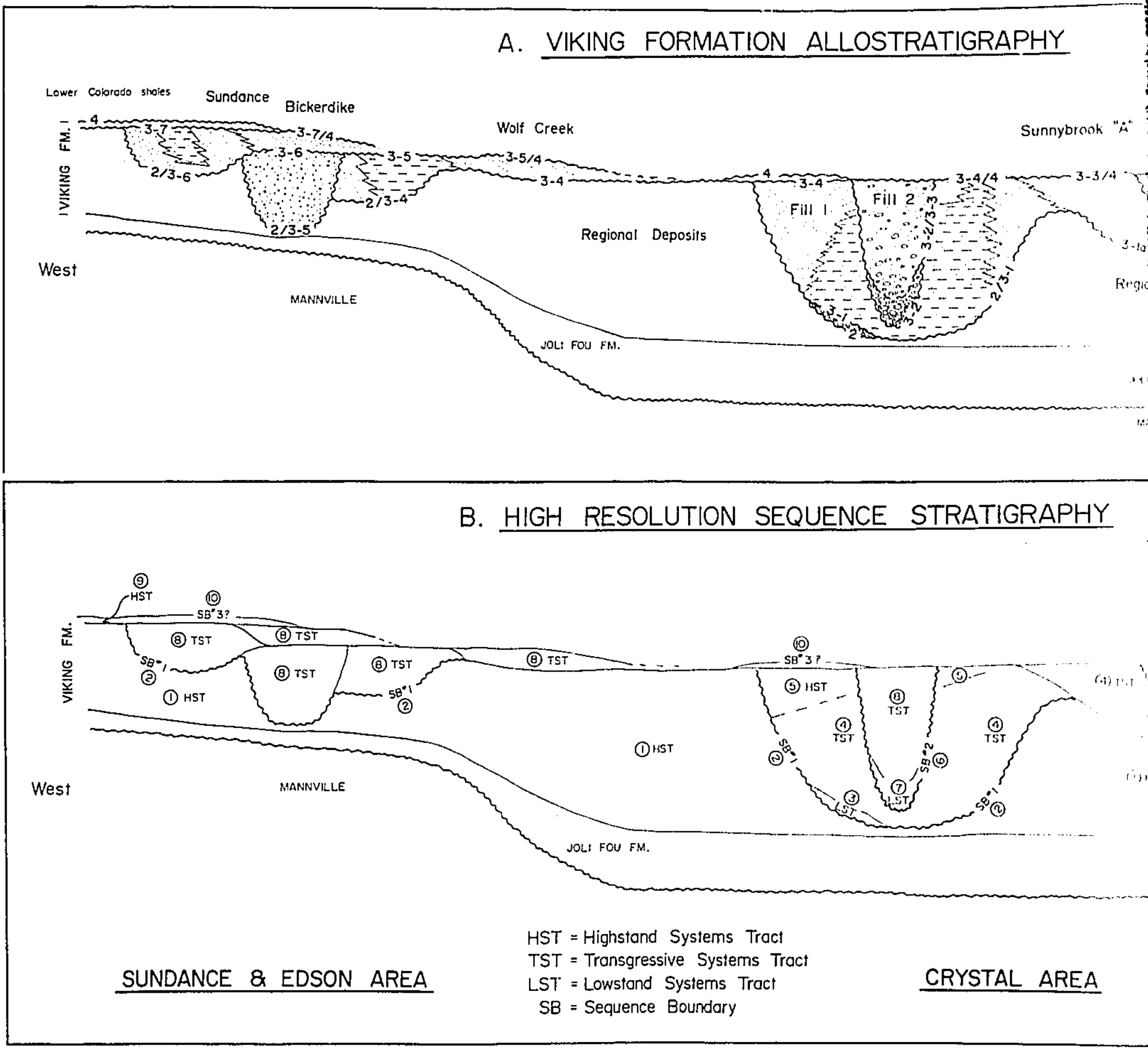
are defined on the basis of their position and stacking pattern within the sequence (Van Wagoner et al., 1988). Systems tracts link contemporaneous depositional systems (Brown & Fisher, 1977) that were deposited during specific periods on a relative or eustatic sea level curve (Posamentier et al., 1988; Posamentier & Vail, 1988; Jervey, 1988; Van Wagoner et al., 1990). Three different systems tracts are often observed; highstand, transgressive and lowstand (Posamentier et al., 1988; Fig. 10.5).

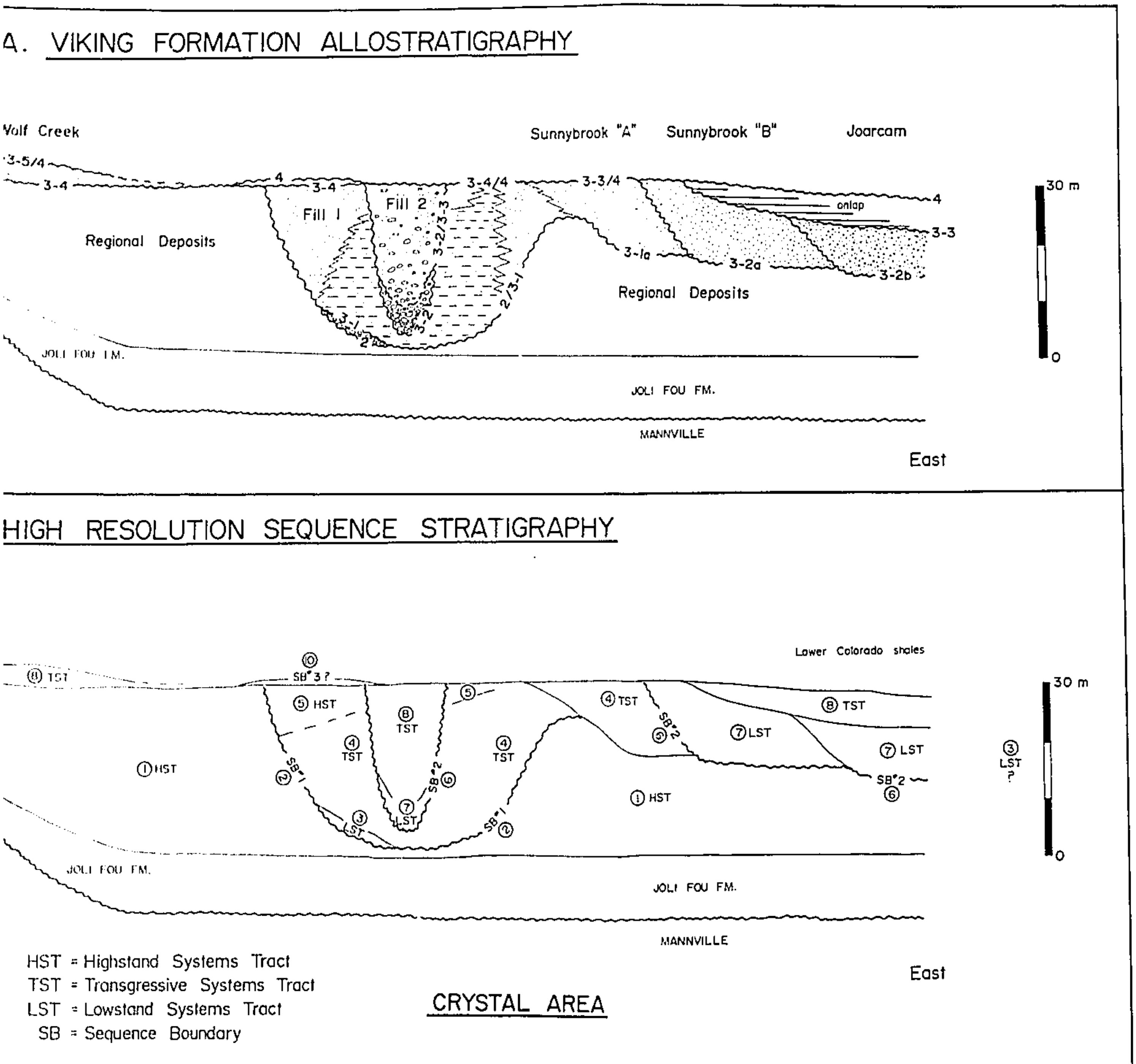
A relatively new branch of sequence stratigraphy examines high-frequency sequences and their associated systems tracts, which are deposited on a fourth- or fifth-order time scale (Mitchum & Van Wagoner, 1991). This scale matches the depositional cyclicity of the Viking Formation sediments.

10.3.1 Viking Formation - High Resolution

The sediments of the Viking Formation can be subdivided into highstand (HST), transgressive (TST) and lowstand (LST) systems tracts (Fig. 10.6). Three sequence boundaries (SB) are also recognized, including SB #1 (VE2), SB #2 (VE3-2) and SB #3 (VE4; Fig. 10.6). The sequence boundaries of the Viking are identified based on a basinward shift in facies across the boundary and the significant depth of incision (up to 30 m). These sequence boundaries differ from the definition of a sequence boundary (Van Wagoner et al., 1990) in that there is no evidence of subaerial exposure (e.g. roots or soils) or subaerial erosional truncation. Both the

Figure 10.6. A comparison of the allostratigraphy (A) and the high resolution sequence stratigraphy (B) of the Viking Formation. Circled numbers associated with the systems tracts and sequence boundaries refer to the geological history; 1 is the oldest. Note the complexity of the Crystal valley-fill relative to the Sundance and Edson valley-fill complex. Also note the de-emphasis of the transgressive erosion surfaces (most VE3 surfaces) using the sequence stratigraphic approach.


A. VIKING FORMATION ALLOSTRATIGRAPHY
Lower Colorado shales
Sundance
Bickerdike
Wolf Creek
Sunnybrook "A"
VIKING FM.
4
3-7
3-7/4
3-6
3-5
3-5/4
3-4
2/3-6
2/3-5
2/3-4
Fill 1
Fill 2
3-4/4
3-3/4
3-2/3-3
2/3-1
3-1
2
Regional Deposits
West
MANNVILLE
JOLI FOU FM.
B. HIGH RESOLUTION SEQUENCE STRATIGRAPHY
⑨ HST
⑩ SB#3?
⑧ TST
SB#1
②
① HST
⑤ HST
④ TST
SB#2
⑥
⑦ LST
③ LST
VIKING FM.
West
MANNVILLE
JOLI FOU FM.
HST = Highstand Systems Tract
TST = Transgressive Systems Tract
LST = Lowstand Systems Tract
SB = Sequence Boundary
SUNDANCE & EDSON AREA
CRYSTAL AREA


A. VIKING FORMATION ALLOSTRATIGRAPHY
Wolf Creek
Sunnybrook "A"
Sunnybrook "B"
Joarcam
3-5/4
3-4
4
3-4/4
3-3/4
Fill I
Fill 2
3-2/3-3
2/3-1
onlap
3-3
3-1a
3-2a
3-2b
Regional Deposits
Regional Deposits
3-1
2A
30 m
0
JOLI FOU FM.
JOLI FOU FM.
MANNVILLE
East
HIGH RESOLUTION SEQUENCE STRATIGRAPHY
Lower Colorado shales
⑩
SB*3 ?
⑧ TST
⑤ HST
⑧ TST
⑤
④ TST
⑧ TST
① HST
④ TST
④ TST
SB*1 ②
SB*2 ⑥
⑦ LST
⑦ LST
③ LST
⑦ LST
SB*2 ⑥
① HST
③ LST ?
30 m
0
JOLI FOU FM.
JOLI FOU FM.
MANNVILLE
East
HST = Highstand Systems Tract
TST = Transgressive Systems Tract
LST = Lowstand Systems Tract
SB = Sequence Boundary
CRYSTAL AREA

cutting of the sequence boundaries and the development of the systems tracts can be related to a specific position on the relative sea level curve (Fig. 10.7).

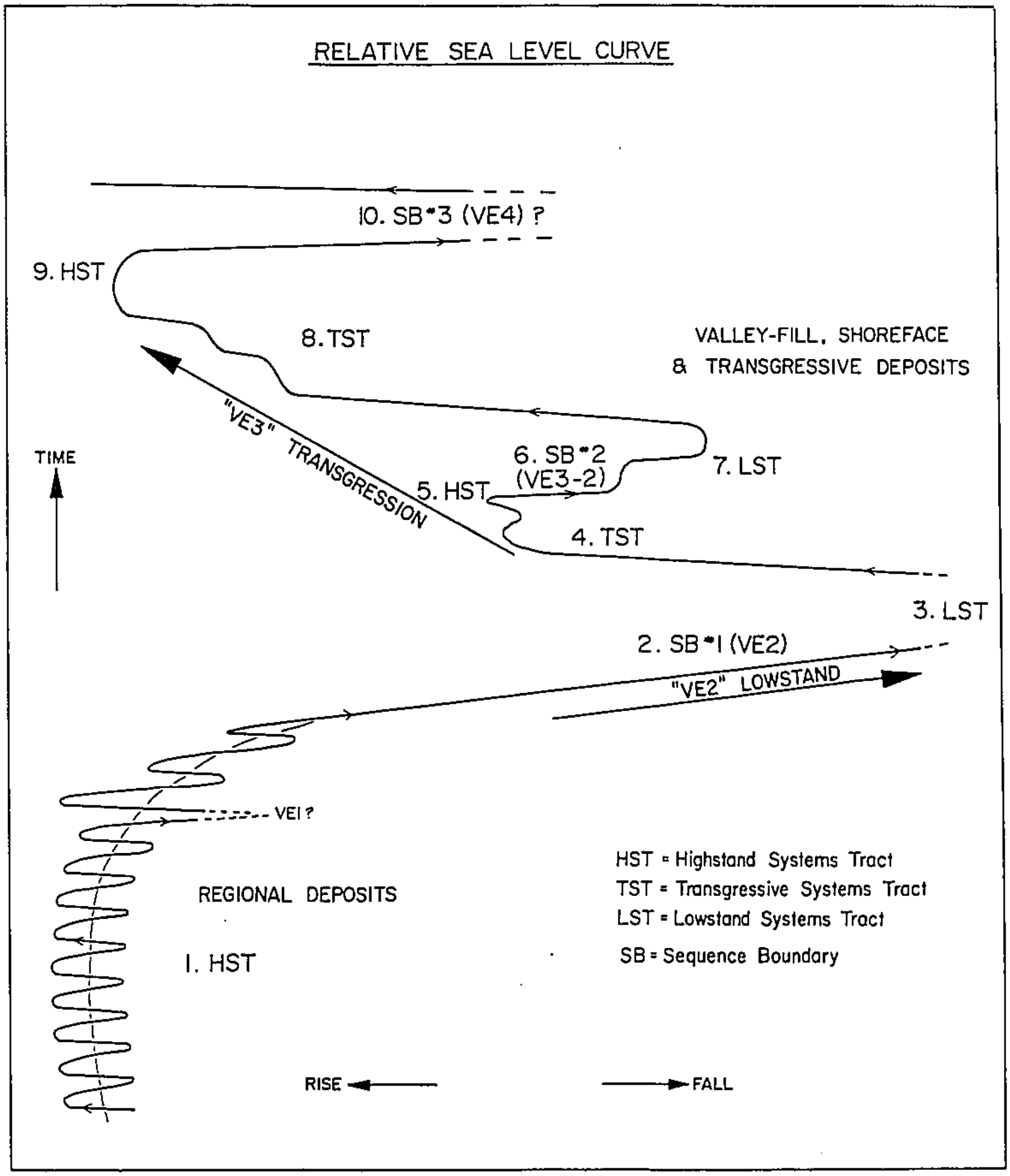
Regional deposits (successions 1 to 5) form a HST and can be described as a progradational parasequence set (event 1; Figs 10.6 & 10.7). The Crystal valley-fill deposits can be subdivided into two LST's (events 3 & 7; Figs 10.6 & 10.7), two TST's (events 4 & 8; Figs 10.6 & 10.7), and one HST (event 5; Figs 10.6 & 10.7). Sequence boundary #1 occurs at the base of fill 1, and SB #2 occurs at the base of fill 2 (Fig. 10.6). The Sundance and Edson valley-fill complex forms one TST (event 8; Figs 10.6 & 10.7) and is bounded below by SB #1.

The shoreface deposits form one LST (Sunnybrook "B" & Joarcam; Fig. 10.6), two TST's (Sunnybrook "A", Chigwell, Wolf Creek/Gilby-Joffre & Bickerdike; Fig. 10.6), and one HST (Caroline-Garrington; Fig. 10.6). Only the LST shoreface deposits are bounded by a sequence boundary below (SB #2; Fig. 10.6). The transgressive deposits obviously form a TST, and they are usually associated with event #8 (Figs 10.6 & 10.7).

10.3.2 <u>Limitations & Suggestions</u>

It is obvious from a comparison of the allostratigraphy (Fig. 10.6A) and sequence stratigraphy (Fig. 10.6B) of the Viking, that the sequence stratigraphic approach has some limitations. The most striking limitation is the under-emphasis of transgressive erosion surfaces (e.g. VE3; Fig.

Figure 10.7. Relative sea level curve for the Viking Formation. The timing of the deposition of systems tracts and the cutting of the sequence boundaries are shown (Fig. 10.6B).


RELATIVE SEA LEVEL CURVE
10. SB*3 (VE4) ?
9. HST
8. TST
VALLEY-FILL, SHOREFACE
& TRANSGRESSIVE DEPOSITS
"VE3" TRANSGRESSION
TIME
6. SB*2
(VE3-2)
7. LST
5. HST
4. TST
3. LST
2. SB*1 (VE2)
"VE2" LOWSTAND
VEI ?
HST = Highstand Systems Tract
TST = Transgressive Systems Tract
LST = Lowstand Systems Tract
SB = Sequence Boundary
REGIONAL DEPOSITS
1. HST
RISE
FALL

10.6A). The only type of erosion surface that is emphasized using sequence stratigraphy is the sequence boundary (lowstand incision). A quick comparison of Figures 10.6A and 10.6B shows a remarkable difference in the number of erosion surfaces.

Van Wagoner et al. (1990) suggest that two major transgressive surfaces occur within a sequence, including the flooding surface on top of the lowstand deposits and the maximum flooding surface. They also state that the transgressive surfaces are characterized by <u>minor</u> transgressive scour. Both of these statements are erroneous when one examines the high resolution sequence stratigraphy of the Viking.

A study of the Viking sediments has revealed that at <u>least</u> 5 major transgressive surfaces, including VE3-3, VE3-4, VE3-5, VE3-6 and VE3-7, exist in the sequence between SB #2 (VE3-2) and SB #3 (VE4; Fig. 10.6). These erosion surfaces bound the shoreface and valley-fill deposits. Significant amounts of erosive truncation exist at various points on these surfaces (Fig. 10.6A), including an estimated 5-10 m of transgressive ravinement and up to 11 m of shoreface scour (Gilby-Joffre trend; Downing & Walker, 1988).

Most of the aforementioned complexity can be linked to the sedimentology and stratigraphy that developed during the "VE3" transgression. This transgression was punctuated with stillstands and a minor regression which led to the cutting of numerous widespread erosion surfaces, some of which cut into underlying sequence boundaries. For example, the Sunnybrook "A" shoreface scour (VE3-1a) cuts at least 14 m into the underlying regional deposits (section 9.1). By applying the concepts of sequence stratigraphy, one can not accurately reflect the complexity of the VE3 erosion surface, nor can one fully describe the possible implications of transgressive erosion.

A second limitation of the sequence stratigraphic approach is the description of incised valley-fill sediments. Most sequence stratigraphic models discuss valley-fills that consist of one LST and one TST (Posamentier & Vail, 1988; Van Wagoner et al., 1990). These models do not consider how the LST and TST are identified and separated in a valley-fill, nor do they discuss the nature of the surface that separates the LST from the TST. The sequence stratigraphic models could be improved by addressing and examining some of these problems.

A third limitation in using sequence stratigraphy is the definition and characteristics of sequences and sequence boundaries, as described by Van Wagoner et al. (1990). Van Wagoner et al. (1990) define the thickness of a sequence as greater than 10 m. However, the sequences in the Viking are often thinner than 10 m, including (1) the southern part of fill 2 at Crystal, (2) the central part of fill 1 at Crystal, and (3) the distal deposits of most shoreline trends (e.g. Bickerdike). Therefore, the definition of a sequence (Van Wagoner et al., 1990) does not accurately describe the Viking sequences. Also, the sequence boundaries in the Viking are unlike the sequence boundaries defined by Van Wagoner et al. (1990) because they do not show evidence of subaerial exposure.

In general, it would appear that allostratigraphy is a much more flexible and appropriate tool for subdividing the Viking Formation, rather than sequence stratigraphy (Fig. 10.6). Allostratigraphic units are defined and identified on the basis of their bounding discontinuities, and can be subdivided based on a "well documented geologic history" (NACSN, 1983; p.866). This allows for a practical subdivision of the sediments based on their simplist terms, and has led to the development of the Viking allostratigraphy presented in this thesis.

One of the main reasons for favouring allostratigraphy is that all bounding erosion surfaces have equal weight, including those that are cut during transgressive ravinement and lowstand incision. In contrast, the entire "VE3" depositional and erosional history is de-emhasized when the sediments are subdivided into sequence stratigraphic units.

CHAPTER 11 - SUMMARY & BROADER IMPLICATIONS

The purpose of this chapter is to provide a brief summary of the significance of this thesis on both a local and a broader scale. This will be accomplished by describing some of the important contributions of this work.

On a local scale, the understanding of shallow marine depositional systems in the Alberta Foreland Basin has been advanced through the detailed description and interpretation of the sediments of the Viking Formation (chapters 3-10). Relative fluctuations in sea level play a significant role in controlling the style and extent of sand body deposition in the Alberta Basin. Recognizing and correlating bounding discontinuities, and understanding their relationship to relative fluctuations in sea level are essential for reconstructing the regional geological history of a formation.

On a broader scale, three different aspects of this thesis provide significant contributions. These are summarized below.

11.1 Valley-Fill Deposits

The Crystal, Sundance and Edson valleys are filled with fluvial, tidal, estuarine and marine sediments, forming tripartite facies geometries (chapters 6 & 8). Few examples of ancient valley-fill or estuarine systems have been discussed in the literature, therefore, the documentation and interpretation of the Viking valley-fill deposits expands our knowledge of these systems. The valley-fill deposits of the Viking can be related to two different styles of modern estuarine sedimentation; Gironde-type and Georgia coast-type.

The geometry and scale of the Crystal valley is similar to the geometry and scale of the Gironde estuary in France (Allen, in press). Both the Crystal valley and the Gironde estuary are 5-12 km wide, and both have funnel-shaped geometries. However, the 120 km long Gironde estuary is approximately twice as long as the Crystal valley (55 km; chapter 6).

The main similarity between the Crystal valley (fill 1) and the Gironde estuary is the well developed tripartite facies geometry. These systems have extensive estuarine mudstone deposits in the central part of the valley that are flanked by sandstone plugs at either end of the valley. The sandstone plug at the seaward end of the Gironde estuary consists of tidal inlet or tidal delta-like shoal sandstones, while the sandstone plug at the landward end consists of fluvial and tidal channel deposits (Allen, in press). In contrast, the sandstone plug at the seaward end of fill 1 consists of transgressively reworked shoreface sandstones, while the sandstone plug at the landward end consists of bay head delta sandstones (chapter 6). The abundance of tide-generated structures in the Gironde estuary, compared to the paucity of similar structures in fill 1 suggests that the Gironde has relatively strong tidal currents compared to those that existed in the Crystal valley during the deposition of fill 1. The Gironde estuary is a macrotidal system that has a tidal range of 2.5-6.0 m (Allen, in press). No evidence exists for a similarily strong tidal range in the sediments of fill 1 at Crystal.

The deposits of fill 2 at Crystal are very similar to the sediments observed in the sandstone plug in the landward part of the Gironde. The sediments of fill 2 consist of coarse-grained fluvial and tidal channel deposits (chapter 6), and they exhibit a similar down valley transition from fluvial to tidal deposits as the sediments of the Gironde.

Despite the similar geomorphological zonations of sediments in the Gironde and Crystal valleys, the stacking of the fill units in these two systems is significantly different. The sediments at Crystal consist of two discrete fills separated by a sequence boundary (fills 1 & 2; chapter 6), while the sediments of the Gironde consist of a relatively conformable stack of transgressive and regressive units (Allen, in press). The fluvial sediments at Crystal (FA-8; fill 2) are concentrated in a small channel-like scour that cuts into the underlying tripartite deposits of fill 1. This scour was cut during a relative fall in sea level and was filled during the stillstand and transgressive conditions that followed this fall. In contrast, the fluvial sediments of the Gironde are concentrated in the upper estuary zone and are gradationally interbedded with the tidal estuarine sandstones that occur downstream (Allen, in press). These sediments have been deposited during both transgressive and regressive conditions, and are conformable with the adjacent valley-fill sediments.

In summary, the geometry, scale and sediments of the Crystal valley are very similar to those of the modern Gironde estuary. Therefore, the Crystal valley-fill can be referred to as an ancient example of a Gironde-type estuary or valley-fill system.

The geometry and scale of the Sundance and Edson valley-fill complex resembles the geometry and scale of the Georgia coast estuaries (Dorjes & Howard, 1975; Greer, 1975; Frey & Howard, 1986). These estuaries are 10-30 km long and 1-15 km wide, and they form broad embayments that are protected from the open sea by barrier islands (e.g. Sapelo Island & Sapelo Sound; Howard & Reineck, 1972; Frey & Howard, 1986).

Most Georgia coast estuaries exhibit tripartite facies geometries that consist of estuarine-marine sandstones at the mouth of the estuary, laterally extensive estuarine mudstones in the central part of the estuary, and thin, laterally confined fluvial sandstones at the head of the estuary (Frey & Howard, 1986). The Georgia coast estuaries are micro- to meso-tidal, and they experience a tidal range of 2-3 m (Dorjes & Howard, 1975; Greer, 1975; Frey & Howard, 1986).

The sediments of the Sundance and Edson valley-fill complex form a "double" tripartite facies geometry that consists of two shoreface deposits (Wolf Creek & Bickerdike; chapter 8), two zones of estuarine mudstones and two zones of bay head delta or transgressively reworked sandstones. These sediments are subdivided into two separate fills (NE & SW fills; chapter 8), and were deposited during stillstands that were superimposed onto the overall "VE3" transgression. The scale, tripartite facies geometries, lateral extent and sedimentology of the Sundance and Edson valley-fill deposits are very similar to those of the Georgia coast estuaries. In summary, the Sundance and Edson valley-fill complex can be referred to as a Georgia coast-type estuary.

By comparing the modern Gironde and Georgia coast estuaries, it is possible to determine some of the controlling factors on estuarine sedimentation. Four different aspects of these estuaries provide significant controlling influences on sedimentation; (1) valley shape, (2) input of fluvial sediments, (3) tidal range, (4) geomorphology at the mouth of the estuary (e.g. barrier island vs. "open" valley mouth). The Gironde estuary has a funnel shape, a significant input of fluvial sediments, a macrotidal range and a relatively "open" valley mouth (Allen, in press). In contrast, the Georgia coast estuaries are characterized by broad valleys, a minor input of fluvial sediments, a micro- to meso-tidal range and barrier islands at the mouth of each valley (Frey & Howard, 1986).

These factors also controlled the sedimentology of the Viking valley-fill deposits. The Crystal valley-fill had a funnel-shape, a significant input of fluvial sediments, and a relatively "open" valley mouth. In contrast, the Sundance and Edson valley-fill complex formed a broad embayment, had a minor input of fluvial sediments and had a shoreface that blocked the mouth of the valley. Also, the sequence of relative fluctuations in sea level that influenced the valleys during their filling played a significant role in controlling the sedimentation. For example, the Crystal valley was initially filled during transgressive and stillstand conditions (e.g. fill 1; chapter 6), and was later re-incised and filled during regressive, stillstand and transgressive conditions (e.g. fill 2). In contrast, the Sundance and Edson valley-fill complex was filled during two stillstands that were superimposed onto an overall transgression (chapter 8).

In summary, at least five different factors can control the style of estuarine or valley-fill sedimentation, including (1) valley shape, (2) input of fluvial sediments, (3) tidal range, (4) geomorphology at the mouth of the valley, and (5) sequence of relative fluctuations in sea level. These factors probably control or controlled the styles of deposition in many other modern and ancient estuaries.

11.2 Valley to Shoreline Relationships

The excellent and extensive core and well log data base used in this study has led to the identification and correlation of sedimentary rock packages and their bounding erosion surfaces. The bounding erosion surfaces are mappable and continuous over a relatively wide area, and have been used to relate the cutting and filling histories of the valleys to their adjacent shoreline trends. The sedimentological and stratigraphic relationships have been established for four valley-fill and up to eight shoreline trends in the Viking Formation (chapters 6-10).

The relationship between adjacent shoreline and valley-fill deposits has been determined for the Viking sediments that were deposited during different positions on a relative sea level curve; relative rises, relative falls and stillstands. In general, relative rises of sea level are characterized by valley filling, ravinement and transgressive reworking of shoreline deposits into the mouths of the valleys (e.g. FA-3; fills 1 & 2 at Crystal; chapter 6). Stillstands are characterized by shoreline progradation and valley filling, and relative falls in sea level are characterized by valley incision and the basinward shift of shoreline trends. Some shorelines were developed during periods of valley incision (e.g. Joarcam & Sunnybrook "B"; chapters 9 & 10), and are not physically connected to the mouth of a Viking valley. Other shorelines were developed during periods of valley filling (e.g. Sunnybrook "A"; chapters 9 & 10), and are physically connected to the mouth of a Viking valley (e.g. Crystal; chapters 6 & 9). The Sunnybrook "A", Wolf Creek and Bickerdike shoreface deposits form the marine end member or sandstone plug of the tripartite valley-fill deposits at Crystal (fill 1), and at Sundance and Edson (NE & SW fills), respectively. These shoreface sediments are genetically related to the adjacent valley-fill deposits and are bounded by similar erosion surfaces.

This work provides a guide and a framework in which other valley to shoreline relationships can be examined. It also represents the best documented study of ancient valley-fill and shoreline systems.

11.3 Transgressive Ravinement

The complex history of the "VE3" transgression, with the superimposed stillstands and minor regression provides another well documented ancient example of a punctuated transgression similar to the punctuated Holocene rise in sea level (Carter et al., 1986; chapters 9 & 10). Other ancient examples include the stillstands superimposed onto the transgressions during the deposition of the sediments of the Cardium Formation in Alberta (Plint et al., 1986, 1987; Bergman & Walker, 1987; Walker & Eyles, 1988; Leggitt et al., 1990; Pattison & Walker, 1991), and the stillstands superimposed onto the transgression during the deposition of the sediments of the Muskiki Formation in Alberta (Plint, in press).

The subdivision of the "VE3" transgression into many smaller events reinforces the idea that transgressions can be relatively complex phenomena. The geological expression of this complexity (e.g. stillstands & regressions) are preserved in the sedimentary rock packages (e.g. shoreface packages), and their bounding erosion surfaces.

Walker (1990) discusses the complexity of transgressive erosion surfaces in shoreface settings and identifies two main types of transgressive surfaces: an initial transgression (IT) and a resumed transgression (RT). Both IT and RT surfaces are recognized in the valley-fill and shoreface deposits of the Viking Formation. The base of each valley-fill is characterized by an IT or a transgressive modification surface (e.g. VE3-1 at Crystal; chapter 6), and the top is characterized by an RT or a transgressive ravinement surface (e.g. VE3-4 at Crystal & Cyn-Pem; chapters 6 & 7). Most shoreface deposits are bounded by an IT surface below and an RT surface above (e.g. Wolf Creek shoreface; VE3-4 & VE3-5; chapters 8 & 9).

Furthermore, the overall "VE3" transgression is punctuated by a relative fall in sea level that resulted in the re-incision at Crystal and the basinward shift of the shoreline to Sunnybrook "B" and Joarcam (chapters 6, 9 & 10). Therefore, the IT/RT transgressions described by Walker (1990) can also be punctuated with relative falls in sea level that result in the cutting of sequence boundaries.

CHAPTER 12 - CONCLUSIONS

(1) The sediments of the Viking Formation can be subdivided into four different types of sedimentary rock packages; regional, valley-fill, shoreface and transgressive deposits. Most of these rock packages are bounded above and below by erosion surfaces, labelled VE2, VE3 and VE4.

(2) The regional deposits consist of a stack of 12 shelf-to-shoreface (bioturbated mudstones and sandstones), coarsening-upward successions that form a progradational parasequence set. These sediments were deposited during highstand conditions and are the distal deposits of shorelines that were oriented N-S or NNE-SSW.

(3) The depositional cyclicity of the regional parasequences could be controlled by glacio-eustatic fluctuations in sea level or differential subsidence. The cyclicity of regional parasequences 1a-1e and 2a-2d might also be controlled by changes in the rate of sediment supply or changes in the position of the sediment point sources.

(4) The Viking valleys were initially cut during the "VE2" lowstand and were filled during the ensuing "VE3" transgression.

(5) During the early stages of the "VE2" lowstand, uplift in southwestern Alberta led to the incision of the valleys and introduction of coarse-grained sediments into the study area. This uplift combined with differential subsidence to re-orient the Viking shoreline trends from N-S or NNE-SSW to

NW-SE.

(6) The "VE3" transgression was punctuated by stillstands and a minor regression. Each stillstand or regression led to the cutting of a "new" VE3 erosion surface (VE3-1 to VE3-7).

(7) The Crystal valley-fill deposits rest in two separate incisions that are separated by a sequence boundary (VE3-2 erosion surface or SB #2). The sediments of fill 1 form a tripartite facies geometry and from south to north, consist of bay head delta sandstones, estuarine mudstones and transgressive marine sandstones. This fill was deposited during transgressive and stillstand conditions. The sediments of fill 2 are confined in a relatively small channel in the central part of the Crystal valley and from south to north, consist of fluvial conglomerates, tidal-fluvial sandstones and transgressive marine sandstones. This fill was deposited during lowstand and transgressive conditions.

(8) The Cyn-Pem valley-fill is time equivalent to the Crystal valley-fill, but is poorly understood because of the lack of core control. Both the Crystal and Cyn-Pem valleys are located along the Sunnybrook shoreface trend.

(9) The Sundance and Edson valley-fill deposits rest in two separate incisions (northeastern and southwestern). Both have tripartite fills. The sediments of the NE fill are time equivalent to the Wolf Creek shoreface deposits, and the sediments of the SW fill are time equivalent to the

Bickerdike shoreface deposits. The Sundance and Edson valley-fill sediments were deposited after the Crystal and Cyn-Pem valley-fill sediments.

(10) Seven paleoshoreline trends are recognized in the study area, and these were deposited during the stillstands and regression that were superimposed onto the "VE3" transgression. An eighth paleoshoreline trend probably exists basinward of Joarcam and would represent the "lowest" lowstand shoreline.

(11) The valley-fill deposits are genetically linked to their surrounding shoreface deposits because bounding erosion surfaces and sedimentary rock packages can be traced between adjacent valleys and shorelines.

(12) Relative fluctuations in sea level control the position of the "VE3" shoreface trends. These relative fluctuations in sea level occur on a 63,000 year cyclicity, and are possibly controlled by glacio-eustatic mechanisms.

(13) The third-order relative fall ("VE2" lowstand) and rise ("VE3" transgression) in sea level is correlative to the third-order eustatic sea level cycle at 97-98 Ma. Regional tectonic, glacio-eustatic and/or autocyclic mechanisms control the depositional cyclicity of the Viking sediments (19 parasequences). The exact mechanism or combination of mechanisms is unknown.

(14) An application of sequence stratigraphic concepts and models to the Viking sediments leads to many problems, including the simplification of the "VE3" transgression and

the under-emphasis of transgressive erosion. Also, the complex stratigraphy and sedimentology of valley-fill deposits is not fully addressed in these models.

(15) An application of allostratigraphic concepts allows for a simple and practical subdivision of the Viking sediments based on the recognition of sedimentary rock packages and their bounding erosion surfaces.

(16) The sediments of the Crystal valley-fill resemble the deposits of the Gironde estuary, while the sediments of the Sundance and Edson valley-fill complex resemble the deposits of the Georgia coast estuaries.

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APPENDIX 1

The following is a list of all the cores that have been examined for this research.

Core Location	Depth
11-17-43-5W5	2007-2043 m
06-12-43-7W5	2209-2230
07-16-43-7W5	2188.3-2205.1
08-17-44-3W5	1753-1771.6
06-15-44-4W5	1864-1882
08-21-44-4W5	1842-1854
16-20-44-6W5	2036-2054
16-04-45-3W5	1737.4-1749.8
14-19-45-3W5	1768-1786
14-20-45-3W5	1763-1781
06-22-45-3W5	1720-1738
06-24-45-3W5	1669-1687
11-26-45-3W5	1726-1744
06-29-45-3W5	1771-1789
06-30-45-3W5	1796-1805
08-30-45-3W5	1785-1801.8
08-31-45-3W5	1781.5-1804
10-31-45-3W5	1778-1796.2
12-31-45-3W5	1812-1820
14-31-45-3W5	1768-1795
06-32-45-3W5	1755-1773
07-32-45-3W5	1750-1768
06-34-45-3W5	1730-1756.4
14-24-45-4W5	1791-1808
16-24-45-4W5	1785.5-1809.5
08-25-45-4W5	1799-1811
10-25-45-4W5	1801-1819
08-26-45-4W5	1807-1837
16-26-45-4W5	1815-1833
14-28-45-4W5	1806-1823.5
14-35-45-4W5	1757-1770.3
10-36-45-4W5	1787-1822.5
14-36-45-4W5	1773-1800
08-22-45-5W5	1876-1894
06-32-46-2W5	1586-1603
12-05-46-3W5	1746-1764
16-05-46-3W5	1748.3-1762.8
10-06-46-3W5	1730-1766
11-06-46-3W5	1739-1757
12-06-46-3W5	1718-1754
02-07-46-3W5	1734-1752
04-07-46-3W5	1717-1753
08-07-46-3W5	1719-1737
10-07-46-3W5	1704-1722
14-07-46-3W5	1691-1711
16-07-46-3W5	1690-1708

14-08-46-3W5	1703-1721
16-08-46-3W5	1698-1708.8
08-10-46-3W5	1700-1717.6
04-17-46-3W5	1702-1720
06-17-46-3W5	1723-1741
14-17-46-3W5	1721-1754
16-17-46-3W5	1730-1747
02-18-46-3W5	1702-1721.5
03-18-46-3W5	1685-1707.5
05-18-46-3W5	1686.6-1704.8
10-18-46-3W5	1707-1740
14-18-46-3W5	1723-1741
16-18-46-3W5	1726-1744
06-19-46-3W5	1742-1760.5
08-19-46-3W5	1729-1747
10-19-46-3W5	1726-1744
12-19-46-3W5	1732.5-1750.5
14-19-46-3W5	1705-1721.8
08-20-46-3W5	1711-1729.3
12-20-46-3W5	1717-1735
14-20-46-3W5	1692-1710.2
08-24-46-3W5	1628-1646
11-27-46-3W5	1646.8-1655.6
10-28-46-3W5	1658.0-1676.0
06-29-46-3W5	1670-1671.8
02-30-46-3W5	1687-1705.4
06-30-46-3W5	1692-1705
08-30-46-3W5	1678-1693.3
08-31-46-3W5	1658-1674.8
10-34-46-3W5	1605-1615
12-35-46-3W5	1565-1581.7
02-01-46-4W5	1764-1796
04-01-46-4W5	1774-1806.3
06-01-46-4W5	1752-1779.8
08-01-46-4W5	1737-1762
09-01-46-4W5	1710-1748
10-01-46-4W5	1700-1744
12-01-46-4W5	1739-1773
14-01-46-4W5	1709-1739
16-01-46-4W5	1705-1737.8
08-02-46-4W5	1762-1785.5
14-02-46-4W5	1723.5-1740.8
16-02-46-4W5	1728-1760
16-03-46-4W5	1735-1753
08-10-46-4W5	1711.5-1731.5
16-10-46-4W5	1697-1705.2
06-11-46-4W5	1717-1735
08-11-46-4W5	1713-1731
14-11-46-4W5	1698-1716.5
06-12-46-4W5	1709-1745.5
08-12-46-4W5	1721-1752
11-12-46-4W5	1702.5-1733
08-13-46-4W5	1692-1701
16-13-46-4W5	1732-1750

08-15-46-4W5	1704-1722.2
08-23-46-4W5	1679-1697
06-24-46-4W5	1708.8-1723.8
08-25-46-4W5	1699-1716.8
16-36-46-4W5	1657-1666
06-32-46-5W5	1773-1785
06-20-47-2W5	1542.2-1557.5
04-01-47-3W5	1571-1589
05-02-47-3W5	1540-1566
04-11-47-3W5	1562-1577
08-15-47-3W5	1623-1639
14-19-47-3W5	1548-1566
14-21-47-3W5	1588-1605
06-27-47-3W5	1578-1596
14-29-47-3W5	1606-1631.3
08-32-47-3W5	1564-1577
16-33-47-3W5	1544-1553.5
04-36-47-3W5	1552.0-1584.9
16-02-47-4W5	1660-1678
02-06-47-4W5	1696-1736.7
06-36-47-4W5	1570-1589
10-13-47-5W5	1667-1685.1
10-22-47-5W5	1685-1693
06-24-47-5W5	1651-1669
16-12-47-6W5	1795.2-1816.5
06-18-47-6W5	1821.4-1836.6
06-15-47-7W5	1871.7-1899.4
04-36-47-7W5	1815-1833
08-16-48-3W5	1513.5-1533.8
08-15-48-4W5	1560.6-1570.9
16-31-48-5W5	1585-1589.8
14-29-48-6W5	1692.8-1720.8
06-07-48-7W5	1821.7-1834.8
14-13-48-7W5	1726.6-1737.9
06-09-49-2W5	1371.6-1386.8
08-31-49-5W5	1515.1-1522.1
16-10-49-6W5	1599-1617.3
08-11-49-12W5	2154.8-2194.5
14-02-50-9W5	1776.9-1787.6
04-12-50-12W5	2095.4-2130.4
04-25-50-12W5	2081.7-2112.2
03-34-50-12W5	2078.0-2090.4
05-10-51-4W5	1337.7-1402.6
06-05-51-7W5	1645.2-1660.5
02-17-51-10W5	1883.0-1913.4
13-05-51-11W5	1996.3-2038.1
06-12-51-11W5	1939-1957
11-11-51-20W5	2868.0-2889.4
01-07-52-8W5	1644-1661
15-02-52-10W5	1730.0-1763.5
03-01-52-11W5	1841.2-1870.2
09-06-52-11W5	1908.9-1960.1
14-28-52-11W5	1801.9-1852.8
03-22-52-19W5	2592-2614

12-34-52-19W5	2574-2589
10-21-52-20W5	2699.2-2717.5
14-20-52-21W5	2885-2903
06-27-52-21W5	2868.0-2883.0
10-33-52-21W5	2855.8-2868.6
11-09-53-8W5	1539.2-1541.6
13-07-53-9W5	1638.5-1656.7
08-15-53-9W5	1595.0-1613.1
04-16-53-9W5	1619.0-1624.3
16-07-53-10W5	1712.0-1726.6
11-26-53-10W5	1587.9-1607.7
11-16-53-12W5	1809.8-1820.5
07-08-53-13W5	1963.7-1981.7
06-11-53-13W5	1898-1916
10-04-53-18W5	2404.4-2420.0
06-15-53-19W5	2470.6-2488.9
10-16-53-19W5	2482.5-2496.2
10-18-53-19W5	2522.1-2540.4
07-20-53-19W5	2490.4-2501.4
13-31-53-19W5	2520-2541
02-34-53-19W5	2445.9-2453.2
10-05-53-20W5	2685.5-2697.7
11-31-53-20W5	2676.6-2694.9
15-21-53-21W5	2802-2813.8
15-23-53-21W5	2722.6-2733.8
16-07-54-19W5	2487-2505
10-08-54-19W5	2456.9-2485.2
06-16-54-19W5	2438.0-2447.4
10-17-54-19W5	2450.5-2468.8
11-21-54-19W5	2396.7-2405.0
01-30-54-19W5	2423-2441
10-09-54-20W5	2610.8-2621.1
12-12-54-20W5	2615.1-2631.8
10-23-54-20W5	2545.3-2563.6
13-30-54-20W5	2766-2783
10-34-54-20W5	2576.6-2594.9
07-36-54-20W5	2480.0-2498.3
12-13-54-21W5	2722.0-2743.2
11-14-54-21W5	2751.0-2755.9
07-15-54-21W5	2712.6-2730.9
10-34-54-21W5	2641-2659
09-36-54-21W5	2724-2741
01-06-55-20W5	2669-2694
08-08-55-20W5	2665-2683

APPENDIX 2

Methods Used to Construct Cross Sections

The local and regional correlations of the facies associations is accomplished by constructing core and well log cross sections, which represent a two dimensional view of the sedimentology. Three dimensional views of the sedimentology are provided in isopach maps.

Each cross section is constructed by choosing a line of reference or geographic orientation on a map of the study area, and then selecting each well log and/or core that coincides with this line of interest. The cores and well logs are then placed side by side in their appropriate geographic order and are then correlated. The well log cross section correlations were achieved by superimposing tracings of one well log over the next, thus using overall log shapes as well as individual log deflections. The core cross section correlations were achieved by carefully matching the sediments with their corresponding well log signatures and correlating distinct markers or beds.

Each cross section is hung on a stratigraphic datum which is a prominent well log or core marker that occurs above or below the Viking Formation. These markers reflect an abrupt change in the lithology, a specific lithology or an erosional surface, and are assumed to be near horizontal, planar surface. This is a necessary assumption because in reality, these surface probably have gentle undulations and a shallow dip.

Six different datums could have been used in this study, including two upper datums (Base of Fish Scales and top Viking) and four lower datums (top Mannville, top Joli Fou, regional and bentonites). The Base of Fish Scales (BFS) is a prominent gamma-ray and resistivity well log marker that can be observed throughout the entire study area. In core, this marker consists of organic rich shale, with abundant fish scales, and is believed to represent a condensed section of sediments (Leckie, 1987; Cant, 1989). By definition, a condensed section can be related to a maximum relative sea level high and is developed when the sedimentation rates are at a minimum (Van Wagoner et al., 1988). The BFS marker is the most frequently used datum in this thesis. The second upper datum is the top of the Viking Formation. Although this is not a good choice as a planar datum because of its erosive character, it is useful for providing a horizontal upper surface of the valley-fill deposits and makes correlations within the valleys easier.

Lower datums are infrequently used due to the difficulties in identifying and correlating these markers. The top of the Mannville is a prominent marker but has been shown to be an erosional surface (Stelck & Kramers, 1980; Koke & Stelck, 1984; Cant, 1989) and is, therefore, unacceptable as a datum. The top of the Joli Fou Formation and the top of the regional Viking successions are difficult to identify with consistency from one region to another. However, in smaller scale cross sections (10-20 km), these two markers are easy to identify and provide ideal datums. The fourth type of lower datum are the bentonite beds which occur within the regional CU successions. These beds can be traced for up to 200 km and can be used for local correlations of the Viking sediments in central Alberta (Amajor & Lerbekmo, 1980).