SEDIMENTOLOGY, STRATIGRAPHY, AND DEPOSITIONAL HISTORY OF THE LOWER CRETACEOUS VIKING FORMATION AT WILLESDEN GREEN, ALBERTA, CANADA

SEDIMENTOLOGY, STRATIGRAPHY, AND

DEPOSITIONAL HISTORY OF THE

LOWER CRETACEOUS VIKING FORMATION

AT WILLESDEN GREEN, ALBERTA, CANADA

BY

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ABSTRACT

The Lower Cretaceous Viking Formation is a complex stratigraphic unit containing a variety of geographically separated sand bodies of varying orientation, thickness and lithology. Many of these sand bodies are prolific hydrocarbon reservoirs which have been extensively drilled by industry. Despite this fact, their origins and interelationships are largely unknown. Establishment of a Viking Allostratigraphy in the Willesden Green area (1) allows the recognition of distinct allomembers based on bounding discontinuities and facies associations, and (2) determines the exact stratigraphic relationships and depositional histories of the Viking oil and gas fields as defined by basin-wide sea level fluctuations.

Detailed core and log correlations indicate that in the Willesden Green area, the Viking Formation is made up of 4 distinct packages of sediment separated by 3 major stratigraphic breaks. The lower most package is regional in extent, and consists of three gradational coarsening-upward cyclic offshore mudstone/siltstone sequences (Members A and B). At Willesden Green, Member B is erosively incised by a major unconformable scour surface (VE2 - Viking Erosion surface 2) filled with conglomerate-rich channel/estuarine sediments (Member C). The VE2 incision was carved during an initial Viking lowstand, and infilled during a temporary stillstand in the ensuing transgression. The top of Member C is erosively truncated by a regionally tracable pebble-mantled ravinement surface (VE3).

Member D, a sandying-upward sequence of storm-dominated lower shoreface to transitional offshore sediments, overlies VE3, and records

a second major Viking progradational event. This unit thickens southward, and can be traced laterally into correlative upper shoreface and non-marine sediments at Caroline and Harmattan. The top of Member D is bevelled by a second basin-wide ravinement surface (VE4) which rises in a step-like fashion towards the south. This surface is mantled by a thin veneer of pebbles which locally accumulate to form the elongate shale-encased, conglomeratic shelf sand bodies of Member E. Member E gradationally passes upward into the silty shales of the Colorado Group and records a final transgressive flooding of the Viking basin.

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CHAPTER 1 : INTRODUCTION

1.1 Introduction

This study began in 1987 with the goal of gaining additional information about several elongate, shale-encased sandstone and conglomerate bodies of the Late Albian Viking Formation in west central Alberta. Many of these sandbodies are prolific hydrocarbon reservoirs, and extensive drilling by industry has provided an abundance of subsurface data. Estimated initial oil in place for the major Viking fields totals 281.9 x 10^6 m^3 (approximately 1.8 billion bbl), and initial gas in place totals 378,446 x 10^6 m^3 (approximately 13 tcf) (Energy Resources Conservation Board, 1986). Primary investigations were centered on the sedimentology and stratigraphic relationship of four adjacent Viking fields: Ferrier, Willesden Green, Gilby A, and Gilby B.

Although several earlier studies had dealt specifically with the sedimentology of the Gilby A and B fields, most of these works were confined by reservoir boundaries, and did not attempt to correlate their findings to surrounding areas. Determining how these sandbodies fit into a Viking regional framework became a major objective. The diverse sedimentological interpretations also had to be synthesized and re-examined in light of recent advances in the area of sequence stratigraphy. Since the Willesden Green and Ferrier fields were previously undescribed, an in depth study of the sedimentology and stratigraphy of these sand bodies was considered to be a high priority. As the research progressed, it became apparent that sorting out the complex geology of the Willesden Green area would be pivotal in determining the regional Viking stratigraphy. The central location of the study area allowed correlations to be made southward to Caroline, east to Joffre and northward into the

Crystal field areas. A diverse assemblage of interelated coastal to shallow marine sandbodies, bounded by major stratigraphic markers, was found to be present.

1.2 Problem

Numerous studies have been carried out in an attempt to characterize the diverse sediments of the Lower Cretaceous Viking Formation of Alberta and Saskatchewan. The anomalous juxtaposition of open marine shales and elongate conglomerate-rich sand bodies has offered a unique problem to researchers, and several theories have been put forth to try and explain the problematic offshore transport and alignment the gravels comprising them. Early interpretations suggested sediment dispersal through such diverse mechanisms as shallow marine turbidity currents, storm-currents, and offshore shoaling processes on localized topographic highs.

Recently however, with the advent of the concepts of sequence stratigraphy, an alternative viewpoint has emerged. Several independant field studies have concluded that multiple fluctuations of relative sea level, and major shifts in shoreline position were ultimately responsible for the sedimentology and stratigraphic breaks found within many of the Viking sand bodies. The most significant of these fluctuations are thought to have generated widespread hiatuses across the shallow shelf, caused the incision of large unconformable valleys, and created dramatic lateral shifts in shoreline position.

Unfortunately, detailed regional correlations linking many of the local field areas have not been initiated, and a comprehensive basinwide Viking allostratigraphy has not yet been developed. Many areas in the Viking basin, such as the Willesden Green and Ferrier fields, have been virtually unexamined. Through determination of the patterns of deposition in these areas, a more unified and complete picture of regional Viking deposition can only follow. In an attempt to address these problems, preliminary examination of several of the fields surrounding the research area was carried out to enable the detailed sedimentological observations at Willesden Green to be put into a larger Viking framework. The results of this research follow.

CHAPTER 2 : STRATIGRAPHY AND STUDY METHODS

2.1 Study Area

The detailed study area encompasses a 90 sq mile grid in west central Alberta, covering Townships 39 - 43, and Ranges 4 - 8 west of the fifth Meridian [fig. 2.1]. Within this area an intensive examination of cores and wireline logs was carried out to determine the sedimentology and stratigraphy of the Willesden Green, Ferrier and Gilby B Viking oil and gas fields. Several cores and logs were also inspected along a 129 township bordering area in an attempt to tie this work into concurrent studies carried out by S.D. Davies (pers. comm., 1989) at Caroline, S.A.J. Pattison (pers. comm., 1989) at Crystal, and also to link into the Gilby A and Joffre field areas previously examined by Raddysh (1988), and Downing and Walker (1988) respectively.

2.2 Stratigraphy

The Lower Cretaceous (Upper Albian) Viking Formation of central Alberta and Saskatchewan is part of the Lower Colorado Group, and consists of a dominantly marine sandstone encased between two marine shales; the underlying Joli Fou and the overlying Colorado [fig. 2.2]. It was first defined by Slipper in 1918, and is correlative with the sands of the Newcastle Formation in North Dakota, the Muddy Sandstone of Montana and Wyoming, and the 'J' Sandstone of Colorado (McGookey et al, 1972). In western Canada the Viking formation is equivalent to the Paddy Member of the Peace River Formation in northwestern Alberta (Stelck and Koke, 1987), the Pelican Formation in northeastern Alberta (Boethling, 1977a), the Silt Member of the Ashville Formation in Manitoba (Rudkin,1964), and the Bow

STUDY AREA

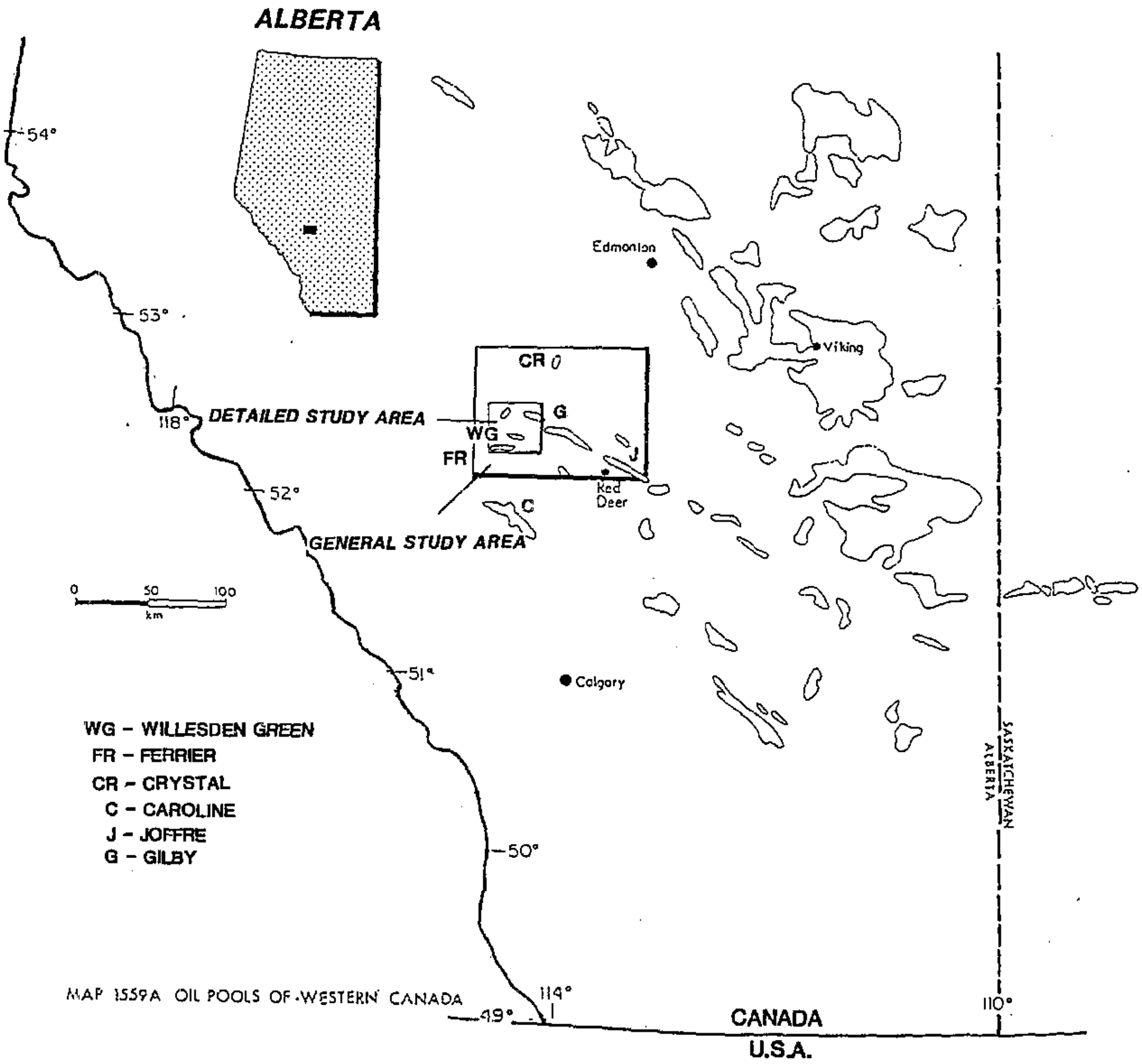


Figure 2.1 - Distribution map of Viking sandbodies in Alberta showing thesis study area.

UPPER ALBIAN STRATIGRAPHIC NOMENCLATURE

CENTRAL ALBERTA

	KOLDIJK 1976	AMAJOR/ LERBEKMO 1980	BEAUMONT 1984 *THIS STUDY*
UPPER CRETACEOUS	*BASE FISH SCALES*		
LOWER CRETACEOUS COLORADO GROUP *UPPER ALBIAN*	MOWRY FORMATION	LLOYDMINSTER SHALE	*COLORADO SHALE*
	VIKING FORMATION	VIKING FORMATION	*VIKING FORMATION*
	JOLI FOU FORMATION	JOLI FOU FORMATION	*JOLI FOU FORMATION*

Figure 2.2 - Stratigraphic Nomenclature (modified from Raddysh, 1986).

Island Formation in southwest Alberta (Glaister, 1959). The Viking Formation ranges from 15 to 45 m thick over most of central Alberta, progressively thins from southwest to northeast, and eventually pinches out in the vicinity of St. Paul (Tp. 58, Rg. 9 W4M) (Gammell, 1955). The Viking sandstones can be found only in the subsurface, and display a gentle regional dip of approximately 2 degrees towards the southwest.

Underlying the Viking Formation are the dark marine shales of the Joli Fou Formation. Originally designated by Stelck in 1958, the Joli Fou represents the initial transgressive phase of the Kiowa-Skull Creek Marine Cycle, and is correlative with the shales of the Skull Creek Member in Manitoba and the Dakotas, the Kiowa Member of Kansas, and the Thermopolis Member of Montana (Caldwell, 1984). In the subsurface of Alberta and Saskatchewan the Joli Fou shales generally range between 15 to 35 m thick, but rapidly thin in the deformed belt to the west. To the south the Joli Fou coalesces with the Viking Formation and both grade laterally into the thick Bow Island Formation (Glaister, 1959).

Overlying the Viking Formation is the Colorado Shale, a widespread unit of black, silty marine shale which reaches thicknesses of up to 61 m (200 ft) (Evans, 1970). Several informal names have been assigned to this strata including the Lloydminster Shale (Tizzard and Lerbekmo, 1975), the Colorado Shale (Stelck, 1958) , and the Un-named Shale (Evans, 1970). In this study the upper shale will be referred to as the Colorado Formation. Equivalent units in the American Great Plains include the Mowry and Graneros Formations (McGookey et al, 1972). The top of the Colorado Shale is marked by the Base of Fish Scale Marker, an interbedded mudstone/graded sandstone bed that contains a high percentage of phosphatic fish-skeletal debris (Simpson, 1979). The lower contact of this sandstone gives a distinctive wireline log response and marks the boundary between the Lower and Upper Cretaceous (Stelck and Armstrong, 1981).

2.3 Biostratigraphy and Chronostratigraphy

The lack of diagnostic foraminiferal assemblages within the Viking Sandstone makes precise biostratigraphic dating of the formation difficult (Stelck, 1958). The Viking Formation lies between the underlying *Haplophragmoides gigas* Zone of the Joli Fou Shale, and the overlying *Miliammina manitobensis* Zone situated between the top of the Viking sand and the Base of Fish Scale Marker (Caldwell et al, 1978) [fig.2.4]. The *Miliammina manitobensis* Zone has been dated at approximately 98 Ma (Stelck, 1975), and puts the Viking Formation in the middle Late Albian.

Potassium-Argon radiometric dates obtained from bentonites within the Viking Formation in south-central Alberta (Tizzard and Lerbekmo, 1975), gives the formation an age of approximately 100 Ma (+/- 2).

2.4 Internal Viking Stratigraphy - Introduction

A basinwide internal Viking stratigraphy is currently being developed at McMaster University (A.D. Reynolds, pers. comm., 1989). Simultaneous studies include an examination of the Harmattan field by S.W. Hadley (pers. comm., 1989), Caroline and Garrington fields by S.D. Davies (pers. comm., 1989), Crystal by S.A.J. Pattison (pers. comm., 1989), Chigwell by Raychaudhuri (1989), and Viking-Kinsella by J.J. Bartlett (pers. comm., 1989). Earlier works carried out by Power (1988) at Joarcam, Downing and Walker (1988) at Joffre, and Raddysh (1988) at Gilby A-B were also incorporated into the study. Individual research areas were carefully overlapped to ensure that no 'information gaps' existed between fields, and to make large scale regional correlation easier [fig. 2.3].

2.5 Viking Stratigraphy at Willesden Green

As research progressed at Willesden Green, it became apparent that certain distinctive facies packages occurred repeatedly throughout the study area. Several of these packages displayed a preferred sequence of vertical stacking and also showed regularly occurring pebble-mantled bounding surfaces which could be traced over large distances. By recording the vertical and lateral relationships of these depositional packages and bounding surfaces, it was discovered that their associations started to become predictable in their occurance. Larger scale correlation between fields became possible, and careful logging and identification eventually enabled the development of a coherent Viking allo-stratigraphy.

Figures 2.4 and 2.5 show the Viking Stratigraphy as it occurs in the Willesden Green study area. It can be seen that the Viking Formation is approximately 30 m thick, and consists of 5 members, separated by 4 major erosion surfaces. Laterally heterogenous depositional sequences were identified and correlated through extensive mapping of pebble-mantled bounding surfaces. These contacts separate distinctive packages of sediment, and usually mark abrupt vertical changes in depositional style. The large number of wells penetrating the Viking Formation provide an excellent basis for correlation, and identification of individual members and specific surfaces can be carried out with a high degree of confidence.

Each Viking allomember is defined according to the North American

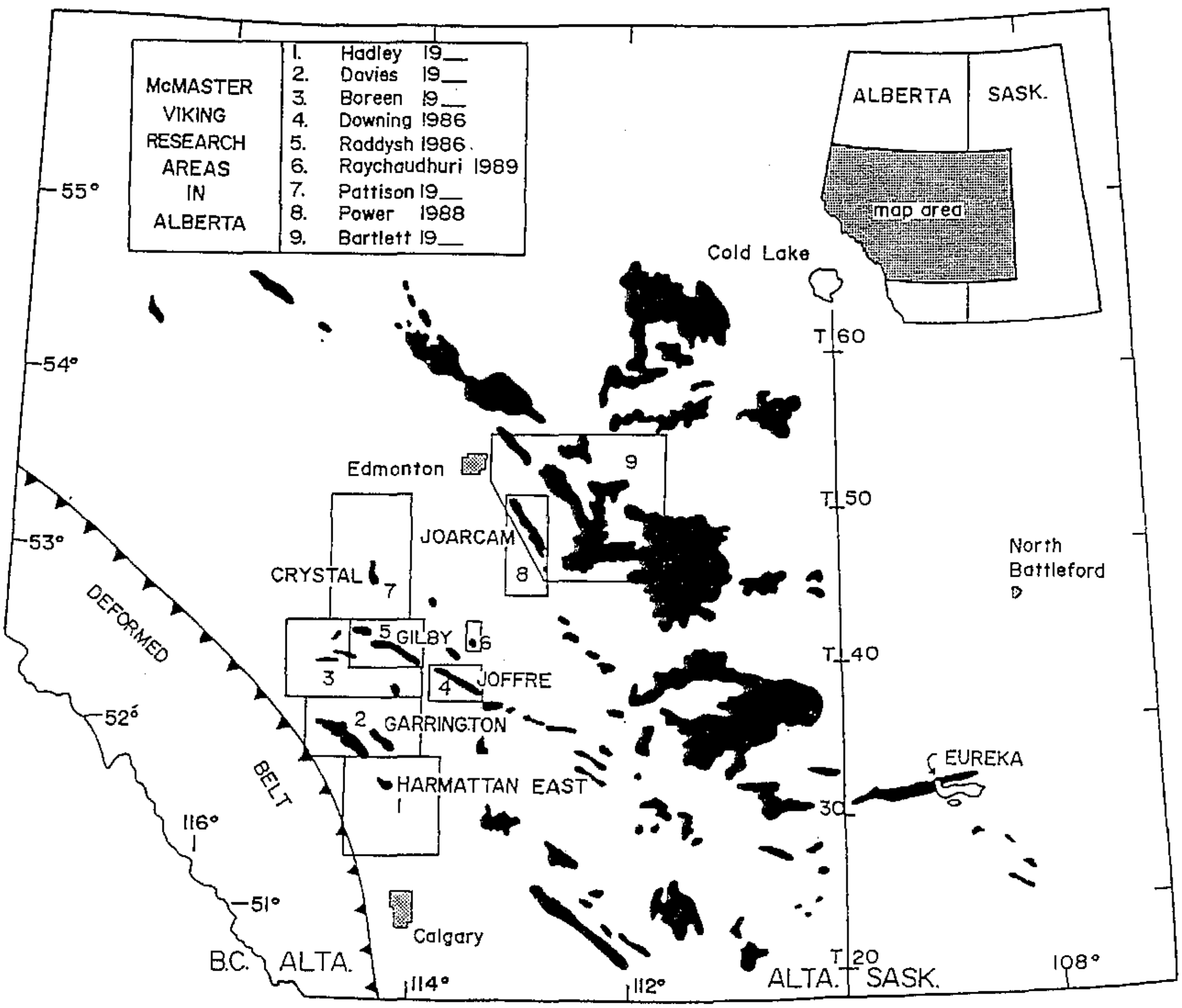


Figure 2.3 - McMaster Viking Research Areas in Alberta.

Commission of Stratigraphic Nomenclature (NACSN, 1983, p.865) as "...a mappable stratiform body of sedimentary rock that is defined and identified on the basis of its bounding discontinuities". Individual Viking erosion surfaces are numbered consecutively upward from VE1 to VE4, and stratigraphically separate allomembers A to E [fig. 2.4]. A short description outlining the individual members and bounding surfaces follows:

The **base of the Viking Formation** is defined at the inflection point of the first prominent shoulder of the resistivity profile above the Joli Fou Formation [fig. 2.4]. In core, this contact is veneered by a few scattered granules, and marks a break between the underlying black Joli Fou Shales and overlying, slightly siltier shales of the Viking Formation.

Member A characterizes the interval between the base of the Viking and VE1, and has its most prominent expression in the Willesden Green area. This member consists of a single small scale, silty coarsening-upward cycle, the top of which gives a prominent, identifiable 'kick' on resistivity logs (LM4).

VE1, which is mappable throughout much of the Viking basin (A.D. Reynolds, pers. comm., 1989), in the Willesden Green area is expressed only as a correlative conformity at the top of the member A sequence, and is identified by log marker 4 (LM4).

Above VE1, **member B** is subdivided into separate subunits B1 and B2, which are defined by the presence of two gradational small scale coarsening-upward cycles, similar to that of member A. The top of the lowermost cycle (B1) is identified by log marker 3 (LM3). The uppermost cycle (B2) displays a distinctive double bentonite which can be correlated across much of the Viking basin.

Member B is abruptly truncated by a thin veneer of coarse-grained sandstone and pebbly mudstone which locally appears to split into up to three vertically distinct pebble covered horizons. The stratigraphically lowest of these is the VE2 contact below Member C. **VE2** defines a broad unconformable valley incision in the Willesden Green area, that is correlative with the basal erosion surface of the Gilby A sand body (H.K. Raddysh, 1988), and the Crystal vally incision (S.Pattison, pers. comm., 1989).

At Willesden Green, **Member C** is a sand and conglomerate rich unit defined by an extreme resistivity inflection, sharp upper and lower contacts, and a blocky log profile.

VE3 defines, topographically, a rather flat surface that erosively truncates the top of member C, regionally scours into the coarsening-up cycles of member B, and is overlain by member D.

Throughout most of the Willesden Green area **member D** is a shale rich member less than 2 m thick. This unit does however become dramatically thicker and sandier southward, and displays a marked coarsening-upward trend.

The uppermost Viking Erosion surface, **VE4**, erosively scours into all underlying members. This contact defines a step-like topography, with up to 7 m of erosional relief, and is consistantly veneered by the muddy conglomerates of member E.

Member E consists of an assemblage of coarse grained sandstones and muddy pebble conglomerates, which locally thicken to form elongate bodies up to 2.9 m thick, and which gradationally interfinger with black shales of the overlying Colorado Formation.

In this stratigraphic nomenclature, the top of the Viking Formation is lithologically defined at the top of the stratigraphically highest conglomerate horizon, which translates into the inflection point of the uppermost prominent resistivity shoulder below the Colorado Formation (indicated by log marker 2 (LM2)).

In the Willesden Green study area Log Marker 1 (LM1) was used as a datum on all maps, and shows up on all well logs as a distinctive, sharp resistivity kick which lies roughly parallel to the Base of Fish Scales [fig. 2.4]. In core this marker consists of one or more thin siltstone beds, often sideritized, situated within the black Colorado Shales. The Base of Fish Scales was not used as a datum (except on regional sections), since Log Marker 1 (LM1) was found to be as regionally reliable and in closer proximity to the Viking coarse sediment package.

The Willesden Green study area is the only area where all 5 members, and 3 of the 4 Viking internal erosion surfaces can be found in core. The typically complex nature of the interaction of these surfaces and members is also readily demonstrated [fig.2.5]. A detailed explanation and step by step development of the individual Viking members is given in following chapters.

2.6 <u>Database and Method</u>

The data base used for this study comprises 127 measured cores and 514 well logs from a 25 township area shown in figure 2.6. All available Viking cores and most logs were examined in this area which encloses townships 39-43, and ranges 4-8 W5. Most of the isopach maps and surface diagrams which follow are based on this area. Several additional cores and logs were also inspected along a 129 township grid bordering the

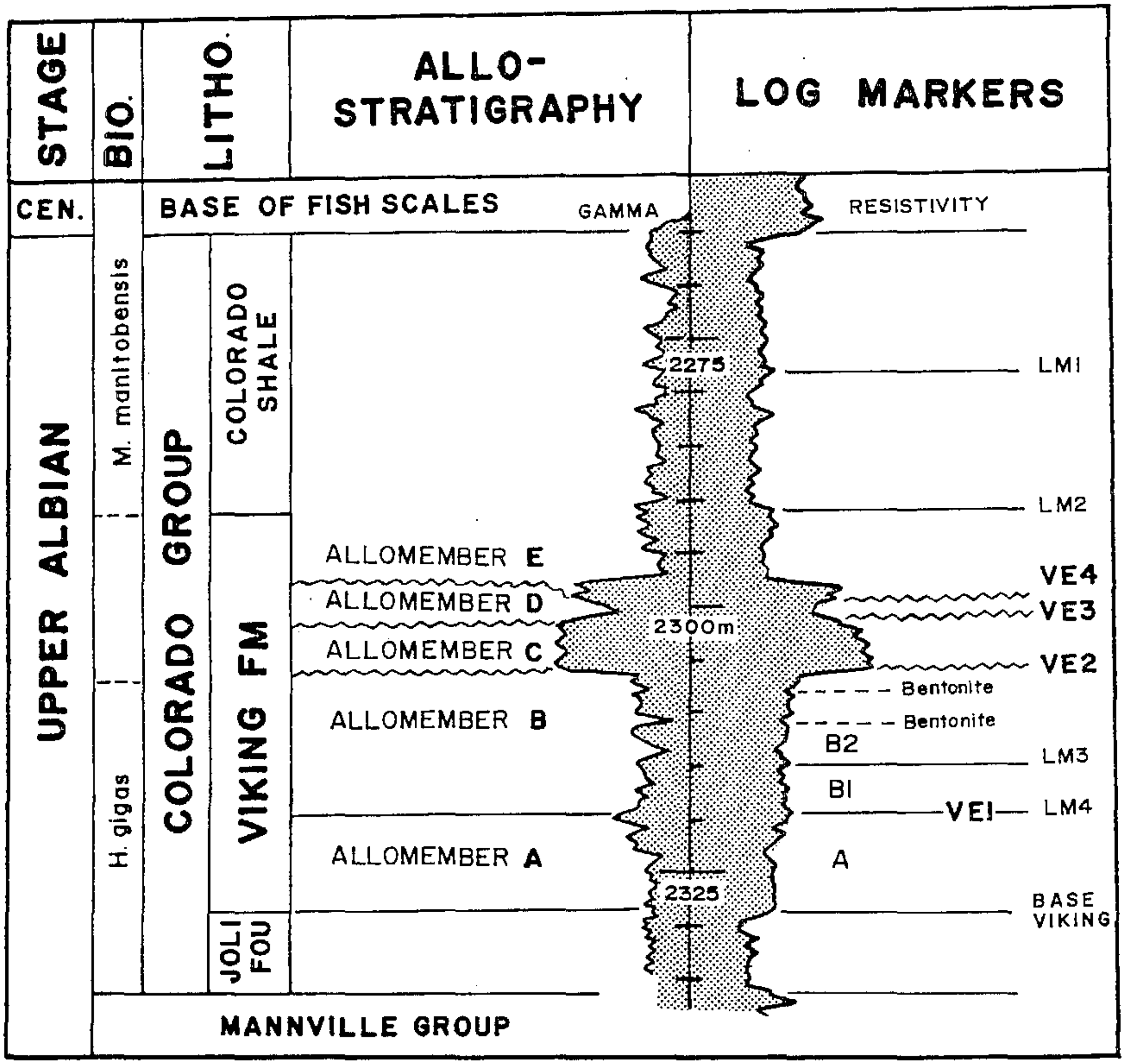


Figure 2.4 - Viking Stratigraphy at Willesden Green.

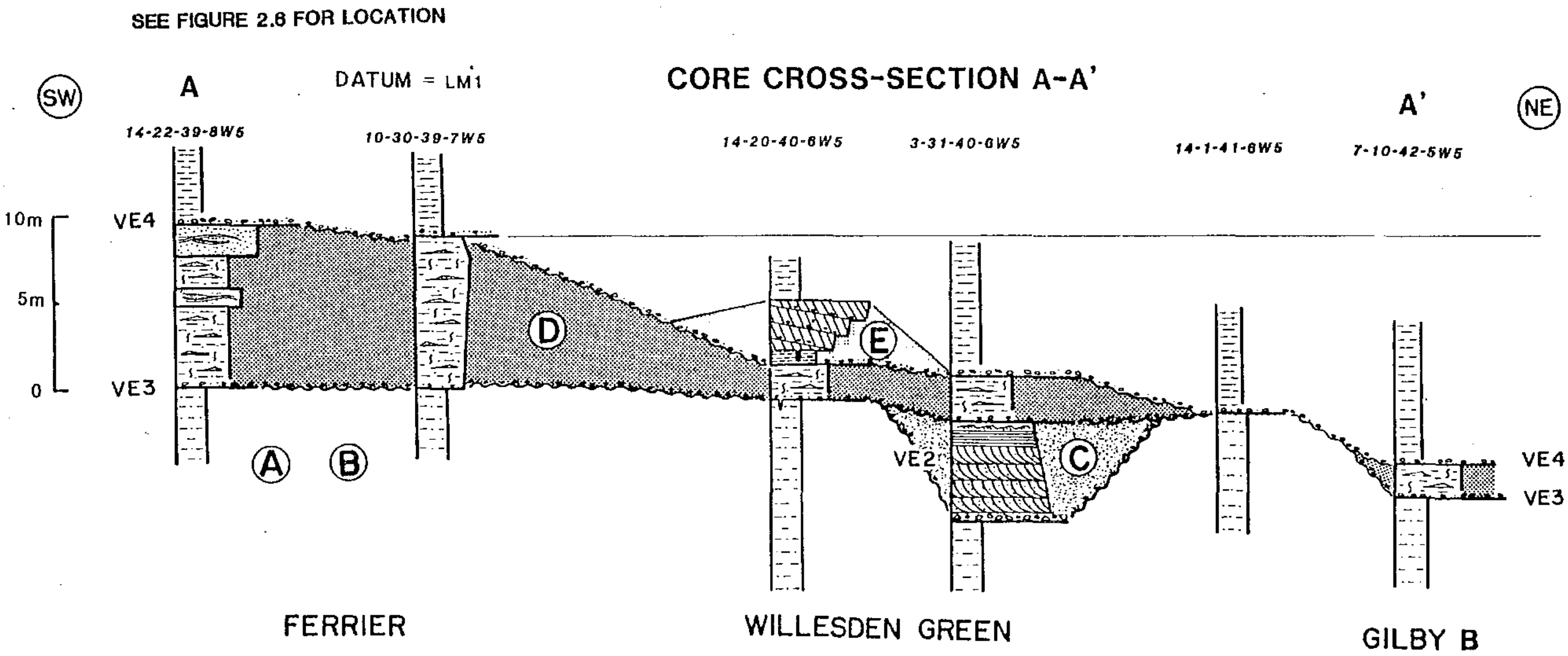


Figure 2.5 - Core Cross Section A - A' showing Viking Stratigraphy in the Willesden Green Area.

detailed area, in an effort to tie into the Gilby A, Joffre, Caroline and Crystal field areas [fig. 2.7]. Locations of core and log cross-sections presented in this thesis are indicated in figures 2.6 and 2.7.

All cores were examined at the E.R.C.B. core laboratory in Calgary, Alberta. Individual cores were measured in detail to determine grain size, and physical and biogenic structures. These observations allowed individual facies to be delineated, and a detailed facies scheme to be developed. Photographs were taken of continuous boxes of core, as well as shots of individual facies and facies contacts. A written description of each core was also recorded, and core cross-sections were assembled to allow correlation between wells. Several of the cores were sampled to facilitate a more detailed petrologic examination which was carried out back at McMaster University.

The 514 wireline logs examined consist primarily of resistivity and micro-resistivity profiles. These are the most available logs in the study area and as such, provided the consistency needed for regional correlation. Where available, gamma-ray logs were also used to confirm the resistivity picks. In most cases the resistivity response to internal core changes is quite good, and detailed correlations can be made with a high degree of confidence; where several core markers are in close vertical proximity however, associated log responses are occasionally limited by inadequate resolution.

2.7 Viking Palaeogeography

The Viking Formation was deposited as part of the Kiowa-Skull Creek Marine Cycle (Kauffman, 1984) [fig. 2.8d], and is believed to be the expression of a globally extensive transgressive-regressive event. Just

WILLESDEN GREEN STUDY AREA

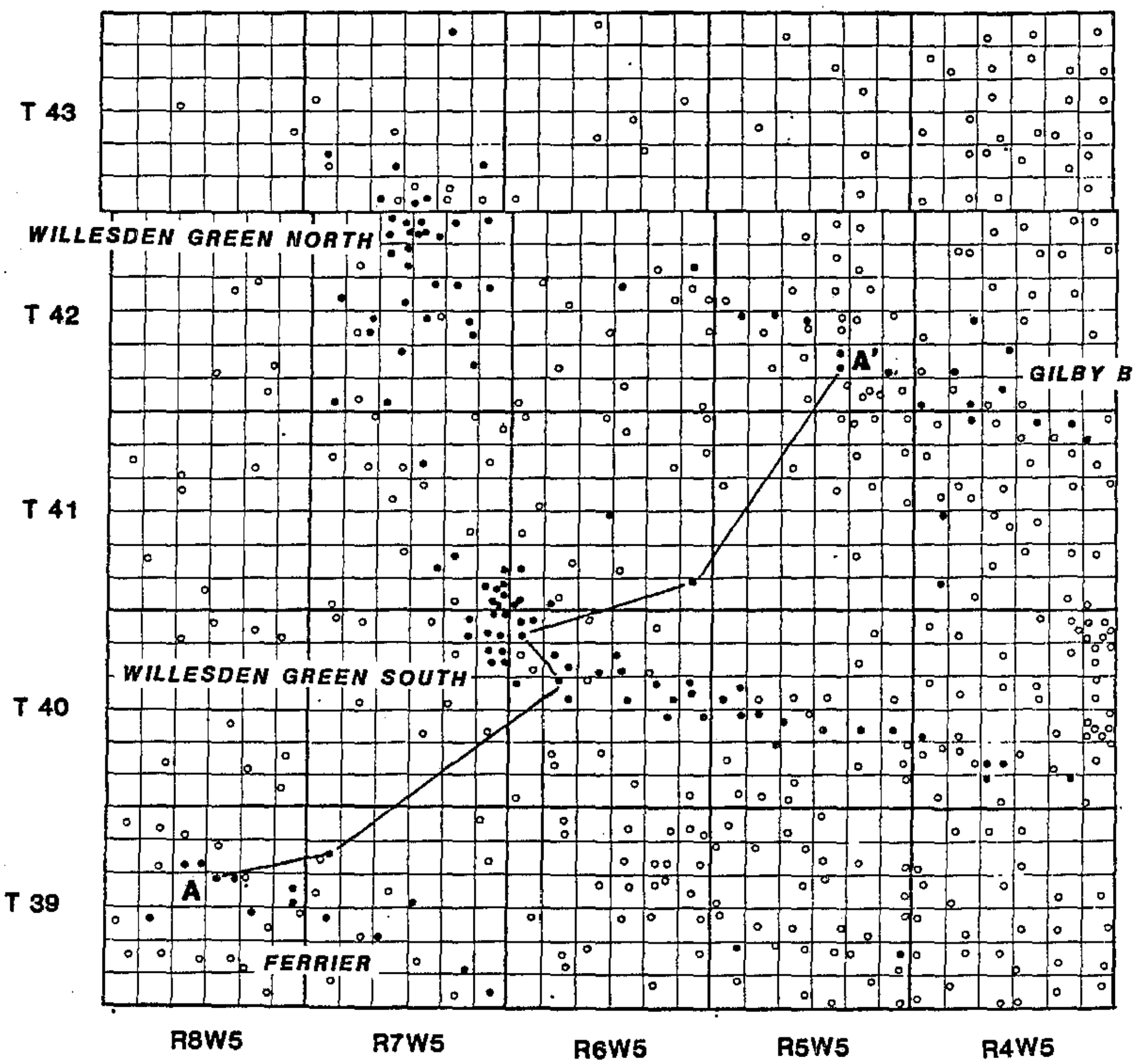


Figure 2.6 - Base map of the Willesden Green study area showing location of cross-section A-A'. Open circles show locations of well logs and dark circles indicate cores examined in this study. Individual oil fields are roughly delineated by concentrations of cored wells.

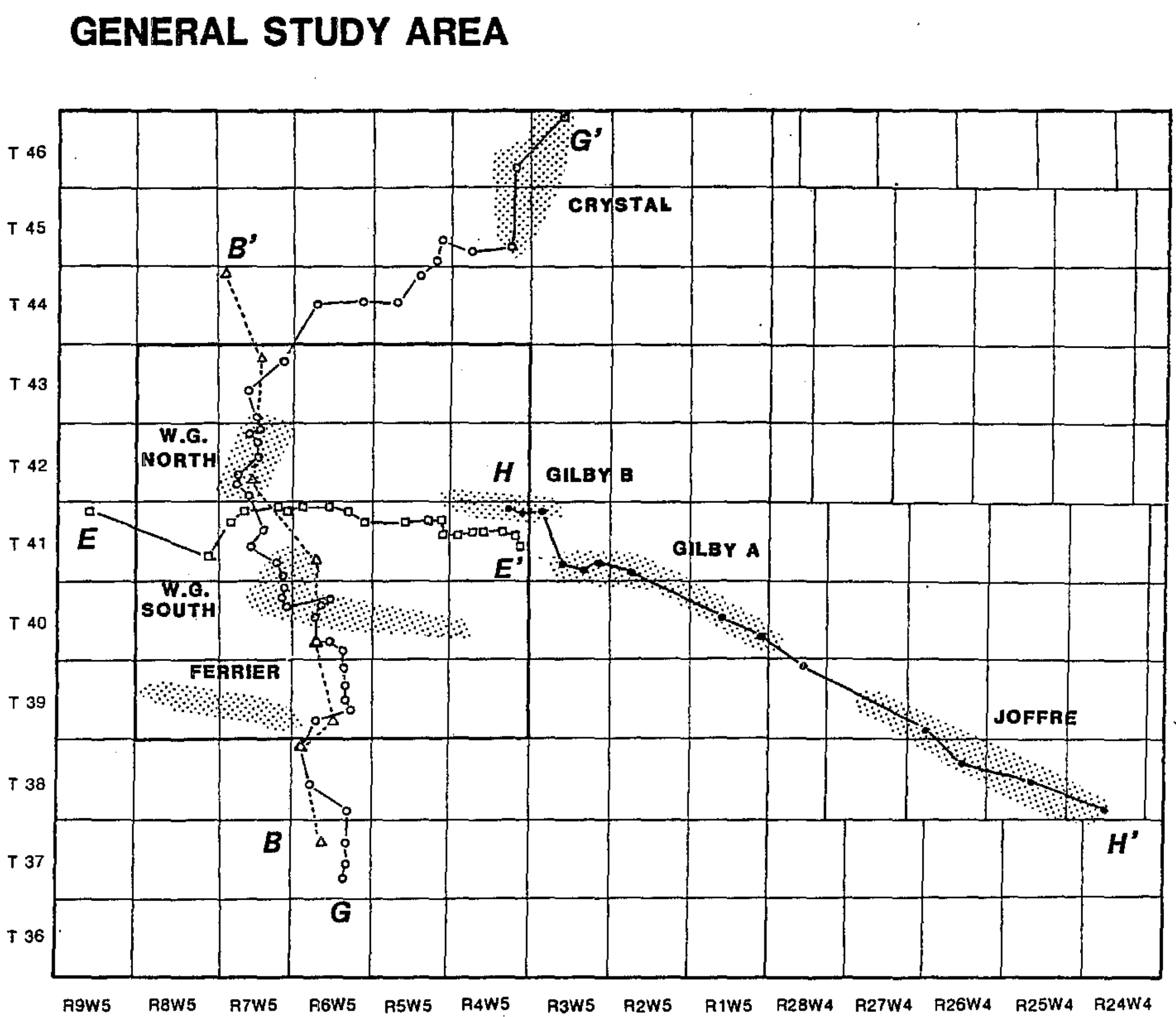


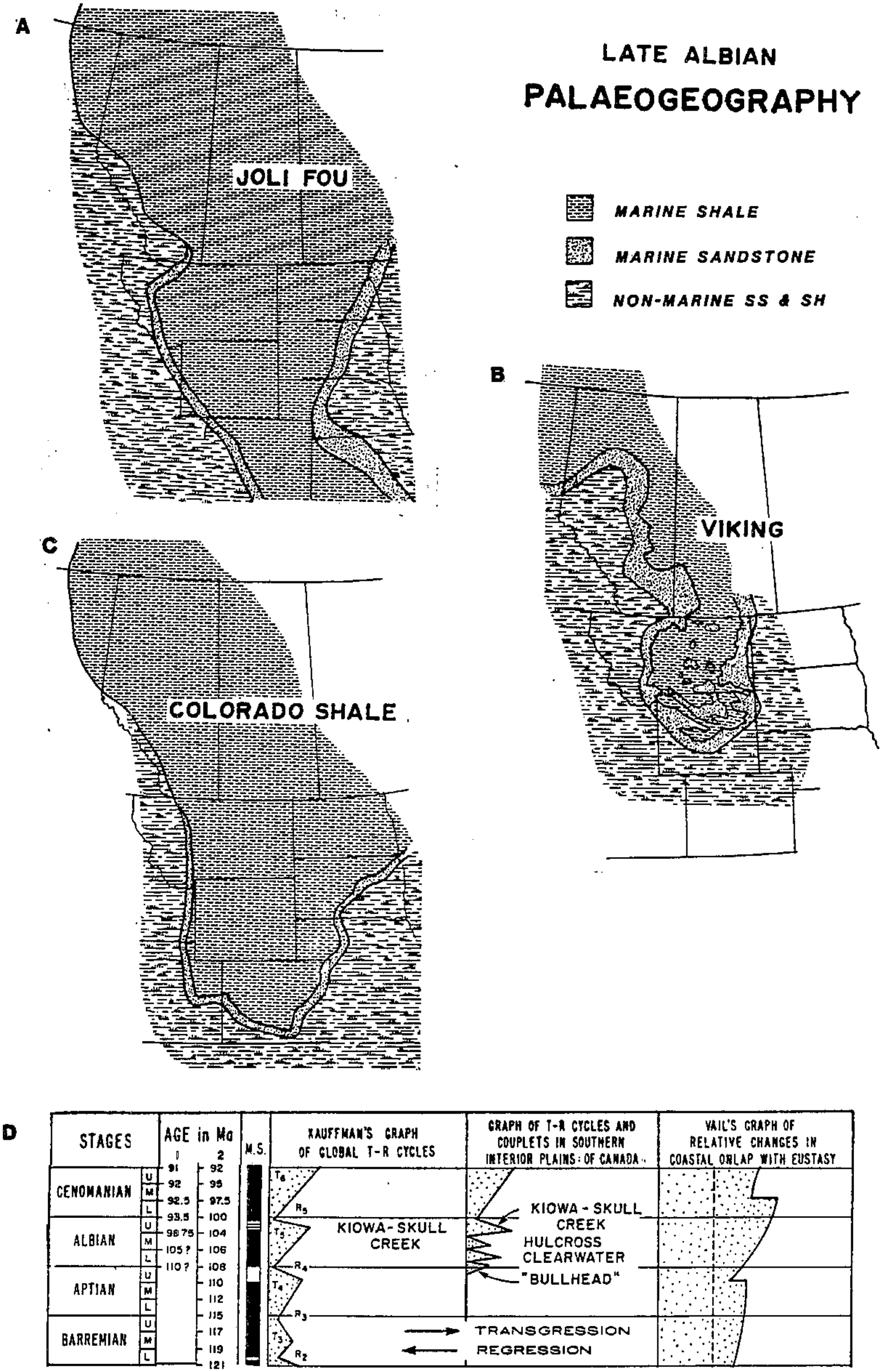
Figure 2.7 - Map of the general study area showing location of Viking oil fields and stratigraphic cross-sections discussed later in the text.

prior to Viking deposition the Kiowa-Skull Creek marine basin extended from the northern limits of the present-day District of Mackenzie to the Gulf coastal states, and effectively split the North American continent in two. Shales of the Joli Fou Formation of Alberta and Saskatchewan were deposited during this period (Caldwell, 1984) [fig. 2.8a].

A sudden regression related to global sea-level drop 97 million years ago (Vail et al, 1977; Haq et al, 1987; Kauffman, 1984) marked the beginning of a second slow transgressive pulse in which the Viking and equivalent sands were deposited. As the regression began the sea separated along the Transcontinental Arch creating a drainage divide through southeastern Wyoming and northwest Nebraska (Weimer, 1978). At the same time the ongoing tectonic activity in the west provided a clastic source for various freshwater to shallow marine depositional environments along the western margin of the seaway (Caldwell, 1984) [fig. 2.8b].

A final rise in relative sea-level, associated with the beginning of the Greenhorn transgressive-regressive event, marked the end of Viking deposition, and blanketed the underlying Viking sands with dark marine shales of the Colorado Formation [fig. 2.8c].

During this period, an actively rising Cordillera, and several related tectonic features apparently influenced deposition along the western margin of the seaway. The most notable of these include the Peace River High, the Sweet Grass Arch, and the West Alberta Basin [fig. 2.9].



A
JOLI FOU
LATE ALBIAN
PALAEOGEOGRAPHY
MARINE SHALE
MARINE SANDSTONE
NON-MARINE SS & SH
B
VIKING
C
COLORADO SHALE
D
STAGES
AGE in Ma
1
2
M.S.
KAUFFMAN'S GRAPH OF GLOBAL T-R CYCLES
GRAPH OF T-R CYCLES AND COUPLETS IN SOUTHERN INTERIOR PLAINS OF CANADA
VAIL'S GRAPH OF RELATIVE CHANGES IN COASTAL ONLAP WITH EUSTASY
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
U
M
L
91
92
92.5
93.5
98.75
105 ?
110 ?
92
95
97.5
100
104
106
108
110
112
115
117
119
121
KIOWA-SKULL CREEK
KIOWA - SKULL CREEK
HULCROSS
CLEARWATER
"BULLHEAD"
TRANSGRESSION
REGRESSION

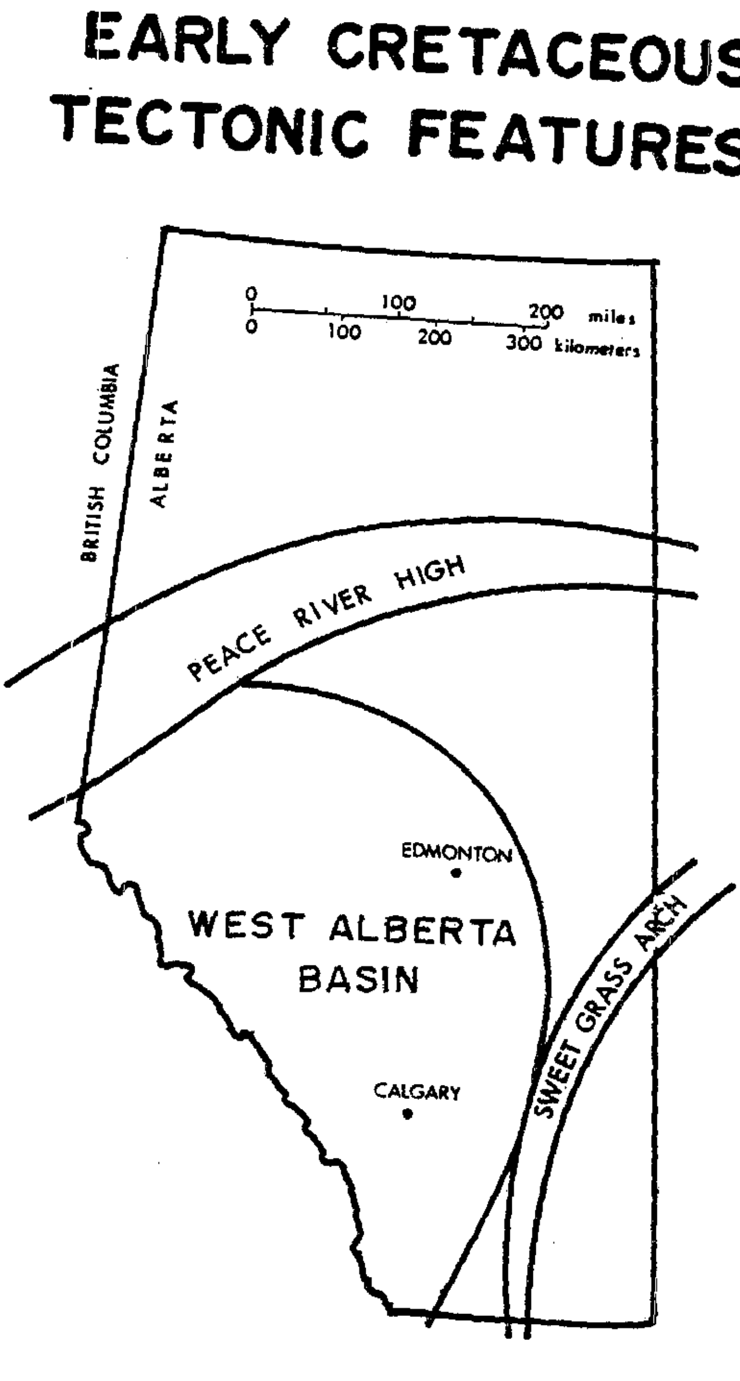


Figure 2.9 - Early Cretaceous tectonic features (modified from Stelck, 1975)

CHAPTER 3 : LITERATURE REVIEW

3.1 History of Ideas

Numerous studies have been carried out in an attempt to characterize the diverse sediments of the Lower Cretaceous Viking Formation since it was first defined by Slipper in 1918. The widespread distribution of pebble horizons within the Viking sands has always fascinated researchers, and several theories have been put forth to try and explain the problematic transport of the gravels comprising them. Pioneering work by Beach (1956) and Roessingh (1959) interpreted the Viking sandstones as shallow marine turbidity current deposits. DeWiel (1956) envisioned sediment dispersal by longshore currents in front of a shifting strand line, and a similar shoreface and offshore bar interpretation was provided by Stelck (1958). A later proposal by Koldijk (1976) suggested storm-driven deposition of the coarse-sediment fraction, and the formation of long, narrow deposits offshore by shoaling processes on localized topographic highs. Several subsequent studies (Evans, 1970; Shelton, 1973; Tizzard and Lerbekmo, 1975; Boethling, 1977b) contributed to a broad consensus that the Viking sands were deposited under shallow marine conditions ranging from coastal-shoreface to inner shelf settings.

3.2 Recent Interpretations

In the past decade, renewed economic interest in the Viking Formation, and the advent of the concepts of sequence stratigraphy (Vail et al, 1977) have led to a series of Viking re-interpretations. Most of these interpretations invoke eustatic sea level changes and major shifts of shoreline position to explain the diverse sedimentological features and stratigraphic breaks which occur within the Viking sandstones.

Amajor's (1980) regional subsurface study of the Viking sandstones in central Alberta and southwestern Saskatchewan concluded that deltas located in southern and northwestern Alberta supplied sediment during a still-stand shoreline condition at the beginning of Viking time. According to Amajor, consecutive southwestward shifts in the loci of sand deposition occurred during subsequent rises in relative sea level, and resulted in the configuration of shale-encased sand bodies seen today. This is very similar to Beaumont's 1984 interpretation.

Beaumont concluded that "a basically transgressive model with minor regressive phases best explain[ed] deposition of the Viking Formation of central Alberta" (1984, p. 173). This conclusion was based on :

1) an apparent unconformity at the base of the Viking
2) the correlation of a series of shingled, retrograding sediment sheets
3) the presence of 'submerged' deltaic deposits
4) thick, discontinuous conglomerate beds preserved 320 kms (200 miles) from the preserved Viking shorelines

Beaumont hypothesized that in the earliest Viking time coarse sediment was deposited onto the Viking shelf by subaerial stream transport during a relative lowstand. Subsequent sea level rise caused a continuous overall transgression punctuated by minor regressive pulses in which retrogradationally stacked sediment sheets were deposited. On each of these sheets, he suggested, were superimposed linear sand bodies, formed by restructuring of the sand by the "shelf hydraulic regime" (1984, p.171).

More recent papers which document detailed facies relationships and depositional environments of specific areas include Leckie (1986), Hein et al (1986), Pozzobon (1987), Power (1988), Raddysh (1988), Reinson et al (1988), and Downing and Walker (1988). In each of these studies multiple fluctuations of relative sea level are called upon to explain the sedimentology and stratigraphic breaks found within the local Viking sand bodies; however, no detailed regional correlations were carried out.

The most recent work by Leckie and Reinson (in press) attempts to correlate the Late Albian Viking, Peace River and Boulder Creek formations of Alberta and northeastern British Columbia. Several major unconformities are documented within what is interpreted to be an overall basinwide transgressive phase. It is suggested that from upper Viking time onward relative sea level was rising steadily, but was punctuated by at least two lowstands.

The study by Leckie and Reinson takes a first step towards integrating isolated fields at Caroline, Gilby and Crystal into a unified picture of Viking deposition. Their research, in conjunction with all previous efforts, gives us insights into many of the initial problems posed by this unique stratigraphic unit. Deposition appears to have been closely tied to dynamic changes in relative sea level. The most significant of these fluctuations caused the incision of large unconformable valleys, and created dramatic lateral shifts in shoreline position. The sedimentological expression of these events is apparent in the anomalous superposition of coarse grained conglomeratic sediments encased in deep marine shales. Determining the patterns and causes of these variations however, are problems that have remained unresolved, and much of the detailed work necessary for convincing basinwide correlation and interpretation has yet to be carried out. This study attempts to address some of these problems, and hopefully adds a few more pieces to the Viking puzzle.

CHAPTER 4 : FACIES ASSOCIATIONS AND BOUNDING SURFACES

4.1 Introduction to Facies Descriptions

The Viking Formation in the Willesden Green study area has been divided into 5 major facies associations based upon observation of over 125 cores. Each facies association is defined by a distinctive lithology and assemblage of physical and biological structures occurring between discrete bounding surfaces. Both vertical and lateral sequence changes within a given assemblage are discussed, as well as detailed examination of surfaces bounding the individual assemblage packages. A vertical reference sequence, detailed facies and contact photographs, core and log cross-sections, and isopach maps are provided for each facies association. Figure 4.1 offers a diagramatic listing of individual facies, and acts as a guide to deciphering the numerous schematic core diagrams. A brief interpretation of depositional environment and palaeogeographic reconstruction concludes each chapter.

The facies associations are presented in stratigraphic order within the formation, proceeding from the earliest deposited association. In this manner, an internal stratigraphy and depositional history of the Viking Formation are sequentially established.

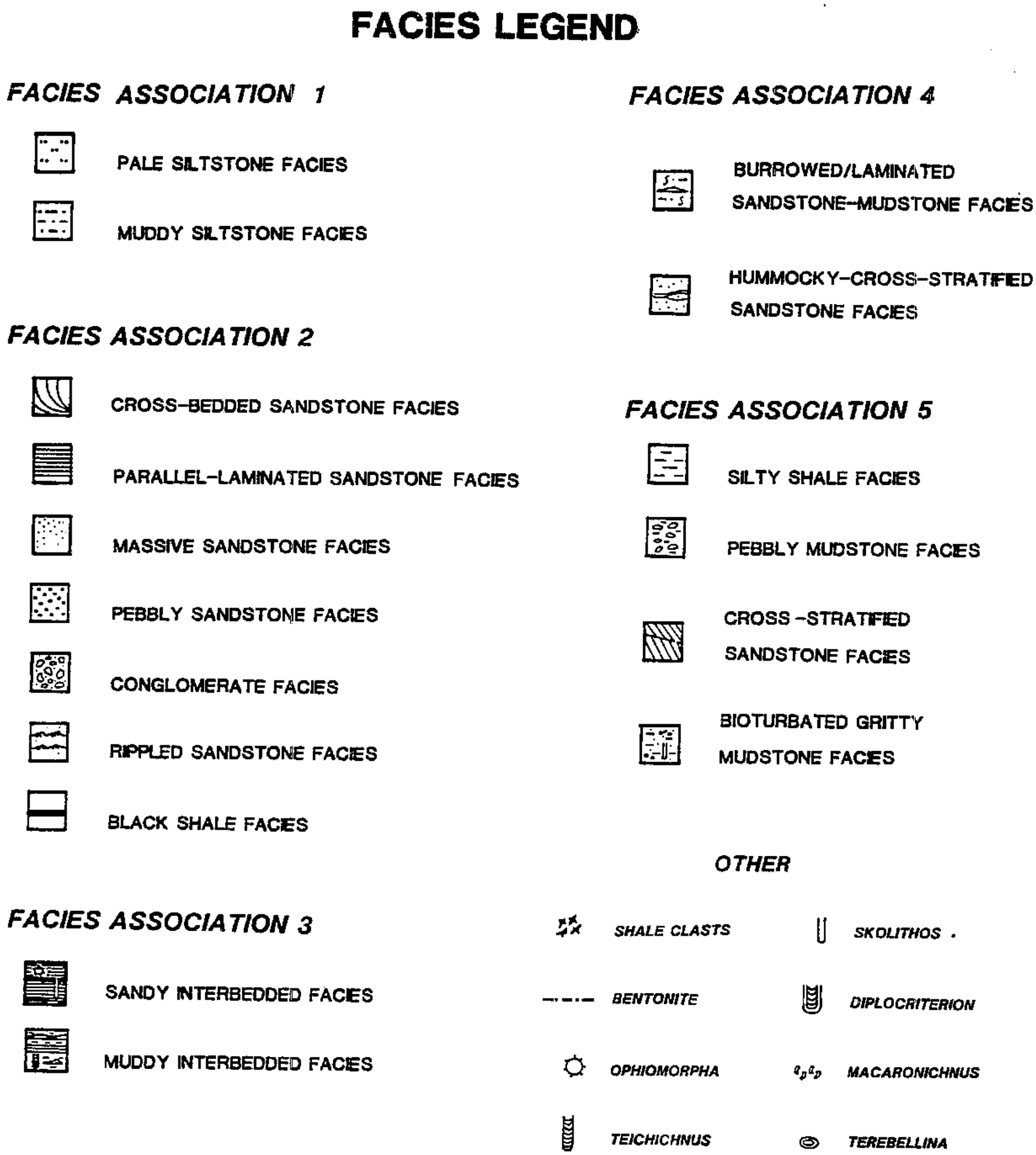


Figure 4.1 - Viking Facies Scheme at Willesden Green.

CHAPTER 5 : FACIES ASSOCIATION 1 (BASAL SILTSTONE ASSEMBLAGE)

MEMBERS A + B

5.1 Introduction

The basal siltstone assemblage characterizes the lower part of the Viking Formation, and has been observed as a relatively uniform facies sequence throughout many parts of south-central and central Alberta. It is equivalent to the "regional shelf-shoreface facies" of Reinson et al (1988), and the "basal siltstone association" of Downing and Walker (1988). This unit is ubiquitous throughout the study area and consists of a series of coarsening-upward sequences comprising two main facies: bioturbated muddy siltstones and bioturbated sandy siltstones.

5.2 Facies Description

Muddy Siltstone Facies

The muddy siltstone facies was defined by Downing and Walker (1988), and consists of a homogenous non-fissile mixture of silt, clay and minor very-fine sand [fig. 5.1]. Commonly thorough churning by bioturbators gives a mottled and structureless appearance to this facies, making individual traces very difficult to determine. Recognizable burrows are dominantly horizontal and include Terebellina, Zoophycos, and Helminthopsis. Bivalves and fish remains frequently occur along bedding planes [figs. 5.2, 5.4]. Although this facies generally has a rather homogenous black- to dark grey appearance, faint horizontal layering occasionally occurs in the form of delicately laminated silt beds. Fully preserved beds are very rarely seen, however when they do occur, they are usually thinner than 1 cm thick, have sharp bases and bioturbated tops, and display undulatory to parallel laminated internal structure. Rare bentonitic silt layers occur along some parting planes, and dark green nodules of pyrite up to 2 cm in diameter are common in this facies.

The muddy siltstone facies reaches a maximum thickness of 4.5 m in the study area, and is prevalent towards the base of each of the small-scale coarsening-upward sequences seen in Member A. Within the sequences the muddy siltstone facies consistantly grades upward into a pale siltstone facies.

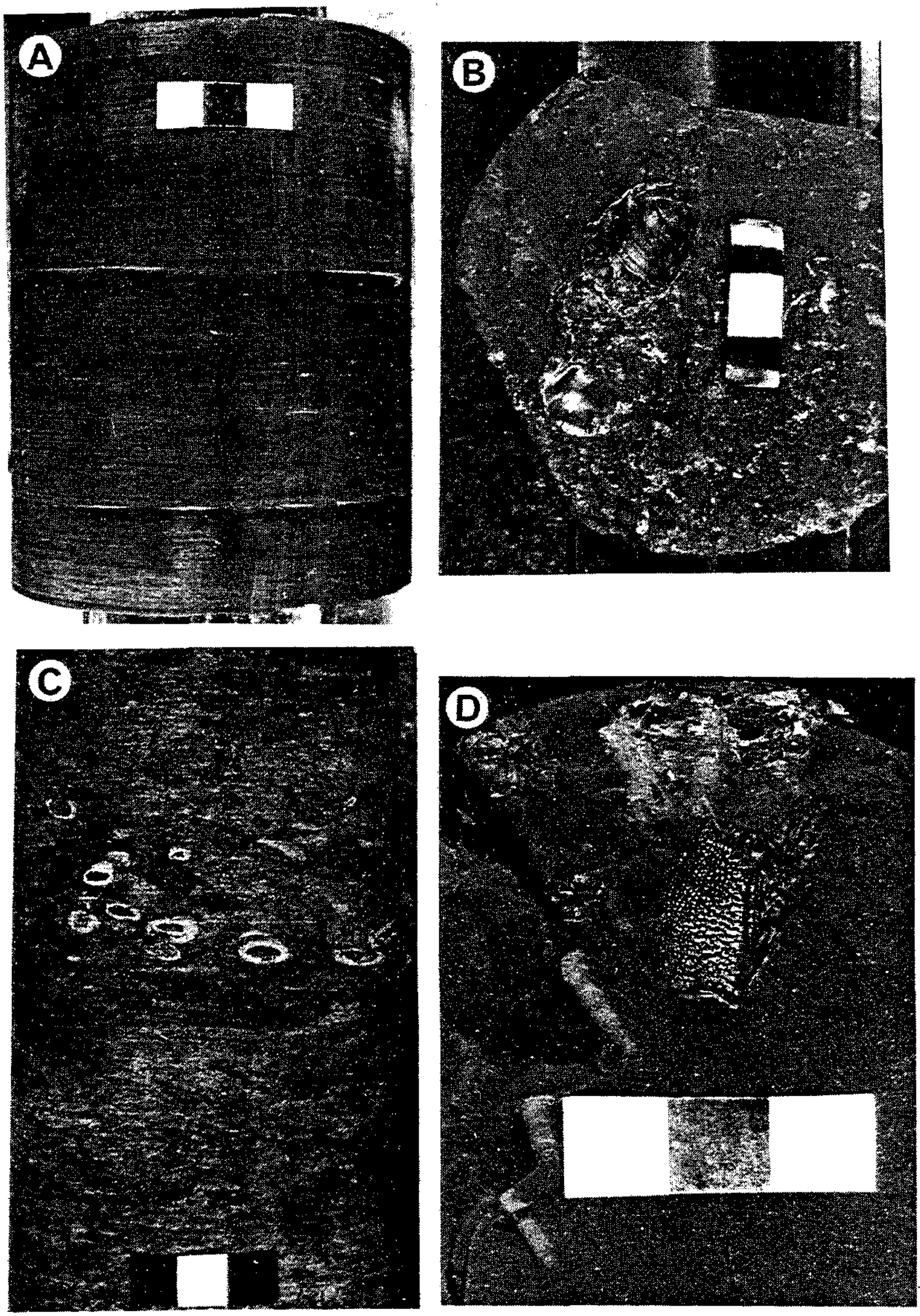
Pale Siltstone Facies

The pale siltstone facies is equivalent to the pale gray siltstone facies of Downing and Walker (1988), and is a bioturbated mixture of silt, clay and minor very-fine sand [fig. 5.3]. A marked increase in the ratio of silt and sand to clay causes this facies to be distinctly lighter in colour than the muddy siltstone facies. It consistantly occurs gradationally overlying the muddy siltstone facies. A characteristic trace fossil assemblage is present, and individual burrows are generally well defined by contrasts in clay and sandstone fill. The dominant burrows appear to represent a mix of Zoophycos and Cruziana ichnofacies, with a domination of horizontal and diagonal burrowing forms. Individual traces include Asterosoma, Terebellina, Zoophycos, Chondrites, Rhizocorallium, Conichnus, Cylindrichnus, and Helminthopsis.

Physical structures are rare and consist primarily of discrete sandstone beds 1 to 3 cm thick, with sharp bases, undulatory to parallel laminated internal structure, and bioturbated tops. Complete beds are only rarely preserved however, due to the intensity of the burrowing.

5.3 Vertical Sequence

In the study area Association 1 consists of 3 distinct coarsening-


A
B
C
D

upward sequences which can be traced and correlated regionally in all directions. Each coarsening-upward cycle imparts a distinct log signature which can easily be matched to changes in core lithology. Well 6-12-43-7 W5 was chosen as the Association 1 reference well since all three coarsening-upward sequences are well developed and can be easily detected in both core and on well log [fig. 5.5]. The top of each cycle is expressed by a pronounced "kick" on resistivity logs (and gamma-ray) which can be used to correlate individual sequences A, B1 and B2 throughout the study area. A pair of distinctive bentonitic markers which occur in cycle B2 can also be correlated in log and in core across the study area. Although the bentonites are not present in the reference well due to erosive truncation by overlying strata, they can be clearly seen in figure 2.4.

5.4 Contacts

In the Willesden Green study area, the lower contact of the basal siltstone assemblage abruptly marks the base of the Viking Formation, which is defined at the inflection point of the first prominent shoulder of the resistivity profile above the Joli Fou Formation. In core 10-35-40-7W5, this contact is veneered by a few scattered granules, and marks a distinct break between the underlying black Joli Fou Shales and overlying, slightly siltier shales of the Viking Formation. VE1, an erosive contact defined in north central Alberta (A.D. Reynolds, pers. comm., 1989), is expressed only as a correlative conformity at the top of cycle A in the Willesden Green area.

The basal siltstone assemblage is erosively truncated by overlying Viking erosion surfaces VE2, VE3, and VE4, which usually display a coarse-

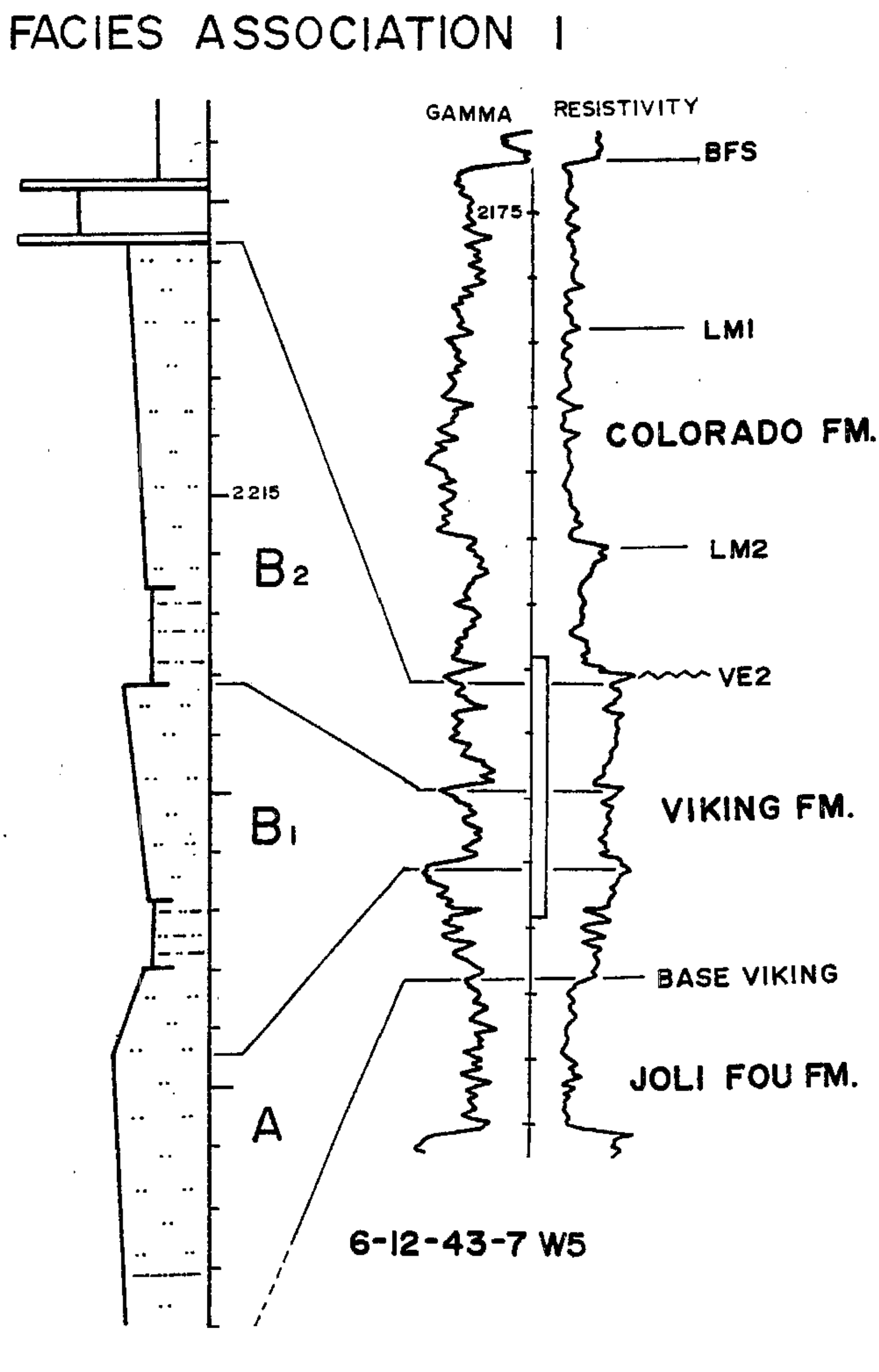


Figure 5.5 - Facies Association 1 - Reference Well 6-12-43-7W5; illustrating vertical facies relationships and correlatable log and core markers.

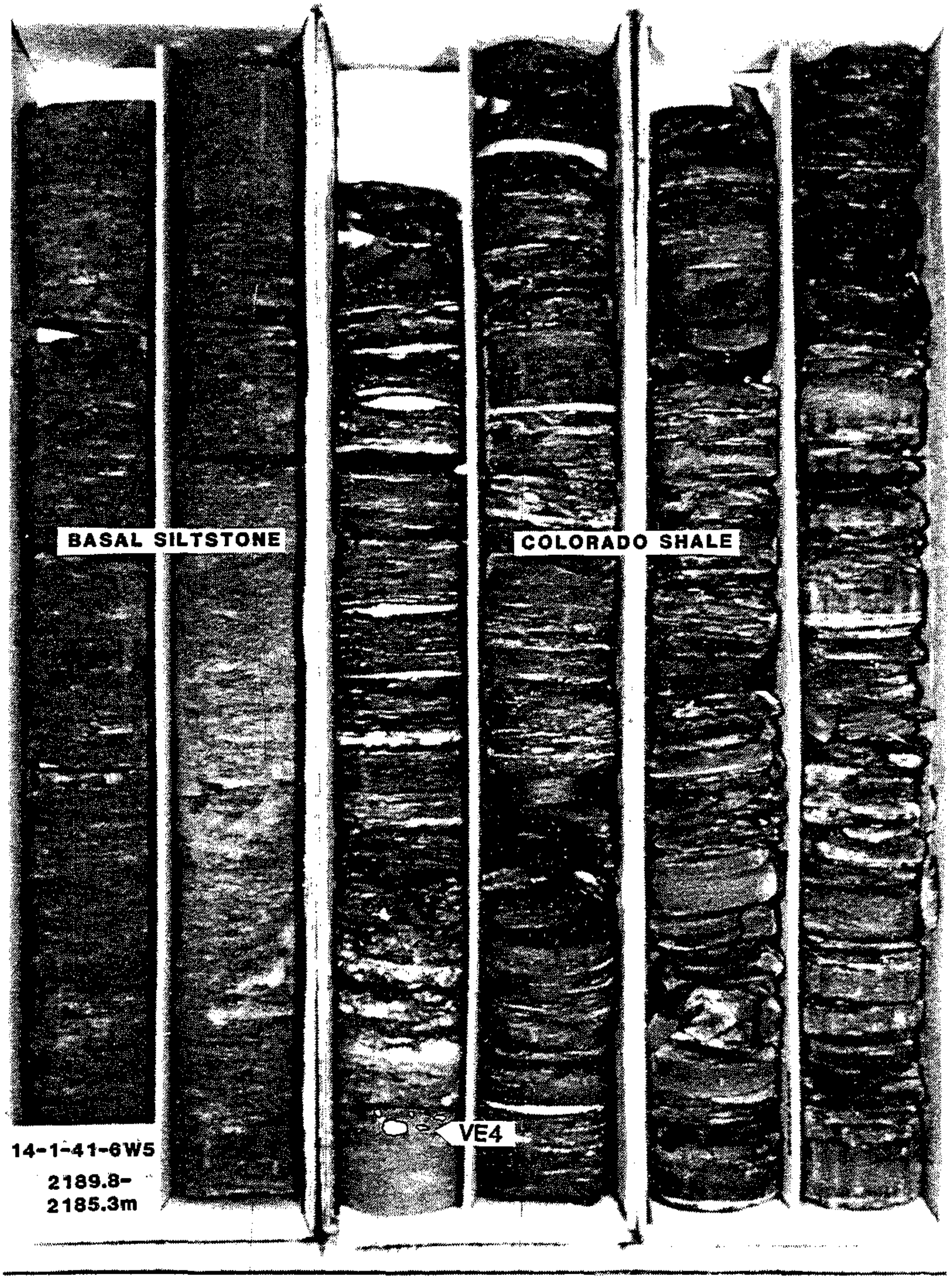
grained lag, and which scour into one another in an intricate fashion. A more detailed discussion of the location and characteristics of these overlying bounding surfaces will follow in later chapters. In many off-field wells these multiple erosion surfaces are expressed as a single thin pebble lag (VE4) which separates the silty regional sequences from the overlying black Colorado Shales [fig. 5.6].

A three dimensional palaeotopographic surface map generated from well log and core picks using SURFER software package [fig. 5.7a] indicates the erosional topography on the top surface of Viking regional member B2 (a mixture of erosion surfaces). The relative location of overlying coarse sediment packages which make up the major Viking oil and gas fields in the area are also indicated on the 3-D, and associated 2-D isopach map [fig.5.7b]. It is apparent that many of the reservoir sand accumulations are directly associated with distinct scours on this surface.

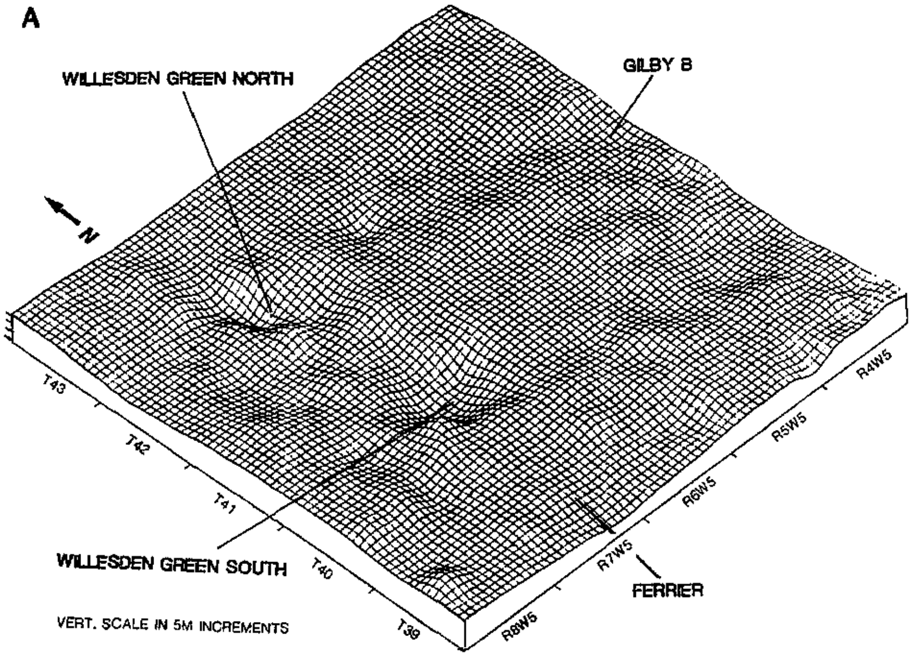
5.5 Facies Distribution

Two notable trends occur within the regional cycles of the basal siltstone assemblage in the Willesden Green area. Core and log analysis indicates that the three regional cycles (A,B1,B2) all become thicker, and sandier, in the northern part of the study area. Figure 5.8 (resistivity log cross-section) shows that cycle top inflections become increasingly more pronounced northward from township 39 to township 43. This wireline trend is reinforced by evidence from the associated cores. In township 37 cycle tops contain approximately 40 % silt and sand and 60 % mud; in township 43 however the maximum sand content has increased to approximately 70 %. The trend is notably expressed in figures 5.9 and

OFF-FIELD ASSOCIATION

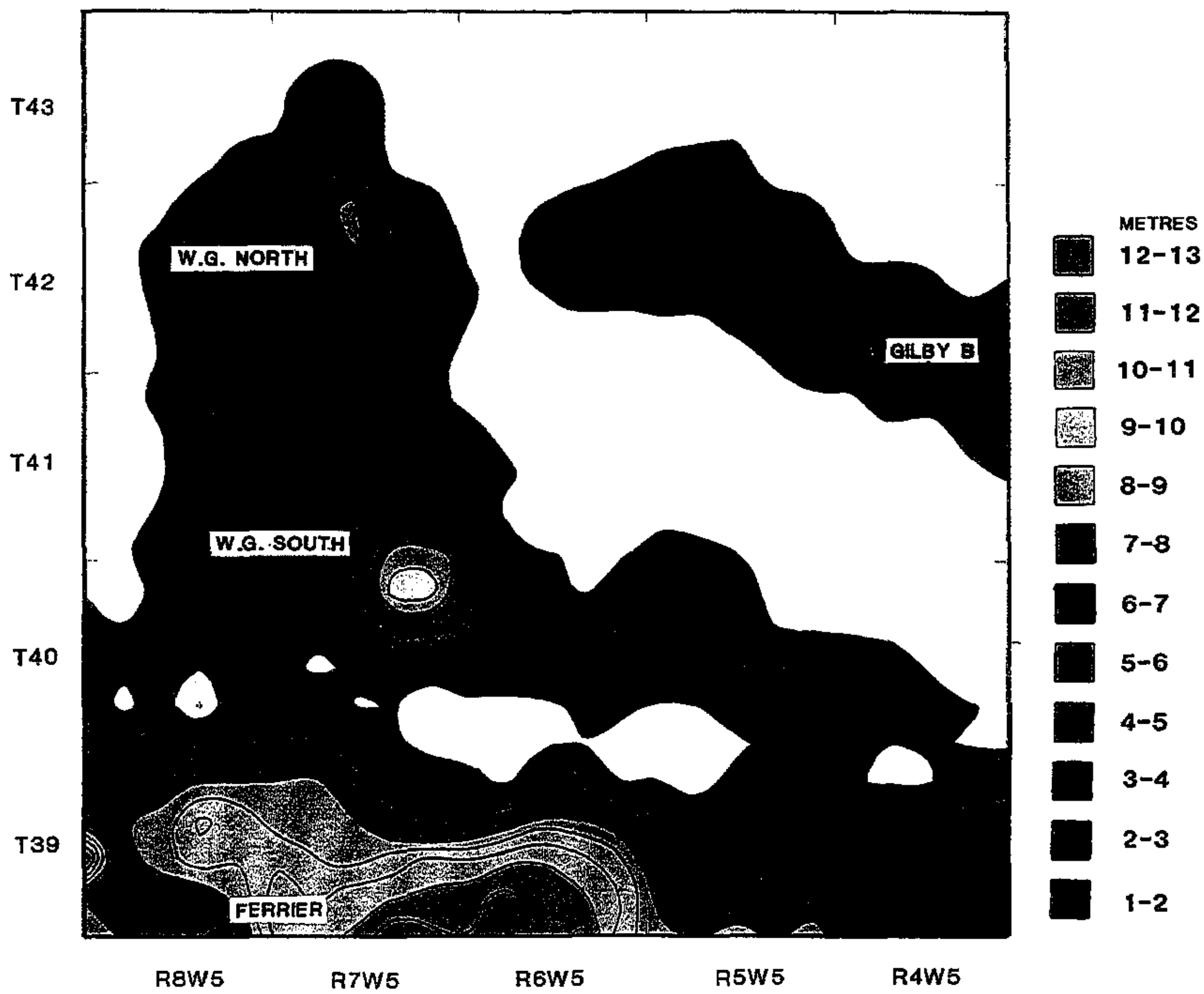


A



EROSIVE TOPOGRAPHY - TOP OF BASAL SILTSTONE ASSEMBLAGE

B **VIKING COARSE SEDIMENT THICKNESS (Membs. C-D-E)**



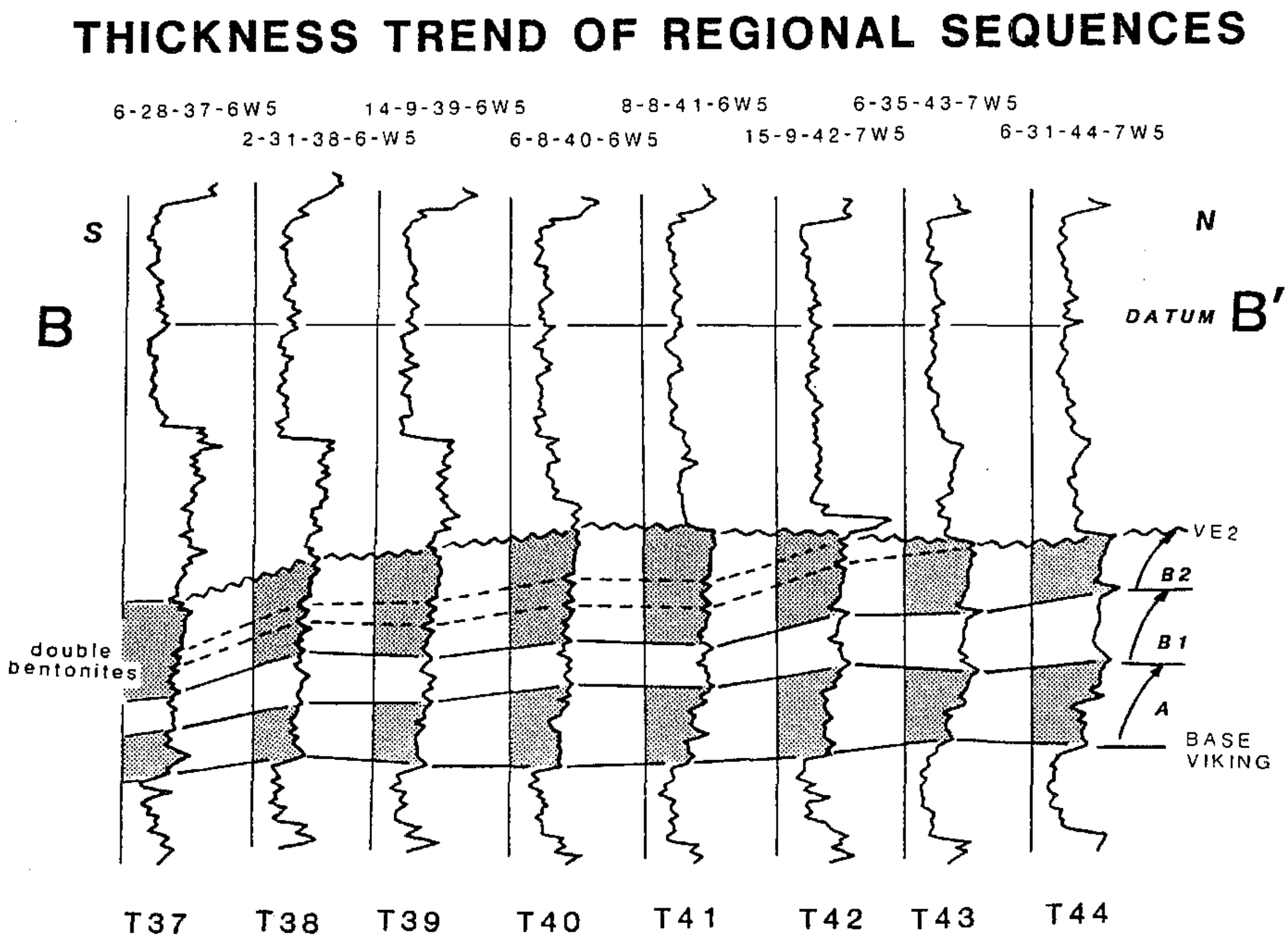
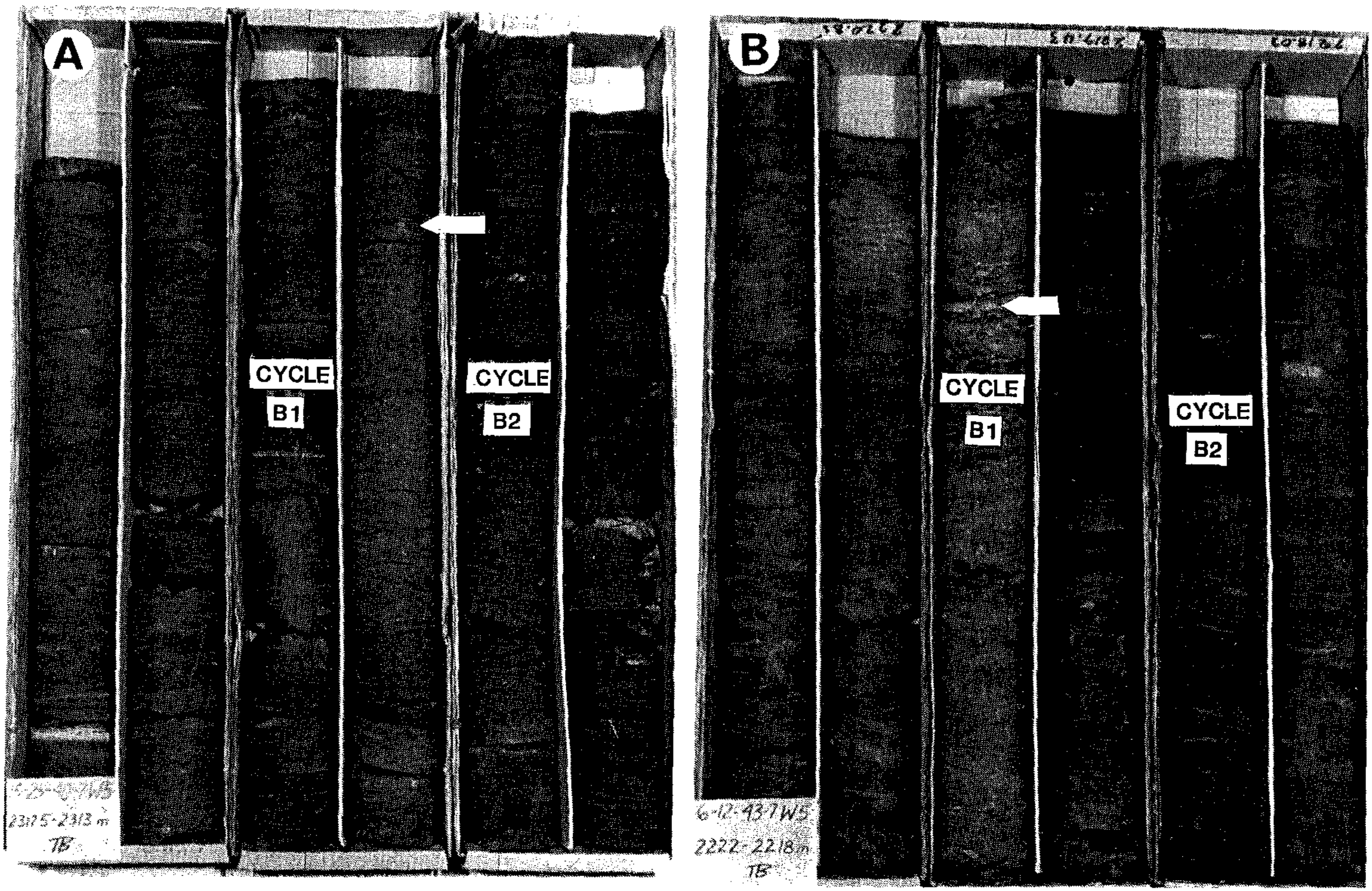


Figure 5.8 - Log Cross Section B-B' showing regional cycle trends. Note northerly thickening of cycles, and increase in the prominence of cycle top resistivity inflections in the same direction. Bentonitic markers in the uppermost cycle (B2) become erosively truncated by township 43 (location map on page 18; figure 2.7).

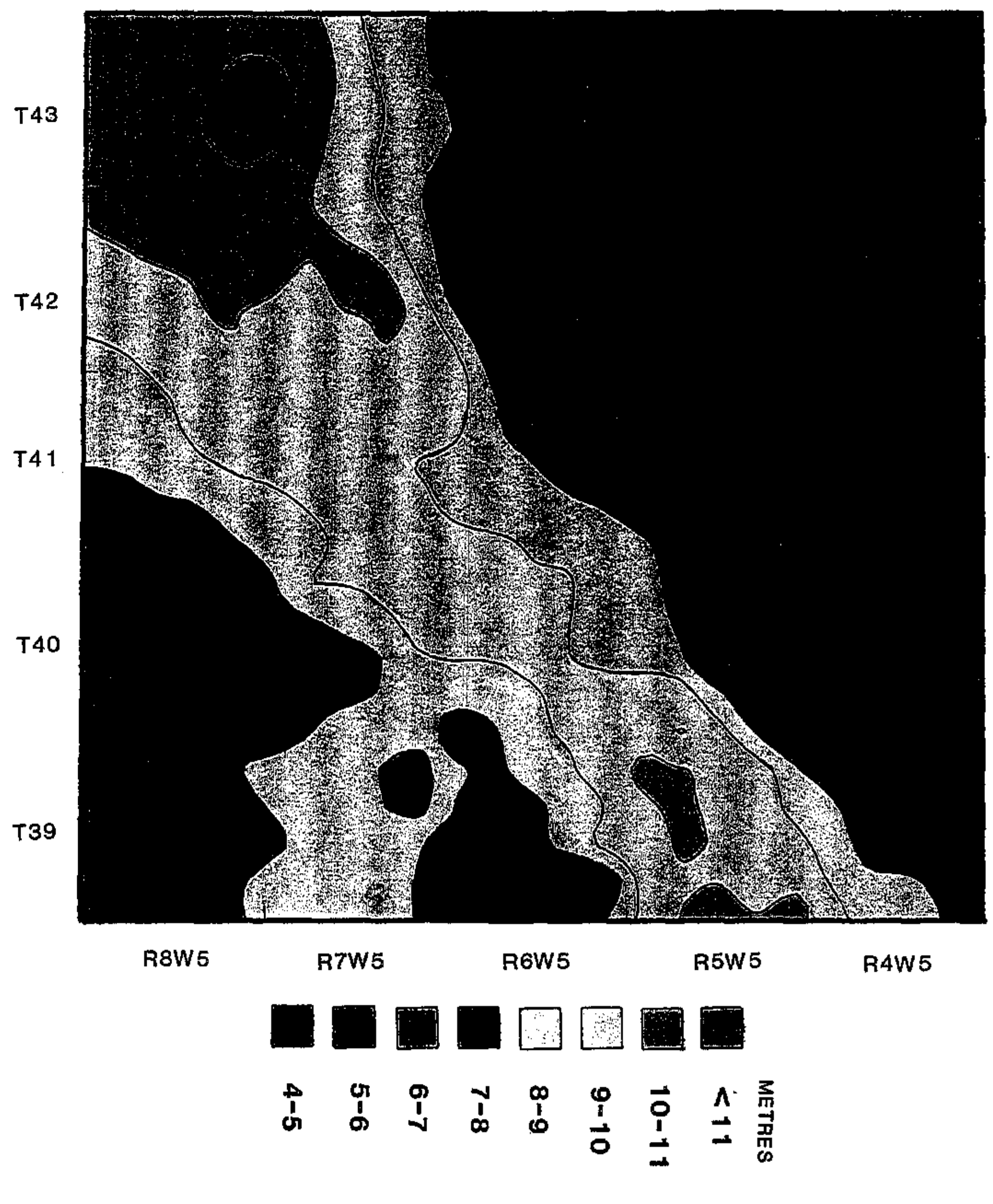

A
CYCLE
B1
CYCLE
B2
B
CYCLE
B1
CYCLE
B2

5.10. North of the detailed study area, in the vicinity of the Crystal oil field (townships 45,46), sand content in correlatable sequences reaches percentages in excess of 80 % (S.A.J. Pattison, pers. comm., 1989).

Isopach maps of cycle thickness [figs. 5.11, 5.12, 5.13] indicate that sequences A and B1 show a general thickness increase in the direction of increasing sandiness, northwestward, and pinch out towards the south and east. Sequence A decreases from 12.4 m to 4.2 m; sequence B1 from 7.0 m to 2.1 m. The cycle packages also display a slight thickening along a broad 2 km wide tongue striking approximately north-south and running the length of the study area at the intersection of ranges 7 and 8 [figs. 5.11, 5.12]. Stratigraphic cross-sections hung upon an upper datum indicate that these thicks were not deposited as convex palaeotopographic highs but rather resulted from the infilling of a broad, elongate low [fig. 6.72].

An isopach map of the uppermost cycle (B2) shows a marked variation from the characteristics expressed in A and B1, and results from erosive truncation by overlying contacts. While cycles A and B1 both thicken to the northwest, cycle B2 shows a reversed trend. From a maximum thickness of 19 m in the southeast it progressively thins to less than 4 m at township 43, ranges 7 and 8. Examination of this cycle in core however, shows that petrographically it precisely mimics the two underlying regional sequences, having a progressively greater sand to shale ratio towards the northwest. Similarly, figure 5.8 clearly shows that the thickness of the sediment package between the base of cycle B2 and the double bentonite markers also increases northwestward. The sediment thickness between the bentonites and the member top however, gets

MEMBER A - THICKNESS



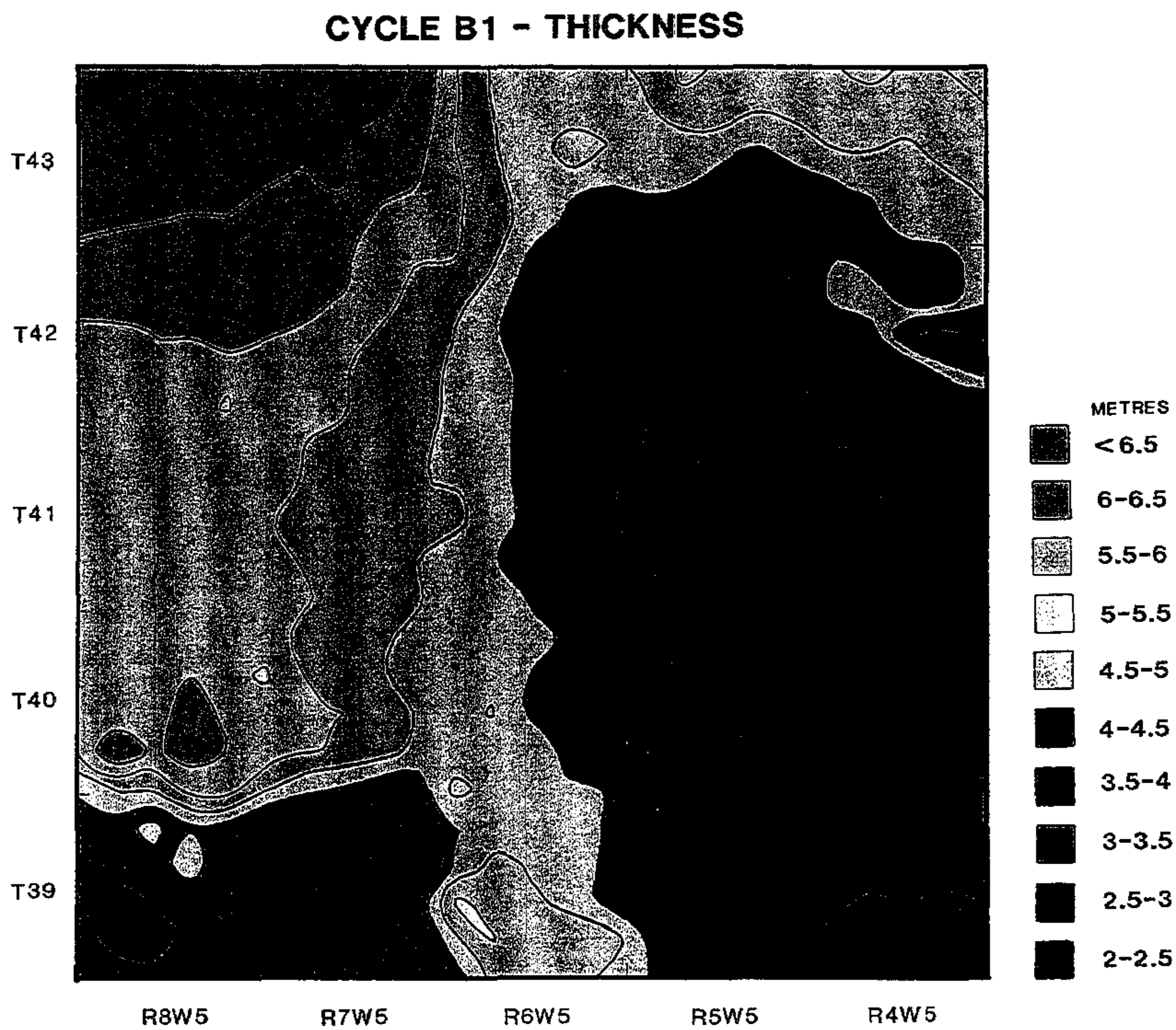


Figure 5.12 - Isopach of regional cycle B1 thickness.

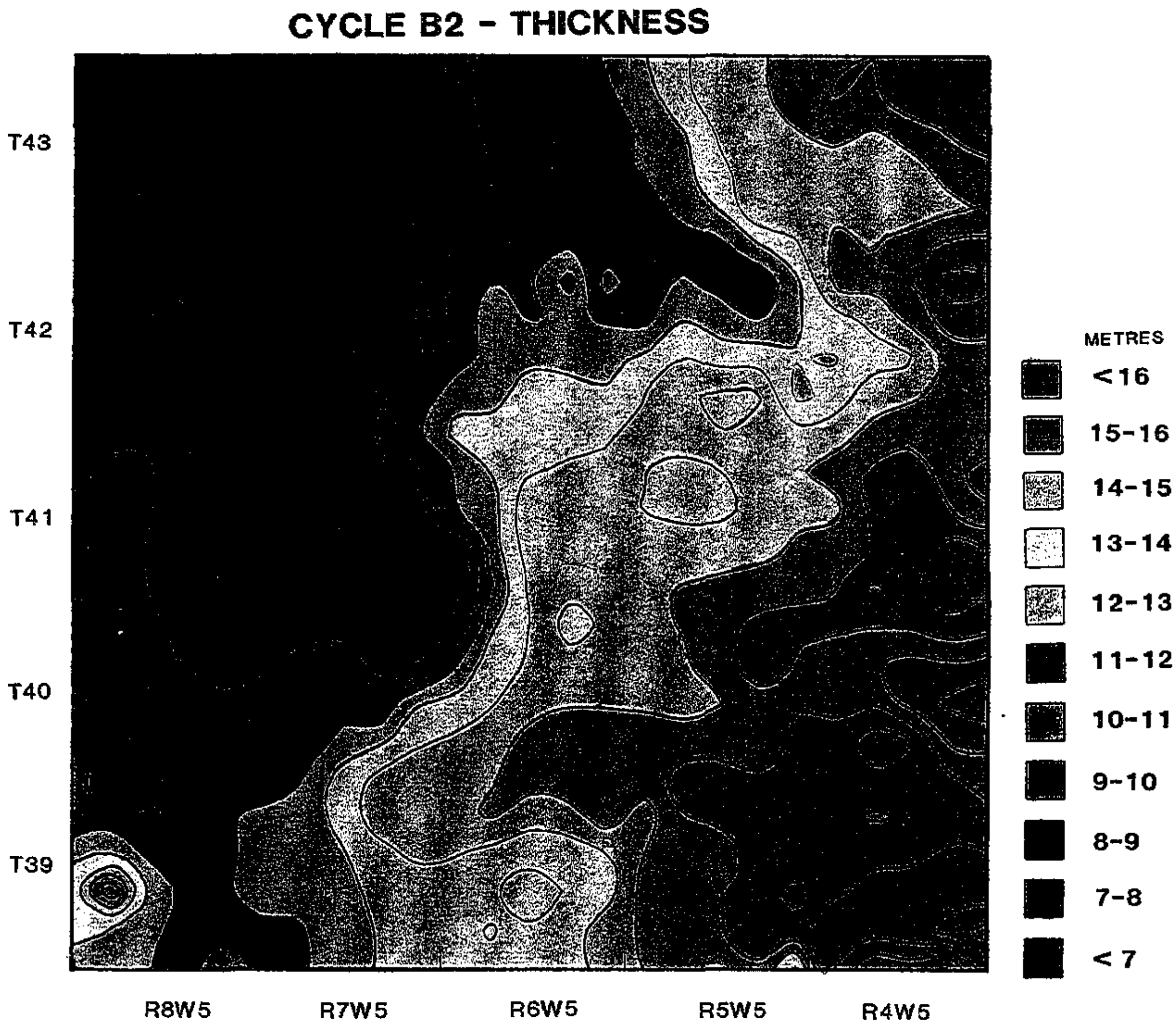


Figure 5.13 - Isopach of regional cycle B2 thickness.

progressively thinner in the same direction, up to township 43 where the bentonites can no longer be detected. The abrupt removal of these markers, and the consistancy of petrographic characteristics to underlying cycles, indicates that the overall thinning of the B2 package was not depositionally related, but rather, resulted from erosive truncation.

5.6 Interpretation

The basal siltstone assemblage was deposited in an environment in which clay and silt was the common form of sediment available. The undulatory nature of the rarely preserved laminated silt beds suggests deposition from suspension under the influence of storm waves, and the intensity of bioturbation is indicative of vigorous biological reworking during periods of fair weather. The combination of these factors suggests slow continuous deposition in a quiet offshore setting well below fairweather wave base. Reinson et al (1988) interprets similar deposits in the Crystal field area as "offshore transitional" and "lower shoreface" deposits; Downing and Walker (1988) place correlatable Joffre sediments in an "offshore" setting.

The cyclic nature of these deposits indicates that, at the time of deposition, minor fluctuations in relative sea level were affecting the northern part of the Viking basin. Reinson and Leckie (in press) suggest that these "cyclical perturbations...may reflect the influence of local and/or regional tectonics, or autocyclic processes which could have affected variations in sediment supply" (p.33). The consistant thickening and sandying of these cycles to the northwest in both the Willesden Green and Crystal field areas, also indicates that at the commencement of Viking deposition a substantial amount of sediment was being supplied from the north or northwest, undoubtedly from the Peace River Arch [fig. 5.14].

The subtle thickening of cycle packages that occurs along a 2 km wide band striking approximately north-south at the intersection of ranges 7 and 8W5, may also reflect some type of palaeotopographic effect. As noted, stratigraphic cross-sections hung upon an upper datum indicate that this thick was not deposited as a convex palaeotopographic high, but rather resulted from the infilling of a broad, elongate trough. The absence of erosional surfaces within this package suggests that at the time of deposition, small-scale flexural downwarping, or local subsidence caused by underlying structural control, were the primary mechanisms acting to create the additional accomodation space in this area. The fact that this trend is consistant throughout the three regional cycles, implies that subsidence was continuous all during this period.

The anomalous northwesterly thinning of the uppermost regional cycle (B2), and the abrupt disappearance of its double bentonite marker can only be attributed to erosive truncation. Examination of this cycle in core shows that petrographically it precisely mimics the two underlying regional sequences, having a progressively greater sand to shale ratio towards the northwest. Similarly, figure 5.8 clearly shows that northwestward across the study area the thickness of the sediment package between the base of cycle B2 and the double bentonite markers also increases. This implies that as with the underlying two regional cycles, at the time of deposition there was a greater sediment supply in that direction. The sediment thickness between the bentonites and the member top however, progressively thins in the same direction, up to township 43 where the bentonites can no longer be detected. Since the bentonites can be thought of as instantaneous and continuous markers, the abrupt

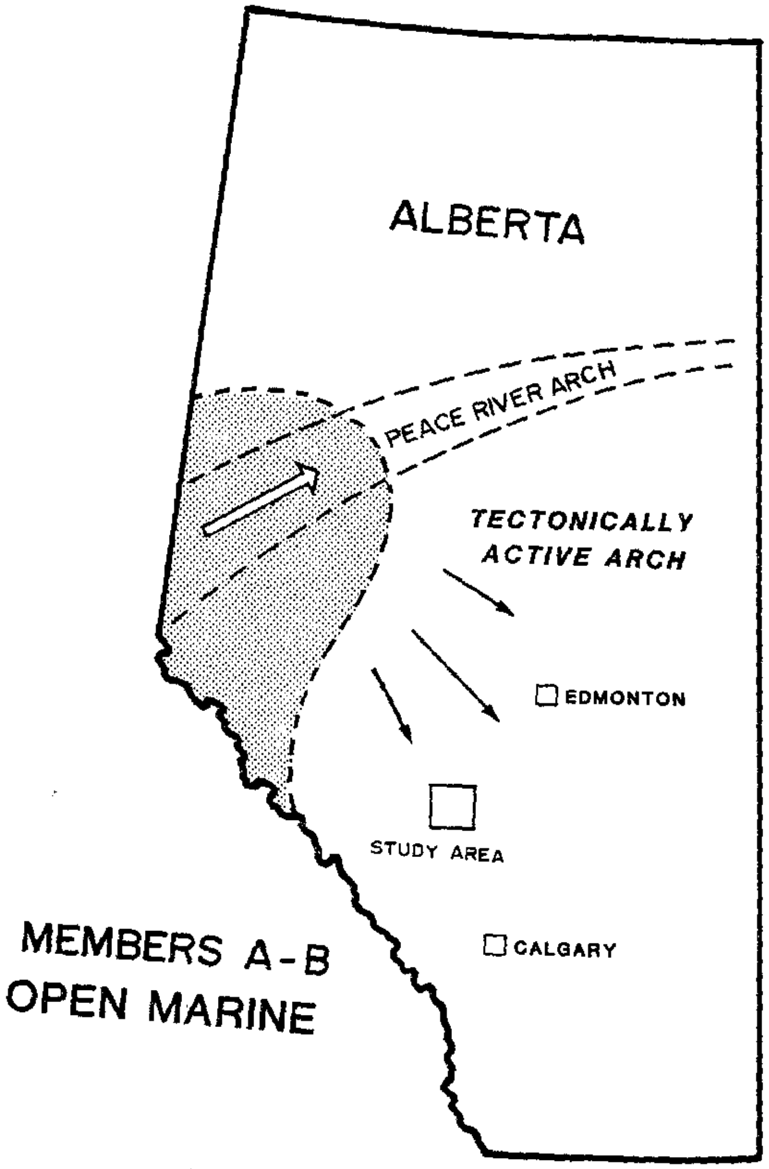


Figure 5.14 - Interpreted palaeogeography during earliest Viking deposition: (regional cycles - Members A and B).

disappearance of these beds and the northwesterly thinning of the B2 package, can only be explained as the result of subsequent erosive truncation. The fact that the uppermost regional cycle shows the maximum erosive truncation in an area that petrographic evidence indicates is the most shore proximal is entirely consistant with the findings one would expect under conditions of rapid relative sea level drop. This regression marked the initial onset of the first Viking lowstand.

5.7 Reservoir Properties

The basal siltstone assemblage has no commercial use as a hydrocarbon reservoir. The fine-grained, bioturbated nature of the sediment offers minimal porosity and permeability.

CHAPTER 6 : FACIES ASSOCIATIONS 2 and 3

(CROSS-BEDDED AND INTERBEDDED SANDSTONE ASSEMBLAGE)

MEMBER C

6.1 Introduction

Member C characterizes the Viking Formation between VE2 and VE3, and in the Willesden Green area represents the incision and infilling of a major unconformable valley into the underlying regional Viking succession. Research indicates that these previously undocumented sand and conglomeratic sediments are shallow marine in origin, and may be analagous to deposits described by Reinson et al (1988) in the Viking Crystal area. At Willesden Green Member C consists primarily of two distinct facies associations:

A) Cross-bedded facies association (FA2)

B) Sandy/muddy interbedded facies association (FA3)

6.2 Facies Descriptions - Cross-bedded Facies Association 2

The main body of the cross-bedded sandstone association is made up essentially of well sorted, fine- to medium-grained sandstone, pebbly sandstone, conglomerate, and minor amounts of shale in the form of mud drapes. Physical structures in the sandstones include large scale trough cross-bedding, planar tabular cross-bedding, massive bedding, parallel-lamination, and both wave- and current-rippling. Conglomerates are massively-bedded, or vaguely imbricated. Extremely rare biogenic features include the trace fossils *Skolithos*, *Ophiomorpha*, and *Macaronichnus*.

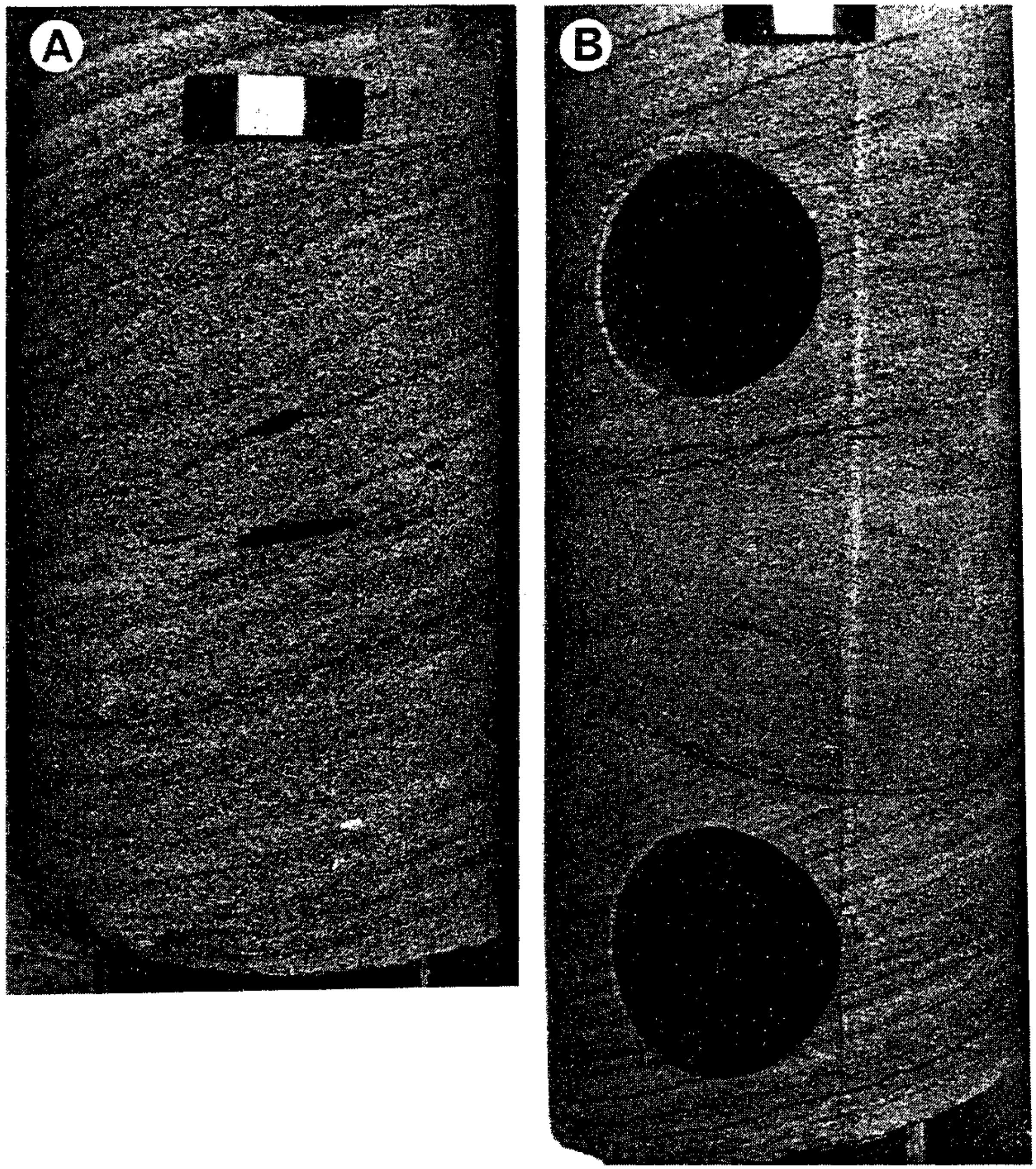
Cross-bedded Sandstone

The dominant sedimentary structure in Facies Association 2 is fine-grained cross-bedded sandstone. Individual cross-bed sets typically display a graded base with mud rip-ups, angle of repose cross-lamination, a rippled top, and occasionally are capped by a mm to cm scale organic mud drape. Laminae within the sets generally have slopes of 15 to 28 degrees, and in many cases a notable increase in laminae slope angle can be detected progressively upward through a set [fig. 6.1]. Individual preserved cross-bed sets range in thickness from 8 to 43 cm, but the majority are between 20 to 26 cm thick. In most cases only the basal portion of the cross-bed set is preserved due to erosive scouring associated with overlying sets. Small scale reactivation and scour surfaces mark the vertical intersections of sets throughout the cross-bedded facies association [fig. 6.2].

Commonly the cross-bed sets occur in continuous stacked successions up to 3.5 m thick. Within these successions overall fining-upward and thinning-upward trends are often apparent and the cross-beds frequently grade up into wave- and current- rippled fine-grained sandstones, or into the planar-laminated /bioturbated couplets of facies association 3. The limited scribed core available indicates both unimodal and crude bi- to poly-modal palaeocurrent directions through vertically stacked sets. The trough cross-bedded sandstones may be interbedded with parallel-laminated sandstones, massive sandstones, pebbly sandstones, and conglomerates.

Parallel-laminated Sandstone

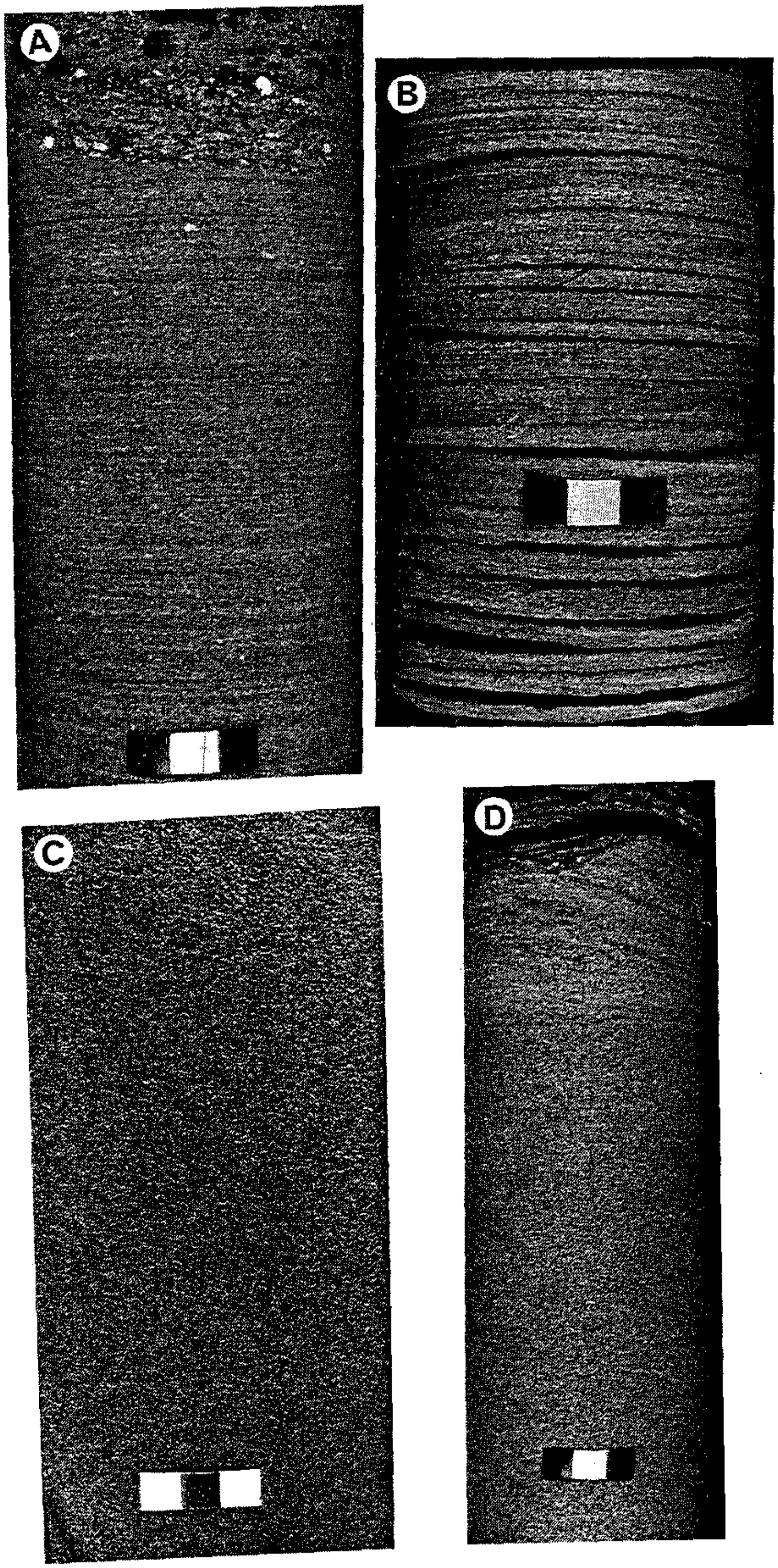
Parallel-laminated sandstones are fine-grained, well sorted, and consist of extremely regular mm-thick (occasionally cm thick) gently dipping parallel laminae of sand and clay in packages up to a few dms



thick [fig. 6.3]. Stratification is defined by minute laminations of organic-rich mud and heavy minerals. Dip angles generally range from horizontal to 7 degrees, but in some instances angles of up to 12 degrees are attained. Individual beds usually have an erosive base, often with a scattered granule lag and normal grading, and as with most beds in the assemblage, occasionally have a mud draped top. Parallel-laminated sandstones are found throughout facies association 3, however individual packages tend to be much thicker in the upper portion of the association, reaching a maximum thicknesses of 1.6 m. They often occur interbedded with cross-bedded sandstones, and both sharp and gradational transitions between the two facies are apparent. Although parallel-laminated sandstones are generally well consolidated, the internal mud laminae often weather out to produce a series of disk-like sandstone plates [fig. 6.4].

<u>Massive Sandstone</u>

Massive sandstones are generally fine- to medium-grained and typically occur as cm to dm thick layers interbedded with cross-bedded sands, or as continuous units up to 4.8 m thick. The massive sandstones are characterized by their lack of visible stratification [fig. 6.5], although the tops of some massive beds occasionally display a minor amount of normal grading, faint wave- or current-rippling, or mud draping [fig. 6.6]. Massive sandstone beds can be continuously stacked upon one another, separated only by scour surfaces or, more commonly by black mud drapes up to 1 cm thick. Massive sandstones are generally found in the lower half of the cross-bedded facies association but are also interbedded with the conglomerates and pebbly sandstones found higher up in the succession.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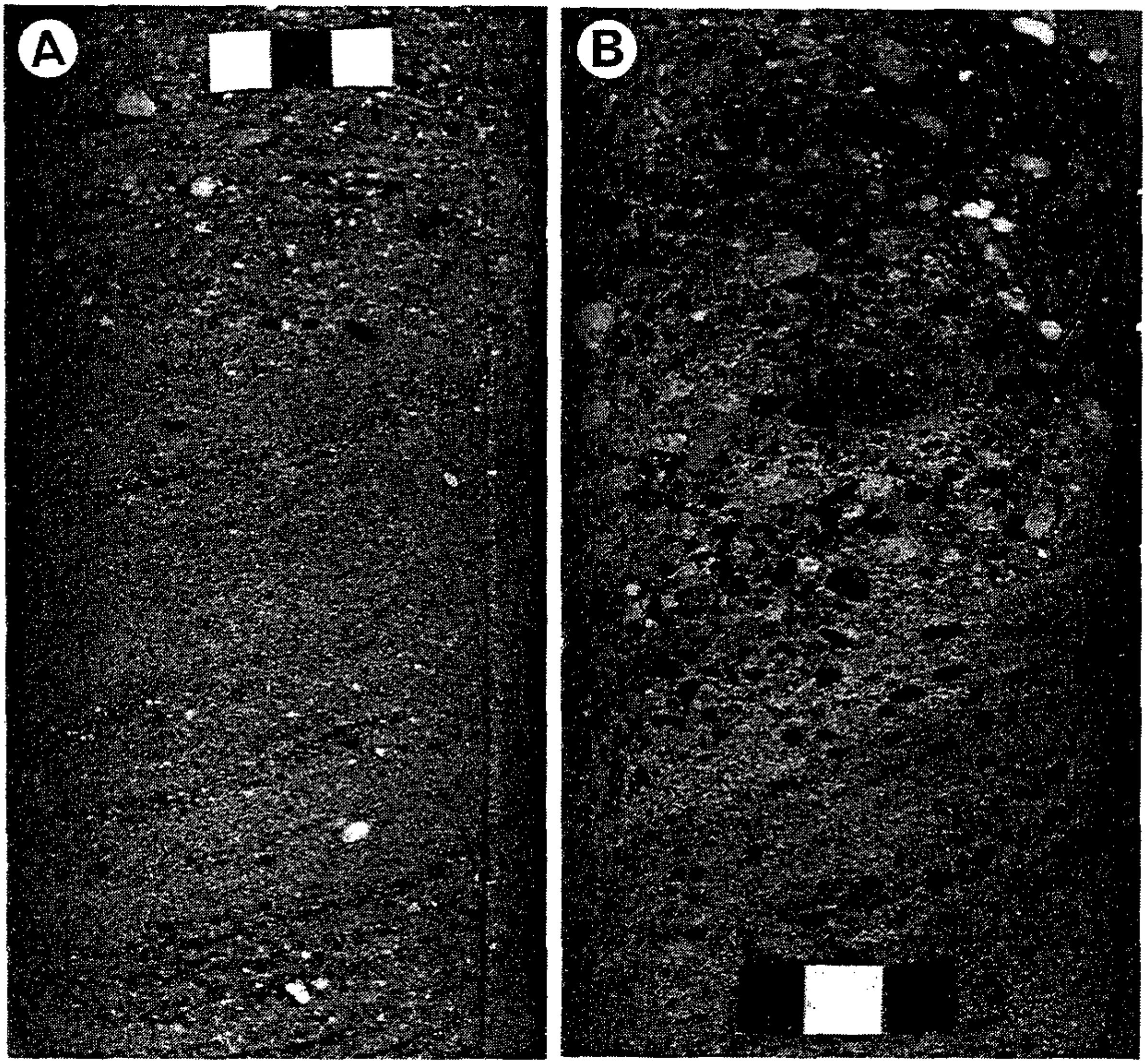
<u>Pebbly Sandstone</u>

Pebbly sandstones are very similar to the cross-bedded sandstones described above, but consist of a poorly sorted mixture of small pebbles, granules, and fine-grained salt-and-pepper sand. Distinct polymictic pebble layers and sideritized mud clasts often define angle of repose cross-stratification (24 to 30 degree dips) [fig. 6.7]. Due to variable clast size, bounding surfaces of cross-bed sets are indistinct and are often difficult to determine. An average set thickness is estimated to range between 15 and 30 cm. Both normal and inverse grading is apparent within the pebbly sandstone facies. Although the facies is generally matrix supported, where coarse grain sizes predominate the pebbly sandstone often becomes clast supported and develops a rather structureless appearance [fig. 6.8]. The pebbly sandstones are interbedded with, and transitional between the cross-bedded sandstones and conglomerates. Contacts between the facies may be either sharp and erosive, or gradational.

<u>Conglomerate</u>

The conglomerate facies is polymictic, poorly sorted and clast supported. Clasts are well rounded, often oblong in shape, and consist primarily of quartz, chert and rock fragments [figs. 6.9, 6.10]. Individual clasts range in size up to a maximum of 2.5 cm (average long axis, 10 largest clasts). The matrix is fine- to medium-grained salt-and-pepper sand similar to that found in the cross-bedded facies. Visible porosity is often apparent. Physical structures are generally absent within the conglomerate facies, although possible vague imbrication is occasionally noted [fig. 6.9]. The conglomerate facies has two occurances within the cross-bedded facies association: as a lag deposit up to 23 cm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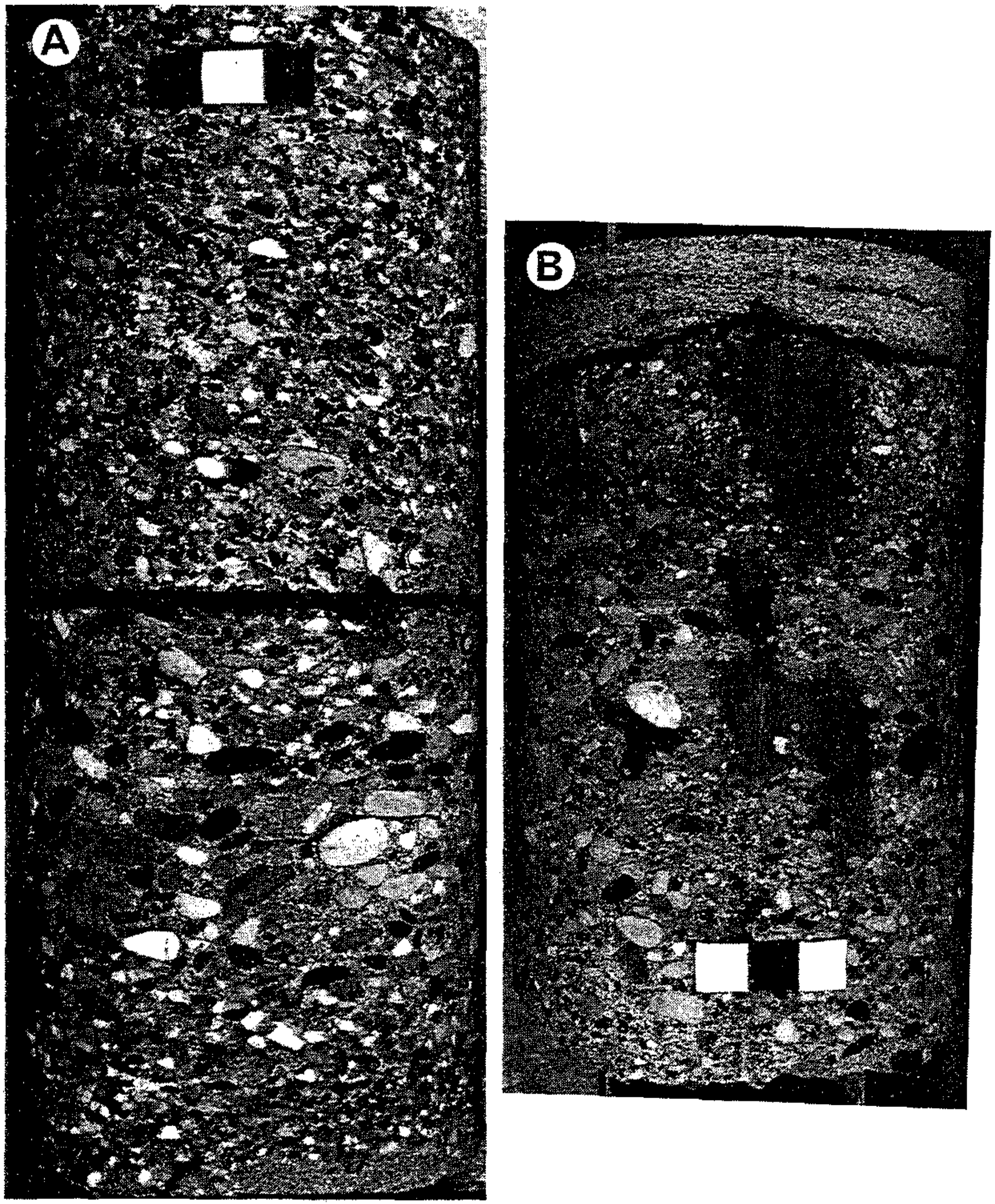
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thick above the basal erosion surface, and as thick units gradationally interbedded with pebbly and massive sandstones in the upper half of facies association 2.

Rippled Sandstone

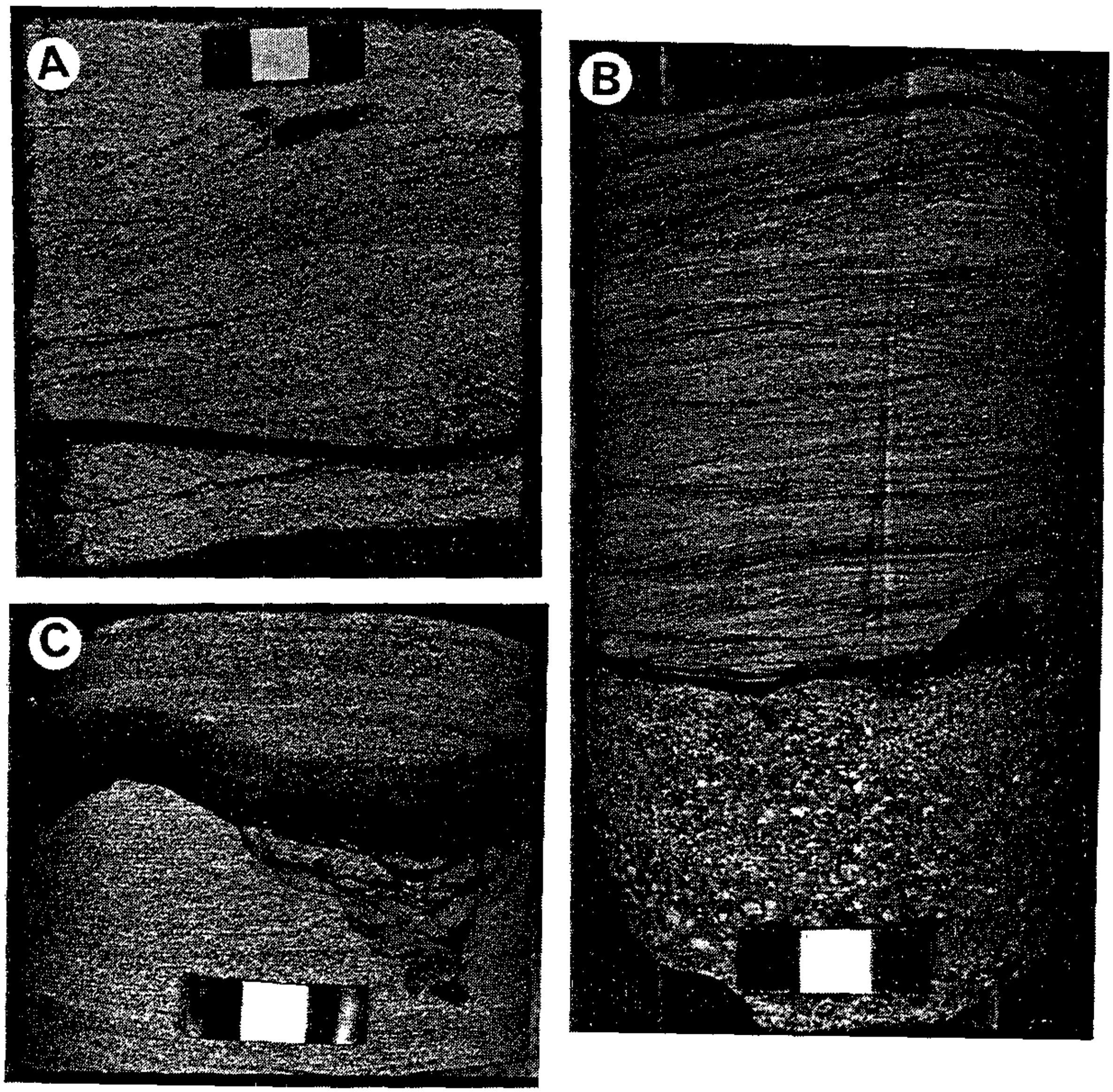
Within facies association 2, wave-, current-, and combined-flow-rippled sandstones are ubiquitous. These small scale structures occur with the greatest abundance and in the thickest packages at the tops of large scale fining-upward sequences, although isolated occurances as discrete units between coarser-grained (even conglomeratic) high energy bedforms are not uncommon [fig. 6.12]. As previously noted, fine-grained rippled sands also regularly cap the tops of individual massive, cross-bedded, and pebbly sandstone beds and probably represent the waning flow stage of deposition. In most cases these rippled bed tops are overlain by a thick black mud drape [fig. 6.11], and occasionally may be disrupted by marine bioturbators. A common sequence consists of a cross-bedded sandstone bed grading upward into a thin band of climbing current-ripples with a wave-rippled, mud-draped top. At the tops of large scale fining-upward sequences however, packages of unidirectional climbing-ripples can reach thicknesses of 34 cms. Stacked sets of wave-ripples also occur, but they are generally less than 10 cm thick.

Black Shale

Throughout the cross-bedded facies association, black shale occurs in three distinctive forms: (1) as thick drapes overlying individual bed sets, (2) as angular rip-up clasts, and (3) as thin laminae which veneer the lower foresets and bottomsets of sandstone cross-beds.

Most commonly, individual mud drapes occur as 1 to 2 cm thick, black, friable and organic-rich bands [figs. 6.11, 6.13]. In rare instances, they display thin internal silt laminations ("pinstripes"), or associated shallow marine ichnofossils (eg. Planolites). Deformation and loading of these mud intervals is frequently observed. As noted, drapes are found consistantly at the tops of individual large- and small-scale bedsets, and distinctly mark boundaries between consecutive depositional units. At other bedset intersections however, their early removal through erosive scouring is almost certainly indicated by the close association of reactivation surfaces and overlying mud rip-ups.

Throughout the cross-bedded facies association mud rip-up clasts are very common. These clasts usually line bases of internal scour surfaces [fig. 6.14], and also occur along the foresets of individual cross-bed laminae. Most rip-up clasts contain a high organic content and are black in colour, however complete sideritization of clasts is not uncommon. The angular geometry and fragile, wispy appearance of the majority of rip-ups strongly suggests a short transport distance. Dense bands of these delicate mud rip ups are occasionally associated with thick packages of cross-bedded, planar-laminated or massive sandstone deposits [fig. 6.15]. Other mud rip-up clasts display fine silt and mud laminations which have a distinctive varve-like appearance [fig. 6.16]. Dissolution of these clasts occasionally produces a form of "vuggy" porosity that is commonly hydrocarbon stained [fig. 6.17]. Within the cross-bedded facies association mud also occurs as very thin drapes which veneer the sandstone laminae of the lower foresets and bottomsets of the cross-beds [fig. 6.15]. These argillaceous laminae are mm scale, and occur in isolated bands up to 8 cm thick. Although periodicity of mud laminae and sand laminae spacing is common, consistant coupling was not observed.



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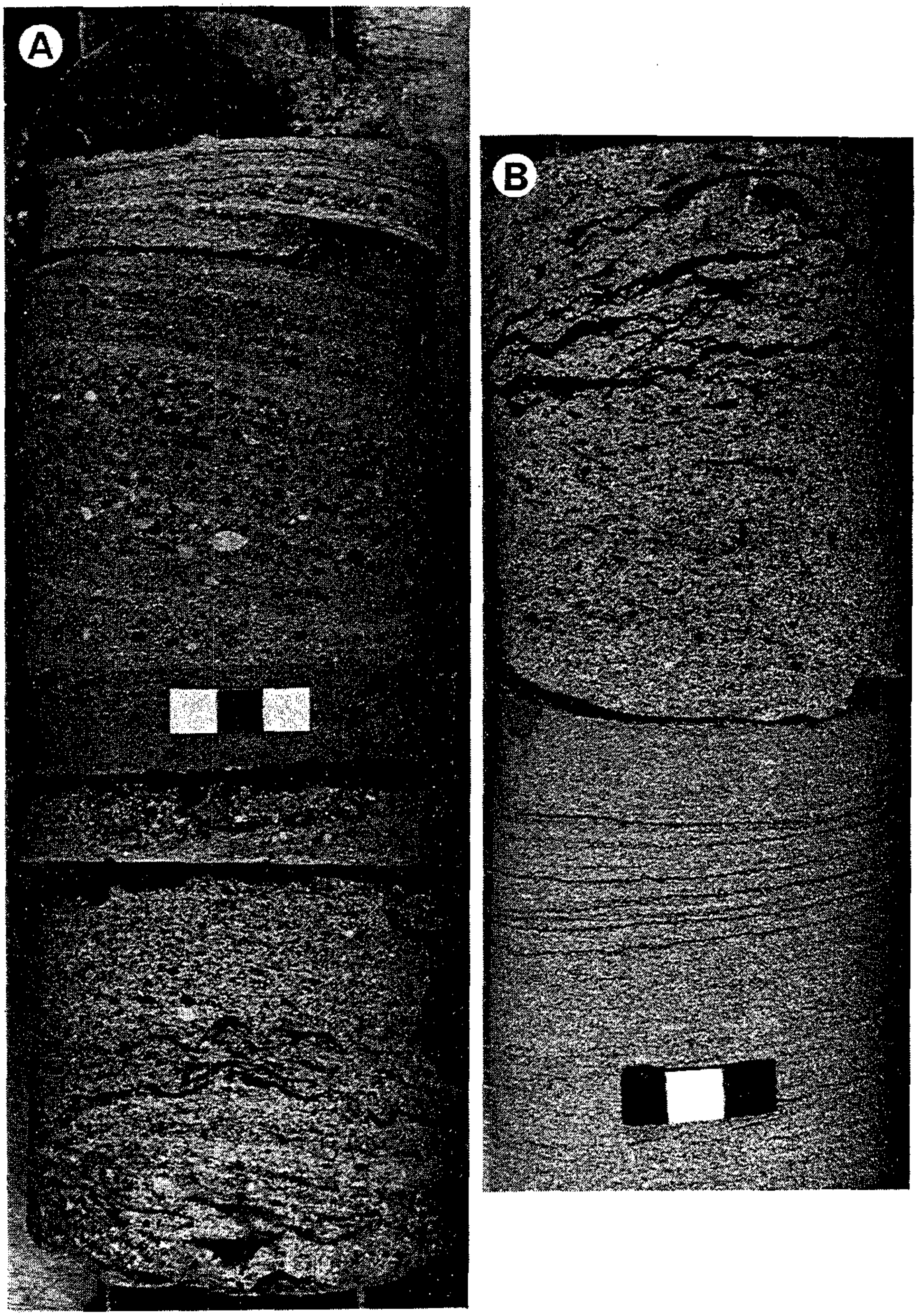
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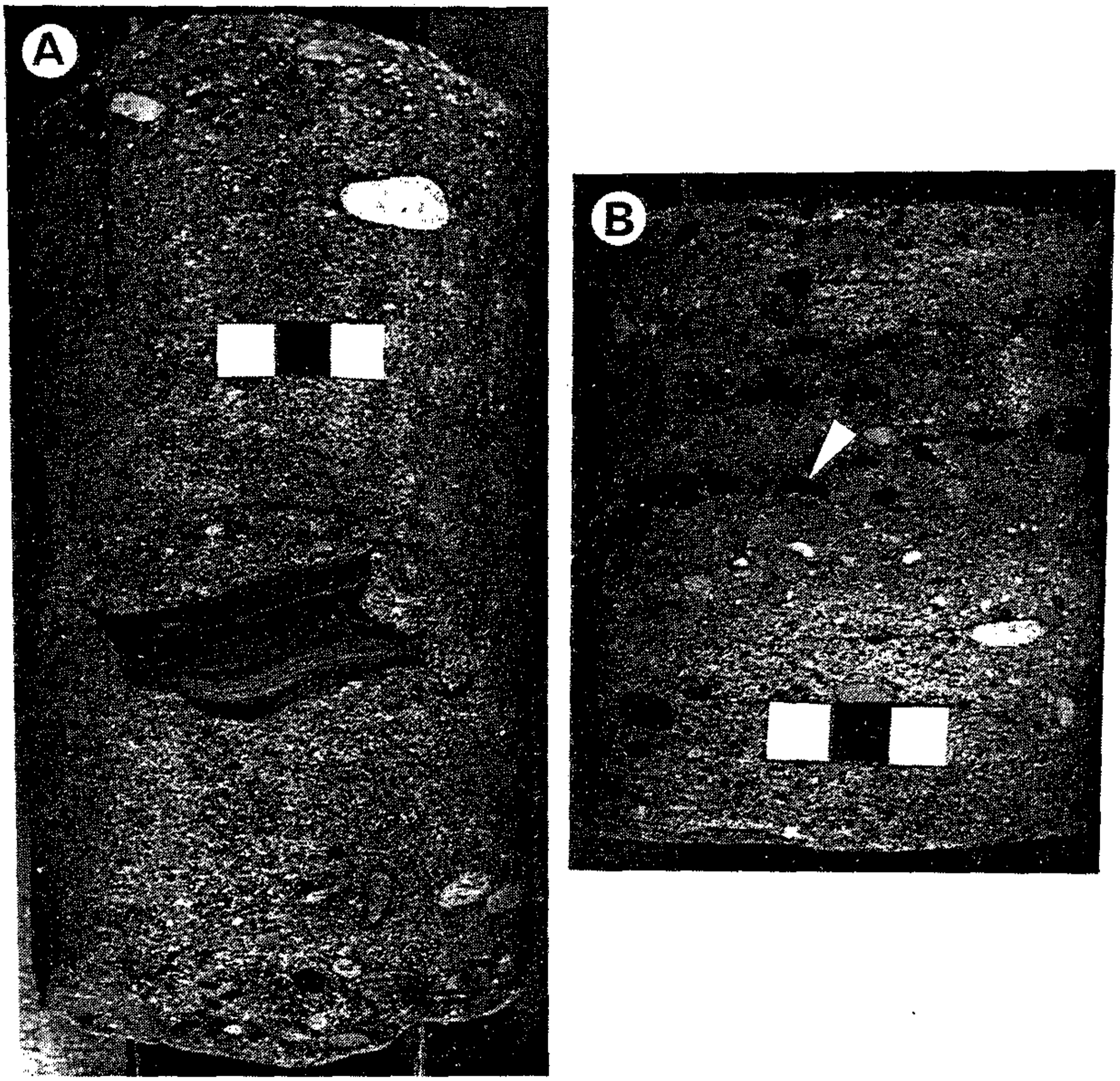
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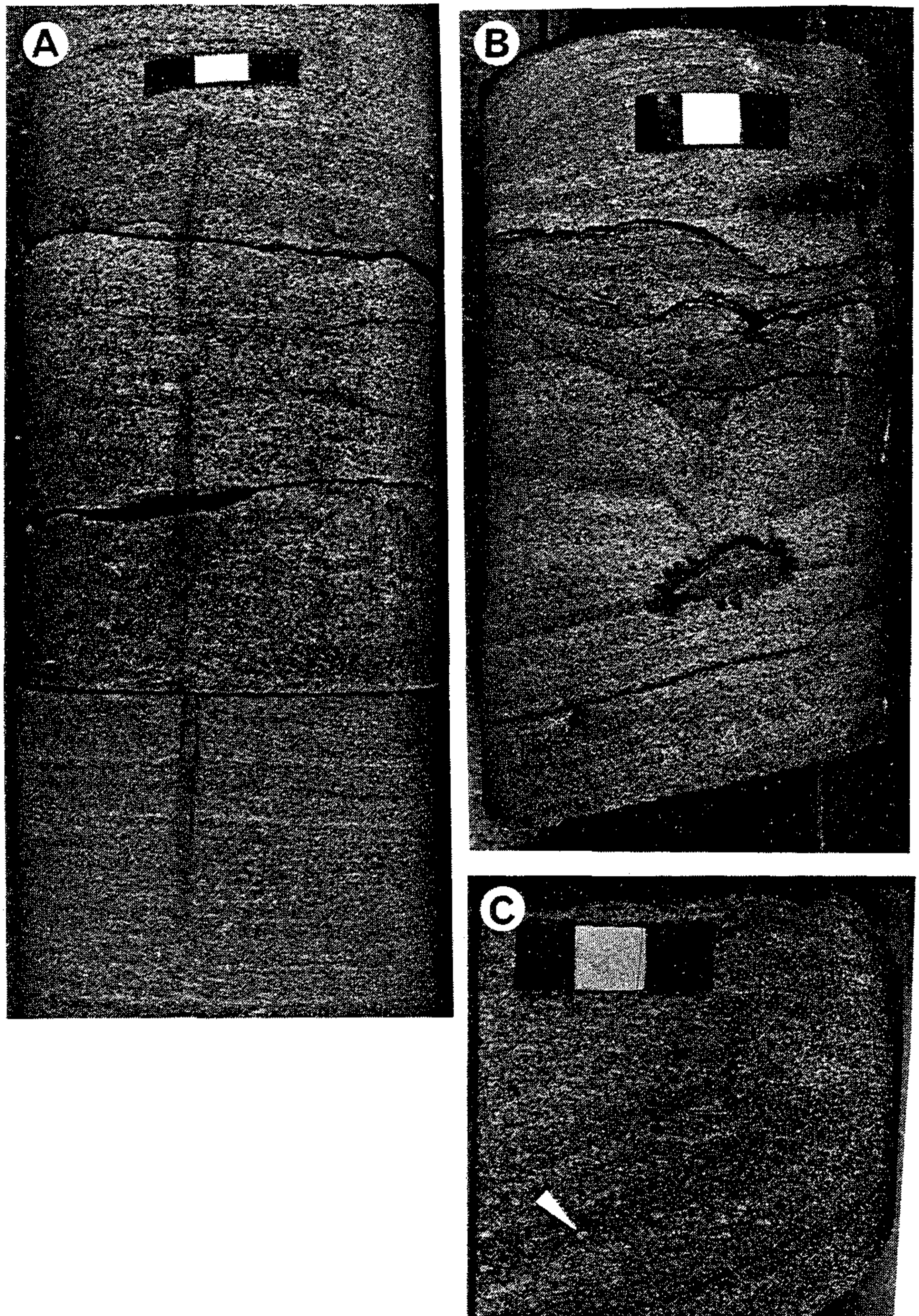
Biogenic Structures

Biogenic structures within the cross-bedded facies association are very sparse relative to the abundant high energy physical structures and as such, constitute a very minor element of the overall sequence. The limited structures present are characteristic of the near shore, high energy, marine Skolithos ichnofacies and consist primarily of Skolithos [fig. 6.18], Ophiomorpha [fig. 6.19], and extremely rare Macaronichnus [fig. 6.20]. These traces are most abundant at the top of large scale fining-upward sequences, and are usually associated with the planar-laminated and rippled sandstone facies, however both Ophiomorpha and Macaronichnus also occur along the foresets of cross-stratified sandstones.

6.3 Vertical Sequence - Cross-bedded Facies Association (FA2)

Throughout the study area, the cross-bedded association is recognized by a distinctive "blocky" log response which erosively truncates markers of the underlying basal siltstone assemblage. The upper and lower contacts of this association are marked by extreme resistivity inflections, and are easily matched to corresponding pebbly lag deposits in core. In some instances stacked 'funnel-' or 'bell-shaped' log profiles may be prevalent within the association, indicating superimposed small-scale fining-upward trends [figs. 6.21, 6.22, 6.23].

At least 2 stages of infill can be recognised in most wells of facies association 2. The first stage is made up almost entirely of fine- to medium-grained stratified sandstone, with a pebble lag at its base. The second stage of infill is generally much coarser-grained than the first [figs. 6.21, 6.22, 6.23], and is usually characterized by the presence of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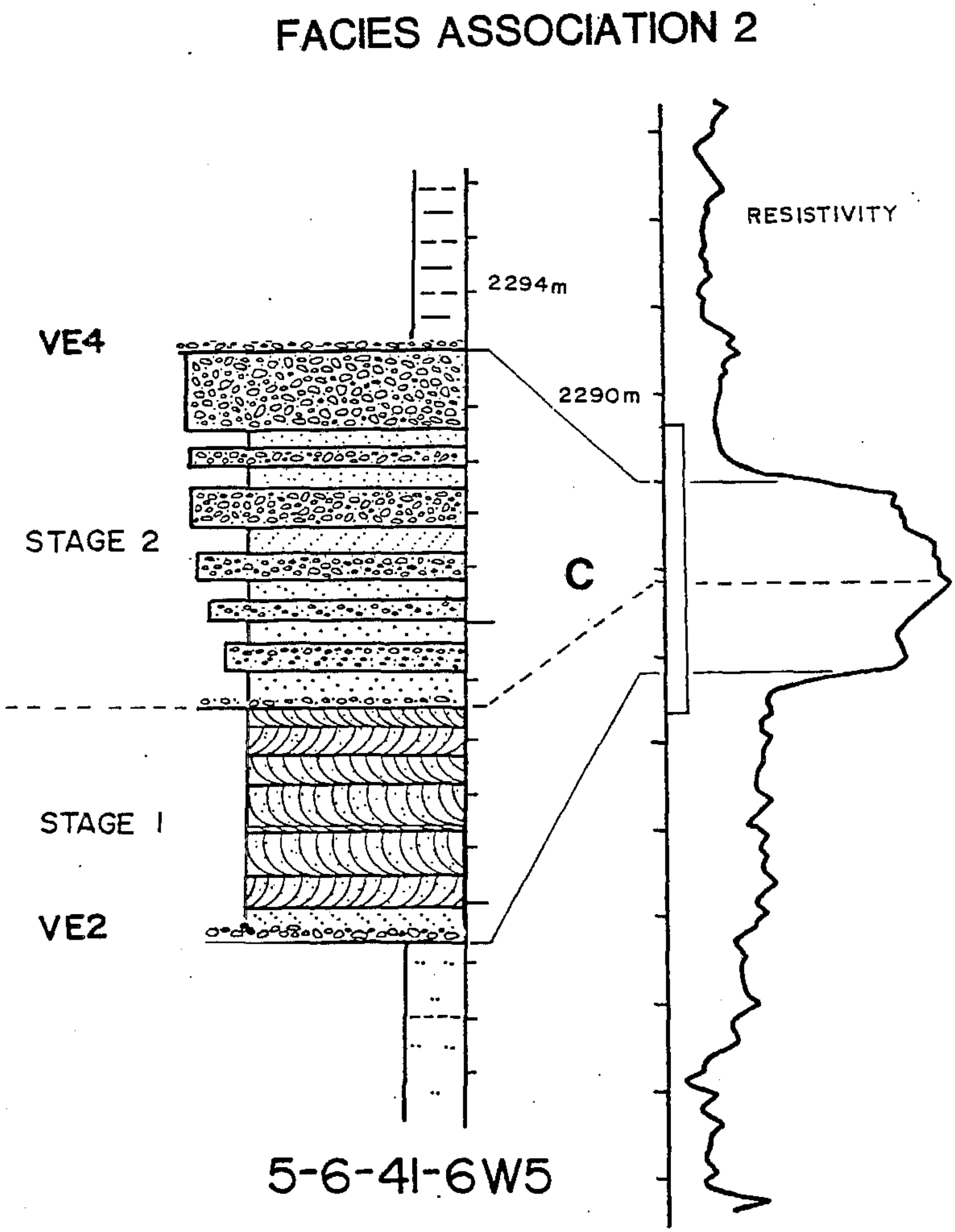


Figure 6.21 - Facies Association 2 - Reference Well 5-6-41-6W5 illustrating vertical facies relationships and correlatable log and core markers.

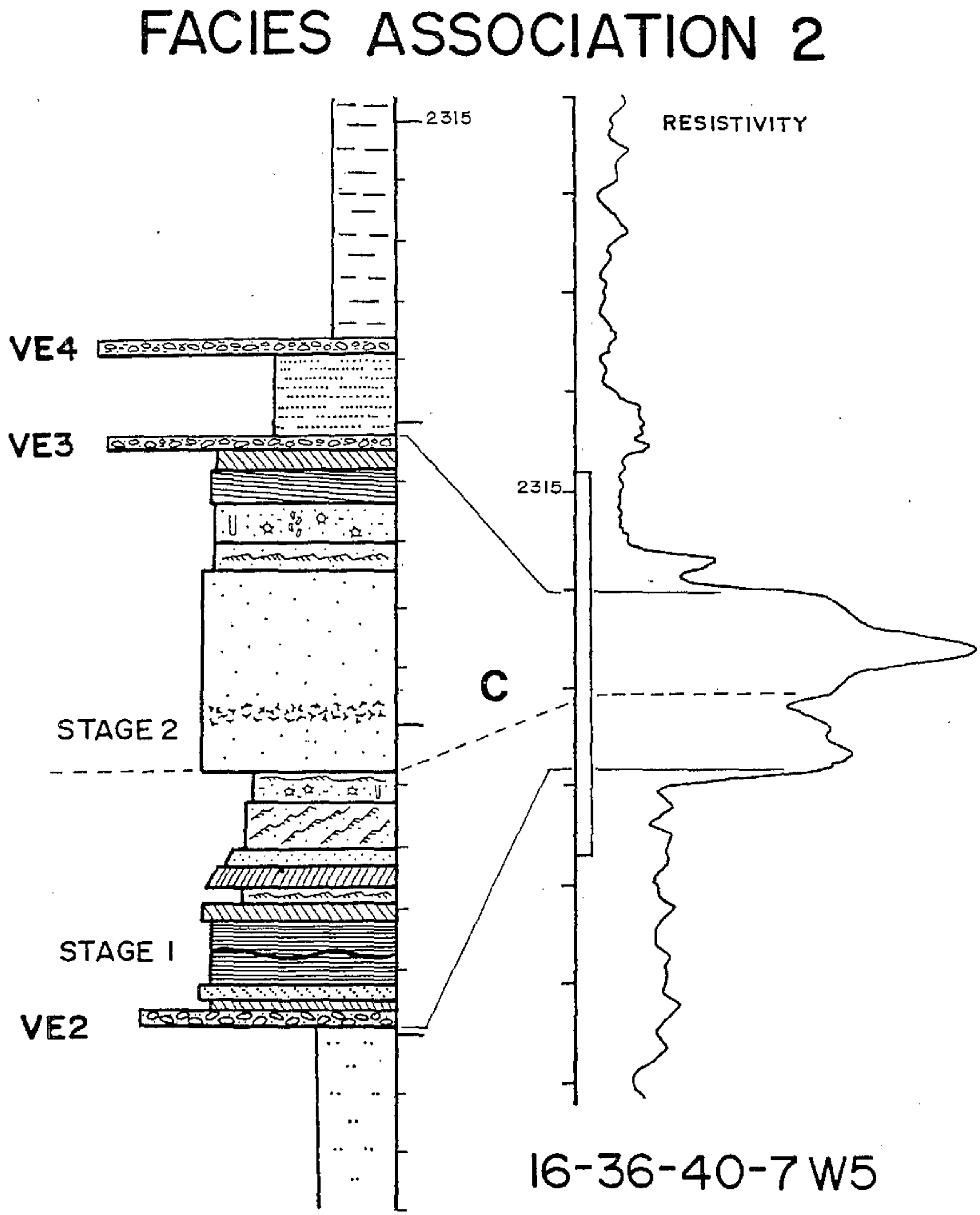
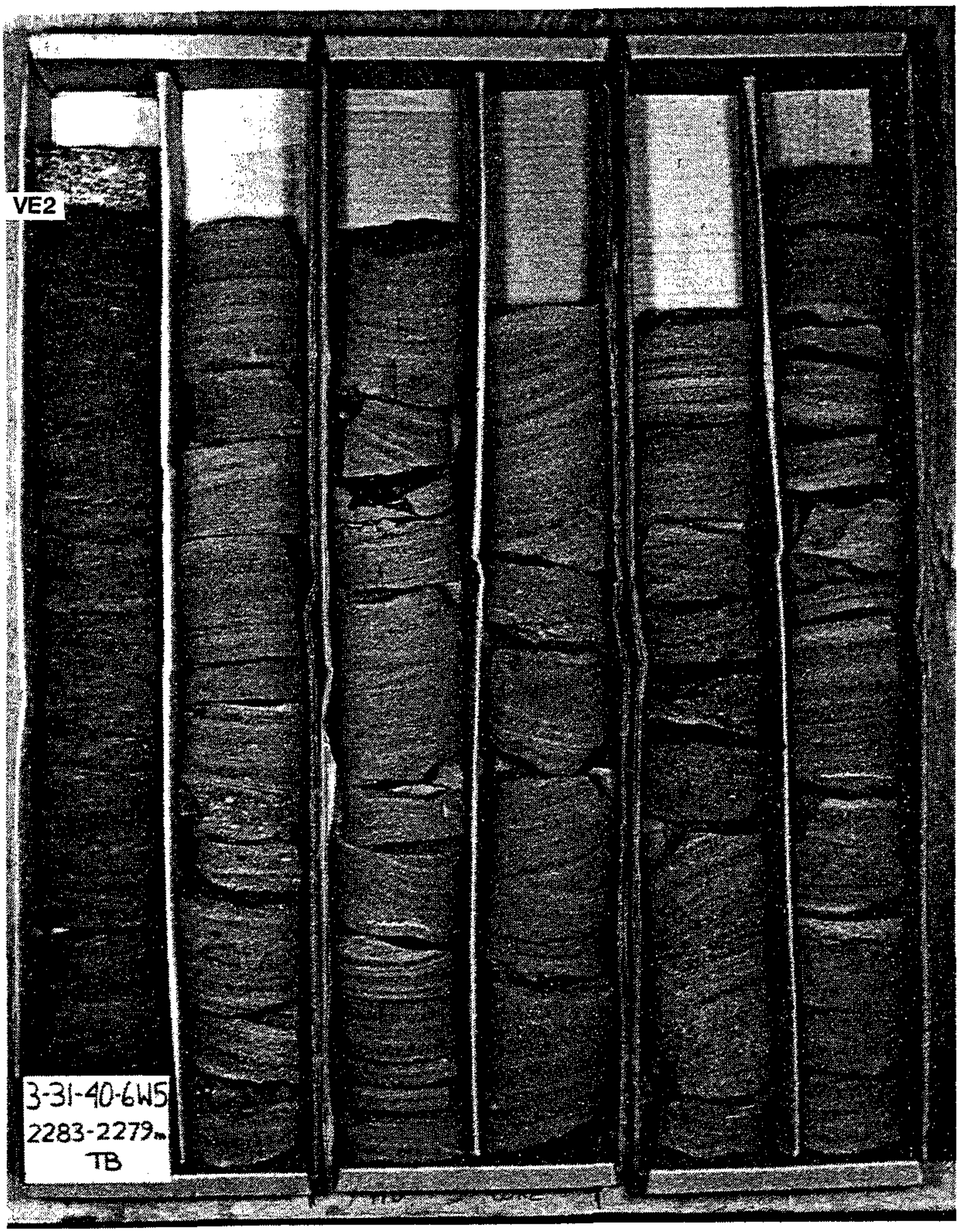
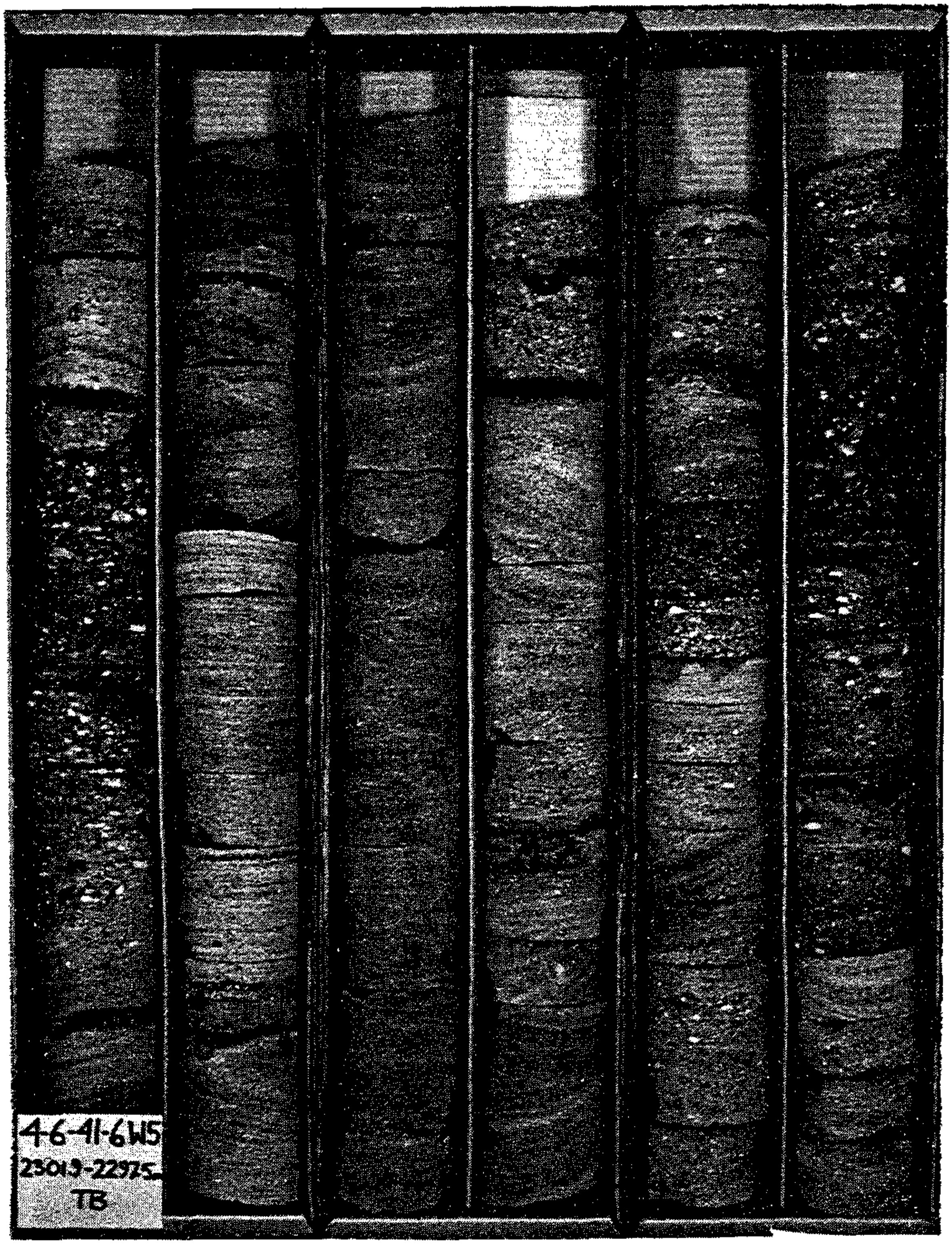


Figure 6.22 - Facies Association 2 - Reference Well 16-36-40-7W5 illustrating vertical facies relationships and correlatable log and core markers.


VE2
3-31-40-6W5
2283-2279m
TB


STAGE 1
STAGE 2
4-6-41-6W5
2305-2301.9m
TB


4-6-41-6W5
23019-22975
TB


VE4
VE3
4-6-41-6W5
22975-2293m
TB

interbedded sandstones and conglomerates. Within facies association 2 (FA2), the contact separating these two packages is usually quite sharp, however, as it is traced laterally into the sands and muds of the interbedded facies association (FA3), picking a distinct boundary becomes very difficult and the two stages eventually become indistinguishable. In the northern sand trend, poor core recovery makes differentiation of discrete depositional stages impossible.

Facies association 2 may grade upward into facies association 3, or be erosively truncated by overlying erosional surfaces. A more detailed explanation of lateral facies relationships is present in section 6.7.

6.4 Facies Description - Interbedded Facies Association

The interbedded facies association occurs laterally adjacent to the cross-bedded facies association and shows a distinct fining and muddying trend laterally from the main sand and conglomerate accumulation. It rests on an erosive surface which truncates underlying regional sequences, and usually has a basal lag deposit consisting of a few scattered pebbles or granules. The interbedded facies association can be broken down into two subfacies:

1) sandy interbedded facies
2) muddy interbedded facies

Sandy Interbedded Facies

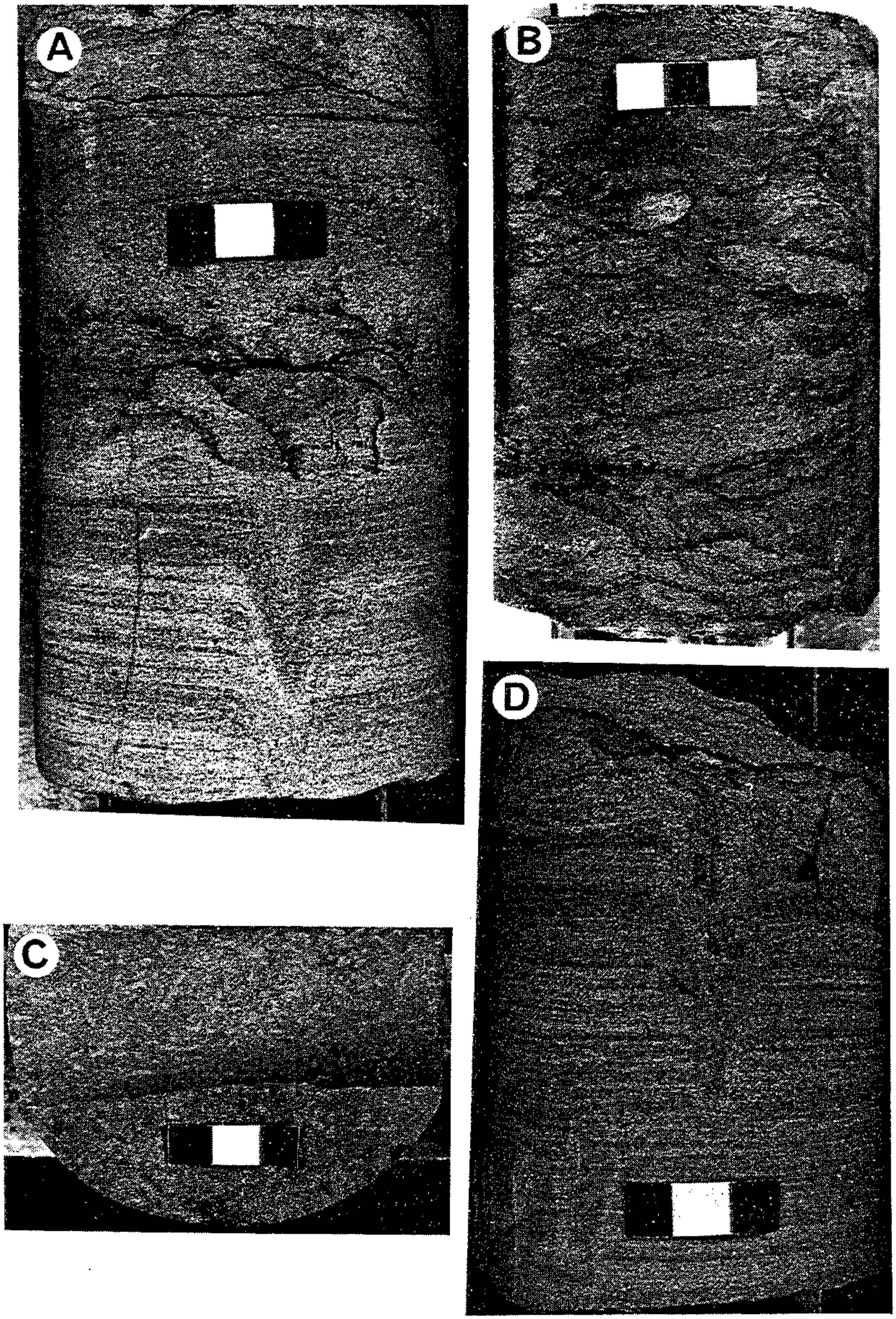
The sandy interbedded facies in the Willesden Green area is made up primarily of parallel laminated, fine to medium-grained sandstones interbedded with bioturbated muddy sandstones and silts. Each laminated/bioturbated couplet has a sharp erosive base, is normally graded, has a rippled or burrowed, mud-draped top, and probably represents an individual episodic, waning flow depositional event [fig. 6.24]. These couplets average between 15 to 28 cm in thickness and may be preserved in a stacked succession up to 8 m thick. The ratio of bioturbation to lamination within individual couplets often tends to increase upward within a succession, and successions often display fining-upward and muddying-upward trends, although reversed sequences can also be found. Irregular stratification including soft sediment folding, load structures, and fluid escape structures commonly occur within this facies.

Biogenic Structures

Although biogenic structures in the sandy interbedded facies are slightly more abundant than in the cross-bedded association, they still record an ichnofacies relatively low in diversity, with small numbers of large individuals. This ichnofacies assemblage is characterized by a mixture of simple, horizontal and vertical structures common to both the *Skolithos* and *Cruziana* ichnofacies and is dominated by *Ophiomorpha* [fig. 6.24], *Planolites* [fig. 6.25], *Skolithos* [fig. 6.26], and *Diplocraterion* [fig. 6.27]. Several of the planar-laminated beds also display patchy occurances (up to 10 cm thick bands) of *Macaronichnus* [fig. 6.26] and large bivalve burrows. Infrequently, isolated accumulations of *Ophiomorpha* and *Planolites* become relatively dense, but such occurances are not common. Escape traces (*Fugichnia*) [fig. 6.24] are abundant within this facies. No body fossils were detected in this, or any other facies of Member C.

Muddy Interbedded Facies

The muddy interbedded facies occurs laterally adjacent to, and interfingers with the sandy interbedded facies, in a position most distal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to the main sand and conglomerate accumulation (FA3). This facies consists primarily of normally-graded mm to cm scale ripple- and planar-laminated very-fine sandstone beds interbedded with sparsely burrowed muddy sandstone and black shale beds up to 22 cm thick. Physical structures include a variety of small scale bedding from lenticular (mud > sand), to wavy and flaser bedding (sand > mud), as well as horizontal lamination, synaeresis cracks, and deformation structures [figs. 6.28, 6.29, 6.30, 6.31, 6.32, 6.33, 6.34, 6.35]. Very rarely, thick (up to 51 cm) medium-grained (upper flat-bed) planar-laminated sandstones interupt the sequence, and anomalous pockets of granules and pebbles occur scattered throughout.

Biogenic Structures

A distinctive trace-fossil assemblage and unique bedding style distinguishes the muddy interbedded facies from the Viking regional sequences into which they scour. As previously noted, the underlying basal siltstone assemblage is a homogenized, thoroughly churned mixture of bioturbated siltstone. In contrast, the muddy interbedded facies is made up of discretely bedded sand lenses alternating with unbioturbated, black mudstones. Moreover, within the muddy interbedded facies, a significant reduction in the degree of bioturbation, and a sharp contrast between burrow fill and linings (eg. sand vs. black mud), make individual traces much easier to identify.

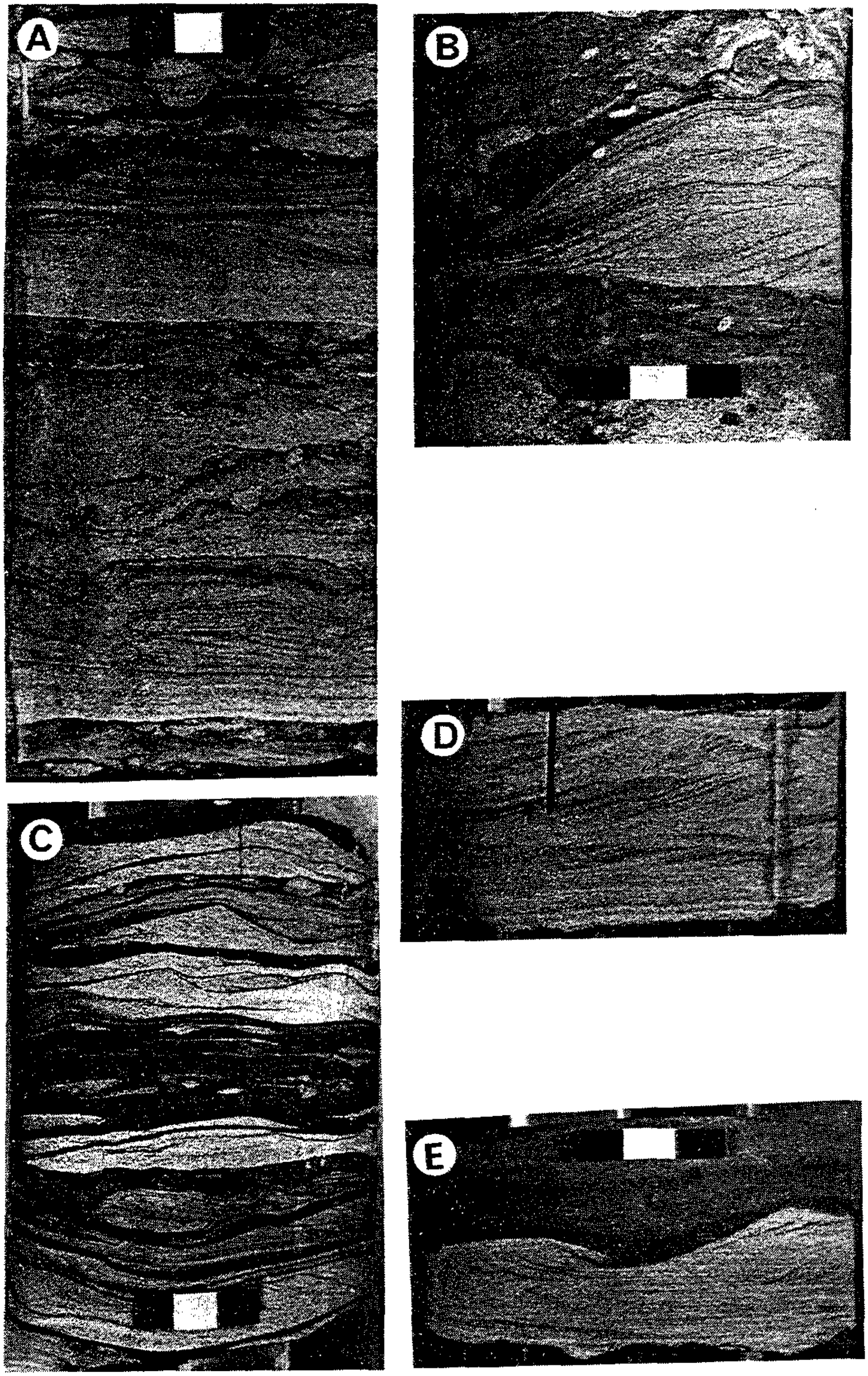
There is also a major difference between the type of ichnofacies found in the basal siltstones and the muddy interbedded facies. The basal siltstone assemblage is dominated by a diverse abundance of horizontal to diagonal forms such as Terebellina, Asterosoma, Helminthoida, Rhizocorallium, Zoophycos, and Chondrites. These traces belong to the

Cruziana and Zoophycos ichnofacies typical of open marine conditions. The muddy interbedded facies on the other hand, consists of an assemblage of simple horizontal and vertical structures, low in diversity and numbers, common to both the Skolithos and Cruziana ichnofacies. Individual traces commonly encountered include Diplocraterion [figs. 6.38, 6.39, 6.42], Thalassinoides [fig. 6.41], Skolithos [fig. 6.43], Ophiomorpha [fig. 6.40], Planolites [fig. 6.36], Paleophycus, Rosselia [fig. 6.36], and Teichichnus [figs. 6.37, 6.44]. Less commonly found are Asterosoma [fig.6.45], Terebellina [fig. 6.47], Chondrites [fig. 6.47], and a form of Macaronichnus [fig. 6.46]. 'U'-shaped vertical burrows are relatively abundant, and organisms are commonly found to colonize only the tops of individual sand beds.

The most noticeable difference between the biogenic structures of the muddy interbedded facies and the basal siltstones is size, abundance and diversity. Individual traces of the basal siltstone assemblage reflect a healthy open marine population with high diversity of organisms, all of a moderate, relatively consistant size. In contrast the muddy interbedded facies records an assemblage greatly reduced in numbers and diversity, in which only very small and very large individuals appear to be present. Within this stressed assemblage, burrowing generally increases progressively away from the axis of the main sand accumulation, and the percentage of fully preserved bedding declines accordingly. Degrees of bioturbation seen in the underlying regional sequences however, are never achieved within the muddy interbedded facies.

6.5 Vertical Sequence - Interbedded Facies Association (FA3)

Facies Association 3 is characterized by an irregular, disordered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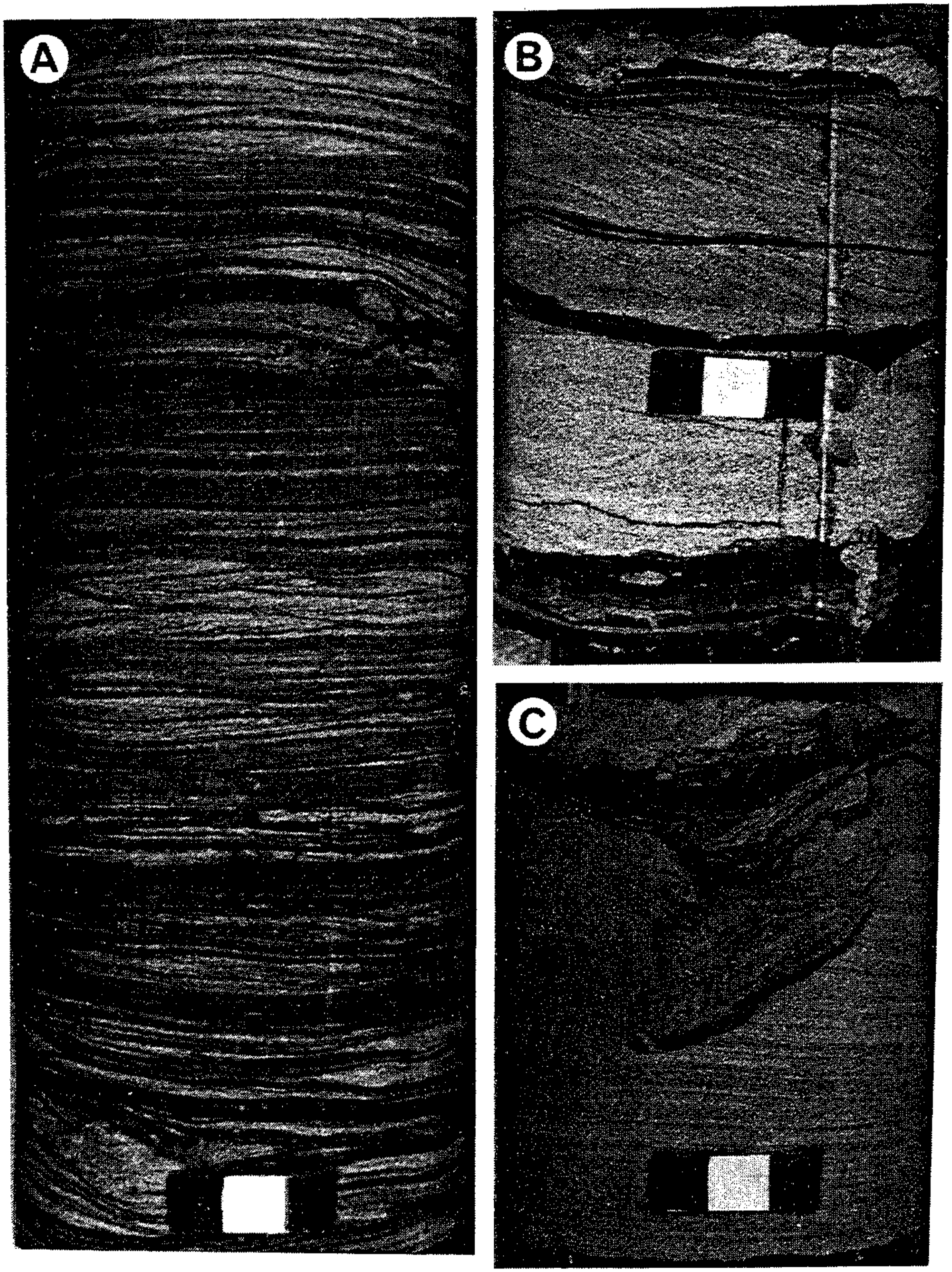
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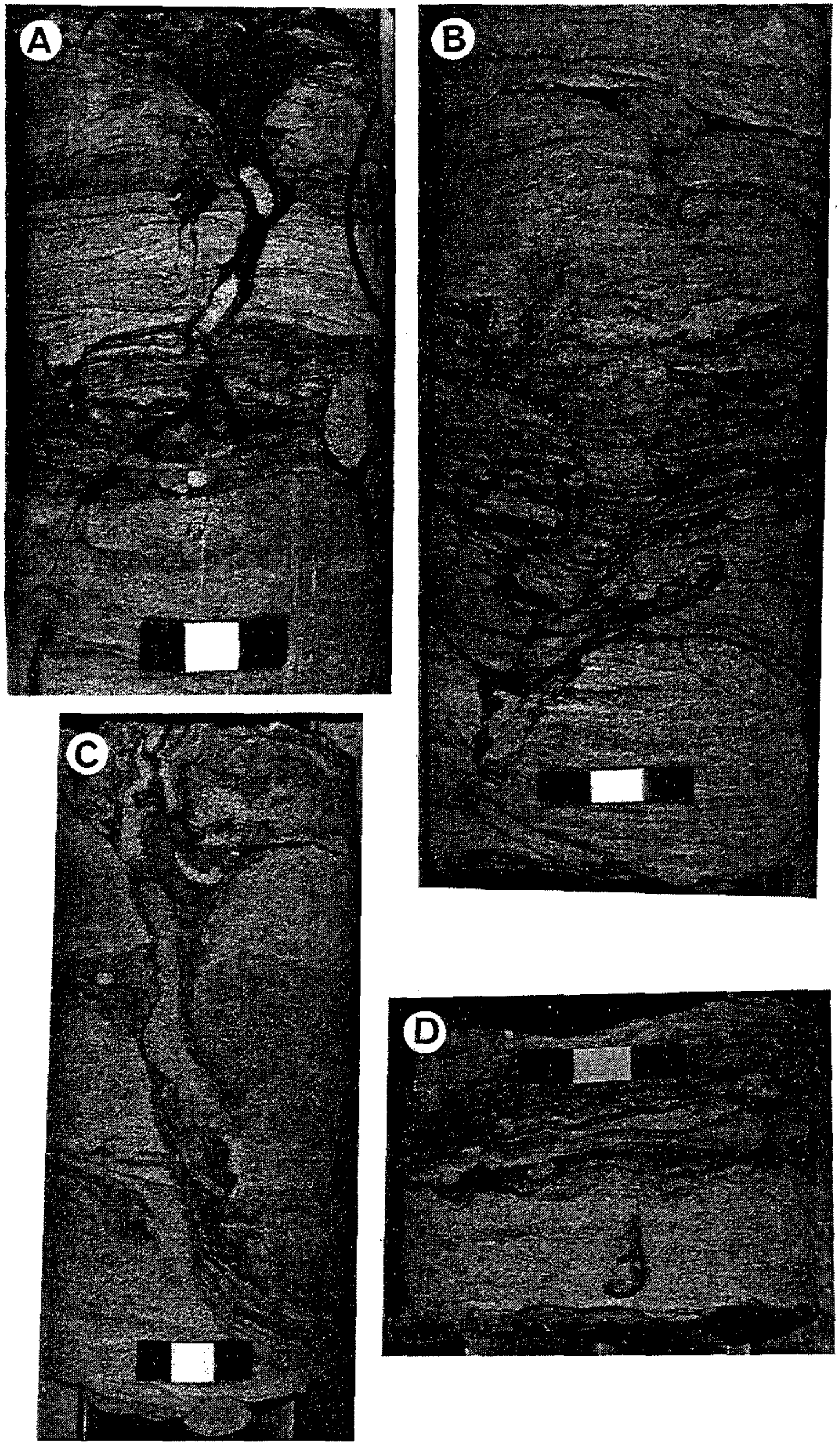
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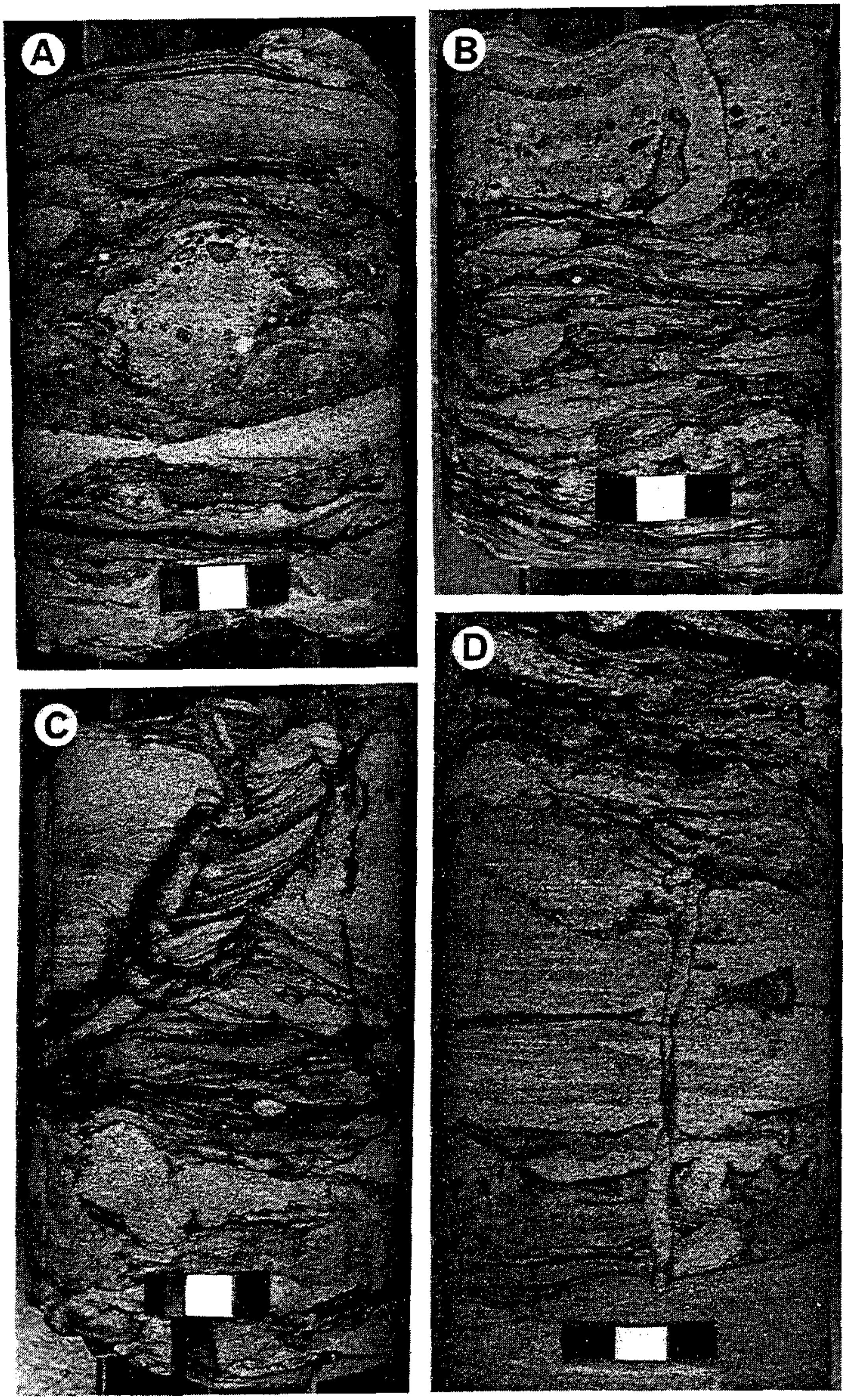
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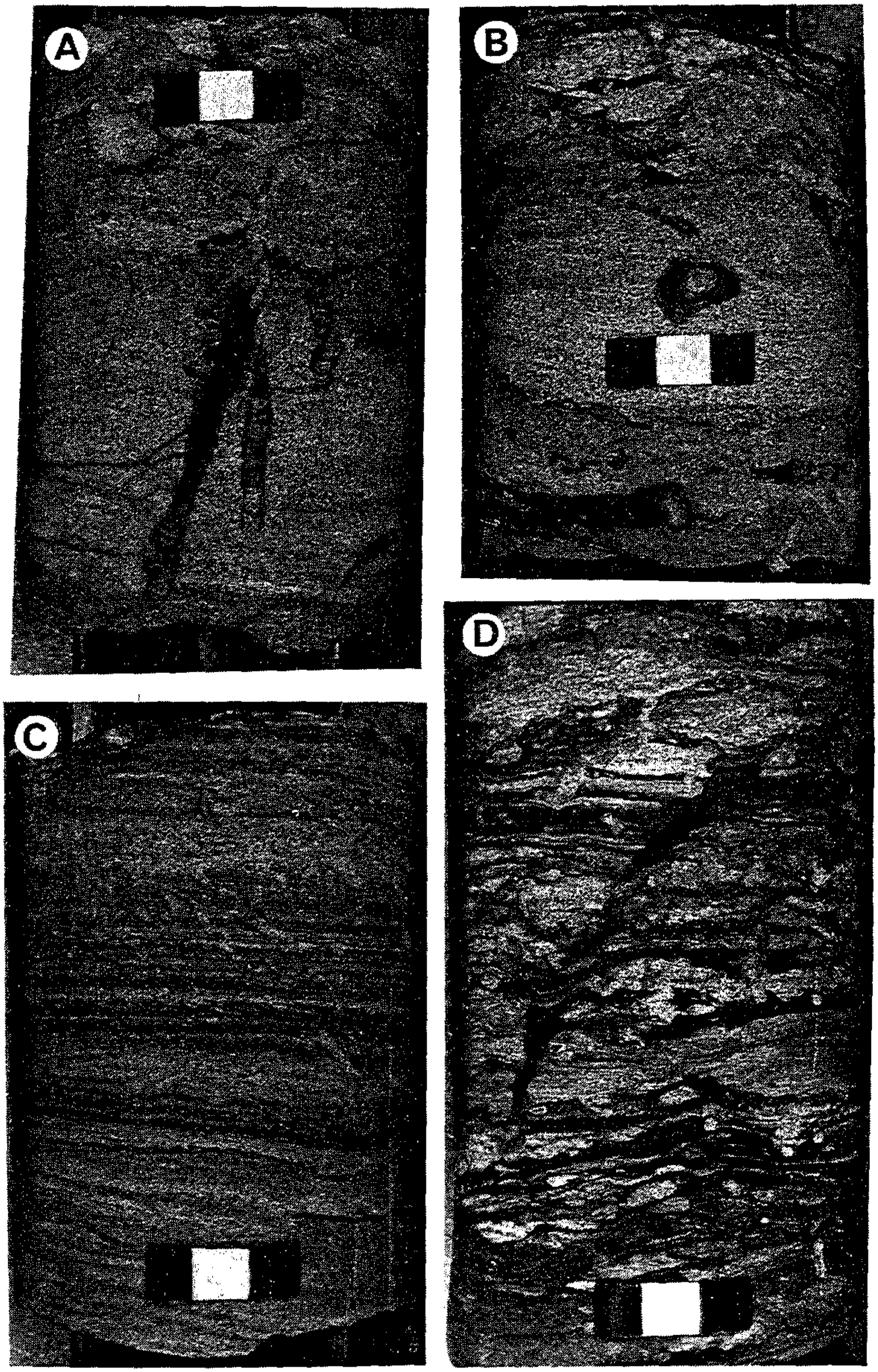
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D

log response which erosively truncates markers of the underlying basal siltstone assemblage. The upper and lower contacts of this association are marked by sharp resistivity inflections, and are easily matched to corresponding pebble or granule lags in core. Both overall fining- and coarsening-upward sequences can be detected within this assemblage, and a complex interfingering of muddy and sandy interbedded facies often exists [figs. 6.48, 6.49, 6.50, 6.51].

The interbedded facies association reaches a maximum thickness of 8.2 m closest to the main sand and conglomerate accumulation (FA2), and progressively thins to a zero erosive edge laterally. Although this assemblage occassionally has a "channelized" base, the much higher percentage of fines, and ragged log response differentiate it from the cross-bedded facies association. In resistivity log profile it can also be distinguished from the underlying basal siltstone assemblage by a stronger inflection to the right, and a total lack of predictable, correlatable markers.

6.6 Contacts

In the Willesden Green study area the lower contact of Member C (VE2) marks a distinct boundary between facies associations 2 and 3, and the underlying basal siltstone assemblage (FA1). Erosion on this contact is demonstrated by the sharp truncation of distinctive marker horizons (double bentonites) within regional cycle B2 of the basal siltstone assemblage. On a large scale VE2 defines a distinctive incised valley morphology [fig. 6.57].

In core, the lower contact of Member C (VE2) is consistantly overlain by a coarse pebble lag. This lag can reach thicknesses of 23

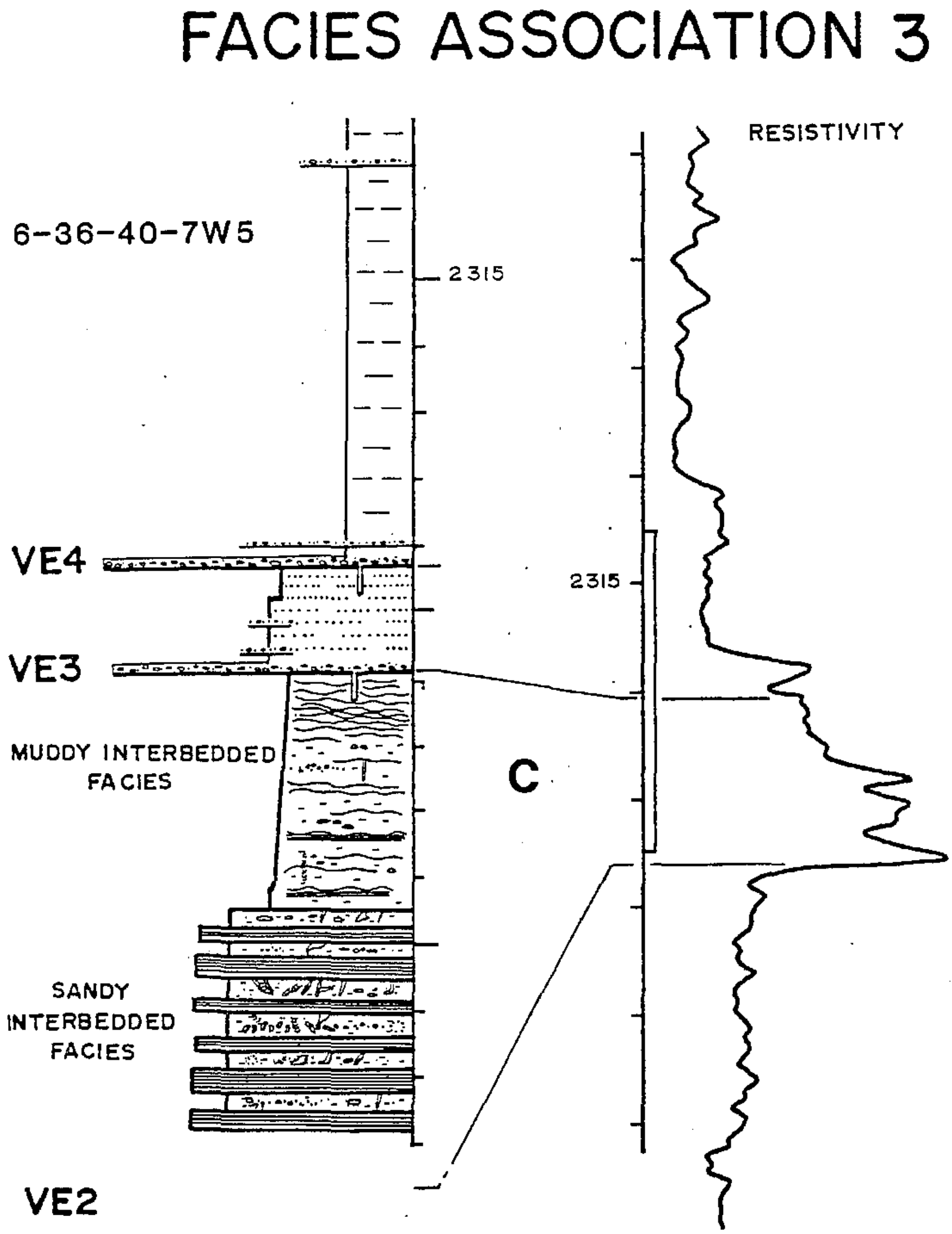


Figure 6.48 - Facies Association 3 - Reference Well 6-36-40-7W5; illustrating vertical facies relationships and correlatable log and core markers.

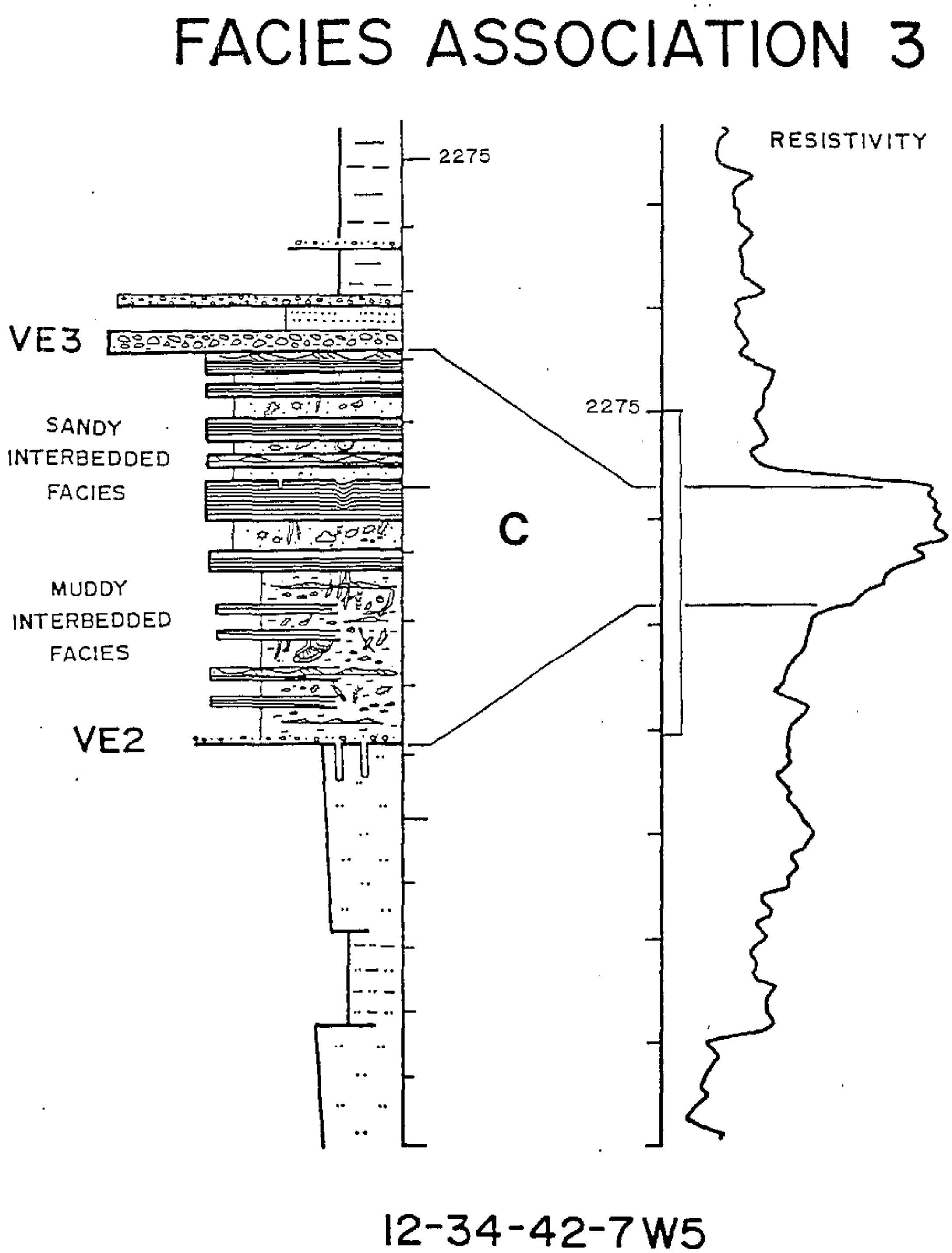
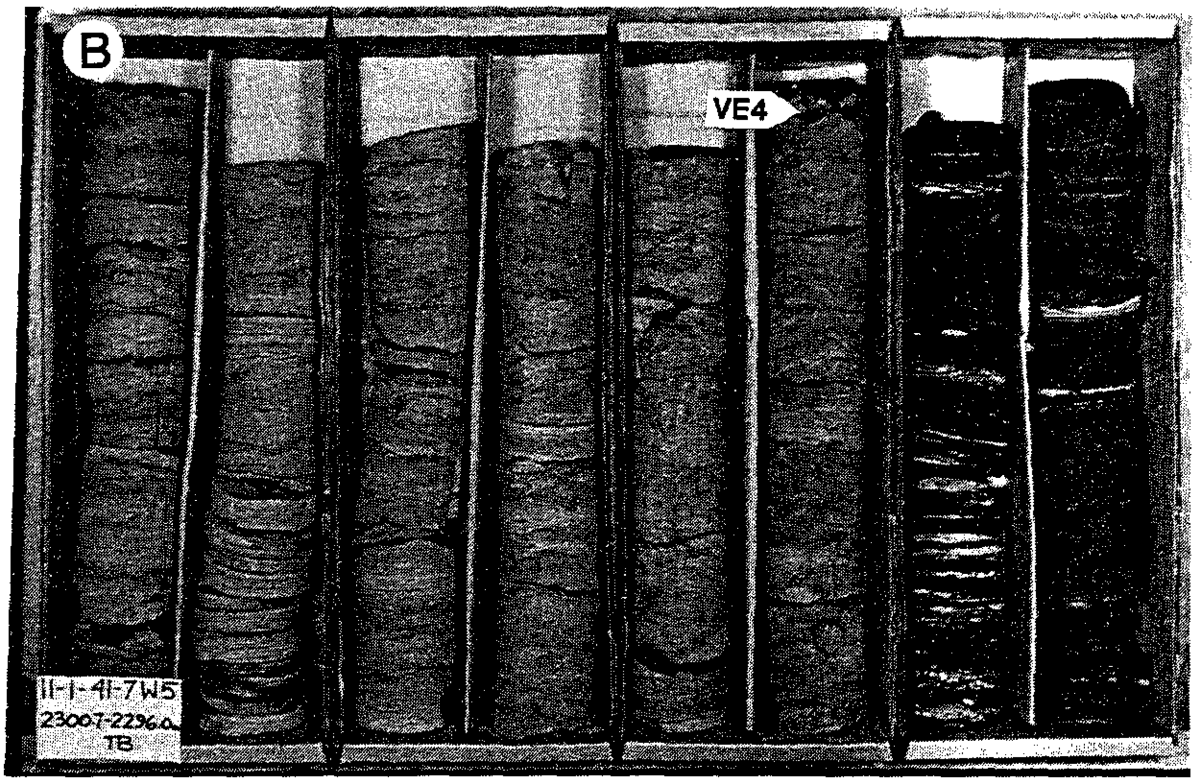


Figure 6.49 - Facies Association 3 - Reference Well 12-34-42-7W5 illustrating vertical facies relationships and correlatable log and core markers.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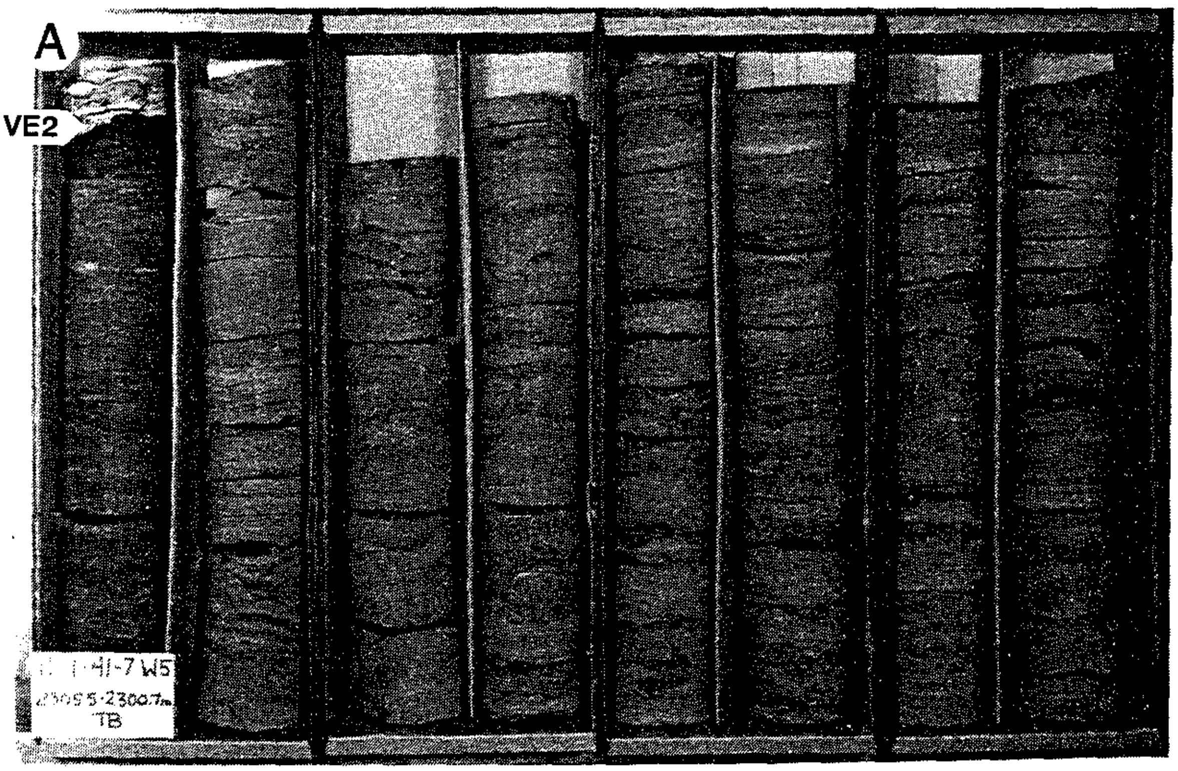
VE4
11-1-41-7W5
2300.7-2296.0m
TB


A
VE2
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2305.5-2300.7m
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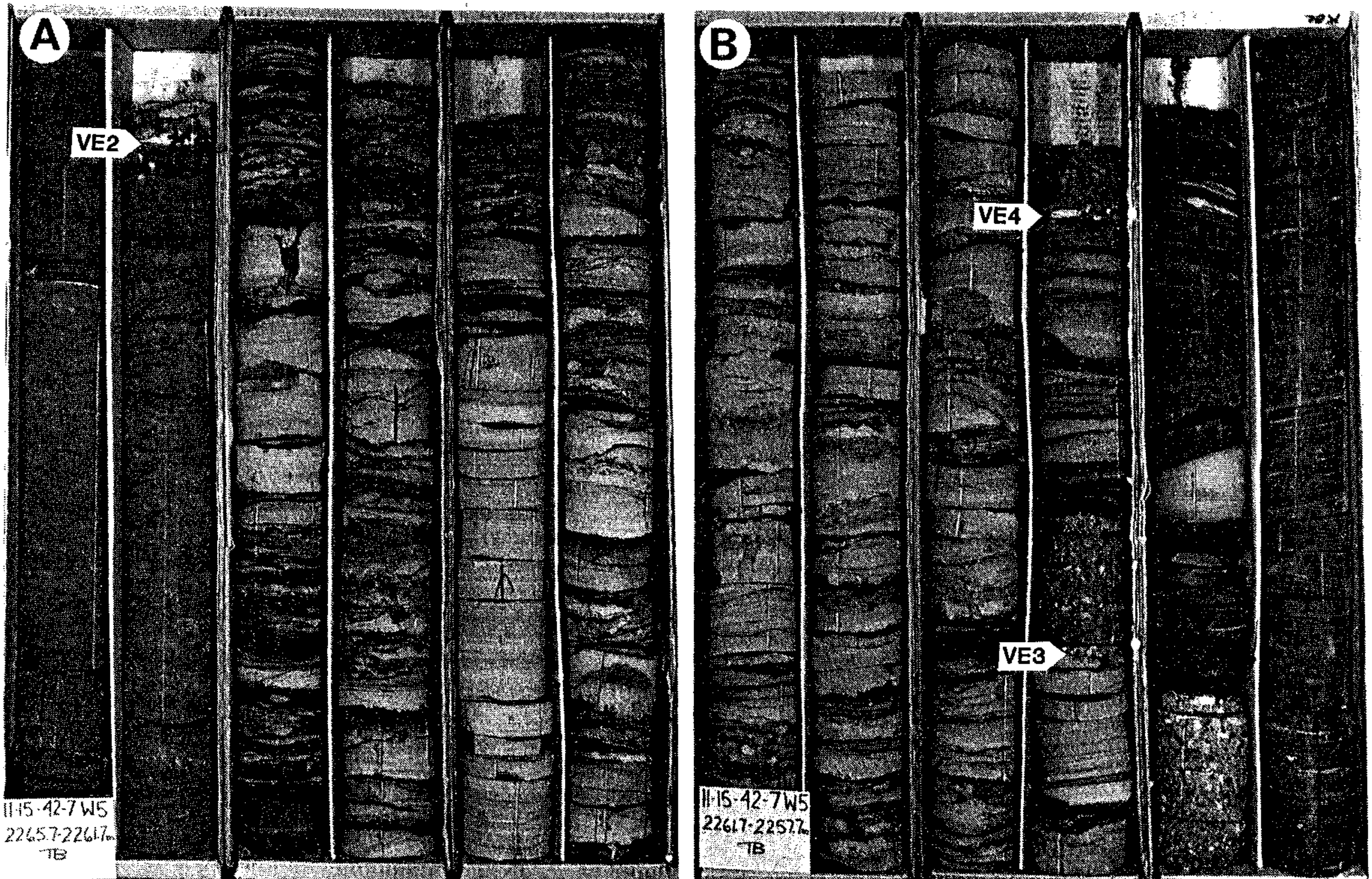

A
VE2
11-15-42-7 W5
2265.7-2261.7m
TB
B
VE4
VE3
11-15-42-7 W5
2261.7-2257.7m
TB

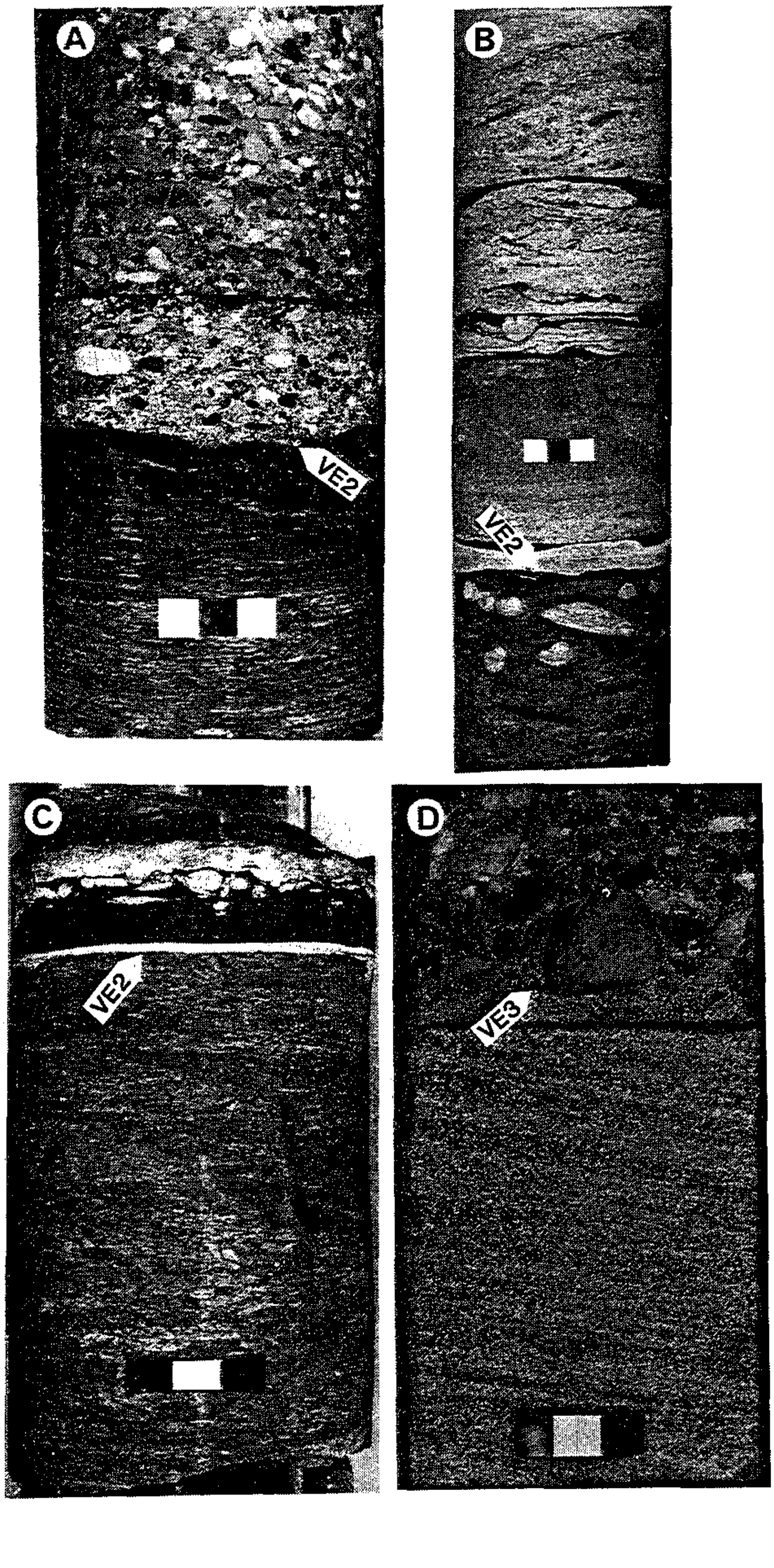
cm, with an average clast size of 25 mm. Generally the thickest lag deposits occur associated with the main axis of the coarse sand trend (FA2) [fig. 6.52], and progressively smaller clasts and thinner lag deposits occur laterally. Detailed petrological examination reveals the presence of poikilotopic calcite cement preferentially associated with the thick VE2 basal lag deposit of several facies association 2 (FA2) wells. The poikilotopic nature of the calcite, together with its patchy distribution, suggests that this early-emplaced cement may be related to the occurance and distribution of an original shell debris lag (Scholle, 1979).

Commonly, sand-filled Planolites, Skolithos, and Ophiomorpha burrows extend down into the underlying regional mudstones along this contact [fig. 6.53]. Within the laterally equivalent interbedded facies association (FA3) there is generally a persistant occurance of pebbles or scattered granules directly above the VE2 contact. In the muddiest locations furthest from the main sand accumulations, discrete sand lenses or black mudstone commonly drape this surface, in sharp contrast to the underlying bioturbated regional siltstones [fig. 6.54].

The top of the Member C package is abruptly truncated by Viking erosion surface VE3. This surface consists of a thin muddy conglomerate or granule layer (1-10 cm thick) [fig. 6.55] overlain either by sandstone-mudstones of member D, or directly by black shales of the Colorado Formation (where VE4 scours into VE3). This surface is described in more detail in chapter 7.

6.7 Facies Distribution

Figure 6.56 was constructed from subsurface data and illustrates


A
VE2
B
VE2
C
VE2
D
VE3

sand thickness and lateral facies distribution of Member C deposits in the Willesden Green area. Figure 6.57 demonstrates the morphology of the VE2 valley scour in which the Member C sediments are preserved, and figures 6.58, 6.59, and 6.60 are log and core cross-sections providing a view of the vertical and lateral relationship of facies across the unit.

From figure 6.56 it is apparent that the 2 main reservoir sands of the Willesden Green field are separated by an area of mainly muddy deposition. An isopach of Member C thickness shows definite elongate trends associated with each of the main sand accumulations. Facies distributions indicate that the thickest parts of these trends correspond to the cross-bedded facies association, with adjacent sandy interbedded facies deposits being slightly thinner. The muddy interbedded facies occupies the areas most distal from the main sand trend and, in general, is the thinnest of the three facies.

6.8 Interpretation

Interpretation - Cross-bedded Facies Association

Several aspects of the cross-bedded facies association (FA2) indicate deposition within the subtidal part of an estuarine channel, in an environment subject to a strong marine influence and highly fluctuating current conditions.

A sharp, erosive base, coarse pebble lag, common mud rip-up clasts, abundant cross-bedding, and large scale fining-upward trends are all features commonly associated with channel deposition. Other notable characteristics include the thickness of the facies (over 11 m), and its distinct channel morphology. Imbricated pebble beds, planar and trough cross-bedding, and parallel-lamination indicate deposition from strong

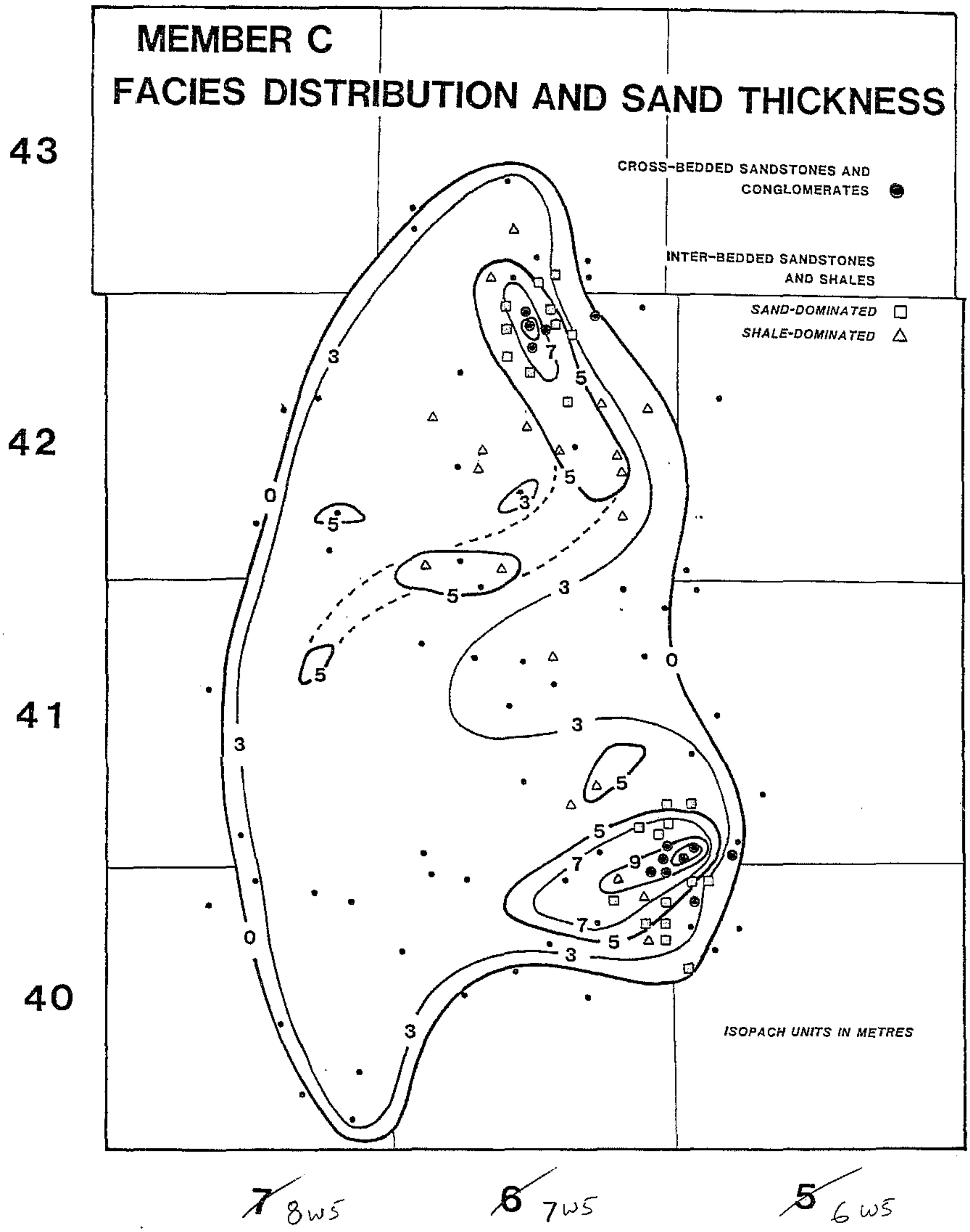


Figure 6.56 - Map of Member C sand thickness and facies distribution. Each coloured symbol represents a cored well examined; black circles indicate log control.

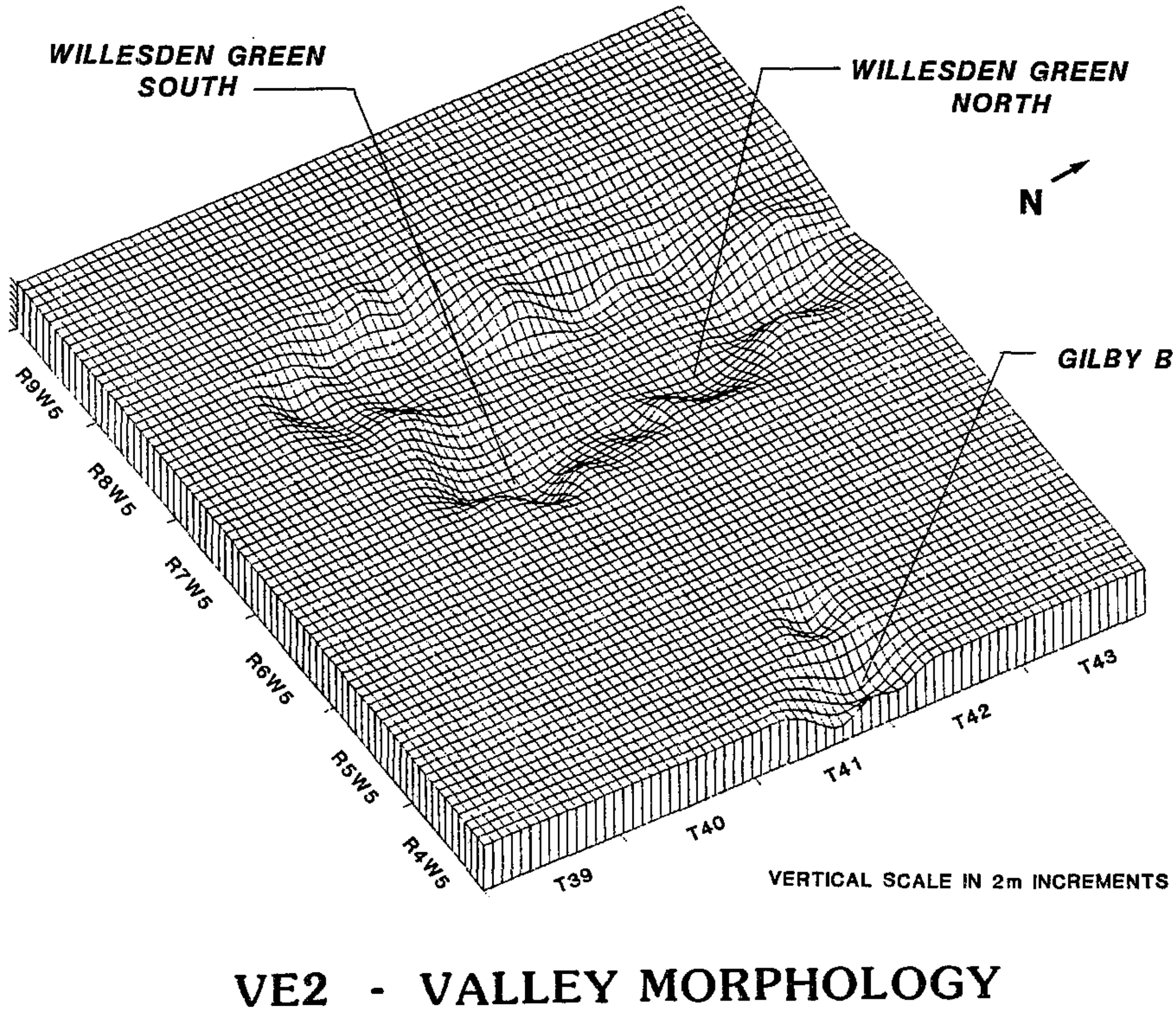


Figure 6.57 - Surface diagram indicating the morphology of the VE2 valley incision at Willesden Green (constructed using Surfer software package).

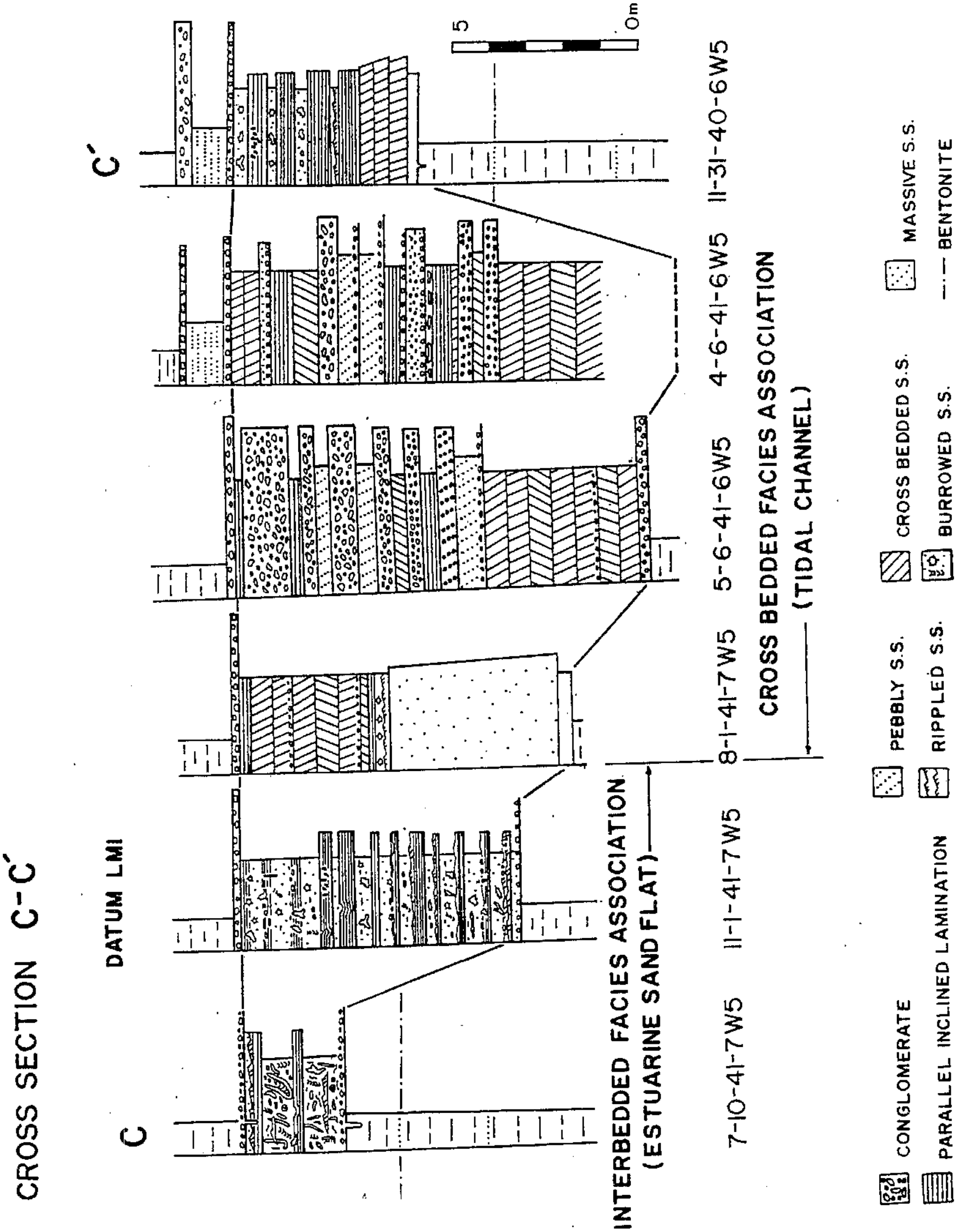
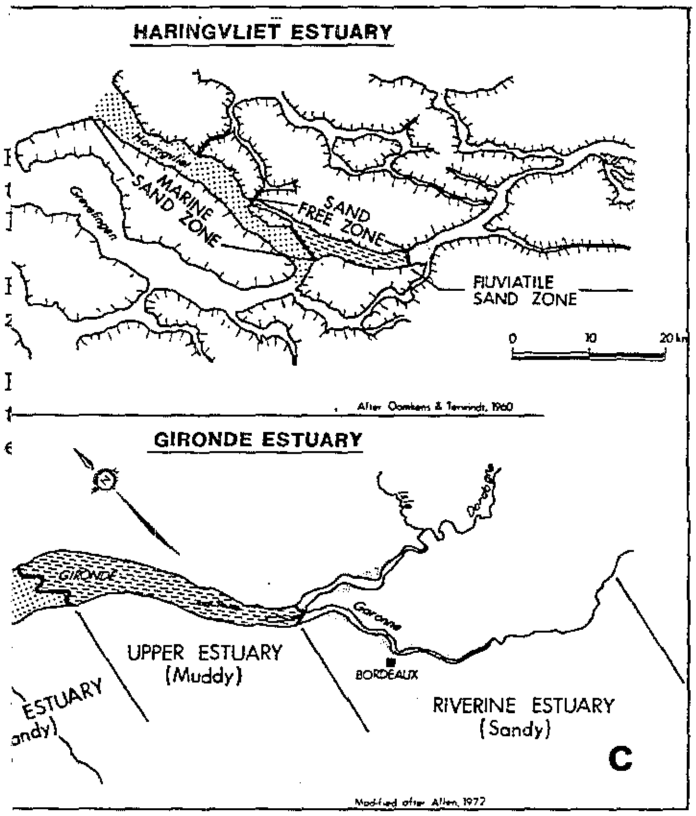


Figure 6.59 - Core cross-section C-C′ showing vertical and lateral facies relationships of Member C (see fig. 6.58 for location).



From Rahmani, 1988

traction currents, and thick (up to 4.8 m) massively bedded sandstones are typical of rapid deposition from suspension, or from very highly concentrated sediment dispersions (Blatt, Middleton and Murray, 1980). Dense patches of fragile, angular mud clasts associated with high flow regime deposits are interpreted to be channel wall collapse features.

The common occurance of mud laminae and drapes associated with upper flow regime deposits, indicate an environment where high energy traction currents capable of moving both sandstone and pebble size clasts (flow regimes in excess of 100 cm/sec), periodically oscillated with intervals of very quiet (slack) water. In marginal marine channelized environments, such conditions routinely occur during major flood/waning flood events, or more commonly, during periodic tidal reversals. At Willesden Green, the presence of fine mudstone laminae within the scour troughs of 3-dimensional bedforms provides evidence that in some instances incremental sand movement and regular changes in flow velocity must have occurred over relatively short time intervals. In the modern day mesotidal estuary of Willapa Bay, Washington, Clifton (1983) found a similar occurance of mud drapes throughout many of the subtidal parts of the estuary. Several ancient estuarine examples also consistantly record clay-mantled pause planes within their cross-bedded sets (Driese et al, 1981; Bosence, 1973). At Willesden Green, black angular mud rip ups, which commonly occur along cross-bed toesets within facies association 3, undoubtedly resulted from the destruction of these slack water drapes during subsequent increase in the flow velocity.

Within Member C small scale erosion surfaces and reactivation planes occur on all scales, from boundaries separating individual channel fill sequences several metres thick, to minute erosive planes separating stacked mm scale ripple sets. Their occurance however, is most prominent between sets of the cross-bedded and planar-laminated sandstone facies. Small scale (dm-m) vertically stacked bedsets characterized by both fining- and coarsening-upward sequences and abrupt facies changes [fig. 6.12] often overlie these surfaces, and reflect rapid alterations in flow pattern under the influence of both unidirectional and wave orbital currents. The consistant occurrence of such sequences of reactivation - full vortex - slackening structures is further evidence of a depositional environment dominated by a highly dynamic and fluctuating flow regime, much like that recorded in the macrotidal Bay of Fundy.

Dalrymple et al (1975, 1978) describe intertidal and subtidal sand bodies from the Bay of Fundy which have several mobile superimposed bedforms, including current ripples, dunes (or megaripples), sandwaves, and sandbars. As a result of changes in flow direction during tidal cycles, and modification due to wave and storm action, planing off and erosion of these bedforms is a common occurance. As a consequence, reactivation and complex erosion surfaces occur throughout the deposits. A more detailed discussion of the formation of these surfaces can be found in Blatt, Middleton and Murray (1980), and in Reading (1986).

Palaeocurrent diagrams indicate that, at the time of deposition facies association 3 was dominated by a wide current variance. Although limited scribed cores are available in the study area, those present show definite indications of crude unimodal, and vertically stacked bi- to multi-modal directions of flow [fig. 6.61]. These findings suggest that the depositional environment was affected by laterally variable flow patterns which, through time, could remain relatively constant in one area, while fluctuating markedly in an adjacent locality.

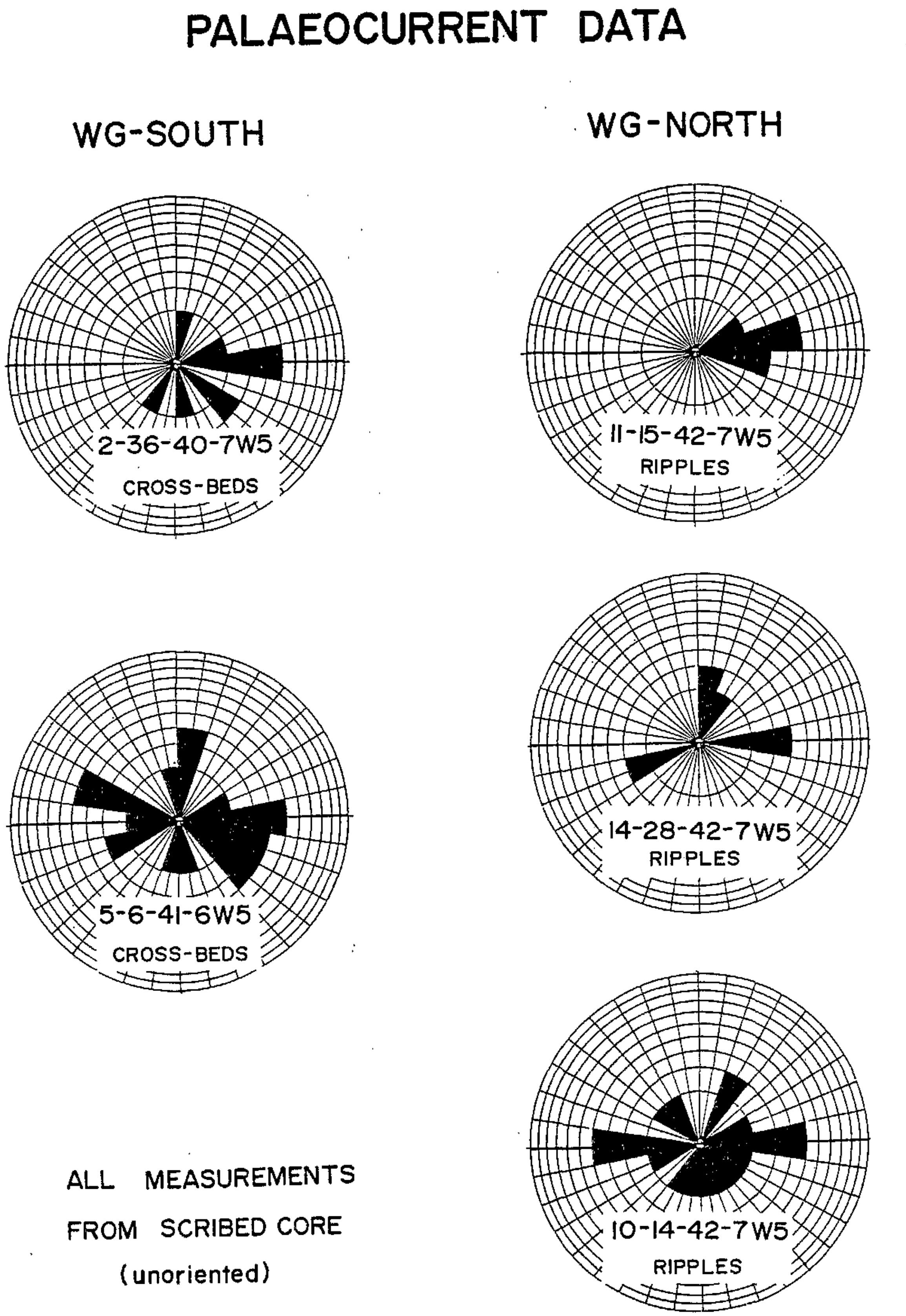


Figure 6.61 - Equal area rose diagrams of Member C palaeocurrent data. Each enclosed "square" represents one measurement.

This overall complex palaeocurrent pattern appears to be quite typical of modern tidal channels and estuaries. In a study of the mesotidal Havingvliet Estuary of southwestern Netherlands, Terwindt (1971) noted a clear dominance of one current direction at any one area, but a wide overall current variance. Similar findings were recorded by Dalrymple et al (1978) in the Bay of Fundy, and by Allen et al (1984) in the macrotidal Gironde Estuary in France. This phenomenon results from the fact that although currents in tidal environments reverse direction, each channel or part of a tidal sand flat is dominated generally by one part of the tidal cycle (Blatt, Middleton and Murray, 1980). Thus an expected sequence for tidal channel and estuarine deposits would display an overall complex palaeocurrent pattern. Several ancient deposits, interpreted as estuarine in nature, show just such a sequence (Rahmani, 1988; Baldwin and Johnson, 1977; Mazzullo, 1978). Although meandering fluvial systems could potentially record a similar palaeocurrent pattern through the progressive downstream migration of meander loops, the ubiquitous occurance of marine ichnofossils precludes such an interpretation.

The extremely sparse biogenic structures present in the Willesden Green cross-bedded facies association appear to be consistant with the types of organisms found in modern high energy coastal environments. Frey and Mayou (1971) indicated that organisms that inhabit these zones typically tend to be suspension feeders that construct vertical dwelling burrows. Characteristic organisms along the Georgia coast include the shrimp Calianassa major and the polychaete worm Onuphis microcephala, whose burrows, if preserved, would be Ophiomorpha nodosa and Skolithos linearis respectively (Ekdale et al, 1984) [fig. 6.62].

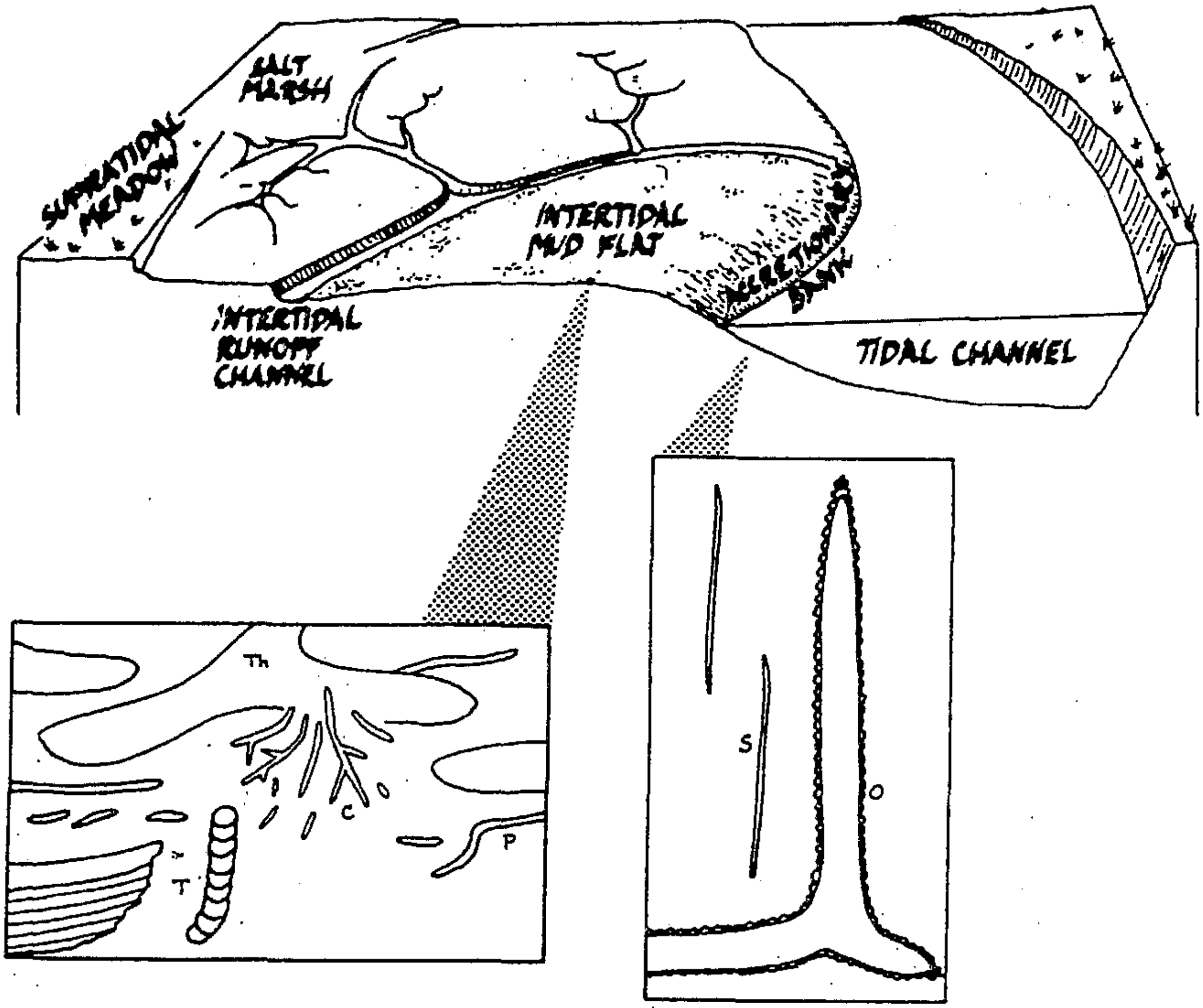


Figure 6.62 - Schematic representation of the mixed Skolithos-Cruziana assemblage that is typical of many estuarine point bars. Lower left: Th, Thalassinoides; T, Teichichnus; P, Planolites; C, Chondrites. Lower right: S, Skolithos; O, Ophiomorpha (Modified from Ekdale et al, 1984).

Ancient examples of tidal channel ichnofacies are relatively poorly documented, however Ophiomorpha has been reported in shallow tidal channel facies of ancient inlet-fill sequences by Carter (1978), and Skolithos and Ophiomorpha have been described by Reinson et al (1988) in the Viking Crystal field. Several other ancient estuarine examples (de Boer et al, 1988) do not identify specific ichnogenera, but do record subtidal sands weakly bioturbated by 'shallow marine fauna'.

Interpretation - Interbedded Facies Association

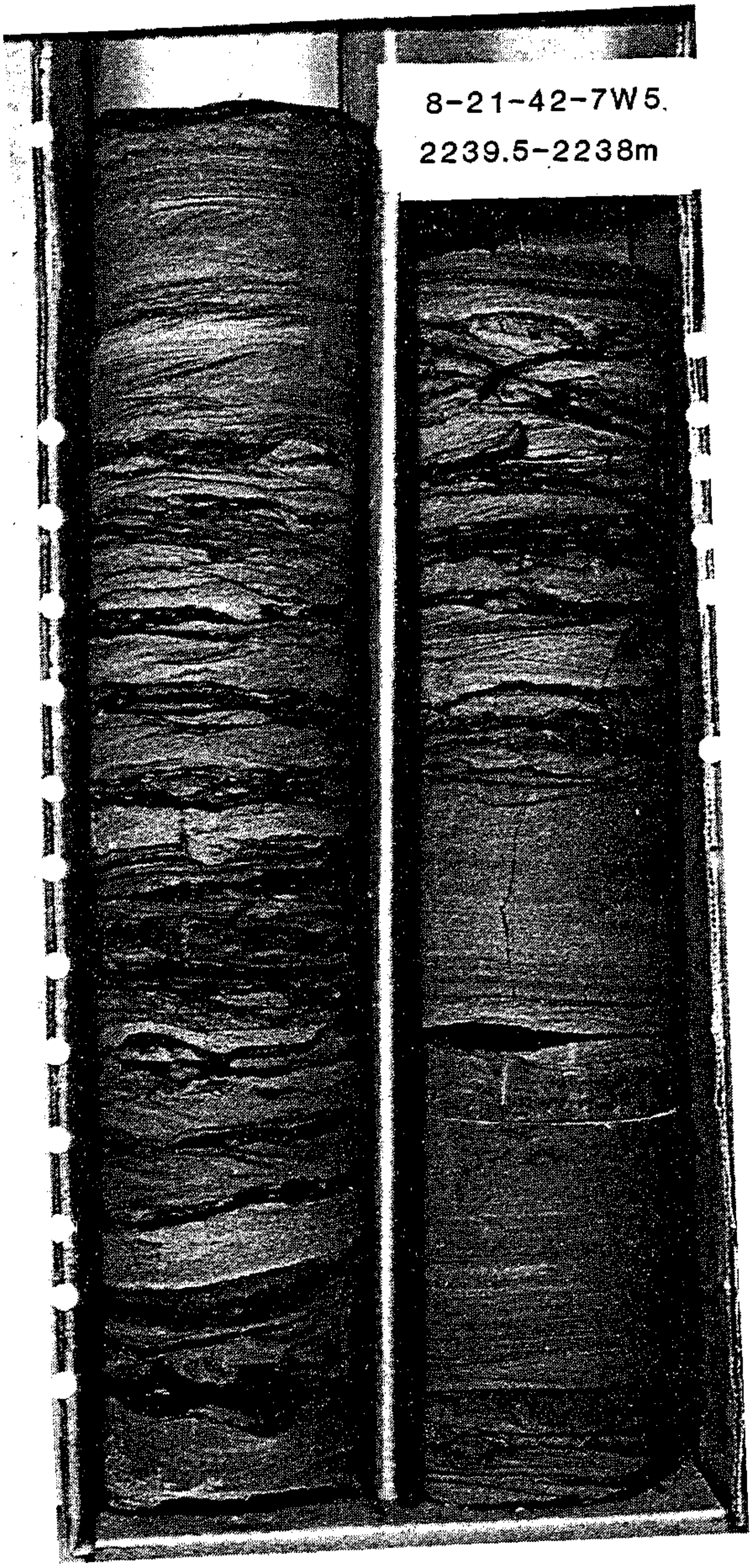
Several aspects of the interbedded facies association (FA3) indicate deposition in a shallow marine to brackish sand/mud flat environment, dominated by episodic sedimentation.

A delicate balance between physical and biogenic processes appears to be at work in this environment. The typical sandy sequence, consisting of interbedded packages of planar-laminated and mud-draped, burrowed couplets, points to a depositional regime in which events of erosion and rapid deposition, rhythmically alternated with periods of slow sedimentation. Organisms which were regularly covered by sediment during high flow periods, had time to re-establish themselves at the sediment/water interface during the intervening quiescent intervals.

The nature of the individual planar laminated beds (less than .3 m thick), suggests that limited accomodation space and relatively shallow water depths were characteristic of this environment. Stratigraphic cross sections show that at the time of deposition, this facies lay laterally adjacent to the elongate axis of the tidal channel, and accreted on the 'shoulder' of the main valley incision. As such, during peak flow periods this environment would be subject to similar current velocities and sediment saturation levels as the main channel, but would produce bedforms which reflected a much shallower water depth. The migration of large three dimensional dunes in the main thalwag of the channel would be accompanied by upper plane bed movement higher up on the sand flat. Similarly, periods of slack water, reflected by mud laminae and reactivation surfaces in the tidal channel (FA2), would be expressed as thick mud drapes and burrowing on the adjacent, relatively quiet, sand flats (FA3). The increased occurance of wave and current rippling in this facies (FA3) also highlights fundamental differences in water depth and current regime.

In the muddier portion of the association, starved-ripples, flaser and linsen bedding, and mud encased laminated sand beds reflect the distal effects of these complex waxing and waning flow patterns. Such bedding types are formed by rippled sand migrating across a muddy substrate, and are most commonly associated with tidal flat sedimentation (Blatt, Middleton, and Murray, 1980). Other indicators of episodically fluctuating flow conditions include repetitive small scale waning flow sequences (graded bed > planar-> current- > wavey-lamination > mud drape) [fig. 6.28], stacked current ripples separated by small scale reactivation surfaces [fig. 6.30], and continuous packages of regularly spaced sand and mud beds [fig. 6.63]. The ubiquitous presence of black shale interbeds indicates that large quantities of suspended fines were available for deposition during intervening quiescent periods.

While many of the structures discussed above indicate the presence of tidal influences, the thickness of some of these shales (up to 10 cm), precludes their deposition during a single low-speed "slack water" period. Such occurances probably reflect a lack of immediately available coarse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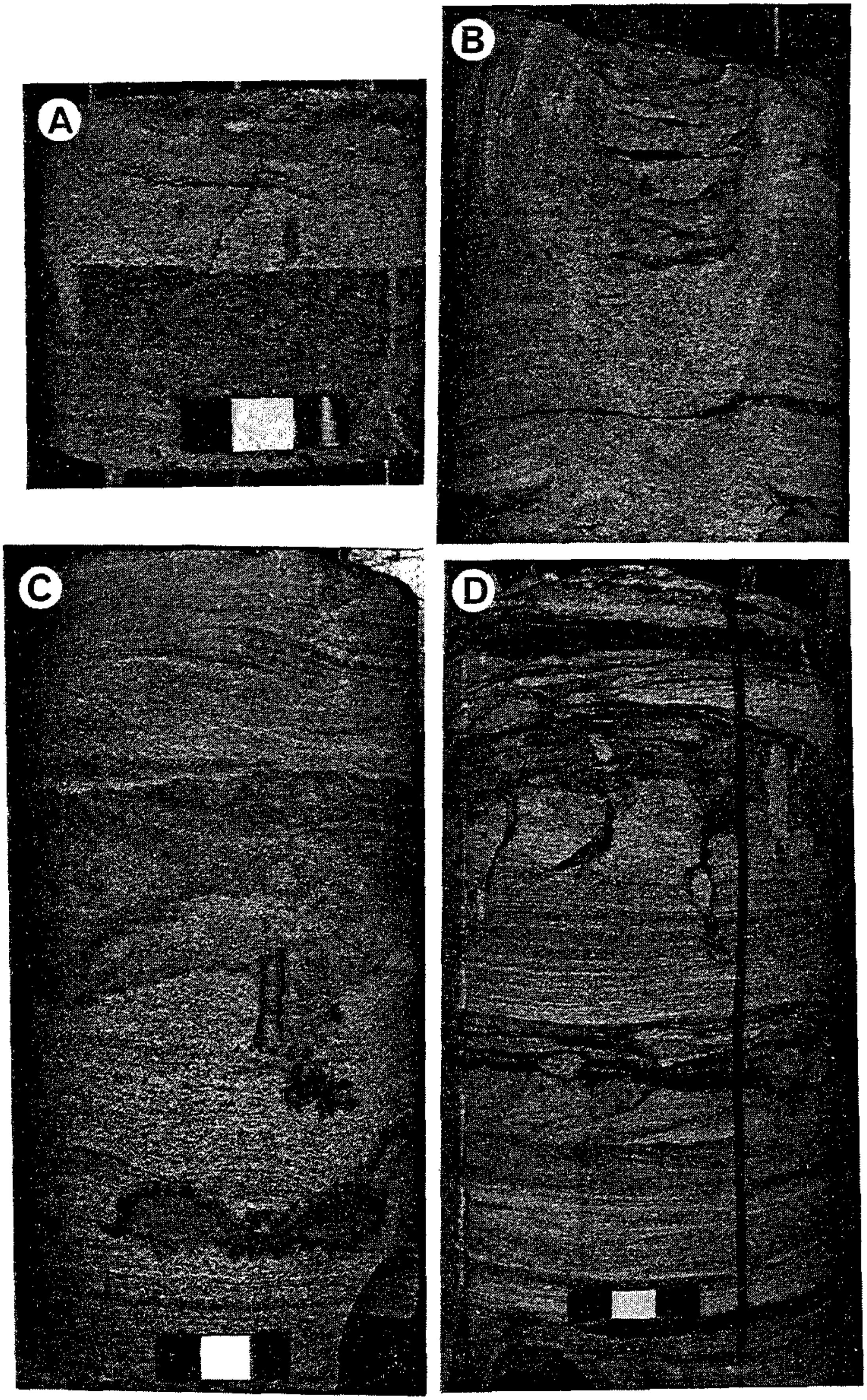
grain sizes, and suggest that in certain locations fine grained sands and silts only entered the system on a longer term basis, possibly during peak spring tide, or yearly flood and storm events. The rare occurance of thick packages of upper flat bed sandstone (up to 51 cm thick) and scattered granules in this otherwise fine grained assemblage, are almost certainly a reflection of catastrophic flooding or major storm events.

Although unidirectional current rippling and planar lamination are the dominant forms of stratification in the muddy interbedded facies, several less common structures provide additional information about its depositional environment. The rare occurence of thick packages of wave- and combined-flow-rippled sandstones [fig. 6.33] indicate that certain areas of this mud flat environment were dominated by wave orbital currents. These deposits show alternating bands of dominantly sandy or muddy composition and are extremely similar to the estuarine "muddy point bar" sediments described by Rahmani (1988, his figure 21) at Drumheller, Alberta. Convoluted bedding is also common [fig. 6.35], and reflects an environment dominated by the episodic deposition of sand, rapidly emplaced above previously deposited shale-draped, water-saturated beds. Synaeresis cracks, frequently found within the muddy interbedded facies [fig. 6.34], are indicative of a subaquatic environment with fluctuating salinities (Donovan and Foster, 1972) (Van Straaten, 1954). Perhaps the greatest environmental insights however, are gained by examination of the pristine biogenic structures present in both the sandy and muddy interbedded facies.

The common style of burrowing in facies association 3 indicates an environment dominated by short-lived, episodic depositional events, very similar in concept to those recorded in turbidity deposits (Ekdale, Bromley and Pemberton, 1984). **Pre-depositional** open burrows formed prior to a high energy sedimentation event are cast by sediment from overlying deposits [fig. 6.64], and burrowing along the tops of the stacked parallel-laminated packages records **post-depositional** recolonization by pioneering infaunal organisms [fig. 6.67]. Numerous post-depositional escape traces [fig. 6.65], identified by their uniformly-dipping laminae, also contribute to the picture of an environment in which daily or seasonally high flow regimes cause sporadic movement of bedforms in an otherwise quiet environment.

The abundant vertical and U-shaped burrows within this facies would have provided a distinct advantage to organisms that were frequently covered by sediment (S.G.Pemberton, pers. comm., 1989), and the close juxtaposition of dwelling and feeding burrows is a feature commonly encountered in modern tidal flat environments (Tillman, 1975). Common tidal flat trace-makers along the Atlantic and Pacific coasts of North America include amphipods (eg., Corophium volutator, which produces a vertical U-shaped spreiten burrow), polychaetes (eg., Arenicola marina, Scoloplos armiger, Nereis diversicolor, Onuphis, Diopatra, which produce a variety of feeding and dwelling burrows), crustaceans (eg., Callianassa sp., Callianassa californiensis, Upogebia pugettensis), which produce a branching system of dwelling burrows), numerous trail making gastropods (eg., Cerithium sterusmuscarum, Olivella damae, Natica chemnitzii) and bivalves (eg., Macoma baltica, Mya arenaria, Cardium edule)(Ekdale et al, 1984).

Other ichnologic characteristics observed, such as low diversity and small numbers of relatively large burrows are consistant with the biogenic structures one would expect in a relatively stressed environnment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dominated by episodic deposition and salinity fluctuations (M.J. Risk, pers. comm., 1989). According to Dorjes and Howard, (1975) brackish waters generally are reduced in species numbers with respect to both fresh water and fully saline water, and are characterized by limited opportunistic euryhaline species (Perkins, 1974). Many marine species also display a size reduction of individuals with decreasing salinity (Milne, 1940), however a reversed trend of increased burrow size may not unusual. This trend may be response to factors such as:

1) limited competition.
2) osmo-regulation and ionic-regulation (limiting surface area to volume).
3) inability of smaller organisms to withstand fluctuating salinity and energy conditions and frequent burial.

Within the interbedded facies association at Willesden Green, there is also a trend towards progressively increasing burrowing away from the main sand axis (sandy interbedded facies --> muddy interbedded facies). This biogenic gradient undoubtedly reflects specific environmental factors at the time of deposition. Lower sedimentation rates, reduced energy conditions, and a higher organic mud:sand ratio, are all factors which may have contributed to greater degree of biogenic reworking in this upper mud flat region. Similar conditions and responses have been well documented for both modern and ancient tidal flat environments (Weimer et al, 1982; Reineck and Singh, 1973).

The problem of whether the muddy interbedded facies records sub- or inter-tidal sedimentation is not easily answered. According to Terwindt (1988) it is often very difficult to distinguish the two deposits in the fossil record. Most of the characteristics thought to be indicative of the intertidal zone can also occur in the shallow subtidal zone, and no one feature is absolutely diagnostic. A lack of identifiable root traces, and the presence of synaeresis cracks suggest that at least portions of this environment were probably subaquatic, however these characteristics in no way discount the fact that both environments may be represented at Willesden Green.

Overview - Modern Estuarine Sequences

In macrotidal, sand-dominated coastal areas such as the German Bight [fig. 6.68c], the Aquitaine Coast [fig. 6.68d], and Bay of Fundy, the estuarine subtidal zone includes a complex of channels, bars, and shoals (Elliot, 1986). The channels are deep, funnel-shaped extensions of estuaries with characteristic sandwave, dune and ripple bedforms (Reineck and Singh, 1973), and sand shoals exist both at the mouths of the channels and in the inter-channel areas. Medium- and large-scale cross-bedding are common features of the channel facies, whereas the shoals and bars are characterized by finer-grained sands dominated by ripple lamination and wave-produced flat lamination. While sand is concentrated in central parts of the estuary, silt and mud occur in a continuous fringe of inter- and supra-tidal flats along the margins (Nichols and Biggs, 1985).

Dalrymple et al (1975, 1978) described intertidal and subtidal sand bodies from the Bay of Fundy up to 1 km wide and several kms in length, which form parallel to tidal currents, and which separate major tidal channels. Tidal channel deposits merge laterally into finer-grained tidal flat sediments or barrier island beaches.

Subtidal estuarine facies in the Haringvliet estuary in Holland were described by Terwindt (1971), and were found to be made up of three distinct facies:

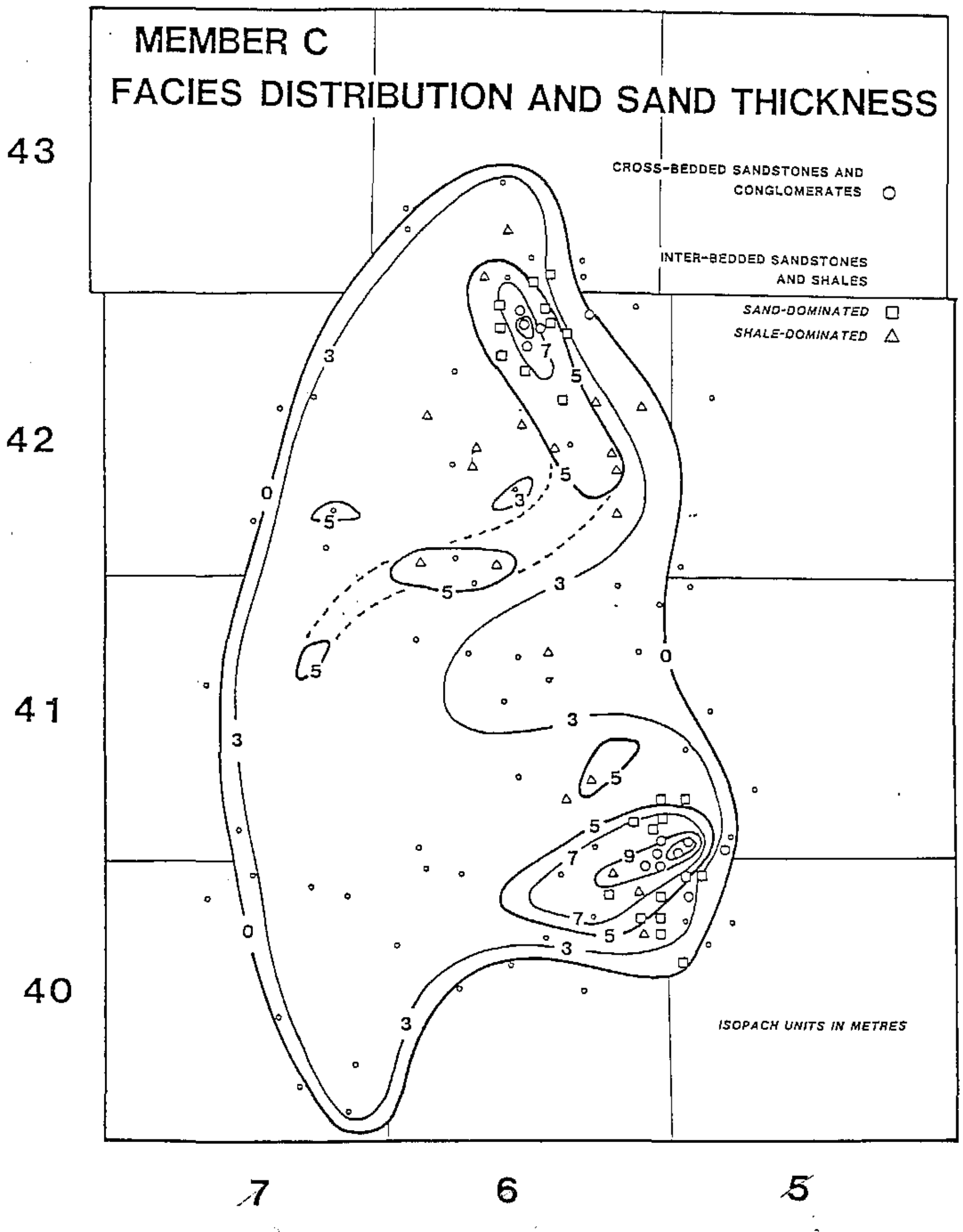
1) Coarse-grained sand with opposed sets of large-scale, trough or planar cross-beds in which the foresets occasionally are draped with thin silt layers

2) Medium-grained to fine-grained sand exhibiting flat lamination, ripple lamination and flaser bedding

3) Fine-grained sand and clay with lenticular bedding produced by rippled and parallel-laminated sand beds that are draped with thin mud layers

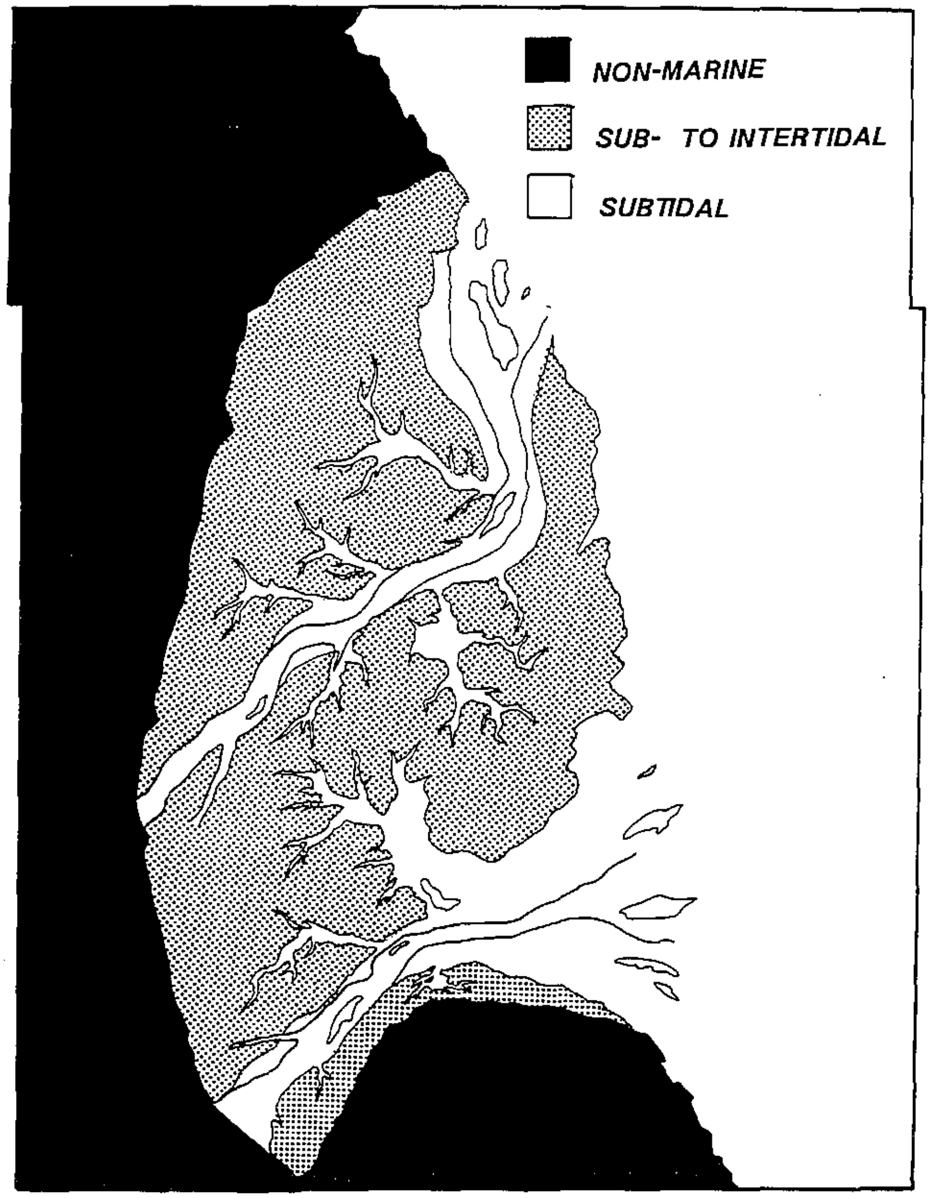
Clearly, the close lateral relationship between the facies associations of Member C are compatable with a complex channel-estuarine depositional setting [figs. 6.68a, 6.68b]. In the deepest part of a modern tidal channel, high flow periods result in the migration of two and three dimensional bedforms. These structures are reflected in the prominent cross-bedded sandstones and conglomerates of facies association 2 [fig. 6.69]. Shallower water depths associated with interchannel sand bars maximize peak flow velocities to produce thin packages of sharp-based, planar-laminated sandstones, such as those defining the sandy interbedded facies. Intervening slack water periods are reflected in the rippled, burrowed and mud-draped intervals at the top of each parallel-laminated package. Across the broad, gently inclined interchannel and estuarine margin areas, dampening of the wave and current effects results in the deposition of only very fine grained sandstones and clays in the form of flaser and linsen bedding; the main constituent of the muddy interbedded facies. Only under extreme rare event flood or storm conditions are units of parallel-laminated sandstone and scattered granules from the laterally adjacent channel brought into this relatively

A


MEMBER C
FACIES DISTRIBUTION AND SAND THICKNESS
CROSS-BEDDED SANDSTONES AND CONGLOMERATES
INTER-BEDDED SANDSTONES AND SHALES
SAND-DOMINATED
SHALE-DOMINATED
ISOPACH UNITS IN METRES
43
42
41
40
7
6
5

B

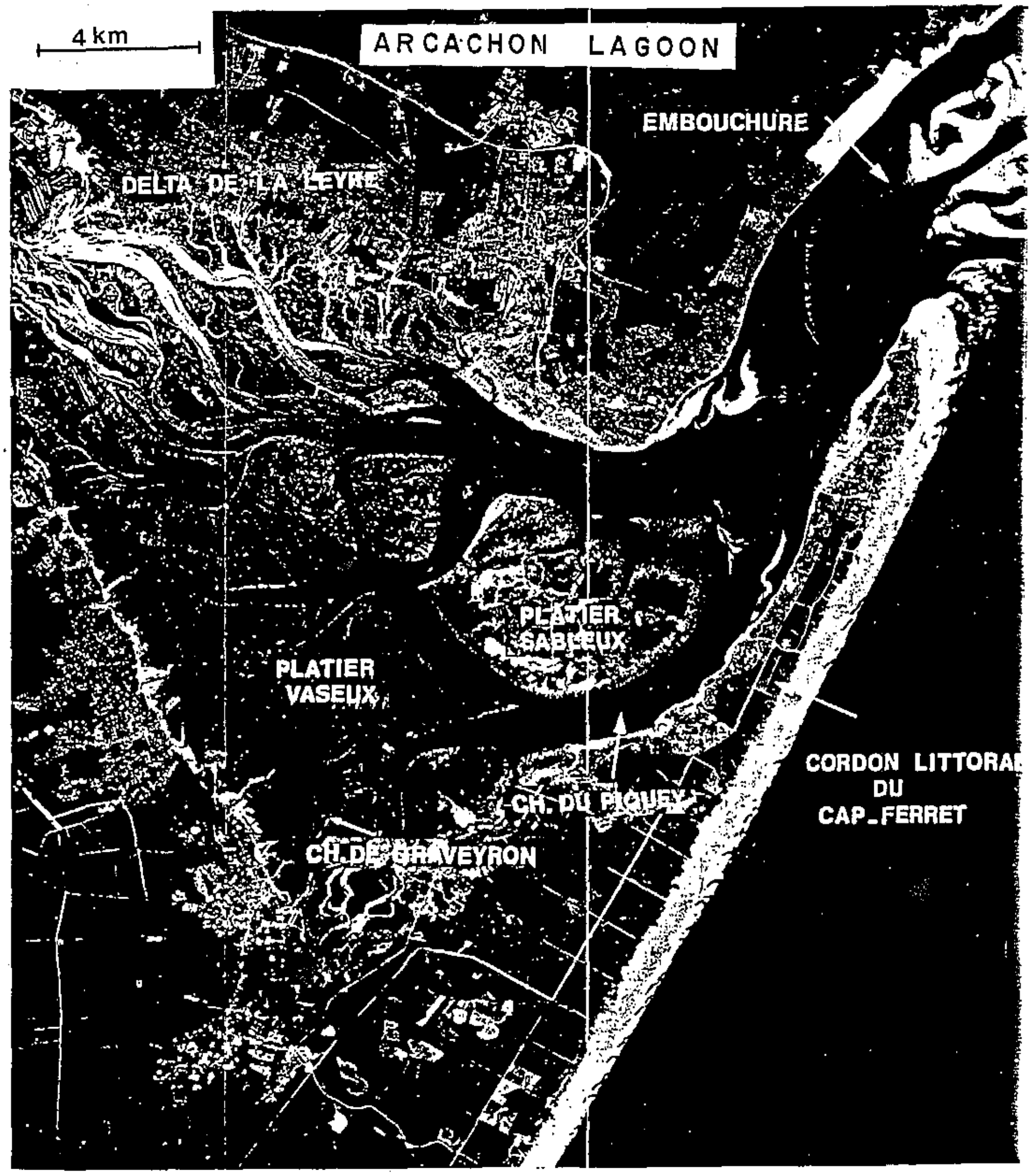
MEMBER C PALAEOGEOGRAPHY



CRETACEOUS

WILLESDEN GREEN , ALBERTA

D

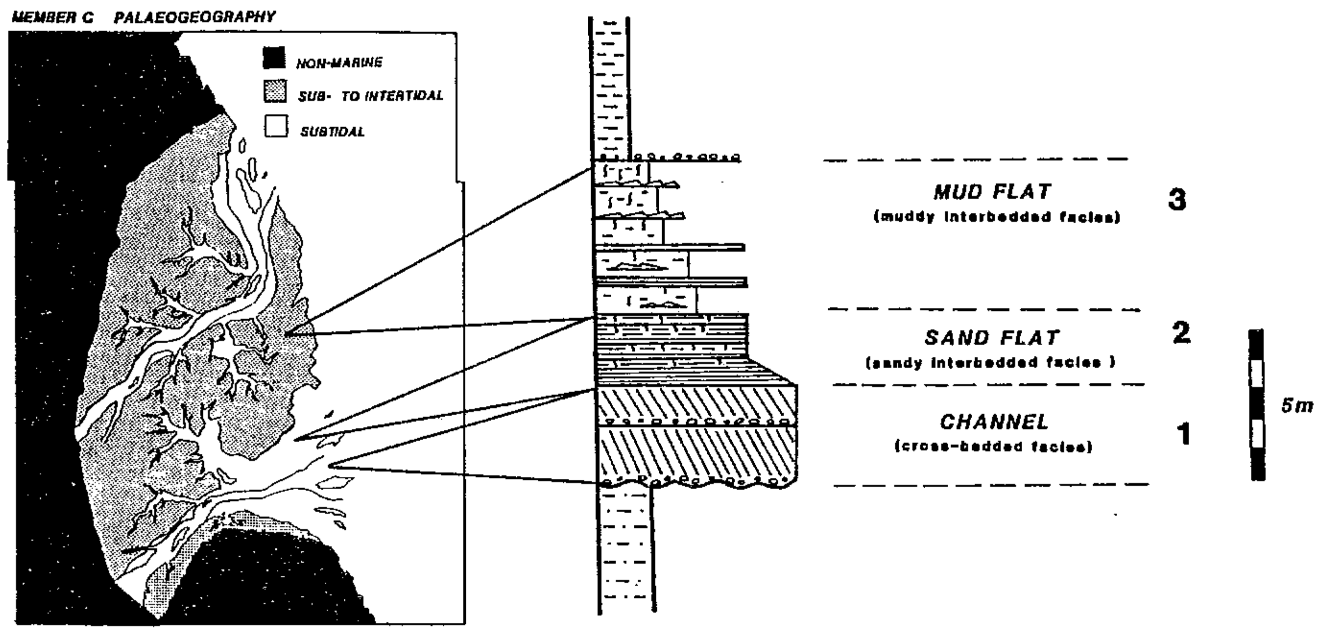


MODERN

AQUITAINE COAST

Figure 6.68d - The Arcachon Lagoon, a possible modern analogue for the Viking Willesden Green estuary.

IDEALIZED VERTICAL ESTUARINE SEQUENCE



	1	2	3
LITHOLOGY	Fine- to Coarse-grained Sandstone Conglomerate	Fine-grained Sandstone Black Shale Drapes	Silty Sandstone Black Shale Beds Rare Granules
SEDIMENTARY STRUCTURES	Planar and Trough -cross-stratification Abundant Reactivation Surfaces Massive Bedding Parallel Lamination Ripples	Parallel Lamination Ripples	Flaser and Linsen Bedding Parallel Lamination Synaeresis Cracks
ICHNOFOSSILS	very rare Ophiomorpha , Skolithos, and Macaronichnus	Rare Ophiomorpha , Macaronichnus, Diplocraterion, and Skolithos	Thallasinoides, Planolites Teichichnus, Asterosoma, Skolithos, Diplocraterion, Palaeophycos, Chondrites
	Increasing Burrowing Density →		
RESERVOIR POTENTIAL	GOOD	MARGINAL	POOR

Figure 6.69 - Schematic diagram of an idealized estuarine sequence (Cretaceous Western Interior).

quiet environment. The biogenically stressful conditions present in modern brackish estuarine settings are dramatically reflected in the unique assemblage of trace fossils characteristic of Member C.

<u>Interpretation - Contacts</u>

A good channel morphology, 11 m of focussed relief, and the erosive truncation of underlying bentonitic markers all suggest that the VE2 valley incision was produced through a mechanism of subaerial or shallow marine channelized erosion. By definition, estuarine deposition requires that a fluvial valley be present to focus tidal currents and supply a fresh water inlet, and in the case of the Willesden Green estuary this was undoubtedly the case. Initial fluvial incision however, was apparently overprinted by later shallow marine processes. The presence of marine, sand-filled burrows along the base of the VE2 contact, as well as in the overlying sands indicates that subsequent scouring and infilling of the valley occurred entirely under marine to brackish conditions.

The fact that these burrows are filled with the overlying sands and pebbles indicates that, at the time of cutting of the VE2 surface, and during subsequent emplacement of the coarse-grained sediments, the underlying open marine siltstones were at least partially consolidated. Since these regional siltstones were probably deposited as a rather soupy substrate (thoroughly churned, indistinct and "fuzzy" burrow walls, distorted traces (G. Pemberton, pers. comm., 1989)), some method of consolidation must have occured between the time of deposition and subsequent burrowing at the base of Member C. The simplest and most probable mechanism would involve some type of dewatering and compaction caused by the weight of overlying sediments. This partially consolidated horizon could then easily be exhumed, leaving a cohesive but non-lithified substrate, or "firmground". Such a mechanism is highly compatable with the hypothesis of a major drop in sea level and subaerial or shallow marine scouring of the VE2 surface.

Palaeogeography

The extensive preservation of incised valleys, and the great areal extent of correlative lowstand sand bodies at the VE2 stratigraphic horizon, suggests that this was the most substantial lowering of sea level recorded during Viking times. Lowstand shorefaces advanced at least as far northeast as the Gilby-Joffre trend (Downing and Walker, 1988; Raddysh, 1988), and possibly much further into the basin. It was almost certainly a eustatically controlled event, and probably correlates to a major sea level drop that occurred approximately 97 million years ago (Vail et al, 1977; Haq et al, 1987; Kauffman, 1984). Evidence from Willesden Green, when viewed in conjunction with data from other known Viking channels at Crystal (Reinson et al, 1988; S.A.J. Pattison, pers. comm., 1989) , Cyn Pem, Edson and Sundance, strongly suggests that during the first Viking lowstand, the drainage system radiated from southwest to northeast, with the primary sediment source in the southwest [fig. 6.70]. Correlatable upper shoreface sediments in the Caroline area (S.W. Hadley, pers. comm., 1989) contribute to the hypothesis that by this time the main depositional source had shifted from the vicinity of the Peace River Arch to points southwest, although much of the Peace River area was probably subaerially exposed at this time. While the lowering of sea level was undoubtedly eustatically controlled, the southward shift of depositional source can only be attributed to the effect of renewed tectonic thrusting in the southwest. During subsequent sea level rise the Willesden Green incised valley became estuarine and progressively filled under transgressive conditions [fig. 6.71].

While the erosion surface at the base of Member C (VE2) represents initial scouring predating deposition of the Willesden Green estuarine complex, the VE3 surface which truncates its top represents a ravinement surface marking the final flooding of the estuary, renewed transgression, and the end of the first Viking lowstand [fig. 6.72]. This surface can be traced across the entire study area and erosively truncates both the underlying deposits of the basal siltstone assemblage, as well as the estuarine-fill sediments of Member C. The lack of subaerial deposits associated with the Willesden Green estuary are attributed to erosive removal during this ensuing transgression. The VE3 contact defines a rather flat topography, and is mantled by a thin muddy conglomerate or granule layer (1-10 cm thick). Both sand-filled Arenicolites and Skolithos burrows commonly occur along this surface, as well as a large sand-filled synaeresis cracks. The lower shoreface and offshore transitional sediments of Member D abruptly overlie the VE3 surface.

Tripartite Estuarine Model

Figure 6.60a, a log strike section down the interpreted axis of the southern Willesden Green tidal channel, indicates a rapid facies transition from cross-bedded and conglomeratic sandstone to dominantly bioturbated muddy silts and sands over a relatively short distance (<1km). These deposits jointly infill a scour over 9 m deep in the main "channel axis" trend. These two styles of deposition would appear to reflect widely varying processes and environments of sedimentation, and any

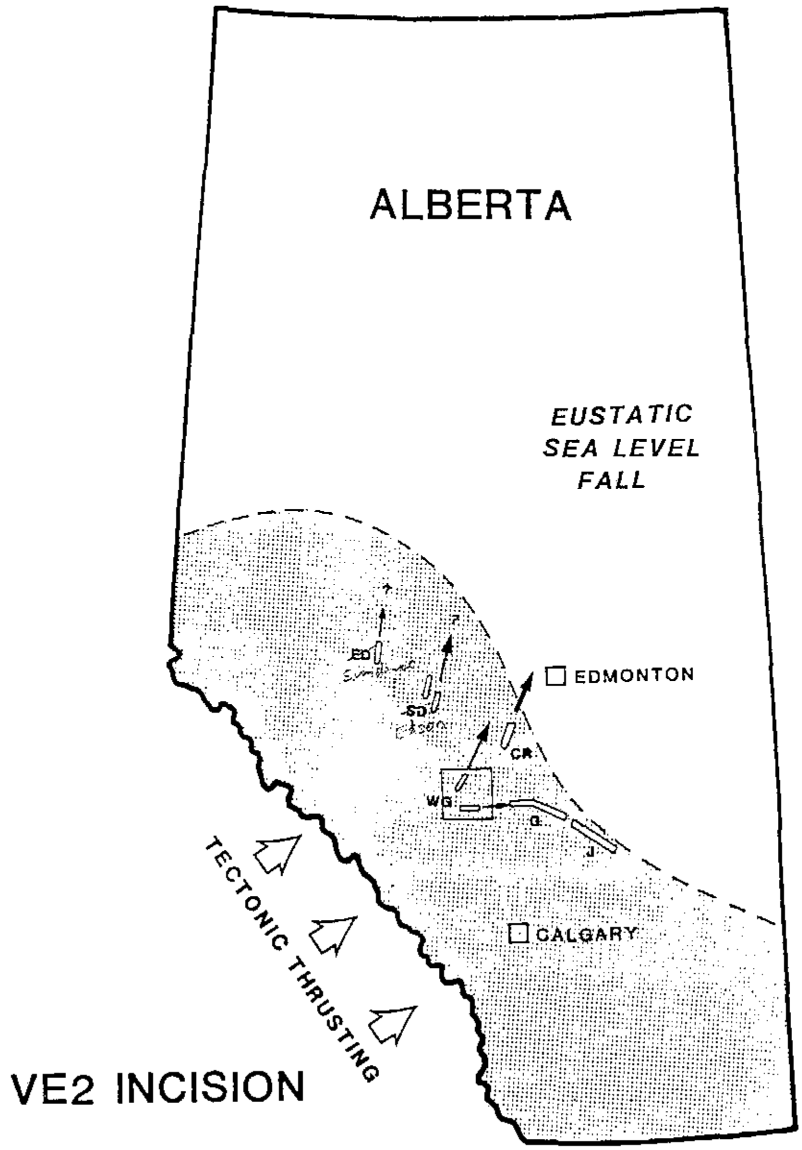


Figure 6.70 - Interpreted palaeogeography during the first Viking lowstand (incision of the VE2 surface). Viking sand bodies indicated include: ED - Edson, SD - Sundance, CR - Crystal, WG - Willesden Green, G - Gilby, J - Joffre. Dashed line indicates interpreted shoreline position.

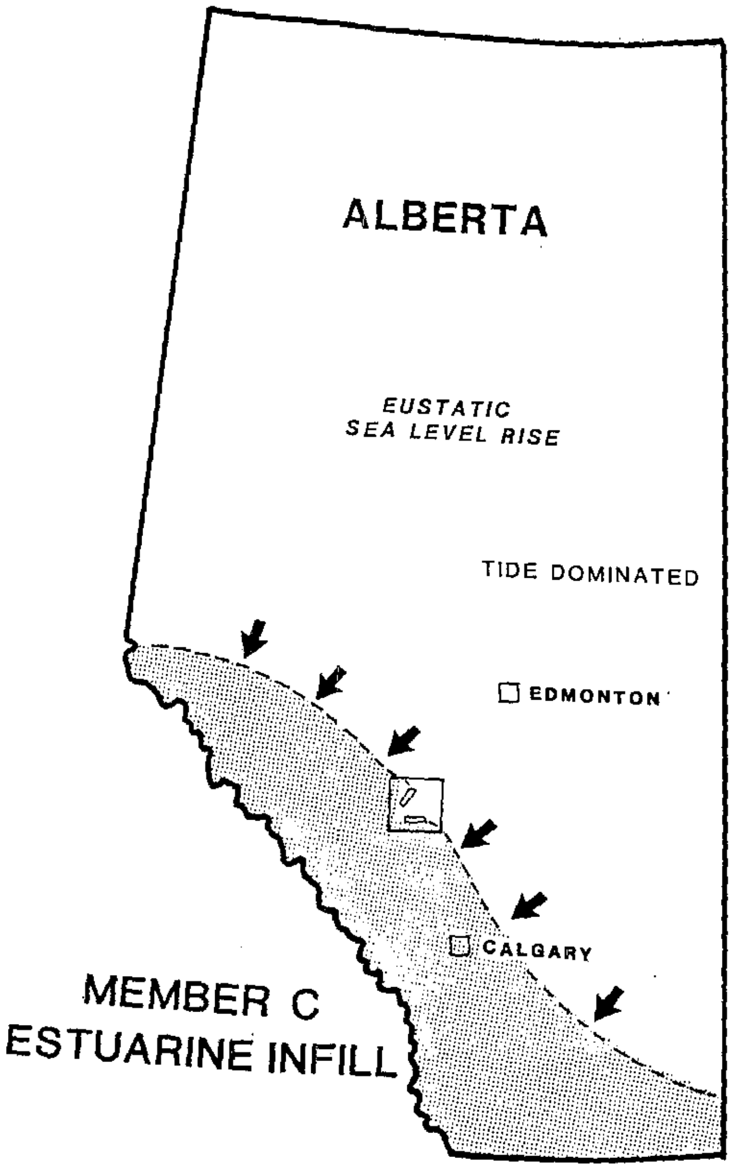


Figure 6.71 - Interpreted palaeogeography during infilling of the Willesden Green estuary (Member C).

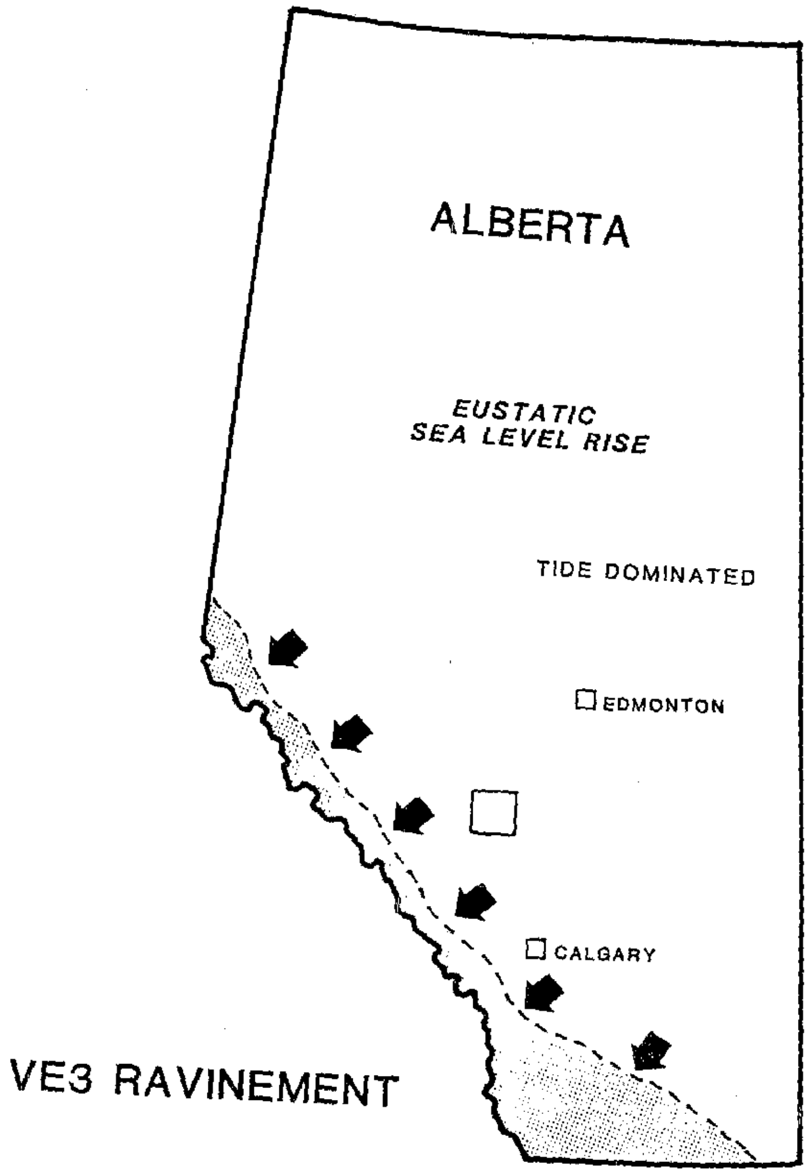


Figure 6.72 - Interpreted palaeogeography during maximum transgression (VE3 ravinement).

attempt to interpret their relationship must account for these variations. The most convincing explanation of the anomalous relationship of thick mudstones and conglomeratic sandstones may be provided by the tripartite estuarine model (Dyer, 1986). Simply stated, the lower reaches of tidal estuaries are sand-filled to a certain point upstream. Beyond that point is an area with mud deposits of certain width, followed upstream by another (fluviatile) sand filled channel (Rahmani, 1988). Modern examples of this zonation include the Gironde estuary of France, and Haringvliet estuary of the Netherlands [fig. 6.60c].

The estuarine depositional system can generally be divided into three zones (Nichols and Biggs, 1985): estuarine fluvial, estuary, and estuarine marine [fig. 6.60b]. The estuarine marine zone occurs at the most seaward end of the estuary, and includes shallow elongate subtidal to intertidal sandbars. This area can be considered similar to the ebb-tidal delta portion of micro to mesotidal estuaries, and is generally characterized by cross-bedded coarse-grained sand (Hayes, 1975). In this zone, sediments brought in by flooding tides from the nearshore are progressively moved upstream. In the Willesden Green example this zone appears to extend approximately 3 to 5 km in length.

The estuary zone is the central, muddy part of the depositional system. At this point, a zone of turbidity maximum occurs due to the interaction of saline tidal waters and fresh fluvial waters, resulting in salt wedge formation and two-layered circulation patterns. This zone is characterized by multiple channels bifurcating around fine-grained sandbars. The area is fringed with muddy to mixed sand and mud tidal flats (Hayes, 1975; Zaitlin, 1987). The primary mode of deposition is from suspension, resulting in sediments dominated by rippled and laminated clays and silts, interbedded with rare sand lenses (Nichols and Biggs, 1985).

The estuarine fluvial zone occurs upstream of the mud zone and is dominated by river-derived coarse clastics. This area is generally characterized by a single confined asymmetric channel bordered by salt marsh, and consists of fining up laterally accreted channel deposits (pointbars). The estuarine fluvial zone was not detected in the Willesden Green area either due to its erosive removal during subsequent transgression, or alternatively, due to insufficient drilling density away from the main estuarine marine sands.

By using the tripartite estuarine model in conjunction with observed facies associations and unit thickness maps, it is possible to roughly determine the palaeoflow direction at the time the estuary was infilling; approximately W-SW to E-NE.

Estuarine Fill Model

As was stated earlier, the Willesden Green southern channel appears to reflect two separate stages of channel infill. Stage one consists primarily of cross-bedded fine- to medium-grained sandstones; stage two is noticably coarser and is characterized by interbedded sandstones and conglomerates. Clifton's (1982) estuarine infill model suggests that estuarine deposits such as these may accumulate as a series of stacked "stillstand units" through sequential stages of sea level rise. The nature of the Willesden Green fill however, may indicate a much simpler continuous two stage filling process.

At Willesden Green, the first fine-grained stage of infill records an initial balance created between sediment influx and a rising sea level.

Although some rare scattered pebbles are present within this package, fine and medium grained sand was by far the dominant sediment being transported, primarily in two and three dimensional bedforms. The second coarser-grained stage of channel fill on the other hand comprises a high percentage of pebbly sandstones and conglomerates. This apparently abrupt switch in sediment supply during the final stages of infill almost certainly reflects a late stage influx of 'winnowed' shallow marine sediment.

This coarse-grained 'cap' would appear to be a natural consequence of the fractionating effect of the nearshore environment. During initial infilling, mixed sediments deposited in the estuarine marine zone would begin to migrate shoreward [fig. 6.73]. The episodic upstream transport of sediment by strong flood tides would cause the segregation of individual grain sizes, and result in the preferred landward migration of the lightest sand fractions. Continued transgression would cause the residual sediment at the mouth of the estuary to be increasingly depleted in sand. As conditions at the mouth of the estuary became subject to increasingly higher energies, eventually the coarser-grained 'lag' would also begin to migrate landward. The fine-grained (sand) fraction would outpace the coarser-grained lag, resulting in a distinctive two-stage fill. By this simple mechanism, the coarsest-grained sediments would be the last to be funneled into the main axis of the channel. In the Willesden Green estuary, this final stage of fill preceeded flooding of the entire estuarine complex in which most of the sub-aerial and inter-tidal deposits were transgressively removed.

Although it is possible that the Willesden Green estuarine complex was filled during separate stillstand events, or during fluvial reactivation,

Figure 6.73 - SCHEMATIC MODEL OF TRANSGRESSIVE ESTUARINE INFILL.

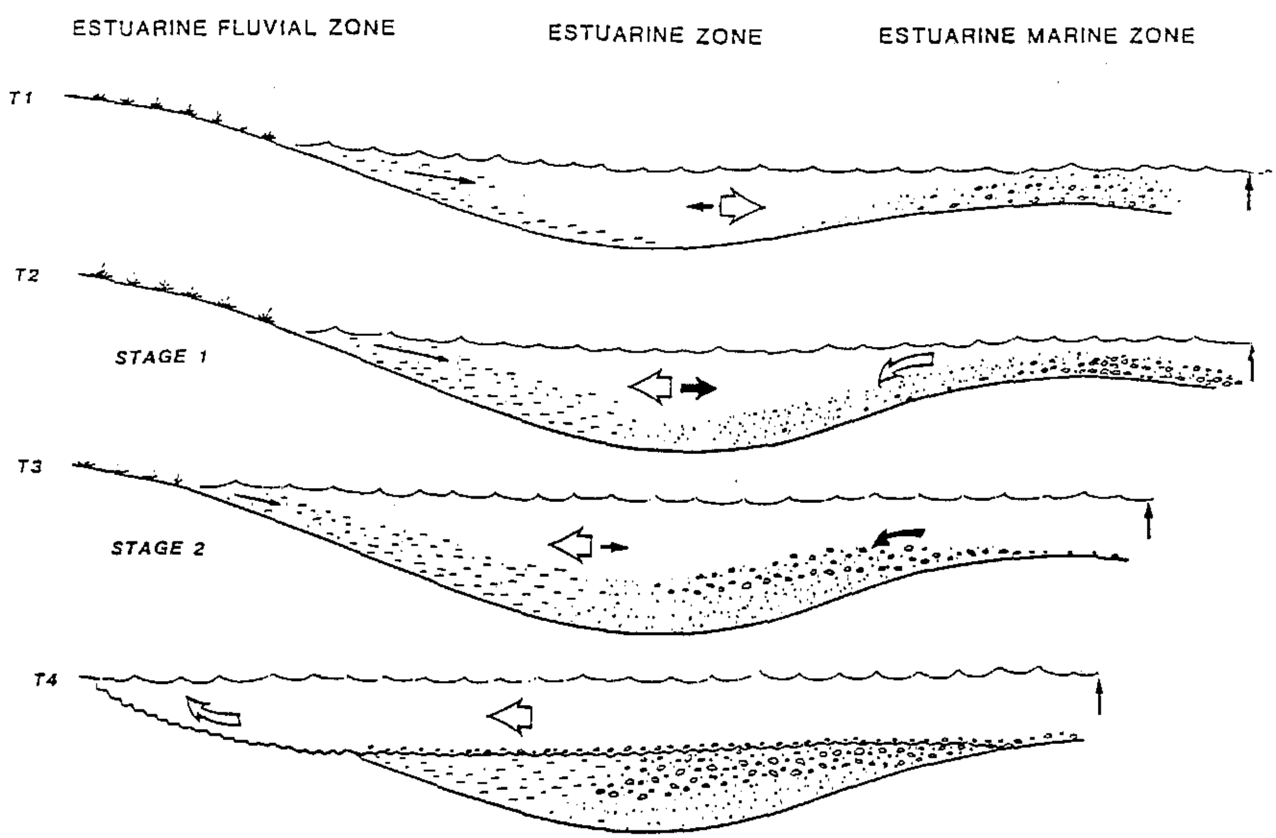
T1 - Coarse- and fine-grained marine sediments are perched at the estuary marine zone in inter- and sub-tidal sand bars. Silt and clay sediment is deposited in the estuarine zone, and is fluvially derived.

T2 - An increasing sea level results in intensification of flood tides within the estuary, and increased shallow marine reworking at the estuarine mouth. Estuarine marine sediments are selectively winnowed, and the fine-grained fraction (sand) progrades into the estuary zone.

T3 - Transgression continues, maximum flood tides occur, and the coarse-grained (conglomeratic) marine lag is funneled into the estuary zone. These coarse sediments overlie the slightly earlier emplaced sandstones, resulting in an apparent 2 stage fill.

T4 - Estuarine complex is totally breached and non-marine sediments are removed during subsequent erosive shoreface retreat.

MODEL FOR ESTUARINE FILL AT WILLESDEN GREEN



the geologically instantaneous rates of estuarine infill recorded in modern estuaries (eg. Van den Berg, 1982), suggests that a continuous two-stage event may be a more probable mechanism. From the apparent superposition of these infill units, and the almost vertical stacking of facies, one can speculate that during the time of deposition, there was very little movement of the mouth of the estuary.

Controls on Estuarine Emplacement

One major question that remains concerns the location of the Willesden Green estuary. Several similar incised valleys in the Cretaceous Western Interior are proven hydrocarbon reservoirs, and resolving the patterns and features common to all of these isolated sand bodies is necessary to define future exploration targets. Specific analysis of the factors responsible for initial drainage patterns, and determination of the conditions necessary for preservation are essential. In the case of the Willesden Green estuary, it appears the answer may be related to underlying palaeotopographic controls.

As discussed in chapter 5, thicknesses of the basal siltstone cycles underlying the Willesden Green estuarine complex appear to indicate the presence of a broad structural low in this area. During the earliest Viking time apparent subsidence or compaction along this trough provided the additional accomodation space necessary to cause a noticable thickening of the regional sediment sequences. The Willesden Green estuarine complex directly overlies these basal cycle thicks, and erosively truncates the uppermost cycle.

Analysis of underlying Mannville palaeotopography in this area also reveals the presence of an elongate north-south trending scarp running the length of the study area at rg 8 [fig. 6.74, 6.75]. The Member C valley incision appears to directly overlie the foot of this bevel, which may indicate an important genetic link between Mannville palaeotopography and Viking valley location.

According to Weimer (1984), one of the most important premises in control on sedimentation is that underlying structural variations can determine topography and bathymetry. He goes on to state the following generalities:

1) Depending upon sediment supply, topographically low areas will be associated with river drainage, deltas, estuaries and turbidite sequences whereas topographically high areas will tend to be related to interchannel, interdeltaic, shoal and reef areas (Weimer, 1984).
2) Palaeotopography will also cause thickness variations in units deposited. In general thick units will accumulate in low areas, whereas, thin units will be deposited over high areas (Weimer, 1984).

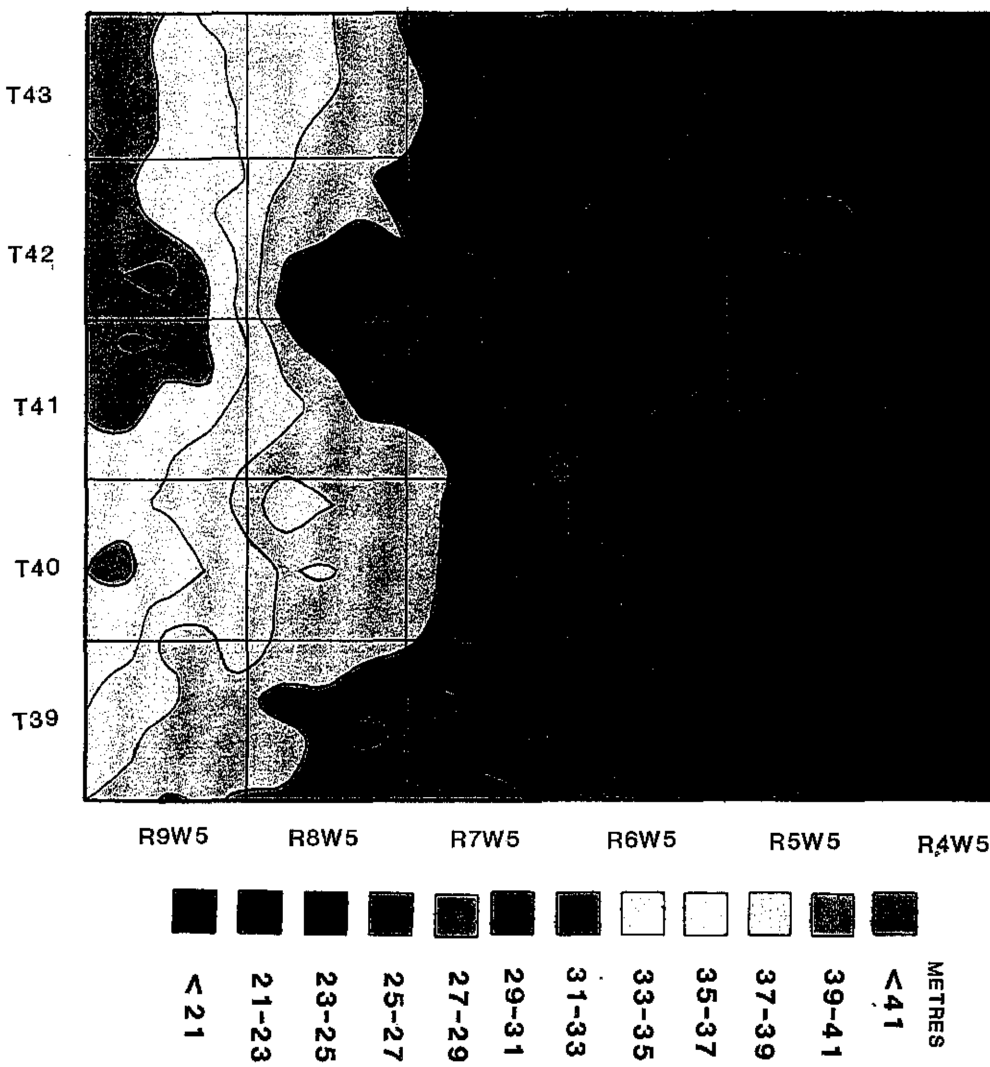
Although the evidence is subtle, the Willesden Green estuarine sands appear to fulfil both of these criterion. Preserved estuarine deposits clearly overlie an area characterized by anomously thick cyclical deposits of the basal siltstone assemblage, which in turn may be related a palaeotopographic low on an underlying unit. This association suggests that thickening of the regional sequences and in turn, location of the overlying Willesden Green channel, may have been related to the original scarp-like Mannville palaeotopography.

Mapping of regional cycle thicknesses and Mannville

OG

-41-6W5

MANNVILLE SURFACE ISOPACH (100-(Mann-BFS))



palaeotopography around other Viking channels should be carried out in order to determine if a similar pattern is present in those areas, and ultimately to prove or disprove the hypothesis. In an effort to tie the topography of the Mannville to possible underlying structural controls at Willesden Green, an analysis of structure contour and first order residual of the top of the Palaeozoic were carried out, however no correlation was found to be present.

6.9 Reservoir Properties

Detailed analysis of the distribution of hydrocarbon producing sands shows that there is a strong depositional facies control on reservoir quality. Hydrocarbon production from the two main pools of the Willesden Green field (W.G. Viking A; W.G. Viking H) is strictly confined to the sands of the cross-bedded and interbedded facies associations. Production records also reveal that the best producing wells consistantly lie within wells of the cross-bedded (tidal channel) facies. The sandy interbedded facies (estuarine sand flat) generally has slightly lower production figures, and the muddy interbedded facies (estuarine mud flat) is consistantly tight. The coarse-grained, conglomeratic nature of the cross-bedded facies association generally offers both high porosity and permeability, while the abundant mud drapes present in the laterally adjacent sandy interbedded facies effectively limit permeability. Total disconnection of sand lenses within the muddier portions of the interbedded facies precludes hydrocarbon production from this facies. Preliminary petrographic analysis indicates that diagenetic overprinting of these deposits, mainly in the form of quartz overgrowth cement and authigenic kaolinite locally reduces porosity and permeability, however the primary control of reservoir quality is undoubtedly depositional in nature.

Deposits of Member E, which postdate and erosively scour into the sands of the southern Willesden Green channel, form a continuous part of Willesden Green Viking Pool A, and make up the elongate east-west oriented part of the reservoir. The relationship and characteristics of these sands follows in chapter 8.

CHAPTER 7 : FACIES ASSOCIATION 4

(HUMMOCKY-CROSS-STRATIFIED SANDSTONE ASSOCIATION)

MEMBER D

7.1 Introduction

Member D is characterized by a coarsening-upward sequence consisting of interbedded wave-rippled silty sandstones, bioturbated shales, and hummocky-cross-stratified sandstones. This sequence is equivalent to the "Viking regressive facies" of Leckie (1986), and the "fine-grained sandstone association" of Hein et al (1986). Member D is best developed in the southern one third of the study area (Ferrier), although thin patchy occurrences can also found in more northerly locations.

7.2 Facies Descriptions

Burrowed/laminated Sandstones-Mudstones

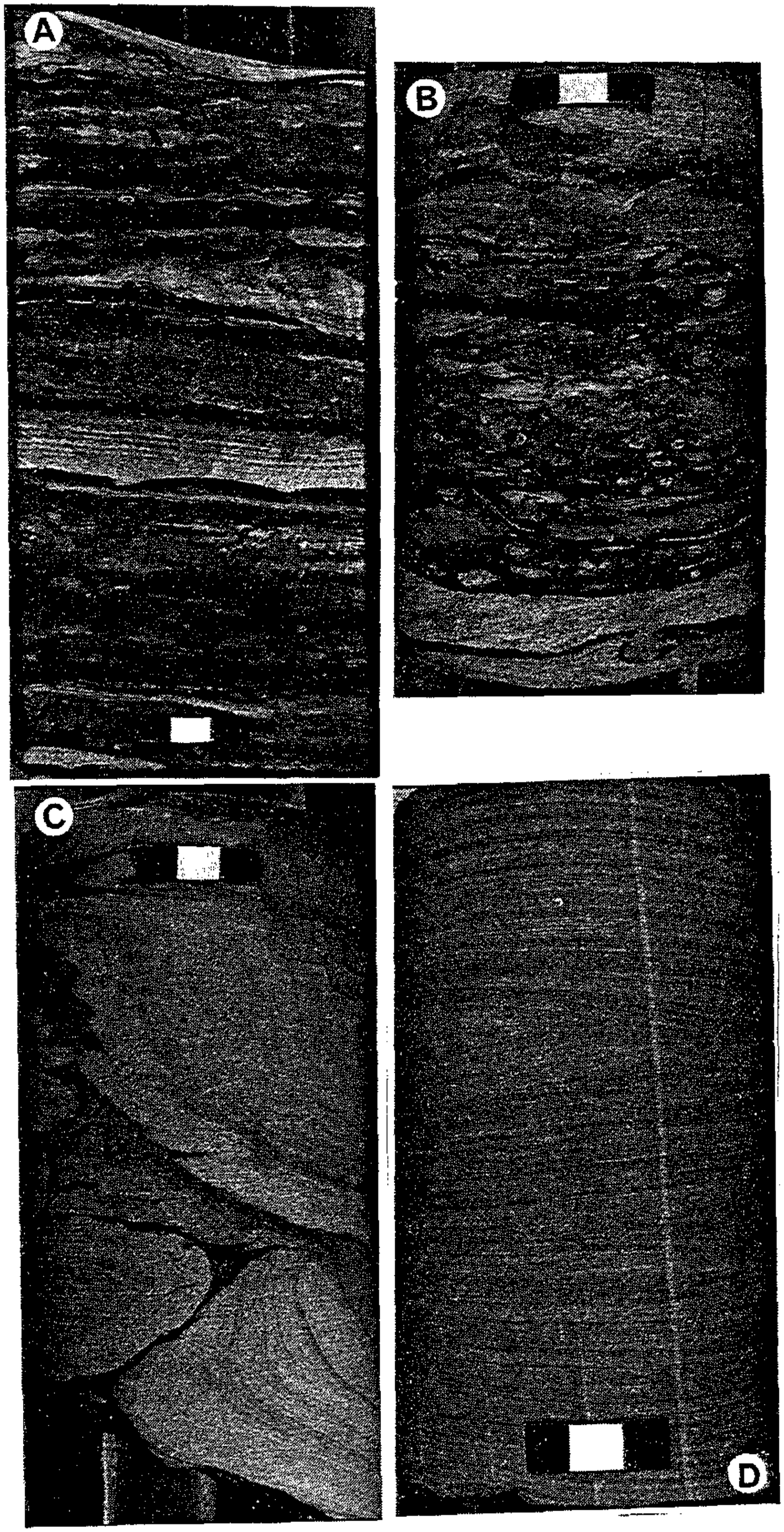
This facies consists of cm-scale interlaminated shales, and very-fine- to fine-grained sandstones and siltstones (in almost equal amounts) [figs.7.1, 7.2]. The black shales may be either non-bioturbated, or weakly to highly burrowed. The physical structures present within the sandy beds of this facies include low angle, symmetrical wave cross-lamination, undulatory laminations, and combined-flow cross-lamination. Individual sand beds vary between 0.5 and 5 cm thick, and have either parallel upper and lower contacts, or are lenticular in shape. Most beds have a sharp base, internal laminations, normal grading, and a mud-draped top. Some beds also display burrowing which can totally disrupt all physical structures, although the intensity of burrowing may vary immensely. Trace fossils include Planolites, Terebellina, and Zoophycos.

In the Ferrier area this facies displays, on average, the least amount of burrowing, and has a relatively high percentage of normally-graded very fine sand to silt beds. These beds display faint parallel laminations, or lack internal structures all together. Often, individual sand beds have a distinct undulatory upper contact, or less commonly, gradationally diminish upward into black non-burrowed shales up to 8 cm thick. These shales may be entirely made up of fissile, black mudstone, or commonly contain thin whisps of discontinuous silt laminae usually less than 5 mm thick. The shales are in turn sharply overlain by the next graded bed.

The interlaminated sandstone and mudstone facies generally has a sandying-upward trend, and in the southernmost portion of the study area grades upward into hummocky-cross-stratified sandstones.

Hummocky-cross-stratified Sandstone

This facies gradationally overlies the burrowed/laminated sandstone-mudstone facies, and is characterized by interbedded black shales, and fine grained sandstones with parallel-laminated to low-angle inclined stratification. Individual sandstone beds consistantly have sharp bases and often display scour or load features. Internal stratification consists of parallel inclined lamination with low angle divergences and intersection angles consistantly less than 12° [fig. 7.4]. Commonly, laminations are gently curved, and individual sandstone beds occasionally display wave-rippled tops. Individual sandstone beds range in thickness from 5 to 44 cm, and tend to show a thickening upward trend through the sequence. Convoluted beds and slump structures frequently occur within these sandstones [fig. 7.3], and sideritized intervals are common. The H.C.S. sandstones are consistantly very well sorted; however, well rounded, sideritized mud rip up clasts, and chert pebble clasts up to 2.2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cm in diameter, are locally present at the base of some beds. The H.C.S. sandstone beds generally lack bioturbators.

Interbedded silty shales generally range in thickness from 1 to 15 cm and consist of black mudstone drapes or interlaminated silty sandstones and mudstones similar to those of the burrowed/laminated sandstone-mudstone facies described above. Individual silty beds have sharp bases, are usually normally graded, and are dominated by wavey- and parallel- to undulatory-laminations. Bioturbation is generally quite sparse, and tends to decrease upwards through the sequence. As mentioned, burrowers consist of shallow marine forms such as _Planolites_, _Terebellina_, and _Zoophycos_.

7.3 Vertical Sequence

Member D is characterized by a sharp base and top, and a distinct coarsening-upward sequence which grades from burrowed/laminated sandstones and mudstones upward into hummocky-cross-stratified sandstones [fig. 7.5]. This package reaches a maximum thickness of 13 m in the southernmost end of the study area. The thickness of individual H.C.S. beds tends to increase upwards through the sequence, as does the overall percentage of sand to mud in the interbeds. Although bioturbation is rather patchy throughout, a noticable decrease can sometimes be detected upward through the sequence. The base of this package scours into the underlying basal siltstone assemblage (Member B), and also into the Willesden Green estuarine-fill sediments (Member C). It is abruptly overlain by the muddy sandstones and conglomerates of Member E.

7.4 Contacts

The basal contact of Member D (VE3) can be traced across the entire

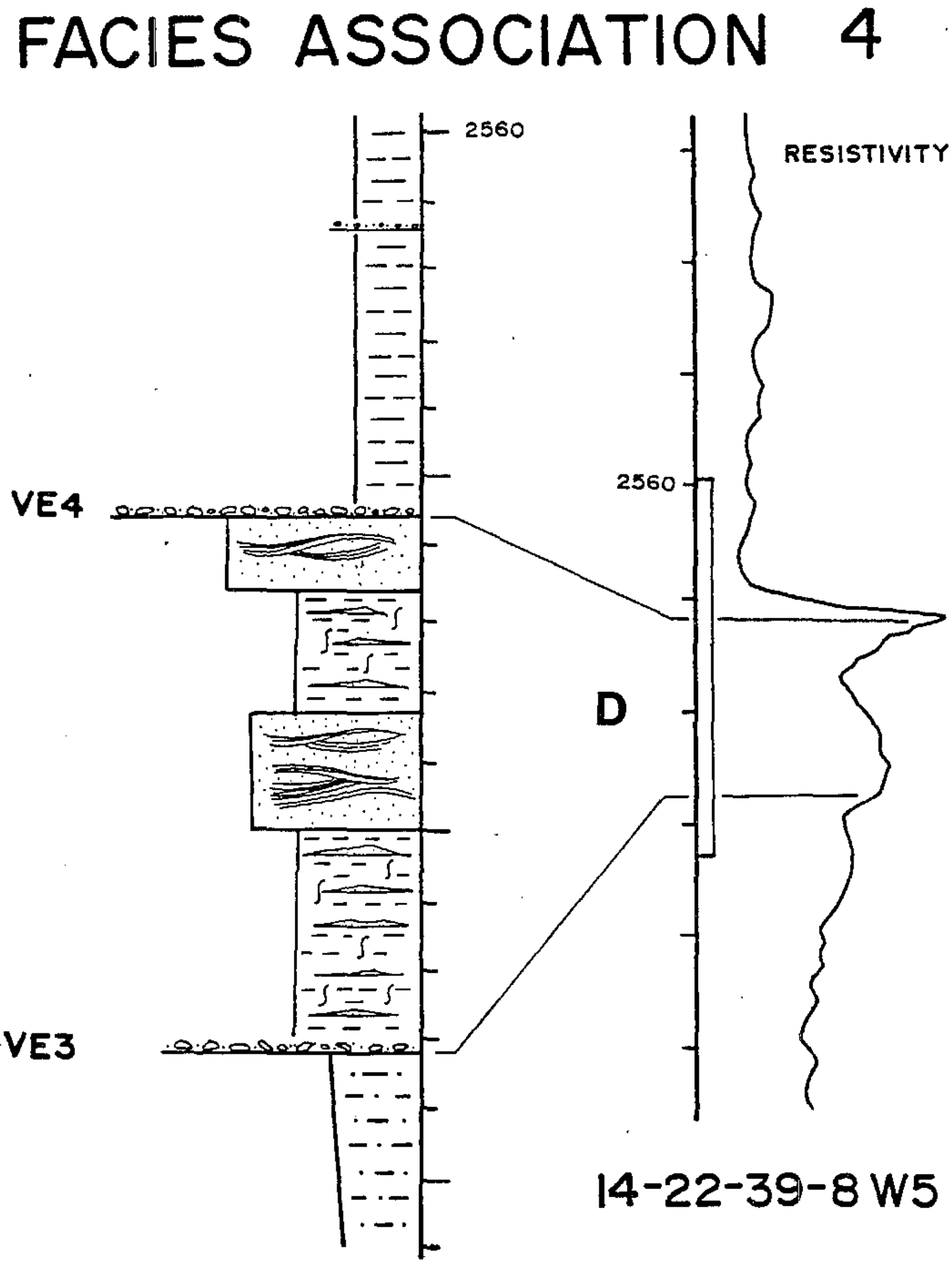


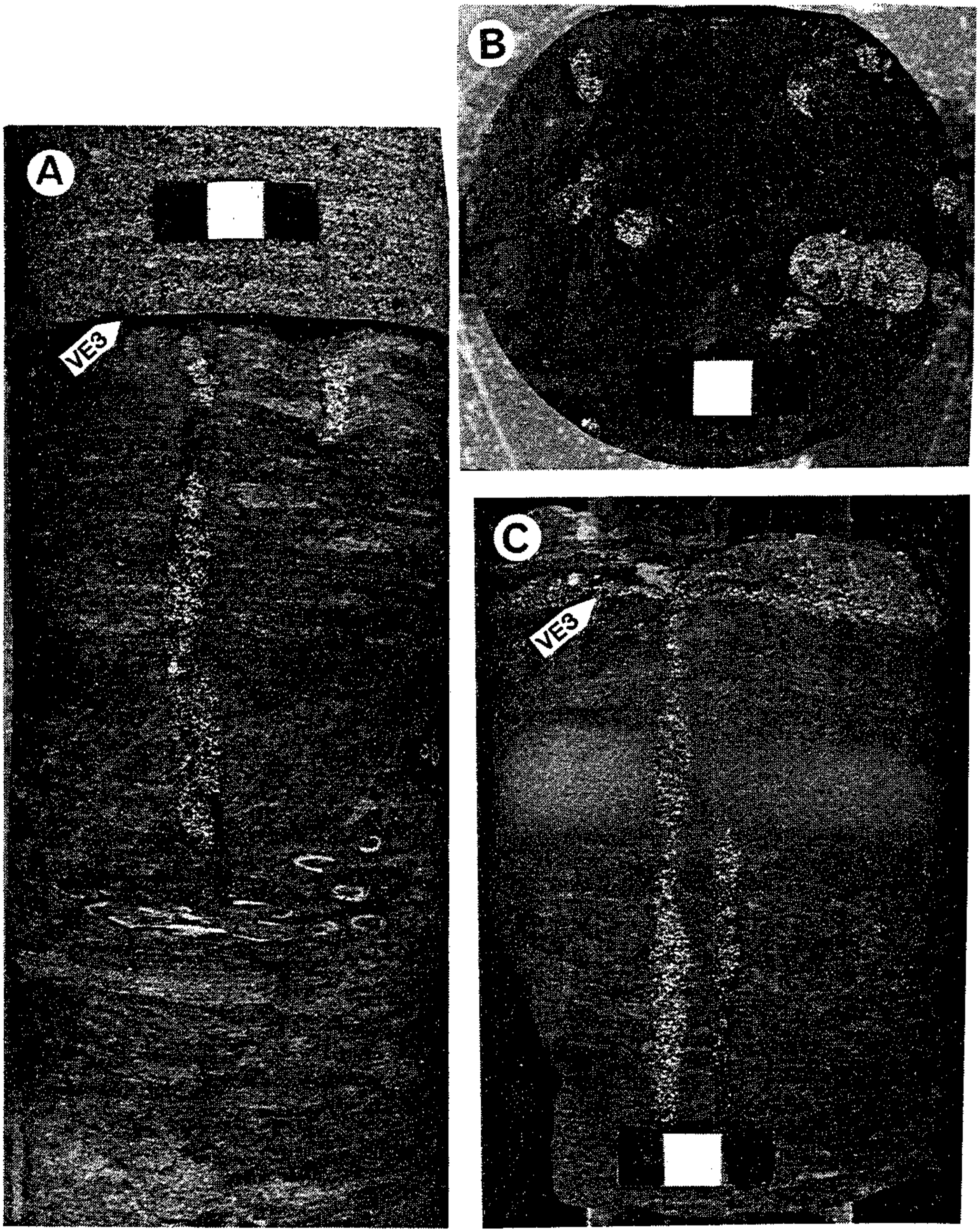
Figure 7.5 - Facies Association 4 - Reference Well 14-22-39-8W5; illustrating vertical facies relationships and correlatable log and core markers.

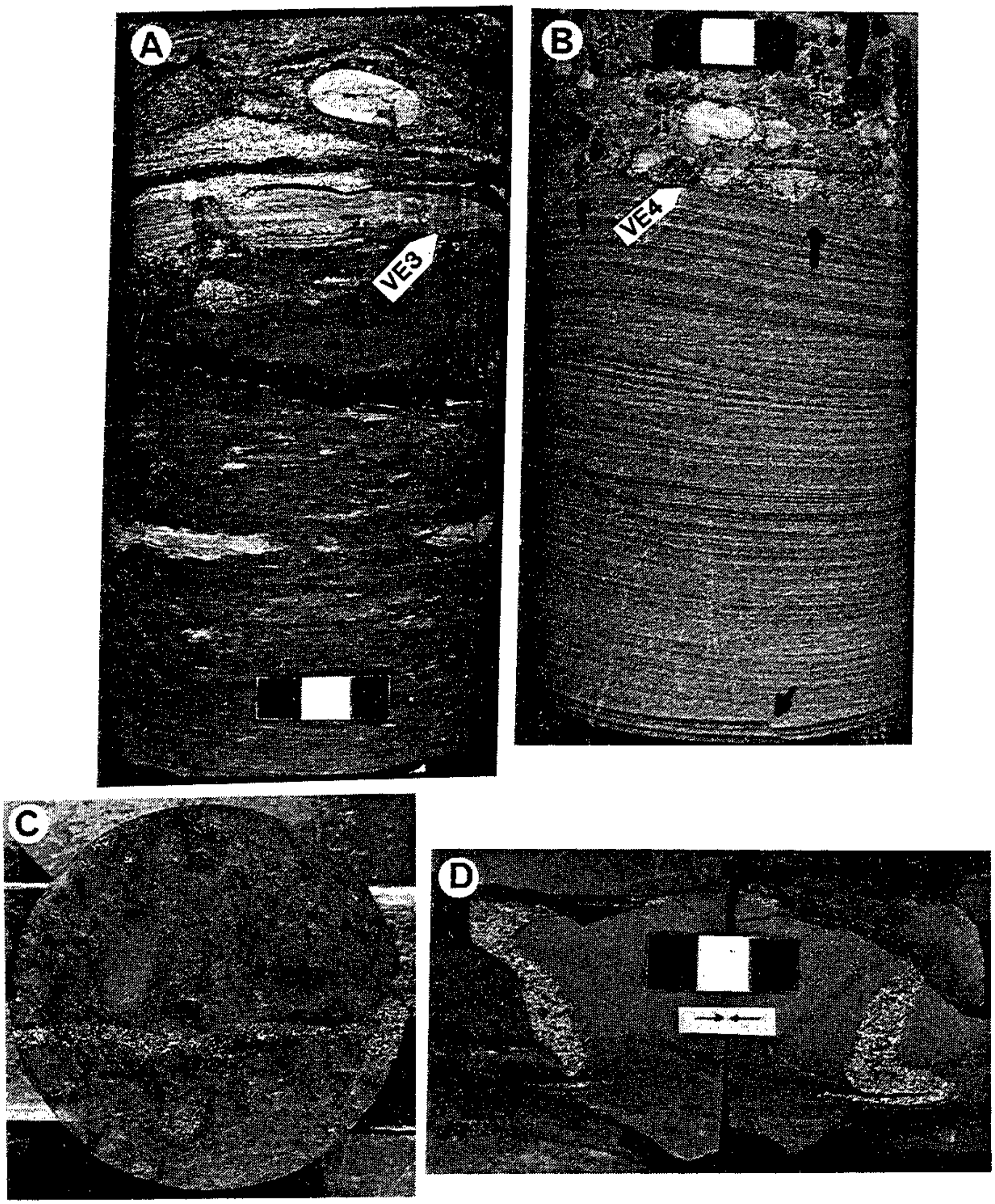
study area and erosively truncates both the underlying deposits of the basal siltstone assemblage (Member B), and the Willesden Green estuarine-fill sediments (Member C). Topographically, the VE3 contact defines a rather flat surface which is mantled by a thin muddy conglomerate or granule layer (1-10 cm thick). Both sand-filled Arenicolites and Skolithos burrows commonly occur along this surface [figs. 7.6, 7.7, 7.8, 7.9], as well as a large (4 cm deep) sand-filled synaeresis crack at 12-16-40-5W5 [figs. 7.11, 7.12]. As noted, the burrowed/laminated sandstones-mudstones, and H.C.S. sandstones of Member D rest on the VE3 surface.

The top of the hummocky sandstone association is in turn erosively truncated by an upper contact (VE4). This contact is knife sharp, consistantly blanketed by a thin veneer of mainly clast supported pebbly mudstone, and once again, marks a distinctive change in depositional style [fig. 7.10]. The VE4 surface has a unique topography which progressively rises in a step-like fashion towards the south [fig. 8.11]. This surface is the sedimentological expression of the final sea level rise in Viking times, and marks the transition zone between the Viking sandstones and Lower Colorado shales. A more detailed examination of the VE4 surface and overlying sediments follows in Chapter 8.

7.5 Facies Distribution

Member D ranges in thickness from 0 m to 13 m in the study area, and displays a progressive thickening and sandying towards the south (Ferrier) [fig. 7.13]. H.C.S. preservation is confined to wells only as far north as Twp 39 (Ferrier). Beyond this point only burrowed/laminated sandstones-mudstones can be found. These sediments are present in patchy


A
VE3
B
C
VE3


A
VE3
B
VE4
C
D

distributions throughout the northerly portion of the study area, but rarely exceed a maximum thickness of 2 m. Figures 7.14, 7.15 and 7.16 illustrate the substantial variation in thickness of this package across the study area.

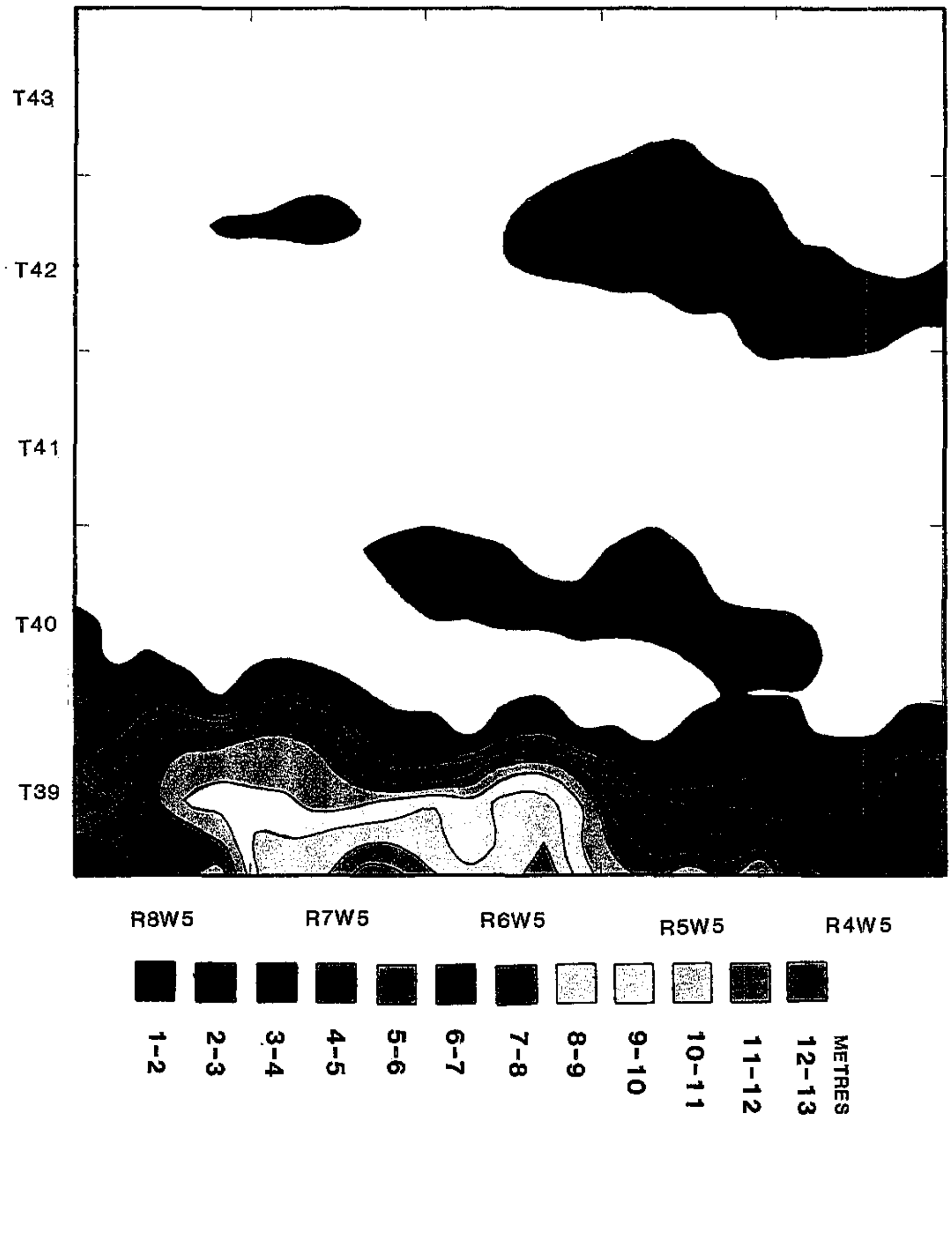
7.6 Interpretation

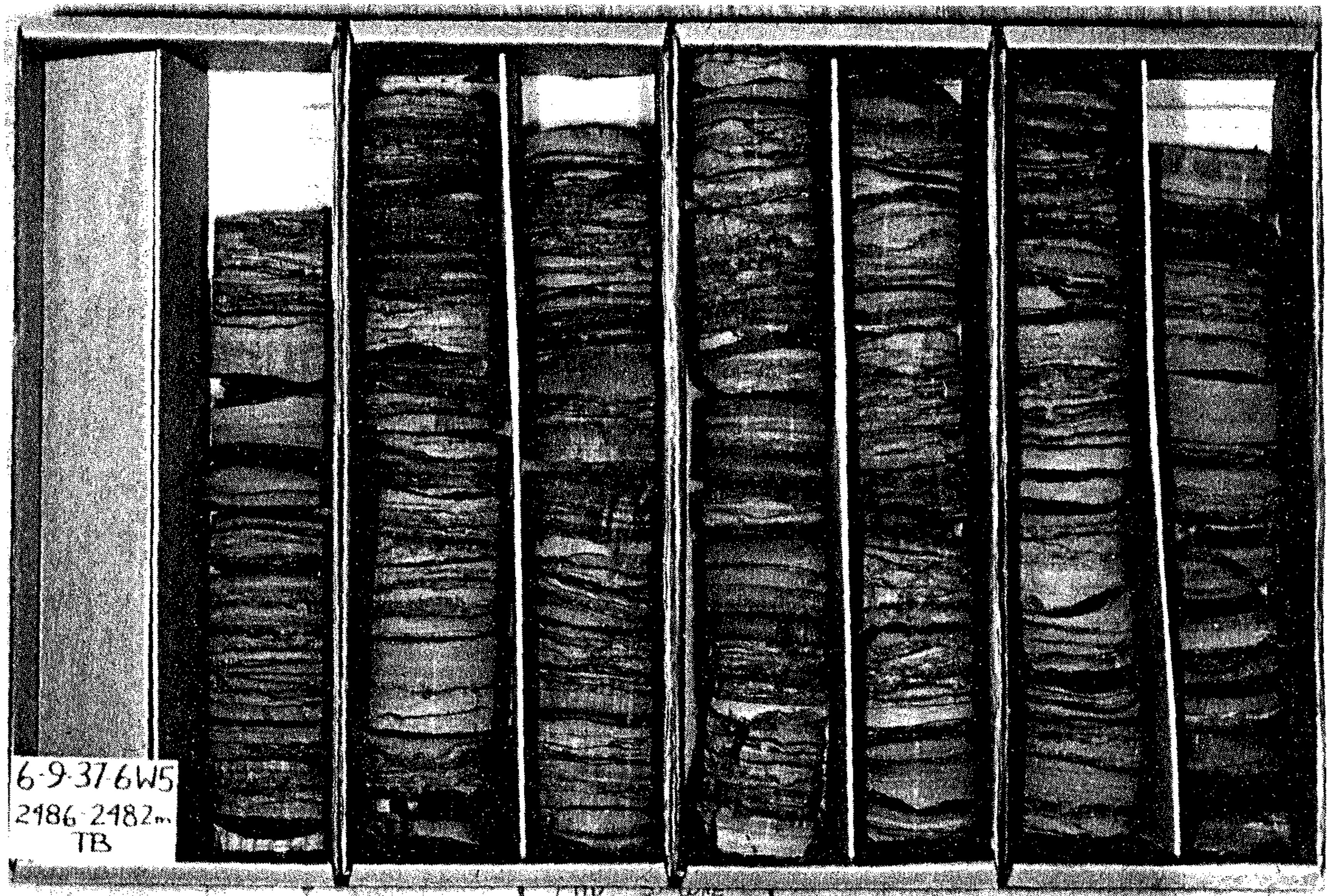
The dominance of erosive-based, fine- to medium-grained sandstone beds, wavey laminations, and low-angle inclined stratification in an overall coarsening-upward sequence suggests deposition in a progradational, wave-dominated offshore transitional to lower shoreface environment.

Hummocky cross-stratification is the most diagnostic feature of the thick, erosively-based sandstones of Member D. This structure has been shown by Harms et al (1975) to be characteristic of storm wave activity below fair-weather wave base (usually about 10 m). The base of these beds are sharp, often scoured and contain mud rip-up clasts indicative of rapidly emplaced sediment under strong flow conditions. The low angle stratification which reflects storm wave deposition, merges upward into parallel lamination and wave- to combined-flow ripple cross-stratification, representative of deposition by lower energy, short period waves probably under waning-storm conditions.

Intervening mudstones contain sharp-based, undulatory, rippled and parallel-laminated silty lenses which are often moderately burrowed. These delicate structures and fine-grain sizes indicate deposition by weak episodic currents, probably at depths well below fair weather wave base. The high percentage of mudstone in this facies (>50 %) is indicative of an environment in which large amounts of suspended sediment was present.

MEMBER D THICKNESS




6-9-37-6W5
2486-2482 m
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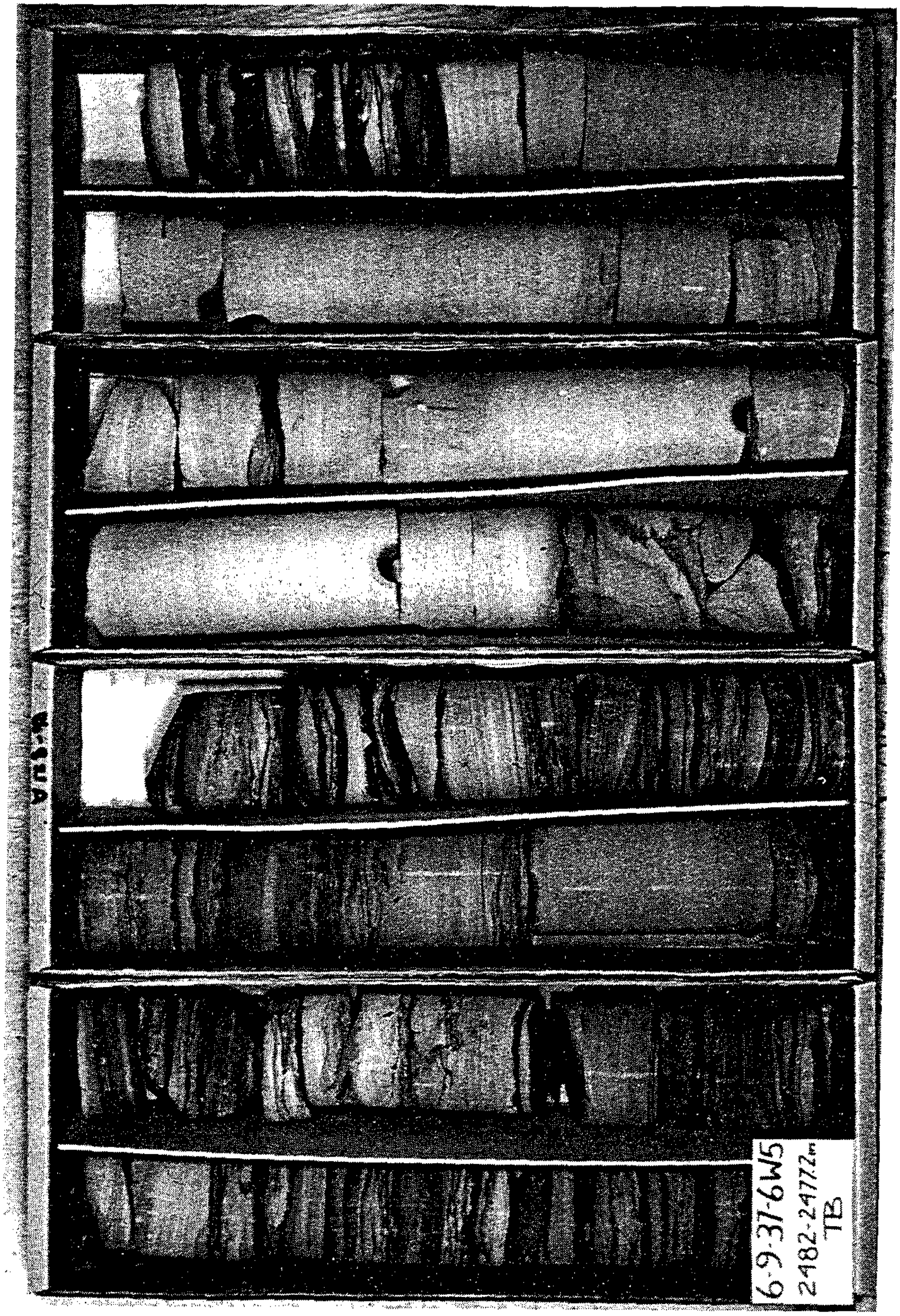
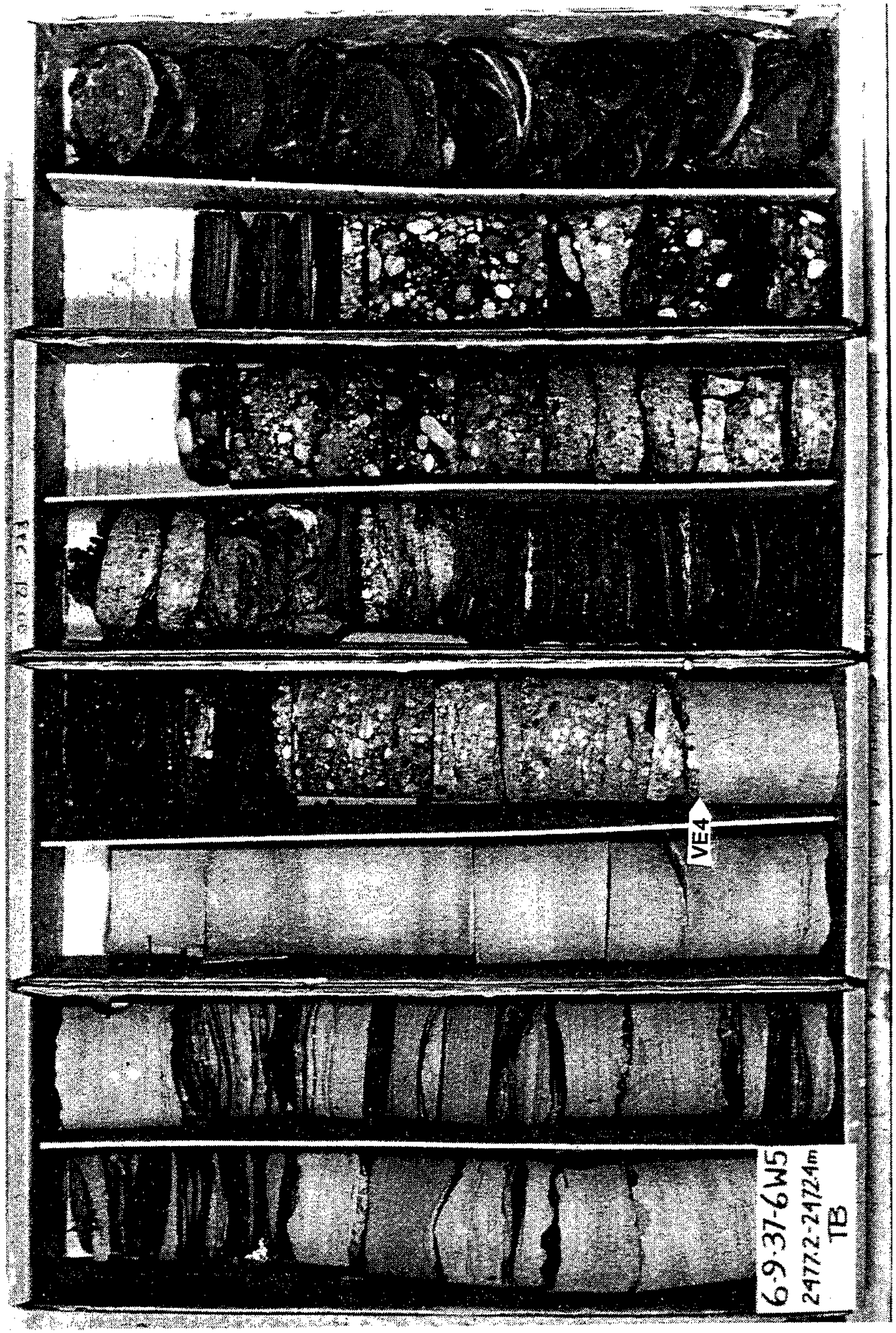
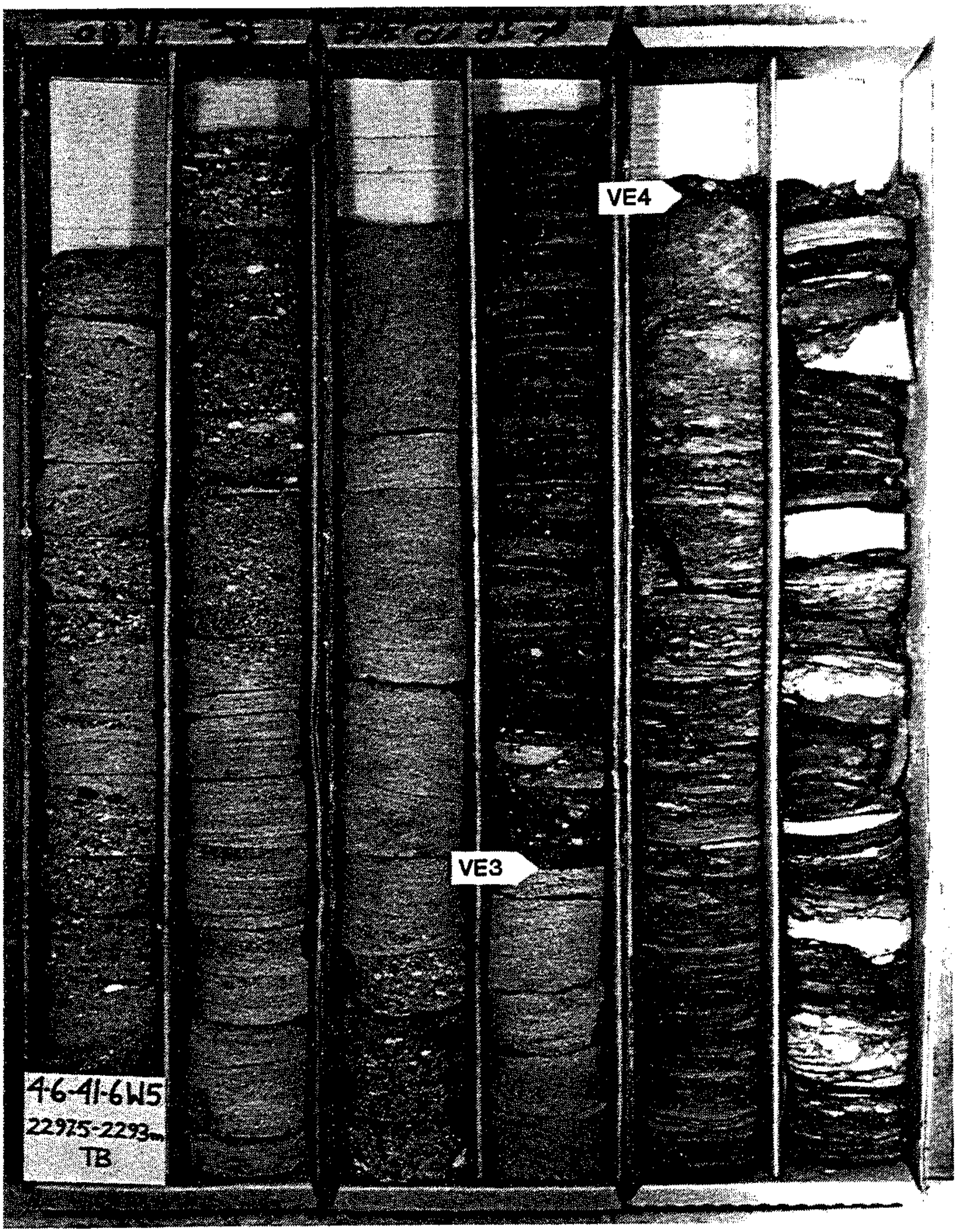
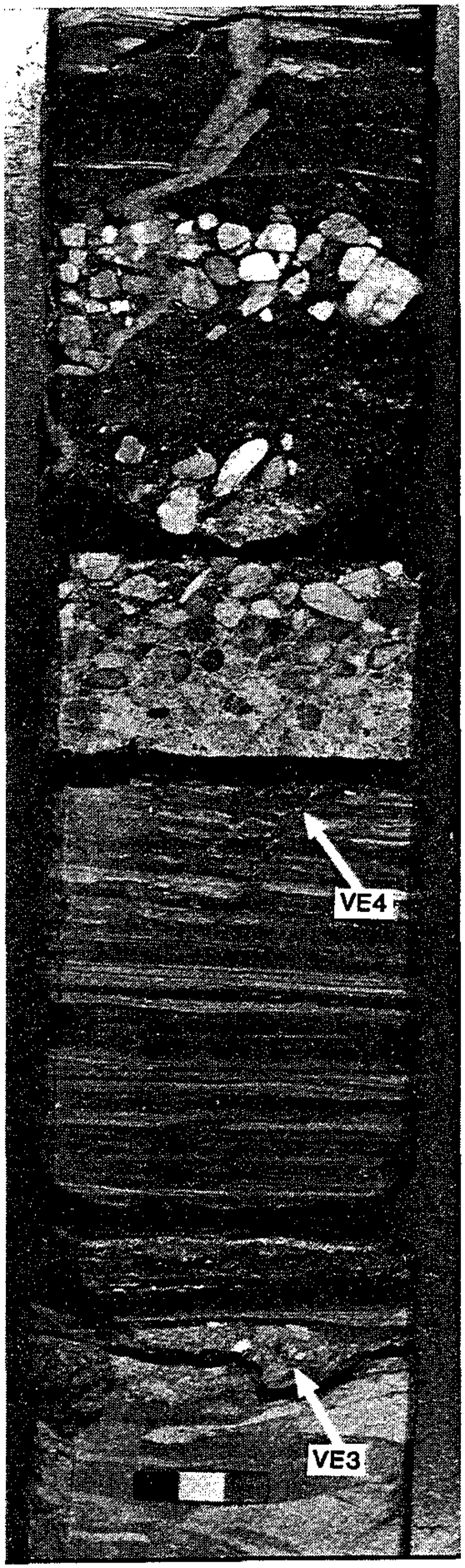

6-9-37-6W5
2482-2477.2m
TB


VE4
6-9-37-6W5
2477.2-2472.4m
TB


VE4
VE3
4-6-41-6W5
22925-2293m
TB


VE4
VE3

Bioturbators, which are most commonly associated with the coarser sandstone lenses, were probably brought in with the sandstone during individual storm events smaller than those responsible for the deposition of the major H.C.S. beds. The relative lack of burrowers in the interbedded mudstones and finer-grained silt beds suggest that under fairweather conditions the high percentage of suspended sediment in the water column may have inhibited colonization by marine fauna. This unit can be traced back to the Caroline and Harmattan areas where the H.C.S. beds become thicker and pass vertically upward into swaley-cross-stratified sandstones, horizontal-laminated sandstones, and finally paleosols and rooted horizons (S.D. Davies, pers. comm., 1989) (S.W. Hadley, pers. comm., 1989). The overall thinning and muddying of Member D towards the north probably largely reflects depositional factors, however the preserved patchy distribution and dramatic thickening south of Twp 39 may also be a function of erosive scouring during subsequent transgressive reworking. This hypothesis is explored in more detail in chapter 8.

The presence of sand filled <u>Skolithos</u> and <u>Arenicolites</u> burrows along the VE3 contact suggests that a major pause in deposition occured at this time which enabled both partial compaction and colonization of the sediment. A large (4 cm deep) sand-filled synaeresis crack in the VE3T surface at 12-16-40-5W5 [figs. 7.11, 7.12], also suggests that major salinity fluctuations may have accompanied the distinctive changes in depositional style above and below this marker. The fact that the pebble-mantled VE3 surface marks a sharp boundary separating the transgressively deposited estuarine sediments of Member C and the overlying progradational lower shoreface/offshore transitional deposits of Member D [fig. 7.15], suggests that it is in fact a ravinement surface marking the end of the first Viking lowstand. The progradational nature of the overlying (Member D) shoreface deposits indicates that a second Viking lowstand must have occured as the Caroline sediment wedge advanced northward [fig. 7.17]. The subsequent erosive truncation of this package by another ravinement surface (VE4) signaled the final sea level rise in the Viking.

7.7 Reservoir Properties

The hummocky-cross-stratified sandstone assemblage (Member D) has no commercial use as a hydrocarbon reservoir. The fine-grained nature of the sediment offers inadequate porosity and permeability, and the occurance of mud interbeds are incompatable with fluid migration. The presence of rare conglomeratic stringers within this facies however, suggests that the location of pebble-rich feeder channels across this prograding shoreface may have influenced the location of winnowed, hydrocarbon-bearing coarse-grained sediment 'thicks' in the overlying transgressive shelf package. With this in mind, a detailed palaeogeographic reconstruction of the prograding shoreface package, such as that carried out by S.D. Davies (pers. comm., 1989) and S.W. Hadley (pers. comm., 1989), could prove invaluable in determining future exploration targets.

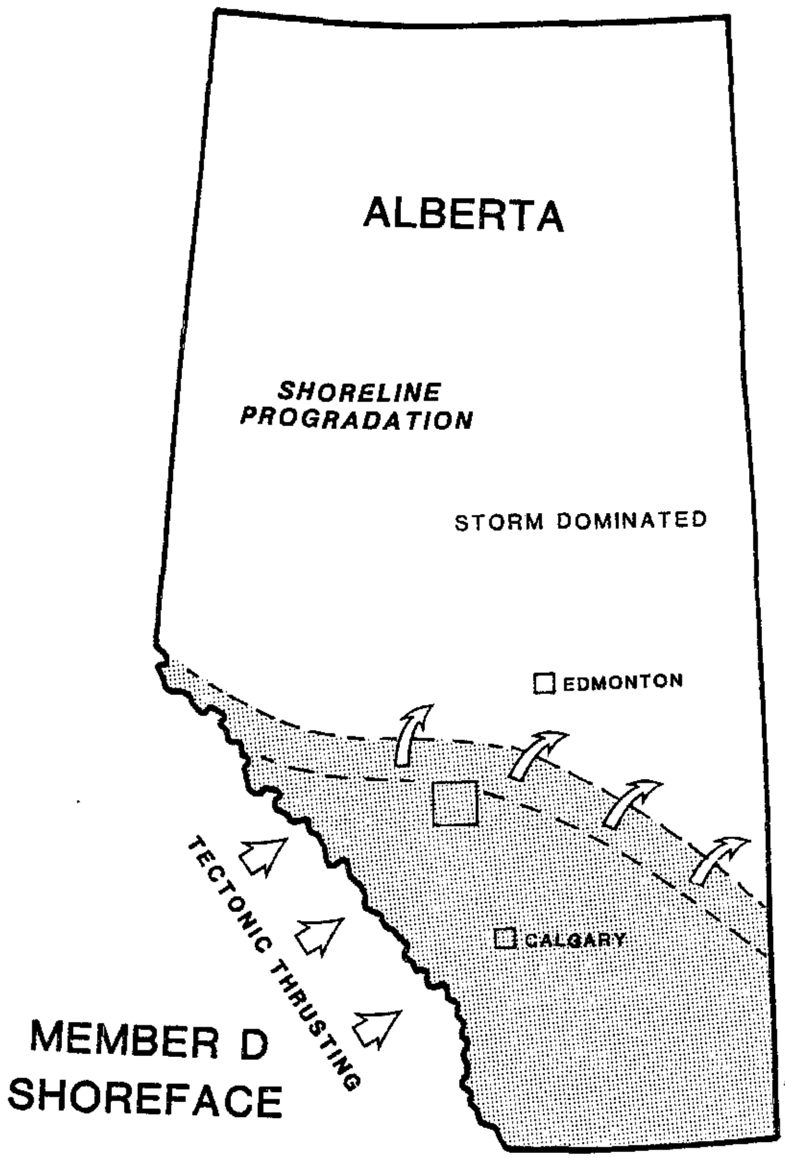


Figure 7.17 - Interpreted palaeogeography during the second Viking lowstand (deposition of prograding shoreface Member D).

CHAPTER 8 : FACIES ASSOCIATION 5

(SHALE, CONGLOMERATE, AND CROSS-STRATIFIED SANDSTONE ASSOCIATION)

MEMBER E

8.1 Introduction

Facies association 5 occurs exclusively above erosive marker VE4, and comprises an interbedded assemblage of cross-stratified coarse pebbly sandstones, conglomerates and black mudstones. These deposits are equivalent to the "transgressive shelf complex" of Leckie (1986), and the "chert-pebble conglomerate and pebbly sandstones" of Hein et al (1986). The Member E coarse-grained assemblage is mappable throughout the study area, and grades conformably upward into the overlying Colorado Shale.

8.2 Facies Descriptions

Facies association 5 is characterized by discretely interbedded packages of pebbly mudstone, cross-stratified sandstone, bioturbated gritty muddy sandstone, and clast-supported conglomerate encased in black shales. Over most of the study area the coarse-sediment package consists of a sheet-like deposit of muddy conglomerate less than .5 m thick which blankets the VE4 surface. Thicker accumulations however, also occur in the form of elongate E-W trending sand and conglomerate bodies up to 2.9 m thick, which display a variety of cross-stratification types.

Silty Shale

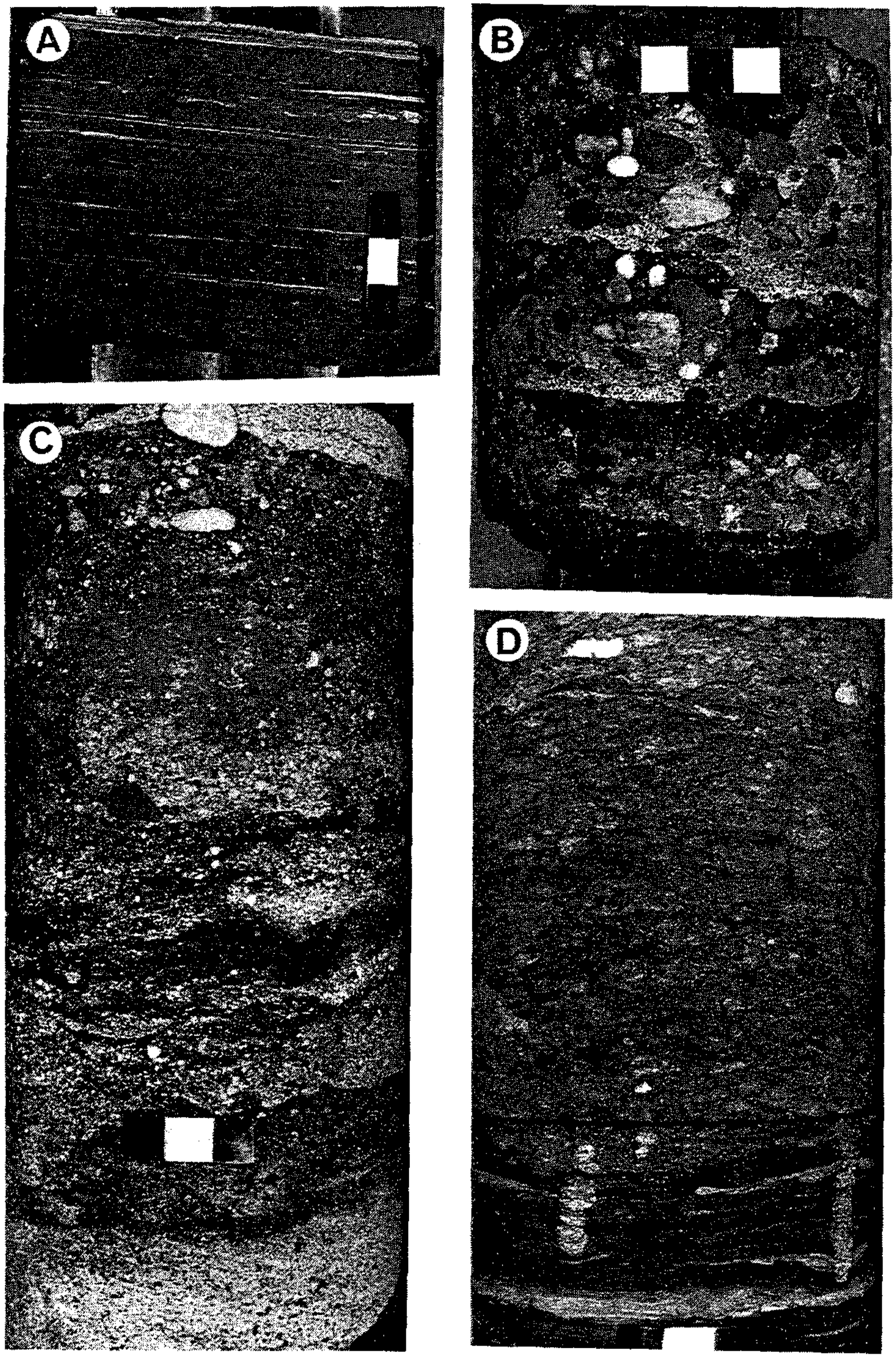
The silty shale facies consists of black, fissile mudstone, with irregularly interspersed thin, greyish-white, laminated silt beds. Sand-size material and biogenic structures are extremely rare, however fish scales are found throughout. Physical structures include delicate "pinstripe" silt laminae within the mudstone [fig. 8.1], and slightly thicker lenticular silt beds (.5-5 cm thick) that display sharp bases and parallel-, combined-flow or wavey lamination. Very rarely, sideritized mudstone beds, often associated with a thin (1-10 cm) sand or pebble stringer, occur at widely spaced intervals within this facies.

Pebbly Mudstone

The pebbly mudstone facies is characterized by poorly sorted beds of pebbles and granules in a dark black shale matrix [fig. 8.2]. The pebbles are generally well rounded and oblong in shape and reach maximum diameters of 2.6 cm (avg. 10 largest, long axis). They may be chaotically oriented with an apparently random fabric, or occasionally are massively bedded with weak imbrication or cross-bedding. Clasts are commonly matrix-suppported, although clast supported intervals are also present. The top of this facies often has pebbles protruding at high angles into overlying black mudstones. Thin silt laminae may also drape the upper contact. Individual beds range from 2 to 12 cm in thickness and tend to occur throughout Member E.

Bioturbated Gritty Mudstone

The bioturbated gritty mudstone facies is a biogenically churned mixture of black mudstone, medium to coarse grained sandstone, and scattered pebbles [figs. 8.3, 8.4]. The polymict nature of the sediment and the high degree of bioturbation in this facies often makes individual traces difficult to identify. Those most commonly present include Arenicolites, Skolithos, Terebellina, Palaeophycus, and Planolites. Individual bioturbated beds occur randomly interbedded with all other facies of Member E, and often occur at the base of the individual cross-bedded packages. The intense burrowing in this facies occurs in sharp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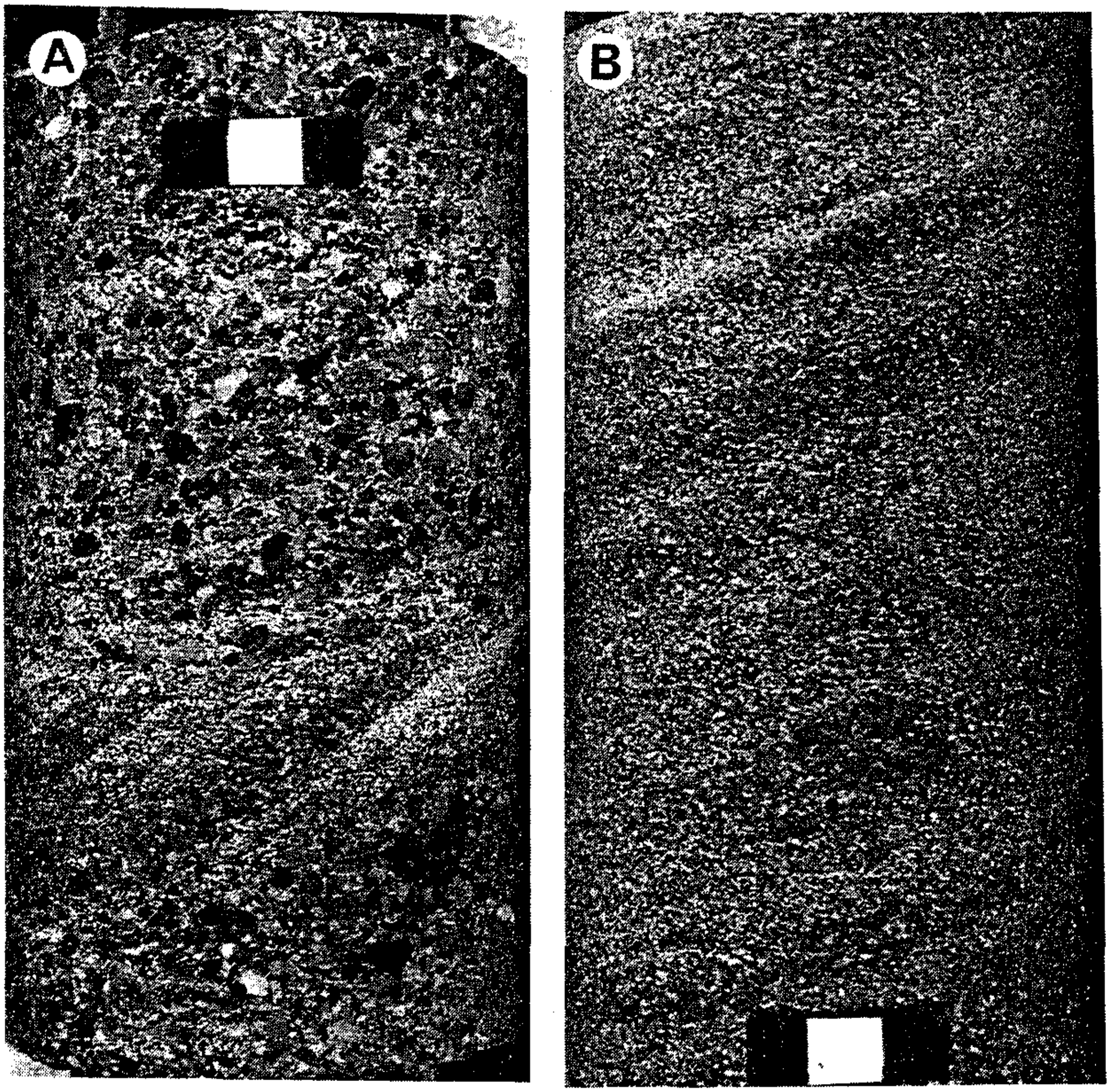
contrast to the unburrowed black mudstones with which it is also commonly associated.

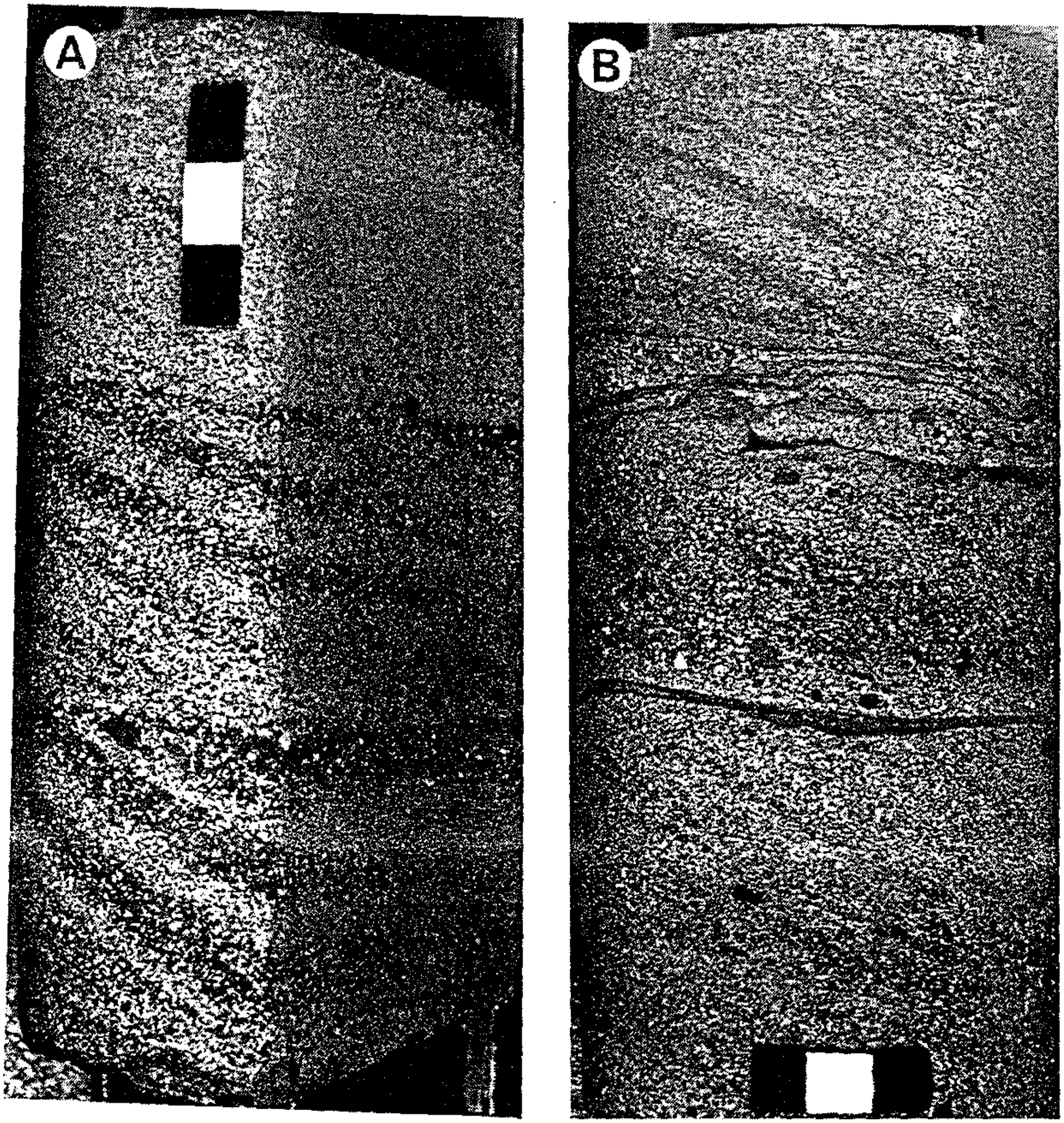
Cross-stratified Sandstone

The cross-stratified sandstones are composed of medium to coarse grained salt-and-pepper sandstone [fig. 8.5, 8.6]. Cross-bedding is generally well defined and occurs in sets up to 46 cm thick. The crossbeds may be continuously stacked or can alternate with bioturbated gritty mudstones, and pebbly mudstones. Mudstone partings up to 10 cm thick often separate individual beds. Sideritized angular mud rip-ups commonly occur at the bases and along the foresets of individual cross-bed sets. Coarser clast sizes within the sandstones (granules and pebbles up to 1.2 cm in diameter) also tend to define individual foresets.

Stratification within this facies varies considerably, and both trough and planar-cross-bedding may co-exist. Cross-bed foresets usually display high angle bedding up to 28^0, although bed angles may occasionally be as low as 17^0. Reactivation surfaces or black mud partings separate individual cross-bed sets. Often thin lenticular sand beds up to 4 cm thick may be interbedded with the cross-bedded sandstones, and tend to have a cross-stratified or massive appearance.

One diagnostic feature of this facies is the occurance of compound cross-bedding [fig.8.7, 8.8]. This distinctive stratification type is characterized by two scales of cross-bedding. Small high-angle sets with dips of 18 to 25 degrees are regularly bounded by lower angle surfaces dipping between 4 and 7 degrees. The high-angle sets appear to "down-climb" on the lower angle surfaces (master bedding surfaces) and may be found in stacked successions up to four sets high. Individual high angle sets have an average thickness of 4 to 7 cm. Laminations are generally


A
B


A
B

defined by segregation of grain sizes and heavy minerals, although thin mud drapes may also occur along the lower angle surfaces. In several instances compound sets are not clearly defined, but explicit evidence of heirarchical bedform development occurs in the form of isolated anomalously high angle sets within regularly cross-stratified packages, often with an associated change in grain size [fig. 8.5]. The compound cross-bedded sandstone sets may be interbedded with all other facies in member E.

8.3 Vertical Sequence

The coarse sediment package of Facies association 5 varies from 0.2 to 2.9 m thick in the study area. The base of this sequence is consistantly marked by, and may be made up entirely of a thin muddy conglomerate bed (VE4) (2 to 12 cm thick) which erosively truncates underlying strata. In specific areas however this coarse-grained package thickens up to 2.9 m, and forms large elongate linear sand and conglomerate bodies. Within these thickened packages, basal contacts of individual beds are usually sharp and often scour into underlying sands and shales. Bed tops are commonly mud-draped. Although these muddy sandstones and conglomerates of Member E often appear to be rather randomly interbedded, in a few cores of the Willesden Green South field a general facies sequence does appear to reoccur [fig. 8.9, 8.10].

The thin muddy pebble lag (VE4) is overlain either directly by the main body of the coarse sand package, or by a thin layer of black mudstone (up to 16 cm thick) which separates the two packages. The mudstone is generally non-bioturbated and fissile with minor fine silt laminations. Where the base of the main coarse-sediment package is not congruent with

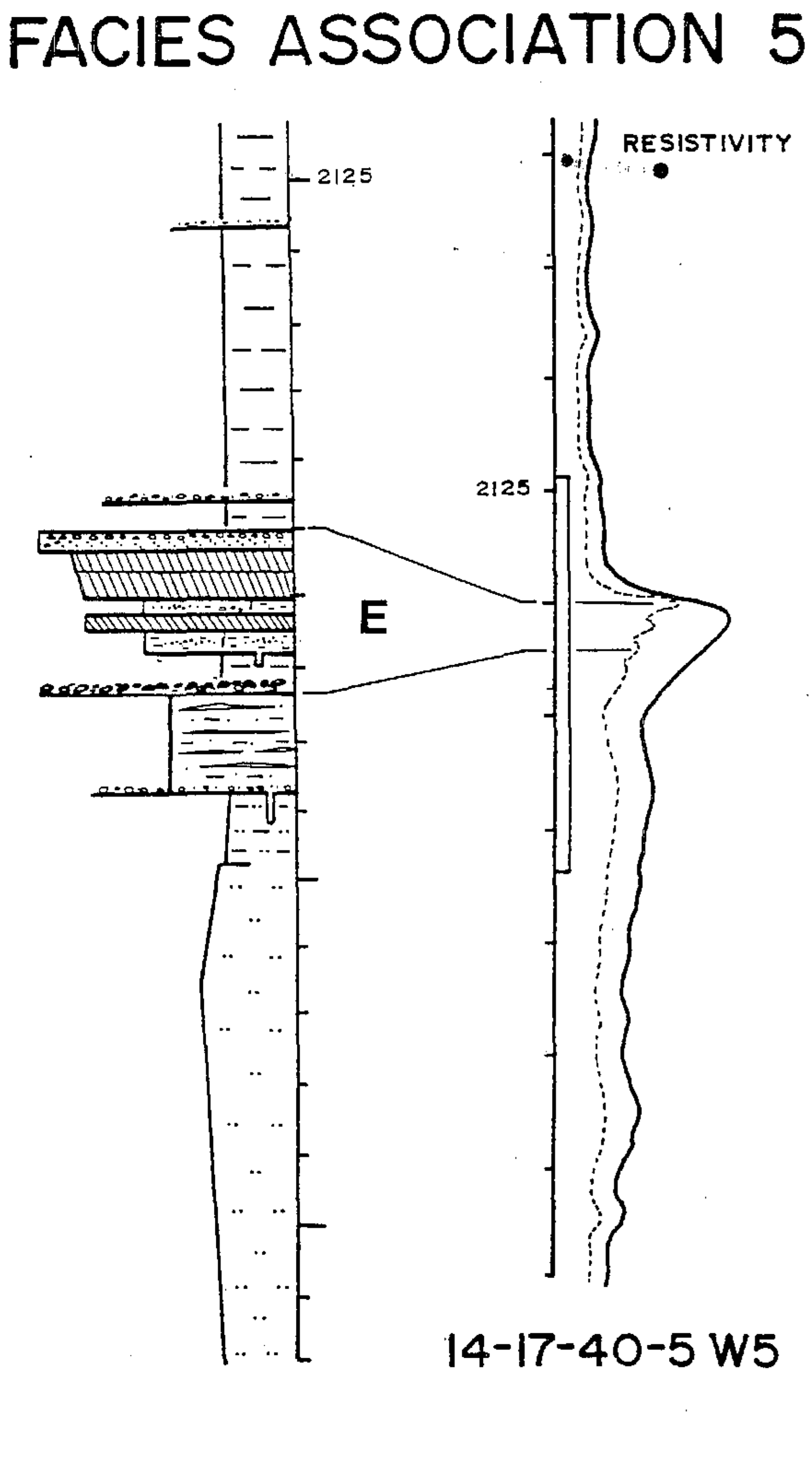
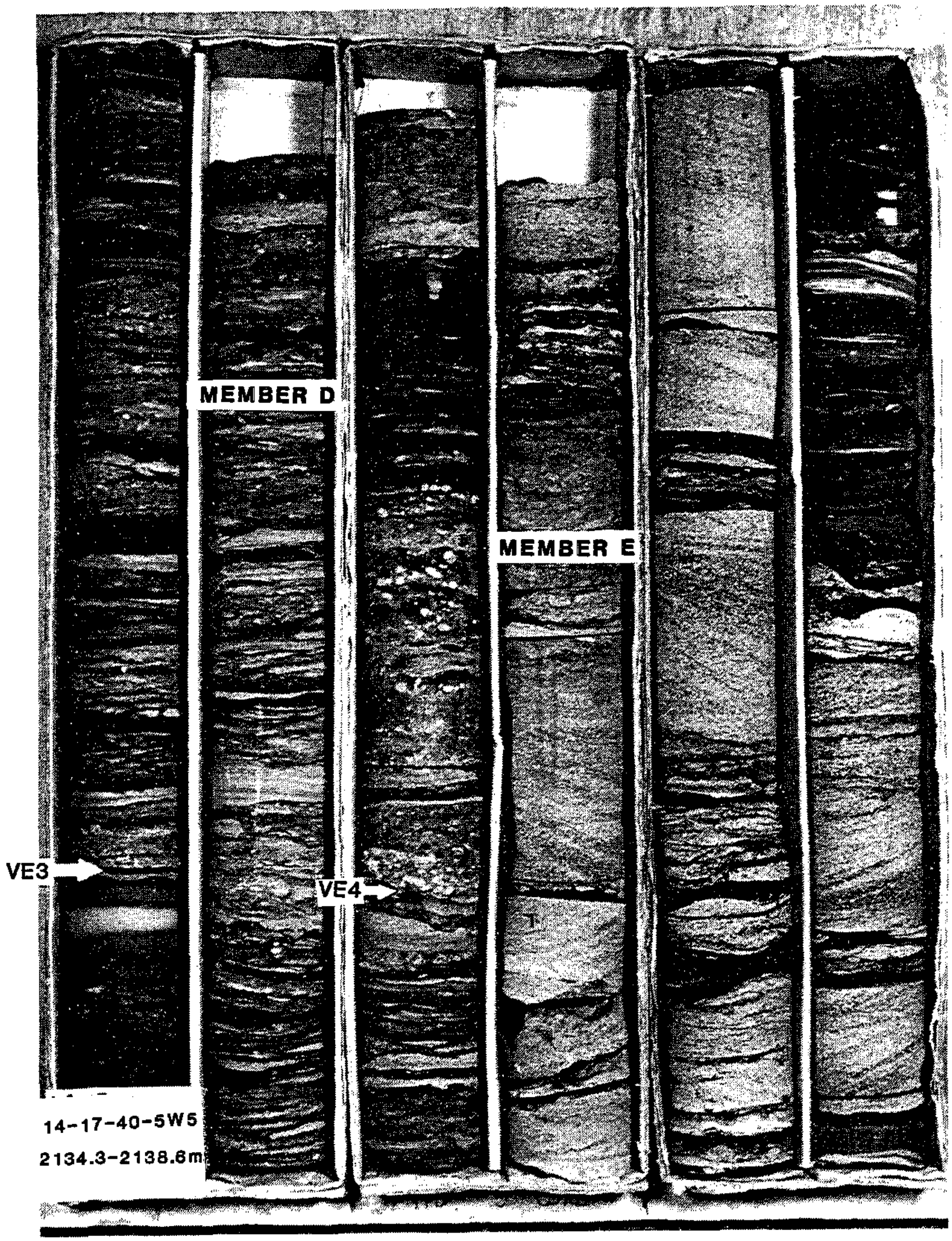


Figure 8.9 - Facies association 5 - Reference well 14-17-40-5W5 illustrating vertical facies relationships and correlatable log and core markers.

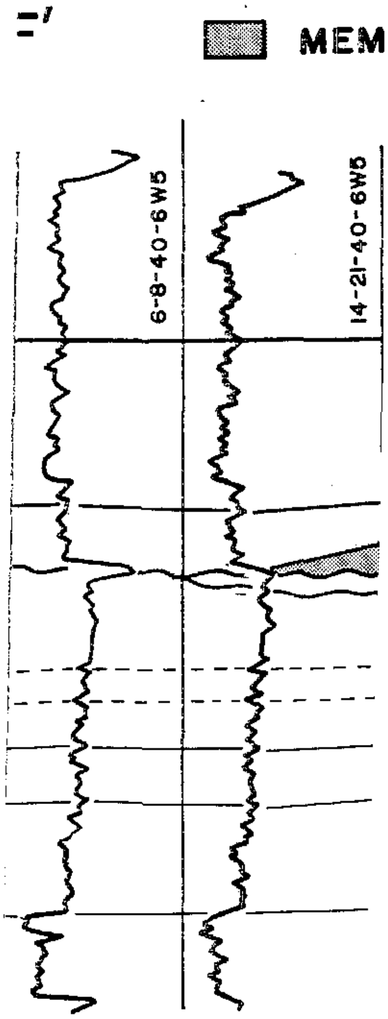

MEMBER D
MEMBER E
VE3
VE4
14-17-40-5W5
2134.3-2138.6m

the VE4 surface, it is commonly defined by a bioturbated gritty sandstone, often with large sand filled Skolithos and Arenicolites burrows which protrude down into the underlying mudstone [fig. 8.4]. The gritty bioturbated interval may occur up to 50 cm thick. This thoroughly churned interval is usually overlain by an interbedded assemblage of cross-stratified sandstones with mud drapes, pebbly mudstones and occasional bioturbated interbeds. An overall coarsening upward pattern is often noted within the sandy package, with a notable increase in the percentage of granular, and pebbly sandstones near the top of the sequence. The uppermost contact is commonly draped by mudstones of the overlying Colorado Formation. A few thin sand or pebble stringers may occur slightly above the main body of the sandstone package, before passing upward into a thick sequence of black Colorado Shales.

8.4 Contacts

The basal contact of facies association 5 (VE4) erosively truncates the underlying sandstones and shales of the hummocky sandstone association. This contact has a distinctive topography which progressively rises in a step-like fashion towards the south [figs. 8.11, 8.12]. As noted, it is consistantly blanketed by a thin veneer of mainly clast supported pebbly mudstone which locally thickens to form the isolated elongate sand and conglomerate bodies of Member E.

The top of facies association 5 is conformable with the overlying Colorado Shales. In allostratigraphic terms the uppermost bounding discontinuity of Member E is in fact the Base of Fish Scales marker. The top of the Viking is arbitrarily marked by the uppermost thin conglomerate lens which is present throughout the study area (LM2). Detailed



:al and

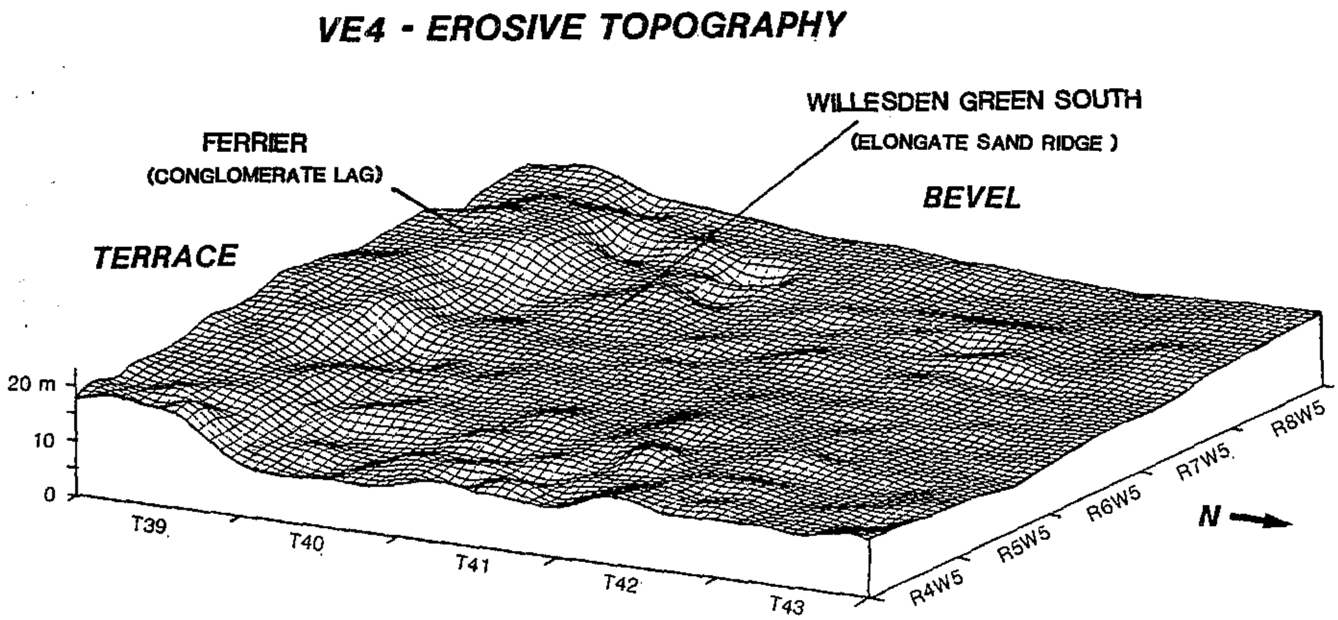


Figure 8.12 - Surface diagram showing scarp and bevel palaeotopography on the VE4 surface at Willesden Green.

correlations indicate that this lens is contiguous with the main FA5 coarse sediment package in the vicinity of Ferrier (twp 39; rg 8).

8.5 Facies Distribution

The coarse sediment of facies association 5 occurs as a thin veneer across the entire field area. Throughout much of this area it is characterized only by a thin pebble 'lag' deposit, usually less than .3 m thick, and often only as a few scattered pebbles or granules. The major areas of thickening occur in three elongate E-W trends in the vicinity of Willesden Green north (twp 42; rg 5-6), Willesden Green south (twp 40; rg 4-7), and in the Ferrier area (twp 39; rg 7-8). Cross-sections hung on an upper datum (Marker A) reveal that these coarse sediment thicks occur as positive features.

The Willesden Green north FA5 sediment thick, ranges from .5 to 1 m thick [fig. 8.13]. In Ferrier, similar deposits reach a maximum thickness of 1.2 m (except 1 well), while the deposit at Willesden Green south is the most substantial of the three, and reaches a maximum thickness of 2.9 m. Willesden Green south also displays a relatively high abundance of coarse-grained cross-stratified sandstone, and extremely good compound cross-stratification in some locations. The thinner deposits at Ferrier and Willesden Green north on the other hand are made up almost entirely of conglomerate and pebbly mudstone, and appear to be more of a thick winnowed lag deposit. Dimensions of the main sand body at Willesden Green south are approximately 3 km x 0.7 km x 2.9 m.

8.6 Interpretation

The unique assemblage of physical and biogenic features present in

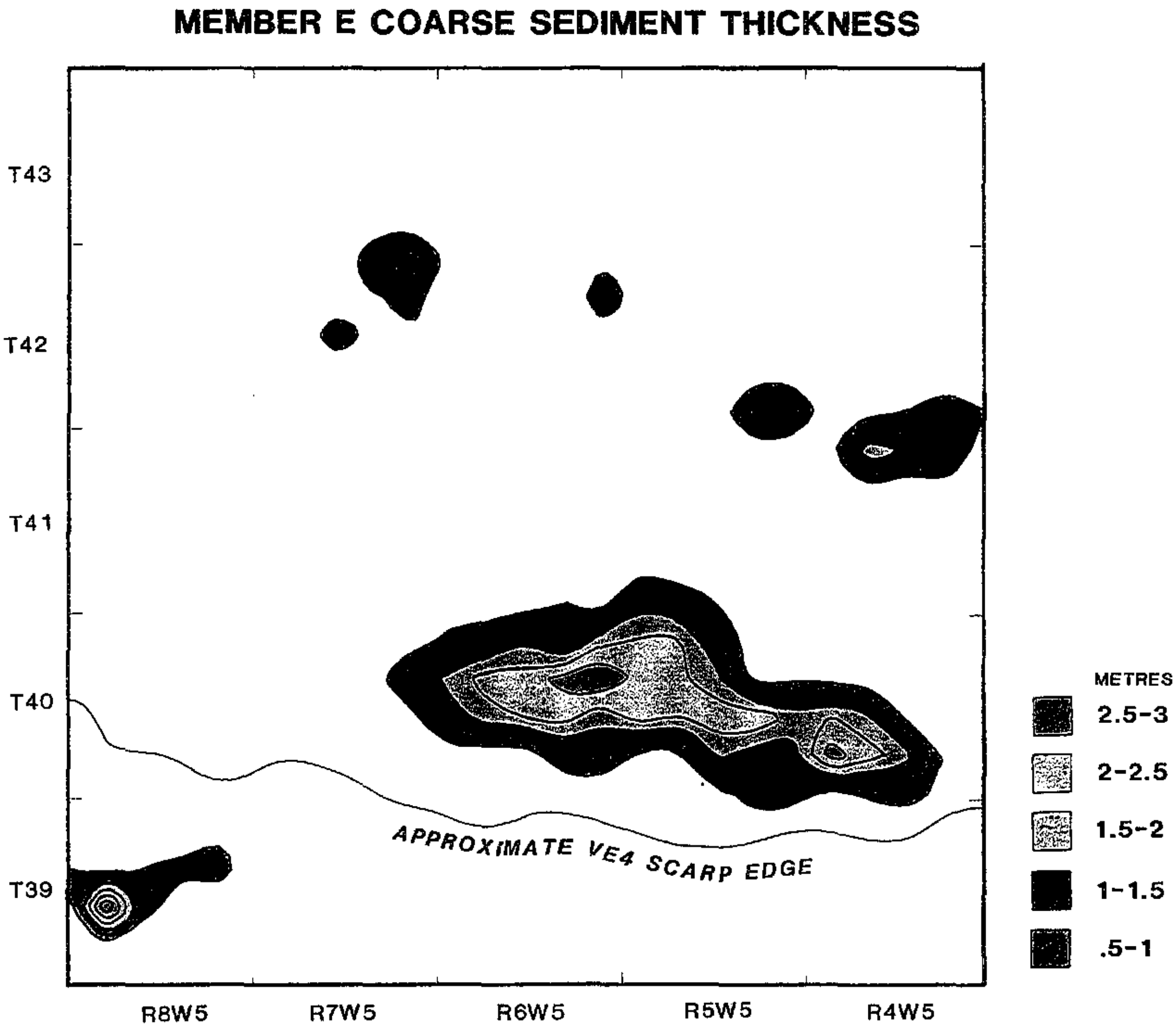


Figure 8.13 - Isopach map of Member E coarse-grained sediment, showing location relative to VE4 scarp.

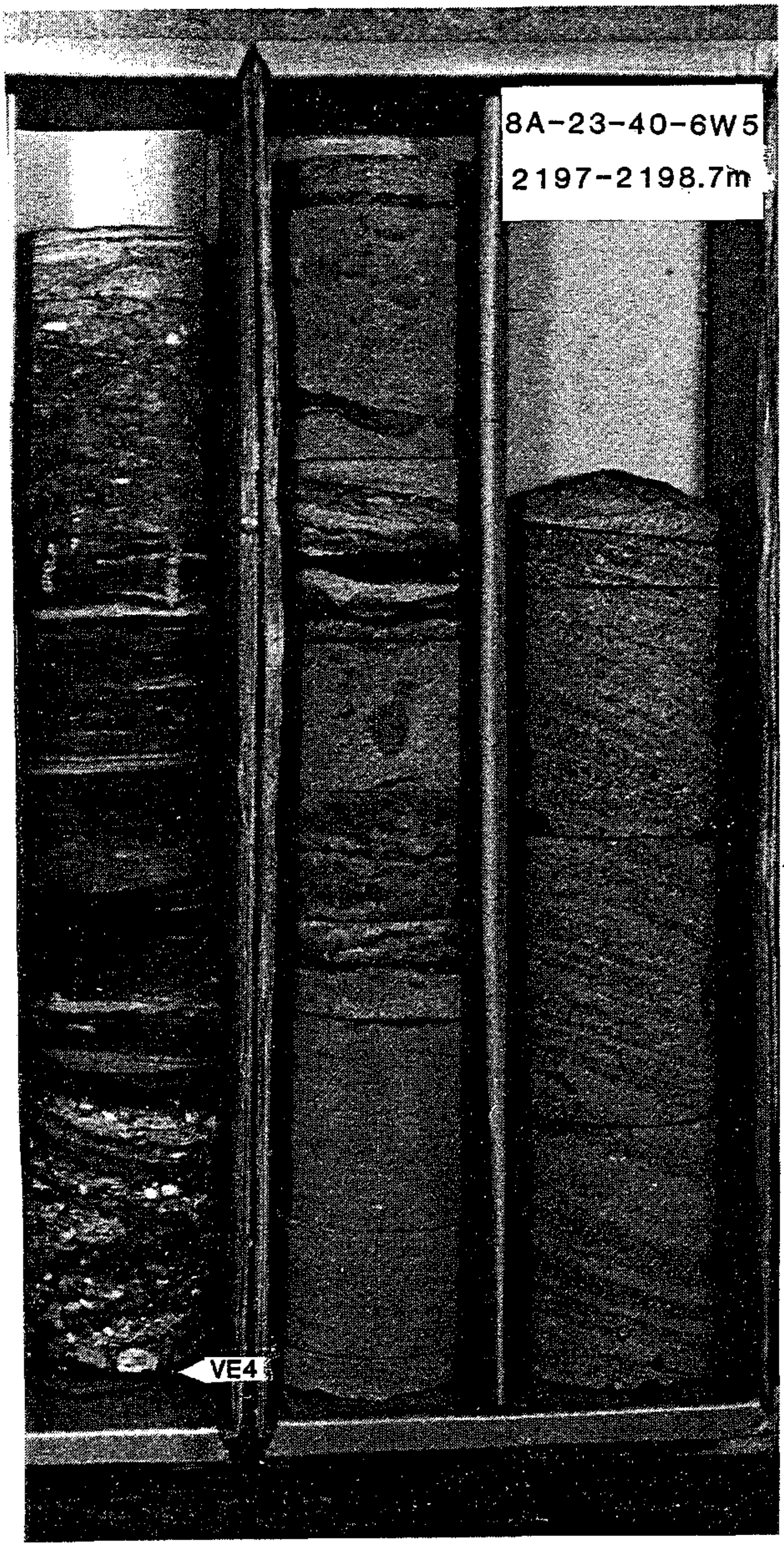
Member E indicate deposition in an open marine environment, characterized by alternating periods of rapid coarse-sediment deposition and quiet periods of muddy sedimentation from suspension. These deposits are interpreted to represent open marine transgressive lag and tidally influenced sand ridge sediments, deposited during the final sea level rise of the upper Albian.

The presence of cross-bedded sandstones and imbricated pebble beds reflects sediment transport by strong unidirectional traction currents capable of moving clasts up to 2.6 cm. Scoured bases and mud rip clasts also attest to the strength of these currents. The common occurence of several orders of reactivation surfaces, and mud draped pause planes throughout the cross-bedded sandstones also suggests an environment with a regularly fluctuating flow pattern. Short term, regular interruption to bedform migration is implied by the presence of shale partings which drape individual sand or pebble beds. These mud drapes are significant in the fact that they highlight what must have been substantial shifts in flow velocity, in an environment in which significant quantities of suspended sediment could be delivered from a sediment choked water column during intervening periods of quiescence.

Distinctive laterally extensive erosion surfaces and mud drapes are often associated with inferred tidal shelf deposits (Levell, 1980; Allen, J.,1980). MaCave (1970) suggests that mud drapes in open shelf settings may not necessarily reflect tidal periodicities but are more likely to be produced by high suspended sediment concentrations, low current velocities, and low wave intensities over a longer period. According to Leckie (1986) they may reflect a response to seasonal fluctuations in flow conditions (storms in winter take fines into suspension; quiet summer allows redeposition). Lithologically, the interbedded black shales are identical to the shales of the Colorado Formation. Ichnofossils and fish scales associated with these mud drapes locate the Member E deposits on the open shelf, and indicate deposition under quiet water conditions.

Within the deposits of Member E, the presence of both tangential and planar-tabular cross-bedding indicate the palaeo-migration of 2-dimensional straight crested and 3-dimensional sinuous crested bedforms. Although most of the sets are truncated by overlying reactivation surfaces, the scale of the largest preserved sets (up to 46 cm) [fig. 8.14] indicates potential initial bedform heights of at least 1 to 1.5 m. According to Johnson and Baldwin (1986) the most distinctive property of offshore tidal deposits is the extensive range of cross-stratification, and the large size of the sedimentary structures (set size approx. 1-10 m thick). The Lower Greensand in England, an established tidal deposit, contains individual cross-bed sets up to 4 or 5 m thick (de Raaf and Boersma, 1971).

Within Member E, the most definitive indicator of open shelf tidal conditions is the presence of systematically dipping compound cross-stratification. This unique bedding style is interpreted to represent the regular migration of small-scale bedforms (sinuous crested megaripples) down the lee face of a larger bedform (sandwave). A similar interpretation was offered by Leckie (1986) for correlative deposits in the Viking Caroline field. Although modern tidal sand ridges and sand waves have not been cored systematically, work by Houbolt (1968) suggests that their internal structure might be characterized by such low angle surfaces (5-6^0), with smaller sets of cross-bedding dipping down or up the


8A-23-40-6W5
2197-2198.7m
VE4

"master bedding surfaces" (Walker, 1984). The internal structures of several inferred ancient tidal sand wave deposits (Levell, 1980; Hein, 1982; Anderton, 1976) typically comprise a variety of large-scale cross-bedding, including simple avalanche foresets, and complex compound sets made up of large low-angle surfaces separated by smaller scale, mainly downslope dipping, cross-bedding (Johnson and Baldwin, 1986).

Similar compound cross-bedding sets from the late Precambrian in Norway (Levell, 1980) are interpreted to represent " either a large bed-form with megaripples superimposed on its lee face... or a large bedform with extremely closely spaced, periodic, reactivation surfaces formed by reworking of a single angle-of-repose lee face". J.R.L. Allen's (1980) widely accepted model of sandwave migration under fluctuating unidirectional flows, produces a sequence remarkably similar to those seen in Member E [fig. 8.15]. In his model, variations in sand wave lee-slope inclinations are primarily governed by the time velocity asymmetry of the tidal currents.

The ichnofossils present in Member E are representative of a shallow marine fauna typical of both the Skolithos and Cruziana ichnofacies. Their patchy occurence in some muddy intervals and not others indicates that conditions for colonization were not always optimal, possibly due to the fluctuating current regime or major changes in substrate and water column characteristics. Even their limited presence within the coarser-grained facies is significant however, since the overlying Colorado Shales and many of the interbedded shale beds are virtually free of biogenic traces. This suggests that the success and occurence of these marine organisms was closely tied to the presence of the specific coarse-grained substrate and dynamic conditions present in this unique environment. The

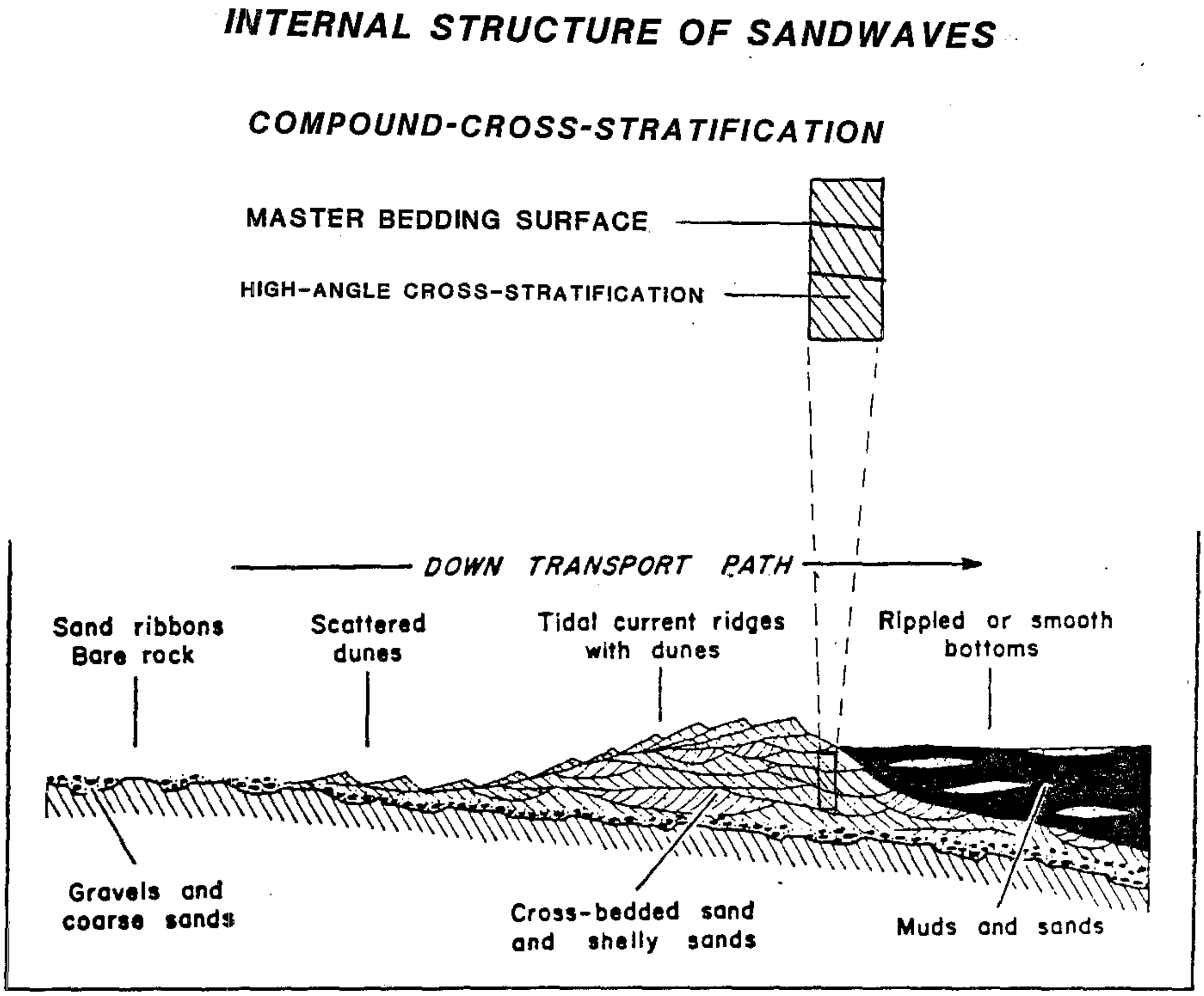


Figure 8.15 - Theoretical model to explain internal structures of sand-waves formed by reversing currents (modified from Walker, 1984; after Allen, 1970).

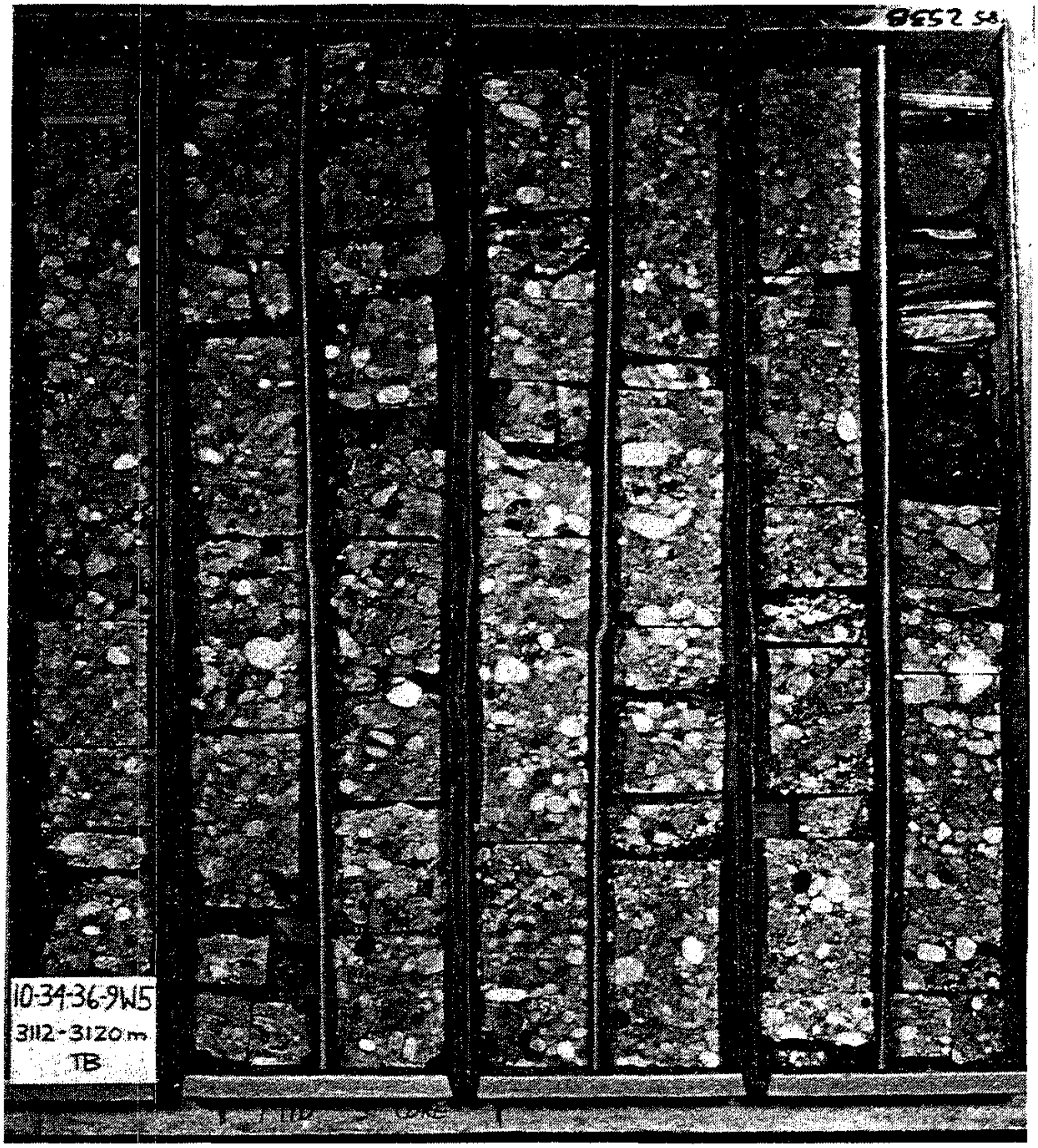
anomalous coexistance of relatively high energy traces such as Skolithos and Arenicolites alternating with black non-burrowed shales apparently of relatively deep water origin, points to an open marine setting periodically affected by extremely high flow conditions. The preferential occurence of the bioturbated muddy sandstones at the base of the coarse-grained sediment package, suggests that a 'fringe' of bioturbated sand probably advanced in front of the main sand body migrating on the open shelf, and that the optimal environmental niche existed in areas peripheral to the main sediment thicks.

The location of these elongate sediment thicks does not appear to be entirely random. The fact that the westernmost edge of the two most northerly linear sandbodies erosively scour into underlying (Member C) sandy estuarine deposits at both Willesden Green north and Willesden Green south suggests that reworking of these earlier sand and conglomerate deposits may have contributed a considerable quantity of palimpsest coarse-clastic material to ridge formation. One can not dispute however, that a substantial amount of sediment was undoubtedly supplied from transgressive winnowing of the shoreface deposits of Member D.

The common occurance of pebbles stringers and granules within the upper shoreface sediments of Member D in the Caroline and Harmattan areas, suggests that the location of coarse sediment thicks on the VE4 surface may be closely related to the original position of conglomerate in the underlying package. Documentation of pebble-rich channel deposits which incise the top of the Caroline shoreface sequence (S.W. Hadley, pers. comm., 1989; S.D. Davies, pers. comm., 1989) adds to the possibility that the location of overlying transgressive lag deposits of Member E may be a reflection of these lowstand feeder systems. An unusually thick (3.5

m) accumulation of conglomerate which mantles the VE4 surface in a single well at Ferrier (11-17-39-8W5), may in fact be the transgressive expression of one of these conglomerate-rich incised drainages. This interpretation remains highly speculative however, since attempts to core this interval were unsuccessful. A similar 8 m thick water wet conglomerate unit at 10-34-36-9W5 [fig. 8.16], is almost certainly another example of this association. During the transgressive retreat of the Caroline shoreface, short term influxes of sediment through these lowstand feeder systems may also be reflected in the terrace and bevel topography and linear sand bodies recorded on the VE4 surface.

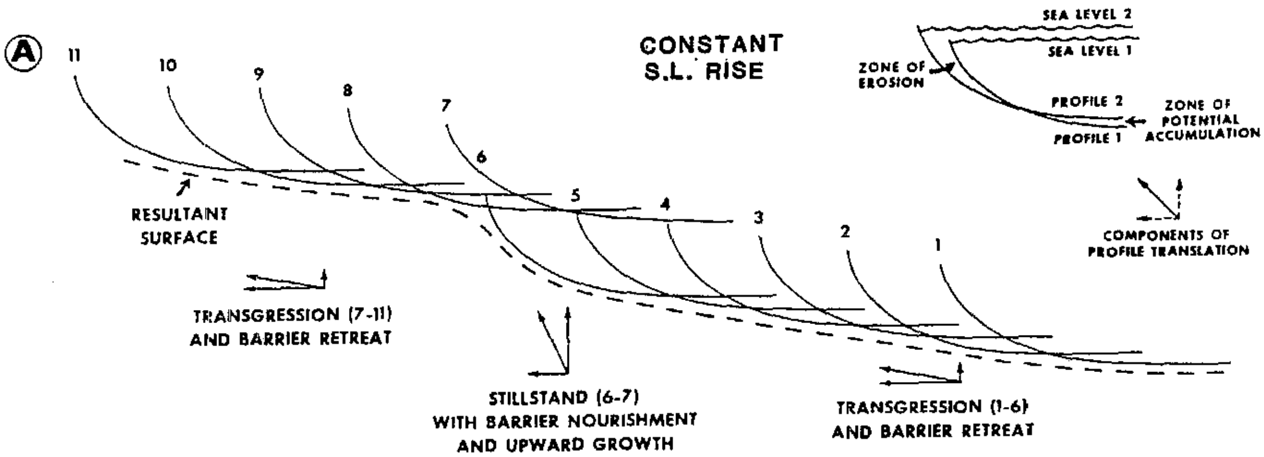
The occurance of the elongate Willesden Green south deposit at the base of a major 'step-up' in the VE4 surface, may indicate that sporadic influxes of sediment from the Harmattan (Ferrier) shoreface, may have supplied subtantial amounts of sediment to the transgressive Viking basin. Swift et al (1984) suggest that through the counterbalancing effect of high sediment input and a rising sea level, erosive shoreface retreat will create a distinctive scarp topography and may result in the preservation of a thick nearshore sediment package [fig. 8.17]. Debate on whether such a mechanism is valid over the time periods required for eustatic sea level rises is ongoing (Rampino and Sanders, 1981; Swift and Moslow, 1982; Leatherman, 1983), however many believe that the effect of regional tectonic influences could make such a mechanism viable. Erosive shoreface retreat has been called upon to explain several incised shoreface deposits throughout the Cretaceous of the Western Interior Basin (Plint et al, 1988; Downing and Walker, 1988; Pattison, 1988), and also to describe the evolution of modern barrier bar deposits off the east coast of North America (Sanders and Kumar, 1975; Panageotou and Leatherman, 1986).


10-34-36-9W5
3112-3120 m
TB

Such a mechanism could potentially account not only for the 'scarp-like' topography seen on transgressive VE4 surface in Twp 39, but also for the location of the coarse sediment thick deposited along the base of this 'step' at Willesden Green south. Continued transgression and subsequent reworking of these thin stillstand deposits by open shelf tidal and storm currents, would overprint their original shoreface signature, leaving them in their present day configuration. A combination of strong storm and tidal currents would modify the original shape of the sand bodies, cause their migration away from the erosional scarp, and act to redistribute much of the sediment across the broad shelf as a thin sheet-like sand or pebble horizon. These sediments would be continuous with the main sediment thick, and progressively thin and fine laterally. The nature of the coarse sand package at Willesden Green south, and the onlapping VE4 lag at Ferrier appear to follow precisely this pattern.

The elongate sand package which sits on the base of the main scarp (VE4) at Willesden Green south, progressively thins from 2.9 m to a thin pebble lag only a few cms thick, in both strike and dip directions. A similar trend occurs in the Member E conglomeratic sands which make up the main reservoir at Ferrier. This sediment package rests on top of the terrace above the Willesden Green scarp. A thin stringer of pebbles and sand onlaps the terrace, and is continuous with VE4 at that point [fig.8.12]. Examination in core shows that just like the Willesden Green tidal package, this onlapping bed thins and fines in a northerly direction, away from the main sediment accumulation. The presence of scattered pebbles and sideritized mud makes this horizon a distinctive marker in core, which can be traced across the entire study area [fig. 8.18]. Synaeresis cracks in some of the finer-grained beds [fig. 8.19]

MODEL FOR VE4 SCARP GENERATION



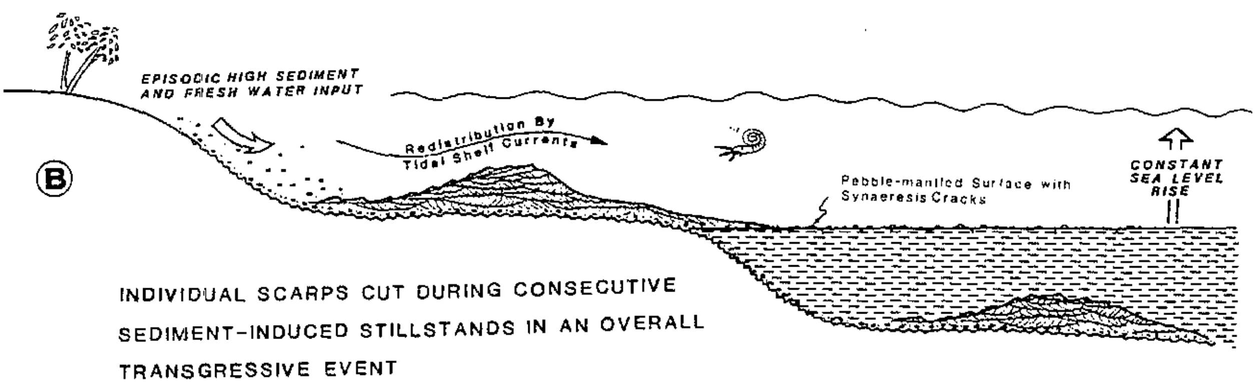
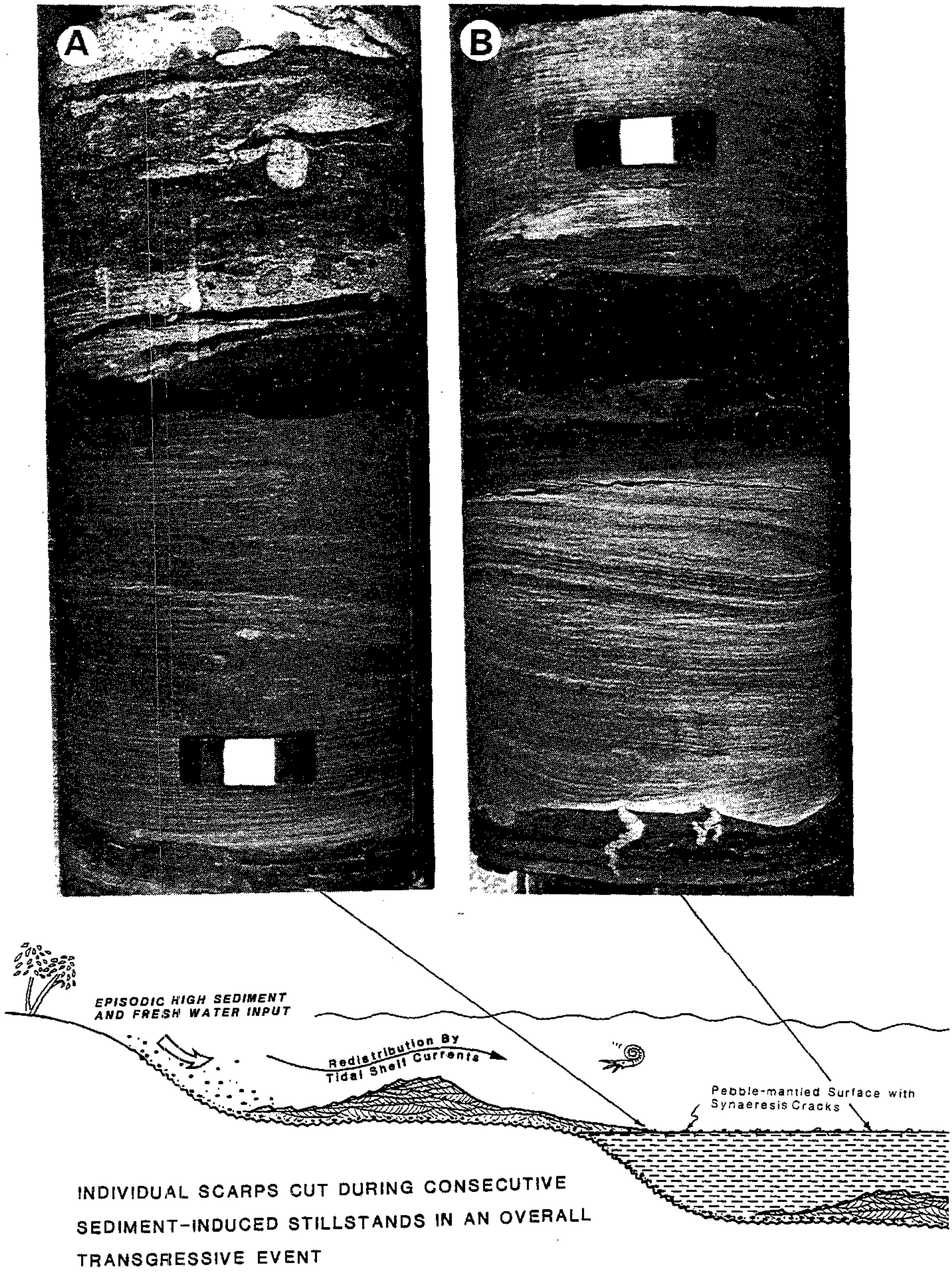


Figure 8.17a - Model for scarp generation by erosional shoreface retreat (from Swift et al, 1984).

Figure 8.17b - Interpreted stratigraphic response model to 8.18a.


A
B
EPISODIC HIGH SEDIMENT AND FRESH WATER INPUT
Redistribution By Tidal Shelf Currents
Pebble-mantled Surface with Synaeresis Cracks
INDIVIDUAL SCARPS CUT DURING CONSECUTIVE SEDIMENT-INDUCED STILLSTANDS IN AN OVERALL TRANSGRESSIVE EVENT

suggests that sediment input and redistribution was also accompanied by fluctuations in water salinity. This association is entirely consistant with a temporary influx of sediment charged fresh water into the basin.

As the sediment input decreased and transgression renewed, deepening conditions resulted in burial of the coarse sediments of FA5 under thick black shales of the Colorado Formation [8.20]. Later still-stands, further to the south would carve similar 'steps' in the underlying shoreface sands in the Caroline and Harmattan areas (S. Davies, pers. comm., 1989; S. Hadley, pers. comm., 1989).

8.7 Reservoir Properties

Three main pools occur within the sandstones and conglomerates of FA5: Willesden Green Viking 'A', Ferrier Viking 'A', and Gilby Viking 'B'. As was noted in chapter 6, sands of the Willesden Green estuarine complex and the Willesden Green tidal sands mutually form the W.G. Viking 'A' pool. Within these Member E pools depositionally related thickness of the coarse sediment package appears to be the main factor dictating reservoir potential. Where the cross-bedded and conglomeratic facies are the best developed (3 m), production figures peak, with a relatively constant drop in production as the sands thin laterally. As in the underlying Member C sediments, increased prominance of shale interbeds, and associated segregation of sand units laterally appear to be the dominant factor in defining reservoir boundaries.

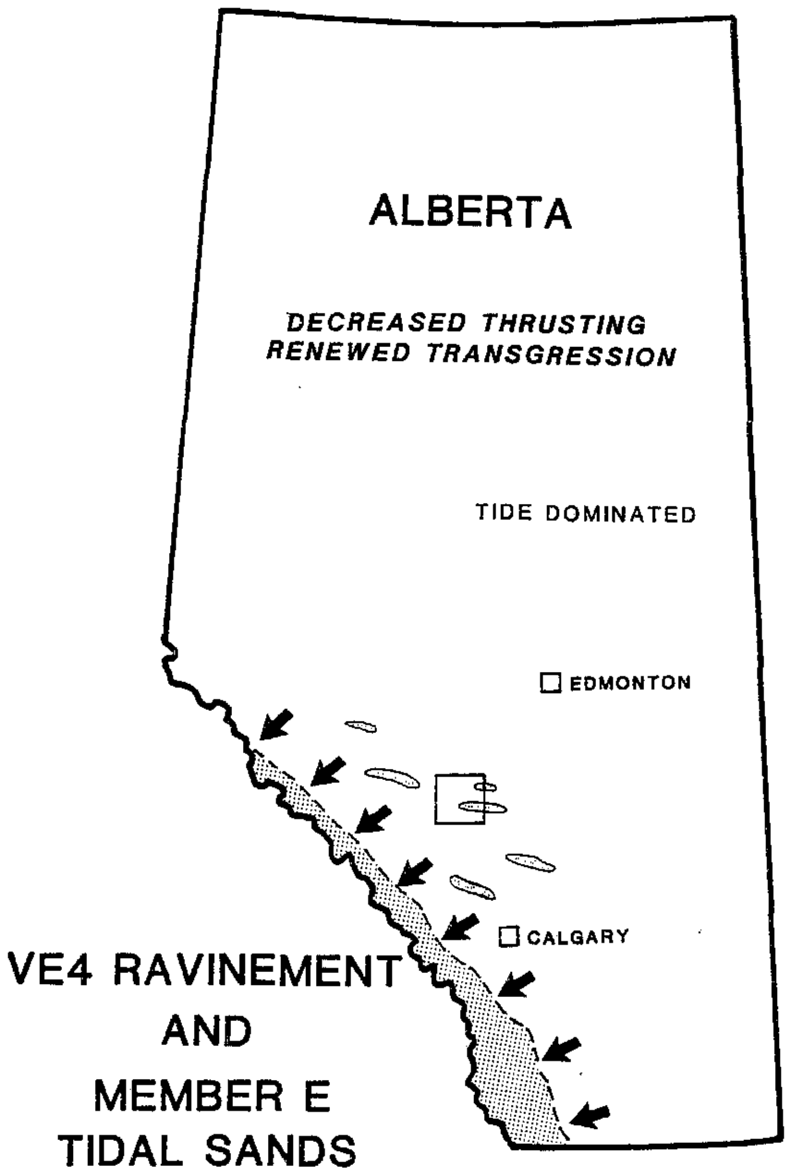


Figure 8.20 - Interpreted palaeogeography during the final Viking transgression (scouring of ravinement surface VE4, and deposition of Member E elongate shelf sand bodies).

CHAPTER 9 - SUMMARY, INTERPRETATIONS AND CONCLUSIONS

9.1 Introduction

Within the Willesden Green study area there are 4 distinct sediment packages separated by 3 major discontinuity planes. Each facies association is distinguished by a unique set of physical and biological structures as well as distinctive grain size trends and vertical and lateral facies sequences. The 3 erosional surfaces are each mantled by unusually coarse sediment, and each is morphologically distinctive.

Analysis of these features was directed towards determining the sedimentology and depositional environments of the individual packages in the Willesden Green area (previous chapters), as well as the relationship of each package to the next. Through the determination of these complex relationships, a history of the dynamic changes occuring throughout the time of Viking deposition might be interpreted. A discussion of the evolution of depositional environments and sequence of sea level variations ultimately responsible for these changes follows.

The erosion surfaces and facies associations documented in earlier chapters are here summarized and discussed in stratigraphic order, starting at the package initially deposited during the earliest Viking time, and continuing upward through the succession. In this manner an internal stratigraphy and depositional history for the Viking Formation is established [figs. 9.1, 9.2, 9.3].

9.2 MEMBERS A-B (REGIONAL SHELF SEQUENCES)

The Viking regional shelf cycles sharply overlie the dark shales of the Joli Fou Formation and represent initial deposition in the Viking.

These deposits occur across the study area and consist of a gradationally interbedded succession of three small-scale coarsening upward bioturbated mudstone and siltstone sequences up to 19 m thick. The sequences are thoroughly churned by organisms indicative of both the Zoophycos and Cruziana ichnofacies, and are dominated by very fine grain sizes. They are interpreted to represent offshore shelf deposits cyclically deposited during minor fluctuations in relative sea level, and are equivalent to the "regional shelf-shoreface facies" of Reinson et al (1988), and the "basal siltstone association" of Downing and Walker (1988). The regional shelf cycles are correlatable throughout much of north-central and south-central Alberta.

Lithologic evidence and isopach maps from the study area indicate that the basal siltstone cycles become progressively thicker and sandier to the north-northwest. Correlation into the Crystal field (TP46-R3W5) confirms this fact (S.A.J. Pattison, pers comm, 1989). Such observations support the hypothesis that during the earliest Viking time the primary sediment source area was to the northwest, possibly in the vicinity of the Peace River Arch (Stelk, 1975; Amajor, 1980). A subtle thickening of the two lowermost cycles (A and B1) along a trough-like extension running approximately N-S, from TP43 - R7 to TP40 -R6, suggests that at the time of deposition this area may have been undergoing active subsidence relative to surrounding areas.

The top of the regional shelf assemblage is abruptly truncated by a thin veneer of coarse-grained sandstone and pebbly mudstone over much of the area. The maximum erosive truncation on this surface occurs in the northwest, in the vicinity of the coarsest-grained and, what are interpreted to be the most shore-proximal sediments. The removal of these sediments is almost certainly related to a relative drop in sea level which followed deposition of members A and B. Locally, this truncating surface appears to split into up to three vertically distinct pebble covered horizons. The stratigraphically lowest of these, and therefore the earliest, is the VE2 contact below Member C.

9.3 VE2 \ MEMBER C (CHANNEL-ESTUARINE COMPLEX)

Viking erosion surface VE2 is found only in the west-central portion of the study area and defines a broad funnel-shaped, unconformable valley consisting of 2 interconnected, elongate scours up to 11 m in depth. In the deepest parts of the scour, VE2 is mantled by a thick conglomerate lag which thins and fines laterally. Bentonitic markers in the underlying basal siltstone assemblage are erosively truncated by this surface, and there is a sharp contrast in depositional style above and below the contact. Sedimentological evidence discussed previously (chapter 6), indicates that the sandstones and mudstones which infill the VE2 valley comprise a tidally influenced, channel-estuarine complex.

The VE2 valley incisement at Willesden Green is undoubtedly time equivalent to other Viking incised channels present in the Crystal (Reinson, 1988), Edson, Sundance and Cyn Pem field areas, and Weimer (1983) documented similar transgressively-filled valleys in the time equivalent Newcastle Formation in the Denver Basin. Research carried out by the author also indicates that coarse grained Viking deposits preserved at Gilby A were emplaced at this time, and probably represent transgressively reworked shoreface deposits.

Although the initial Willesden Green valley incisement undoubtedly occurred subaerially, the presence of marine, sand-filled burrows

(*Ophiomorpha*, *Skolithos*, and *Planolites*) along the basal VE2 contact, as well as in the overlying sands indicates that infilling of the valley took place entirely under marine to brackish conditions. The multi-stage nature of the channel fill and aggradational stacking of facies, suggests that the main channel axis probably remained relatively stationary during deposition. Anomolously thickened sediments beneath the Willesden Green valley (cross section E-E') indicate that its location may have been influenced by underlying palaeotopographic controls on the top of the Mannville.

Several indicators at Willesden Green, Crystal, and Gilby suggest that meso- to macro-tidal conditions may have existed in the Viking basin at this time. Diagnostic characteristics such as abundant reactivation surfaces, rapid facies changes, small scale fining- and coarsening-upward sequences, abundant mud drapes, mud couplets, and flaser and linsen bedding all indicate deposition under fluctuating currents, possibly tidal conditions (Terwindt, 1971-88; Clifton, 1983; Blatt, Middleton, and Murray, 1980; Visser, 1980; Dalrymple et al 1975-78; Elliot, 1986; De Raaf and Boersma, 1971; Driese et al 1981; Bosence, 1973; Allen, 1984; Rahmani, 1988; Baldwin and Johnson, 1977; Mazullo, 1978). The extensive preservation of incised valleys, and the great areal extent of correlative lowstand sand bodies at the VE2 stratigraphic horizon, suggests that this was the most substantial lowering of sea level recorded during Viking times. Lowstand shorefaces advanced at least as far northeast as the Gilby-Joffre trend (Downing, 1988; Raddysh, 1988), and possibly much further into the basin. It was almost certainly a eustatically controlled event, and probably correlates to a major sea level drop that occurred approximately 97 million years ago (Vail et al, 1977; Haq et al, 1987;

Kauffman, 1984).

Evidence from Willesden Green, when viewed in conjunction with data from other known Viking channels at Crystal, Cyn Pem, Edson, and Sundance, strongly suggests that during the first Viking lowstand the drainage system radiated from southwest to northeast, and that the main source of sediment was somewhere in the southwest [fig. 9.1]. Correlatable thick upper shoreface sediments in the Caroline area (S.Hadley, pers. comm., 1989) contribute to the hypothesis that by this time the main depositional source had shifted from the vicinity of the Peace River Arch to points southwest, although much of the Peace River area was probably subaerially exposed at this time. While the lowering of sea level was probably eustatically controlled, the southward shift of depositional source can only be attributed to the effect of renewed tectonic thrusting in the southwest.

9.4 VE3 \ MEMBER D (PROGRADING SHOREFACE)

The top of the Member C estuarine complex is abruptly planed by a second pebble mantled surface : VE3. The VE3 contact can be traced throughout the study area, and can also be found north at Crystal (S.A.J. Pattison, pers. comm., 1989), east at Gilby and Joffre (Downing and Walker, 1988), and as far south as Harmattan (S.W. Hadley, pers. comm., 1989). It locally truncates the top of the Willesden Green estuarine complex (Member C), and regionally scours into the underlying basal siltstone assemblage. The fact that the VE3 surface separates the underlying transgressively filled estuarine sediments of Member C from overlying progradational shoreface sediments of Member D, indicates that it must represent a major transgressive ravinement surface. This pebble mantled horizon is the sedimentological expression of a major regional sea level rise which marked the end of the first Viking progradational event.

In the Willesden Green area this surface is both overlain and underlain by marine to marginal marine sediments, which suggests that any non-marine deposits and possibly a substantial amount of inter- to subtidal deposits associated with the Willesden Green channel-estuarine complex were removed during the subsequent transgression. The VE3 surface defines a rather flat, gently undulating topography with broad localized areas of shallow scour. This surface can easily be traced southward as far as Caroline (S.D. Davies, pers. comm., 1989) and Harmattan (S.W. Hadley, pers. comm., 1989), which suggests that during this period the Late Albian sea had transgressed a large part of central and south-central Alberta. Renewed progradation subsequently blanketed the VE3 surface with the shoreface sediments of Member D.

Member D marks the second regional drop in sea level recorded in the Viking Formation. This unit consists of an upward-coarsening sequence of interbedded wave-rippled sands and muds, and hummocky cross stratification, indicative of a wave-dominated prograding shoreface environment (Walker, 1984; Leckie, 1986; Hein et al, 1986). The shallowest water sediments preserved in the Willesden Green and Ferrier area are offshore transitional to lower-shoreface in origin. Patchy occurances of these sediments can be found as far north as Crystal (S.A.J. Pattison, pers. comm., 1989), and as far east as Joffre (Downing and Walker, 1989); attesting to the extent of the progradation.

The fact that lower shoreface to offshore transitional sediments of Member D abruptly overlie both the Willesden Green estuarine deposits

(Member C), and also the Crystal channel (S.A.J. Pattison, pers. comm., 1989) shows conclusively that the shoreface progradation was a separate, later event, and not penecontemporaneous with channel-fill as was previously suggested for the Viking Crystal reservoir (Leckie and Reinson, 1989). This package can be correlated back to, and is continuous with, thick upper shoreface, beach and non-marine sediments in the Caroline area (S.D. Davies, pers. comm., 1989) [fig. 9.2].

The dramatic southerly thickening of the Member D package suggests that at the time of deposition, the primary depositional source within the Viking had shifted completely to the southwest, and the Peace River Arch had essentially ceased to supply sediment to the eastern basin. Conditions had become primarily storm-dominated, and the effective tidal resonance which had substantially imprinted earlier deposits, was temporarily dampened under a changing basin configuration. Leckie (1986) concluded that the major cause of the shoreline progradation may have been a regional drop in sea level, or a high rate of sediment input into the basin during a tectonically influenced stillstand. Both mechanisms appear plausible. Gravel stringers and shallow fluvial incisions associated with these shoreface sands in the Caroline and Harmattan areas (S.W. Hadley, pers. comm., 1989) indicate that both coarse sand and gravel were supplied to the basin during this lowstand. As previously noted, Member D becomes substantially thicker and sandier towards the south. This trend is interpreted to be a function of not only depositional thickening, but also subsequent step-wise erosive shoreface retreat caused by the final sea level rise of the Lower Albian. This transgressive event is recorded by the VE4 ravinement surface and the coarse-grained deposits of Member E.

9.5 VE4 \ MEMBER E (TIDAL SAND RIDGES)

VE4, the stratigraphically highest contact, can be traced throughout the Viking basin. It erosively truncates the underlying sandstones and shales of the hummocky sandstone association and in places erosively removes all earlier Viking erosion surfaces. It is consistantly blanketed by a thin veneer of mainly clast supported pebbly mudstone, and locally thickens to form the elongate, mud draped, sand and conglomerate bodies of Member E (up to 3 km long, .7 km wide and 2.9 m thick). These deposits are interpreted to represent open marine transgressive lag and tidally influenced sand ridge deposits (chapter 8).

The intersection of VE4 with the underlying shoreface sands of Member D has a distinctive topography which rises in a progressive, 'step-like' fashion towards the south [fig. 9.2]. This surface morphology is thought to represent shifts in base level caused by a series of minor stillstands during the final southward transgressive and erosive shoreface retreat of the Viking sea.

The thickest elongate sediment packages consistently occur at the base of each scarp in the VE4 surface (S.W. Hadley, pers. comm., 1989; S.H. Davies, pers. comm., 1989), suggesting that during the transgression, episodic sediment influxes may have initiated stillstand conditions, and resulted in scarp-forming base level increases (Swift et al, 1984). Subsequent reworking of these 'shoreface' sediments by strong shelf currents would have eliminated the nearshore signature of the deposits and caused redistribution of the sediment. Many of the coarse grained packages laterally thin to form extensive onlapping shale encased pebble horizons, which are tracable throughout the basin. The association of scattered pebbles and synaeresis cracks with these markers reinforces the hypothesis that fresh water influx (Van Straaten, 1954) and a short term increase in sediment supply accompanied each of the scarp-forming stillstand events. Palimpsest reworking of underlying sandy estuarine sediments of Member C, and transgressive winnowing of Member D shoreface (and incised drainage) deposits probably contributed an additional source of coarse clastic material to the Member E transgressive sand bodies.

Within the Member E coarse sediment package, the presence of interbedded shale and conglomeratic sediments, rip up clasts, reactivation surfaces, mud drapes, large scale cross-bedding, and compound cross-stratified sandstones, all indicate that meso- to macro-tidal conditions had returned to the Viking basin during this final transgression (Reineck, 1963; Houbolt, 1968; Levell, 1980; Allen, J., 1980; Walker, 1984; Leckie, 1986). Strong tidal currents apparently acted to mold and rework both newly introduced stillstand sediments, and the underlying deposits of members C and D into elongate bars, and to sweep a thin veneer of coarse sediment into the basin.

Member E conformably grades into the overlying Colorado Shales. The uppermost Member E allostratigraphic bounding discontinuity is the Base of Fish Scales marker. The top of the Viking Formation is arbitrarily marked by the uppermost thin conglomerate horizon present throughout the study area (LM2). Detailed correlations indicate that this lens is contiguous with the main FA5 coarse sand package in the vicinity of Ferrier (twp 39; rg 8), and that it can be traced at least as far east as Joffre and as far north as Crystal. The VE4 boundary is significant in that it marks the end of the second major Viking progradational event, and records the first major inundation of the Lower Colorado Sea.

9.6 CONCLUSIONS

1. In the Willesden Green study area the Viking Formation is made up of of 4 distinct packages of sediment separated by 3 major stratigraphic breaks.

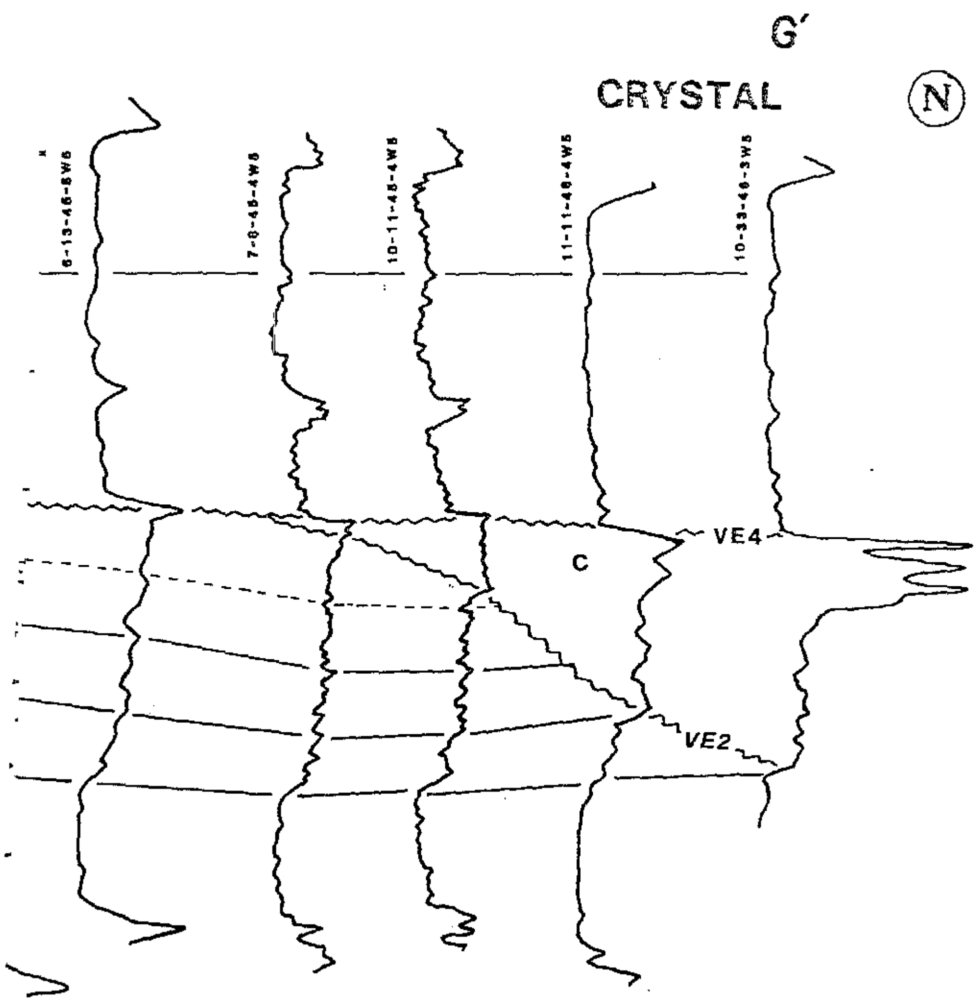
2. Deposition of the Viking Formation in the Willesden Green area was the result of two major regressive events in the Late Albian.

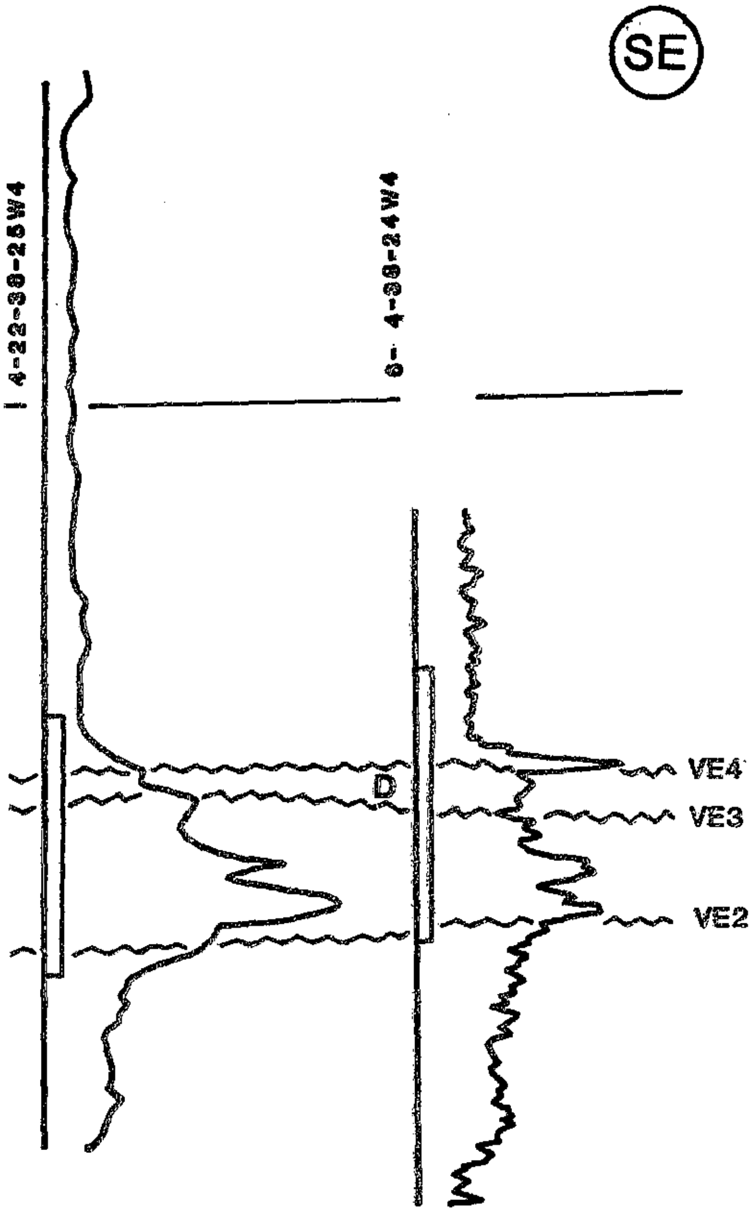
3. Initial sedimentation in the Viking was supplied from the vicinity of the Peace River Arch, and resulted in the deposition of three coarsening upward cyclic offshore mudstone/siltstone sequences in the Willesden Green area (Member A and Member B [B1,B2]).

4. The first Viking lowstand resulted in incisement of a major valley at Willesden Green (VE2). This valley was part of a much larger drainage system which transported sediment northeastward from a tectonically active source area in the southwest. During a stillstand in the subsequent regional transgression, the Willesden Green valley infilled with tidally-influenced channel-estuarine sediments (Member C). Continued transgression eventually caused the inundation of much of central and south-central Alberta, and created a ravinement surface (VE3) that truncates the underlying sediments of Member B and Member C.

5. A second Viking progradational event was supplied from the southwest, and resulted in the deposition of a thick sequence of wave-dominated lower shoreface to transitional offshore sediments (Member D) in the Willesden Green study area. These deposits are correlatable with the Caroline and Harmattan upper shoreface and non-marine sediments in the south.

6. The final event in the Viking was the transgressive flooding of the basin which caused the erosive stepwise retreat of the Harmattan-Caroline shoreface, and the development of a coarse-grained lag surface (VE4), and the deposition of mud-draped tidally influenced sand ridges on the broad Viking shelf (Member E). These sediments were subsequently buried by deeper water shales of the Colorado Group.

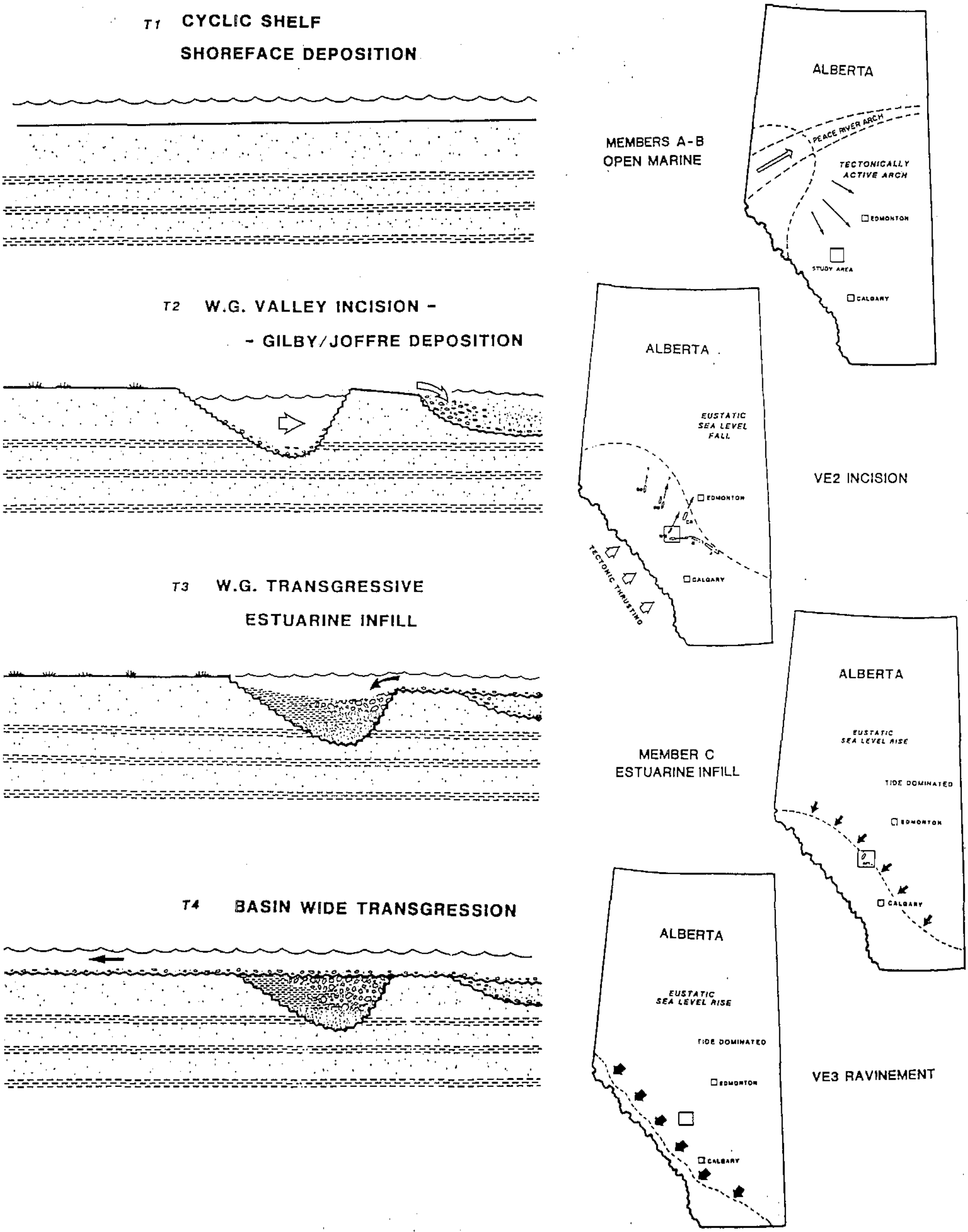

G′
CRYSTAL
N
6-13-46-5W5
7-8-45-4W5
10-11-45-4W5
11-11-46-4W5
10-33-46-3W5
VE4
C
VE2



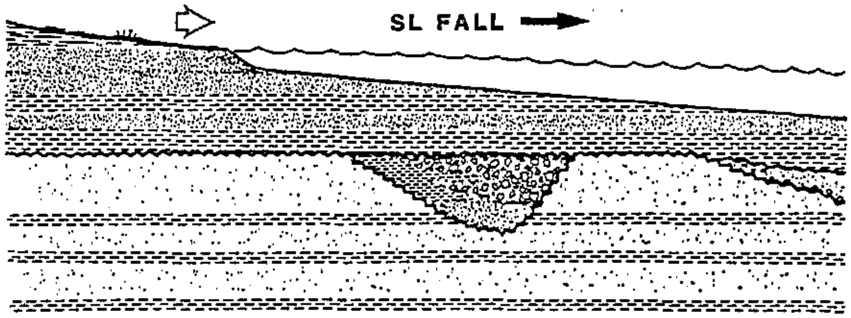
'NING AND WALKER (1988)

Figure 9.3 - Schematic development and interpretation of Viking allostratigraphy in the Willesden Green area.

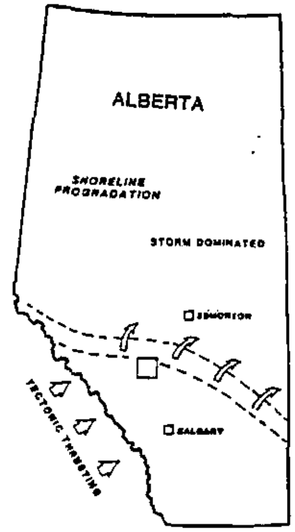
VIKING FORMATION DEPOSITIONAL HISTORY AT WILLESDEN GREEN


T1 CYCLIC SHELF
SHOREFACE DEPOSITION
MEMBERS A-B
OPEN MARINE
ALBERTA
PEACE RIVER ARCH
TECTONICALLY ACTIVE ARCH
EDMONTON
STUDY AREA
CALGARY
T2 W.G. VALLEY INCISION -
- GILBY/JOFFRE DEPOSITION
ALBERTA
EUSTATIC SEA LEVEL FALL
EDMONTON
CALGARY
TECTONIC THRUSTING
VE2 INCISION
T3 W.G. TRANSGRESSIVE
ESTUARINE INFILL
MEMBER C
ESTUARINE INFILL
ALBERTA
EUSTATIC SEA LEVEL RISE
TIDE DOMINATED
EDMONTON
CALGARY
T4 BASIN WIDE TRANSGRESSION
ALBERTA
EUSTATIC SEA LEVEL RISE
TIDE DOMINATED
EDMONTON
CALGARY
VE3 RAVINEMENT

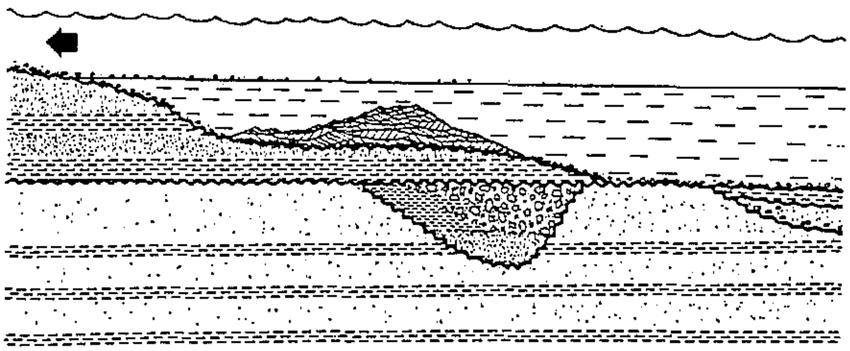
T5 **CAROLINE SHOREFACE PROGRADATION**

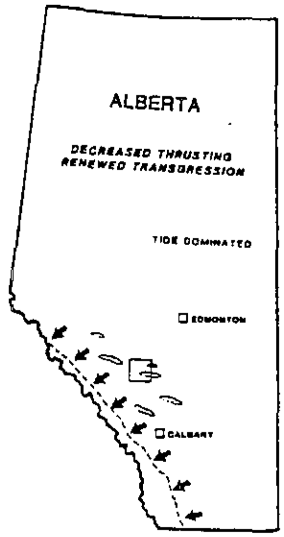


MEMBER D
SHOREFACE



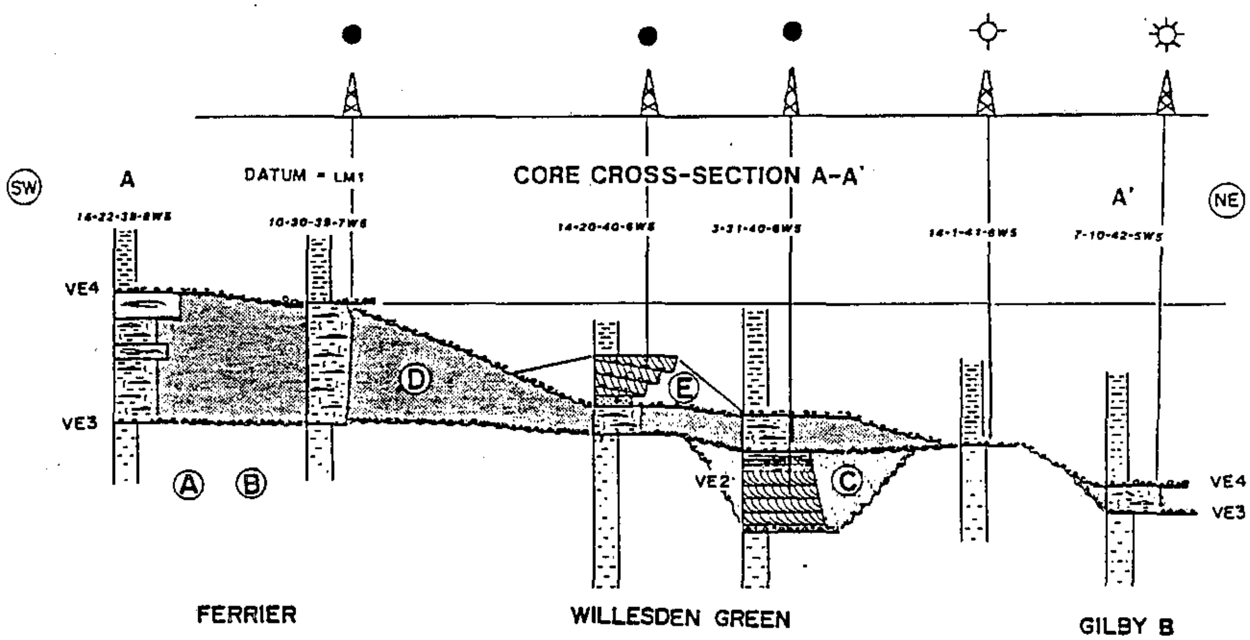
T6 **BASIN WIDE TRANSGRESSION AND DEPOSITION OF SHELF SAND RIDGES**





VE4 RAVINEMENT
AND
MEMBER E
TIDAL SANDS

T7 **DEEP BURIAL**



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