HIBERNIA FORMATION SEQUENCES AND BREATHITT GROUP (KENTUCKY) ANALOGUE

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AND BREATHITT GROUP (KENTUCKY) ANALOGUE

by

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ABSTRACT

The Hibernia oilfield is located 315 km offshore and east-southeast of St. John's Newfoundland. An estimated 620 million barrels of recoverable oil are located in the Hibernia oilfield within a basal Cretaceous, fluvial-dominated delta system known as the lower Hibernia zone of the Hibernia Formation. Informal lithostratigraphic units assigned to the lower Hibernia zone include a non-reservoir, finer grained Layer 1 and sandstone-dominated Layers 2 and 3 separated by the field-wide marine Medial Shale. During deposition of the Hibernia Formation, braided rivers draining the Avalon uplift, located to the south, deposited sands in incised valleys. The Hibernia reservoir sandstones of Layers 2 and 3 represent late lowstand to early transgressive systems tracts and are separated by finer grained lower delta plain, lagoonal and open marine facies which represent late transgressive to highstand systems tracts. The entire lower Hibernia zone is interpreted as a third-order composite sequence; it can be further subdivided into higher frequency fourth- and fifth-ordered cycles.

The Pikeville, Hyden and Four Corners formations of the Pennsylvanian Breathitt Group, eastern Kentucky, constitute a facies and sequence-stratigraphic analogue for the Hibernia Formation. The Breathitt Group is interpreted as a fluvially dominated, shallow-water deltaic succession punctuated by the deposits of a number of marine incursions. The high net sandstone intervals of the Breathitt Group were deposited by a west- or west-northwest-flowing fluvial system characterized by braid bars in distributary channels and incised valley systems. The high net sandstone intervals represent late lowstand to early transgressive systems tracts and are separated by finer grained, lower delta plain, lagoonal and open marine facies, which represent late transgressive to highstand systems tracts. The stacking patterns and sequence stratigraphy of this part of the Breathitt Group strongly resemble those of the Hibernia Formation, and therefore can be used to refine existing models at Hibernia. Despite the differences in age, tectonic setting, and likely scales and frequency of relative sea level change, the Breathitt Group is shown in this thesis to be a suitable stratigraphic and sedimentological analogue for the Hibernia Formation.

Based on excellent outcrop exposure and well data, permeability pathways through the Breathitt Group are postulated. Marine shales and abundant coals are identified as candidates for intraformational seals and pressure barriers, respectively. Vertical sealing attributes are recognized for similar marine shales at Hibernia. This thesis provides a justification for a more detailed field and laboratory study needed to quantify reservoir properties of the Breathitt Group, so that numerical data can be incorporated into reservoir models for the Hibernia field.

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CHAPTER ONE – INTRODUCTION

The key objective of this study is to evaluate whether the sedimentology and stratigraphic architecture of the Pennsylvanian Breathitt Group in Eastern Kentucky provide a good analogue for the Cretaceous Hibernia Formation of the Hibernia oilfield, offshore Eastern Newfoundland. Specific aims of the study are to document the similarities in sedimentary facies, facies associations, depositional environments and sequence stratigraphic architecture of both units in order to assess the suitability of the Breathitt Group as an analogue for improved reservoir characterization of the Hibernia Formation. This study will also evaluate how significant differences in age and tectonic setting might lessen the suitability of the Breathitt Group as an analogue to the Hibernia Formation.

1.1 Comparison of Stratigraphic and Tectonic Settings; Hibernia Formation and Breathitt Group

Stratigraphic and structural complexities encountered in both hydrocarbon-bearing subsurface reservoirs and fluvial outcrops are often best resolved through the application of analogue models. These models can help clarify the main sites of deposition, depositional processes, reservoir geometry and architecture. Valid model parameters are incorporated into existing three dimensional reservoir models to improve reservoir maintenance and production. Currently, both the Hibernia Management Development

Corporation and ExxonMobil view the fluvio-deltaic deposits of the Breathitt Group, eastern Kentucky, as a valid analogue for the fluvio-deltaic deposits of the Hibernia Formation of the Grand Banks, offshore Newfoundland.

The Grand Banks of Newfoundland is a wide segment of the continental shelf underlain by a series of Mesozoic rift basins, one of which is the Jeanne d′ Arc Basin. The Jeanne d′ Arc Basin is a narrow and elongated, northeast-trending basin, that developed in response to three episodes of rifting related to the opening of the North Atlantic Ocean (Hiscott et al., 1990a). The basin contains several significant hydrocarbon accumulations including the Hibernia oil field (Figure 1.1). A thick accumulation of sediment (Triassic to modern) is present in the region of the Hibernia oil field (Figure 1.2). The Berriasian to Valanginian Hibernia Formation has been lithologically divided into the lower and upper Hibernia zones based on core and well data. The lower Hibernia zone contains an estimated 620 million barrels of recoverable oil within a basal Cretaceous fluvial-dominated delta system.

The lower Hibernia zone, from base to top, has been subdivided into Layer 3, the Medial Shale, Layer 2, and Layer 1 (Figure 1.3) (HMDC). This stratigraphic nomenclature has been established by the Hibernia Management Development Company to separate the porous reservoir intervals from the non-reservoir intervals. Fluvial sandstones deposited in distributary channels and in broad, episodically developed incised valleys characterize the Hibernia Formation. These sandstones are vertically separated by fine-grained, lower- delta-plain, delta-front, and marine-bay facies (Figure 1.4) (Hurley et

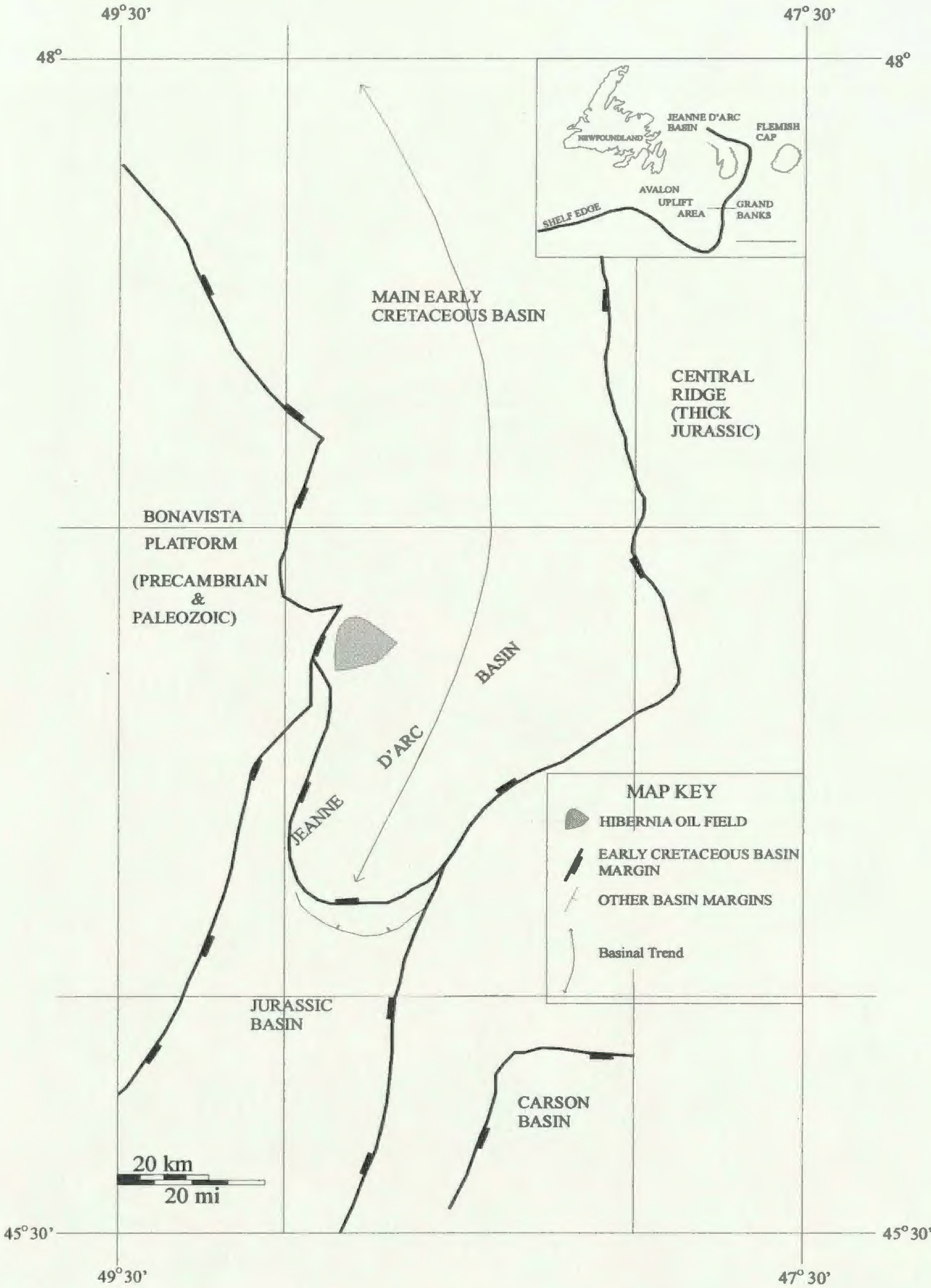


Figure 1.1. Map of the Jeanne d'Arc Basin showing the main structural features and the location of the Hibernia Oil Field (shaded) (Modified from Grant et al., 1986).

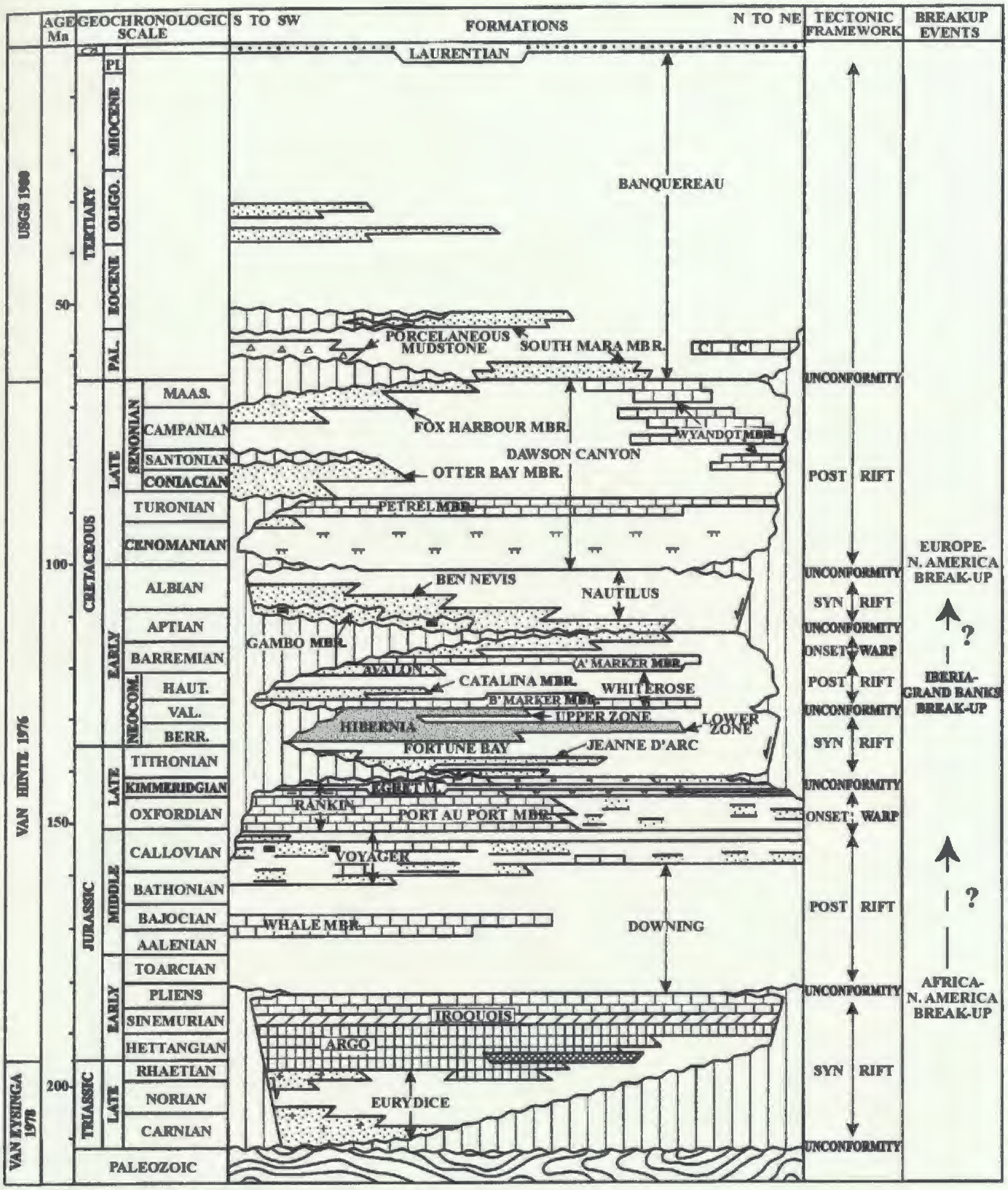


Figure 1.2. Generalized stratigraphy of the Jeanne d'Arc Basin. The highlighted unit is the Berriasian to Valanginian Hibernia Formation (Modified From Canadian Newfoundland Offshore Petroleum Board, 2001).

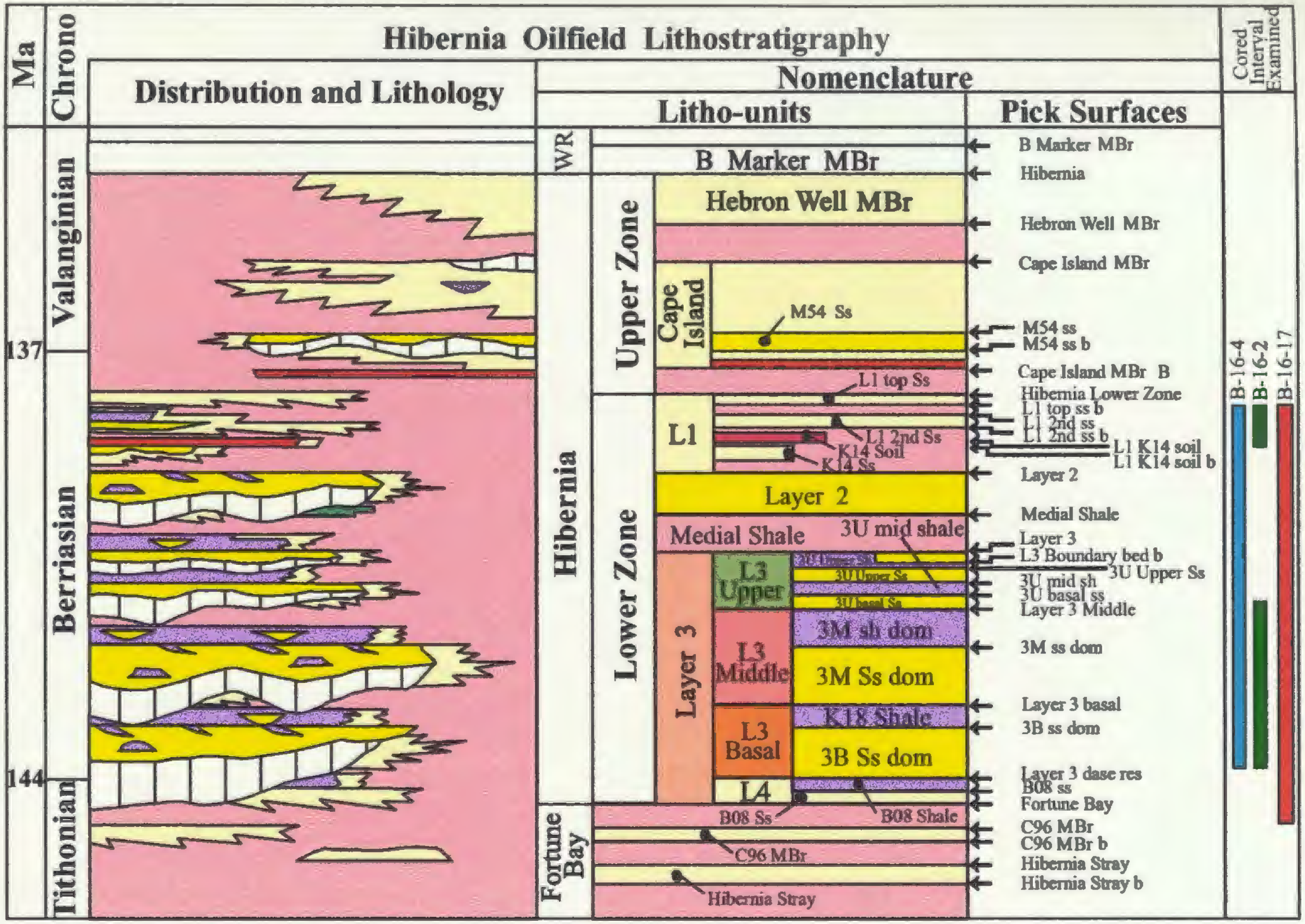


Figure 1.3. Lithostratigraphy of the Hibernia Oilfield. The reservoir sands are located within the lower zone which from base to top has been subdivided into Layer 3, the Medial Shale, Layer 2 and Layer 1. The yellow regions represent sand, the purple regions represent brackish-marine shales, the cream regions represent delta front/mouthbar facies, and the pink regions open marine shales. Hiatuses are marked by vertical rule Also shown are the intervals of core examined from each of the three Hibernia wells (Modified from Flint and Sinclair, 2001).

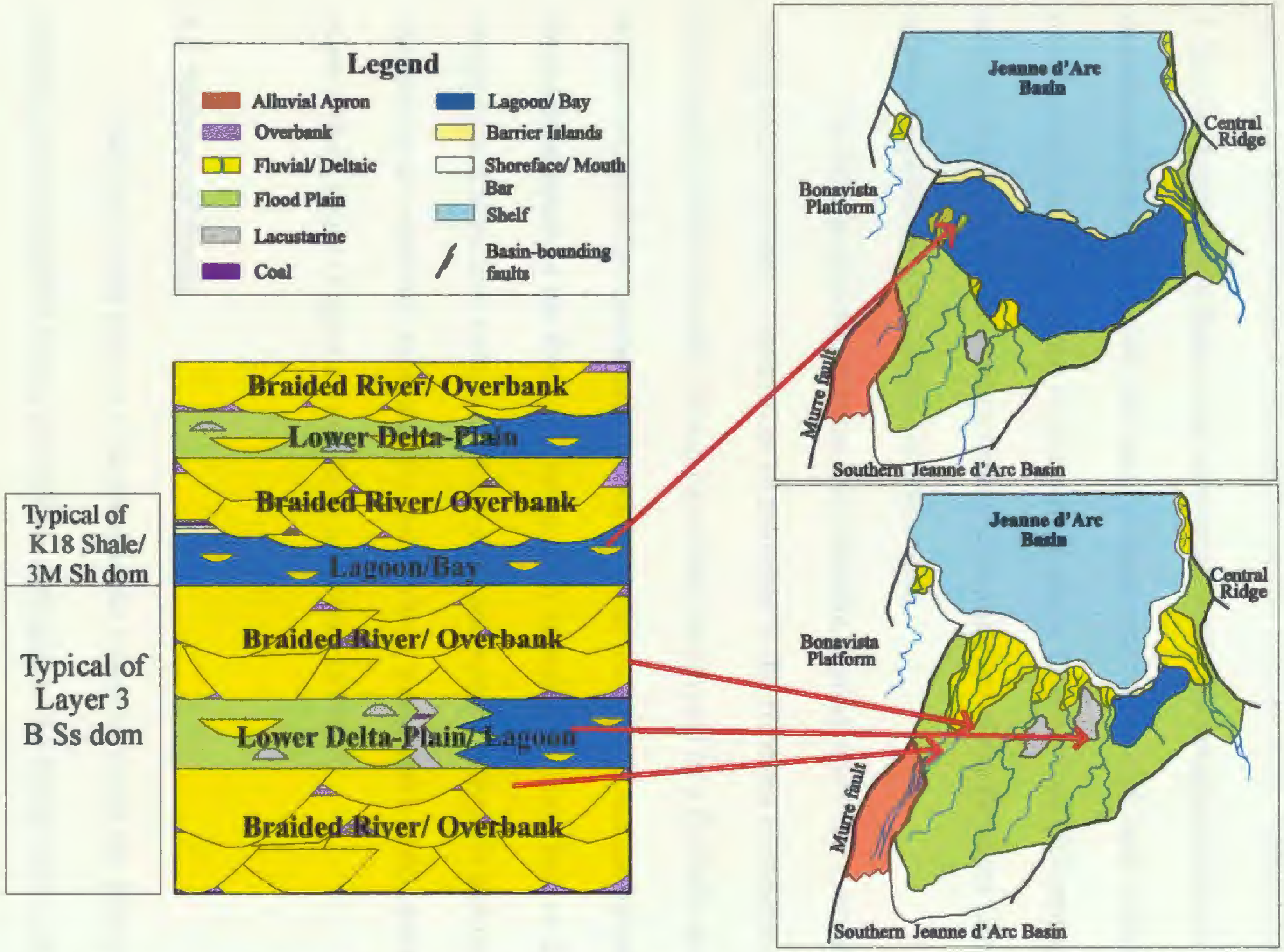


Figure 1.4. The figure on the left is a schematic diagram of the stacked facies identified in the Hibernia cores during the present study. The figures to the right are interpreted to be a representation of the regional paleogeography of the Jeanne d'Arc Basin corresponding to the deposition of sediment in both the Layer 3 Basal Sandstone and K18 shale-dominated lithologic units (HMDC, 2001).

al., 1992).

Portions of the Pennsylvanian Breathitt Group, eastern Kentucky, provide a facies and sequence-stratigraphic analogue for the Hibernia Formation. The mid-Pennsylvanian deposits of eastern Kentucky occupy the central portion of the Appalachian Basin (Figure 1.5). The Appalachian Basin is an elongated, northeast-trending structure. Throughout the eastern portion of Kentucky, the basin contains numerous coal beds, with known reserves of one to five million tonnes of coal still in place. Despite their different age and tectonic setting, the facies characteristics observed in outcrops of the Breathitt Group are very similar to those observed in the Hibernia cores.

Within the Breathitt Group, the Pikeville, Hyden, and Four Corners formations comprise the interval of interest as an analogue to the Hibernia Formation (Figure 1.6). The deposits of the Breathitt Group have been interpreted as a fluvially-dominated, shallow-water deltaic succession associated with widespread marine incursions. The fluvial sandstones of the Breathitt Group were deposited as braid bars in distributary channels and in incised valleys of braid-plain and upper-delta-plain settings. These sandstones are vertically separated by fine-grained, lower-delta-plain, delta-front, and marine-shelf facies (Figure 1.7) (Aitken and Flint, 1995).

1.2 Purpose of Study

The aim of this study is to determine the extent to which the fluvio-deltaic deposits of the Breathitt Group provide an analogue to the fluvio-deltaic deposits of the

Figure 1.5. Location of the Appalachian basin (yellow) and Central Appalachian Basin (green), where the fluvio-deltaic deposits of the Breathitt Group, eastern Kentucky, are located (Modified from Flint and Sinclair, 2001).

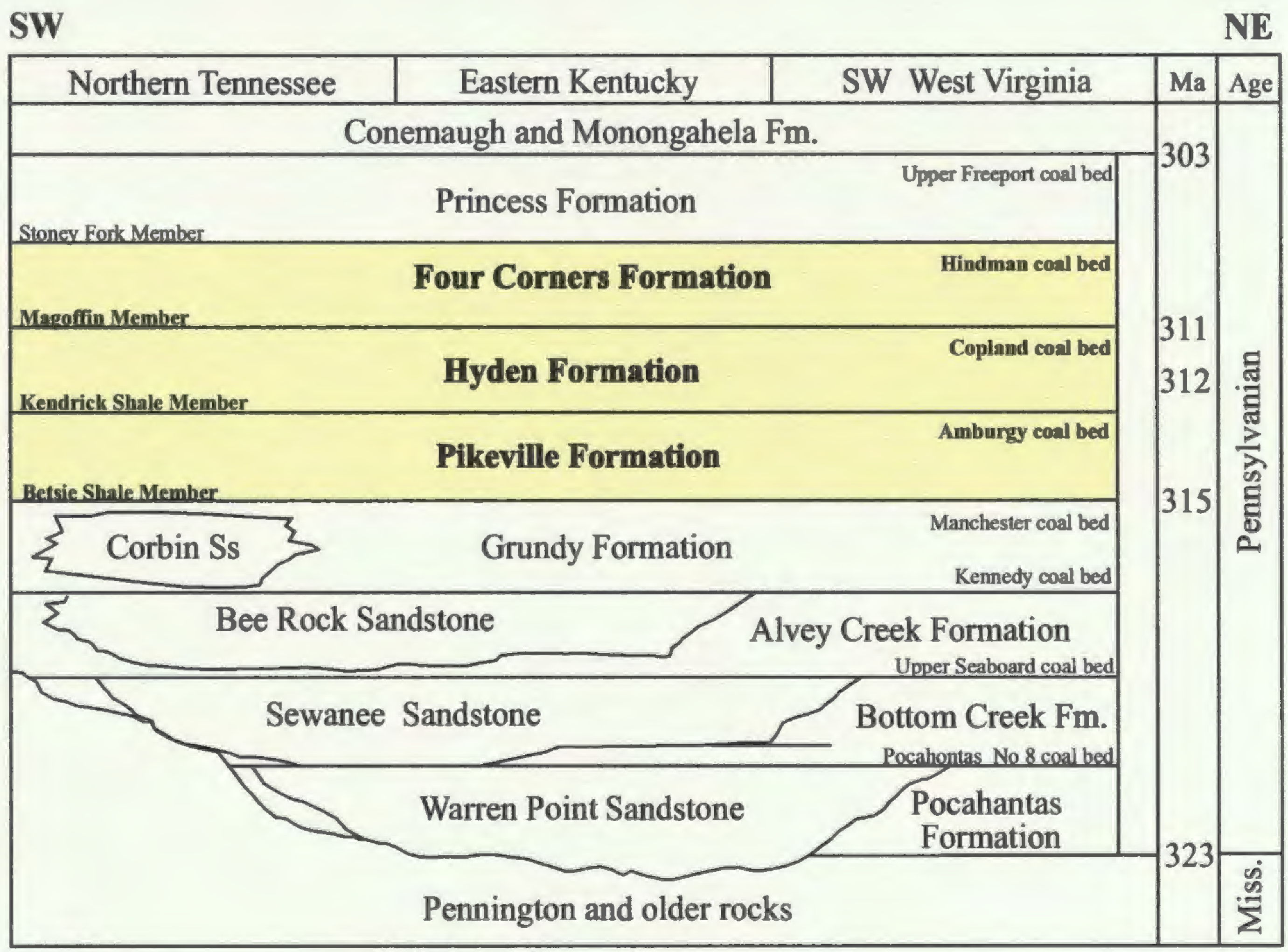


Figure 1.6. Southwest to northeast (left to right) stratigraphic framework of the lower to middle Pennsylvanian rocks which occupy the central Appalachian Basin. Within the Breathitt Group, the Pikeville, Hyden, and Four Corners formations comprise the interval of interest as an analogue to the Hibernia Formation (Modified from Flint and Sinclair, 2001).

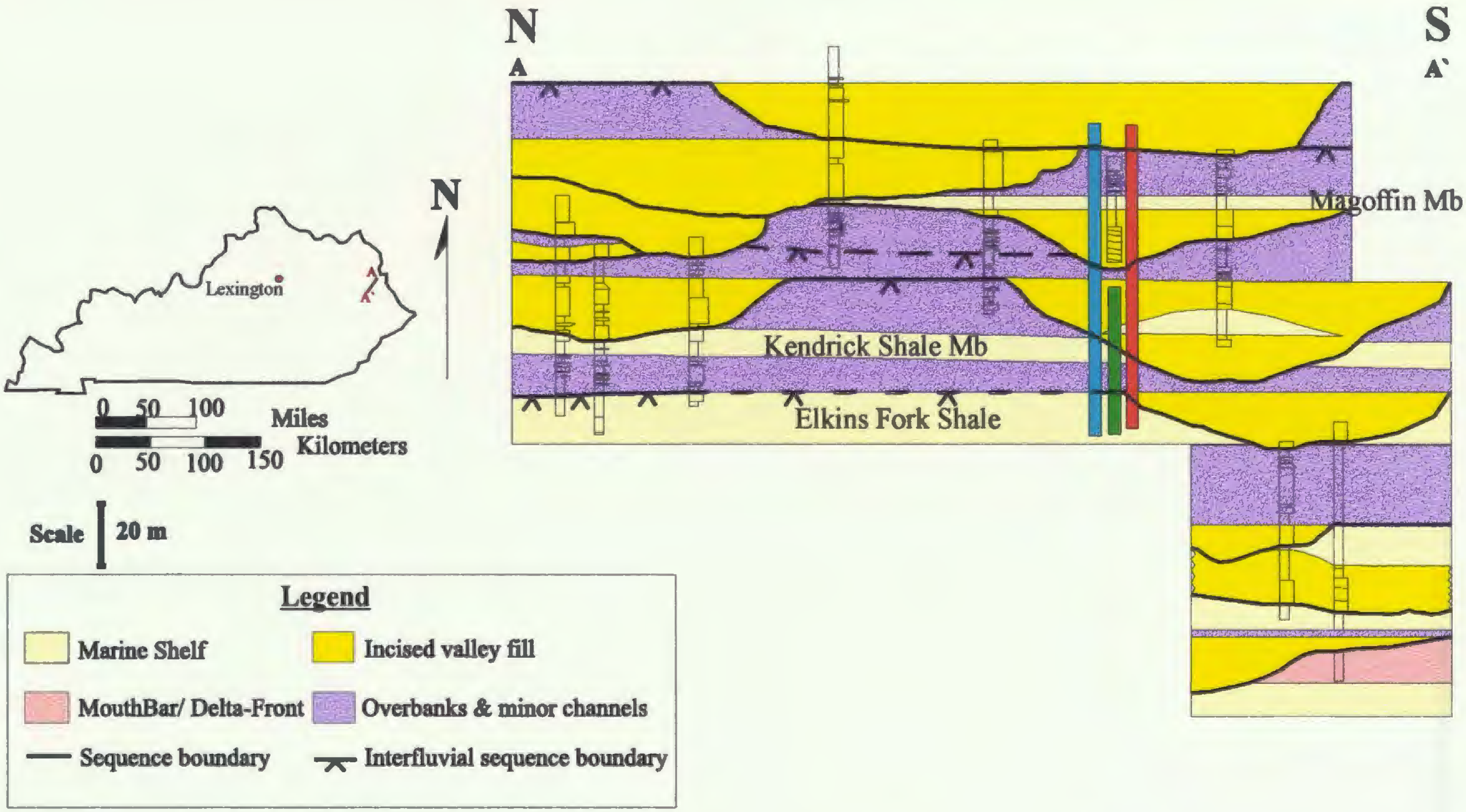


Figure 1.7. A simplified oblique north-south strike section through the Breathitt Group, eastern Kentucky, located on the insert map. The interval shown focuses on the marine deposits of the Pikeville, Hyden, and Four Corners formations shown in figure 1.6. This interval comprises the analogue to the Hibernia Formation. The blue bar on the left hand side shows the cored interval examined in well D-13, the green shows the interval examined in well R-6, and the red bar shows the interval examined in well R-9 (Modified from Aitken and Flint, 1994).

Hibernia Formation and to extract information from the Breathitt Group that can be incorporated into reservoir models offshore Newfoundland. Despite differences in age and tectonic setting, similarities are apparent in both regions with respect to facies and sequence stratigraphic characteristics. Based on these similarities, this study will attempt:

1) to recognize facies distributions and associations in the Breathitt Group, which have the potential to serve as a guide for existing facies models in the Hibernia Formation;

2) to apply a sequence stratigraphic framework to fluvio-deltaic deposits of the Breathitt Group, to guide the development of existing models for the Hibernia Formation;

3) to consider if the different tectonic setting and greater percentage of coal have affected both the distribution of facies throughout the Breathitt Group, rendering it less suitable as an analogue for the Hibernia reservoir.

1.3 Methods of Study

The study is an integration of well data from Hibernia and core and outcrop data from Kentucky. Data acquisition from the Hibernia reservoir involved the detailed logging of three Hibernia wells: B-16-2, B-16-4, and B-16-17 (Table 1.1). These wells were drilled through the Q, R, and V Blocks of the Hibernia reservoir, respectively (Figure 1.8 and 1.9) (HMDC). The combination of these wells provides a complete section through the Hibernia Formation, and into the underlying Fortune Bay Formation. B-16-17 is the only well which penetrates through the base of the Hibernia structure, as

Table 1.1: Summary of the Hibernia drilling data.

Well Name	Well Location	Core Number	Depth (meters)	Core Length (meters)	Formations Penetrated	Lithologic units Sampled
B-16-2	Q-Block	1	4175.00-4180.00	4.60	Hibernia	Layer 1
		2	4180.00-4196.00	16.00	Hibernia	Layer 1
		3	4196.00-4212.50	15.95	Hibernia	Layer 1
		4	4330.00-4355.00	22.80	Hibernia	Layer3
		5	4355.00-4381.00	26.00	Hibernia	Layer3
		6	4381.00-4417.00	36.00	Hibernia	Layer3
B-16-4	R-Block	1	4610.00-4620.00	9.00	Hibernia	Layer1
		2	4620.00-4643.50	20.80	Hibernia	Layers 1-2
		3	4643.50-4672.50	27.80	Hibernia	Medial Shale –Layer 3
		4	4672.50-4681.50	8.90	Hibernia	Layer3
		5	4681.50-4701.50	20.00	Hibernia	Layer3
		6	4701.50-4753.50	50.60	Hibernia	Layer3
B-16-17	V-Block	1	3955.50-4009.60	54.10	Hibernia	Layers 2-3
		2	4009.60-4070.85	61.25	Hibernia	Layer3
		3	4070.85-4099.95	29.10	Hibernia-Fortune Bay	Layer3-Fortune Bay

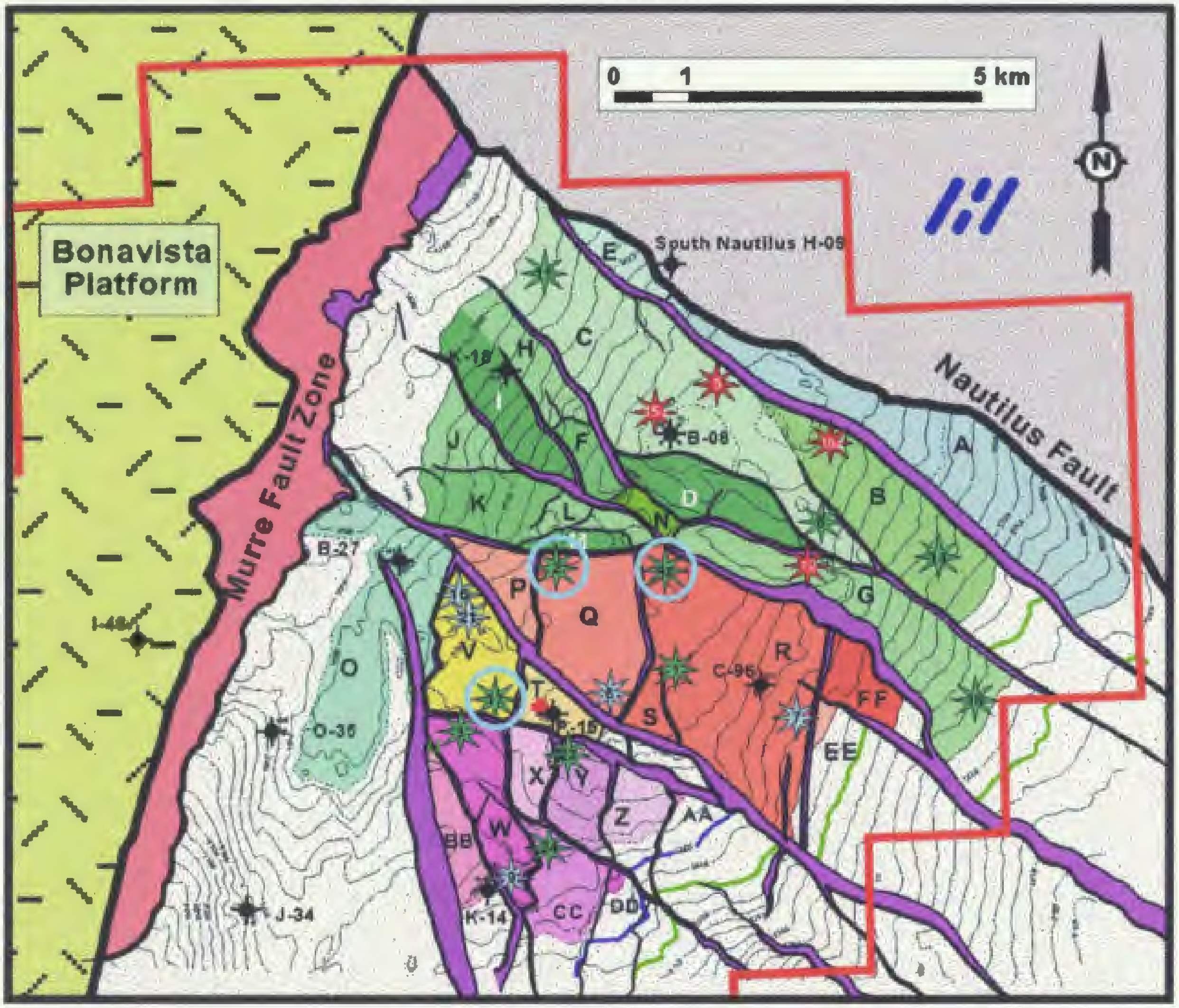


Figure 1.8. Depth map of the Hibernia Formation pinned on the top of the Medial Shale showing the position of the Q, R and V fault blocks and the locations of each well within those blocks. These blocks are denoted by the peach, orange and yellow colors respectively. The green stars represent wells which are oil producers, while the red and blue stars represent gas and water injector wells. The stars represent the location where the Medial Shale has been penetrated by the deviated wells. Bold blue circles mark the wells used in this thesis. See Figure 1.1 for the location of the field. This figure is courtesy of HMDC.

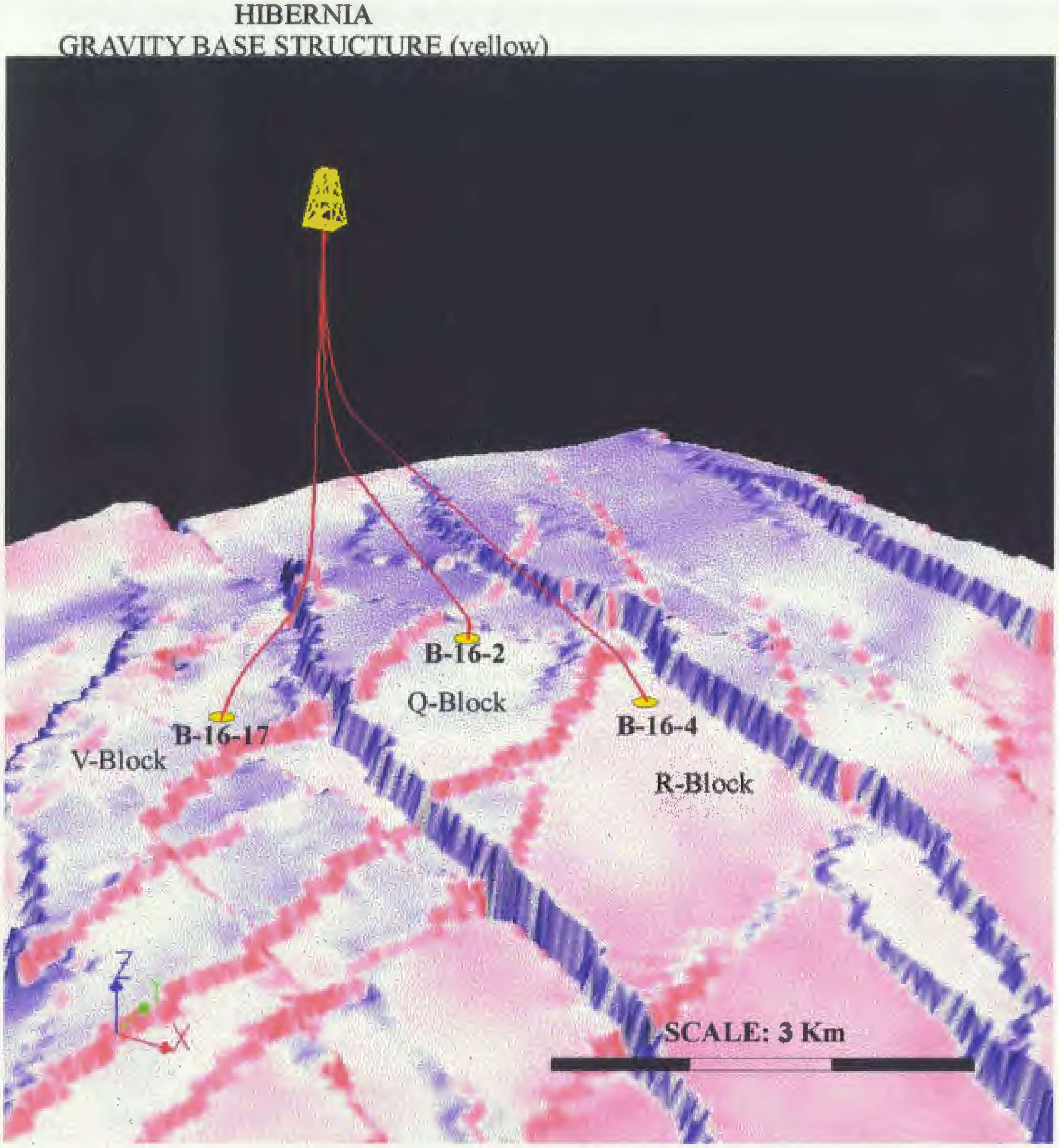


Figure 1.9. A three-dimensional view of the top of the Fortune Bay Formation showing the R, Q and V fault blocks, along with the well trajectories of the B-16-4, B-16-2 and B-16-17development wells. Well separation from B-16-4 to B-16-17 is 3.0 Km. The position of the gravity base structure is shown by the yellow drill derrick. Image is courtesy of HMDC.

the coring of the other two wells ceased prior to penetration of the basal contact. Detailed core descriptions focused on variations in lithology and the identification of sedimentary structures and trace-fossil assemblages. Data collected from each of the wells were used to draft detailed sedimentary columns. Cores and outcrops in the Breathitt Group were selected using core data published by the 1982 Coal Drilling Survey in the Daniel Boone National Forest, eastern Kentucky, maps of the Kentucky Geological survey and by previous work conducted by Aitken and Flint (1995). Data acquisition from the Breathitt Group was completed in two phases. The first phase involved the detailed logging of cores from wells D-13 and R-9, and a brief examination of well R-6 (Table 1.2). Cores from the last well intersect the contacts between various deposits. These wells were selected due to apparent similarities to Hibernia wells B-16-2, B-16-4, and B-16-17. Correlations of the Kentucky wells have revealed a similar marine influence and degree of channeling to that present in the Hibernia Formation (Figure 1.7). Data collected from these cores by the author were used to draft detailed sedimentary columns. The second phase involved the detailed study of three outcrops along the Daniel Bonne National Highway in eastern Kentucky. The highway is highly sinuous and provides excellent exposure of the Breathitt Group in two- and limited three-dimensional outcrops. The terraced nature of each outcrop permits easy access and allows the measurement of detailed sections. The three outcrops studied are situated to the west of Hazard, in Leslie and Clay Counties (Figure 1.10). The data were obtained by completing twenty detailed measured sections through the outcrops, focusing on sand-and shale-body geometries, and

Table 1.2: Summary of Kentucky drilling data.

Well Name	Well Location	Total Depth Drilled (meters)	Core Length Examined (meters)	Formations Penetrated
D-13	Whitley County	604.02	199.39	Upper Pikeville, Hyden and Lower Four Corners
R-6	Leslie County	488.26	67.07	Upper Pikeville and Lower Hyden
R-9	Clay County	606.00	177.43	Upper Pikeville, Hyden and Lower Four Corners

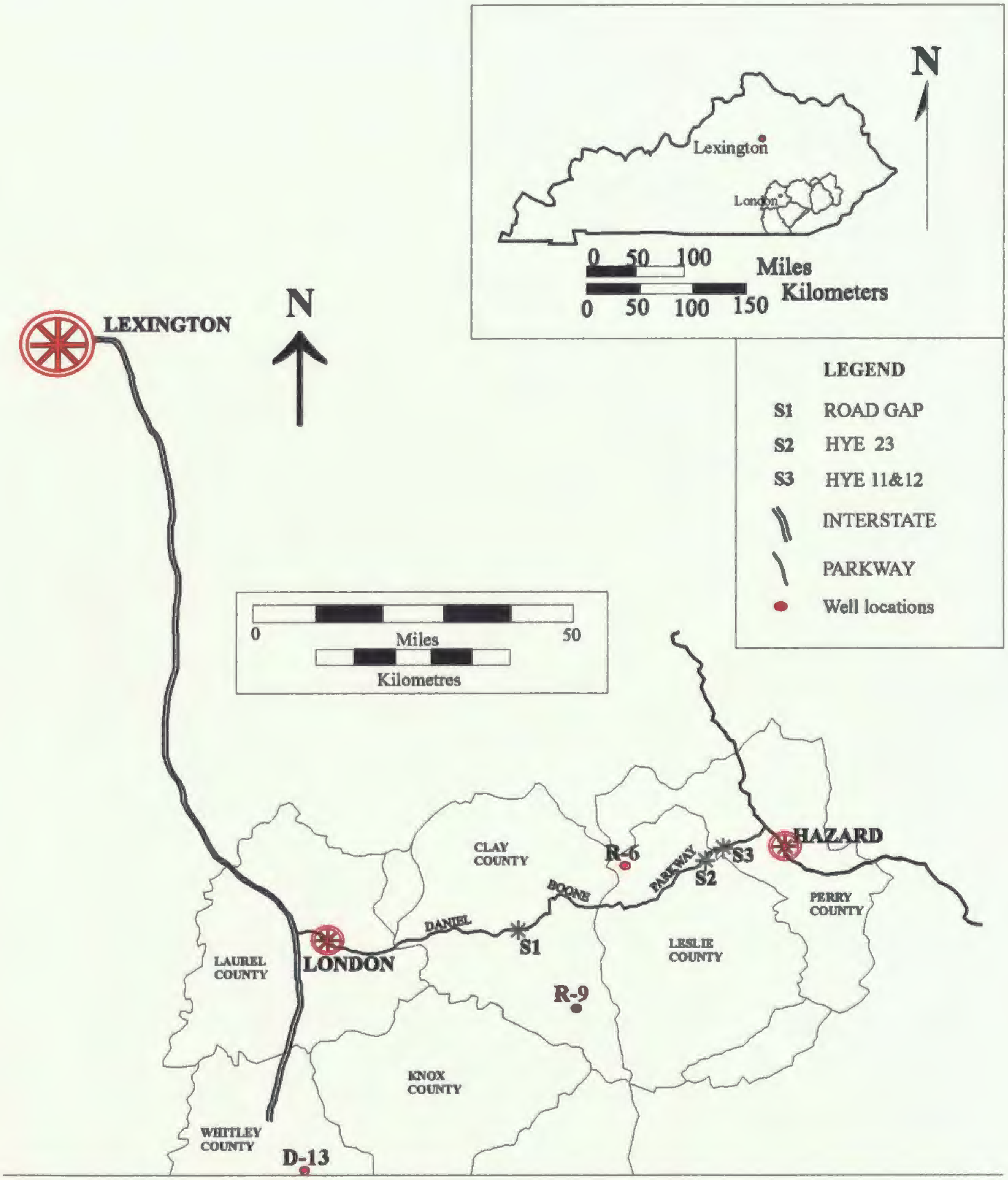


Figure 1.10. Road map of eastern Kentucky along the Daniel Boone Parkway showing the area of interest, and the locations of the three outcrops studied. In red are the positions of the three wells examined in this study.

on detailed facies descriptions. Each of the sections was logged at a centimeter scale using a Jacob=s Staff and tape. Where possible, sections were spaced 15-70 m apart. The majority of the data presented in this thesis were collected from outcrops at mile twenty-five, which is referred to locally as Road Gap, and thin-section studies some petrographic data were acquired from the Hibernia Management and Development Company Ltd. These data are used to enhance facies descriptions in chapter three. Measured sections from the field were used to construct scaled outcrop cross-sections and to augment facies descriptions from the Kentucky cores. These cross-sections, in conjunction with the sedimentary columns, provide the basis for environmental and sequence-stratigraphic analysis.

CHAPTER TWO

STRUCTURAL AND STRATIGRAPHIC SETTING AND COMPARISON OF HIBERNIA FORMATION TO THE BREATHITT GROUP

2.1 Introduction

The Appalachian Basin formed as a foreland basin adjacent to a collisional orogen, whereas the Jeanne d'Arc Basin formed during extension and rifting. The accumulation of sedimentary successions in compressional and extensional basins is dependent on a number of factors. Some of these factors include: the rate of basinal subsidence, the rate of creation of accommodation space and its distribution, the rate of sediment supply, and the rate of relative sea-level change. The deposits which characterize the Breathitt Group and the Hibernia Formation were influenced by these factors. The development of an analogue model based on deposition in such different tectonic settings must include an assessment of how these factors might differ because of tectonic contrasts. This chapter will briefly introduce some of the concepts and terminology of sequence stratigraphy required for interpreting basin stratigraphy. It will also briefly discuss the effects of tectonism on both the development of each basin and the resulting stratigraphy and evaluate some of the similarities and differences that exist between the central Appalachian Basin and the Jeanne d'Arc Basin.

2.1.1 Terminology

The packaging and organization of sedimentary successions are fundamentally a result of the combined effects of tectonics, eustasy, and climate. Tectonics and eustasy control the creation and distribution of accommodation space in which sediments accumulate. Tectonics induces subsidence by either extensional thinning or flexural loading of the lithosphere (Emery and Myers, 1996). Eustasy is global sea-level variation measured against a fixed point or datum, conceptually the center of the earth, and needs to be inferred from the history of relative sea-level changes (Emery and Myers, 1996). Relative sea-level is measured against a local datum, such as a basement or sedimentary surface (Emery and Myers, 1996). Relative sea-level responds to subsidence, uplift and eustasy but is independent of sediment supply. Therefore, stratigraphic signatures and stratal patterns in the sedimentary rock record are created by the balance between sediment supply and the rate of creation of accommodation space; these patterns form the basis for the division of basin-fill successions (Nichols, 1999).

Using the sequence stratigraphic approach, a basin-fill succession can be divided into a series of depositional sequences. A depositional sequence is defined as a stratigraphic unit bounded at its top and base by unconformities or their correlative conformities and represents a complete cycle of deposition. The duration of each cycle is measured between the correlative conformities and is determined by the events controlling the creation and destruction of accommodation space (Emery and Myers, 1996). Due to the variability in magnitudes and durations of tectonic and eustatic cycles of rising and falling sea-level, sequences are classified into orders based on duration. This is a hierarchical classification, with first-order cycles being formed of a number of higher order cycles. There is some controversy as to the number of orders within a depositional sequence. Vail et al. (1977b) subdivided a depositional sequence into three ordered cycles, whereas Miall (1990) subdivided a depositional sequence into five ordered cycles. Emery and Myers (1996) and Duval et al. (1992) depict four orders of stratigraphic cycles whose durations are comparable to those suggested by Vail et al. (1991) (Table 2.1). Haq et al. (1987) have added to the controversy by proposing a standard scheme of global cycles for the Triassic to Recent, which span two orders of magnitude in time duration. However, for the purposes of this study, the stratigraphy of both regions will be discussed with respect to cycles that span five orders of magnitude in time duration. Vail et al. (1991) designated these five orders as first-to fifth-order cycles. They will be introduced briefly in this chapter, and will be discussed in further detail in chapter five.

The subdivisions are commonly referred to as first-, second-, third-, fourth- and fifth-order cycles respectively (Table 2.1). First-order cycles are the longest in duration and represent continental encroachment cycles controlled by tectono-eustasy (Emery and Myers, 1996). Second-order cycles form the basic building blocks of first-order cycles. These cycles are caused by changes in basin subsidence rates or rates of uplift of the sediment source (Emery and Myers, 1996). Third-order cycles are commonly referred to as the building blocks of sequence stratigraphy and occur on a small enough scale to be resolved on seismic data. Fourth-order and fifth-order cycles are those less than 1 m.y. in duration and are commonly attributed to Milankovitch forcing (Miall, 1990). Fourth- and fifth-order cycles encompass the time scales for accumulation of coal-bearing cycles called cyclothems.

Table 2.1: A summary of stratigraphic cycles and their durations.

Miall (1990)		Vail et al. (1977b)		Emery and Myers (1996)	
Type	Duration (m.y.)	Type	Duration (m.y.)	Type	Duration (m.y.)
First order	200-400	First order	200-300	First order	50+
Second order	10-100	Second order	10-80	Second order	3-50
Third order	1-10	Third order	1-10	Third order	0.5-3
Fourth order	0.2-0.5			Fourth order	0.08-0.5
Fifth order	0.01-0.2			Fifth order	0.03-0.08

2.2 Jeanne d'Arc Basin

The Jeanne d'Arc basin is one of several Mesozoic extensional basins that underlie the Grand Banks of Newfoundland. The basin covers approximately 10,000 km^2 and contains 17 km of post-Paleozoic sedimentary fill (Tankard et al., 1989). The basin is composed of several significant structural components including the Avalon Uplift to the south, the Bonavista Platform to the west and the Outer Ridge Complex to the east. The Murre Fault is a north-northeast trending listric fault that separates the pre-Mesozoic rocks of the Bonavista Platform from the Mesozoic strata within the basin. The basin-bounding Murre Fault soles out eastward beneath the basin at approximately 26 km depth (Tankard and Welsink, 1987). The Hibernia roll-over structure formed against the Murre fault. In response to differing rates and amounts of extension, transfer faulting contemporaneous with normal faulting is also evident within the basin (Tankard and Welsink, 1987). The transfer faults developed orthogonal to the normal basin-bounding fault. The Hibernia structure is bounded to the north by the Nautilus transfer fault (Figure 1.8). This section will present a brief overview of the tectonic history and stratigraphy of the Jeanne d'Arc Basin, with emphasis on the Berriasian to Valanginian Hibernia Formation.

2.2.1 Tectonic History

The extensional processes responsible for the development of the Jeanne d'Arc Basin have been the focus of some debate in recent years. Earlier publications by Enachescu (1987), Sinclair (1988), Hubbard (1988), Tankard et al. (1989) and Hiscott et al. (1990a) agree that the Jeanne d'Arc Basin developed in response to the intersection of three rift trends related to a step-wise opening of the North Atlantic Ocean. However, a debate exists as to the number of rift episodes that affected the Grand Banks. Hubbard (1988) and McAlpine (1990) suggested that the Grand Banks experienced two rift episodes: initial rifting during the Late Triassic, and a second major episode during the Neocomian. Enachescu (1987), Sinclair (1988) and Hiscott et al. (1990a) suggested that the Grand Banks experienced three rift episodes. The first rifting was Triassic-Early Jurassic, and was followed by the break-up of Africa and North America. Sinclair (1988) assigned this break-up to the mid-Pliensbachian, but Gradstein and Sheridan (1983) showed this breakup to be Callovian, or some 20 m.y. younger. According to Sinclair (1988), the second rift episode was Tithonian-early Valanginian, and was followed by the break-up of Iberia and the Grand Banks during the mid-Valanginian. Instead, Hiscott et al. (1990a) suggested that this rifting was initiated during the Kimmeridgian and ended with breakup with Iberia in the mid-Aptian. The third rift episode was Aptian-Albian, and was followed by the break-up of NW Europe and North America during the Cenomanian or latest Albian (Sinclair, 1988) (Figure 1.2). A broad regional warping preceded each of these rifting episodes. Each episode was followed by a period of thermal subsidence and post-rift sedimentation (Sinclair, 1988).

Tankard et al. (1989) suggested that the evolution of the Jeanne d'Arc Basin occurred in four broad stages of basin subsidence. They suggested that initial rifting occurred during the Late Triassic and was followed by a gradual reduction in subsidence and deposition of a Lower-Middle Jurassic succession of mudstones and carbonates. This was followed by renewed rifting in the late Callovian to early Aptian that was in turn followed by postrift subsidence (Tankard et al., 1989).

The Hibernia Formation developed in response to the Late Jurassic-Early Cretaceous second rift phase. The resulting deposits and depositional systems were greatly influenced by the effects of the thermal subsidence and the associated creation of accommodation space. Following the initiation of the second rift phase, high rates of basement subsidence created significant accommodation space (Hiscott et al., 1990a). Hiscott et al. (1990a) suggested that these high rates of basement subsidence were a response to asymmetrical extension between the Grand Banks and Iberia. Tankard et al. (1989) also recognize accelerated subsidence rates during the Late Jurassic to Early Cretaceous. They associate the increase in subsidence to pronounced normal faulting in the late Kimmeridgian to Valanginian. Hiscott et al. (1990a) suggested that sediment supply from mainly the Avalon Uplift to the south kept pace with the creation of accommodation space, resulting in a thick Lower Cretaceous succession, including the Hibernia Formation. This combination of increased subsidence rate and abundant sediment supply resulted in two pulses of fluvio-deltaic sedimentation during the Early Cretaceous.

2.2.2 Stratigraphy

In the region of the Hibernia oil field, a thick accumulation of sediment (Triassic to present) unconformably overlies the Paleozoic basement (Figure 1.2). This section will focus on the Upper Jurassic to Lower Cretaceous interval. The Port au Port Member of the Rankin Formation marks the base of the Upper Jurassic. In the south, it is composed of a thick, massive, oolitic limestone that becomes shalier towards the north (Sinclair, 1988). The Kimmeridgian sediments that characterize the remainder of the Rankin Formation are composed of thick limestones with common interbeds of shale and sandstone to the south. To the northeast, these Kimmeridgian sediments become predominantly siliciclastic, and are composed of poorly sorted, very fine grained to coarse grained graded beds interbedded with low-energy shales. These clastics are termed the "Tempest" sandstones and are interpreted as submarine-fan deposits (DeSilva, 1994).

The limestones of the Rankin Formation were cut by a series of north-south-trending channels containing a series of sandstones, conglomerates, and shales known as the Jeanne d'Arc Formation (Sinclair, 1988). The marine shales of the Fortune Bay Formation cover these coarser clastics. Together, the Jeanne d'Arc and Fortune Bay formations record a series of marine transgressions and regressions (Hiscott et al.,1990a).

During the second rift phase, renewed uplift south of the Jeanne d'Arc Basin resulted in the progradation of the Hibernia sandstones over the Fortune Bay Formation. The Hibernia Formation marks the base of the Lower Cretaceous. The "B" Marker member of the Whiterose Formation unconformably overlies the Hibernia Formation. The "B" Marker member is an oolitic, bioclast-rich limestone and is used as a prominent stratigraphic marker in seismic interpretation (Sinclair, 1988). The Catalina Member of the Whiterose Formation conformably overlies the "B" Marker member. The Catalina Member is composed of thinly interbedded shales and calcareous sandstones (Sinclair, 1988). The "A" Marker member conformably overlies the Catalina Member. It is composed of thick, calcareous sandstones grading to sandy, oolitic limestones in the southeastern portion of the Jeanne d'Arc Basin. Interbedded shales and upward coarsening sandstones that characterize the Avalon Formation prograded northward over the "A" Marker during the Barremian (Sinclair, 1988). The Aptian-Albian Ben Nevis Formation unconformably overlies the Avalon Formation.

2.2.3 Lithostratigraphy of The Hibernia Formation

The Berriasian to Valanginian sandstones of the Hibernia Formation were deposited during two episodes of fluvio-deltaic sedimentation. The clastics that characterize the lower Hibernia zone were sourced from the Avalon Uplift to the south. The lower Hibernia zone, from base to top, is subdivided into Layer 3, the Medial Shale, Layer 2, and Layer1 (Figure 1.3). The first progradational event deposited the reservoir-bearing sandstones of Layers 3 and 2 as a series of braided fluvial channels constrained within incised valleys (Flint and Sinclair, 2001). These sandstones are predominantly medium to very coarse grained and are characterized by planar and trough crossbedding, sharp erosional bases, pebble lags, and localized occurrences of carbonaceous debris, siderite and mudstone clasts. These reservoir-quality sands are separated by non-reservoir, fine-grained sandstones and mudstones associated with overbank, flood-basin, lagoonal-bay, marsh, and abandoned- channel depositional environments (Hurley et al., 1992). The finer-grained deposits are characterized by wavy laminations, wave ripples, ripple cross lamination, moderate to intense burrowing, siderite clasts, rare to moderate rooting, and thin coal beds. A wide variety of trace fossils are also present (Hurley et al., 1992; Pemberton et al., 2001).

The braided fluvial deposits of Layer 3 represent the fills of incised valleys active during the late lowstand to early transgression. The top of Layer 3 is characterized by a sharp contact and is overlain by a field-wide marine shale, called the Medial Shale. This shale separates Layers 3 and 2 and is composed of moderately to intensely burrowed mudstones, containing oyster shells, corals, and a variety of bivalves (Figure 1.3). Various trace fossil assemblages are present. The lower portion of the Medial Shale belongs to a transgressive systems tract, while the upper portion forms part of a highstand systems tract (I. Sinclair, pers. comm., 2001)

Layers 2 through 1 are composed of interbedded medium grained to very fine grained sandstone and mudstone characterized by planar and trough crossbedding, ripple cross lamination, pebble lags, siderite and mud clasts, soil and rooted zones, and localized occurrences of carbonaceous debris. Various trace fossil assemblages are developed. Layers 2 through 1 form part of a highstand systems tract (I. Sinclair, pers. Comm., 2001).

The full Lower Zone is interpreted to represent a complete third-order depositional sequence with Layer 3 representing a lowstand systems tract, lower Medial Shale a transgressive systems tract, and the upper Medial Shale through Layer 1 a highstand systems tract. Layer 3 comprises three higher frequency sequences. The lower two consist of fourth-order incised valleys, while the upper sequence consists of two stacked fluvial packages forming fifth-order cycles (Figure 1.3). The dominant sandstone in Layer 2 consists of a fourth-order incised-valley fill similar in geometry and character to those in Layer 3.

2.3 Appalachian Basin

The state of Kentucky contains components of four major structural provinces which define the eastern mid-continent (McDowell, 1986). These structural provinces include the Illinois Basin to the west, the Appalachian Basin to the east, the Cincinnati Arch which separates these basins in the central portion of the state, and the Mississippi Embayment to the southwest (Figure 2.1). The mid-Pennsylvanian deposits of the Breathitt Group, eastern Kentucky, occupy the western portion of the Pocahontas Basin (central portion of the Appalachian Basin) (Adkins and Eriksson, 1998).

The Appalachian Basin is an elongated, northeast-trending structural depocenter that extends from New York to Alabama (McDowell, 1986). The basin covers approximately 27,000 km^2 and contains several major structural features including the Pine Mountain thrust fault to the southeast and the Waverly Arch to the northeast (McDowell, 1986) (Figure 2.1). The basin has been structurally divided into an eastern highly deformed, fold and thrust belt, and a western mildly deformed region referred to as the Appalachian Plateau (McDowell, 1986). The Pine Mountain overthrust fault is a component of the Appalachian fold and thrust belt and has been recognized as the boundary between these two structural provinces. This section will provide a brief overview of the tectonic history and stratigraphy of the Appalachian Basin, with emphasis on the Pennsylvanian Breathitt Group.

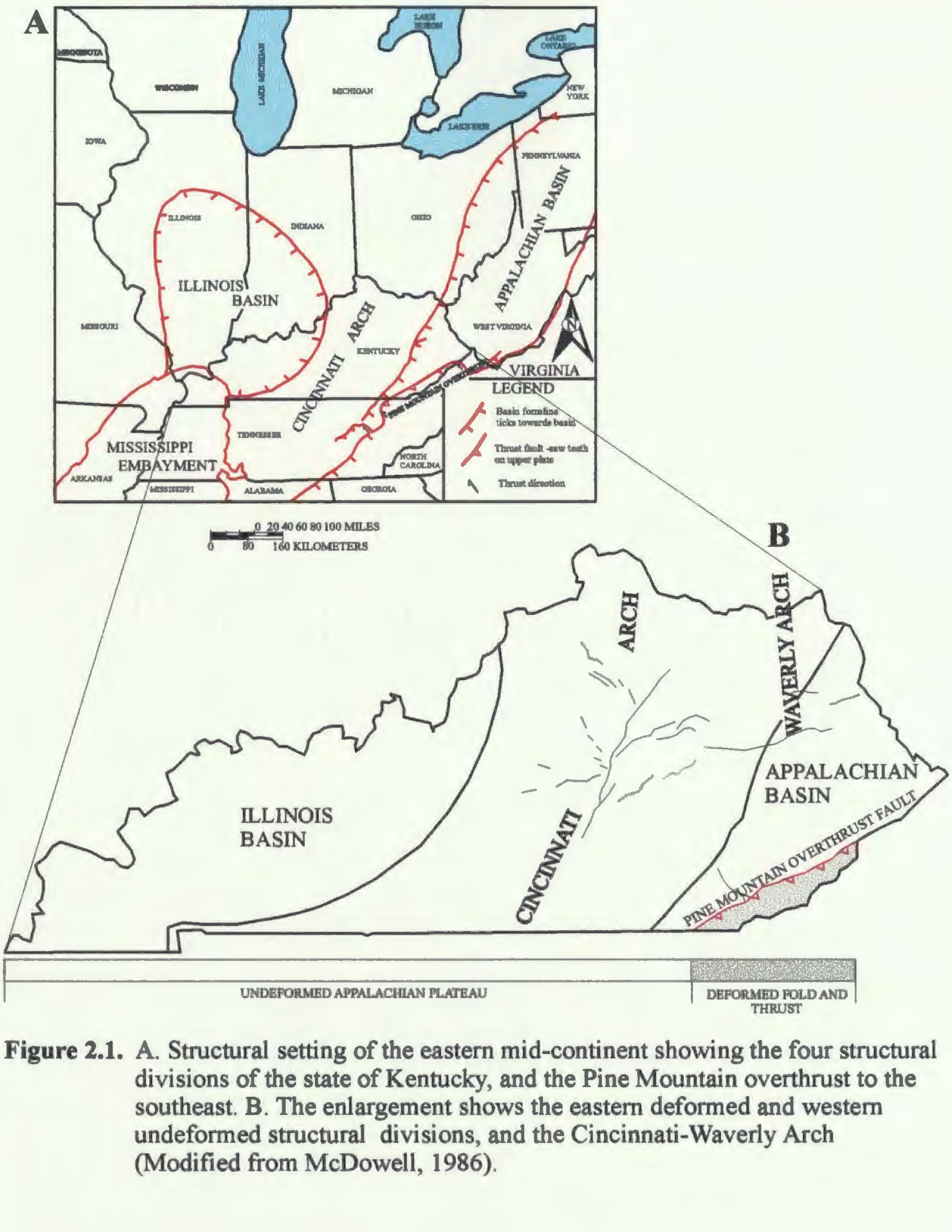


Figure 2.1. A. Structural setting of the eastern mid-continent showing the four structural divisions of the state of Kentucky, and the Pine Mountain overthrust to the southeast. B. The enlargement shows the eastern deformed and western undeformed structural divisions, and the Cincinnati-Waverly Arch (Modified from McDowell, 1986).

2.3.1 Tectonic History

The episodic evolution of the Appalachian foreland fold and thrust belt occurred during the Taconic, Acadian, and Alleghenian orogenies. The basin developed by lithospheric downwarp under the loads of successively emplaced Taconic, Acadian and Alleghenian thrust sheets in the adjacent Appalachian Mountains (Quinlan and Beaumont, 1984). Although it had a long history, the Appalachian foreland thrust belt evolved mainly during the Pennsylvanian-Permian Alleghenian orogeny (Tankard, 1986a) when the third stack of thrust sheets loaded the continental lithosphere. The load caused depression of the craton edge to form a basin, and the development of a forebulge inland from the load (Figure 2.2). The overthrusts are a key component in that they both form a source for clastic sediments and depress the lithosphere to allow for sediments to be trapped within the foreland basin (Quinlan and Beaumont, 1984). As the load remains constant during periods of tectonic quiescence, the viscoelastic properties of the lithosphere allow plastic flow to develop there, which results in a relaxation of the load-induced stress. This relaxation results in a deepening of the basin, and both the progressive uplift and migration of the peripheral bulge toward the load (Quinlan and Beaumont, 1984) (Figure 2.2). Renewed thrust-sheet emplacement results in a repetition of this process, the migration of the forebulge inland, and the development of a wider and shallower basin (Tankard, 1986a) (Figure 2.2). This sequence of events affected the development of the Appalachian basin during the Pennsylvanian-Permian Alleghenian Orogeny. Several times during the Pennsylvanian, the basin experienced tectonic pulses that resulted in renewed flexural downwarping, migration of the forebulge inland, and

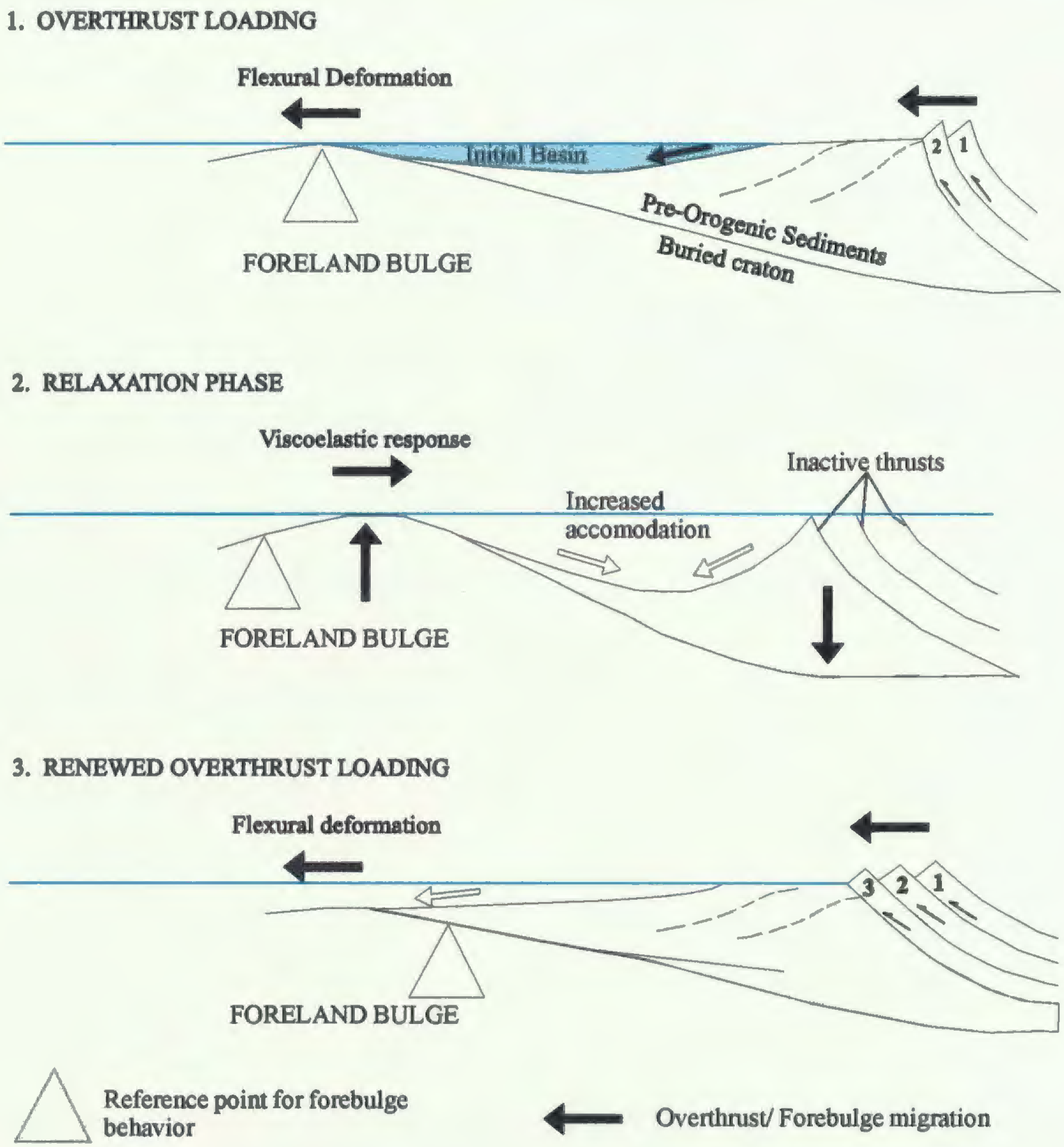


Figure 2.2. Elements of deformation during the development of a foreland basin. These elements were all present in the development of the Appalachian basin. The first step shows emplacement of stacked thrust sheets onto the edge of the stable craton. This develops the initial basin. This is followed by step two, during which time there is a relaxation of the load-induced stress, allowing the basin to deepen. The third step is renewed thrusting and sedimentation in a wider, shallower basin. These steps are repetitive throughout the evolution of the basin. Note that if sediment supply equals or exceeds increased accommodation, the basin will be filled and will not be a bathymetric low (Modified from Tankard, 1986a).

clastic deposition. With the emplacement of each successive thrust sheet, a clastic wedge was deposited in the basin. Because the cratonic basement was depressed during each episode of thrusting, the ensuing subsidence created a relative sea-level rise whenever global (eustatic) changes did not counteract these regional effects. Relative sea-level falls could occur near the migrating forebulge during relaxation phases, or whenever major eustatic falls occurred at rates exceeding tectonic subsidence rates.

The Pennsylvanian strata of the Breathitt Group were deposited in response to renewed tectonism during the Alleghenian orogeny. Thrust-induced subsidence and sedimentation were greatest eastward towards the Pine Mountain overthrust (Figure 2.3).

2.3.2 Carboniferous Stratigraphy of the Appalachian Basin

Carboniferous strata account for two-thirds of the surface rocks in Kentucky. The deposition of Pennsylvanian strata was directly influenced by orogenic events. In contrast, Mississippian strata record orogenic quiescence (Tankard, 1986a). Following the Alleghenian Orogeny, the thrust load remained constant, which led eventually to a deepening of the basin and deposition of marine strata. These deposits range from relatively deep-water basinal shales to shallow subtidal and supratidal deposits, to lower-delta-plain sediments (Rice et al., 1979).

Recent stratigraphic studies of the Breathitt interval have resulted in revisions to the lithostratigraphic scheme for eastern Kentucky. USGS publications throughout the late 1970's and 1980's classified the "Lee" sandstones as a formation separate from the interbedded sands, shales and coals of the Breathitt Formation. However recent

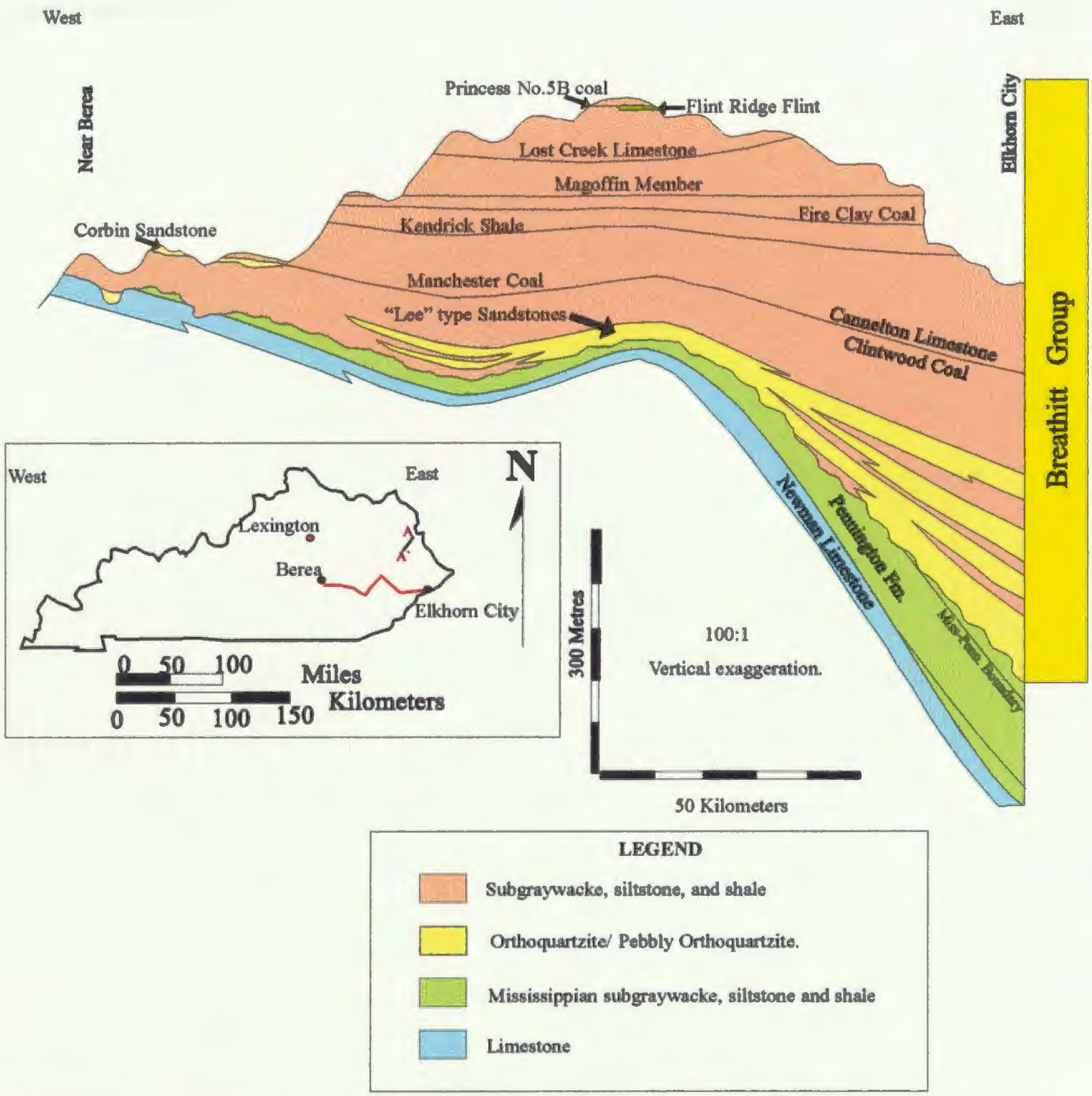


Figure 2.3. Generalized cross section through the Pennsylvanian Breathitt Group from the Cincinnati Arch in central Kentucky near Berea to the Pine Mountain Thrust Fault near Elkhorn City in the east. The cross section shows dramatic thickening towards the Pine Mountain Thrust Fault. The Breathitt Group is thickest toward the east because of accentuated subsidence craton-ward of the Pine Mountain Thrust fault.(Modified from USGS, 1979).

publications by Chesnut (1992) state that all lithofacies, including the "Lee" sandstones, are now included within the redefined Breathitt Group.

Throughout much of eastern Kentucky, a Pennsylvanian clastic wedge unconformably overlies Mississippian strata. The wedge consists of part of the Pennington, and all of the overlying Lee, Grundy, Pikeville, Hyden, Four Corners, Princess, Conemaugh and Monongahela formations (Figure 1.6). In the east, the unconformity occurs just above the Mississippian-Pennsylvanian boundary (Figure 2.3). The Pennsylvanian strata vary in thickness throughout eastern Kentucky, and are only entirely preserved in a 250 m-thick interval in the northeastern part of the state (Rice et al., 1979). The lowermost quartzose ("Lee") units of the Breathitt Group consist of conglomeratic to pebbly sandstones deposited by south- to southwest-flowing braided rivers. The "Lee" type sandstones include the Warren Point, Sewanee, and Bee Rock sandstones (Figure 1.6).

The Pikeville, Hyden and Four Corners formations contain deposits consisting of alluvial to delta-plain facies of siltstone, mudstone, sandstone, coal, minor siderite and limestone. The sandstones accumulated in distributary channels and incised valleys. They were transported by a fluvial system flowing to the west or west-northwest. Therefore a change in the orientation of the fluvial system occurred within the Appalachian Basin after "Lee" time.

A series of marine shales divide the middle Pennsylvanian strata. The most significant marine zones are the Betsie Shale Member at the base of the Pikeville Formation, the Kendrick Shale Member at the base of the Hyden Formation, and the

Magoffin Shale Member at the base of the Four Corners Formation (Figure 1.6). The Pikeville Formation also contains the Elkins Fork Shale, which differs from the more open marine, transgressive Kendrick and Magoffin Shale members; instead, it represents a more fresh-or brackish-water bay depositional environment (McDowell, 1986). The Elkins Fork Shale is characterized by an upward coarsening sequence of interbedded shales, siltstones and very fine grained to fine grained sandstones with marine fossils. The Amburgy coal zone overlies the Elkins Fork Shale and marks the top of the Pikeville Formation. This zone consists of interbedded fine grained sandstones, shales, siltstones and coals.

The Kendrick Shale Member overlies the Amburgy coal zone and marks the base of the Hyden Formation. The Kendrick Shale Member is an upward coarsening marine shale, which is overlain by a series of coal zones, including the Whitesburg and Fire Clay coal zones. These coal zones are associated with sandstones that accumulated within incised valleys and distributary channels, or with siltstones and shale. These coal zones were examined in detail during the course of this study and are important stratigraphic markers throughout much of eastern Kentucky.

The Four Corners Formation overlies the Hyden Formation. The Magoffin Shale Member marks the base of the Four Corners Formation and is the most laterally extensive of all the marine shales in the Breathitt Group (Adkins and Eriksson, 1998). The Magoffin Shale is characterized by an overall upward coarsening succession. The base of the member is marked by a thin limestone, which is overlain by fossiliferous and carbonaceous grey shale. This grey shale is overlain by an upward coarsening succession of interbedded sandstones, siltstones and shales. The Haddix coal zone is contained within this sequence. The Magoffin Shale is overlain by a series of stacked fluvial sandstones of the Four Corners Formation that are associated with incised valley fills.

2.4 General Comparisons between the Breathitt Group and Hibernia Formation

Despite differences in tectonic regimes (collisional *verses* extensional, respectively) and climate forcing of sea-level change, there are similarities between the Breathitt Group and Hibernia Formation. These similarities include the grain size of the deposits, the presence of coals, the stratal thicknesses of the deposits, and the time ascribed to the deposition of the deposits considered in this thesis. Both studied successions accumulated in 7-8 million years (Figures 1.3 and 1.6).

The complete succession of the Jeanne d'Arc Formation through Hibernia Formation closely resembles the Breathitt Group with respect to both grain size and stratal thickness variations. The lowermost quartzose, coarse to pebbly sandstones ("Lee" units) of the Breathitt Group are comparable to the medium grained to coarse grained quartz, quartzite and chert sandstones and cobble conglomerates of the Jeanne d'Arc Formation (Flint and Sinclair, 2001). The remaining sandstones in both regions are predominantly medium to coarse grained. Thick successions of strata, due to high rates of basinal subsidence, are also characteristic of both regions along their respective basin-bounding faults. The complete Jeanne d'Arc to Hibernia sequence exhibits similar stratal thickness variations to those of the Breathitt Group. Both regions show an overall upwards decrease in stratal thickness variation (Flint and Sinclair, 2001). The "Lee" type sandstones thicken into the Pine Mountain Overthrust fault (Figure 2.3). Stratal thickness variations in the middle to upper Breathitt Group are minor compared to those of the lower Breathitt Group. Similar stratal patterns are also evident at Hibernia. Data collected from a series of wells oriented east to west show substantial thickening of the Hibernia Formation in the vicinity of the Murre Fault, where subsidence rates are the highest (Figure 2.4). This variation in thickness is evident between the lower and upper Hibernia zones (Figure 2.5).

Both regions are underlain by carbonates that limited early-incised valleys to rather narrow widths. These underlying carbonates are restricted to the lower stratigraphic intervals in both regions, and are not repeated throughout the successions. The climates of both regions also promoted the development of coal. However, coal is more abundant in the Appalachian Basin because eastern Kentucky was situated approximately 15 degrees south of the equator, while the Jeanne d'Arc Basin was less equatorial at approximately 23 degrees north of the equator at the beginning of the Cretaceous (Flint and Sinclair, 2001). This difference of about 8 degrees accounts for a greater abundance of coal in eastern Kentucky. Thick coals along the base of incised valleys of the Breathitt Group have resulted in a key sequence stratigraphic difference in the two regions (Flint and Sinclair, 2001). The high resistance of cohesive peats (now coals) to erosion caused channels and valley systems to generally cut no deeper than the thicker peats, cutting down to greater depths only locally. In contrast, the absence of thick peat/coals in the Hibernia Formation permitted valley systems to achieve their maximum erosive potential during relative falls in sea-level (Flint and Sinclair, 2001). The

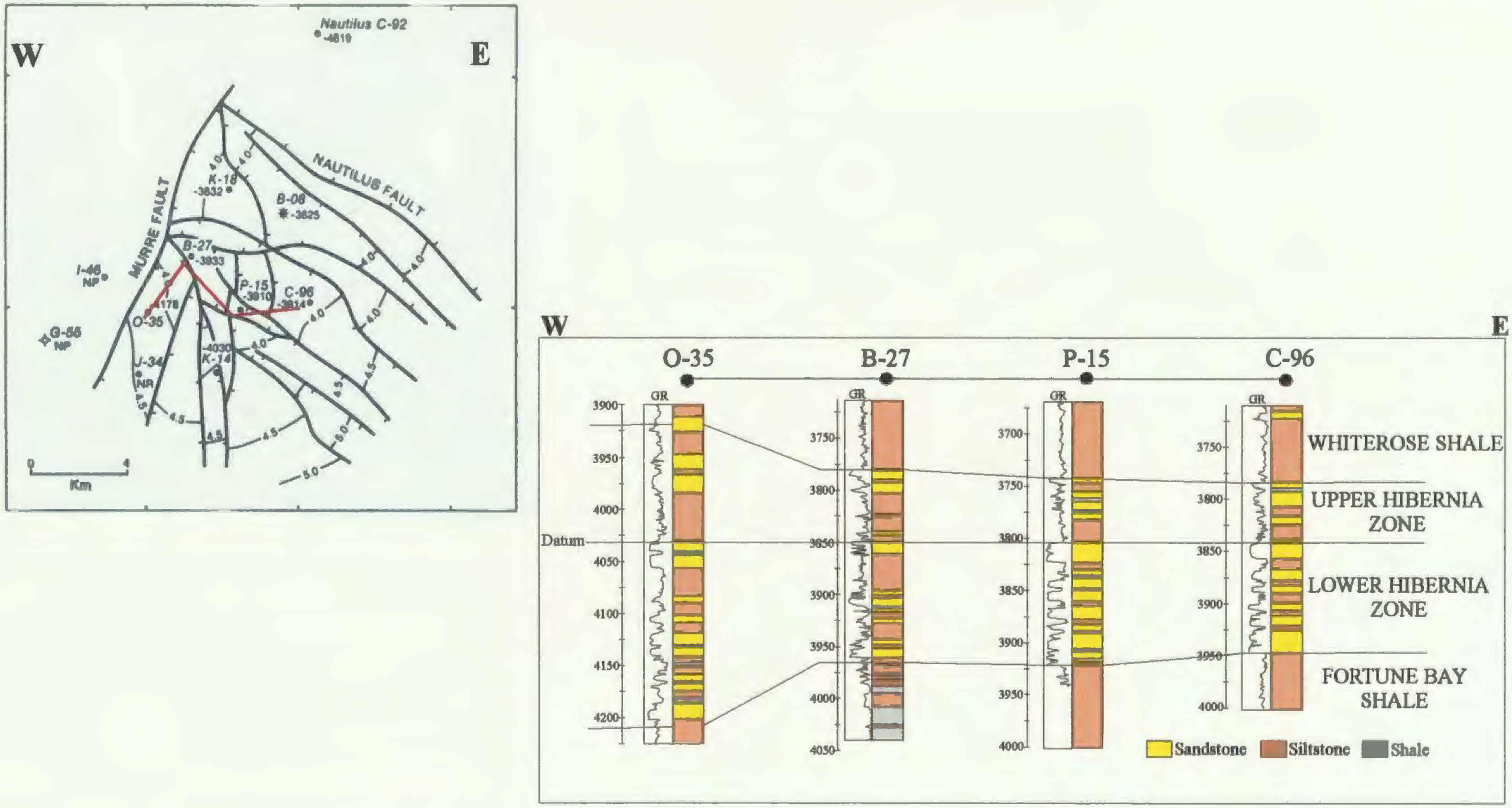


Figure 2.4. West to east cross section of the Hibernia Formation through the Hibernia oil field. Datum is the lithostratigraphic boundary between the lower and upper Hibernia zones. A progressive thickening of the Hibernia Formation is seen towards the O-35 well. This thickening is in response to increased subsidence in the western portion of the basin. (Modified from Brown et al., 1989).

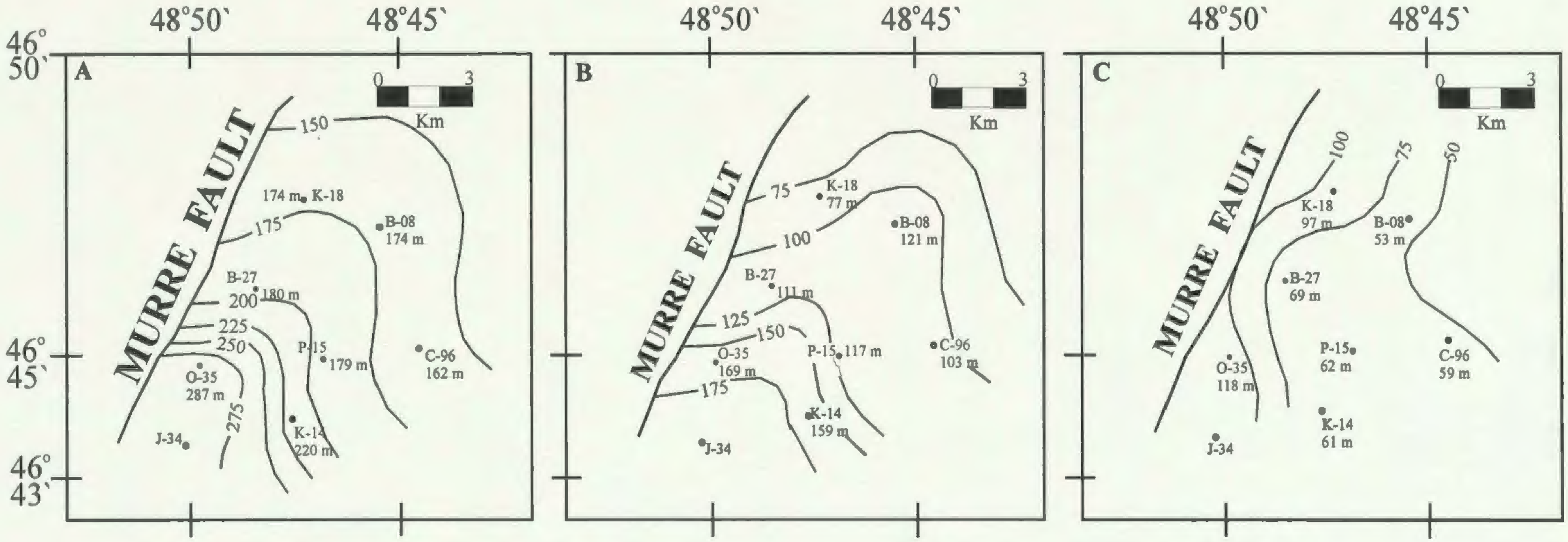


Figure 2.5. Isopach maps of the (A) Hibernia Formation, (B) the lower Hibernia zone, and (C) the upper Hibernia zone. Isopach maps B and C show an overall upwards decrease in thickness through the Hibernia Formation. This pattern is similar to the one observed between the lower and upper deposits of the Breathitt Group (Modified from Brown et al., 1989).

abundance of coal debris within valley fills at Hibernia suggests that coals were completely reworked during incision events, while coal debris within incised valleys of the Breathitt Group implies partial reworking of coals by incision events.

Differences in the abundance of coal have been explained by contrasts in the local climate. There were also fundamental differences in global climate between the Carboniferous and the Cretaceous that likely influenced allocyclic controls on stratigraphic development, for example the amplitudes and frequencies of sea level changes. The Carboniferous Breathitt Group was deposited during a time when polar ice caps waxed and waned, leading to glacial-interglacial eustatic sea level changes like those of the Quaternary; these conditions are described by climate modelers as "icehouse" conditions. Relative sea level changes during these glacial-interglacial cycles would have been characterized by high amplitudes and high frequencies in the Milankovitch bandwidth (Seranne, 1999), coinciding with alternating drier and wetter climate conditions in relation to the growth and decay of polar ice caps. In contrast, the Cretaceous Hibernia Formation was deposited during a "greenhouse" or "hot house" climatic state when there were no high-latitude ice caps, and therefore no glacio-eustatic forcing on relative sea level change. Seranne (1999) states that global greenhouse conditions associated with long-term high sea-level existed during the Cretaceous, reached a climax in the Cenomanian, and were characterized by low amplitude, high frequency eustatic sea level changes and even climatic conditions.

The difference in the state of the global climate system between the Carboniferous and the Cretaceous, and associated different mechanisms for eustatic sea level change, are difficult to impossible to read from the fluvial-delatic deposits of the Hibernia Formation and Breathitt Group. This may be the result of a dominant tectonic control on relative sea level changes in both areas. For this reason, the contrasting "greenhouse" verses "icehouse" conditions for the two stratigraphic units are played down in the ensuing discussions, and are not taken as an argument against considering the Breathitt Group as a stratigraphic analogue for the Hibernia Formation.

CHAPTER THREE

HIBERNIA FACIES DESCRIPTIONS, FACIES ASSOCIATIONS AND INTERPRETATIONS

3.1 Introduction

The purpose of this chapter is to provide detailed descriptions and environmental interpretations for the facies recognized from each of the three Hibernia wells. Facies are defined by lithology, grain size, sediment composition percentages, sedimentary structures, trace-fossil assemblages and bed thicknesses. Textural ratios (e.g. sand: silt: shale) were calculated in a two-step process. First, the ratio for each well was calculated by taking the average of each occurrence in that well. The final ratio was calculated by taking the average of the values obtained from step 1. The recognition of trace fossils is based on criteria provided in Pemberton et al. (2001). Each facies is then interpreted in terms of physical and biogenic processes. Finally, in order to facilitate an interpretation of depositional environment, facies are grouped into facies associations (see table 3.1 for a summary of facies, facies associations, and environmental interpretations). Facies associations are groups of facies that tend to occur together and which are genetically or environmentally related (Walker, 1992). They can be compared with the deposits of modern environments in order to establish valid environmental interpretations. The spatial distributions of facies associations will also be discussed.

Through the use of drafted stratigraphic sections, a total of sixteen facies were recognized in the three Hibernia wells. Appendix one contains a summary of the descriptive nomenclature used throughout the facies descriptions such as bed, lamination,

Table 3.1: Summary of facies descriptions and interpretations for Hibernia.

FACIES	DESCRIPTION	PROCESS INTERPRETATION	FACIES ASSOCIATIONS	ASSOCIATION INTERPRETATION
14	-interbedded bioclast-rich shale and siltstone -common to abundant shell debris -common siderite nodules -dominant trace: *Chondrites*	-deposition by suspension settling -abundant and well developed *Chondrites* suggest fully marine settings with high oxygen levels as opposed to brackish water settings	**I** Offshore	Open marine
1	-interbedded grey shale and siltstone, -siltstone is shell rich and exhibits moderate to intense burrowing -rare siderite nodules and shell debris present in shale -sideritic shales are fissile in nature	-suspension settling in low energy conditions with fluctuating energy levels -*Cruziana* traces indicate marine conditions with normal salinity and high oxygen levels	**II** Prodelta- Delta-front Transition	Prodelta
2	-upward coarsening shale to fine grained sandstone -traces of both *Cruziana* and *Skolithos* ichnofacies. -sandstones are horizontal laminated and have carbonaceous debris	-increasing energy conditions -deposit and suspension feeders -normal salinity, well oxygenated waters		Delta-Front

6	-interbedded to interlaminated shale, siltstone and fine grained sandstone -traces of *Cruziana* and *Skolithos* ichnofacies present -siderite and carbonaceous debris -rare ripple cross lamination and a more subdued cross lamination	-suspension settling in low energy conditions with fluctuating energy conditions -deposit feeders and suspension feeders show fluctuating energy -simple and diminished traces show stressed settings	**III** Lagoon to bay	Lagoon to bay with minor crevasse splay/channel deposits
13	-bioturbated, fine grained to very fine grained sandstone and shale -sharp planar bases, erosional lags, shell debris and carbonaceous debris -vertical burrows and diverse suite of traces belonging to the *Cruziana* and *Skolithos* ichnofacies -horizontal lamination, trough cross bedding and current ripple lamination	-fluctuating energy levels -preservation of carbonaceous debris and biogenic reworking suggest reduced energy -deposit and suspension feeders -traces indicate sandy substrates in high-energy settings -traces indicate marine influence in shallow to emergent conditions		Washover fan

11	-rooted black to grey shale -shale contains siderite, soil horizons, carbonaceous debris and pryite -rooting abundant in bleached regions below very thin bedded coals	-low energy conditions dominated by suspension settling -rooting and soil zones indicate exposure and non-deposition -leaching of alkalis and alkaline earths from soils results in seat earths below coals		Marsh
8	-upward coarsening shale to fine-grained sand -carbonaceous debris, trough cross lamination and climbing ripple lamination -no burrows present	-increasing flow energy -fine-grained sediment deposited by suspension settling -climbing ripples indicate rapid sedimentation	**IV** Overbank-Lower Delta-Plain	Lower delta-plain-Crevasse splay
4	-grey shale with rare interlaminated to interbedded silt. -minor to common bioturbation -traces belong to *Cruziana* ichnofacies. -rare current ripple lamination	-low energy settings dominated by suspension settling -weak unidirectional currents -diminished size of traces indicate low oxygen levels		Interdistributary Bay

10	- burrowed siltstone -horizontal and wavy lamination and ripple cross lamination present -carbonaceous debris also present -bleached horizons below very thin bedded coals -traces belong to *Cruziana* and *Skolithos* ichnofacies -a single *Glossifungites* surface	-low energy conditions with fluctuating energy conditions. The dominant process is suspension settling -deposit feeders suggest low energy conditions -rooted and bleached horizons suggest episodes of exposure and non-deposition -*Glossifungites* surface indicate erosion, exhumation and colonization by marine fauna	**IV** Overbank-Lower Delta-Plain	Interdistributary bay
9	-medium-to very fine-grained sand -erosive bases with pebble lags -carbonaceous debris vertical burrows and traces belonging to the *Cruziana* and *Skolithos* ichnofacies -horizontal, wavy laminations and current ripple lamination	-upper flow regime with decreasing energy levels -horizontal laminations and lags indicate upper flow regime -planar crossbedding and current ripple lamination indicate decreased flow velocity	**V** Minor channel sands	Crevasse channel sandstones

5	-medium to very fine grained sand -erosive based sands defined by pebble lags -ripple cross lamination and planar cross bedding -rare *Planolites* traces present	-upper flow regime with decreasing energy levels -common trough crossbedding and ripple cross lamination indicate lower flow regime conditions -rare *Planolites* suggests influence by marine or brackish-water processes	**VI** Major channel sands on Delta-Plain	Major Distributary Channel
12	-bioturbated medium-to very fine-grained sand and shale -parallel laminations and ripple cross lamination -sharp-based, fining-upward sands -rare cross stratification -traces belong to *Cruziana* and *Skolithos* ichnofacies	-upper flow regime with decreasing energy -horizontal laminations indicate upper flow regime -fine-grained sediments, cross stratification and ripple cross lamination indicate lower flow regime		Major Distributary Channel with estuarine influence

3	-upward fining, well sorted, very coarse to very fine sandstone -thin to very thick bedded sands -horizontal lamination, trough cross bedding, planar cross bedding, current ripple lamination -no carbonaceous debris	-upper flow regime with rare episodes of waning flow energy -ripples and cross-bedding indicate lower flow regime conditions	**VII** Braided river-major stacked fluvial bodies	Incised valley – braided river
7	-upward fining, very coarse to fine grained sandstone -sandstones are thin to very thick bedded -horizontal lamination, planar cross- bedding and current ripple lamination -carbonaceous debris	-upper flow regime conditions with decreasing flow velocity -crossbedding and ripple lamination indicate lower flow regime conditions		
15	-granular sand -no carbonaceous debris -granule laminae	-upper flow regime conditions of limited traction transport		
16	-granular sand -carbonaceous rich -erosive bases	-upper flow regime indicated by erosive contacts and transported debris		

and bed thickness (Boggs, 1995). Appendix two contains the legend and a detailed stratigraphic section for each of the three Hibernia wells. The core photographs in this chapter are mostly from deviated wells, so that bedding dip is an artifact of the drilling strategy. Where unclear, bedding is indicated in core photographs. The core diameter also limited the recognition of crossbedding to foreset geometry, instead of traditional methods. Foresets with a straight geometry were recognized as planar-tabular crossbedding, whereas foresets with a curved geometry were identified as trough crossbedding.

3.2 Facies Descriptions and Process Interpretations

Facies H1: Interbedded grey shale and bioturbated siltstone

DESCRIPTION: Facies H1 is composed of interbedded grey shale and light grey, bioturbated siltstone. The facies is composed of 55 % shale and 45% siltstone. The shales are medium to thick bedded (22-80 cm thick). Shales contain rare siderite nodules (3.5 cm in length), concretions (6 cm in diameter), silt laminae and rare articulated gastropod shells (1.0 cm in length) (Figure 3.1). The sideritic shales appear to be fissile in nature.

The siltstones are thick bedded (62-92 cm thick). They contain rare very fine grained sandstone lenses (4-8 cm in length), shale laminae and rare disk-shaped siderite nodules (2-4 cm in length). Disarticulated oyster shells are common to abundant (0.5-1.2 cm in length). Common traces identified include: *Asterosoma, Thalassinoides, Teichichnus, Chondrites* and rare *Planolites*.

Figure 3.1. Shell debris and siderite concretions characteristic of facies H1. Shell debris is observed in siderite concretions, but rarely found in clasts.

PROCESS INTERPRETATION: The fine-grained nature of the sediment, lack of wave or current generated structures and abundant biogenic reworking of the sediment suggests that these sediments were deposited by suspension during low energy conditions. The occurrence of siderite nodules and concretions in the shales indicate reducing, alkaline conditions in the shallow subsurface. Potter et al. (1980) suggest that the precipitation of mineral matter in shales can displace the host rock, occur within voids and open fractures, or precipitate syngenetically at the sediment-water interface. Shell debris within the concretions suggests that the precipitation of the siderite did not displace the host rock, but instead occupied the voids in the shale, thus encompassing the shell debris during precipitation. Alternatively, the shell debris may have formed the nucleus for precipitation of the concretionary material allowing the concretion to form around the position of the animals soft parts, while the hard parts (e.g. the shell debris) remains undisturbed (Collinson and Thompson, 1982). There is no evidence of shell debris in the siderite nodules.

The *Cruziana* trace assemblage present in facies 1 indicates marine depositional settings. The facies associated with such marine settings provided habitats well-suited to deposit feeders of the *Cruziana* ichnofacies including *Planolites, Chondrites, Asterosoma* and *Teichichnus.* Howard (1978) states that the occurrence of *Cruziana* suggests marine conditions characterized by normal salinity, high oxygen content and stable bottom water conditions except during storms. Pemberton et al. (2001) state that deposit feeders of the *Cruziana* ichnofacies thrive in low energy environments where food particles have been deposited through suspension. The abundance of *Cruziana* traces in facies H1 indicates that energy levels were reduced, thus allowing common deposit feeding organisms to flourish in well-oxygenated and normal saline conditions; therefore the presence of deep deposit feeding burrows such as *Chondrites* suggest low-energy, well-oxygenated settings. Disarticulated shell debris indicates episodic increases in energy levels, disturbance by bioturbation or dispersal due to aquatic activity scavengers.

Facies H2: Upward coarsening, shale to fine grained sandstone

DESCRIPTION: Facies H2 is composed of upward coarsening succession of shale to fine grained sandstone. It is composed of 45% shale, 25% siltstone and 30% sandstone. The shales are characterized by thin to thick beds (3-62 cm thick), rare siderite nodules (2.5 cm in diameter) and rare silt laminae. Trace fossils identified in the shale include rare *Asterosoma*, common *Planolites* and *Chondrites*. The siltstones are thin to thick bedded (3-40 cm thick) and contain shale laminae, rare disarticulated shell debris (0.8-1.2 cm in length) and rare carbonaceous debris. The traces encountered in the silt are simple and diminutive, including common *Planolites, Chondrites, Teichichnus and* rare *Asterosoma* (Figure 3.2). The sandstones are thin to thick bedded (3-32 cm thick) and are characterized by sharp bases, carbonaceous debris and rare siliceous clasts (2.0 cm in diameter). Traces identified in the sands include rare *Palaeophycus* and *Skolithos*.

Sedimentary structures include horizontal laminations defined by carbonaceous debris, and rare current ripple lamination (set thickness 0.6 cm).

PROCESS INTERPRETATION: This facies formed during periods of slightly increasing energy. The presence of shales and siltstones suggests suspension settling in

HIBERNIA B-16-17 Well
DEPTH 4095.60 m

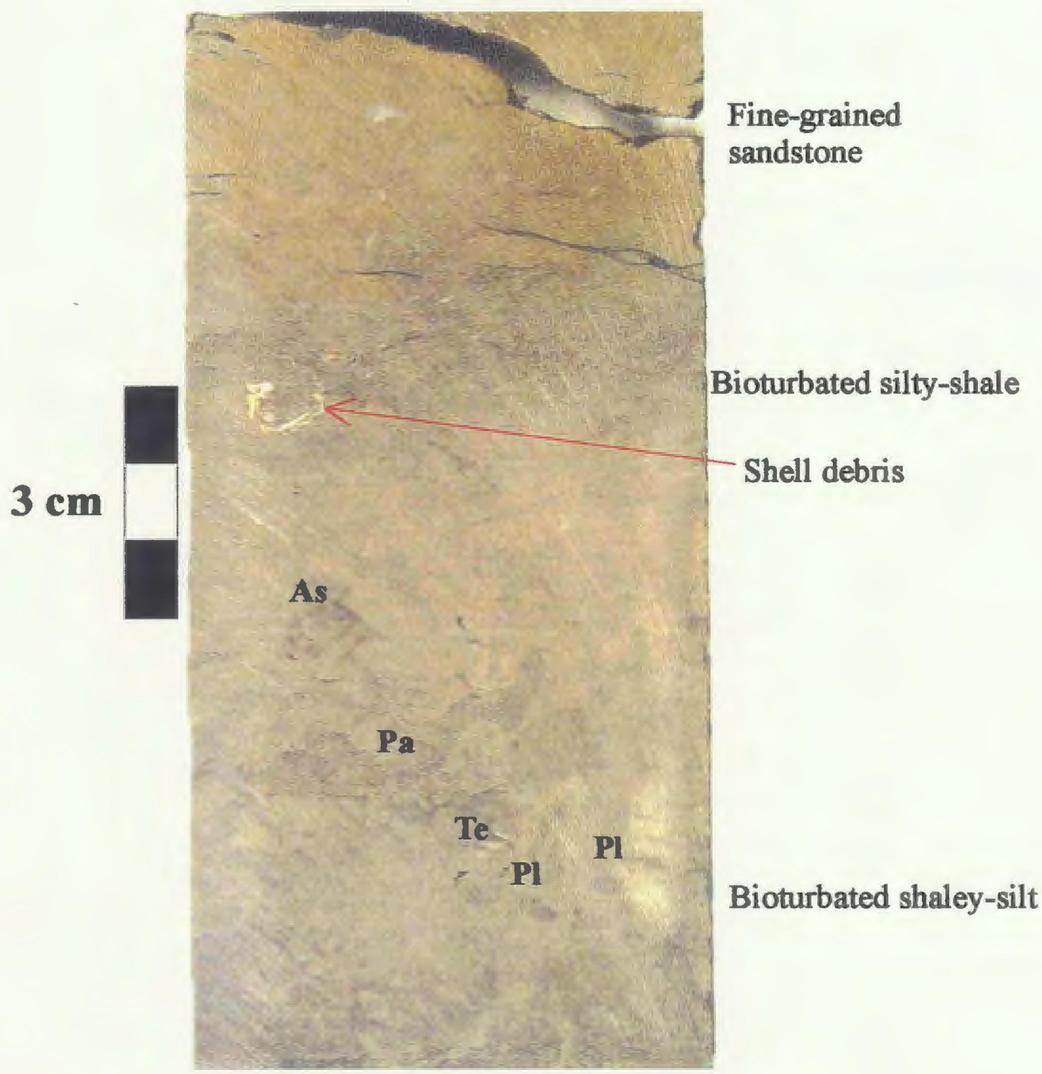


Figure 3.2. Coarsening-upward, bioturbated shale to fine grained sandstone characteristic of facies H2 . Traces present in the shale include: *Planolites* (Pl), *Teichichnus* (Te), *Asterosoma* (As), and *Palaeophycus* (Pa).

quiet water. Increasing energy levels are indicated by the presence of coarser sediment, erosive bases and rare transported material.

The *Cruziana* ichnofacies (*Planolites, Chondrites, Teichichnus* and *Asterosoma*) and *Skolithos* ichnofacies (*Skolithos* and *Palaeophycus*) present in facies H2 indicates marine depositional settings characterized by normal salinity, high oxygen content and stable bottom water conditions except during storms (Howard, 1978). The *Cruziana* trace assemblages are common in the lower portion of the upwards coarsening sequences, while the upper portion of these sequences is dominated by the *Skolithos* ichnofacies. Pemberton et al. (2001) suggest that the temporary excursion of *Skolithos* –type conditions into *Cruziana* –type setting indicate increased energy levels, which are also evident by the traces trophic classification. Pemberton et al. (2001) propose that the deposit feeders of the *Cruziana* ichnofacies are commonly associated with low energy settings, where food particles are deposited and that suspension feeders of the *Skolithos* ichnofacies are commonly associated with regions where food particles are suspended under increased energy levels. The presence of *Cruziana* traces in the lower portion of the upwards coarsening sequences suggest that in these regions, energy levels were sufficiently low enough to allow deposit feeding organisms to flourish in normal saline and well-oxygenated settings. Increased energy levels in the upper portion of the upwards coarsening facies are indicated by suspension feeding and dwelling organisms such as *Skolithos* and *Palaeophycus* traces respectively. The occurrence of horizontal lamination, current ripple lamination and carbonaceous debris in the sandstones suggests a fluvial component of deposition. The interaction of fluvial and marine processes proposes that facies H2 was deposited under shallow-water conditions. Coleman and Prior (1981) state that the shallow-water nature of the deposits and their close proximity to fluvial settings allows currents associated with riverine floods to develop a variety of sedimentary structures such as current ripple lamination, horizontal lamination and erosional truncation. They further suggest that nutrient laden currents from fluvial input make the environment favorable for burrowing organisms, resulting in increased levels of bioturbation in a seaward direction.

Disarticulated shell debris also suggests increasing energy levels under marine conditions. As an alternative, seabed scavengers might have disarticulated and scattered the bivalve shells, but the association of this debris with erosive bases and coarser sediment is believed to be more compatible with enhanced physical transport of the shells.

Facies H3: Upward fining, very coarse grained to very fine grained sandstone

DESCRIPTION: Rocks comprising facies H3 are composed of upward fining, poorly to well sorted, light beige to dark brown, very coarse grained to very fine grained sandstone. These sandstones are thin to very thick bedded (9-100+ cm thick) and locally contain siltstone laminae. The lower contacts of these beds are sharp (planar and slightly irregular) and some beds exhibit lags of pebbles, mud rip-up clasts, siderite nodules and ironstone clasts immediately above the erosional surface. The siderite nodules and ironstone clasts are generally rounded (0.5-5.0 cm in diameter), while the mudstone clasts are disk-shaped and elongated (0.5-6.5 cm in length). Quartz clasts and pyrite nodules

(0.5-2.5 cm in diameter) are also characteristic of this facies, but are very rare. This facies is characterized by a lack of carbonaceous debris.

Sedimentary structures include horizontal laminations, trough and planar crossbedding, current ripple lamination and pinch and swell structures. Massive sandstones are also locally common. Horizontal laminated sandstones are abundant throughout the facies, and are defined by grain size variations, mud chips and very coarse to pebble horizons in the sandstone. Trough crossbedding has a set height ranging from 5-30 cm, whereas planar crossbedding has sets ranging from 5-15 cm thick (Figure 3.3). Current ripple lamination (set thickness 2-4 mm, wavelength 6cm) is also present in very fine grained sandstone. The lower contact of H3 sandstones is sometimes demarcated by a single *Glossifungites* (firmground) trace-fossil assemblage. The *Glossifungites* traces range in diameter from 0.8-1.3 cm and consist predominantly of sand-filled *Thalassinoides* burrows that appear out of place in the mudstones of H2 below.

PROCESS INTERPRETATION: Much of facies H3 would have formed in the upper flow regime with episodes of waning current flow. The presence of horizontal lamination, erosive contacts, mud rip-up clasts and basal lags also supports an upper flow regime interpretation. The lag deposit formed when flow conditions were strong enough to erode all but the coarsest clasts. The succession of horizontal laminated fine grained sandstone, succeeded upward by current ripple lamination in very fine grained sandstones indicates waning energy conditions. Like the ripple lamination, the trough and planar crossbedding also records periodic lower flow regime conditions.

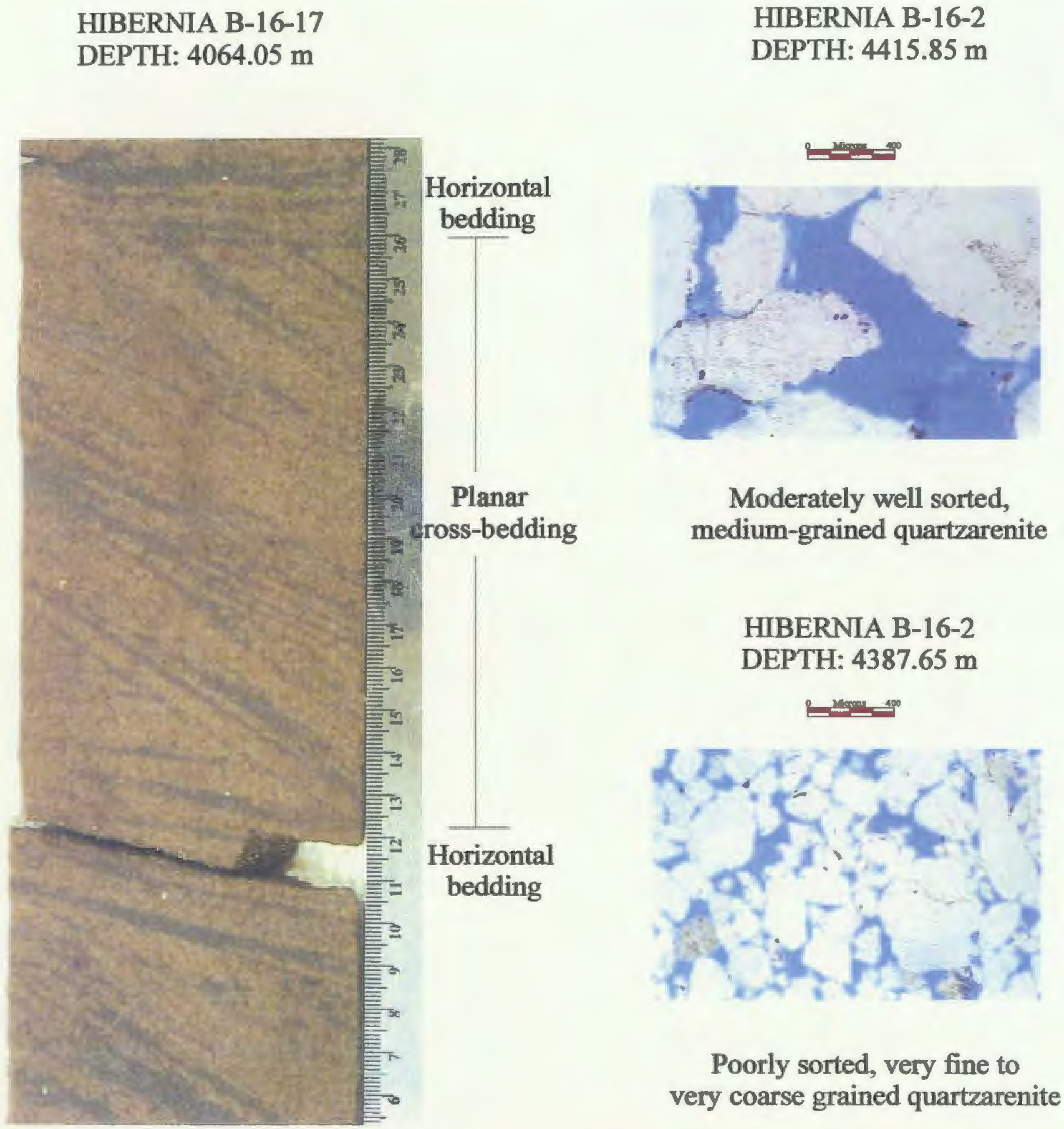


Figure 3.3. Planar cross bedded, medium grained sandstone, characteristic of facies H3. Also shown here is the truncation of horizontal bedding by planar cross beds. Photomicrographs shown on the right show the poorly to moderately well sorted, very fine to very coarse grained quartzarenites characteristic of a portion of the reservoir sands of facies H3. Photomicrographs taken by corelabs are courtesy of HMDC.

The lack of burrows in facies H3 might indicate non-marine deposition, or high energy levels and constant reworking leading to an unfavorable habitat for organisms. The former interpretation is preferred, because the finer-grained parts of this facies would be expected to contain burrows if these were marine sediments, even in high-energy marine settings. Also, deeply burrowing infauna (e.g. *Ophiomorpha*) can tolerate high-energy conditions in the marine realm, yet no such burrows are present in facies H3.

The *Glossifungites* trace-fossil assemblage develops in firm but unlithified substrates (e.g., dewatered muds; Pemberton et al., 2001). Pemberton and Frey (1985) state that these substrates dewater as a result of burial and become available to tracemakers if exhumed by later erosion. The presence of *Glossifungites* (? *Thalassinoides*) at the base of H3 indicates that brackish to marine conditions existed just prior to the deposition of the H3 sandstones. The presence of these traces along the lower contact of facies H3 indicates exhumation and erosion of pre-H3 deposits, colonization of the re-submerged firm surface by marine fauna, then occurrence of an hiatus prior to the deposition of the overlying non-marine sediments. The hiatus follows the burrowing and allows time for conditions to change to non-marine.

Facies H4: Interbedded to interlaminated grey shale and siltstone

DESCRIPTION. Facies H4 is composed of interbedded to interlaminated grey shale siltstone and very fine grained sandstone. The facies is composed of 60% shale, 35% siltstone and 5% very fine grained sandstone. Shales are very thin to thick bedded (1-46 cm thick). The shales contain lenses and laminations of siltstone and rare laminations of very fine grained sandstone (Figure 3.4). Siderite nodules (1.0-6.0 cm in length) are present, but are very rare. Lenticular bedding is defined by the presence of silt and very fine grained sandstone lenses in shale. Siltstones are thin to thick bedded (5-45 cm thick) while siltstone lenses range in length from one to eight centimeters and are occasionally surrounded with carbonaceous debris. Sandstone lenses are smaller (1-4 cm in length, 0.5-1.0 cm in central thickness) and contain carbonaceous debris. Vertical burrows (2.5-3.0 cm in diameter) and an extremely simple and diminutive trace-fossil assemblage including rare *Planolites* and *Chondrites* are also characteristic of this facies. Rare current ripple lamination (set thickness 0.4-1.0 cm) is characteristic of this facies.

PROCESS INTERPRETATION: Facies H4 formed under low energy conditions by suspension settling with minor higher energy fluctuations, which account for coarser-grained sediment throughout the facies and lenticular bedding that forms due to fluctuations in sediment supply and current velocity (Boggs, 1995). Current ripple lamination indicates weak unidirectional currents.

The traces identified in facies H4 are suggestive of marginal-marine (lower delta-plain) environments. Pemberton et al. (2001) state that such environments are characterized by steep salinity gradients, such that, when combined with temperature fluctuations, turbulence, exposure, and oxygen levels stressful habitats for a wide variety of organisms result. They further propose that trace fossil suites under such conditions are: 1) low in diversity; 2) display an impoverished marine assemblage as opposed to a mixed marine and freshwater forms; 3) dominated by morphologically simple structures; 4) diminished in size; and 5) dominated by *Skolithos* and *Cruziana* ichnofacies. The

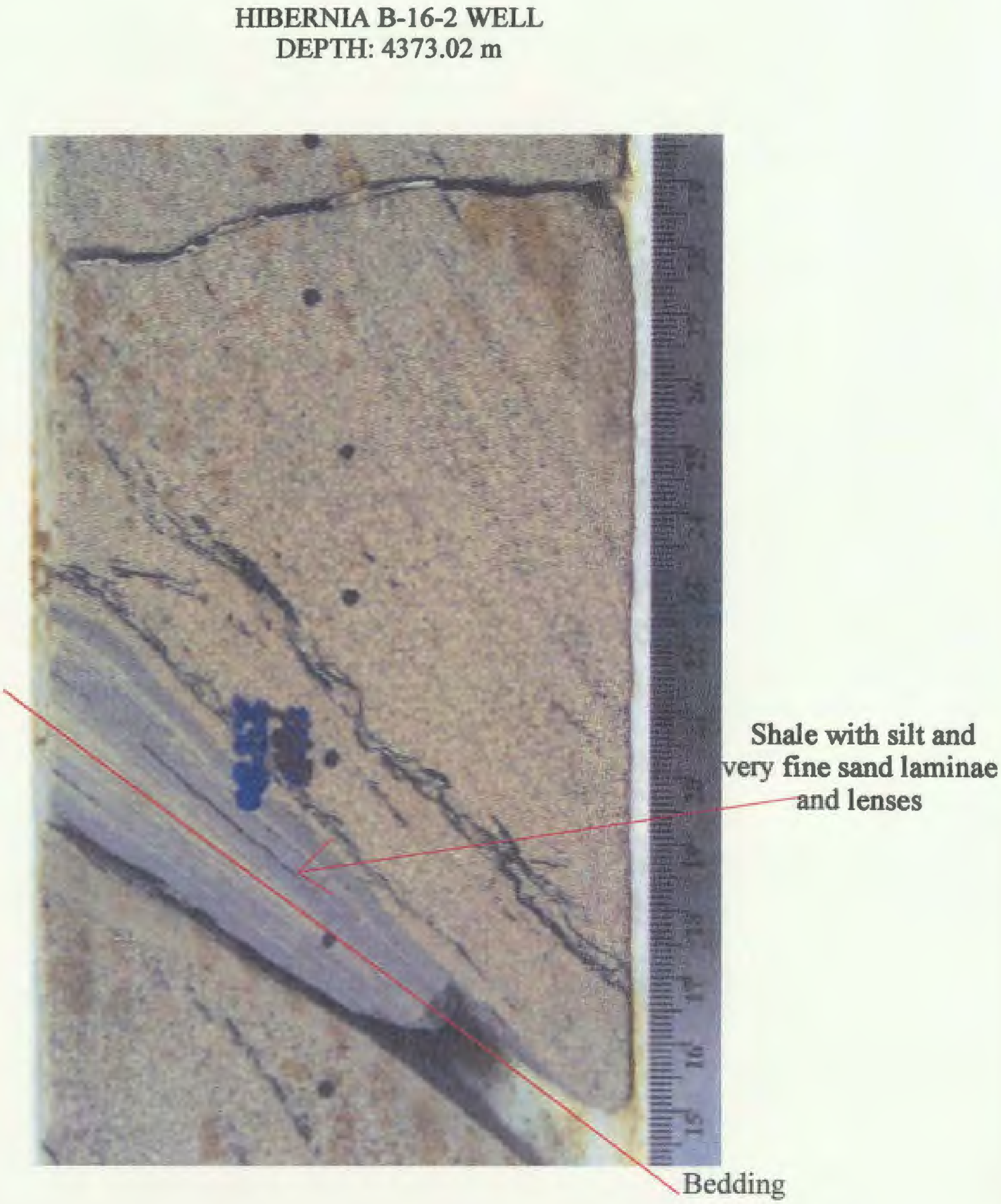


Figure 3.4. Shale with silt and very fine sand laminae characteristic of facies H4. The laminations are slightly discontinuous in places.

traces identified in facies H4 are low in diversity, diminished in size and belong predominantly to the *Cruziana* ichnofacies, where the former two characteristics indicate low oxygen levels and stressed conditions. *Chondrites* is a deep, deposit feeder burrow resulting from the successive probing activities of a sediment-mining organism (Ekdale, 1992). *Chondrites* is found in oxygen depleted sediment below the redox level in a substrate where unoxidized organic matter is plentiful and requires oxygenated water for its survival. Their presence implies oxygenated waters, however, the low diversity and diminished size suggest minimal oxygen levels. These stressed conditions are further supported by the presence of siderite nodules. Sengupta (1994) states that siderite forms under anoxic conditions which are nonsulphidic. The presence of siderite nodules in facies H4 suggests anoxic, reducing conditions. The fine-grained nature of the sediment and low diversity traces of the *Cruziana* ichnofacies are suggestive of marginal-marine (delta-plain) settings.

Facies H5: Very coarse- to very fine grained sandstone

DESCRIPTION: Facies H5 is composed of very coarse grained to very fine grained sandstone. The sandstones are medium to thick bedded (15-90 cm thick). Erosive bases, siderite lags (nodules are 1-7 cm in length), disk-shaped mud rip-up clasts (0.8-5 cm in length) and carbonaceous debris (1-3 cm in length) are all characteristic of this facies. Erosive-based sandstones with a scour depth of 4-6 mm are defined by pebble lags whose matrix is predominantly coarse to medium sandstone (Figure 3.5). Rare siltstone

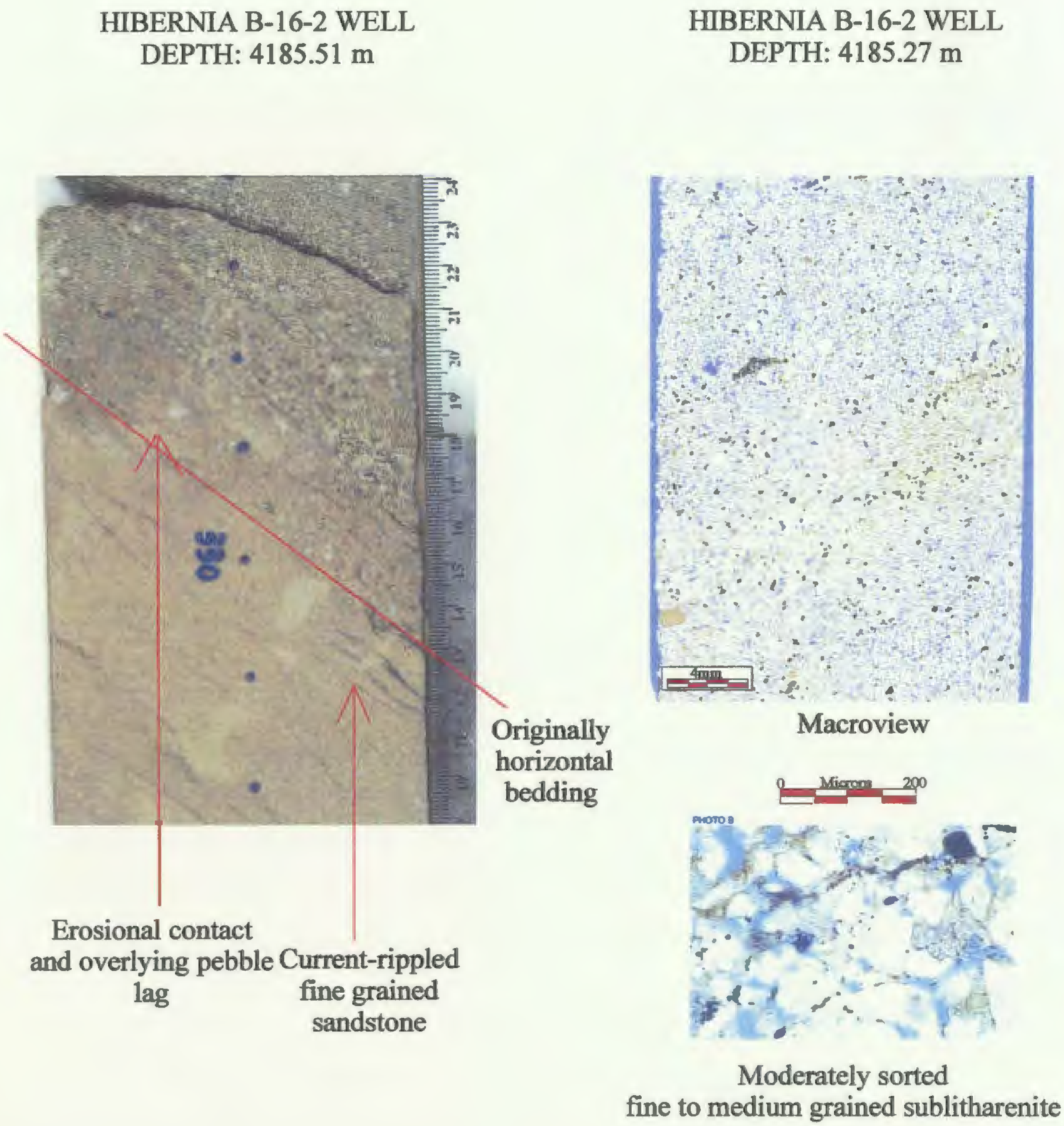


Figure 3.5. Erosional contact between a fine grained, current rippled sandstone and a medium grained sandstone. The erosional contact is defined by a pebble lag composed of quartz pebbles and mud chips. These features are characteristic o f facies H5. Photomicrographs on the right show the moderately sorted, fine to medium grained sandstones characteristic of facies H5. Photomicrographs taken by corelabs are courtesy of HMDC.

laminae are present in the very fine grained sandstone. Identified traces in siltstone laminae include very rare *Planolites*.

Sedimentary structures include: horizontal laminations, current ripple lamination and planar crossbedding. Common to abundant horizontal laminations are defined by carbonaceous debris. Common current ripple lamination in the very fine grained sandstones has a set thickness of 0.2-1.0 cm. Trough crossbedding is common throughout the facies and has a set height of 6-15 cm, whereas planar crossbedding with a set height of 14 cm occurs only once.

PROCESS INTERPRETATION: The erosive, coarse-grained nature of this facies is suggestive of upper flow regime conditions. Basal lags composed of siderite nodules and mud rip-up clasts were formed when flow conditions were strong enough to erode all but the coarsest clasts. Nichols (1999) states that mud rip-up clasts are formed from the erosion of consolidated mud from river banks by fluvial processes. Upper flow regime conditions are also indicated by horizontal laminations in the fine grained sandstone. A decrease in energy levels is recorded by the presence of unidirectional trough and planar crossbedding in the medium grained to fine grained sandstone and current ripple lamination in the very fine grained sandstone. Finer-grained sediments indicate low energy conditions when deposition was dominated by suspension settling. The predominance of unidirectional flow indicators, availability of plant debris and mud rip-up clasts suggest a non-marine, fluvial setting.

The general lack of burrows in facies H5 might indicate predominantly non-marine deposition, or high energy levels and constant reworking leading to unsuitable habitats for organisms. However, the presence of very rare *Planolites* might suggest that deposition may have been slightly influenced by marine or brackish-water processes.

Facies H6: Interbedded to interlaminated shale, siltstone, and fine grained sandstone

DESCRIPTION: Facies H6 is composed of interbedded to interlaminated, bioturbated, shale, siltstone, and very fine to fine grained sandstone. The facies is composed of 55% shale, 25% siltstone and 20% sandstone. The shales range from laminae to very thick bedded and contain siltstone lenses (1-3 cm in length, 0.5-1.0 cm in central height), siderite nodules (1-4 cm in length), shell debris (1-3 cm in length) and both silt and very fine sand laminae (Figure 3.6a). The siltstones range from laminae to thick bedded (<1-59 cm thick). They contain shale laminae, lenses of very fine grained sandstone (2-9 cm in length), pyrite nodules (2-4 cm in diameter), current ripple lamination (set thickness 6 mm) and rare to locally common carbonaceous debris. The sandstones are very thin to medium bedded (2-30 cm thick), and contain locally common carbonaceous debris, which in places defines a weak horizontal lamination in the sands. Shaley silt clasts (0.5-5.0 cm in length) are also present in the sands, but are rare. Vertical burrows (2-4 cm in height) are rare, whereas identified traces such as *Planolites, Chondrites, Teichichnus*, *Thalassinoides* and *Skolithos* are common to abundant (Figure 3.6b).

Sedimentary structures are limited to rare ripple cross lamination (set height of 4 cm) in fine grained sandstones and more subdued cross lamination (set thickness of 5-7

HIBERNIA B-16-2 WELL
DEPTH: 4178.14 m

HIBERNIA B-16-17 WELL
DEPTH: 4012.60 M

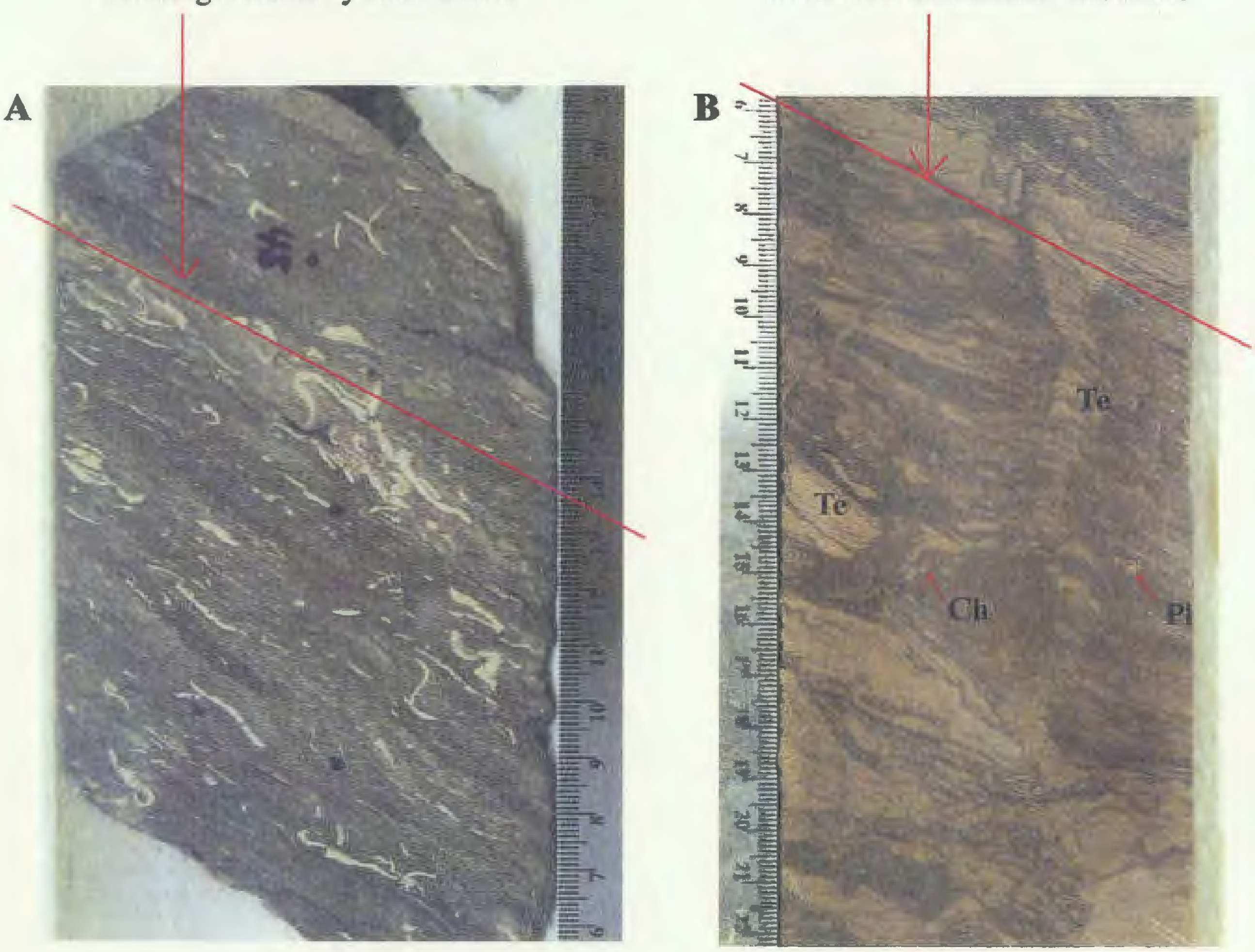


Figure 3.6. (A). Disarticulated shell debris in a silty-shale characteristic of facies H6. The shell debris demonstrates a weak parallel lamination. **(B).** Interbedded sandy shale characteristic of facies H6. Traces present identified include *Teichichnus* (Te), *Planolites* (Pl), and *Chondrites* (Ch).

mm) in very fine grained sandstones. Rare pinch and swell structures with a maximum height of six millimeters are also characteristic of this facies.

PROCESS INTERPRETATION: This facies formed under low energy conditions with episodes of fluctuating energy. The abundance of fine-grained sediment and the preservation of carbonaceous debris might suggest that the deposition of the sediment was by suspension settling in quiet water conditions. Ripple cross lamination in the siltstone is also consistent with these conditions. As well fine and very fine grained sandstones and rare trough cross lamination suggest episodes of fluctuating energy. The presence of siderite and pyrite suggest reducing conditions in restricted settings.

Traces identified in facies H6 belong to both the *Cruziana* and *Skolithos* ichnofacies and are suggestive of fluctuating energy in brackish-water, marginal marine depositional environments. Pemberton et al. (2001) state that deposit feeders of the *Cruziana* ichnofacies are commonly associated with low energy settings where food particles are deposited, whereas suspension feeders of the *Skolithos* ichnofacies are associated with increased energy levels where food particles are kept in suspension; thus, the presence of both deposit feeders and suspension feeders suggest fluctuating energy levels. As well, the presence of *Chondrites, Planolites,* and *Teichichnus* (*Cruziana* ichnofacies) indicate well-oxygenated waters, where it is known that *Chondrites* and *Teichichnus* are found in oxygen depleted substrates and require oxygenated waters for their survival. *Skolithos* (*Skolithos* ichnofacies) are suspension feeders, and thus require oxygenated substrates that lack sedimentary organic matter (Ekdale, 1992). Although these traces are fairly well developed, there overall low diversity and association with the

Skolithos and *Cruziana* ichnofacies suggest an overall physiologically stressful environment. According to Pemberton et al. (2001) such environments display steep salinity gradients, and fluctuations in temperature and oxygen levels. The traces present identified indicate periodic inundation of oxygenated waters into somewhat restricted marginal marine settings.

Facies H7: Upward fining, carbonaceous, very coarse to fine grained sandstone

DESCRIPTION: Rocks comprising facies H7 are composed of upward fining, moderately to well sorted, carbonaceous, very coarse to fine grained sandstone. The characteristic that separates this facies from facies 3 is the abundance of carbonaceous debris. The sandstones are thin to very thick bedded (10-100+ cm thick). Sharp-based, erosive contacts, which define the base of the upward fining sandstones are commonly marked by both pebble lags and abundant carbonaceous debris (Figure 3.7). The pebble lags are composed of mud rip-up clasts (1-4.5 cm in length), sideritic nodules (2-7cm in diameter) and coal clasts (0.6-3.0 cm in length). Rare quartz pebbles and pyrite nodules are also characteristic of this facies. Authigenic pyrite laminations occur in this facies, but are rare. Abundant carbonaceous debris occurs in the form of discontinuous laminations and clasts (2-5 cm in length). Rare mud laminae in fine grained sand are present.

Sedimentary structures include horizontal lamination, trough crossbedding and planar crossbedding. Horizontal laminations are marked by variations in grain size and by

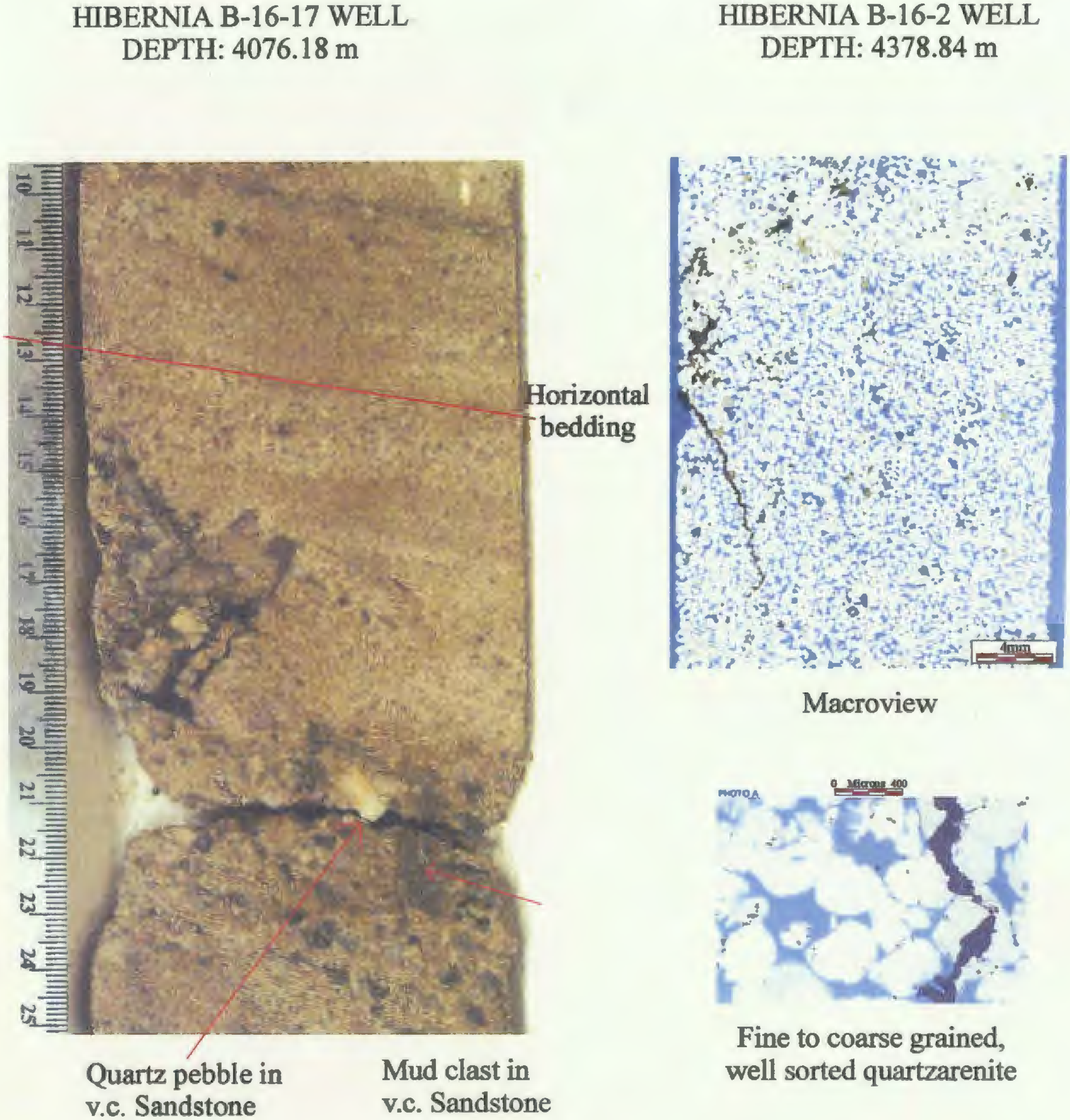


Figure 3.7. Carbonaceous rich, very coarse to fine grained sandstone characteristic of facies H7. Photomicrographs on the right show the fine to coarse grained, well sorted quartzarenite characteristic of the sands in facies H7. Photomicrographs taken by corelabs are courtesy of HMDC.

aligned mud clasts and carbonaceous debris. Trough crossbedding has a set height ranging from 5-10 cm, whereas planar crossbedding has a set height of 7-15 cm.

PROCESS INTERPRETATION: The presence of horizontal laminations, mud rip-up clasts and abundant carbonaceous debris all indicate energetic, upper flow regime conditions. Trough and planar crossbedding indicate lower flow regime conditions. The predominance of tractional, unidirectional flow indicators and availability of plant debris suggest a non-marine, fluvial-deltaic setting.

Facies H8: Upward coarsening shale to fine grained sandstone

DESCRIPTION: The rocks comprising facies H8 are composed of coarsening upward succession from shale to fine grained sandstone (Figure 3.8). Sorting in both the siltstones and sandstones ranges from poor to moderate. The facies is composed of 30% shale, 25% siltstone and 45% sandstone. The dark grey shales are very thin to medium bedded (2-33 cm). They contain common silt laminae towards the top of each occurrence. The siltstones are thin to medium bedded (5-17 cm thick) and contain shale laminae at the base and very fine sand laminae at the top. The very fine grained sandstones are thin to medium bedded (4-21 cm). They are characterized by horizontal laminations, mud laminae and upward increasing carbonaceous debris. Common trough cross lamination is present in the fine grained sandstones and has a set height of 4 cm. Rare climbing-ripple lamination (set height 3 cm) and common horizontal laminations are also present in the fine grained sandstone. *Skolithos* traces are also identified, but are rare in occurrence.

HIBERNIA B-16-17 WELL
DEPTH: 4010.61 m

Figure 3.8. Top of a upward coarsening succession characteristic of facies H8. The contact with the next succession is marked by an abrupt contact. Traces identified include *Skolithos* (Sk). Fractures, presumably related to faulting offset the *Skolithos* traces and the top of the sandstone.

PROCESS INTERPRETATION: This facies formed under conditions of increasing flow energy in a fluvial setting. The fine-grained sediments at the base of each upward coarsening sequence were deposited by suspension settling during low energy conditions. Increased energy is inferred from the presence of non-bioturbated, horizontal laminated, fine grained sand. Horizontal laminated fine grained sands are indicative of the upper flow regime. Climbing ripples form when the rate of addition of sand is high such that there is no net removal of sand from the stoss side, thus allowing each ripple to migrate up the stoss side of the ripple form in front (Nichols, 1999). Nichols (1999) further states that climbing ripples indicate rapid sedimentation and owe their development to the rate of sand addition to the flow being either equal or exceeding the rate of downstream ripple migration.

Facies H9: Bioturbated, medium to very fine grained sandstone

DESCRIPTION: Facies H9 is composed of upward fining, poorly to moderately sorted, medium to very fine grained sandstone. The sandstones are thin to thick bedded (9-50 cm thick) and contain rare mud laminae. Erosive bases, siderite lags (clasts are 1-5 cm in length), mud rip-up clasts (0.8-2.1 cm in length) and carbonaceous debris are all characteristics of this facies. One occurrence of this facies exhibits medium sand fining to a current ripple laminated siltstone (set thickness 2-4 mm) (Figure 3.9). Erosive-based sands are defined by pebble lags whose matrix is predominantly composed of medium sand. However, in one occurrence, the matrix is composed of coarse grained sand.

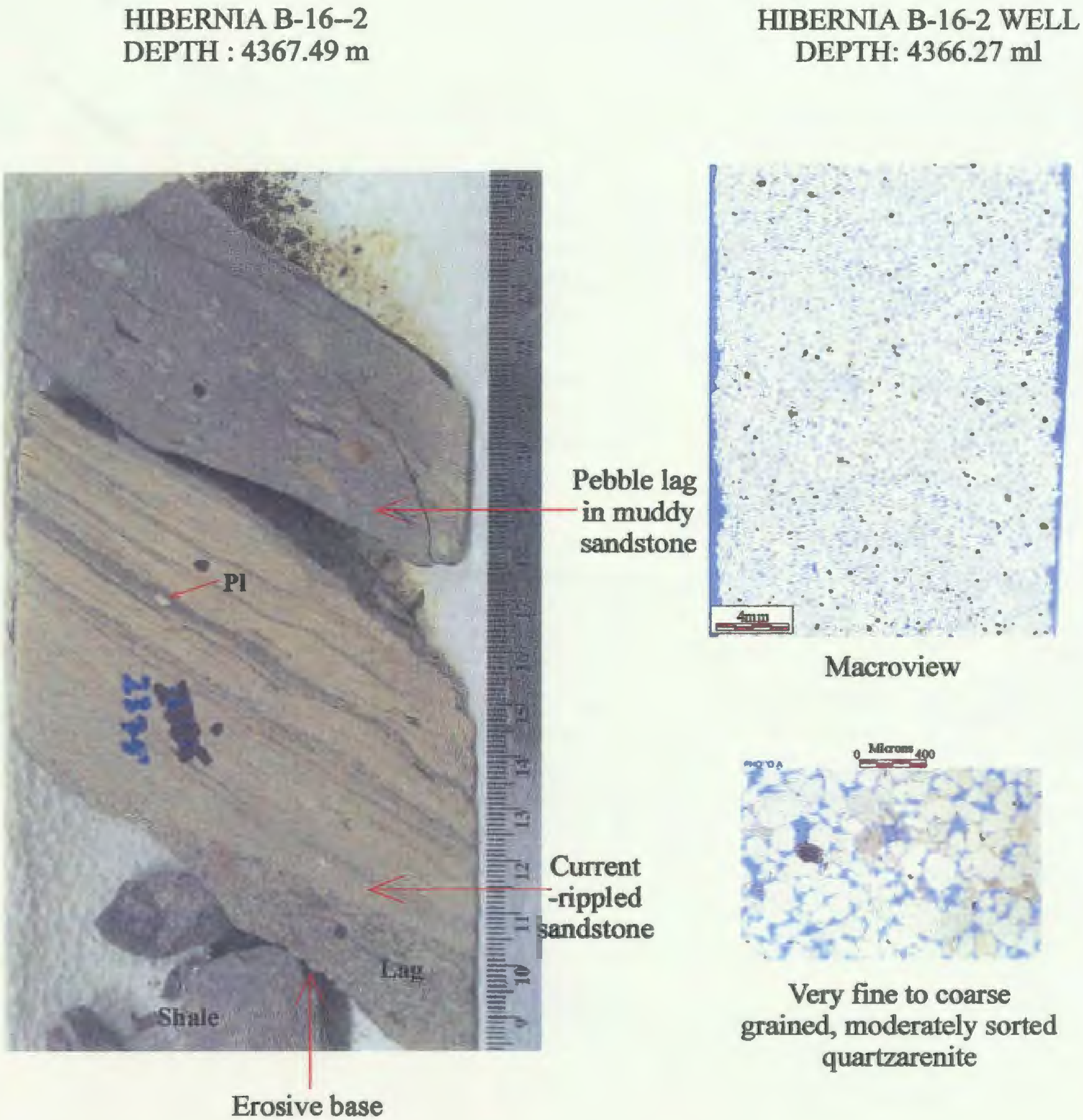


Figure 3.9. Upward fining succession, characteristic of facies H9. The upward fining succession is marked by an erosive base and pebble lag. The lag is overlain by current-rippled fine to very fine grained sandstone that fines to bioturbated shale. Traces identified include *Planolites* (Pl). Photomicrographs on the right show the very fine to coarse grained, moderately sorted sandstones characteristic of the sands of facies H9. Photomicrographs taken by corelabs are courtesy of HMDC.

Vertical burrows (1-2 cm in height) and identified traces include: rare *Planolites, Chondrites* and *Thalassinoides,* and common *Ophiomorpha, Skolithos* and *Palaeophycus* are characteristic of the facies.

Sedimentary structures include both horizontal and wavy laminations. The horizontal laminations are defined by carbonaceous debris. Uneven or wavy laminated very fine grained sandstone with siltstone partings are also evident. Local planar crossbedding in the sand has a set height of 12 cm. Current ripple lamination (set thickness 0.8 cm) is present.

PROCESS INTERPRETATION: This facies formed in the upper flow regime followed by decreasing flow energy into the lower flow regime. The coarse-grained nature of the sediment, horizontal laminations, lag deposits and the presence of erosive bases are consistent with upper flow regime conditions. The lags were formed when flow conditions were strong enough to erode all but the coarsest clasts. The presence of planar crossbedding, and finer-grained sediment with current ripple lamination suggests a decrease in energy flow. Unevenly laminated very fine grained sandstone and siltstone partings also suggest a decrease in flow energy. The presence of erosive pebble lags, mud rip-up clasts and availability of plant debris suggest fluvial settings.

Traces identified in facies H9 are commonly associated with both the *Cruziana Skolithos* ichnofacies. Suspension-feeders including *Ophiomorpha, Skolithos* and *Palaeophycus* (*Skolithos* ichnofacies) are commonly associated with increased energy settings where food particles remain in suspension. The *Skolithos* ichnofacies are found in the lower portion of the upward fining successions, whereas deposit feeders identified such as *Planolites, Chondrites* and *Thalassinoides* (*Cruziana* ichnofacies) are found in the upper portion of the upward fining successions. These traces are consistent with those in marginal-marine settings. According to Pemberton et al. (2001), a typical trace fossil suite in such environments reflect stressed conditions, which are characterized by a low diversity, a impoverished marine assemblage as opposed to a true mixture of marine and fresh water traces, a diminished size as well as a mixture of elements common to both the *Skolithos* and *Cruziana* ichnofacies. The low diversity and diminished sizes of these traces in facies H9 suggest low oxygen levels and stressed conditions in brackish water settings. These brackish trace-fossil assemblages indicate that the fluvial sandstones of facies H9 were at one time influenced by saline estuarine conditions and perhaps a estuarine environment existed.

Facies H10: Bioturbated siltstone

DESCRIPTION: This facies is composed of light grey to grey-red, bioturbated siltstone. The siltstone is medium to thick bedded (15-35 cm thick) and is characterized by shale laminae, carbonaceous debris, and locally common to abundant rooting in bleached horizons (Figure 3.10). The root traces are preserved as carbonaceous films. Very thin coal beds (2 cm thick) are present in this facies, but are rare. Rooting becomes common to abundant in regions that exhibit bleaching below thin coal beds. Siderite nodules (3-5 cm in length), concretions and pyrite nodules (2-4 cm in length) are also characteristic of this facies. Rare vertical burrows (3-5 cm in height) and an impoverished

HIBERNIA B-16-17 WELL
DEPTH: 3999.80 m

Figure 3.10. Bleached and rooted siltstones characteristic of facies H10. These siltstones are commonly overlain by carbonaceous intervals.

suite of rare traces including: *Planolites, Chondrites, Teichichnus, Palaeophycus* and *Thalassinoides* make up a typical assemblage.

Sedimentary structures include horizontal and wavy lamination and ripple cross lamination. Subtle horizontal and wavy laminations are defined by both the shale laminations and carbonaceous debris. Current ripple lamination (set thickness is 0.6-0.8 cm) is also present.

PROCESS INTERPRETATION: The fine-grained nature of the sediment, preservation of carbonaceous debris and lack of abundant current generated structures suggest that this facies was deposited under quiet water conditions by suspension settling with rare increases in energy. This would account for the presence of horizontal and slightly wavy laminations in the sediment. The presence of current ripple lamination in the silt is also characteristic of low-energy conditions.

The traces identified in facies H10 indicate brackish-water depositional settings and are predominantly associated with the *Cruziana* ichnofacies; however, *Palaeophycus* belongs to the *Skolithos* ichnofacies. Pemberton et al. (2001) state that deposit-feeders occur in low energy settings were food particles are deposited through suspension, whereas suspension feeders are commonly associated with increased energy conditions where food particles remain in suspension. Since the *Cruziana* ichnofacies is comprised of deposit-feeders, their dominant, yet overall rare occurrence within facies H10 suggests suspension settling under low-energy conditions. The impoverished suite of traces identified in facies H10 is suggestive of low oxygen levels in low energy, stressed and brackish water settings.

Common to abundant rooting in bleached horizons below thin coals are often associated with fluvial-deltaic settings. The rooted and bleached horizons are associated with episodes of exposure and non-deposition on the marshy/bay fringes of low-lying areas. Potter et al. (1980) state that siderite nodules, siderite concretions and pyrite nodules are commonly associated with organic compounds, as well as nuclei that consist of animal or plant fossils. The presence of siderite and pyrite indicates reducing, poorly oxygenated conditions.

Impoverished traces along with rooted and bleached horizons suggest inundation of the low-lying marshy fringes of bays by brackish waters. It is also possible that there was an initial period of marine influence allowing burrowers to colonize the area, then later isolation in a brackish setting where vegetation thrived to produce root zones and thin coals.

Facies H11: Rooted black to grey shale

DESCRIPTION: This facies is composed of black to grey, medium to thick bedded (20-80 cm thick) shale and is characterized by common rooting (0.5-2.0 cm in length), ironstone nodules (1-3 cm in length), carbonaceous debris, siderite nodules (1-6 cm in length), siderite alteration and a single siderite granule lag. Locally, the shale ranges in color from grey to greenish-red (Figure 3.11). Vertical burrows (2-4 cm in height) filled with pyrite and siderite are also present, but are rare. In some instances, the pyrite is completely surrounded by carbonaceous debris. Rooting becomes abundant in regions that exhibit bleaching, immediately below very thin coal beds.

HIBERNIA B-16-17
DEPTH: 4010.14 m

Figure 3.11. Rooted shale characteristic of facies H11. These shales exhibit common to abundant rooting and contain siderite. The shales range from grey to slightly greenish-red in color. The siderite occurs as staining and is also seen within root traces.

PROCESS INTERPRETATION: This facies formed under very low energy conditions. Due to the preservation of carbonaceous material, and the fine-grained nature of the deposits, it is clear that the sediment was deposited by suspension settling. Rooting and soil horizons suggest episodes of exposure and non-deposition on marshy fringes of low-lying areas. Diessel (1992) states that the leaching of alkalis and alkaline earths from soil zones, results in the development seat earths below coal beds. These seat earths are pale grey to dark in color and generally lack bedding, although occasionally near the coal contact, a transitional zone of shaly coal and coaly shale may be evident. Siderite and pyrite nodules and common to abundant rooting commonly characterize these seat-earths. The presence of siderite and pyrite suggest anoxic, reducing conditions. Rooting and dark grey shales with carbonaceous debris below very thin bedded coals in facies H11, suggest the leaching of alkalis and alkaline earths from soil zones to form seat earths during episodes of exposure and non-deposition. Therefore, the fine-grained sediment was deposited from suspension during episodes of inundation into low-lying regions that were otherwise subaerially exposed.

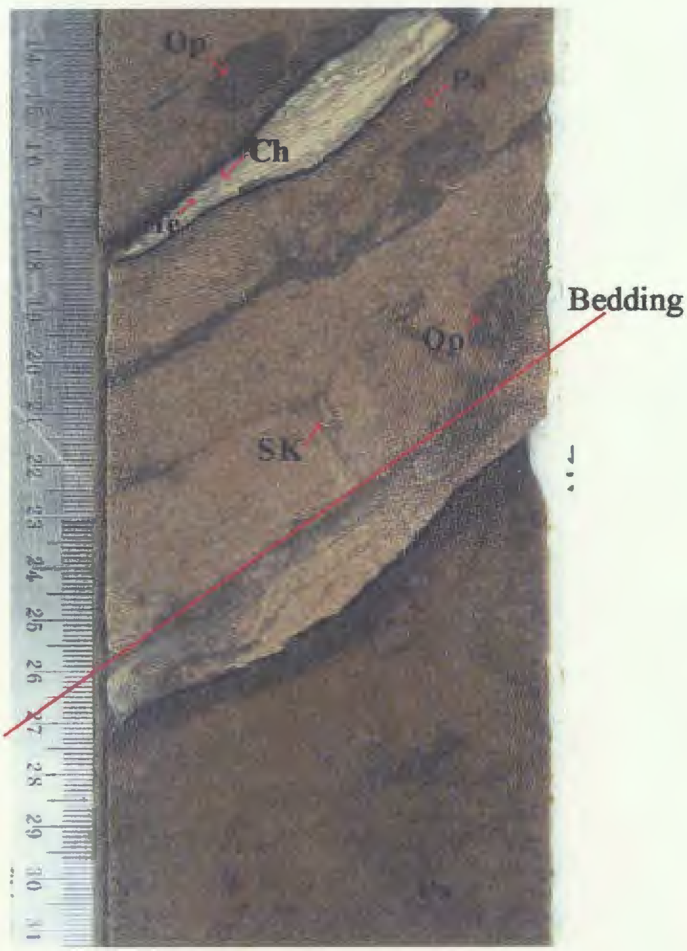
Facies H12: Bioturbated coarse to very fine grained sandstone and shale

DESCRIPTION: The rocks of facies H12 are composed of interbedded, bioturbated coarse grained to very fine grained sandstone and shale. The facies is composed of 90% sandstone and 10% shale. The sandstones are very thin to thick bedded (2-88 cm thick), and are organized into sharp based, upward fining sequences. Sandstones contain shale and silt laminae and carbonaceous debris. Sedimentary structures include horizontal lamination and current ripple lamination (set thickness 3-6 mm). Rare cross stratification (set thickness 5 cm) is also present. The shales are very thin to thin bedded (1-5 cm thick). Traces identified in the very fine grained sands and shales include *Planolites, Teichichnus, Chondrites, Skolithos*, *Ophiomorpha* and *Asterosoma* (Figure 3.12). There are no traces present in the medium grained to fine grained sandstone that form the lower parts of the upward fining sequences.

PROCESS INTERPRETATION: Coarse to medium grained sandstones, and horizontal laminated fine grained sandstones of facies H12 were deposited under upper flow regime conditions. Reduction in flow velocity is indicated by the presence of finer-grained sediments deposited by suspension settling, and the presence of lower flow regime current ripple lamination in very fine grained sands. The predominance of unidirectional flow indicators in the fine-grained sediment and availability of plant debris suggests a fluvial setting; however, rare cross stratification at the base of one of the upward fining sequences suggests rare tidal influence during deposition.

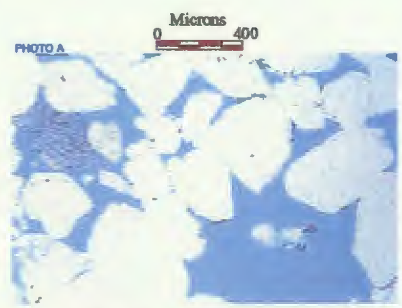
Identified traces of the *Cruziana* and *Skolithos* ichnofacies suggest marginal marine depositional settings. The predominance of *Skolithos* and *Ophiomorpha* (*Skolithos* ichnofacies) in the medium grained to fine grained sandstone, imply an increase in energy levels towards the base of the upward fining sequences. These traces are suspension feeders and are commonly associated with higher energy settings where food particles remain in suspension (Pemberton et al., 2001). The predominance of deposit feeders such as *Planolites, Teichichnus, Chondrites* and *Asterosoma* (*Cruziana* ichnofacies) in the finer-grained sediments indicate a reduction in energy levels; thus, these traces are

HIBERNIA B-16-4 WELL
DEPTH: 4661.83 m



HIBERNIA B-16-2 WELL
DEPTH: 4684.31 m

Macroview



Fine to coarse grained, moderately well sorted sublitharenite

Figure 3.12. Bioturbated medium to very fine grained sandstone and shale characteristic of facies H12. Traces identified include *Ophiomorpha* (Op), *Palaeophycus* (Pa), *Skolithos* (Sk), and *Chondrites* (Ch). The *Ophiomorpha* trace is the most abundant. Photomicrographs on the right show the fine-to coarse-grained, moderately well sorted sandstones characteristic of those in facies H12. Photomicrographs taken by corelabs Are courtesy of HMDC.

associated with oxygenated waters in lower energy settings where food particles are deposited. The traces of both ichnofacies are commonly associated with brackish-water settings, where the combining of fluvial indicators suggests estuarine depositional settings.

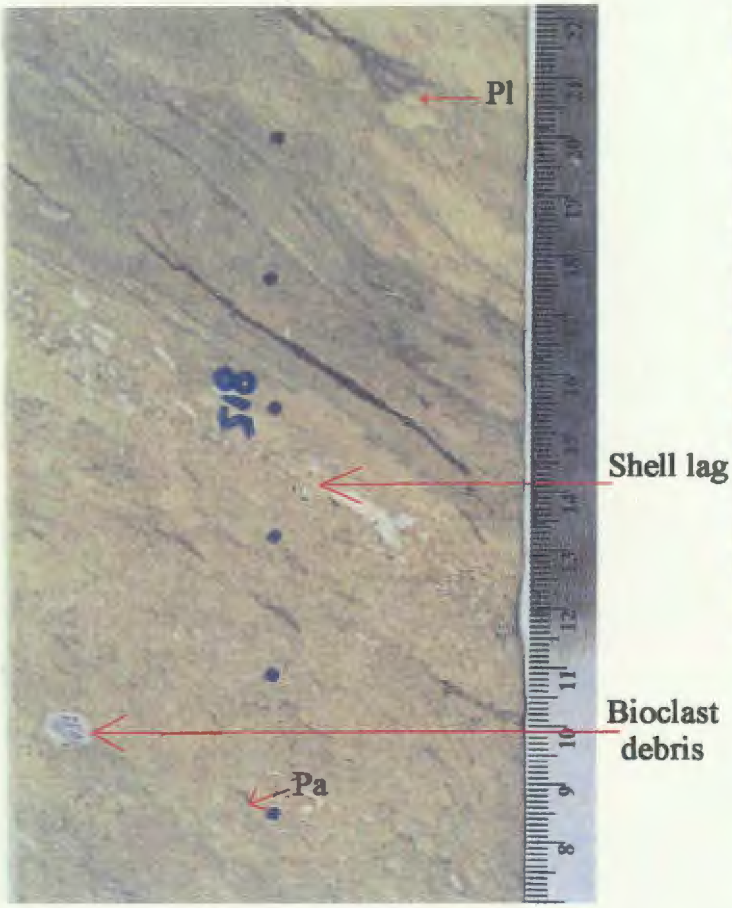
Facies H13: Bioturbated, coarse to very fine grained sandstone and shale

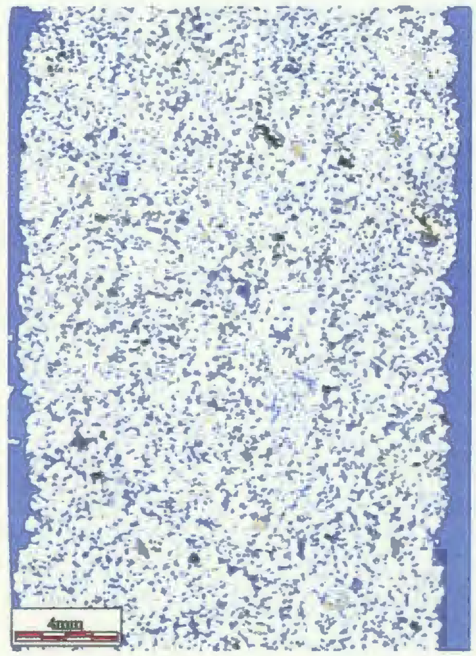
DESCRIPTION: This facies is composed of interbedded fine grained to very fine grained sandstone and shale. It is composed of 83% sandstone and 17% shale. The sandstones are thin to very thick bedded (3-130 cm thick). Sharp, planar bases, disarticulated shell debris (0.3-2.0 cm in length), shell lags, carbonaceous debris, siderite pebble lags (nodules are 0.5-4.0 cm in length), shale laminae, pyrite nodules (1-3 cm in length) and quartz pebbles are all characteristics of this facies. Shales are very thin to medium bedded (2-21 cm thick) and contain both silt and very fine sand laminae. Siderite nodules (2-6 cm in length) are present in the shales, but are very rare. Vertical burrows (2-5 cm in length) and identified traces such as rare *Skolithos, Asterosoma, Thalassinoides* and *Palaeophycus*, common *Chondrites, Teichichnus* and *Planolites* and abundant *Ophiomorpha* are present (Figure 3.13). The sand below the shell lag appears to be well bioturbated, but bioturbation leaves bedding as remnants above the lag (Figure 3.13).

Sedimentary structures include horizontal lamination, trough crossbedding, and current ripple lamination. Horizontal laminations are common to abundant throughout the facies and are defined by carbonaceous debris. Trough crossbedding has set heights

HIBERNIA B-16-2 WELL
DEPTH: 4199.79 m

HIBERNIA B-16-4 WELL
DEPTH: 4697.82 m





Macroview

Fine to coarse grained
moderately sorted quartzarenite

Figure 3.13. Shell debris, slight to moderate bioturbation and carbonaceous debris characteristic of facies H13. Traces identified include *Palaeophycus* and *Planolites.* Photomicrographs to the right show the fine to coarse grained, moderately sorted sandstones characteristic of facies H13. The sand below the hash appears to be well bioturbated, but bioturbation leaves bedding as Remnants above the hash. Photomicrograpghs taken by corelabs are Courtesy of HMDC.

ranging from 8-11 cm. Current ripple lamination (set thickness 6 mm) occurs in very fine grained sand, but is rare.

PROCESS INTERPRETATION: This facies formed under fluctuating energy levels. The erosive, coarse-grained nature of the sandstones and the presence of transported clasts, and debris are indicative of increased energy conditions. The presence of finer-grained sediment, the preservation of carbonaceous debris and the abundant biogenic reworking of both sands and shales throughout facies H13 suggests episodes of reduced energy. The finer-grained sediments were deposited by suspension setting during episodes of quiescence.

Traces identified in facies H13 indicate marginal marine, brackish water settings with fluctuating energy levels. Deposit feeders of the *Cruziana* ichnofacies identified include *Planolites, Chondrites, Asterosoma*, *Teichichnus* and *Thalassinoides*. Pemberton et al. (2001) associate these traces with normal saline, oxygenated waters where food particles are deposited under low energy conditions. The common occurrence of *Chondrites* and *Teichichnus* in facies H13 indicates well-oxygenated, shallow-water settings. Ekdale, (1992) recognize both *Chondrites* and *Teichichnus* in oxygen depleted substrates. *Chondrites* develop in substrates below the redox zone where organic matter is plentiful and thus require that oxygenated waters be transported down from the seafloor to the burrower via an open tunnel system (Ekdale, 1992). *Teichichnus* is also prevalent in oxygen-depleted subtrates and requires oxygenated bottom waters. The common occurrence of both traces in facies H13 indicates oxygenated waters, however there diminished size reflect stressed conditions.

Suspension feeders identified throughout facies H13 include *Ophiomorpha* and *Skolithos.* Pemberton et al. (2001) associate suspension feeders with increased energy levels where food particles remain in suspension. The presence of *Thalassinoides* and *Ophiomorpha* are key indicators of substrate conditions as opposed to bathymetry (Ekdale, 1992). *Ophiomorpha* are commonly associated with sandy substrates in high-energy settings, whereas *Thalassinoides* are consistent with fine-grained, cohesive sediment that is not unstable and prone to collapse. Throughout facies H13, *Ophiomorpha* are found in coarse to fine grained sandstones, and *Thalassinoides* are found in very fine grained sandstones and shales. The abundance of marine burrows including *Ophiomorpha* in facies H13, indicate marine influence and very shallow to emergent conditions (McCubbin, 1982).

Facies H14: Interbedded bioclast rich shale and siltstone

DESCRIPTION: Facies H14 consists of interbedded bioclast-rich shale and siltstone. The facies is composed of 90% silty shale and 10% siltstone. Silty shales range from medium to very thick bedded (30-500 cm thick) and are characterized by silt laminae, rare rooting (1-3 cm in length), abundant disarticulated shell debris (0.5-1.5 cm in length), rare articulated oyster shells (1-2 cm in diameter), gastropods (0.5-4.0 cm in length), siderite nodules (0.5-2.5 cm in length), siderite concretions (11 cm in diameter) and rare pyrite nodules (1.5 cm in diameter) (Figure 3.14a). Siltstones are light beige in color and occur as laminae to thick beds (2mm-60 cm thick). The siltstones are characterized by sharp-based erosive contacts. A *Glossifungites* (firmground) trace-fossil

HIBERNIA B-16-4 WELL
DEPTH 4645.01 m

HIBERNIA B-16-4 WELL
DEPTH: 4647.18 m

A

B

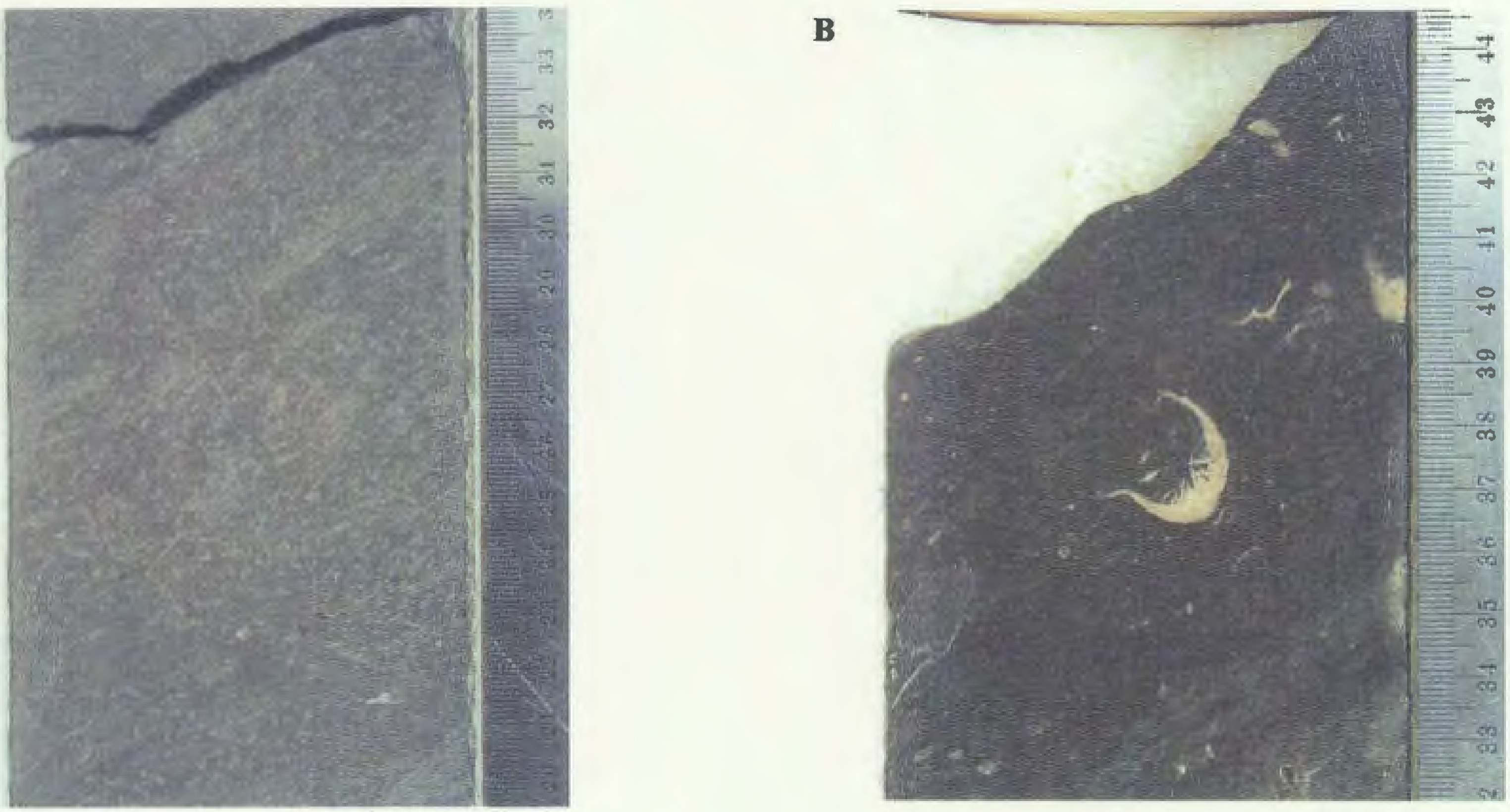


Figure 3.14. (A). Bioturbated shale characteristic of facies H14. *Chondrites* is the abundant trace fossil present.
(B). Shell debris characteristic of facies H14.

assemblage underlies one of the erosional surfaces. The *Glossifungites* assemblage consists predominantly of mud-filled *Thalassinoides* burrows that appear out of place in the sandy siltstone of facies H10 below. Siderite pebbles, quartz pebbles, and abundant shell debris define this surface. Trace fossils elsewhere in this facies include common *Planolites, Teichichnus, Thalassinoides* and *Asterosoma*. *Chondrites* traces are the most abundant (Figure 3.14b).

PROCESS INTERPRETATION: The characteristics of this facies would have formed under fluctuating energy levels. The fine grain size suggests deposition by suspension settling under low energy conditions. Erosive based silts and pebble lags suggest a slight increase in energy levels. The presence of siderite pebbles suggests reducing, alkaline deep-water conditions. Mozely (1989) states that siderite is unstable in oxidizing environments. Therefore, the presence of siderite suggests deeper water, oxygen depleted substrates. The presence of both articulated and disarticulated shells also support fluctuating energy levels.

Deposit feeders of the *Cruziana* ichnofacies identified include *Planolites, Teichichnus, Asterosoma* and *Thalassinoides*. The common occurrence of these traces and abundant occurrence of *Chondrites* suggest marine conditions of deposition. However, Pemberton et al. (2001) associate the *Cruziana* ichnofacies with marginal marine settings characterized by a low diversity, an impoverished marine trace fossil suite, as opposed to a mixture of marine and freshwater forms and a diminished size as opposed to fully marine counterparts. However the occurrence of the well developed *Chondrites* throughout this facies suggest more fully marine settings. *Chondrites* are deep deposit-feeding burrows that form in oxygen-depleted substrates. Well oxygenated, normal saline waters are required for their survival. Their abundant presence within facies H14 suggests well-oxygenated, fully marine settings.

The presence of *Glossifungites* indicates exhumation of the deposits that comprise facies H10 through either fluvial or coastal processes. The fully marine assemblage of the overlying sediments implies exhumation through coastal processes. Their presence along the lower contact of facies H14 indicates exhumation, erosion, colonization by marine fauna and a hiatus prior to the deposition of the overlying sediments.

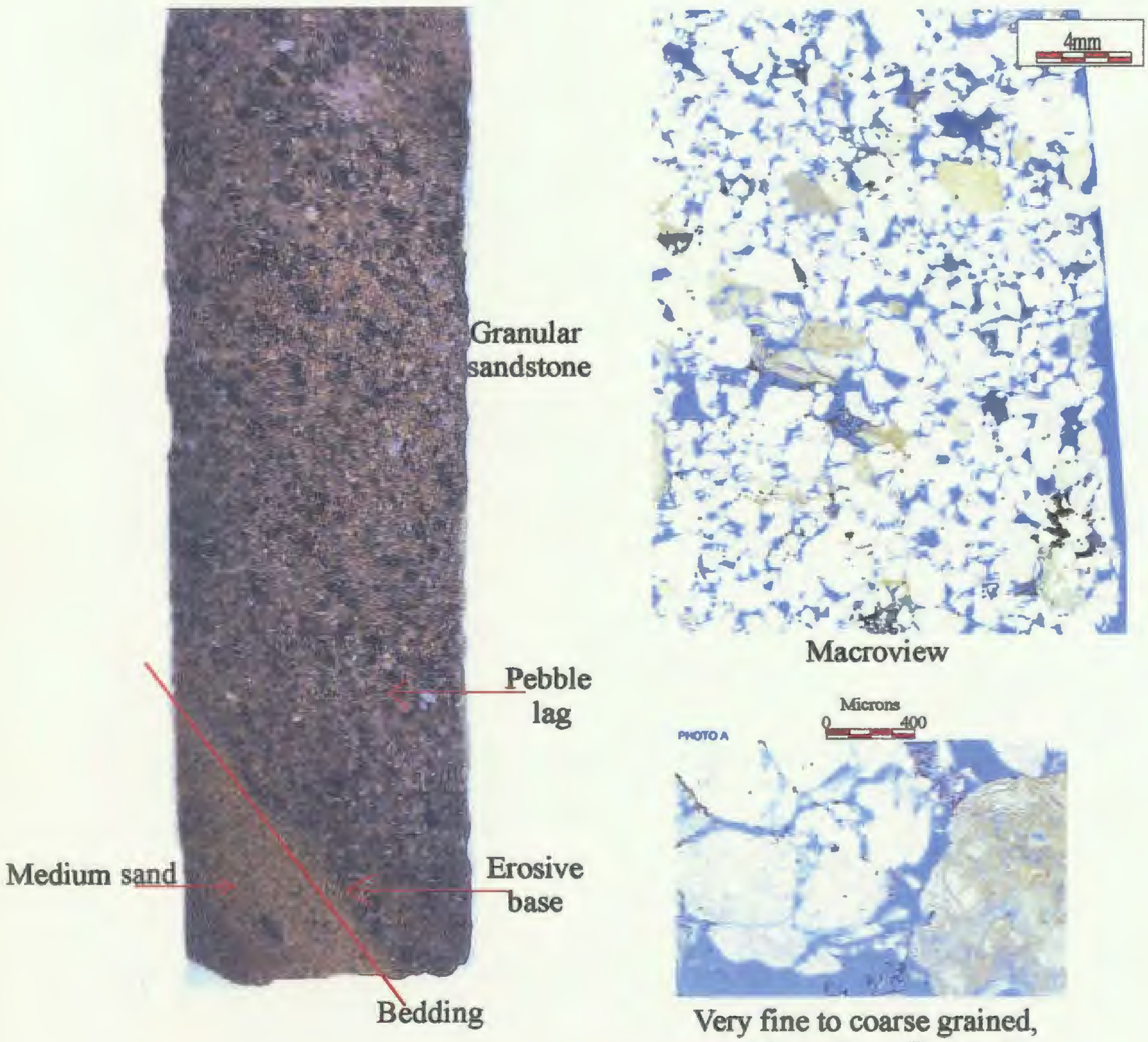
Facies H15: Very coarse sandstone

DESCRIPTION. Rocks comprising facies H15 are poorly to moderately sorted, grey very coarse grained sandstone with scattered granules. However, in rare instances these very coarse grained sandstones fine upwards to medium grained sandstone. Erosional surfaces, pebble and granule lags mark the bases of these very coarse grained beds (Figure 3.15). The lags are composed of mud rip-up clasts, quartz, pyrite, siderite and ironstone clasts within a very coarse to medium grained matrix. Bed thicknesses range from thin to thick bedded (7-92 cm thick). Granule laminations define a crude stratification throughout the facies.

PROCESS INTERPRETATION. Very coarse sandstones and granule laminae may have formed in the upper flow regime under flow conditions of limited traction transport (Arnott and Hand, 1989). The coarse nature of the deposits implies that a high-energy flow was required for sediment transport.

HIBERNIA B-16-2 WELL
DEPTH: 4396.12 m

HIBERNIA B-16-2 WELL
DEPTH: 4394.86 m



Very fine to coarse grained, moderately well sorted quartzarenite

Figure 3.15. Granular sandstone characteristic of facies H15. The bases of these sands are denoted by erosive contacts and pebble lags. Photomicrographs to the right show very fine to coarse grained, moderately well sorted sandstones that commonly overlie the granular sands of facies H15 in upward fining successions. Core and photomicrographs are courtesy of HMDC.

Facies H16: Carbonaceous, Granular Sandstone

DESCRIPTION. This facies is composed of carbonaceous, light grey to dark brown very coarse to medium grained sandstone with abundant granules. The defining characteristic of this facies is the abundance of carbonaceous debris (1.8-3.4 cm in length) in the granular sandstone (Figure 3.16). This facies occurs once in well B-16-2 and it is 78 cm, thick. This bed has an erosive basal contact. There are no visible sedimentary structures in this facies.

PROCESS INTERPRETATION. This facies may have formed under upper flow regime conditions, like facies H15. The presence of erosive contacts, abundant carbonaceous debris and coarse nature of the deposits all reflect high-energy transport.

3.3 Facies Associations and Environmental Interpretations

Facies associations observed in the Hibernia Formation cores reflect a proximal to distal transition with respect to a fluvial source. The facies recognized have been interpreted to range from distal offshore, open-marine to more proximal upper delta-plain depositional settings. Seven major facies associations have been identified. This section will provide environmental interpretations for the facies previously identified in the Hibernia cores.

3.3.1 Facies Association I: Offshore

Facies Association I comprises deposits characteristic of offshore, open-marine, fair-weather conditions. These deposits are characteristic of the field-wide Medial Shale,

HIBERNIA B-16-2 WELL
DEPTH: 4401.85 m

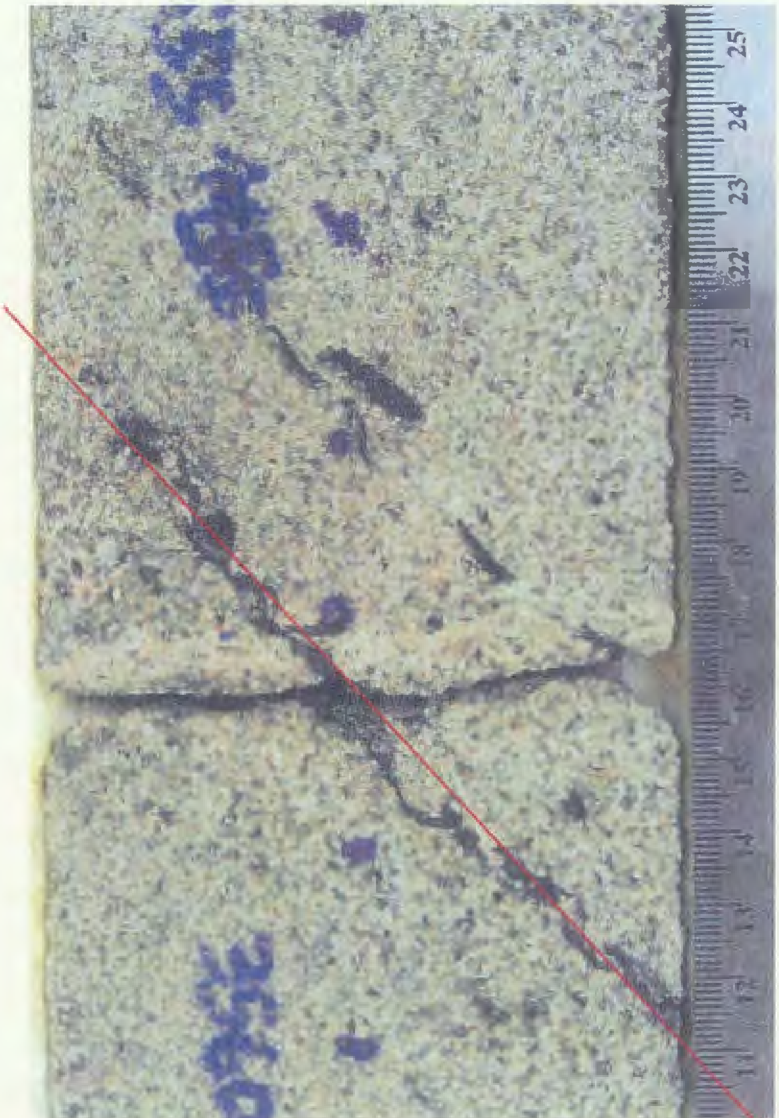


Figure 3.16. Carbonaceous, crudely stratified very coarse to granular sandstone characteristic of facies H16. The stratification is defined by carbonaceous Debris.

which separate Layers 3 and 2 of the Hibernia lower zone (Figure 1.3). This facies association is comprised exclusively of facies H14. A typical interval representative of this facies association can be found in the B-16-17 graphic column in appendix two at a depth of 3993.85-3981.28 m.

The fine-grained nature of the sediment, lack of wave-generated structures, and high levels of bioturbation indicate that deposition occurred by suspension settling below wave base in open-marine depositional settings under fair-weather conditions. The presence of *Chondrites* and *Planolites* in the grey silty shales is also consistent with highly oxygenated, fully open-marine settings (Pemberton et al., 2001).

The deposits characteristic of facies association I indicate a rise in relative sea-level, which resulted in the complete drowning of the pre-existing fluvio-deltaic system. This rise in relative sea-level resulted in the development of a field-wide transgressive marine flooding surface at the base of facies association I. This surface was observed in both the B-16-4 and B-16-17 wells at depths of 4652.10 m and 3993.85 m, respectively. A *Glossifungites* (firmground) trace-fossil assemblage is recognized at the contact between the underlying lower delta-plain to back-barrier lagoonal facies and overlying open-marine shales. In core, this contact is marked by a lag of shell debris, siderite clasts, and quartz pebbles (Figure 3.17). Pemberton et al. (2001) recognize four stages in the development of the *Glossifungites* suite. The muddy substrate is initially buried, dewatered, and compacted. This is followed by erosional exhumation of the muddy substrate, resulting in the development of a firm substrate. This firm substrate is then colonized during a depositional hiatus. The resulting structures are later passively filled

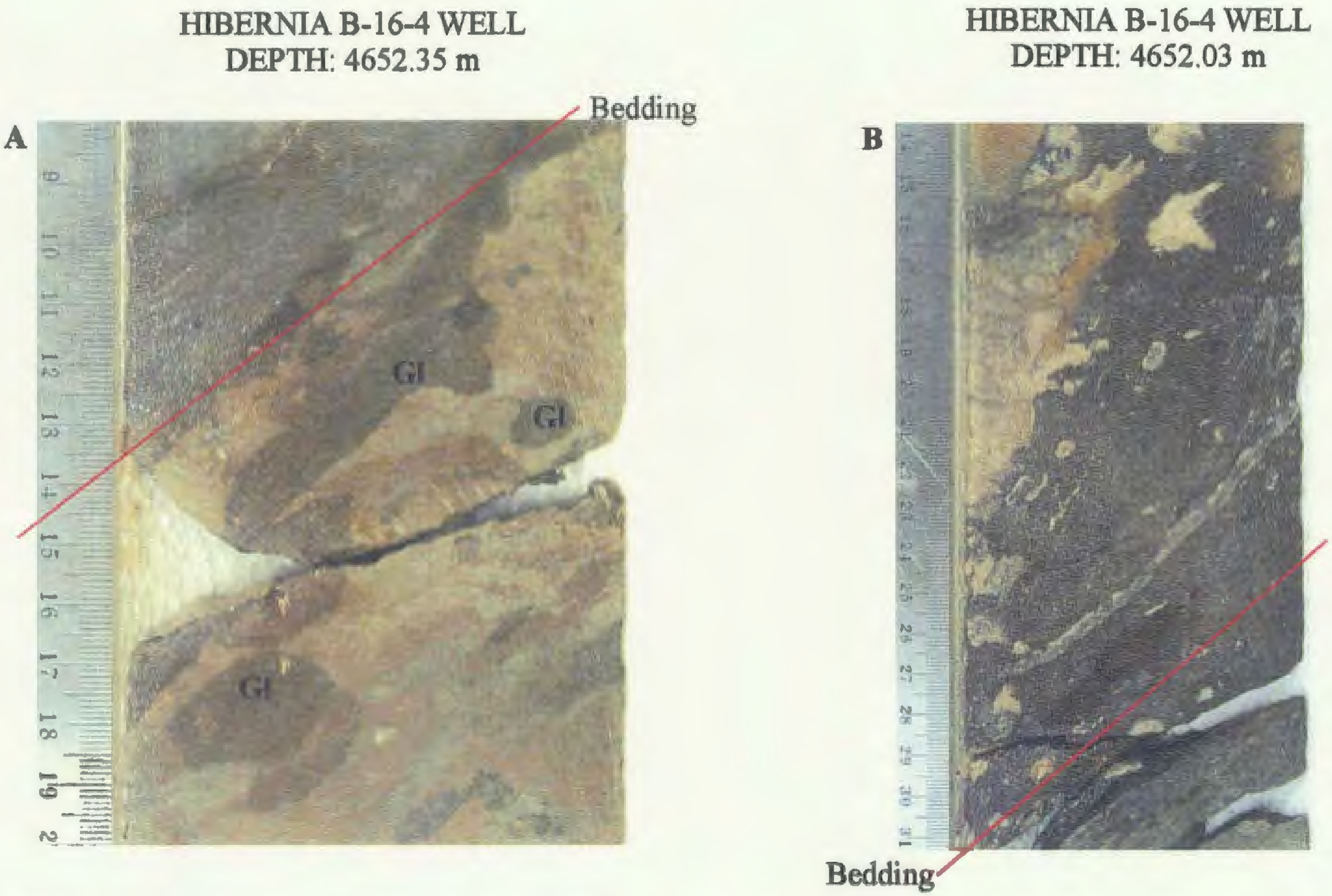


Figure 3.17. (A). *Glossifungites* (Gl) firmground traces below a marine transgressive surface. **(B).** Pebble lag and shell debris overlying the *Glossifungites* trace assemblage.

during the succeeding depositional episode. Thus, recognition of the *Glossifungites* suite indicates a depositional hiatus occurred at some point between the erosional event and the accumulation of the overlying facies. It also indicates that deposition occurred in shallow water to marginal-marine settings (Pemberton et al., 2001).

3.3.2 Facies Association II: Prodelta to Delta-front transition

Facies Association II can be found in the uppermost interval of the Fortune Bay Formation. Of the three wells used in this study, the B-16-17 well is the only one, which samples this interval. This succession records the transition from prodelta to the delta-front facies for the overlying Hibernia Formation. Graphic columns and well logs indicate several upward coarsening cycles, which suggest several progradational events. This facies association includes facies H1 and H2 (see Table 3.1). The only occurrence of this facies association occurs at the base of the B-16-17 graphic column in appendix two at a depth of 4099.95-4088.37 m.

3.3.2.1 Prodelta

The deposits of facies H1 represent the prodelta facies for the overlying Hibernia Formation. This facies consists of interbedded clays and silts deposited from suspension. The lack of wave-generated structures implies fair-weather, sub-wave-base conditions both during and after deposition. Burrowed layers interbedded with layers that show little or no bioturbation and siderite nodules present in the B-16-17 well are also characteristic of prodelta deposits (Coleman and Prior, 1981). Rare silt lenses signal the transition to a delta-front depositional setting.

3.3.2.2 Delta-Front

The deposits of facies H2 represent the delta-front facies for the overlying Hibernia Formation. Upward coarsening shales to fine grained sandstones characterize these deposits. Moderate to locally intense bioturbation, carbonaceous debris, scour-and-fill features, shell debris and current ripple lamination are all characteristics of this depositional environment (Coleman and Prior, 1981). These features are typical of high flood on the river when currents "feel" the bottom and produce a wide variety of sedimentary structures (Coleman and Prior, 1981). Nutrient-laden river outflow reduces the salinity and makes the environment favorable for burrowing (Coleman and Prior, 1981). Shell debris and bioturbation characterize the more seaward portions of the delta front and occur in the lower portions of each upward coarsening cycle. Bioturbation leads to the destruction of lamination, thus accounting for its absence in these deposits. Graphic columns and well logs through the Fortune Bay interval show several upward coarsening cycles. The upper limit of each cycle is marked by a sharp change from interbedded, bioturbated sandstone and shale to non-bioturbated grey shale (Figure 3.18). The significance of these cycle contacts will be discussed in chapter five.

3.3.3 Facies Association III: Lagoonal/Bay

Facies Association III comprises deposits characteristic of lower delta-plain to lagoonal/bay depositional environments. These deposits are characteristic of a portion of the fine-grained sediments that exists between the coarser reservoir sands of the Hibernia Formation. These fine-grained deposits are characteristic of the K18 Shale and 3M Shale-

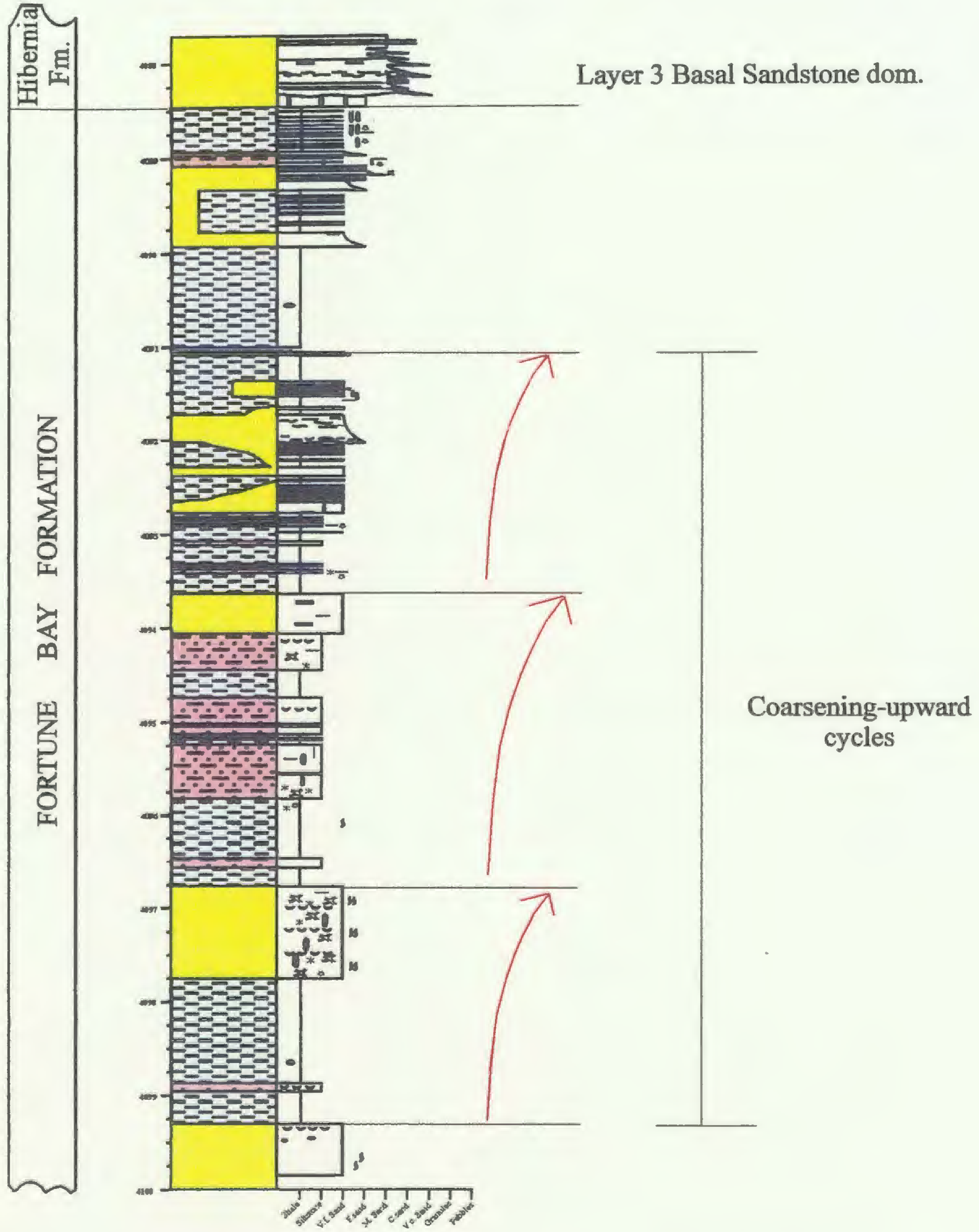


Figure 3.18. Coarsening-upward cycles characteristic of the Fortune Bay Formation observed in the Hibernia B-16-17 well. The top of each cycle is marked by a sharp change from interbedded, bioturbated sandstone and shale to grey Shale.

dominated intervals and several other finer-grained intervals within the reservoir sands themselves (Figure 1.3). This facies association includes facies H13 and H6. A typical interval containing this facies association can be found in the B-16-2 graphic column in appendix two at a depth of 4202.40-4196.0 m.

3.3.3.1 Washover

The sharp-based, bioturbated, coarse to fine grained washover sands of facies H13 contain shell debris and mud clasts along with planar, erosive-base sandstones dominated by horizontal laminations and lags of coarse grained sandstone that subdivide apparently uniform thicknesses of horizontal laminated sandstone into 1-10-cm-thick depositional units characterize washover deposits (Reading and Collinson, 1996). During storms, shell debris can be transported from the foreshore environment and deposited on washover fans. Reinson (1992) states that washover deposits have a high potential for preservation in a transgressive succession. The preservation of common carbonaceous debris and 10 cm thick depositional units are consistent with washover settings. The common carbonaceous debris suggests proximity to an exposed area such as a barrier island. Bioturbation of washover sediments is common shortly after deposition while the sediment is still moist. The diverse suite of brackish-water traces such as abundant *Ophiomorpha* and rare to common *Teichichnus, Planolites, Thalassinoides* and *Skolithos* observed in this facies also supports a washover setting.

3.3.3.2 Lagoon

The fine-grained nature of facies H6 along with the preservation of carbonaceous debris, and a low diversity, brackish-water trace-fossil assemblage all suggests a low energy, lagoon-to-bay depositional environment. The interbedded to interlaminated silts and sands of facies H6 could represent either distal parts of crevasse splays or washover deposits. The lack of shell debris characteristic of lagoonal settings implies that these deposits accumulated well above the transgressive surface where shell debris is more rare. The presence of very thin coal beds could be indicative of either sand or mud flats of the lagoonal margin, or emergent and vegetated washover flats (Reinson, 1992). The sands and silts of facies H6 contain carbonaceous debris and current ripple lamination, which could indicate a fluvial as opposed to a washover setting. However, both of these features are also characteristic of washover deposits. Rooted shales indicative of marsh settings of facies association IV occasionally overlie other components of facies H6. These shales suggest the progradation of subaerial delta-plain facies over the lagoonal facies. The overall fluvial-deltaic nature of the Hibernia Formation makes it more likely that the lagoonal sands and silts are parts of crevasse splays, as opposed to washover deposits. The preservation of carbonaceous material suggests a protected quiet-water setting such as would be expected behind a barrier-island complex. No barrier island was identified in the cores examined for this study, however, the washover deposits of facies H13 point to nearby barrier islands. The presence of a potential nearby barrier system justifies a protected lagoonal setting, as opposed to an open bay setting.

3.3.4 Facies Association IV: Overbank

Facies Association IV comprises deposits characteristic of lower delta-plain depositional settings. These deposits include a moderate portion of the fine-grained sediments that exist within the reservoir intervals of Layers 3 and 2. This facies association includes facies H4, H8, H10 and H11. A typical interval containing this facies association can be found in the B-16-4 graphic column in appendix two at a depth of 4631.0-4616.0 m.

3.3.4.1 Interdistributary bay

The fine-grained deposits of facies 4 and 10 are characteristic of wetland to well drained interdistributary areas on the lower delta-plain. Horizontal and slightly wavy laminations, together with current ripple lamination suggest deposition by suspension settling and limited traction transport under low energy conditions. Interlaminated, poorly sorted claystone, siltstone and very fine grained sandstone, carbonaceous debris, siderite nodules and concretions and rare bioturbation of are characteristic of interdistributary bays settings (Diessel, 1992). The interbedded to interlaminated shales, siltstones and very fine grained sandstones of facies H4 are consistent with interdistributary bay settings. Siderite nodules, suggesting reducing and anoxic conditions are further suggestive of interdistributary bay settings. The bioturbated siltstones of facies H10 exhibit common to abundant rooting and reddish discolorations ascribed to well-drained mature soils, although the preservation of root traces as carbonaceous films suggests reducing conditions.

The characteristics of facies H4 and H10 are suggestive of accumulations in interdistributary bays in close proximity to swamp settings. Rare laminae likely formed in subaqueous ponds with fringing marsh. Better drained areas promoted the development of rooted soils.

3.3.4.2 Marsh

These interdistributary bay deposits are associated with marsh deposits of facies H11 (Figure 3.19). Marshes are low-lying areas of land that experience episodic inundation, during which time suspended fine-grained sediment is deposited through settling. Facies H11 deposits are characterized by muddy sediment, common to abundant rooting, siderite and pyrite nodules, bleached horizons, soil zones, carbonaceous material and thin-bedded coals. Bleached horizons are indicative of oxidizing conditions during episodes of exposure and non-deposition. The greenish-red alterations in the shales suggest periodic development of well-drained soils. The leaching of alkalis and alkaline earths from these soils result in the development of seat earths below the thin-bedded coals (Diessel, 1992) (Figure 3.20). The abundance of carbonaceous material and presence of seat earths overlain by thin-bedded coals at Hibernia suggests that deposition occurred in marsh settings.

3.3.4.3 Crevasse splay

These interdistributary bay and marsh deposits are punctuated by coarser clastic material interpreted as crevasse splays. The deposits of facies H8 are characterized by a brackish-water, slightly burrowed lower interval that coarsens upwards into more well-sorted clastics. Crevasses form as breaks in major distributary channels during flood stages. The flow through the crevasse increases with each successive flood, reaches a time of maximum deposition of a crevasse-splay lobe in the interchannel area, and then wanes causing the splay to become inactive (Coleman and Proir, 1981). With each successive flood, stronger flows transport coarser sediment resulting in an upward

HIBERNIA B-16-4 WELL: INTERVAL 4631.20-4624.0 m

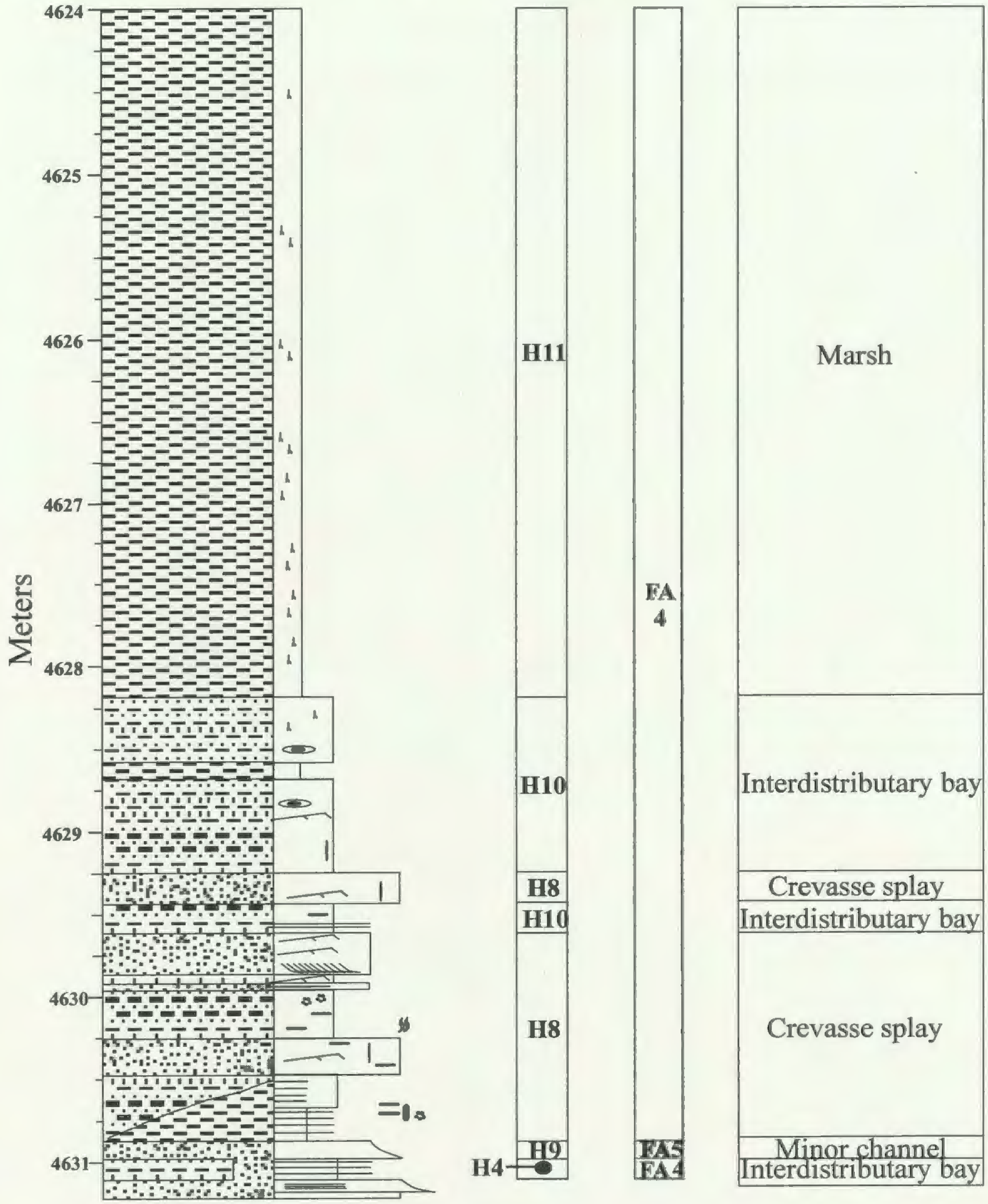


Figure 3.19. Marsh deposits of facies H11are commonly associated with the interdistributary bay deposits of facies H4 and H10. Crevasse splay deposits of facies H8 are also associated with these overbank deposits.

HIBERNIA B-16-17 WELL
DEPTH: 4025.97 m

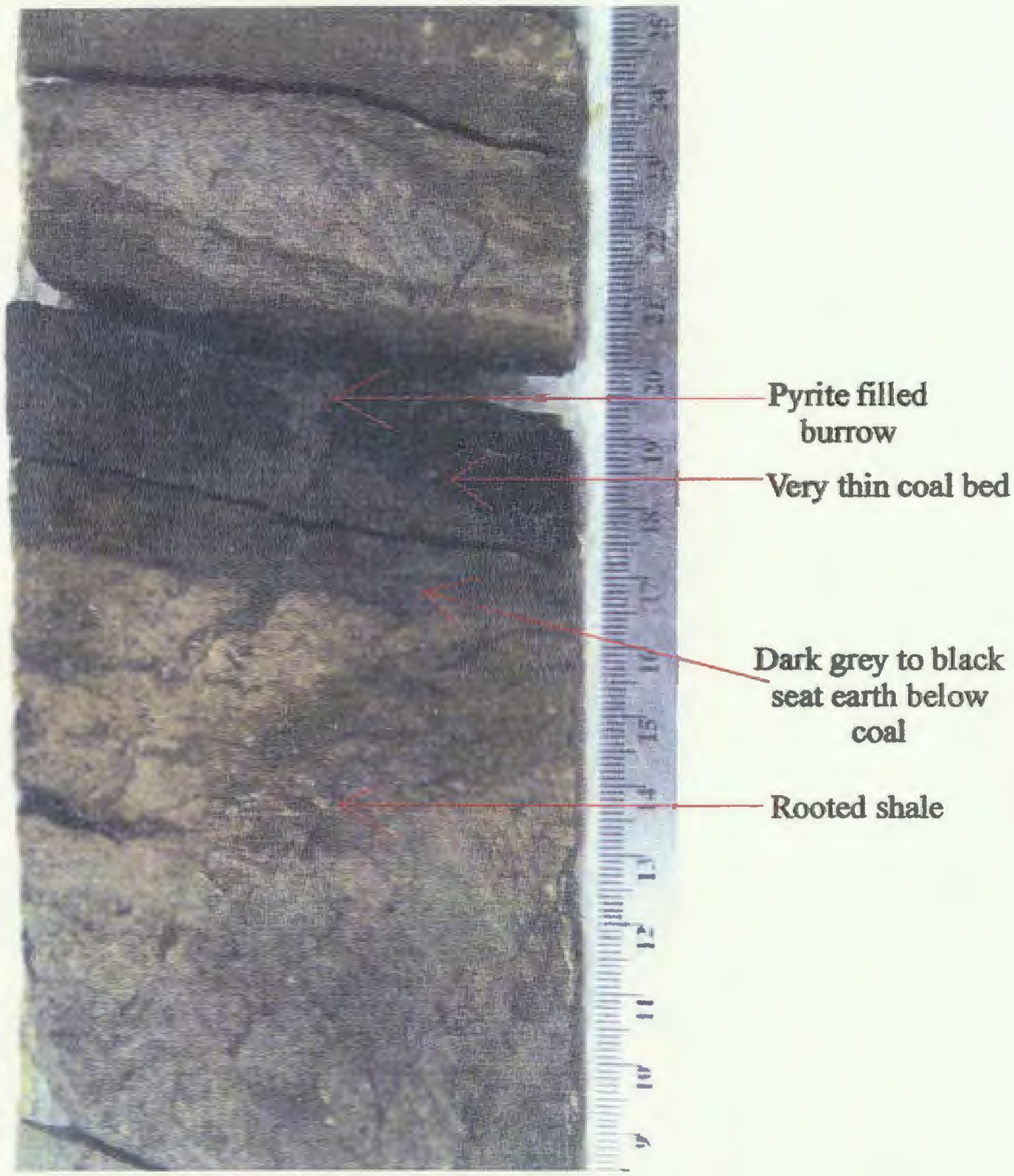


Figure 3.20. Marsh deposits characteristic of facies H11. Rooted shales, dark grey to black shaly coal or coaly shale seat earths below very thin bedded coals are features of this facies.

coarsening succession. Crevasses splays are characterized by an upwards coarsening succession, small-scale crossbedding, climbing-ripple-lamination and horizontal laminations (Reineck and Singh, 1980). Marsh deposits commonly underlie and overlie crevasse-splay deposits. This pattern is observed in the Hibernia cores.

Sedimentary structures that support a crevasse splay interpretation of facies H8 are the presence of common trough cross lamination, rare climbing-ripple-lamination, common horizontal lamination and an overall upwards coarsening succession.

3.3.5 Facies Association V: Minor Channels

The upward fining deposits of facies H9 are interpreted as crevasse channel sandstones. Reading and Collinson (1996) state that medium-scale crossbedding, ripple cross lamination and basal lags comprised of pebbles, reworked nodules and plant debris commonly characterize crevasse channel deposits. The channels were less than 1 m deep and are defined by erosive bases, pebble lags, basal carbonaceous debris, and upward fining, medium grained, planar crossbedded sands to current ripple laminated very fine sandstones and siltstones. The presence of carbonaceous debris suggests a terrestrial source. These deposits are generally only single-story, isolated features and are commonly overlain by lagoonal and overbank facies.

These channel deposits show minor bioturbation. The presence of *Ophiomorpha, Teichichnus, Skolithos* and *Planolites* suggest estuarine conditions in minor distributary channels or crevasse channels on a lower delta plain. The small channel depth suggests that these are crevasse channels. A typical interval representative of this facies association can be found in the B-16-4 graphic column in appendix two at a depth of 4678.30-4676.90 m.

3.3.6 Facies Association VI: Major Distributary Channels

The upward fining sandstones of facies H5 and H12 are characteristic of major distributary channel sands. Erosive bases, pebble lags, carbonaceous debris, and upward fining from planar crossbedded sands to current ripple laminated and horizontal laminated very fine sandstones and rooted siltstones characterize the fill of these channels (Reading and Collinson, 1996). These deposits exhibit minor bioturbation and range in thickness from 1-6 m. Rare apparently bimodal cross stratification at the base of one of the channels suggests that tidal processes may have influenced sand deposition. The distributary channel deposits of facies H12 contains a brackish trace-fossil assemblage consisting of *Ophiomorpha, Teichichnus, Skolithos* and *Planolites*. These traces suggest a tidal/estuarine influence. A typical interval containing this facies association can be found in the B-16-2 graphic column in appendix two at a depth of 4186.0- 4178.30 m.

3.3.7 Facies Association VII: Braided River

Facies Association VII comprises the granular to fine grained, locally carbonaceous braided river sandstones of the Hibernia Formation. These deposits incise into the Fortune Bay Shale marking the base of the Hibernia Formation, and into other brackish-water to open-marine shales within the Hibernia Formation. The recognition and interpretation of incised valleys will be discussed in chapter four. This facies association includes facies H3, H7, H15, and H16 (see Table 3.1). A typical interval comprising this facies association can be found in the B-16-2 graphic column in appendix two at a depth of 4406.0-4386.70 m.

Maill (1977) and Cant (1982) have extensively studied braided river deposits. The features that characterize these deposits are summarized below:

1) Scour-based, sandstones defined by lags of siderite, mudstone and carbonaceous debris define the lower contacts of braided river deposits (Nichols, 1999);

2) Rough upward fining sequences from massive or crudely stratified and crossbedded gravels through trough and planar crossbedded sandstones to horizontal bedded and rippled very fine sands to rooted muds (Miall, 1977);

3) In a undivided channel, the coarsest load is carried along the deepest portion of the channel where competency is the greatest. Waning flow or a reduction in competency results in the deposition of a portion of the coarsest load as a central bar in the deepest portion of the channel (Maill, 1977);

4) Channel abandonment facies comprised of upward fining cycle (Miall, 1977);

5) Facies present include common, crudely stratified gravel, common trough and planar crossbedded sandstones, common rippled and horizontal bedded sandstones and rare to common rooted, rippled and

bioturbated very fine grained sandstone, siltstone and shale (Miall, 1977).

These features will be used to justify the braided river as opposed to meandering river interpretations for the reservoir sandstones of the Hibernia Formation.

The deposits of facies H3, H7, H15 and H16 are composed of granular to fine grained sandstone, deposited in braided fluvial channels constrained within incised valleys. The features observed in the Hibernia sandstones are consistent with those of the Platte type, braided river depositional model proposed by Miall (1977). Facies consistent with this depositional model include common to abundant trough and planar crossbedded sandstones and minor occurrences of horizontally bedded, rippled sandstones and crudely stratified gravel (Miall, 1977).

Facies H15 and H16 occur at the base of the braided river deposits. The minor occurrence of these gravel facies at the base of the braided river deposits in the B-16-2 well are consistent with the features identified by Maill (1977) for longitudinal bars in Platte –type depositional profiles. These gravel bars are characterized by massive or crude horizontal stratification. Miall (1977) attributes longitudinal bar development in a channel to waning flow conditions or a reduction in competency. Miall suggests that the coarsest material is carried along the deepest portion of the channel where competency is the greatest. This coarse material can be deposited as a lag in a scour pool, or as a longitudinal bar due to waning flow or a reduction in competency. The very coarse and granule sediment observed in the B-16-2 well could have been deposited in either way, however the latter is more likely due to the presence of crude horizontal stratification.

Basal lags comprised of siderite clasts, mud rip-up clasts and carbonaceous debris are also consistent with Miall's Platte –type model (Cant, 1982). Braiding commonly occurs in regions where river banks are comprised of noncohesive material as opposed to meandering rivers that occur in regions where river banks consist of fine-grained cohesive material (Campbell, 1976). The erosion into noncohesive river banks results in siderite, mud and carbonaceous debris to be ripped up and re-deposited as lags along channel bases at Hibernia.

The recognition of rough upward fining sequences from massive or crudely stratified gravels through trough and planar crossbedded sandstones to horizontal bedded, rippled very fine sands and rooted siltstones in the Hibernia facies are also consistent with the facies of braided river deposits identified by Miall (1977). Miall (1977) identifies the facies that are used to distinguish braided from meandering rivers.

Table 3.2: Facies characteristic of braided and meandering rivers (Miall, 1977).

Facies occurrence		Braided rivers	Meandering rivers
Gm-	crude gravel	Common (longitudinal bar deposit)	Rare to common (thin lag deposit)
Gt, Gp	trough and planar crossbedded gravel	rare to common	absent
St	trough crossbedded sandstone	common	common
Sp	planar crossbedded sandstone	common	generally rare
Sr, Sh	rippled and horizontal bedded sandstone	common	common
Ss	fine sandstone	rare to common	absent
Fl	sand, silt and mud: rippled, bioturbated, rooted	rare to common	common
Fm	rooted mud	rare to common	common

Trough crossbedding implies that channels were floored by three-dimensional dunes, whereas planar crossbedding implies that straight-crested, two-dimensional dune forms were also present. Maill's Platte –type depositional profile is characterized by stacked planar crossbed sets laid down by linguoid bars (Cant, 1982). Miall further attributes straight-crested dunes as being indicative of transverse bars. Maill (1977) further states that straight crested transverse bars may represent coalesced linguoid bars that formed completely across a channel. The presence of planar crossbedding, and previous evidence for the Platte –type profile suggest the presence of coalesced linguoid bars with a cross channel orientation in the braided river deposits at Hibernia. The common occurrence of planar crossbedding further justifies a braided river as opposed to a meandering river interpretation for the Hibernia sandstones.

The fine-grained facies are locally absent from the braided river succession as seen in the Layer 3Basal Sandstone-dominated interval in the B-16-2 well and in the Layer 3 Middle Sandstone-dominated interval in the B-16-17 well. The absence of these deposits suggests deposition occurred in non-migrating rivers where erosion was augmented by the low rates of fluvial aggradation and limited accommodation space. This results in multi-story sandbodies with numerous internal erosional surfaces. A study by Campbell (1976) focused on well-exposed Jurassic multi-storey channel-fill deposits interpreted to be of braided-river origin. In this study, Campbell recognizes incomplete and complete fluvial sequences. Basal pebble lags and upward fining, trough crossbedded sandstones characterize the incomplete, multistorey fluvial sequences. The complete fluvial sequences are seen at the top of the interval and are comprised of basal pebble lags and upward fining trough crossbedded through to trough cross laminated, parallel laminated and current rippled sandstones at the top. This pattern is also recognized in the Hibernia braided river sandstones. The Layer 3 Middle Sandstone-dominated interval in the B-16-17 well (4049.88-4027.94 m depth), shows numerous incomplete fluvial sequences characterized by basal pebble lags upward fining, planar and trough crossbedded sandstones. The top of Layer 3 Middle Sandstone-dominated interval is marked by a complete fluvial sequence comprised of a basal pebble lag and a upward fining sequence through trough and planar crossbedded and horizontal bedded sandstones, to bioturbated very fine sandstones and rooted siltstones at the top. The criteria provided by Campbell (1976) and Miall (1977) justify a braided river as opposed to a meandering river interpretation for the Hibernia sandstones.

The recognition of a *Glossifungites* assemblage (? *Thalassinoides*) at the lower contact of the facies H3 indicates exhumation, erosion and colonization during a temporary period of brackish to marine influence. The *Glossifungites* assemblage implies an hiatus between the erosional event and deposition of the overlying non-marine facies H3.

3.4 Spatial Arrangements of Facies Associations and Implications for Sedimentary History

The spatial distribution of facies associations within the Hibernia Formation provide criteria for understanding the sedimentary history. Understanding the spatial distribution of facies allows for the recognition of changes in paleogeography that account for the occurrence of the interpreted facies associations.

The prodelta –delta front facies of facies association II mark the transitional facies for the advancing delta system (Figure 3.21) The deposits of facies association VII show that major changes in paleogeography had occurred after the deposition of sediments characteristic of facies association II. The sharp transition from upwards coarsening prodelta –delta-front transitional facies to erosive-based, braided river sandstones constrained within incised valleys, implies a fall in relative sea level and erosion of previously deposited subaqueous deltaic sediments and an overall seaward shift in coastal plain and fluvial sediments.

Within these valley systems, fine-grained, overbank facies of facies association IV are locally present. The preservation of these overbank facies varies throughout the Hibernia Formation (Figure 3.21). These overbank facies are commonly penetrated by minor crevasse channels and major distributary channels of facies associations V and VI respectively. The occurrence of these deposits within the valley systems is broadly consistent with the established paleogeography (Figure 3.22a).

Throughout the Hibernia Formation, lagoonal deposits of facies association III separate each valley system. The lagoonal deposits indicate a change in the paleogeography (Figure 3.22b). Their presence suggests a rise in relative sea level, which allows for drowning of the fluvio-deltaic system. Variable amounts of accommodation space across the field accounts for their significant thickening and thinning across the field (Figure 3.21).

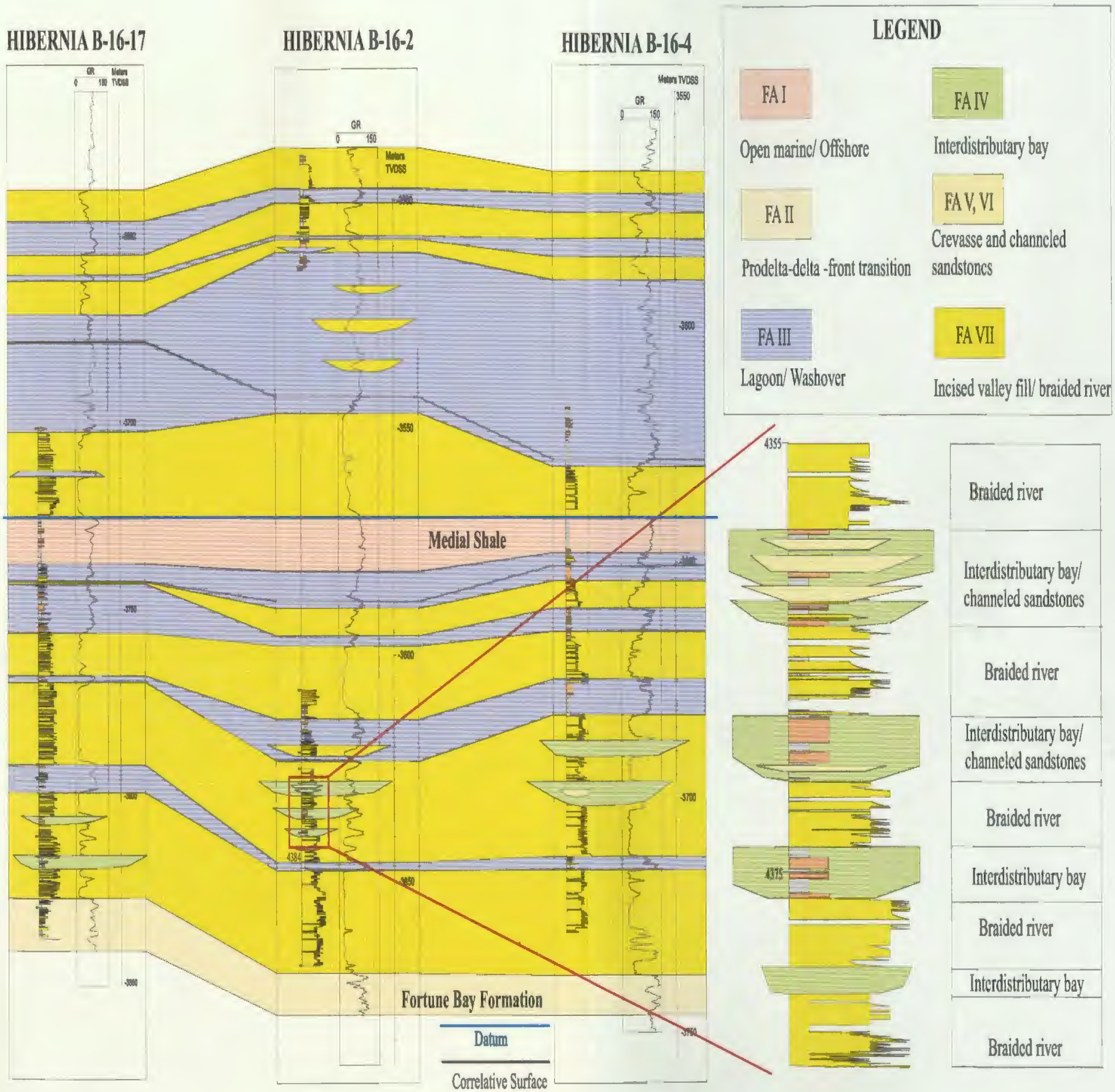


Figure 3.21. Spatial distribution of facies within the Hibernia reservoir. The prodelta-delta-front transition of facies association II occurs within the Fortune Bay Formation. The braided river sandstones of facies association VII are widely distributed throughout the field and show a general thickening towards the east. The overbank facies of facies association IV, are only partially preserved throughout the braided river sandstones. These overbank deposits are commonly penetrated by crevasse splays, minor channels and distributary channels of facies associations IV, V and VI respectively. The lagoonal deposits vary in thickness across the field and separate each of the braided river systems. The offshore, open-marine deposits are fairly evenly distributed throughout the reservoir.

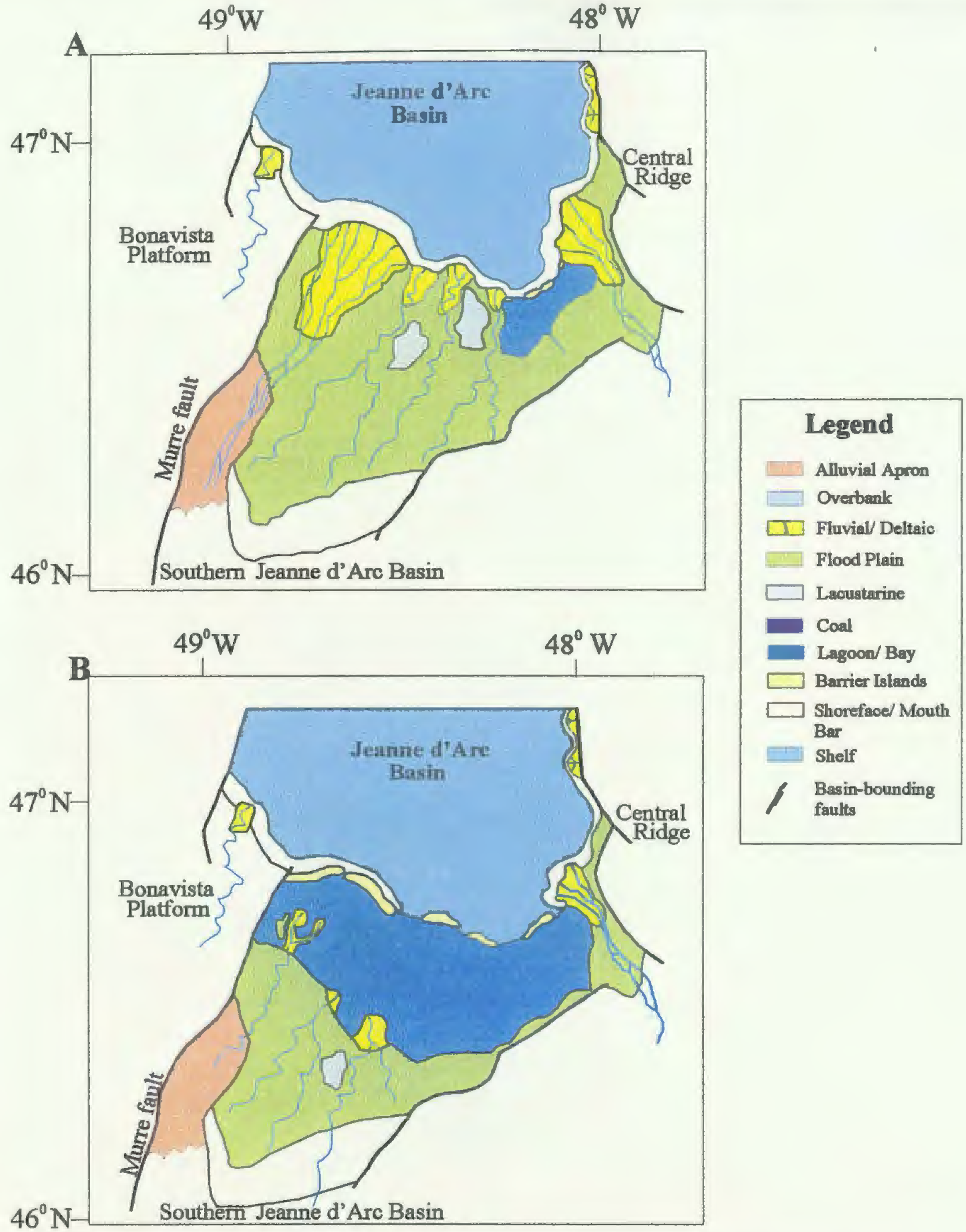


Figure 3.22. (A). The paleogeography of the Jeanne d'Arc Basin during deposition of the braided river sandstones and associated overbank deposits. These sandstones include Layer 3 Basal, Middle and upper sandstones respectively. **(B).** The paleogeography of the Jeanne d'Arc Basin during the deposition of the lagoonal facies which separate the reservoir sandstones. This shows the change in paleogeography which resulted in the drowning of the fluvio-deltaic system (Modified from Sinclair et al., 2002).

A significant change in paleogeography is seen by the occurrence of the offshore facies of facies association I. These deposits indicate a significant rise in relative sea level, which resulted in the complete drowning of the pre-existing fluvio-deltaic system.

CHAPTER FOUR

BREATHITT GROUP FACIES, FACIES ASSOCIATIONS AND ENVIRONMENTAL INTERPRETATIONS

4.1 Introduction

The purpose of this chapter is to provide detailed descriptions and give quantitative facies and qualitative environmental interpretations for the Breathitt Group. Facies descriptions are based on core and outcrop data. The identification of each facies was based on lithology, grain size, textural ratios, sedimentary structures, trace-fossil assemblages and bed thicknesses. Textural ratios (e.g. sand: silt: shale) were calculated in a manner similar to the Hibernia Formation (See Chapter 3, section 3.1). Trace fossils were identified using criteria provided by Howard (1978) and Pemberton (1992). Each facies was then interpreted in terms of the physical and biogenic process by which they were deposited. Finally, in order to facilitate an interpretation of depositional environment, facies were grouped into facies associations (see table 4.1 for a summary of facies, facies associations, and environmental interpretations). The last section of the chapter will discuss the similarities in facies and depositional environments between the Hibernia Formation and the Breathitt Group.

Through the use of drafted stratigraphic sections, a total of fourteen facies were recognized. For this study, no coal descriptions were undertaken. Therefore, coal facies are discussed in conjunction with the facies that immediately underlie the coals. Appendix three contains the general legend used to summarize the characteristics of

Table 4.1: Summary of facies descriptions and interpretations for the Breathitt Group.

FACIES	DESCRIPTION	PROCESS INTERPRETATION	FACIES ASSOCIATIONS	ASSOCIATION INTERPRETATION
7	-black shale and laminated very fine grained sandstone -abundant shell debris -common siderite -dominant trace: *Chondrites*	-deposition by suspension settling under fair-weather conditions -abundance of deposit feeders suggest low energy conditions where food particles are deposited through suspension		Marine shelf
8	-interbedded grey silty-shale and sandstone, -common marine traces -wave ripples present -horizontal laminations	-fluctuating energy levels -articulated oyster shells and horizontal laminations suggest low energy conditions -wave processes suggest increased energy	**I** Offshore	Marine shelf to shoreface transition
9	-erosive-based medium-to very fine-grained sandstone -sands are cross stratified and contain rare shale partings	-formed mainly in lower flow regime -shale partings indicate periodic interruptions in flow		Shoreface

1	-upward coarsening, interlaminated to interbedded shale and sandstone -marine traces of *Cruziana* ichnofacies -current ripples, horizontal laminations and wave ripples -siderite nodules and concretions -shell debris within siderite	-low energy conditions with increasing energy -shales indicate suspension settling in low energy settings. -siderite indicates marine settings characterized by reducing and alkaline conditions. -increasing grain size from clay to very fine sand along with rounded crests of wave modified current ripples suggest higher energy levels.	**II** Mouth bar	Prodelta to delta front transition
2	-fine-grained sandstone -shale content decreases upwards -parallel, current and wave ripple lamination present -carbonaceous debris also present -marine traces of *Skolithos* and *Cruziana* ichnofacies -minor soft sediment deformation	-increasing energy conditions indicated by current ripples overlain by horizontal laminations and upwards decrease in shale -excursion of *Skolithos* conditions on *Cruziana* conditions indicate higher energy levels as opposed to strict *Cruziana* conditions		Distributary mouth bar

4	-interlaminated very fine grained sandstone and shale -carbonaceous debris -simple and diminutive traces belong to the *Cruziana* ichnofacies -current ripple lamination, wave ripples and horizontal lamination -minor oyster shell debris and convolute lamination in sandstones	-deposition by suspension settling under low energy conditions. -fine grained sediment, plant material, horizontal muddy laminations and current ripple lamination indicate suspension settling with limited traction transport. -wave ripples from either marine or wind-generated processes suggest a semi-enclosed water body. -siderite and simple traces suggest reducing and stressed marine conditions	**III** Lagoon to bay	Lagoon
3	-sharp-based, fining upward medium-to very fine-grained sand -current ripple and horizontal laminations -common bioturbation -siderite pebble lags -locally rooted and bleached tops - *Thalassinoides* traces	-waning flow conditions -medium grained sand, horizontal laminations and erosive bases indicate high energy -*Thalassinoides* shows decreased energy	**IV** Overbank-Lower Delta-Plain	Levee/Crevasse Splay

5	-interbedded siltstone and shale -carbonaceous debris, plant debris, moderate rooting, coal and siderite -moderate bioturbation -traces belonging to *Cruziana* ichnofacies -horizontal and current ripple lamination	-deposition by suspension settling with limited traction transport under low energy conditions -current ripples indicate limited traction transport -rooting and soil horizons indicate low energy and periodic exposure	**IV** Overbank-lower delta-plain	Interdistributary Bay
10	-interbedded grey shale and coal -carbonaceous debris, siderite nodules and concretions, common rooting , bleached horizons and pedified zones -minor bioturbation	-low energy conditions with episodes of exposure and non-deposition. -preservation of carbonaceous debris and fine grained sediment suggest suspension settling -siderite suggest reducing and anoxic conditions -leaching of alkalis and alkaline earths from soil zones form seat earths		Marsh

6	-medium to very fine grained sand -erosive bases with pebble lags -carbonaceous debris vertical burrows and traces -horizontal laminations -trough and planar crossbedding, current ripple lamination and convolute lamination.	-upper flow regime with decreasing energy levels -horizontal laminations indicate upper flow regime -trough and planar crossbedding and current ripples indicate lower flow regime conditions	**V** Minor channel sands	Crevasse channel sands and minor distributary channels
13	-upward fining -coarse to very fine grained sand -erosive based sands defined by pebble lags -current ripple lamination, trough and planar crossbedding. -minor bioturbation -horizontal laminations in medium grained sandstone -pebble lags composed of siderite, ironstone and mud rip-up clasts -simple traces of the Cruziana ichnofacies	-upper flow regime with decreasing energy levels -decreasing energy to the lower flow regime seen by presence of trough and planar crossbedding -brackish-water traces indicate an brackish influence during deposition	**VI** Major channel sands on Delta-Plain	Major Distributary Channels

11	-upward fining, well sorted, very coarse to very fine grained sandstone -thin to very thick bedded sands -horizontal lamination, trough crossbedding, planar crossbedding, current ripple lamination -no carbonaceous debris	-upper flow regime with rare episodes of waning flow energy -waning flow energy to the lower flow regime indicated by trough and planar crossbedding and current ripple laminations -massive sandstones formed due to a lack of traction.	**VII** Major fluvial bodies	Incised valley –braided river
12	-upward fining, very coarse to fine grained sandstone -sands are thin to very thick bedded -horizontal lamination, planar and trough crossbedding and current ripple lamination -carbonaceous rich	-upper flow regime with slight decreases in flow energy -crossbedding and current ripple lamination suggest lower flow regime conditions.		Incised valley-braided river

each facies and a detailed stratigraphic section for each of the three Kentucky wells. Measured sections from each outcrop are also included in appendix three.

4.2 Facies Descriptions and Process Interpretations

Facies B1: Upward coarsening, interlaminated to interbedded very fine sandstone and shaly siltstone

DESCRIPTION: Facies B1 is composed of upward coarsening, interlaminated to interbedded shaly siltstone and very fine grained sandstone. It is comprised of 85% shaly siltstone and 15% sandstone. The shaly siltstones are black to grey in color and are thin to very thick bedded (6-76 cm thick). Traces identified in the shale include common to abundant *Planolites* and *Chondrites* and rare *Teichichnus*. Very thin bands cemented by siderite (2 cm thick) and shell debris (2.5 cm in length) are also present, but are rare. Slightly disk-shaped siderite nodules (3 cm in length) and concretions (11 cm in diameter) are also characteristic of this facies. In outcrop, laterally continuous siderite bands and more discontinuous knobby siderite stringers occur vertically about every 10 cm.

The silty sandstones are light beige in color and are thinly laminated to medium bedded (2mm-12 cm thick) (Figure 4.1). Sand content increases upwards throughout each occurrence of the facies. The sands have a lens-shaped geometry in both cores and outcrop. In core, lenticular laminated silty sandstones with lenses ranging in height from 0.2-1.5 cm, and in length from 1-6 cm, exhibit common internal current ripple lamination (set thickness 0.2-1.5 cm) and horizontal laminations. These internal structures are locally

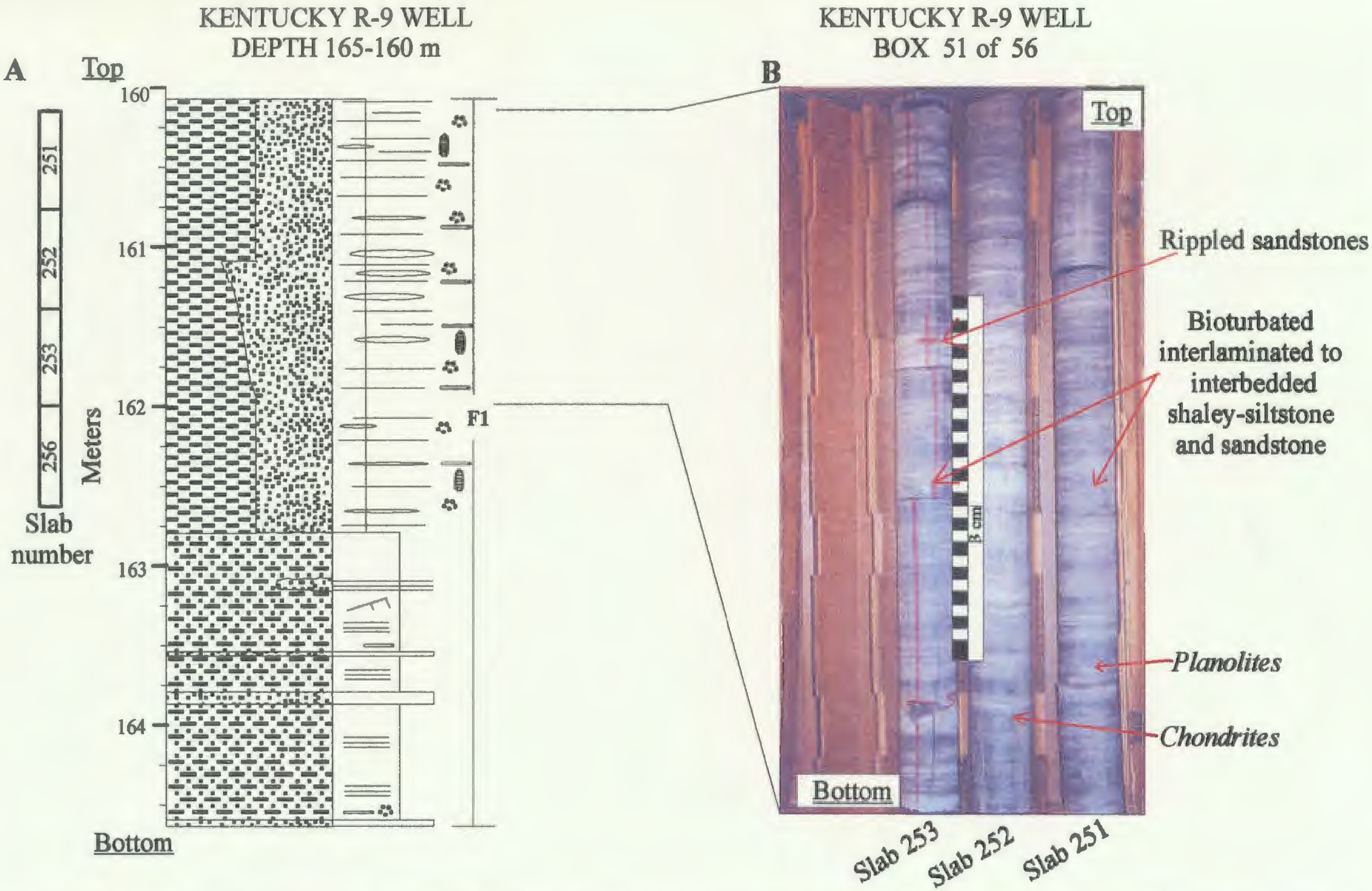


Figure 4.1. Coarsening-upward, interlaminated to interbedded shaley-siltstone and very fine-grained sandstone characteristic of facies 1. **(A).** Graphic sedimentary column showing features characteristic of facies 1. **(B).** Core photo of box 51 of 56 showing bioturbated shale and siltstone and rippled sandstone. Marine traces include *Planolites* (Pl) and *Chondrites* (Ch). .

defined by carbonaceous debris. As sand content increases, rare wave ripples are present. In outcrop, the sandstones pinch out laterally and exhibit wave-modified current ripples (amplitude 2-8 cm). Wave-modified current ripples display slightly rounded crests and have a wavelength of 10 cm. These ripples are symmetrical and contain cross laminae that dip in only one direction. Convolute lamination, approximately 6 cm in height, is also present, but rare. Traces identified include *Planolites* and *Chondrites*.

PROCESS INTERPRETATION: Facies B1 formed under low energy levels with progressively increasing energy with time. Shales were deposited by suspension settling. The precipitation of siderite nodules and concretions further suggest a deeper water, marine setting characterized by reducing and alkaline conditions. Increased energy levels are evident by an upward increase in grain size. Current processes dominated sand deposition with evidence of wave reworking. The coarser grain size and rounded crests of the wave-modified current ripples also suggests an increase in energy conditions. Rounded crests are indicative of higher energy conditions, where concentrations of grains are kept temporarily in suspension during each oscillation, thus allowing grains to be swept from the trough to the crest where they fall from suspension (Nichols, 1999). The subsequent suspension settling results in rounded as opposed to sharp crests, which form due to grain rolling under lower energy conditions.

The *Cruziana* ichnofacies (*Planolites* and *Chondrites*) present in facies B1 indicates marine depositional settings characterized by normal salinity and well-oxygenated waters. *Chondrites* formed in oxygen-depleted portions of substrates in oxygenated settings (Ekdale, 1992). Pemberton et al. (2001) show that the deposit feeders of the *Cruziana* ichnofacies are commonly associated with low energy settings where food particles are deposited. Biogenic reworking of the sediment and siderite suggests deeper water, lower energy settings. The presence of wave modified current ripples indicates increased energy in marine settings.

Facies B2: Upward coarsening fine grained sandstone and shale

DESCRIPTION: Rocks comprising facies B2 are composed of beige, fine grained sandstone and grey shale. The facies exhibits an overall upwards decrease in shale content, from 20% shale in the lower portion to no shale in the upper portion of each occurrence of the facies. The sands are thin to very thick bedded (5-130 cm thick) and are characterized by rare shale laminae, current ripple lamination (set thickness 0.5-1.5 cm), horizontal lamination, carbonaceous debris, siderite nodules (2-4 cm in length) and minor to moderate bioturbation (Figure 4.2). Vertical burrows (2-5 cm in length) and trace fossils identified include common *Planolites* and *Chondrites* in the shales and rare *Palaeophycus* and *Thalassinoides* in the sands are also characteristic of facies B2. In outcrop, the sands are laterally continuous and show oscillation ripples (amplitude 7 cm, wavelength 8 cm). Minor soft sediment deformation includes convolute lamination.

PROCESS INTERPRETATION: Facies B2 formed under conditions of increasing energy. The presence of ripple cross lamination overlain by horizontal lamination and the overall upwards decrease in shale content suggest increased energy settings. Oscillation ripples indicate wave processes have influenced deposition.

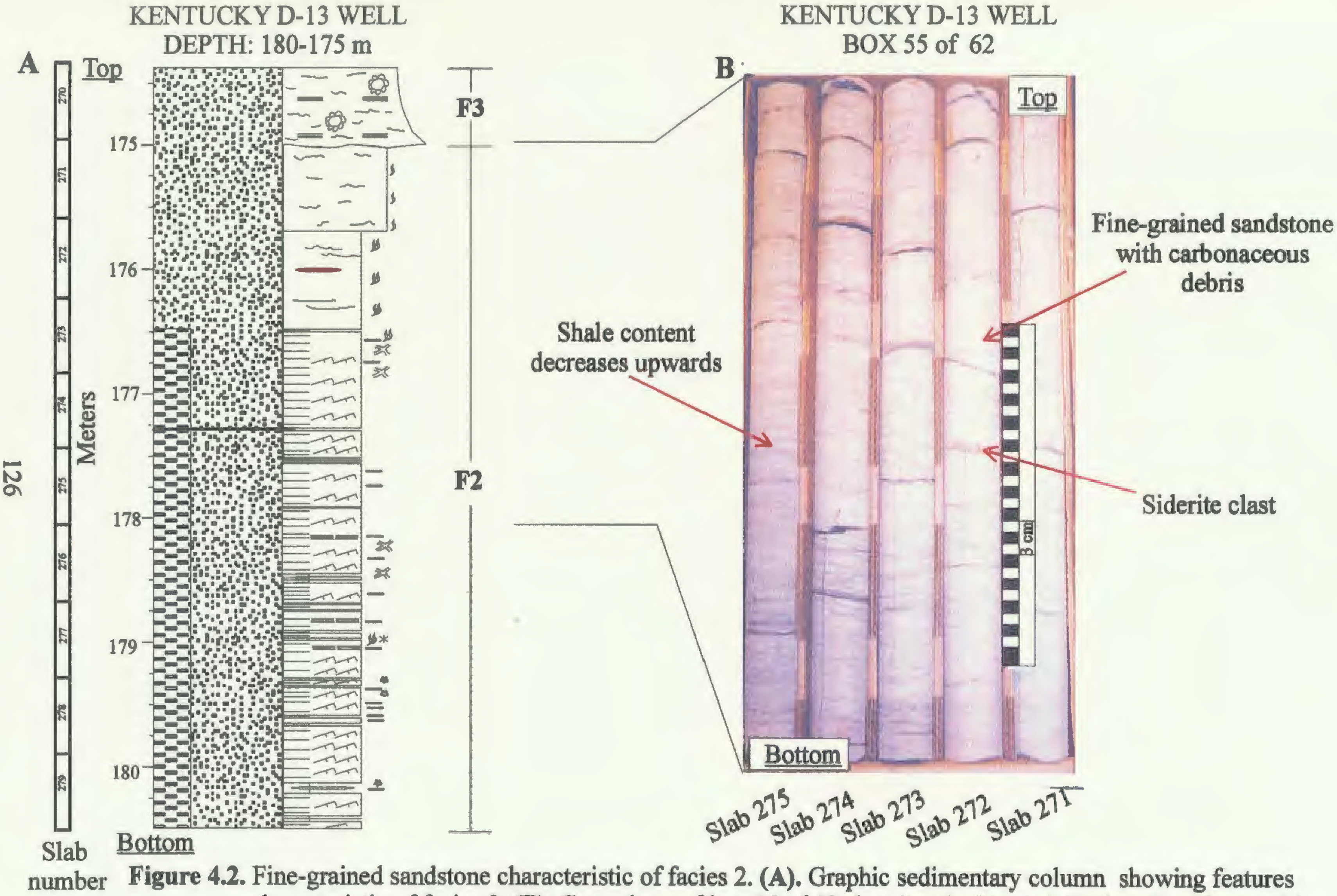


Figure 4.2. Fine-grained sandstone characteristic of facies 2. **(A).** Graphic sedimentary column showing features characteristic of facies 2. **(B).** Core photo of box 55 of 62 showing the interval displayed on the graphic Column. Note the decrease in shale from the base of slab 275 upwards to the top of slab 273.

Traces identified in facies B2 belong to both the *Cruziana* ichnofacies (*Planolites, Chondrites* and *Thalassinoides*) and *Skolithos* ichnofacies (*Palaeophycus*). Pemberton et al. (2001) suggest that the temporary excursion of *Skolithos* –type conditions into a *Cruziana* –type setting indicates an increase in energy levels, which are also evident by the trophic classification of the traces. They show that the deposit feeders of the *Cruziana* ichnofacies are commonly associated with low energy settings where food particles are deposited and suspension feeders of the *Skolithos* ichnofacies are commonly associated with regions where food particles are suspended under increased energy levels. *Cruziana* traces commonly associated with the lower portion of the upwards coarsening sequences suggest, that in these regions, energy levels were sufficiently low enough to allow deposit feeding organisms to flourish in normal saline and well oxygenated settings. Increased energy levels in the upper portion of the upwards coarsening facies are indicated by suspension feeding and dwelling organisms such as *Palaeophycus* traces respectively. Therefore, the biogenic reworking of the sediment also supports deposition under increased energy conditions in marine settings.

Facies B3: Bioturbated medium to very fine grained sandstone

DESCRIPTION: Facies B3 is composed of bioturbated, medium to very fine grained sandstone. Sharp-based, thick-bedded (90 cm thick), normal graded sandstones characterize this facies. Siderite pebble lags (pebbles 2-5 mm in length) define the base of these units. Weak horizontal laminations defined by carbonaceous debris, and current ripple lamination (set thickness 5 cm) locally characterize the medium grained sands. The remainder of the sands exhibit moderate to intense bioturbation (Figure 4.3). The only trace fossil identified in the sandstones were common *Thalassinoides.* In outcrop, the sandstone beds locally have rooted tops, exhibit moderate bleaching, and thin and pinch out laterally.

PROCESS INTERPRETATION: Facies B3 formed under waning energy conditions. The medium sand grade, horizontal laminated fine grained sandstone, and erosive bases indicate high-energy conditions. However, the rarity of physical sedimentary structures and moderate to intense bioturbation suggests that energy levels were low enough during certain periods of time to allow thorough biogenic reworking of the sediment. The lateral thinning and pinching out of sand beds indicates spatially varying flow conditions or limited supply of sand.

The only trace identified in facies B3 belongs to the *Cruziana* ichnofacies (*Thalassinoides*) and is indicative of shallow-marine depositional settings. The distribution of this trace is not controlled by water depth, salinity or sediment composition. Instead, their distribution is controlled by texture and stability of the substrate (Ekdale, 1992). Ekdale (1992) state that *Thalassinoides* forms in quieter depositional settings and suggests waning energy conditions.

The rare rooting and bleaching at the top of the sandstones further suggest a decrease in energy. The rooting and bleaching suggest episodes of exposure and non-deposition.

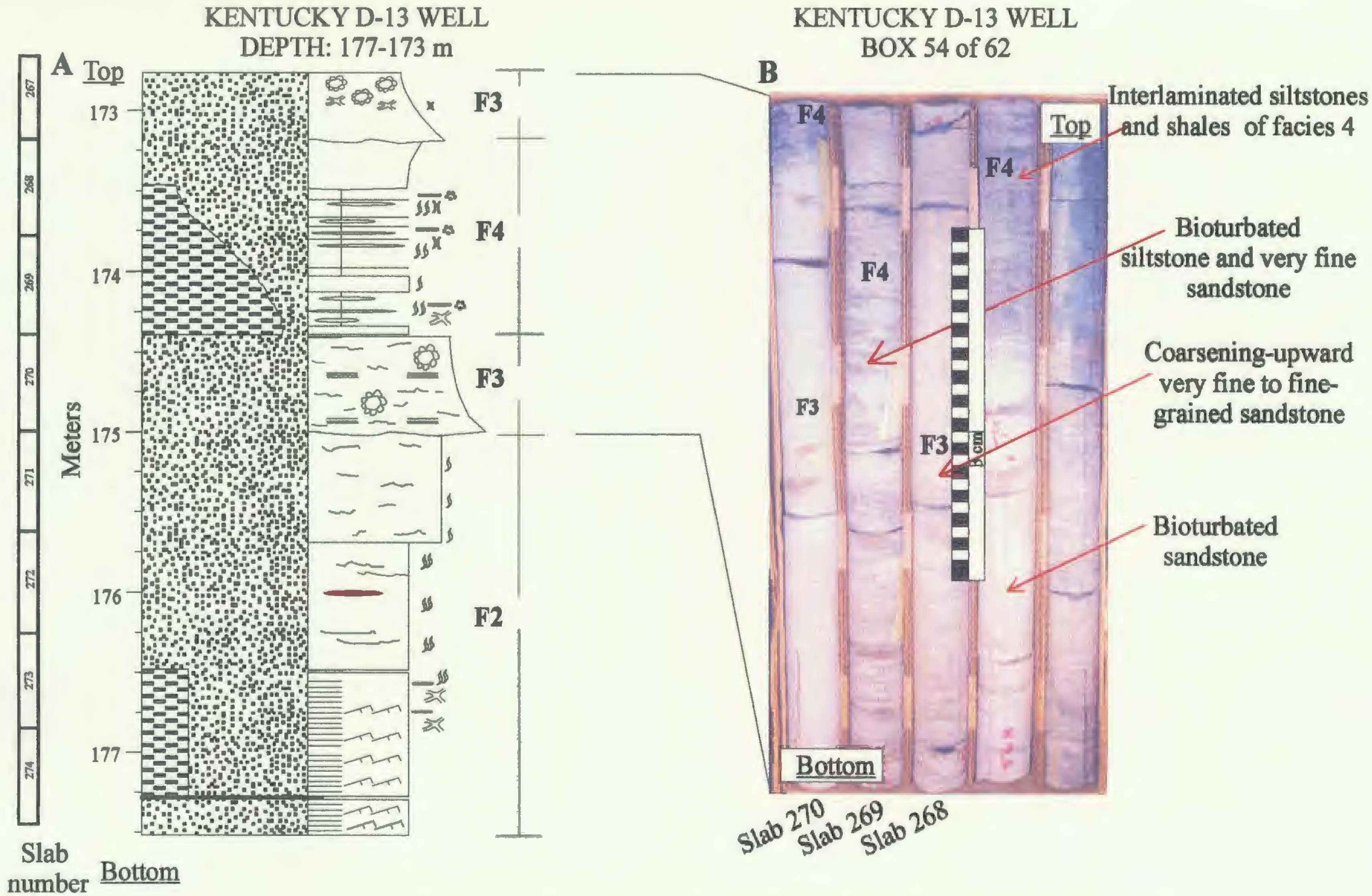


Figure 4.3. Bioturbated, medium-to very-fine grained sandstone characteristic of facies 3. **(A).** Graphic sedimentary column showing features characteristic of facies 3. **(B).** Core photo of box 54 of 62 displayed on the graphic column. These sandstones are interbedded with interlaminated siltstones and shales characteristic of facies 4.

Facies B4: Interlaminated shale, siltstone and very fine grained sandstone

DESCRIPTION: Rocks comprising facies B4 are composed of interlaminated to interbedded grey shale, siltstone and beige very fine grained sandstone. The facies is composed of 55% shale, 30% siltstone and 15% sandstone. The shales and siltstones range from thin to thick bedded (5-65 cm thick). Siderite nodules (1.5 -4 cm in length), thick laminae to thin beds of siderite (0.5-5 cm thick), carbonaceous material, plant debris and slight to moderate and locally intense bioturbation are all characteristic of the shales and siltstones of facies B4. Siltstones exhibit a weak horizontal lamination defined by carbonaceous material and shale laminae. The traces identified are extremely simple and diminutive and include common to abundant *Planolites, Teichichnus, Chondrites,* and ?*Asterosoma* (Figure 4.4). Rare vertical burrows (2 -3 cm in length), locally lined with siderite, are also present in the shales.

The sandstones range from thin laminae to thin beds (0.2-10 cm thick) and locally exhibit a lens-shaped geometry. In outcrop, the sand lenses have a maximum length of five to six meters. Current ripple lamination (set thickness 0.4-2.5 cm), wave ripples (amplitude 2-8 cm, wavelength 5-10 cm), horizontal lamination, minor shell debris, rare convolute lamination and rare *Palaeophycus* traces characterize these sandstones.

PROCESS INTERPRETATION: Facies B4 formed mainly by suspension settling under low energy conditions with fluctuating energy levels. The fine-grained nature of the sediment, preservation of plant material, presence of horizontal muddy laminae and current ripple lamination are all indicative of suspension settling with limited traction

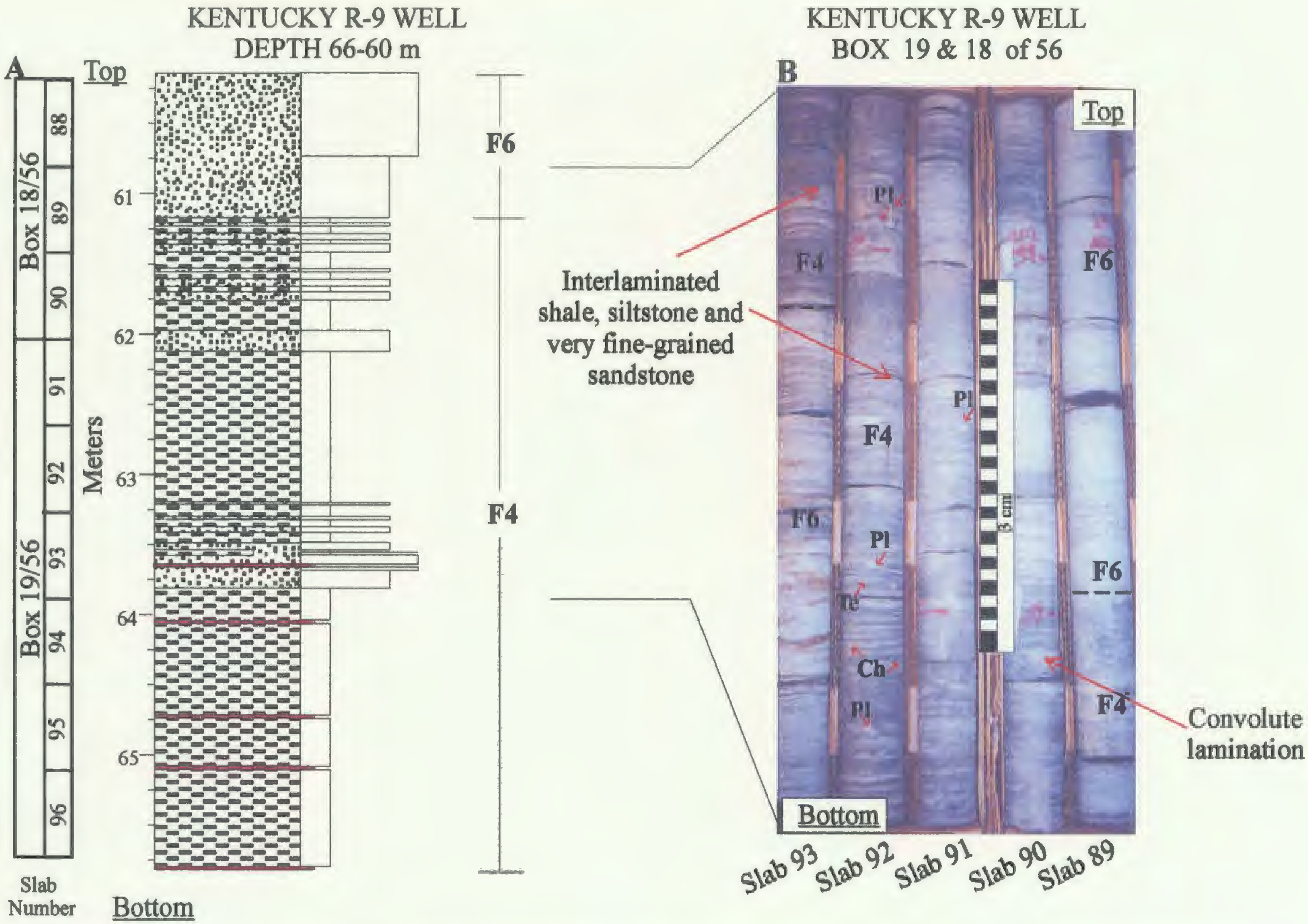


Figure 4.4. Interlaminated to interbedded shale, siltstone and very fine-grained sandstone characteristic of facies 4. **(A).** Graphic sedimentary column showing in detail the features of facies 4. **(B).** Core photo showing moderate to locally intense bioturbation. Marine traces present include *Planolites* (Pl), *Chondrites* (Ch) and *Teichichnus* (Te).

transport in low energy settings. Wave ripples indicate either wave influence during initial deposition in a marginal marine setting, or subsequent reworking by wind generated waves in a semi-enclosed body of water. Siderite nodules tend to form under reducing conditions of shallow burial in organic-rich sediments such as those found in marine deltas.

Traces identified in facies B4 belong to both the *Cruziana* ichnofacies (*Planolites, Chondrites* and *Teichichnus*) and *Skolithos* ichnofacies (*Palaeophycus*) suggesting marginal marine depositional settings (Pemberton et al., 2001). Pemberton et al. (2001) further state that the temporary excursion of *Skolithos* –type conditions into a *Cruziana* –type setting indicates an increase in energy levels, which are also evident by the trophic classification of the traces. Deposit feeders of the *Cruziana* ichnofacies are commonly associated with low energy settings, where food particles are deposited, whereas suspension feeders such as *Palaeophycus* occur in regions where food particles remain in suspension due to increased energy conditions (Pemberton et al., 2001); thus the presence of *Palaeophycus* suggests fluctuating energy levels.

Facies B5: Interbedded shale and siltstone

DESCRIPTION: Rocks comprising facies B5 are composed of 50% grey shale, 45% siltstone and 5% beige very fine grained sandstone. The shales are thin to very thick bedded (4 – 225 cm thick) and are characterized by rare rooting, siderite nodules (1-6 cm in length), thick bedded siderite, rare thick beds of limestone (55 cm thick), siderite pebble lags, carbonaceous material (1-4 cm in length), rare coarser plant debris, reddish-green discolorations, very thin-bedded coals (1-2 cm thick) and rare very fine grained sandstone laminae and lenses. Traces including *Planolites*, *Chondrites* and *Teichichnus* are very rare.

Siltstones are thin to thick bedded (10-90 cm thick) and are characterized by very thin-bedded siderite bands (2cm thick), minor rooting (2-7 cm in length), reddish-green discolorations, carbonaceous material, and slightly discoid siderite nodules (2-4 cm in length). Sedimentary structures include current ripple lamination (set thickness 0.5-1.5 cm), and horizontal laminations defined by shale partings, sandstone laminae and carbonaceous material (Figure 4.5). Vertical burrows (1-3 cm in length) and impoverished traces identified include rare *Planolites* and *Teichichnus.*

The sandstones range from thin laminae to very thin beds (0.2-2 cm thick) and are characterized by horizontal lamination; and current ripple lamination (set thickness 0.5-1.0 cm), and rare convolute lamination (Figure 4.5).

PROCESS INTERPRETATION: This facies comprises fine-grained sediment characterized by the presence of both horizontal lamination and current ripple lamination. These structures suggest that deposition was by suspension settling with limited traction transport. Minor bioturbation, rooting and rare soil horizons suggest low energy conditions and periodic non-deposition and exposure.

Traces identified in facies B5 belongs to the *Cruziana* ichnofacies. Deposit feeders of the *Cruziana* ichnofacies are associated with low energy settings where food particles are deposited through suspension. The dominance of *Cruziana* traces suggests

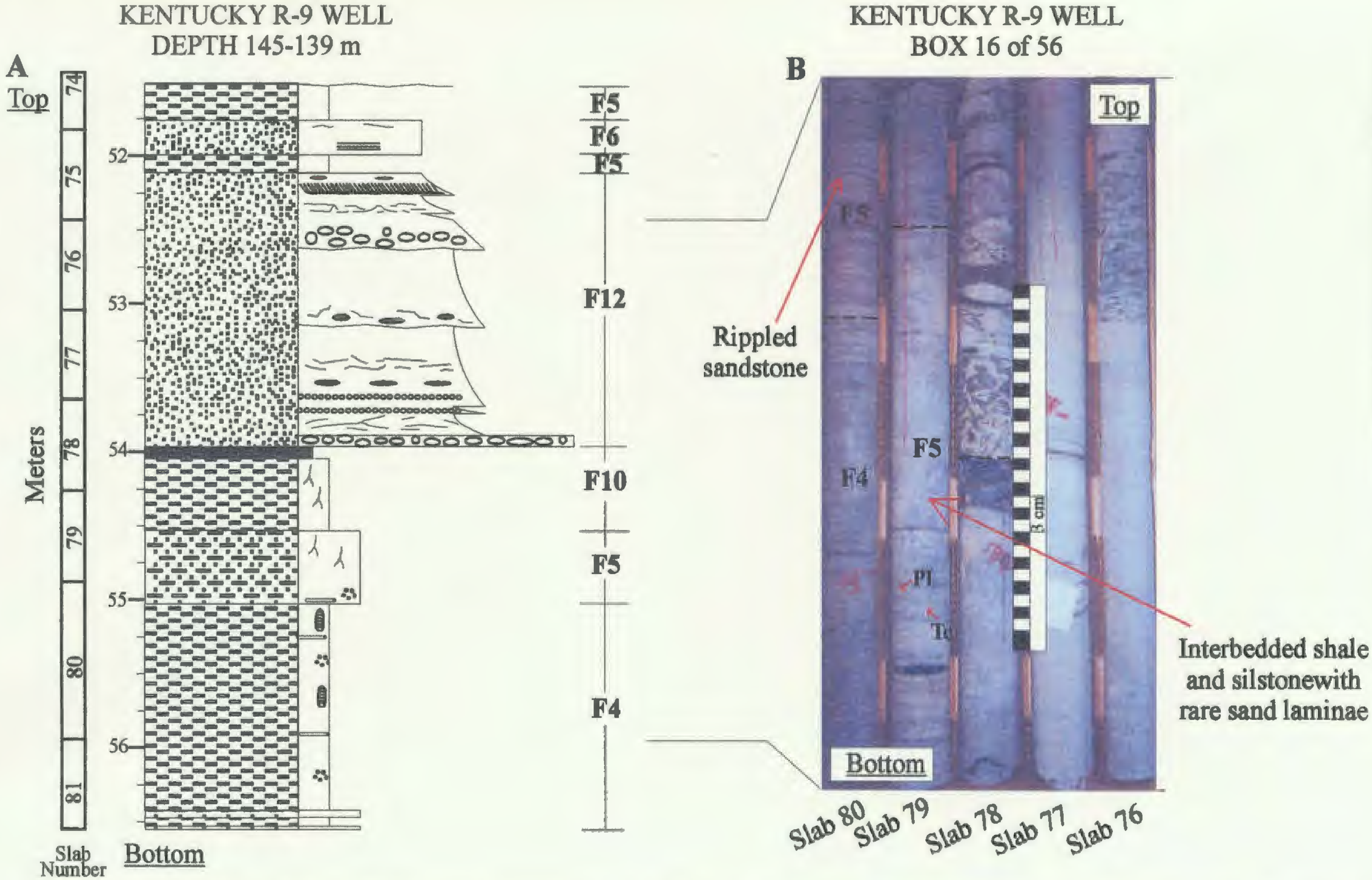


Figure 4.5. Interbedded shale and siltstone characteristic of facies 5. **(A).** Graphic sedimentary column showing the features of facies 5 in detail. **(B).** Core photo of box 16 of 56 showing interbedded shale, siltstone and rippled very fine-grained sandstone. Slight bioturbation is also characteristic of this facies. Dashed lines represent the lower extent of the facies.

low energy settings dominated by suspension settling. The diminutive and impoverished trace fossil assemblage indicate low oxygen levels and overall stressed conditions (Pemberton et al., 2001). These conditions are consistent with marginal marine (lower delta-plain) settings.

Facies B6: Medium to very fine grained sandstone and siltstone

DESCRIPTION: Facies B6 is composed of medium to very fine grained sandstone and interlaminated to interbedded siltstone. The facies is comprised of 90% sandstone and 10% siltstone. The sandstones are medium to thick bedded (10-50 cm thick) and occasionally fine upward from medium to very fine grained sandstone. The sandstones are characterized by sharp erosive bases, minor rooting, slightly discoid and elongated mud rip-up clasts (2-6 cm in length), siderite-cemented laminations and nodules (1-3 cm in length) and carbonaceous material (Figure 4.6). In outcrop, sandstone bed thickness varies laterally from 40-150 cm. Vertical burrows (2-4 cm in height) are also characteristic of the sandstones. Siltstones are associated with the very fine grained sandstones and range from thin laminae to thin bedded (0.2-5 cm thick). Rare current ripple lamination (set thickness 0.5-1.0 cm), vertical burrows (1-4 cm in height) and common traces including *Planolites* and *Chondrites* are characteristic of the siltstones.

Sedimentary structures in the sandstones include horizontal laminations, planar and trough crossbedding, current ripple lamination and convolute lamination. Silt laminae, carbonaceous material and mud chips define the weak horizontal lamination in the sandstones. Planar crossbedding has a set height of 5 cm, whereas trough

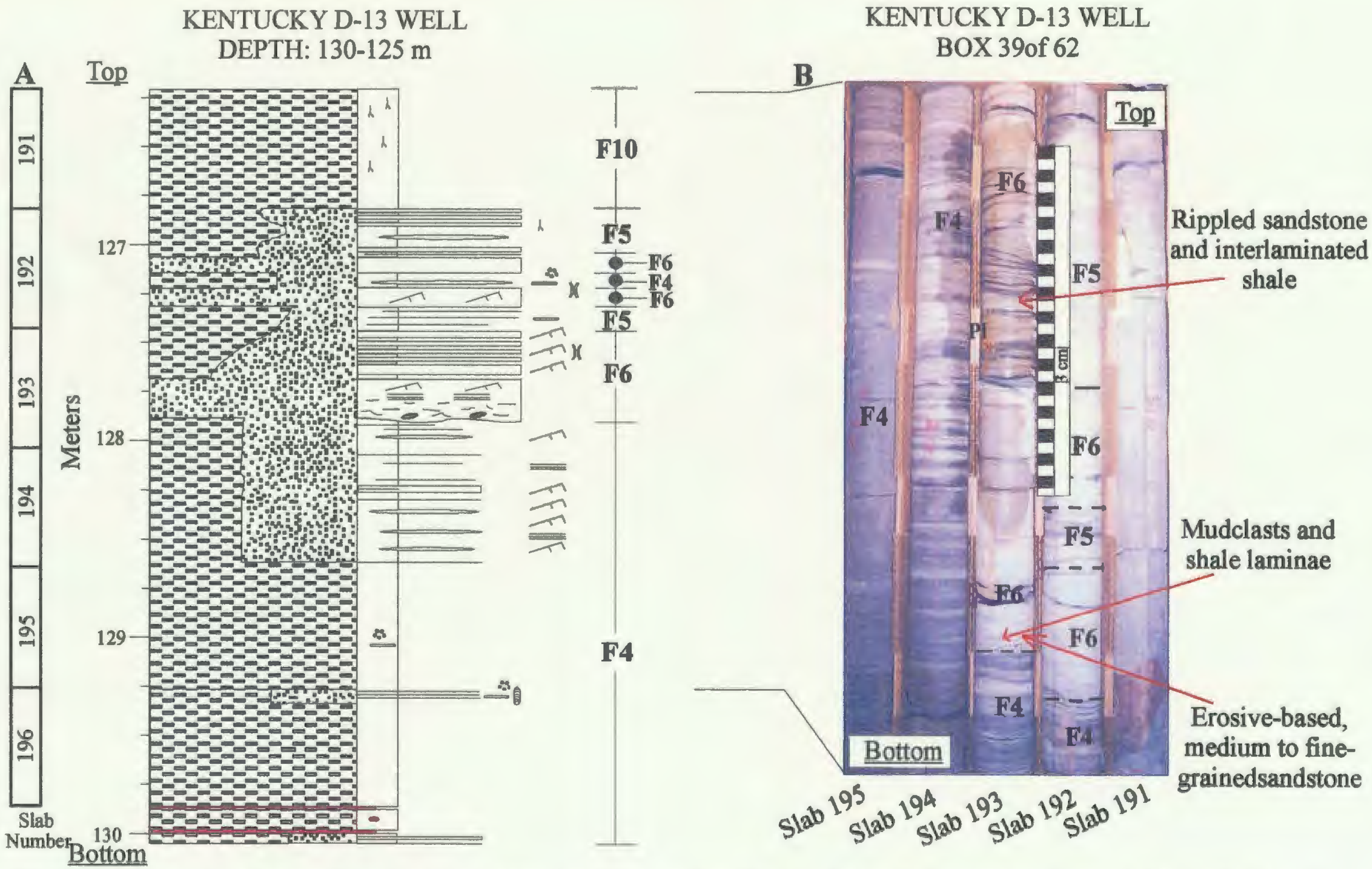


Figure 4.6. Medium-to very-fine grained sandstone characteristic of facies 6. **(A).** Graphic sedimentary column showing in detail the features of facies 6. **(B).** Core photo of box 39 of 62 showing the erosive-based sands of facies 6. These erosive bases are defined by mud rip-ip clasts. Shale laminae contian rare marine traces. Dashed lines represent The lower extent of the facies.

crossbedding has a set height of 5-8 cm. Current ripple cross lamination in the very fine grained sands has a set thickness ranging from 0.5-2.0 cm (Figure 4.6).

PROCESS INTERPRETATIONS: Facies B6 formed under waning flow conditions. Sharp-based sands, mud rip-up clasts, carbonaceous material and horizontal laminations in medium and fine grained sandstones are indicative of upper flow regime conditions. The presence of trough and planar crossbedding overlying the horizontal laminated fine grained sandstones suggests waning flow conditions, as does current ripple lamination in very fine grained sandstones and siltstones, and minor bioturbation.

Common *Cruziana* traces in the very fine grained sandstone and siltstone suggests a waning in flow conditions. Deposit feeders of the *Cruziana* ichnofacies are associated with low energy settings where food particles are deposited through suspension settling. Ekdale (1992) states that *Chondrites* occur in oxygen-depleted substrates below the redox level and therefore requires oxygenated waters for survival. The common presence of *Chondrites* in the fine-grained sediment indicates well-oxygenated settings with overall waning flow conditions.

Facies B7: Black shale and interlaminated very fine grained sandstone

DESCRIPTION: Rocks comprising facies B7 are composed of black shale with laminated very fine grained sandstone towards the upper limits of the facies. The facies is composed of 95% black shale and 5% very fine grained sandstone. The black shale is characterized by very thin to thin bedded siderite bands, siderite nodules (1-5 cm in length), limestone concretions, minor carbonaceous debris, articulated and disarticulated oyster shells (0.3-1.5 cm in length) and brachiopods (figure 4.7). Vertical burrows (1-4 cm in height) and abundant *Chondrites* traces are also characteristic of these shales. Traces identified in the very fine grained sandstone include *Planolites, Teichichnus*, and *Chondrites*.

PROCESS INTERPRETATION: The absence of current or wave generated structures in conjunction with the fine-grained nature of the sediment and articulated oyster and brachiopod shells below the siderite rich zone suggests that the sediment characteristic of facies B7 was deposited by suspension settling below wave base, under fair-weather conditions in more oxygenated waters. The presence of siderite suggests deeper water and restricted oxygen settings. Therefore, both the shell debris and siderite imply fully marine conditions and a potential increase in water depth.

Traces identified in facies B7 belong to the *Cruziana* ichnofacies. Deposit feeders of the Cruziana ichnofacies are associated with low energy settings, where food particles are deposited by suspension settling under low energy settings (Pemberton et al., 2001). The abundance of *Chondrites* is consistent with well-oxygenated, fully marine conditions. Ekdale (1992) states that *Chondrites* forms in oxygen-depleted substrates below the redox level in substrates where unoxidized organic matter is plentiful. *Chondrites* are deep burrows and require oxygenated waters for their survival. The abundance of *Chondrites* in facies B7 indicates well-oxygenated marine conditions. The common occurrence of *Teichichnus* also suggests well-oxygenated settings. *Teichichnus* can also occur in oxygen-depleted substrates and requires oxygenated bottom waters for their survival.

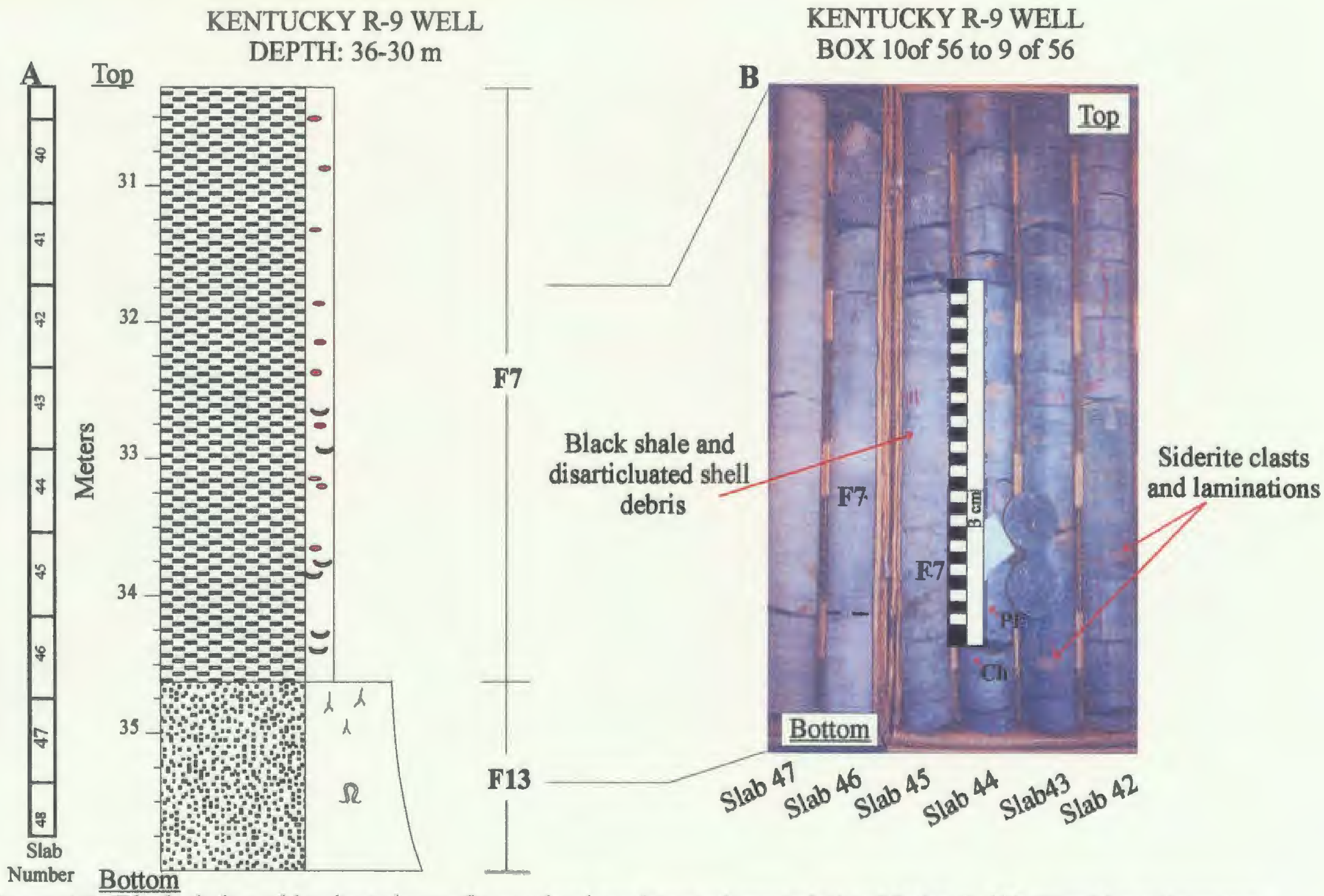


Figure 4.7. Black shale and laminated very fine-grained sandstone characteristic of facies 7. **(A).** Graphic sedimentary column showing in detail some of the features characteristic of facies 7. **(B).** Core photo of boxes 10 and 9 of 56 showing black shale with both siderite clasts and laminations. Marine traces including rare *Planolites* (Pl) and abundant *Chondrites* (Ch) are also characteristic of this facies.

Facies B8: Interbedded silty shale and very fine to fine grained sandstone

DESCRIPTION: Facies B8 is composed of interbedded black shale (15%) and silty-sandstone (85%). Very thin bedded siderite (1-2 cm thick) and articulated bivalve shells (3 cm in diameter) are characteristic of these shales. Locally the shale is fissile. The silty sandstones are composed of interlaminated to interbedded very fine grained sandstone and silty sandstone. Sands occur as thin laminae (2-8 mm), lenses (2-7 cm in length) and rare thin to medium beds (5-12 cm in thickness). In outcrop, the thin to medium bedded sands are discontinuous over distances of 3-4 m. Minor carbonaceous material, vertical burrows (1-4 cm in height) and traces including common *Planolites* and *Chondrites* and rare *Teichichnus* are characteristic of the silty sandstones (Figure 4.8).

Sedimentary structures in the sandstones include horizontal laminations and symmetrical wave ripples that have internal cross lamination dipping towards the west. The silty-sandstones exhibit horizontal laminations defined by laminae of very fine grained sand.

PROCESS INTERPRETATION: Facies B8 formed under low energy conditions with fluctuating energy levels. The fine-grained nature of the sediment implies that deposition was dominated by suspension settling in low energy conditions. Common to abundant bioturbation, articulated bivalve shells and fissile shale in the sediment are suggestive of quiet water settings. Fluctuations in energy levels are evident by the presence of symmetrical wave ripples within the very fine grained sandstone, thus suggesting minor wave reworking during deposition. Wave ripples and bivalve shells are suggestive of marine settings of deposition.

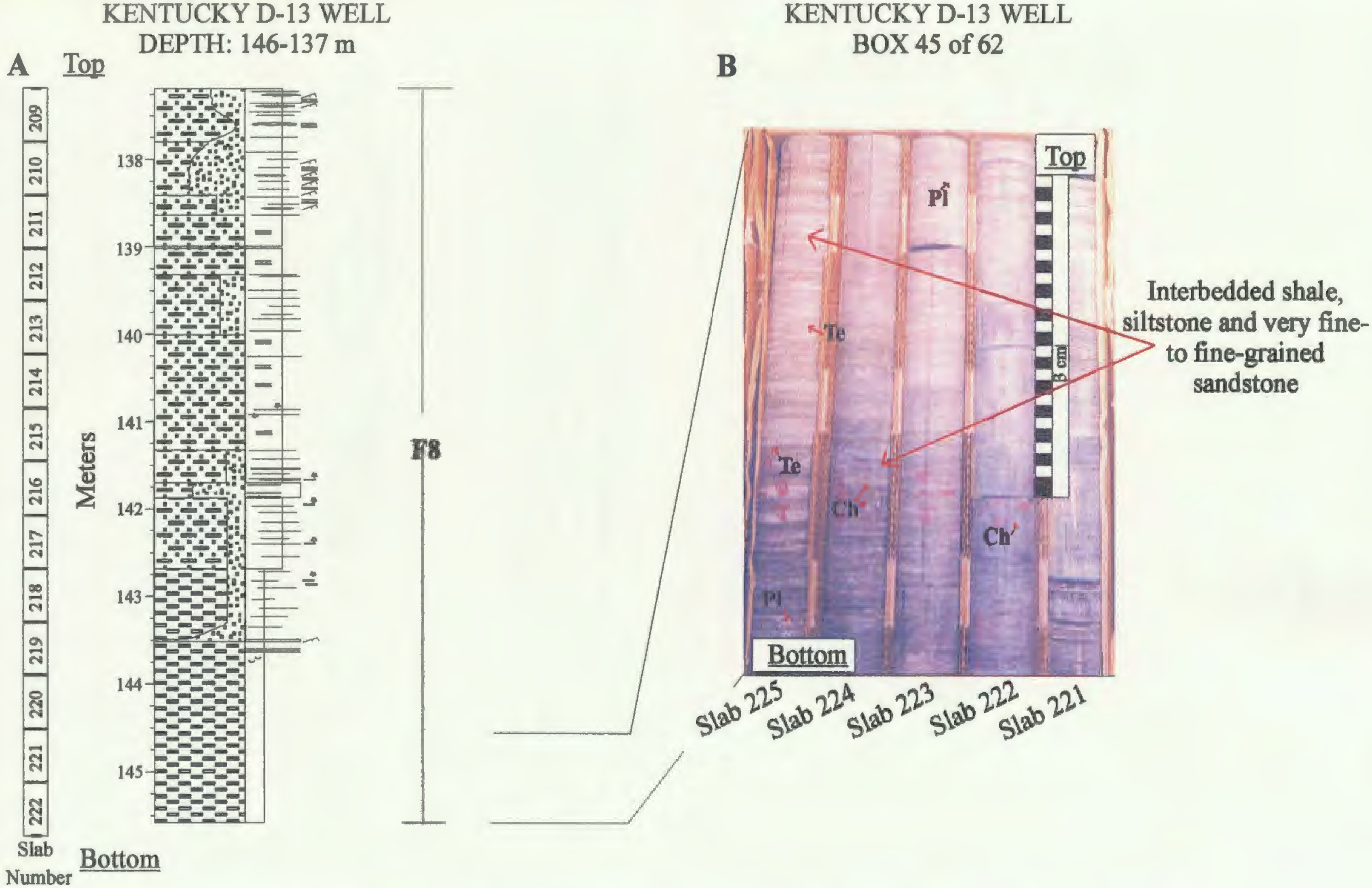


Figure 4.8. Interbedded shale, siltstone and very fine-to fine-grained sandstone characteristic of facies 8. **(A).** Graphic sedimentary column showing in detail the characteristics of facies 8. **(B).** Mmarine traces including Teichichnus (Te), Planolites (Pl) and Chondrites (Ch) are also characteristic of this facies.

The presence of deposit feeders belonging to the *Cruziana* ichnofacies (*Planolites*, *Chondrites* and *Teichichnus*) suggests low energy settings. *Chondrites* and *Teichichnus* occur in oxygen-depleted substrates and therefore require oxygenated waters for survival (Ekdale, 1992). The common occurrence of *Chondrites* and rare occurrence of *Teichichnus* indicate well-oxygenated marine settings of deposition.

Facies B9: Erosive-based, medium-to very fine grained sandstone.

DESCRIPTION: Rocks comprising facies B9 are composed of erosive-based, medium to very fine grained sandstone in medium to very thick beds (15-145 cm thick). The sandstones contain mud clasts (1-2 cm in length), siderite nodules (1-3 cm in length) and discontinuous shale laminae (Figure 4.9). Sedimentary structures include horizontal lamination defined by thicker shale laminae, mud clasts and cross lamination (set height 2 cm). *Planolites* traces are present in the thicker shale laminae, but are very rare.

PROCESS INTERPRETATIONS: Facies B9 formed mainly in the lower flow regime. The horizontal laminations are not indicative of upper flow regime conditions because they are defined by shale partings indicating periodic interruptions in flow. Mud clasts and erosive bases indicate episodes of higher flow velocity. Cross lamination formed beneath migrating current ripples.

Planolites are deposit feeders of the *Cruziana* ichnofacies. Ekdale (1992) states that *Planolites* are less tolerant to benthic oxygen deficiency and therefore, can inhabit a substrate only after bottom –water oxygen concentrations have reached the threshold

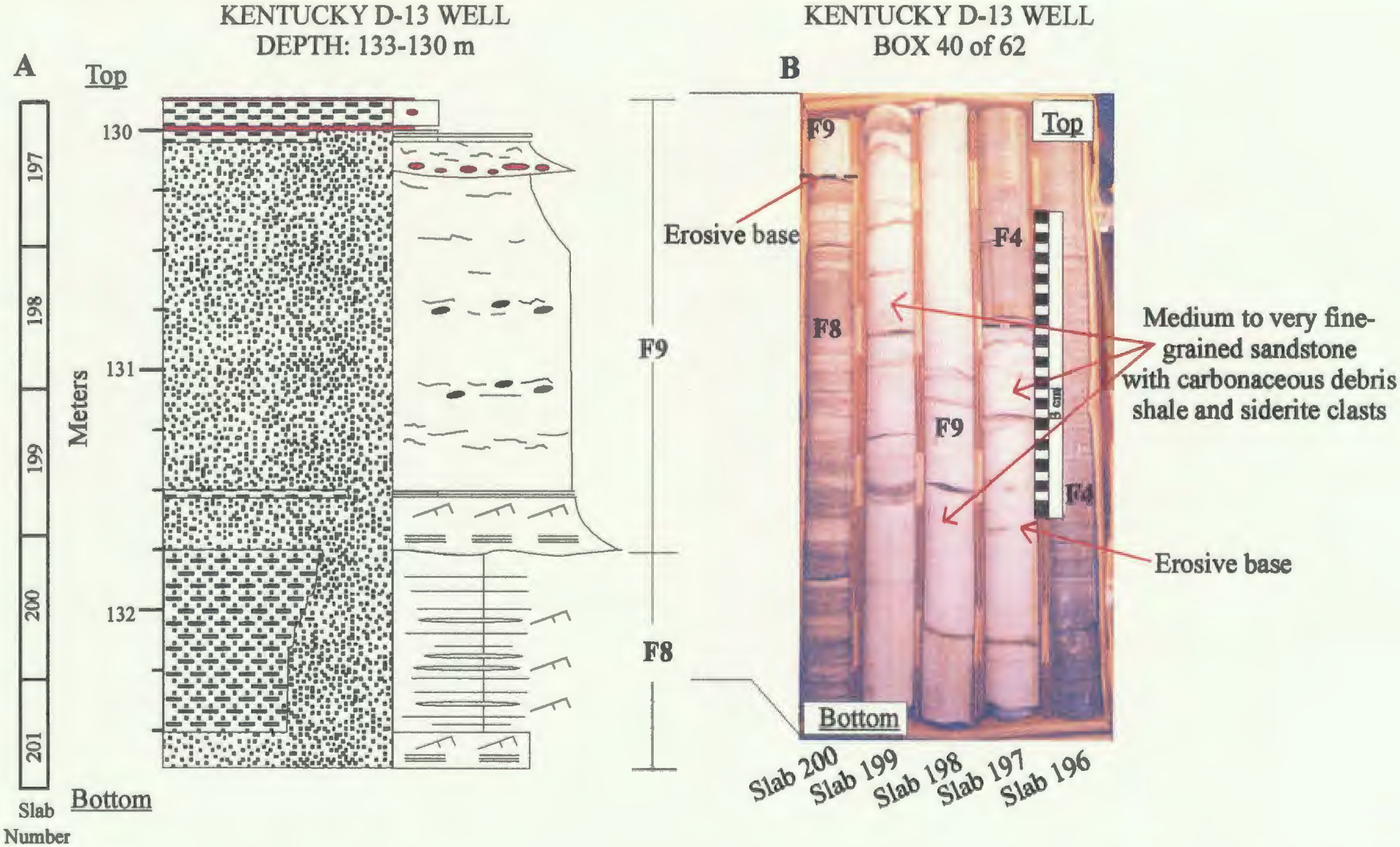


Figure 4.9. Medium- to very fine-grained sandstone characteristic of facies 9. **(A).** Graphic sedimentary column showing in detail the features of facies 9. **(B).** Core photo of box 40 of 62 showing the erosive-based, fining-upward sandstones of facies 9.

required to depress the redox potential discontinuity (RPD). The rare presence of *Planolites* suggests minimal oxygen levels, and a slight marine influence.

Facies B10: Rooted grey shale and coal

DESCRIPTION: Facies B10 is composed of interbedded black to grey shale, siderite and coal. The shales are medium to very thick bedded (10-311 cm thick) whereas the coals are thin to thick bedded (8-59 cm thick). Very thin-bedded siderite bands (1-2 cm thick), siderite nodules (1-7 cm in length), siderite concretions (8 cm in diameter), carbonaceous debris (1-7 cm in length), common rooting (1-7 cm in length), reddish-green discolorations and soil horizons characterize the shales (Figure 4.10). Vertical burrows (1-4 cm in height) and rare, impoverished traces including *Planolites* and *Chondrites* are also characteristic of this facies. Rooting is more abundant bleached shales below coal beds.

PROCESS INTERPRETATION: Facies B10 formed under very low energy, wet conditions. The preservation of carbonaceous material and the fine-grained nature of the deposits suggests that deposition occurred by suspension settling in quiet water. Rooted, bleached and soil horizons imply episodes of exposure and non-deposition on the marshy fringes of low-lying regions. Black shaly siltstones are present below coal beds and are interpreted as seat earths. Diessel (1992) states that the leaching of alkalis and alkaline earths from soil zones results in the development seat earths below coal beds which are pale grey to dark in color and generally lack bedding, although occasionally near the coal contact a transitional zone of shaly coal and coaly shale may be evident. Common to

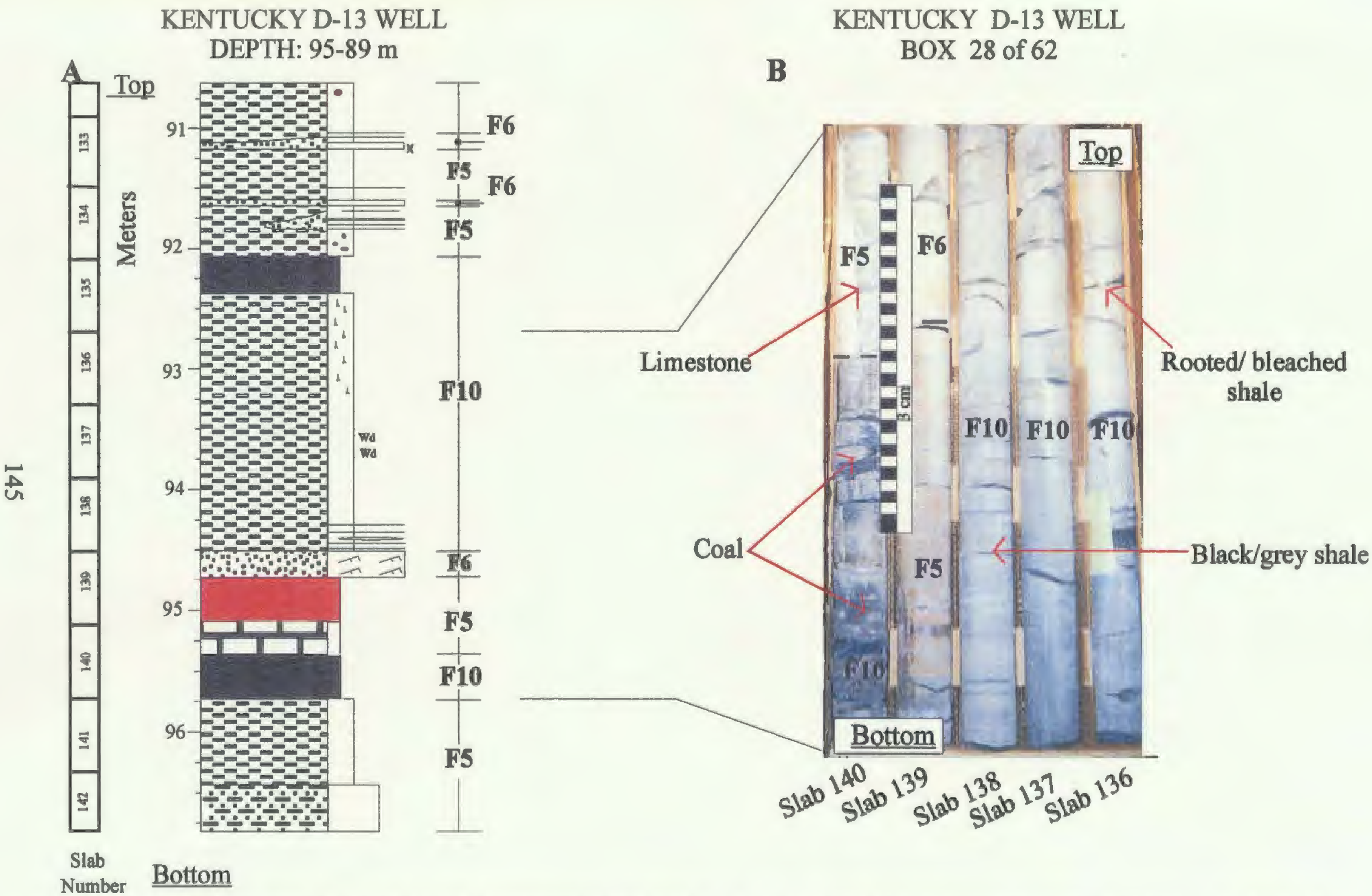


Figure 4.10. Black to grey shale and coal characteristic of facies 10. **(A).** Graphic sedimentary column showing in detail the characteristics of facies 10. **(B).** Core photo of box 28 of 62 showing the rooted and bleached shales and coal beds characteristic of facies 10. These bleached horizons commonly underlie coal horizons.

abundant rooting, siderite and pyrite nodules commonly characterize these seat-earths. The presence of siderite indicates anoxic reducing conditions. The presence of rooting and dark grey shales with carbonaceous debris below very thin bedded coals in facies H11 suggests that the leaching of alkalis and alkaline earths from soil zones to form seat earths during episodes of exposure and non-deposition. Therefore, the fine-grained sediment was deposited from suspension during episodes of inundation into low-lying regions that were otherwise subaerially exposed.

Rare and impoverished traces including *Chondrites* and *Planolites* suggests that there were stressed conditions under episodes of inundation. Ekdale (1992) stated that *Chondrites* are deep burrowers that form in oxygen-depleted substrates below the redox zone, which require oxygenated waters for their survival. *Planolites* are less tolerant to benthic oxygen deficiency and thus can only inhabit a substrate only after bottom-water oxygen concentrations reach a threshold to depress the RPD (Ekdale, 1992). The impoverished traces present within facies B10 suggest minimal oxygen levels, consistent with episodic inundation of oxygenated waters into low-lying regions that were otherwise subaerially exposed.

Facies B11: Very coarse to very fine grained sandstone

DESCRIPTION: Rocks comprising facies B11 are composed of rough upward fining, moderately to well sorted, light beige, coarse to very fine grained sandstone. These sandstones are multi-storey in nature (up to 7.6 m in total thickness) and contain numerous internal erosional contacts. Individual sand beds are thin to very thick (6-390 cm thick). The lower contacts of these beds are sharp (planar and slightly irregular) and some are defined by lags of slightly disk-shaped siderite clasts (1-7 cm in length) and elongated mud rip-up clasts (2-4 cm in length). This facies is characterized by a lack of carbonaceous debris.

Primary sedimentary structures include horizontal lamination, trough crossbedding, planar crossbedding and current ripple lamination. Some sandstones are massive. Horizontal lamination is common to abundant in the fine to medium grained sandstones and is defined by rare shale rip-up clasts and grain-size variations (Figure 4.11). Trough crossbedding has a set height ranging from 4-36 cm, whereas planar crossbedding has a set height ranging from 4-55 cm. Current ripple lamination (set thickness 0.5-2.4 cm) is common to abundant in the very fine grained sandstones. Post-depositional convolute lamination (4-6 cm in height) is also characteristic of this facies.

PROCESS INTERPRETATION: Facies B11 formed in the upper flow regime with episodes of waning flow energy. The coarse-grained nature of the sediment indicates increased flow velocity. The presence of horizontal laminations defined by shale rip-up clasts in the fine grained sandstone indicate upper flow regime conditions. Trough and planar crossbedding and current ripple lamination formed in the lower flow regime. The massive sandstones may have accumulated so rapidly that traction did not occur (Arnott and Hand, 1989), or lamination might be present but not decipherable because of insufficient textural contrasts. Collinson (1996) associates upward fining sequences with both waning flow through time within which there is evidence for waning flow regime and shifting or filling of shallow channels.

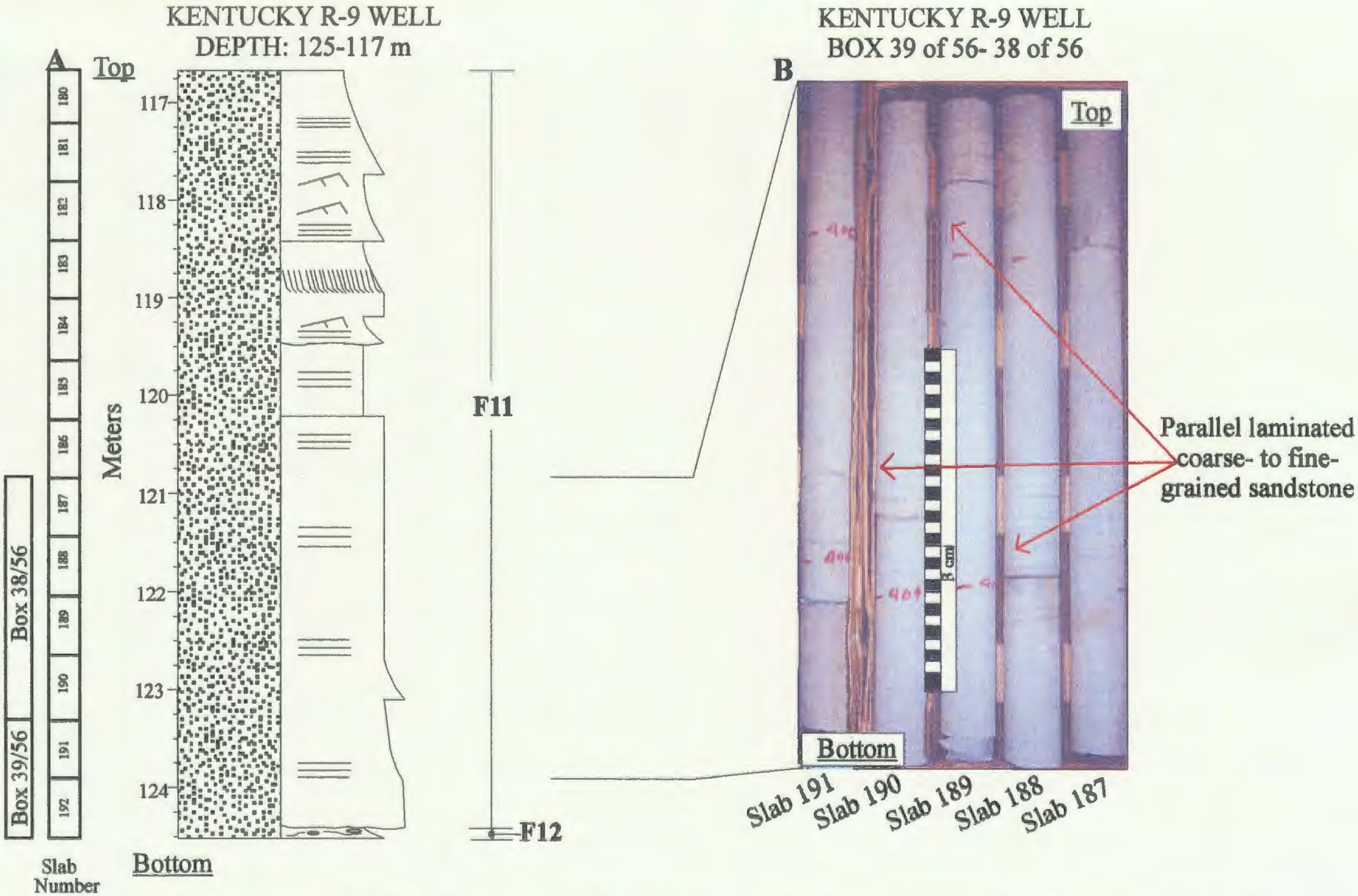


Figure 4.11. Coarse-to fine-grained sandstone characteristic of facies 11. **(A).** Graphic sedimentary column showing the parallel laminated and current rippled sandstones of facies 11. **(B).** Core photo of boxes 39 to 38 of 56 showing The fining-upward, parallel laminated sandstones of facies 11.

Facies B12: Upward fining, carbonaceous coarse to very to fine grained sandstone

DESCRIPTION: This facies is composed of upward fining units of moderately well sorted, coarse to very fine grained sandstone with abundant carbonaceous debris. The sandstones are multi-storey in nature (up to 1080 cm in total thickness) and contain numerous internal erosional surfaces. Individual sandstone beds are thin to very thick-bedded (3-125 cm thick). Sharp-based, erosive contacts that commonly mark the base of sandstone beds are defined by lags of carbonaceous debris (2-8 cm in length), siderite clasts (1-3.5 cm in length) and mud rip-up clasts (0.5-3.0 cm in length). Rare quartz pebbles (0.4-0.6 cm in diameter), disseminated pyrite and thin mud laminae (2.0 mm thick) are also characteristic of this facies (Figure 4.12).

Sedimentary structures include horizontal lamination, trough crossbedding, planar crossbedding and current ripple lamination. Horizontal laminations defined by mud laminae, carbonaceous debris, siderite pebbles, siderite clasts and grain size variations are abundant in the medium and fine grained sandstones. Trough crossbedding has a set height ranging from 15-24 cm, whereas sets of planar crossbedding range from 6-60 cm thick. Current ripple lamination (set thickness 0.2-1.5 cm) is abundant in the very fine grained sandstones.

PROCESS INTERPRETATIONS: Facies B12 would have formed mainly in the upper flow regime. Erosive-based sands characterized by abundant transported carbonaceous material and horizontal laminated fine to medium grained sandstone are indicative of upper flow regime conditions. Trough and planar crossbedding and current ripple lamination are indicative of the lower flow regime. The upward fining and

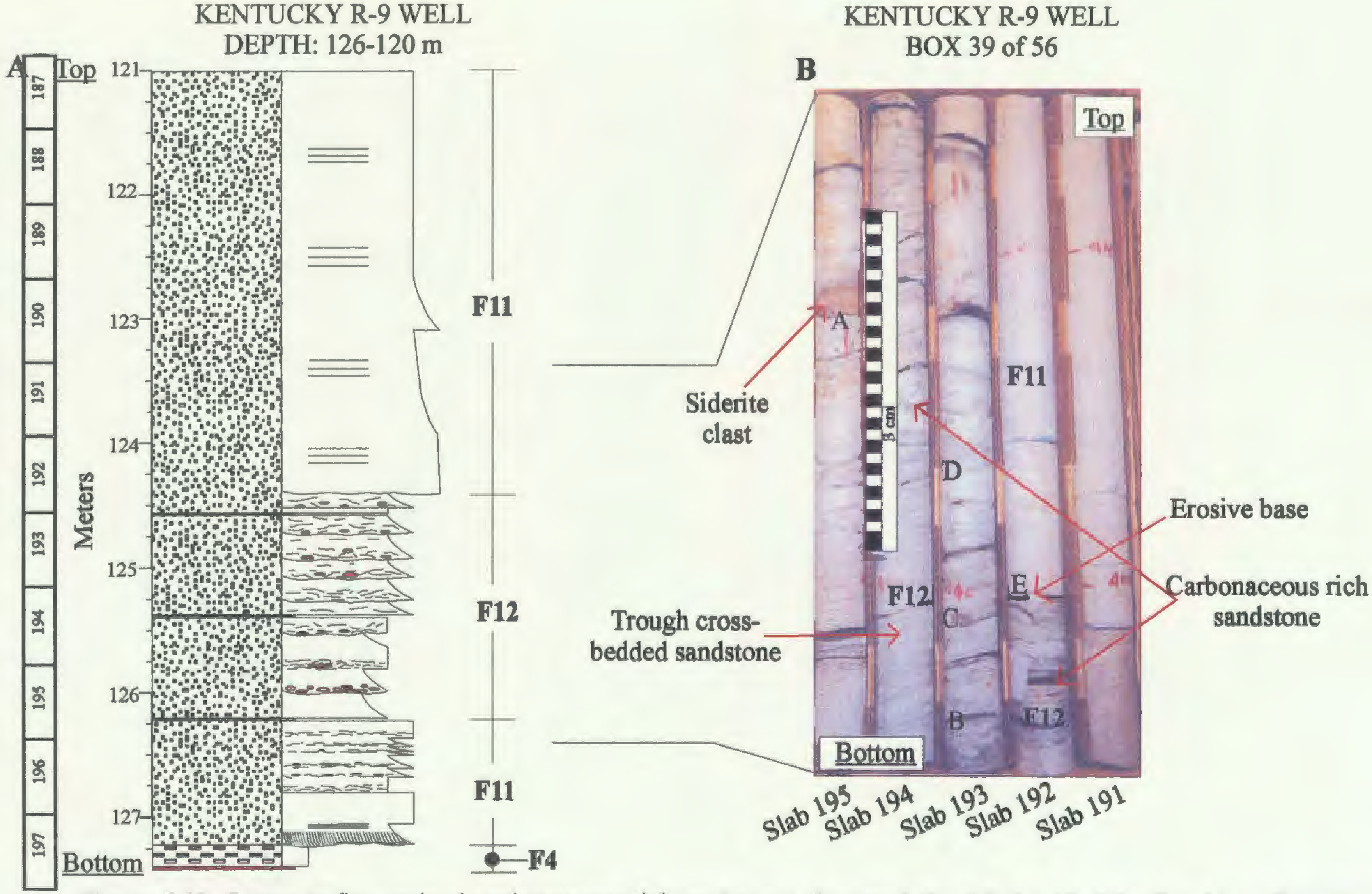


Figure 4.12. Coarse-to fine-grained, carbonaceous rich sandstones characteristic of facies 12. **(A).** Graphic sedimentary column showing in detail the fining upward sandstones of facies 12. **(B).** Core photo of box 39 of 56 showing the trough cross- bedded, carbonaceous sandstones of facies 12. Also shown here are the Numerous internal erosional surfaces labelled A through D which also characterize these sandstones.

associated changes from upper to lower flow regime structures record waning flow conditions. This type of upward fining is characteristic of deposition in shifting or migrating channels (Collinson, 1996).

Facies B13: Upward fining, coarse to very fine grained sandstone

DESCRIPTION: Facies B13 is composed of erosive-based, upward fining coarse grained sandstone to siltstone. The sandstones are thin to thick bedded (5-94 cm thick). Erosive bases defined by lags composed of elongated mud rip-up clasts (2-8 cm in length), ironstone pebble and clasts (0.6-4 cm in diameter) and carbonaceous debris (1-7 cm in length) mark the base of these upward fining sandstone units (Figure 4.13). The units contain numerous internal erosional contacts and are multi-storey in nature. Rare *Ophiomorpha* traces, vertical burrows (1-3 cm in height), and simple, diminished traces including *Planolites, Chondrites, Teichichnus*, and *Palaeophycus* are present in the medium to fine grained sandstone.

Primary sedimentary structures include horizontal lamination, trough crossbedding, planar crossbedding and current ripple lamination. Secondary structures such as convolute lamination are also present. Horizontal lamination in the medium and fine grained sands is accentuated by carbonaceous debris and mud rip-up clasts. Trough crossbedding has a set height of 6-10 cm, whereas planar crossbedding has a set height of 6-9 cm. Current ripple lamination (set thickness 0.5-1.0 cm) is characteristic of the very fine grained sandstone and siltstone. Convolute lamination is also present, but is rare.

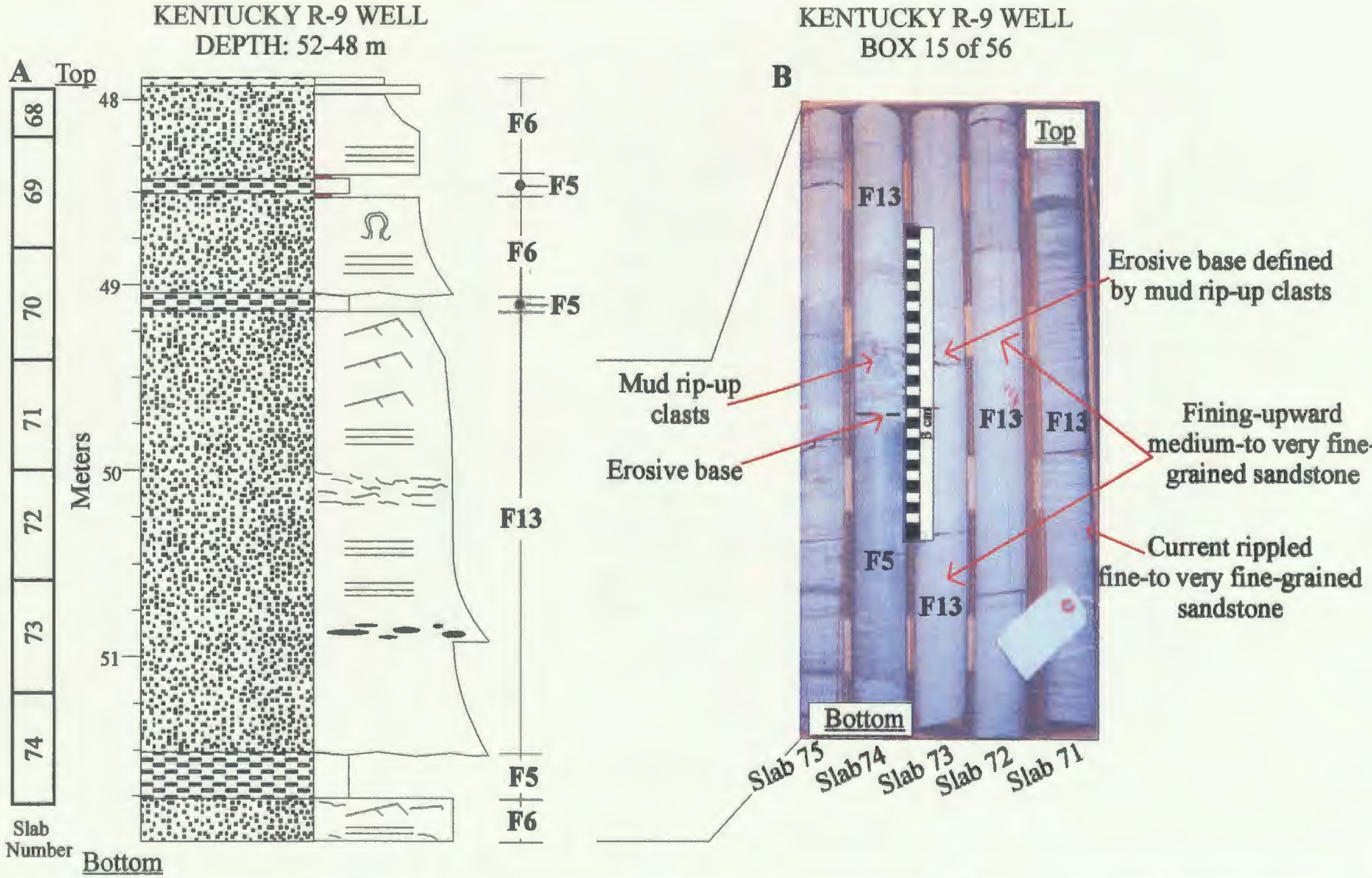


Figure 4.13. Fining-upward, medium- to very fine-grained sandstone characteristic of facies 13. **(A).** Graphic sedimentary column showing the features of facies 13. **(B).** Core photo of box 15 of 56 showing the erosive based sandstones that fine upwards through parallel laminated medium- to fine-grained sandstone to current rippled very fine-grained sandstone.

PROCESS INTERPRETATION: The coarse-grained nature of the sediment, abundant large clasts and horizontal laminations in the medium to fine grained sandstone are indicative of upper flow regime conditions. Gradual upward declining flow velocity is evident by the presence of crossbedding and current ripple lamination as the grain size decreases to very fine sandstone and siltstone. This type of consistent upward fining is characteristic of the deposits of meandering channels.

Traces belonging to both the *Skolithos* and *Cruziana* ichnofacies also suggest a gradual upward declining flow velocity. Pemberton et al. (2001) state that *Palaeophycus* and *Ophiomorpha* (*Skolithos* ichnofacies) are suspension feeders and are associated with higher energy conditions where food particles remain in suspension and that *Planolites, Chondrites* and *Teichichnus* (*Cruziana* ichnofacies) are deposit feeders and are associated with low energy conditions where food particles are deposited through suspension settling. The presence of the *Skolithos* ichnofacies in the medium to fine grained sandstone and *Cruziana* ichnofacies in the fine grained sandstone and siltstone suggests a upwards decrease in flow velocity. Simple and diminutive traces including *Planolites, Chondrites* and *Teichichnus* indicate stressed environmental conditions, here attributed to reduced salinities in an estuarine setting. Only when of large size do the traces indicate fully marine conditions, such as those traces encountered in facies B7. Here in facies B13, their diminished size and low diversity support a brackish water, estuarine interpretation.

4.3 Facies Associations and Environmental Interpretations

Facies associations defined for the Kentucky cores and outcrop data reflect a proximal to distal transition with respect to the fluvial source similar to that observed in the Hibernia cores. Facies are interpreted to range from distal marine shelf to proximal upper delta-plain or coastal-plain settings. Within the Breathitt Group, seven facies associations have been identified.

4.3.1 Facies association I: Offshore transition - marine shelf to shoreface

Facies association I consists of facies B7, B8 and B9. They suggest deposition on a marine shelf, in the transition zone to the upper shoreface, and on the shoreface. This association characterizes the Kendrick Shale and Magoffin Shale members (Figure 1.6). A typical interval comprising this facies association can be found in the D-13 graphic column in appendix three at a depth of 160-129.8m.

4.3.1.1 Marine Shelf

The fine-grained nature of the sediment, lack of wave-generated structures, common to abundant bioturbation, and shell debris are indicative of marine shelf settings under fair-weather conditions and below wave base. The base of the Magoffin Shale marks the base of an upward coarsening succession and represents the maximum extent of a marine transgression. In core, this is evident by the presence of black fissile shale, siderite and abundant shell debris characteristic of facies B7. In the D-13 well, the base of the condensed section is the upper boundary of the Copland coal bed and is interpreted as a transgressive surface (Figure 1.6). The presence of shell debris, black fissile shale and absence of upward coarsening facies in both shale members in the R-9 well suggest that at this locality the lower portions of both the Magoffin and Kendrick shale members were deposited farther out on the marine shelf in deeper marine conditions, or were removed by erosion beneath the overlying sandbody (Figure 4.14).

Black fissile shale, siderite and abundant shell debris characteristic of facies B7 were also observed in the lower portion of the Kendrick shale in outcrop at Roadgap, mile 25 and in the Magoffin Shale in outcrop at Hye 11&12 and Hye 23 (Figure 4.14). The Magoffin Shale at Hye 11&12 and Hye 23 is defined by a basal limestone and is composed of a black shell-rich shale. This black shale is interpreted as a condensed section coincident with the maximum flooding of the depositional surface. Condensed sections represent episodes of very low sedimentation rates in marine environments due to major transgressions (Cant, 1992). Regionally, this condensed section is characterized by an irregular Lingula-bearing shale and persistent limestone (Tankard, 1986). However, the Lingula-bearing shale was not present in the cores examined during this study.

4.3.1.2 Marine shelf to upper shoreface transition

The upward coarsening succession of facies B8 is interpreted as a marine shelf to upper shoreface transition. It is defined at its base by black fissile shale with articulated bivalve shells, then coarsens upward through siltstone to wave rippled very fine to fine

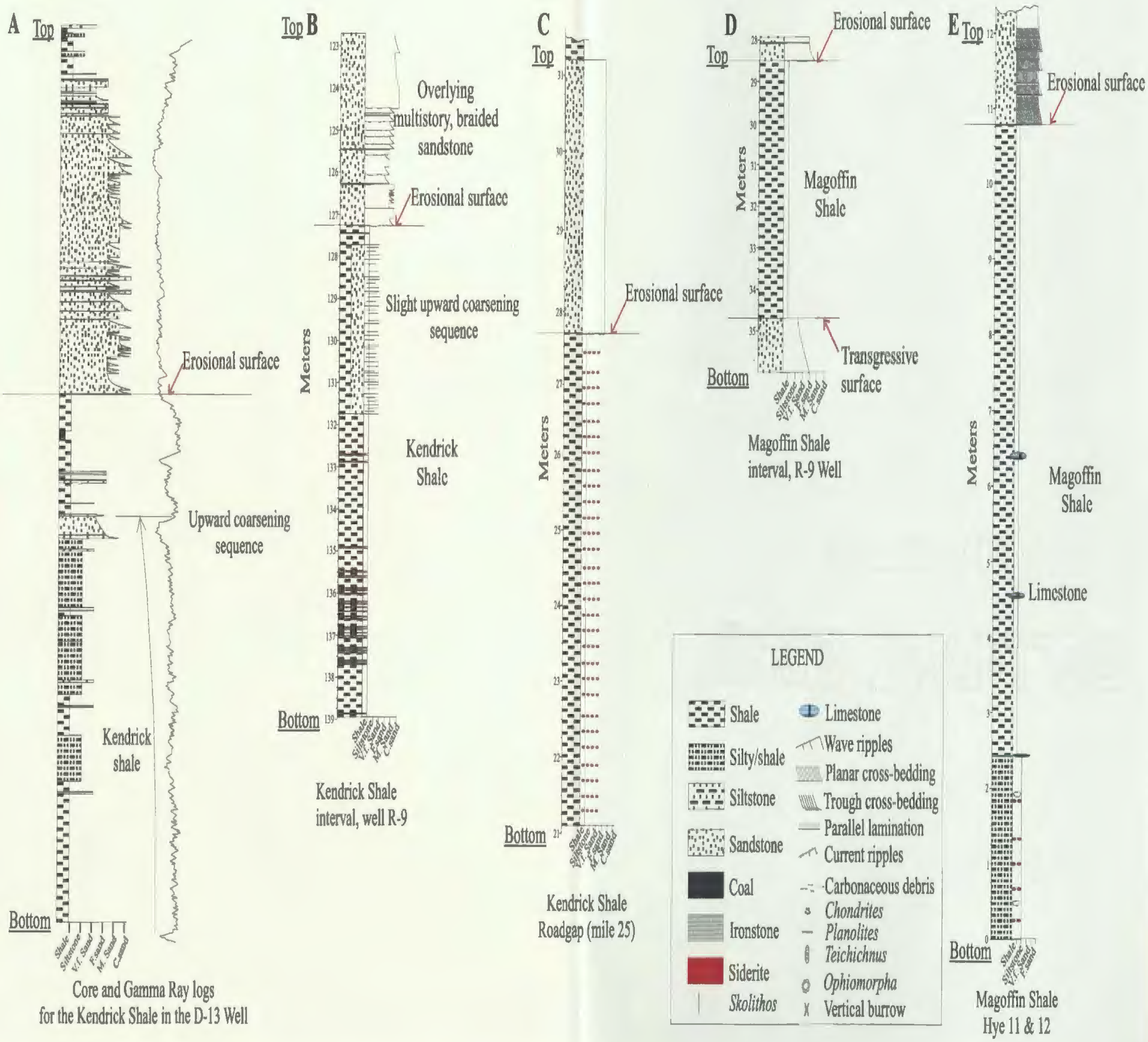
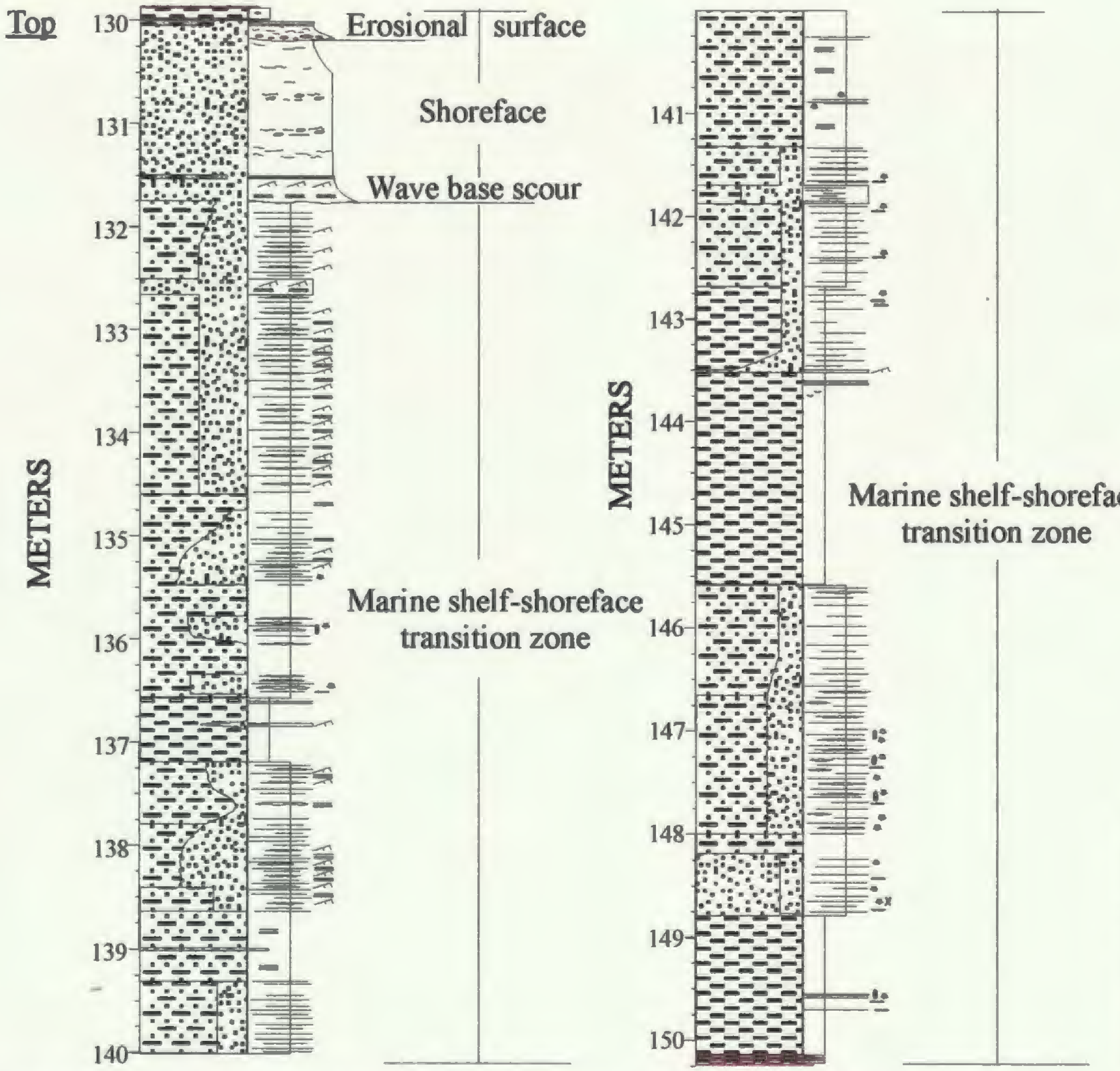


Figure 4.14. Characteristics of the Kendrick Shale and Magoffin Shale observed from well and outcrop data. (A) The Kendrick Shale in the D-13 well shows an upward coarsening sequence. (B) The Kendrick Shale in the R-9 well shows a slight upward coarsening sequence. C. The Kendrick Shale at Roadgap, without an upward coarsening sequence. (D) The Magoffin shale in the R-9 well showing no evidence of upward coarsening. (E) The Magoffin Shale observed at Hye 11 &12 without an upward coarsening sequence. Figures A,B and C show how varying stages of incision by the overlying braided fluvial channels within incised valleys has influenced the preservation of the upward coarsening sequence in the Kendrick and Magoffin shales. The Magoffin Shale shown in figures D and E shows no evidence of upward coarsening.. The presence of limestones in figure E shows that these shales formed in deeper conditions.

grained sandstone at the top. This is characteristic of the upper portion of the Kendrick Shale Member observed in the D-13 well. The fine-grained sediment, shell debris, and moderate to intense bioturbation are all indicative of fair-weather conditions on the lower shoreface, during which time sediment was deposited by suspension settling. The presence of *Planolites, Chondrites* and *Teichichnus* suggest low energy conditions of the lower shoreface. The presence of wave rippled very fine to fine grained sandstone suggests episodes of increased energy conditions and wave reworking when wave base deepened.

4.3.1.3 Shoreface

Facies B9 is interpreted as an upper shoreface deposit. A sharp erosional contact overlain by medium to fine grained sandstone with internal cross stratification and horizontal lamination characterize this facies. During storms, shoaling waves, storm currents and enhanced rip currents can result in erosion of the upper shoreface (Reading and Collinson, 1996). The erosional contact is interpreted as a storm wave base scour, which becomes an extensive surface due to the progradation of the shoreface (Figure 4.15). The erosive and coarse-grained nature of the sediment along with the presence of cross stratification reflect a high degree of physical energy.



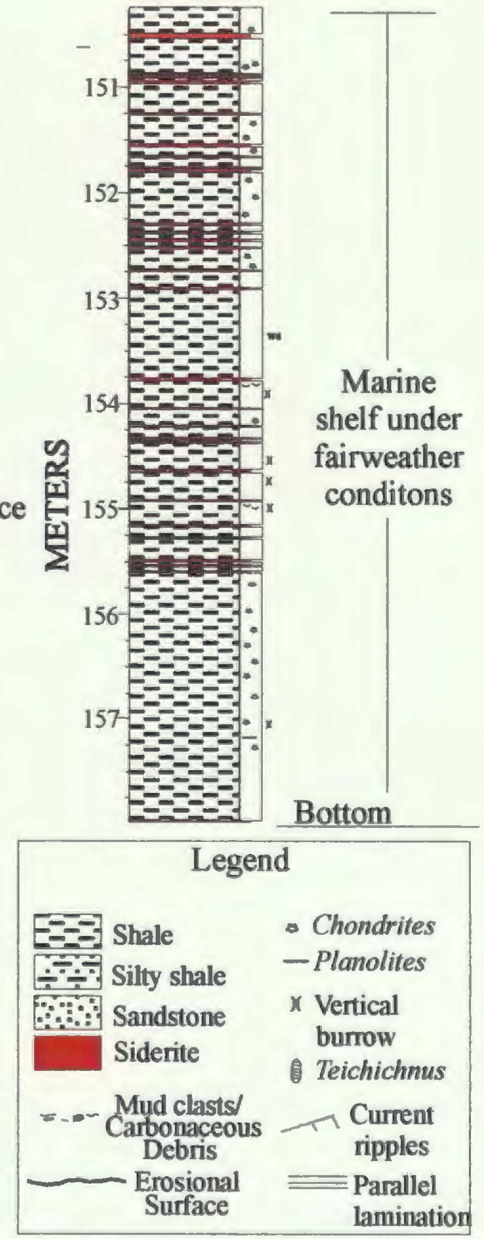


Figure 4.15. The marine shelf to shoreface transition observed in the Kendrick Shale interval from the D-13 well. The top of the upward coarsening sequence is defined by a scour at the depth of storm wave base that propagated due to progradation of the shoreface.

4.3.2 Facies association II: Mouthbar

Facies association II comprises deposits of the Elkins Fork Shale and uppermost portions of the Magoffin Shale. Although marine in nature, the Elkins Fork Shale is interpreted to have been deposited in a brackish-water bay depositional setting. This differs from the lower portions of the open-marine, transgressive Kendrick and Magoffin shales of facies association I. Facies association II is comprised of a upward coarsening succession interpreted as the delta-front to mouthbar deposits of an advancing delta sequence. It encompasses facies B1 and B2. A typical interval representative of this facies association can be found in the D-13 graphic column in appendix three at a depth of 199.4-175.0 m.

4.3.2.1 Delta-front

Facies B1 is interpreted as delta-front deposits, and is characteristic of the lower portion of the Elkins Fork Shale and upper portion of the Magoffin Shale. Coleman and Prior (1981) state that horizontal and lenticular laminations, small burrows, current ripples, scour and fill and erosional truncation characterize delta front deposits. It consists of upwards coarsening silty-shale to very fine grained sandstone characterized by lenticular laminated sandstones, current ripple lamination, rare wave-modified current ripples and erosive-based sands. These characteristics are all suggestive of a delta-front depositional setting. Small vertical burrows in the more seaward portions of the delta-front locally overprint and obscure horizontal and lenticular laminations. The upward coarsening pattern in the Elkins Fork Shale repeats several times in the D-13 well and at Roadgap.

The upper portion of the Magoffin Shale also exhibits deposits characteristic of a prograding delta. The entire Magoffin interval represents a progradational succession from a condensed marine interval at its base, through a relatively thin prodelta to delta-front interval, to mouthbar deposits discussed below. The prodelta to delta-front interval is clearly evident in the D-13 well where it is comprised of upward coarsening, interlaminated to interbedded grey shale, silty shale and very fine grained sandstone. Vertical burrows, marine traces, shell debris and lenticular laminated sandstone characterize this prodelta to delta-front interval.

4.3.2.2 Mouthbar

Facies B2 is interpreted as a prograding distributary mouthbar deposit. These deposits are characterized by scoured-based, fine grained sandstone with interlaminated shale, current and wave ripple lamination, horizontal lamination, mud rip-up clasts, carbonaceous debris, moderate to intense bioturbation and soft sediment deformation. Mud rip-up clasts and carbonaceous debris near the top of the distributary mouthbar represent debris transported down the rivers in times of floods and discharged into the nearshore zone, where they were reworked by wave processes. This reworking resulted in the grinding of coarser wood particles into concentrations of carbonaceous debris. The siltstone deposits interbedded with the sandstones contain marine fauna and are interpreted as offshore siltstones deposited either during minor transgressions or during periods of reduced sediment supply from the river system.

Mouthbar deposits are exposed in the upper portion of the Magoffin Shale in the outcrop at Hye 23. The upward coarsening sequence in the Magoffin Shale is characterized by a decrease in shale content vertically in the section, and by current and wave rippled sandstones, carbonaceous debris, cross stratification and convolute lamination. These characteristics are suggestive of prograding distributary mouth bars (Coleman and Prior, 1981).

4.3.3 Facies association III: Lagoon

Facies association III was deposited in lagoon to bay depositional environments. It consists of single facies B4. The fine-grained nature of these deposits along with the preservation of carbonaceous debris and a low-diversity brackish-water trace fossil assemblage indicates a low-energy lagoon-to-bay depositional setting. The very thin-bedded coals are suggestive of either sand or mud flats of the lagoonal margin, or on emergent washover flats (Reinson, 1992). The absence of shell debris suggest that these lagoonal deposits accumulated well landward of the marine environment, so are unlikely washover-flat deposits. Wave ripples in the very fine grained sand could be either due to wave influence during initial deposition, or reworking by wind generated waves in the lagoon. A typical interval containing this facies association can be found in the R-9 graphic column in appendix three at a depth of 138.94-127.21 m.

4.3.4 Facies association IV: Overbank

Facies association IV is composed of facies B3, B5 and B10. They suggest deposition on the lower delta-plain. A typical interval representative of this facies association can be found in the R-9 graphic column in appendix three at a depth of 72.53-63.87 m.

4.3.4.1 Levee/ Crevasse splay

The sharp-based, upward fining medium to fine grained sandstones of facies B3 are interpreted as levee deposits. They tend to overlie facies association II. These deposits are evident in the both the D-13 well and in outcrop at Roadgap. In core, siderite lags, vertical burrows and brackish-water traces characterize these levee deposits. The moderate to intense bioturbation has disturbed or destroyed whatever now remains as traces of ripple cross lamination in the sands. At Roadgap, the sharp-based sands fine upwards, and are characterized by current ripple lamination, local rooted horizons and bleaching along the upper surfaces of the sandbody. These characteristics along with the thinning and pinching of sandstones are suggestive of levee deposits (Aitken and Flint, 1995).

4.3.4.2 Interdistributary bay

Facies B5 comprises horizontal laminated and current rippled siltstones and very fine grained sandstones interpreted as interdistributary bay deposits. Moderate to intense bioturbation, rare rooting, localized soil horizons, carbonaceous material, siderite nodules and reddish-green discolorations are suggestive of interdistributary bay and fringing marsh deposits (Diessel, 1992). The tractional structures formed in an overbank depositional environment by sheet flow during floods. The reddish-green discolorations indicate periodic development of well-drained, mature soils. Other soil horizons that do not exhibit these discolorations are considered to be immature because of development under wet conditions.

4.3.4.3 Marsh

Facies B10 represents the actual marsh in this association. Marshes are low-lying regions that experience episodes of inundation. During these episodes, fine grained sediment is deposited by suspension settling. Weimer et al. (1981) state that marsh deposits are characterized by abundant carbonaceous debris, common to locally abundant rooting, bleached horizons, thin to thick-bedded coals, soil horizons, reddish-green discolorations and siderite. Bleached horizons developed during episodes of exposure and non-deposition. The abundance of carbonaceous material, seat earths, thin-to thick-bedded coals, reddish-green and rooted horizons in facies B10 support a marsh depositional setting.

4.3.5 Facies association V: Minor channels

Sharp-based, upward fining, medium to very fine grained sandstones of facies B6 are interpreted as the deposits of a variety of minor channels and characterize facies association V. These include minor distributary and crevasse channels. The channels are characterized by sharp, erosive bases, mud rip-up clasts, carbonaceous material and a variety of sedimentary structures including trough and planar cross bedding, horizontal lamination and current ripple lamination. Distributary and crevasse- channel sandstones commonly display medium-scale crossbedding and current ripple lamination and their erosive bases are defined by lags of pebbles, mud and siderite clasts and carbonaceous debris. A crevasse channel commonly overlies a upward coarsening sequence. Slight to moderate bioturbation in many of the channel deposits suggests estuarine or tidal influence.

The deposits of facies association V are commonly associated with the lagoonal and overbank deposits of facies associations III and IV, respectively. This helps solidify their interpretation as a variety of deltaic channels on a lower delta-plain near the sea. A typical interval containing this facies association can be found in the R-6 graphic column in appendix three at a depth of 101.53- 92.39 m.

4.3.6 Facies association VI: Major channels

Upward fining, coarse to very fine grained sandstones of facies B13 are interpreted as the deposits of common distributary channels and rare meandering channels. Lag deposits, trough and planar crossbedding and horizontal and current ripple lamination characterize the erosive-based, upward fining distributary channel sandstones in facies B13. Brackish-water and marine traces suggest estuarine or tidal influence. Meandering channel sandstones are rare, and only present in the upper portion of the R-9 well below the Magoffin Shale. Coleman and Prior (1981) state that meandering channel sandstones are erosive based and fine upward through large-scale crossbedding to well sorted sandstones characterized by climbing ripples, convolute laminations and horizontal laminations. The upward fining, meandering channel sandstones in the upper portion of the R-9 well below the Magoffin Shale are characterized by current ripples, convolute laminations and horizontal laminations. The geometry, scale and presence of convolute lamination distinguishes these deposits from those of facies association V. These deposits contain internal erosional surfaces and may be multi-storey in nature, whereas the minor channels of facies association V are single-storey sandbodies of smaller size. A typical interval comprising this facies association can be found in the R-9 graphic column in appendix three at a depth of 38.59 - 34.62m.

4.3.7 Facies association VII: Braided river

Facies association VII comprises the very coarse to fine grained, locally carbonaceous braided river sandstones of the Breathitt Group. These deposits incise into the underlying Kendrick and Magoffin shales and other brackish water shales throughout the Breathitt Group. The recognition of incised valleys will be discussed in the following section. This facies association comprises facies B11 and B12. A typical interval comprising this facies association can be found in the R-9 graphic column in appendix three at a depth of 111.03 – 100.15m.

Erosive-based, multistorey sandbodies of facies B11 and B12 are interpreted as the deposits of braided fluvial channels constrained within incised valleys. Miall (1977) and Cant (1982) have provided criteria for the recognition of such deposits. These criteria are summarized in the braided river interpretation of the Hibernia sandstones in chapter 3 These criteria will be used to justify braided river as opposed to meandering river interpretations for the sandstones of the Breathitt Group. The features observed in the Breathitt Group sandstones are consistent with those of the Platte type, braided river depositional model proposed by Miall (1977).

Braided rivers are high-energy dispersal systems that are capable of entraining trees and rafts of peat, as are found along the bases of these channels at Roadgap. Basal lags comprised of siderite clasts, mud rip-up clasts and carbonaceous debris are consistent with Miall's Platte type model (Cant, 1982). Campbell (1976) state that braiding is commonly found in regions where river banks are composed on noncohesive material as opposed to meandering rivers that occur in regions where river banks are composed of fine grained cohesive material. The erosion into noncohesive river banks results in siderite, mud clasts and carbonaceous debris to be ripped up and re-deposited as lags along channel bases in the Breathitt Group.

Rough upward fining sequences from trough and planar crossbedded sandstones through horizontal bedded to rippled very fine sands and rooted siltstones in the Breathitt Group facies are also consistent with the facies of braided river deposits identified by

Miall (1977). These facies are summarized in chapter 3 (Table 3.2). The abundance of trough crossbedding indicates that channels were floored by three-dimensional dunes. Common planar crossbedding indicates that straight-crested two-dimensional dune forms or bars were also present. Miall identifies planar crossbedding and trough cross bedding as the common structures in linguoid bars. Common planar crossbedding further justifies a braided river, as opposed to a meandering river interpretation.

Braided river deposits are commonly characterized by an overall crude fining-upward succession from horizontally bedded or cross-stratified gravels at the base that fine upwards through crossbedded and horizontal laminated sandstones to fine grained rippled sands and muds at the top. However, in some instances, sequences will be incomplete due to erosion. Campbell (1976) recognized incomplete and compete fluvial sequences in braided river deposits. Incomplete sequences are evident in the multi-storey sandbodies observed in both core and outcrop. The absence of fine grained rippled sands and muds is contributed to erosion by overlying sandbodies. The incomplete fluvial sequences exhibit numerous internal erosional surfaces and are composed of basal pebble lags, and upward fining trough and planar crossbedded sandstones. Complete fluvial sequences are seen at the top of the interval and are comprised of basal pebble lags and upward fining trough and planar cross bedded through horizontal laminated to current rippled very fine sandstones and rooted siltstones at the top. The preservation of these fine grained rippled sands and muds implies either a decrease in the river energy and possible abandonment of the channel complex, or a increase in accommodation space resulting in the preservation of these fine grained deposits. This will be discussed in more detail in the following chapter.

4.4 Spatial Arrangements of Facies Associations and Implications for Sedimentary History

The spatial distribution of facies associations within the Breathitt Group provides the criteria for understanding the sedimentary history. The spatial distributions can be used to understand the stacking patterns observed in both core and outcrop.

The prodelta-delta front to mouthbar of facies association II mark the transitional facies for the advancing delta system (Figure 4.16). The erosive based, braided river sandstones of facies association VII abruptly overlie these deposits. The sharp transition from upwards coarsening delta front-mouth bar deposits to braided river sandstones constrained within incised valleys implies an overall seaward shift in fluvial deposition systems. Therefore, a major change in paleogeography has occurred.

The fine-grained deposits within the valley systems are consistent with the established paleogeography. These overbank facies are commonly penetrated by minor and major channels of facies associations V and VI respectively.

Marine and brackish water shales (Kendrick shale, Whitesberg Zone) commonly separate these valley systems (Figure 4.16). These lagoonal shales of facies association III indicate a slight change in paleogeography. Their presence suggest a rise in relative sea level which results in the drowning of the fluvio-deltaic system. The distribution of

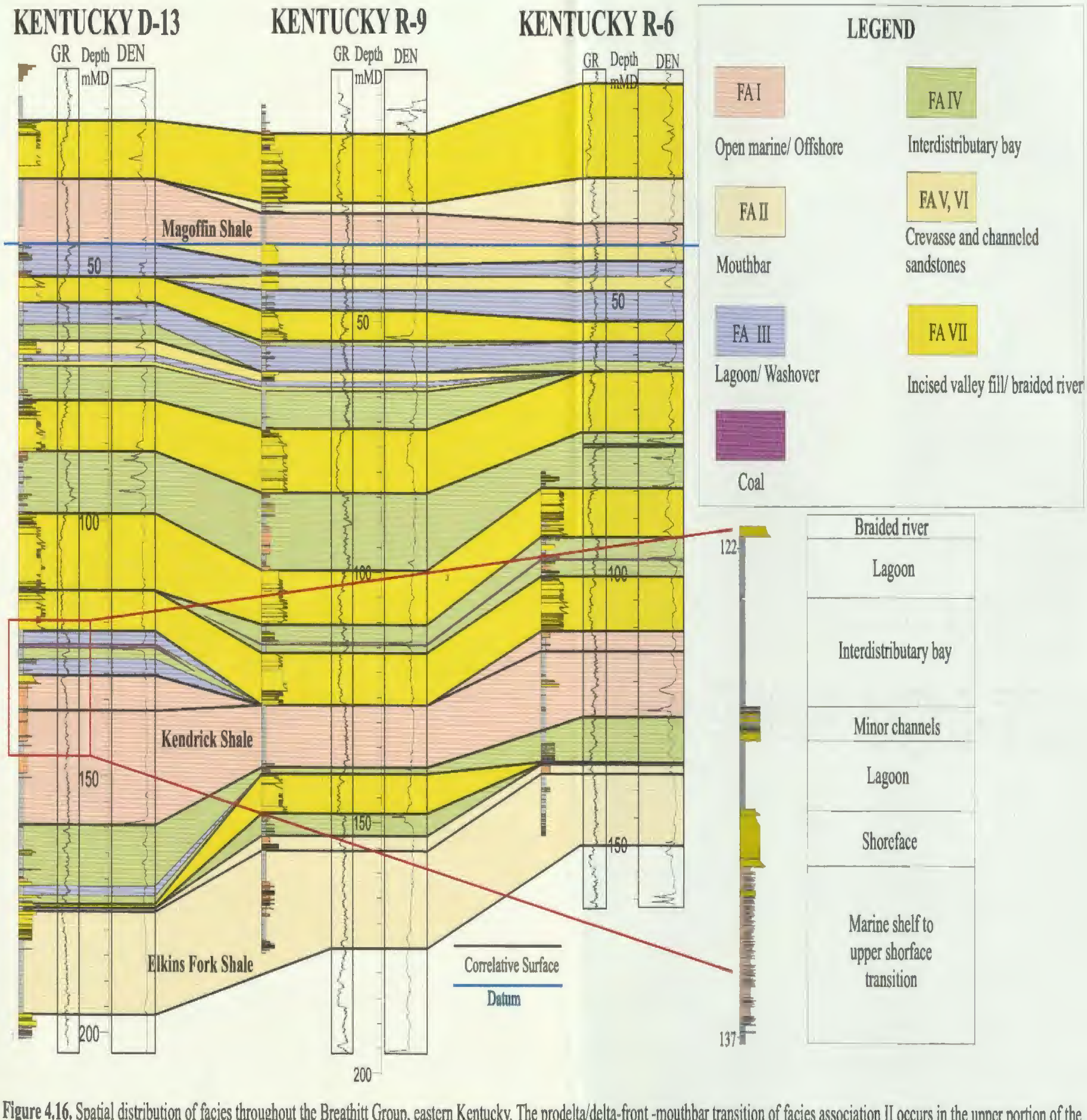


Figure 4.16. Spatial distribution of facies throughout the Breathitt Group, eastern Kentucky. The prodelta/delta-front -mouthbar transition of facies association II occurs in the upper portion of the Elkins Fork shale and the Magoffin shale. The Braided river sandstones of facies association are widely distributed throughout the region. The lagoonal deposits of facies assocition III and the interdistributary bay deposits of facies association IV, are widely developed atop the braided river sandstones. These fine grained facies are commonly penetrated by crevasse splays, minor channels and major distributary channels of facies associations IV, V, and VI respectively. The channel fills below the Magoffin Shale are interprcted as meandering channels. The offshore deposits of facies association VII are only partially preserved at the top of the Kendrick Shale and are widely distributed throughout the Magoffin Shale interval.

these fine-grained deposits is greatly affected by the creation of accommodation space. Regions of increased accommodation space result in the preservation of thick packages of fine-grained sediment, as seen it the Kendrick Shale in the D-13 well (Figure 4.16).

The occurrence of a widespread marine shale (Magoffin Shale) of facies association I indicates a significant change in paleogeography (Figure 4.16). The widespread nature of this marine shale indicates a significant rise in relative sea level and the complete drowning of the pre-existing fluvio-deltaic system.

4.5 Similarities in facies between Hibernia and the Breathitt Group

The facies and associated stacking patterns identified from core and outcrop data of the Breathitt Group are analogous to those identified from the Hibernia Formation. The lithostratigraphic framework of the Breathitt Group is very similar to that of the Hibernia Formation (Figure 4.17). Both regions show braided fluvial sandstones separated by marine shelf-to lagoonal shales and siltstones. This section will discuss these similarities.

The braided river sandstones in both regions are constrained within incised valley systems. Zaitlin et al. (1994) and Pemberton et al. (2001) establish the criteria by which an incised valley system may be recognized in the stratigraphic record. Zaitlin et al. (1994) define a incised valley as a fluvially-eroded, elongate topographic low that is typically larger than a single channel form, and is characterized by an abrupt seaward shift of depositional facies across a regionally mappable sequence boundary at it base. Zaitlin et al. (1994) identify four criteria used to recognize incised valley systems. These criteria are summarized below:

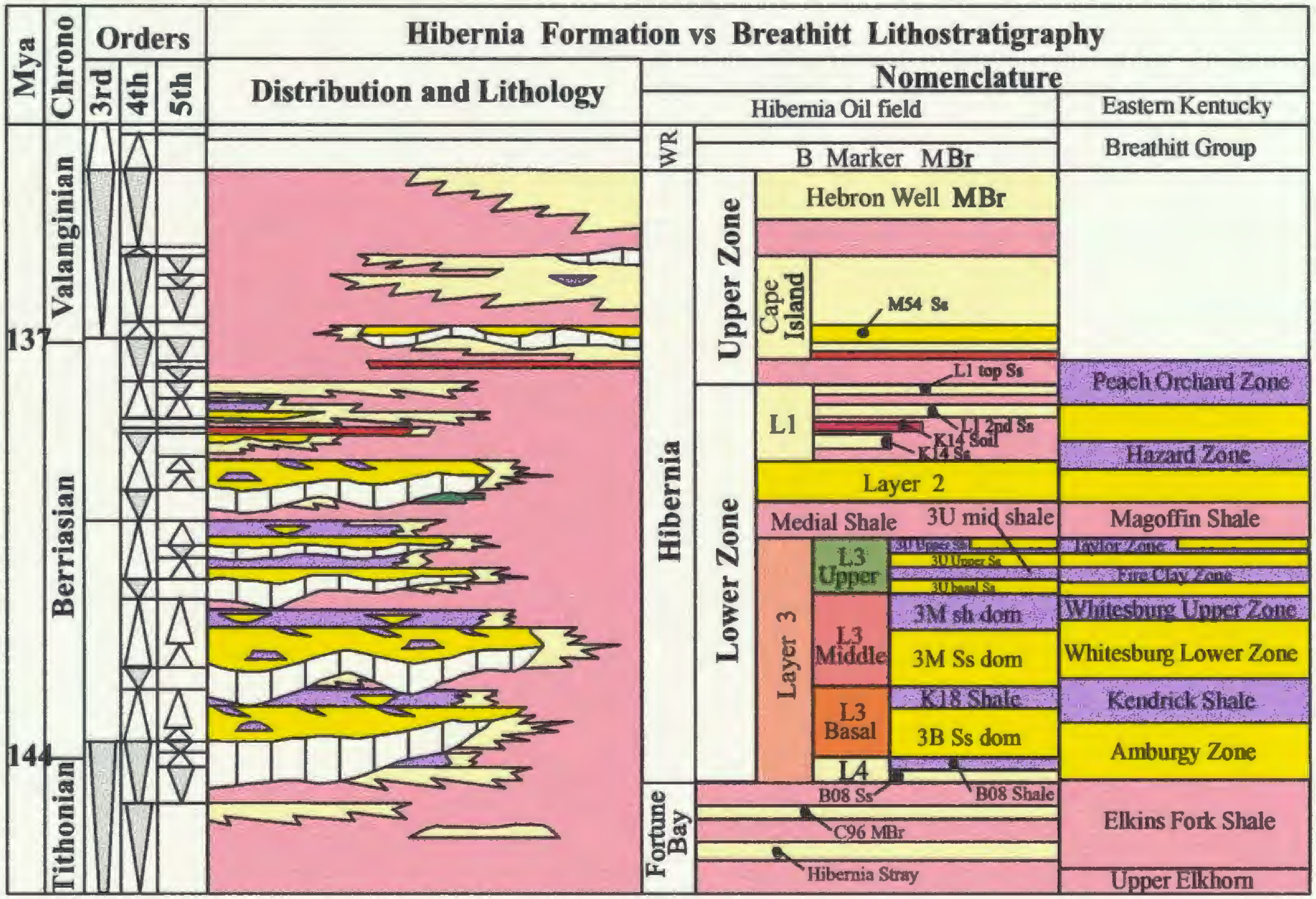


Figure 4.17. Lithostratigraphy of the Hibernia Oilfield vs the Breathitt Group, Eastern Kentucky. The yellow intervals represent sand, the purple intervals represent brackish-marine shales, the cream intervals represent delta front/mouthbar facies and the pink intervals open marine shales. Hiatuses are marked by vertical rule. Modified from Flint and Sinclair (2001).

1) The valley is a negative paleotopographic feature (i.e., erosional) the base of which truncates underlying strata;

2) The base and walls of the valley system represent a sequence boundary that may be correlated laterally to a correlative subaerial exposure surface marked by a rooted horizon (i.e., interfluve). Pebble lags or coal lags usually characterize the sequence boundary;

3) The base of the valley system exhibits a basinward shift in facies which results in the erosional juxtaposition of proximal facies over more distal facies;

4) On seismic data, depositional markers within the valley fill onlap the valley walls.

Some of these criteria will be used to justify the interpretation of incised valley systems within the Hibernia Formation and Breathitt Group.

The facies recognized from the upper Breathitt Group of eastern Kentucky provide a useful analogue to the stacking patterns observed in the Hibernia reservoir. Sharp-based, multi-storey braided sandstones with minor siltstone partings characterize the reservoir intervals at Hibernia, and their analogous equivalents in the Breathitt Group. These stacked braided-fluvial sandstones are incised into underlying delta-front sandstones, marine shales, or lagoonal strata. The incised contacts in both regions are defined by erosional lags of siderite and siliceous clasts, and or carbonaceous material. They are considered to be major boundaries signifying deep erosion for the following reasons:

1) The base of the valley systems in both regions are defined by the erosional juxtaposition of more proximal facies over more distal facies;
2) Truncation of underlying marine and brackish water shales in both regions;
3) *Glossifungites* ichnofacies present at the base of valley systems in the Hibernia Formation suggest significant exhumation, erosion, colonization by marine fauna and a depositional hiatus.

The siderite and carbonaceous debris that define these lag deposits are interpreted as reworked overbank material. The braided fluvial sandstones in both regions are predominantly medium grained; however, grain size variations from granule to very fine sand are also evident. These sandstones are erosive based and are characterized by trough crossbedding towards the base that passes up through planar-tabular crossbedding into rippled sands and siltstones at the top (Figure 4.18).

The greater percentage of coal has had little effect on the distribution of the braided fluvial sandstones throughout the Breathitt Group. The only valley system affected by coal occurs in the Pikeville Formation, above the Elkins Fork Shale. The valley system is only observed in the R-9 well where it directly overlies a one foot thick coal bed and pinches out to the east and west in the R-6 and D-13 wells respectively (Appendix III). The presence of the coal suggests that the valley system could not achieve their maximum erosive potential. As a result, the valley system is considerably thinner than those in the overlying Hyden and Four Corners formations.

These coals are commonly overlain by lagoonal facies. The fine-grained facies of the Breathitt Group are composed of interbedded shales, silts and sands overlain by

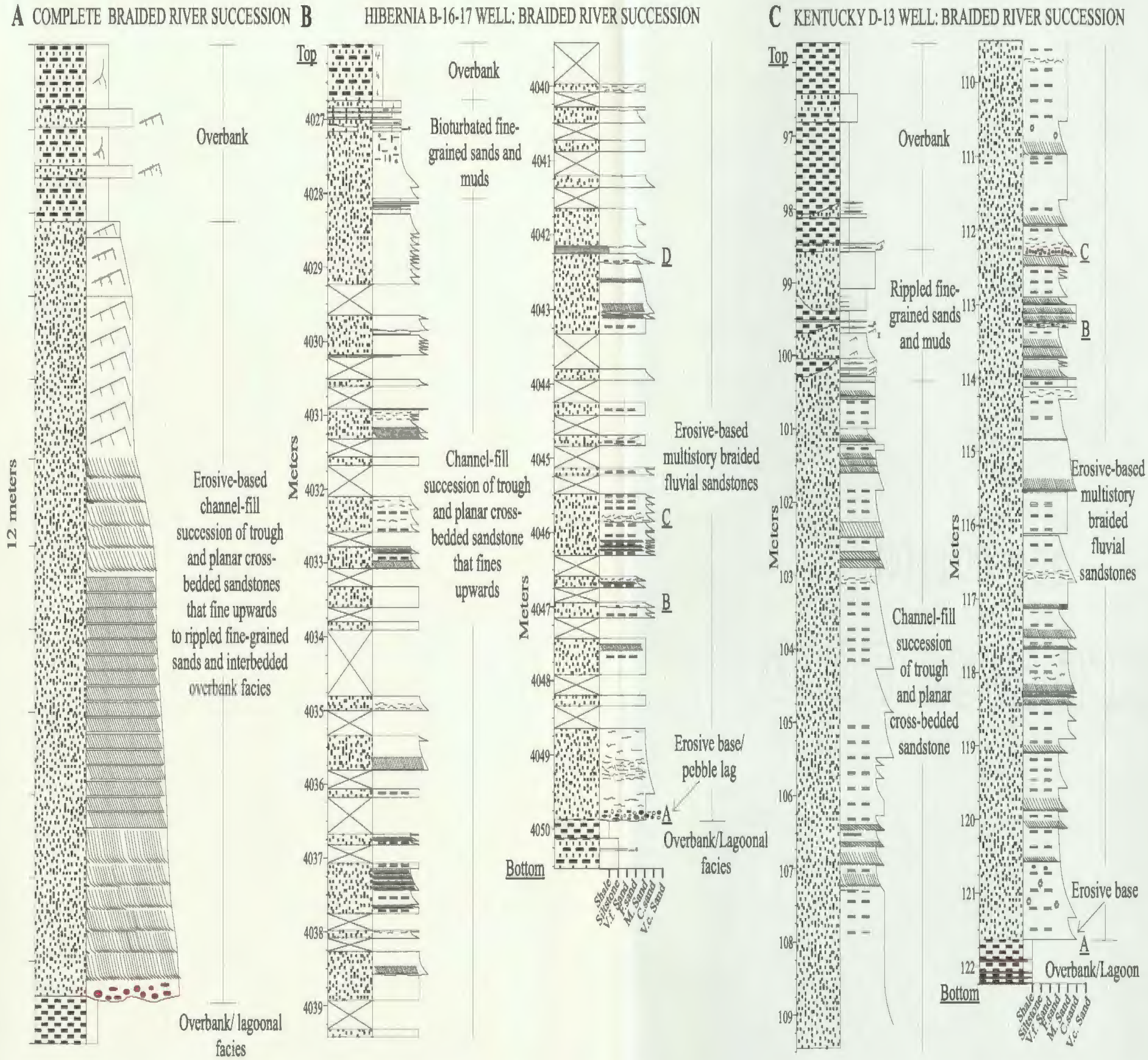


Figure 4.18. **(A).** An idealized, complete typical sedimentary log through a braided river succession. It is defined by an erosive-based sand that fines upwards through trough and planar cross-bedded sandstone to rippled fine sands and muds at the top (Nichols, 1999). The tops of these successions are commonly characterized by fine grained overbank facies. **(B).** Stacking pattern through a braided river succession in the Hibernia B-16-17 well. Numerous internal erosional surfaces labelled A through D show the erosion of the fine-grained deposits. These deposits are observed at the top of the interval. **(C).** Similar stacking pattern in the braided river succession observed in the Kentucky D-13 well. Internal erosional surfaces labelled A through C suggest the erosion of the fine grained deposits in the lower portion of the interval. These fine grained deposits are preserved at the top of the interval. the legend is located on figure 4.14.

rooted shales and coals. Like in the Hibernia Formation, these coals are in turn overlain by lagoonal facies (Figure 4.19). Therefore the stacking patterns observed in the braided fluvial deposits of the Breathitt Group are analogous to those at Hibernia over a range of scales.

The multi-storey braided fluvial sandstones of the Breathitt Group are separated by a series of marine shales similar to those observed at Hibernia. These shales were deposited in response to wide-spread flooding of the fluvio-deltaic complex. The lowermost contacts of these shales are overlain by deposits characteristic of the maximum flooding of the depositional interface. These shales and their analogous equivalents at Hibernia are summarized below:

Table 4.2: Marine strata of the Breathitt Group and Hibernia Formation.

Breathitt Group	Hibernia
Magoffin Shale	Medial Shale
Whitesberg Shale	Layer 3 middle, shale dominated
Kendrick Shale	K18 Shale
Elkins Fork Shale	Fortune Bay Formation

The Elkins Fork Shale is analogous to the Fortune Bay Formation (Figure 4.20). The upward coarsening succession characteristic of the Elkins Fork Shale has been interpreted as the delta-front /mouthbar succession of an advancing delta. A series of upward coarsening sequences define this interval. This is very similar to the upward

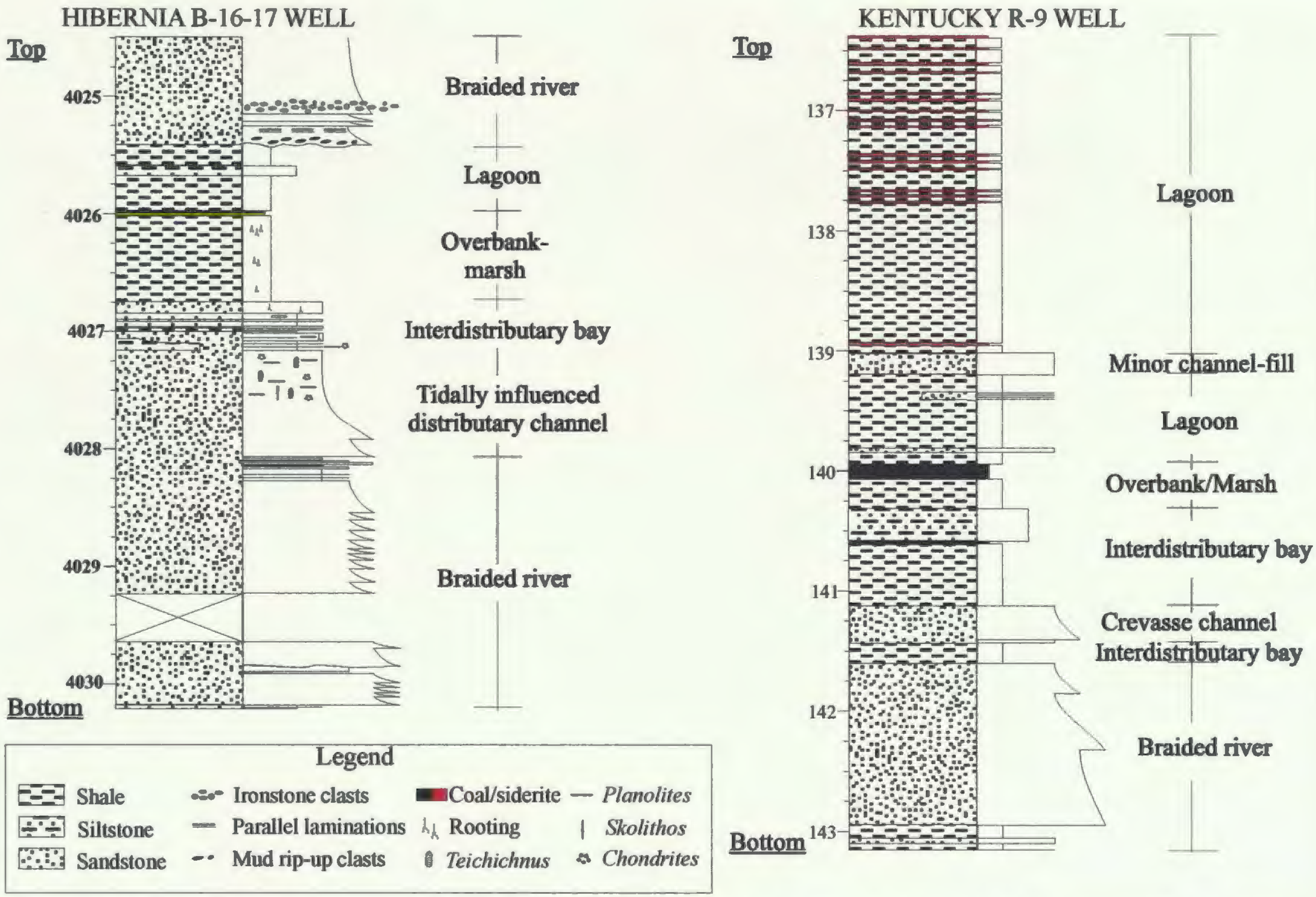


Figure 4.19. Stacking patterns observed in the fine-grained, overbank facies from the Hibernia Formation and the Breathitt Group.

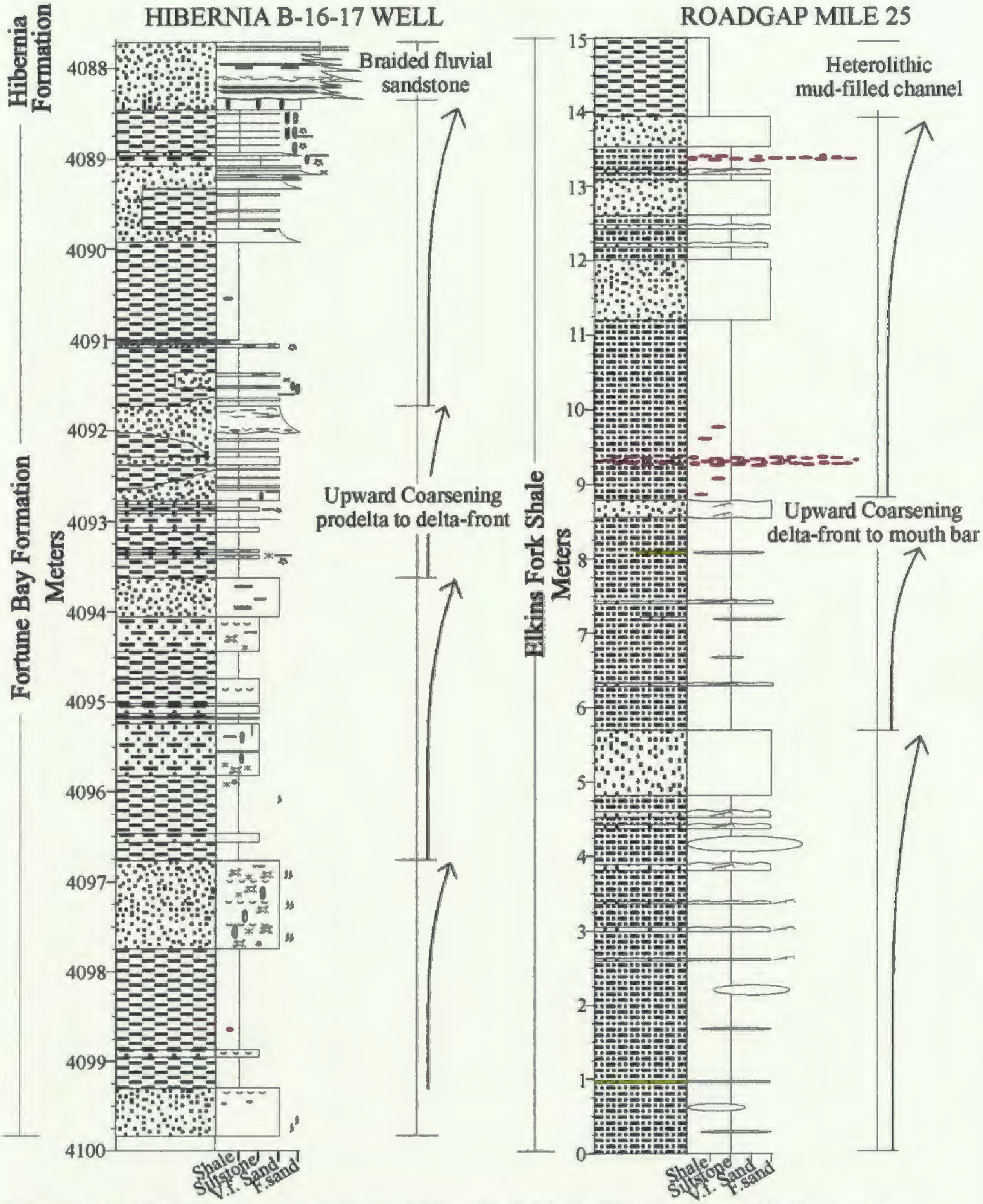


Figure 4.20. Stacking patterns in the Elkins Fork Shale from the Breathit Group are considered analagous to those in the Fortune Bay Formation at Hibernia. Both intervals are characterized by a series of upward coarsening sequences. The Elkins Fork interval studied at Roadgap does not show the prodelta facies; however, this facies was observed in well R-9. Legend located on figure 4.14.

coarsening deposits of the Fortune Bay Formation at Hibernia. The top of the Elkins Fork Shale is interpreted as a mouthbar and associated levee deposit, thus completing the distributary-mouthbar sequence. The Fortune Bay interval observed in the B-16-17 well contains the delta-front sequence, but does not show the mouthbar and overlying levee deposits. The absence of these facies is due to erosion beneath the overlying braided river sandstones. Gamma-ray logs from Hibernia development wells B-16-2 and B-16-4 show a upward coarsening succession towards the top of the Fortune Bay Formation, thus possibly suggesting the presence of mouthbar and levee facies throughout the upper Fortune Bay Formation immediately beneath the Hibernia Formation (Figure 4.21).

The remaining shale-dominated units throughout the Breathitt Group are composed of deposits characteristic of marine-shelf depositional environments. Marine shales characterized by articulated and disarticulated shell debris and a marine trace fossil assemblage of abundant *Chondrites* and other marine ichnofossils characterize these deposits. In the Breathitt Group, these marine shales commonly overlie coal beds, so that the top of the coal bed is the transgressive surface. At Hibernia, the marine shales overlie very thin-bedded coals and marsh deposits.

Both the Jeanne d'Arc Basin and Kentucky also experienced wide-spread marine incursions which resulted in the deposition of marine-shelf strata on top of lower delta-plain and lagoonal facies. The base of the Magoffin Shale in the Breathitt Group is defined by a lower basal limestone overlain by a condensed, fossiliferous black shale. This represents the maximum extent of the marine transgression (Figure 4.22). The Medial Shale at Hibernia, is defined at its base by a firmground *Glossifungites* trace-

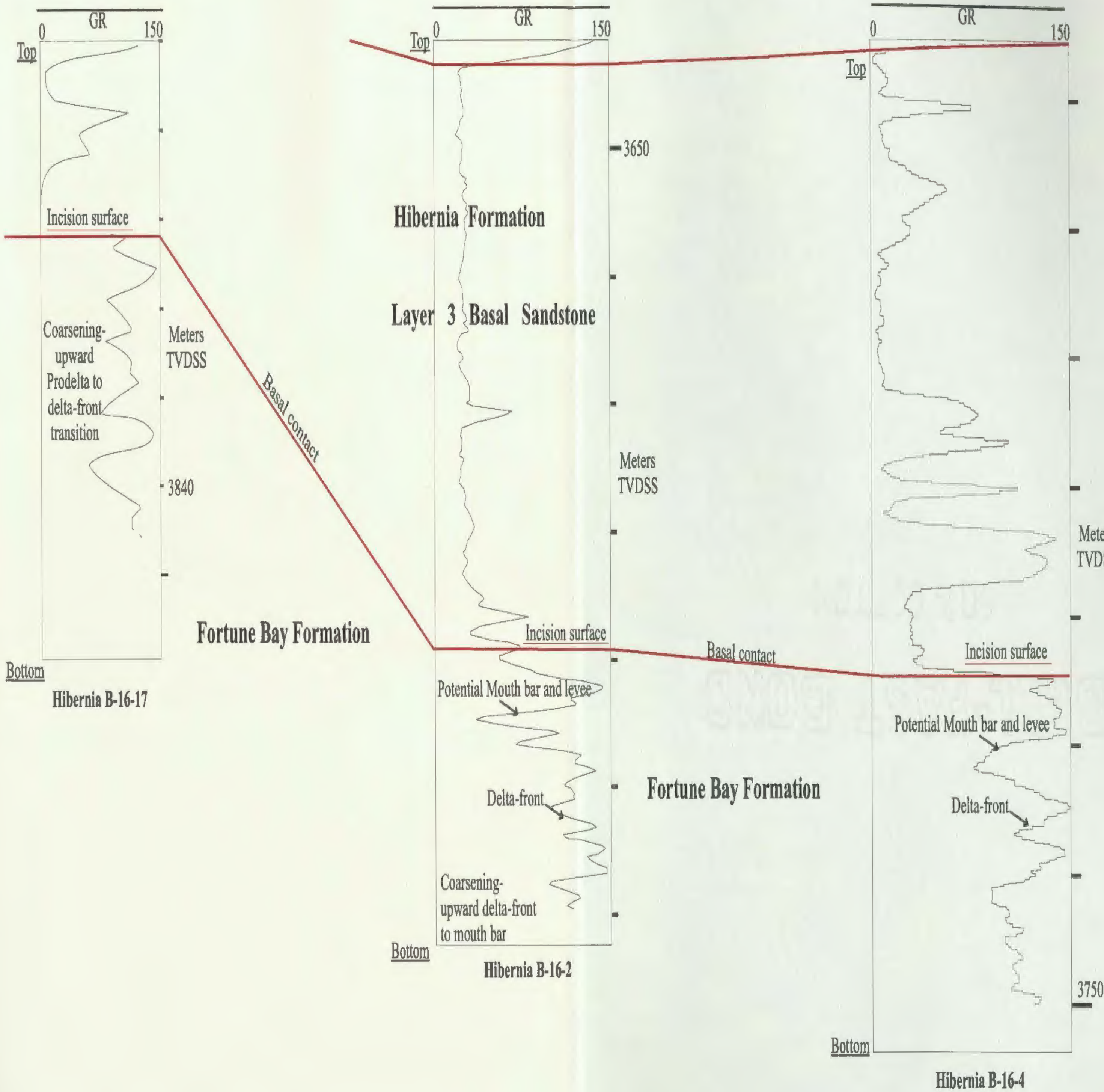


Figure 4.21. This gamma ray correlation shows the incision of the Layer 3 Basal sandstone and subsequent erosion of the underlying Fortune Bay Formation. The Fortune Bay Formation observed in the B-16-17 well shows a coarsening-upward succession of prodelta to delta-front facies. The overlying mouth bar facies are absent due to erosion by the braided-fluvial sandstones characteristic of Layer 3. The gamma ray logs in both the B-16-2 and B-16-4 wells exhibit a more substantial coarsening-upwards succession in the Fortune Bay, suggesting the presence of delta-front and mouth bar facies. This stacking pattern in very similar to that of the Elkins Fork Shale in the Breathitt Group. The datumn for this correlation is the Medial Shale.

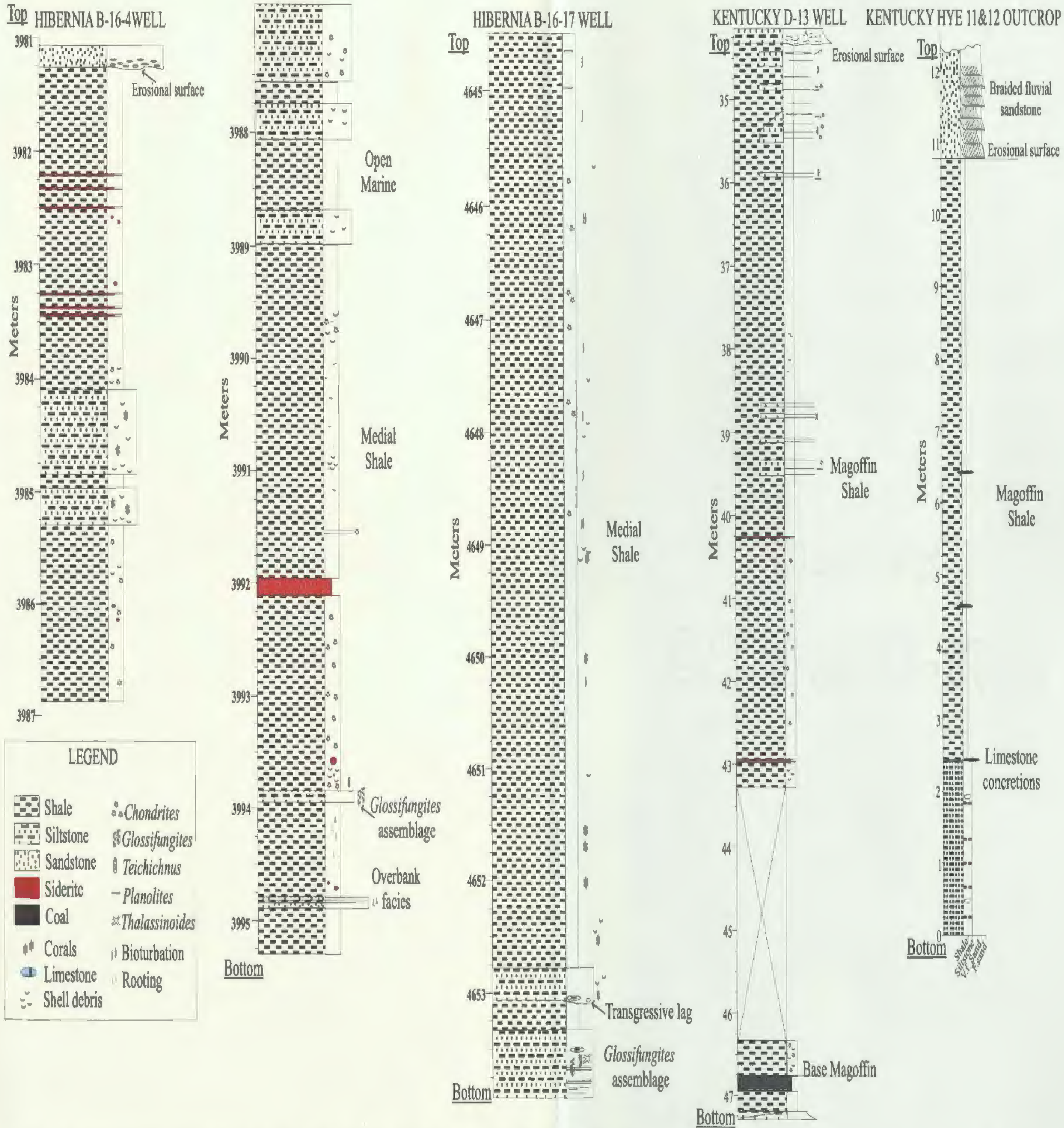


Figure 4.22. Stacking patterns observed from the Medial Shale at Hibernia and from the Magoffin Shale in the Breathitt Group. The base of the Magoffin is interpreted as a transgressive surface and is defined by limestone concretions. The base of the Medial shale is interpreted as a marine transgressive surface and is defined by a *Glossifungites* trace assemblage. Both shales are Characterized by grey shale with common to abundant shell debris and marine traces.

fossil assemblage and bioclast-rich lag deposit which also defines the maximum extent of a marine transgression. This was observed in both the B-16-4 and B-16-17 Hibernia development wells (Figure 4.22). Shell debris and a similar marine trace-fossil assemblage characterizes both marine shales. Therefore, the Magoffin interval is considered analogous to the Medial Shale interval at Hibernia.

Based on similar stacking patterns observed in both the braided fluvial, overbank and marine deposits, the facies and depositional environments identified in the Breathitt group are judge to be very closely analogous to those identified in the Hibernia Formation. The greater percentage of coal throughout the Breathitt Group does not render it less suitable as an analogue for the Hibernia Formation. The degree of similarity is so striking that the characteristics of the Breathitt Group sandstones can likely be used as reliable input to reservoir models for the Hibernia Formation.

CHAPTER FIVE

SEQUENCE STRATIGRAPHIC FRAMEWORK OF THE HIBERNIA FORMATION AND THE BREATHITT GROUP

5.1 Introduction

In recent decades, sequence stratigraphy has become a very important subdiscipline of stratigraphy. Sequence stratigraphy provides guidelines for the description and understanding of sedimentary successions with respect to cycles of sea-level change. As relative sea level rises and falls, coastal and shallow-marine depositional environments may migrate landward or seaward, respectively. The resulting reservoirs are likely to display very different geometries depending on whether they formed during transgression or regression. Sequence stratigraphy is also useful in reconstructing the relative chronology of deposition in basins where biostratigraphic control is either lacking or severely limited. The sequence stratigraphic terminology used throughout this study is that defined by Mitchum (1977), Van Wagoner et al. (1988) and Mitchum and Van Wagoner (1991).

5.1.1 Terminology

The following definitions apply to some of the terms commonly used in sequence stratigraphy. Many of these concepts were originally proposed by Vail et al. (1977) but have evolved in recent years through further discussion. Key definitions for these concepts are provided to ensure that the fundamentals of sequence stratigraphy are communicated properly throughout this study.

Mitchum (1977) defines a **sequence** as a " relatively conformable, genetically related succession of strata bounded at its top and base by unconformities or their correlative conformities". Sequences are the fundamental building block of sequence stratigraphy and can be further subdivided into systems tracts and parasequence sets. Sequences have been interpreted to form in response to the interaction of varying rates of eustatic change, subsidence and sediment supply (Van Wagoner et al., 1988).

An **unconformity** is defined by Van Wagoner et al. (1988) as a surface separating younger from older strata, along which there is evidence of subaerial erosional truncation (and, in some areas, correlative submarine erosion) or subaerial exposure and non-deposition, with a significant hiatus indicated.

A **conformity** is defined as a bedding surface separating younger from older strata, along which there is no physical evidence of erosion or non-deposition or a significant hiatus (Mitchum, 1977).

A **parasequence** is defined as a relatively conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces (Van Wagoner et al., 1988).

A **marine flooding surface** is defined as a surface that separates younger from older strata, across which there is evidence of a abrupt increase in water depth (*ibid.*)

Mitchum and Van Wagoner (1991) define a **parasequence set** as a succession of genetically related parasequences with distinctive stacking patterns. These sets can be retrogradational, aggradational or progradational. These stacking patterns define systems tracts.

Brown and Fisher (1977) defined a **systems tract** as a linkage of contemporaneous depositional systems. Systems tracts are used to subdivide a sequence into three parts: lowstand systems tract (LST), transgressive systems tract (TST) and highstand systems tract (HST). These systems tracts are defined by the nature of the bounding surfaces, their position within a sequence, parasequence and parasequence set stacking patterns and are deposited during different phases of relative sea-level change. Hunt and Tucker (1992) proposed a fourth systems tract known as the forced regressive systems tract. This systems tract was not recognized in the original Exxon model.

A **lowstand systems tract (LST)** is developed in two stages. The first stage, known as the early lowstand systems tract (ELST), occurs during a fall in relative sea level and is characterized by exposure of previous marine settings, stream incision and subsequent valley development and bypass of coastal-plain strata basinward (Van Wagoner et al., 1988). The second stage involves the deposition of the lowstand wedge and infilling of the incised valleys formed during the relative sea-level fall (Van Wagoner et al., 1988). During the second stage, relative sea level falls slowly, stops and then slowly rises during which time deposition slows down dip and starts to infill those areas eroded during stage one. Although initial deposition of the incised valley fill occurs in the lowstand systems tract, the majority of the valley fill accumulates during early base-level rise when augmented accommodation develops within the valley. According to Exxon terminology, the valley fill is late LST, while many have argued that it is early TST as the infill is the result of base-level rise (Flint and Sinclair, 2001). For this reason valley fills will be referred to as late LST-early TST throughout this study. The top of the lowstand systems tract is referred to as the transgressive surface. Since the valley fills in this study are late LST –early TST, the transgressive surface lies in the lower portion of the valley system.

Van Wagoner et al. (1988) define the **transgressive surface** as the first significant shelf-crossing marine flooding surface within a sequence.

The **transgressive systems tract (TST)** is the middle systems tract and is characterized by a retrogradational parasequence set. It is defined at its base by the transgressive surface and at its top by a maximum-flooding surface.

The **maximum-flooding surface** marks the transition from landward, retrogradational facies to aggradational/progradational stacking patterns.

The **highstand systems tract (HST)** is the uppermost systems tract in a sequence and is characterized by a change from aggradational to progradational patterns of deposition. The top of the highstand systems tract is marked by the overlying sequence boundary, so that all highstand systems tracts are subject to exposure, erosion and non-preservation. During the HST, there is a deceleration in the rate of relative sea-level rise through time resulting in initial aggradational and later progradational stacking patterns.

5.2. Sequence Stratigraphic Framework of the Hibernia Formation

Sequence boundaries and systems tracts are required to build a sequence stratigraphic framework for the Hibernia Formation. Emery and Myers (1996), and Aitken and Flint (1995) provide a list of criteria for the recognition of sequence boundaries within the stratigraphic record. Emery and Myers (1996) recognize two kinds of sequence boundaries. Type 1 boundaries are characterized by subaerial exposure and erosion associated with stream rejuvenation, a basinward shift in facies, a downward shift in coastal onlap, and onlap of overlying strata onto the boundary (Emery and Myers, 1996). The basinward shift in facies results in the placement of non-marine or marginal marine strata directly on top of shallow-marine rocks. Aitken and Flint (1995) state that type 1 sequence boundaries can be recognized by a basinward shift in facies, abrupt facies tract dislocation, an abrupt increase in vertical sandstone amalgamation and a increase in mean grain size.

Sequence boundaries can also develop due to a relative sea level fall over a proximal area of the highstand topsets and not at the offlap break (Emery and Myers, 1996). These sequence boundaries are referred to as type 2 sequence boundaries and are not characterized by fluvial incision or sub-marine fan deposition (Emery and Myers, 1996). They are characterized by subaerial exposure and a downward shift in coastal onlap, landward of the lowstand shoreline. However, type 2 boundaries lack both subaerial erosion associated with stream rejuvenation and a basinward shift in facies (Van Wagoner et al., 1988). The shoreline never reaches the shelf edge. Five type 1-sequence boundaries have been interpreted within the Hibernia Formation (Figure 5.1).

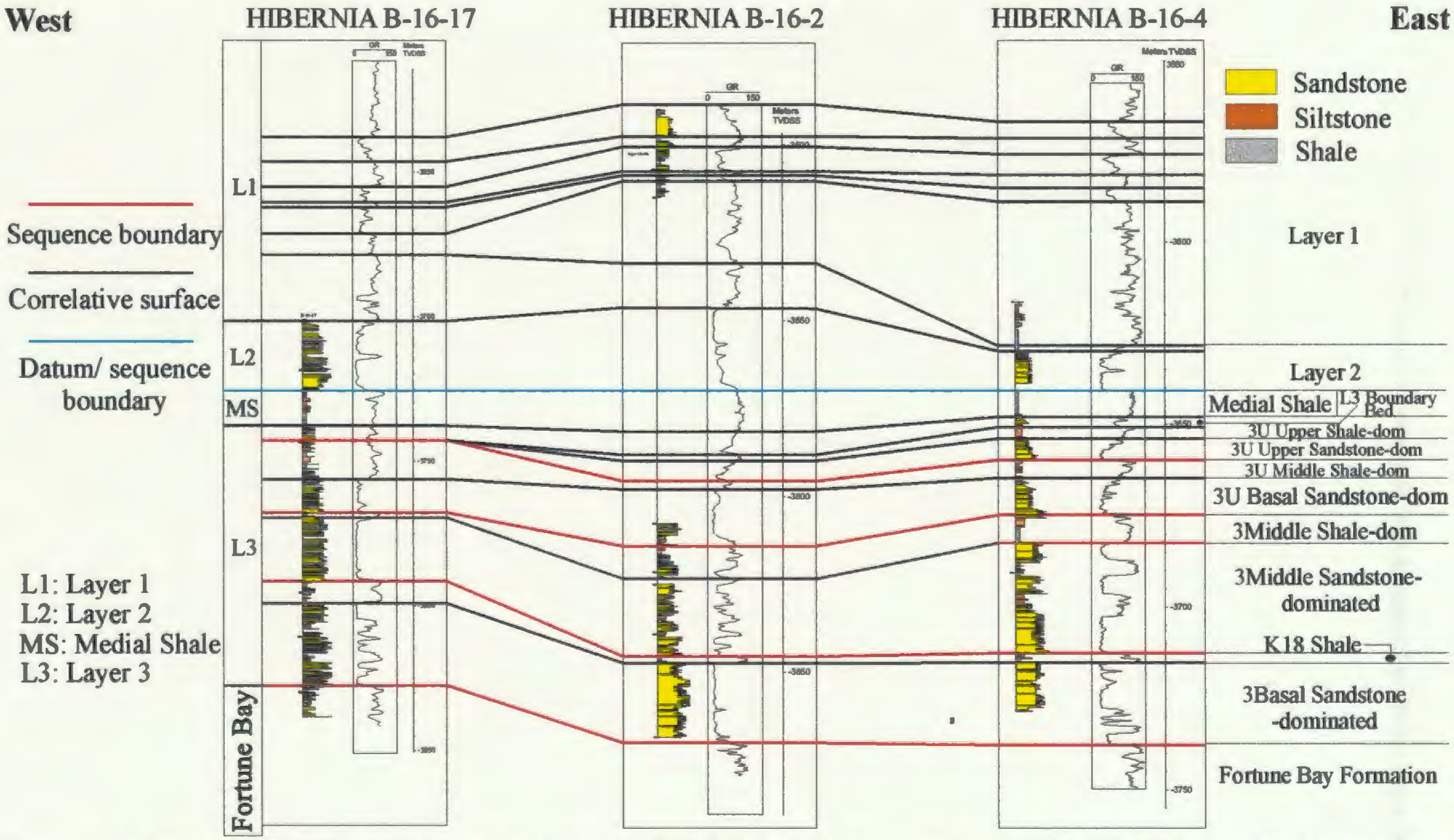


Figure 5.1. Correlated Hibernia well data using the top of the Medial Shale as datum. Sequence boundaries identified in red occur at the base of each sandstone reservoir interval. The correlation shows multiple levels of cyclicity throughout the Hibernia Formation. This cyclicity is apparent in the alternating high and low net sandstone intervals throughout the Hibernia Formation. Note the presence of multistorey sandbodies in the lower portion of Layer 3 and single storey sandbodies in the upper portion of Layer 3. The correlation also shows thickness variations in the K18 and 3M Shale-dominated intervals. Sequence boundaries have been interpreted by the author.

Throughout the Hibernia Formation, the lowstand systems tract (LST) is characterized by multi-storey, braided-river sandstones constrained within incised valleys (facies association VII). These valley systems overlie erosional unconformities and are incised into marine deposits (facies association I), upward coarsening mouthbar deposits (facies association II) and overbank deposits (facies association IV). The top of the LST is a transgressive surface, which is the first significant flooding surface. Throughout the Hibernia Formation, shell debris and marine trace-fossil assemblages mark the transgressive surfaces.

The TST is widely developed throughout the Hibernia Formation. The LST passes upwards into thin, single-storey channel deposits (facies association V) within a framework of fine-grained overbank deposits (facies association IV), marine deposits (facies association I) and /or lagoonal deposits (facies association III). Tidal influence is evident within the TST at Hibernia, but is rare. The TST is only partially preserved throughout the Hibernia Formation, except for the top of Layer 3 where the complete TST is preserved. The partial preservation of the TST in the lower portion of Layer 3 is due to erosion by valley systems during the subsequent early LST.

The erosive effect of the valley systems also influences the distribution of HST deposits throughout the Hibernia Formation. The HST is only preserved at the top of Layer 3 due to an increase in accommodation space and a reduction in the erosion by overlying valley systems. The HST is characterized by isolated crevasse and minor channel deposits (facies association V).

The sequence stratigraphy of the Hibernia Formation will be discussed with respect to third-, fourth- and fifth-order cyclicity. Fourth-order cycles will be discussed in terms of stacking patterns and high and low net sandstone intervals. Correlations are based on the recognition of key correlative surfaces and were constructed using the top of the Medial Shale as datum (Figure 5.1).

5.2.1 Third-order cyclicity

The entire Hibernia lower zone is interpreted as a complete third-order composite sequence (Figure 5.2). Third-order cycles are characterized by a high amplitude, low frequency, sinusoidal, relative sea-level curve (Figure 5.3a). Layer 3 represents the late LST to early TST. Recognition of a third-order sequence boundary at the base of Layer 3 is based on the criteria provided by Emery and Myers (1996). Correlated well data show significant erosion and loss of a portion of the upward coarsening, delta-front facies of the Fortune Bay Formation due to a basinward shift in facies (Figure 4.20). The *Glossifungites* trace-fossil assemblage observed at the base of Layer 3 in the B-16-17 well indicates erosional exhumation and colonization by marine fauna of the underlying delta-front deposits. A significant increase in vertical sandstone amalgamation and grain size is also observed above the *Glossifungites* surface. It is also important to recognize the regional extent of this surface. This sequence boundary can be mapped as a regional surface and develops angularity towards the northern portion of the Hibernia field (Stokes, pers. comm. 2003). Therefore, the base of Layer 3 fulfills the criteria identified

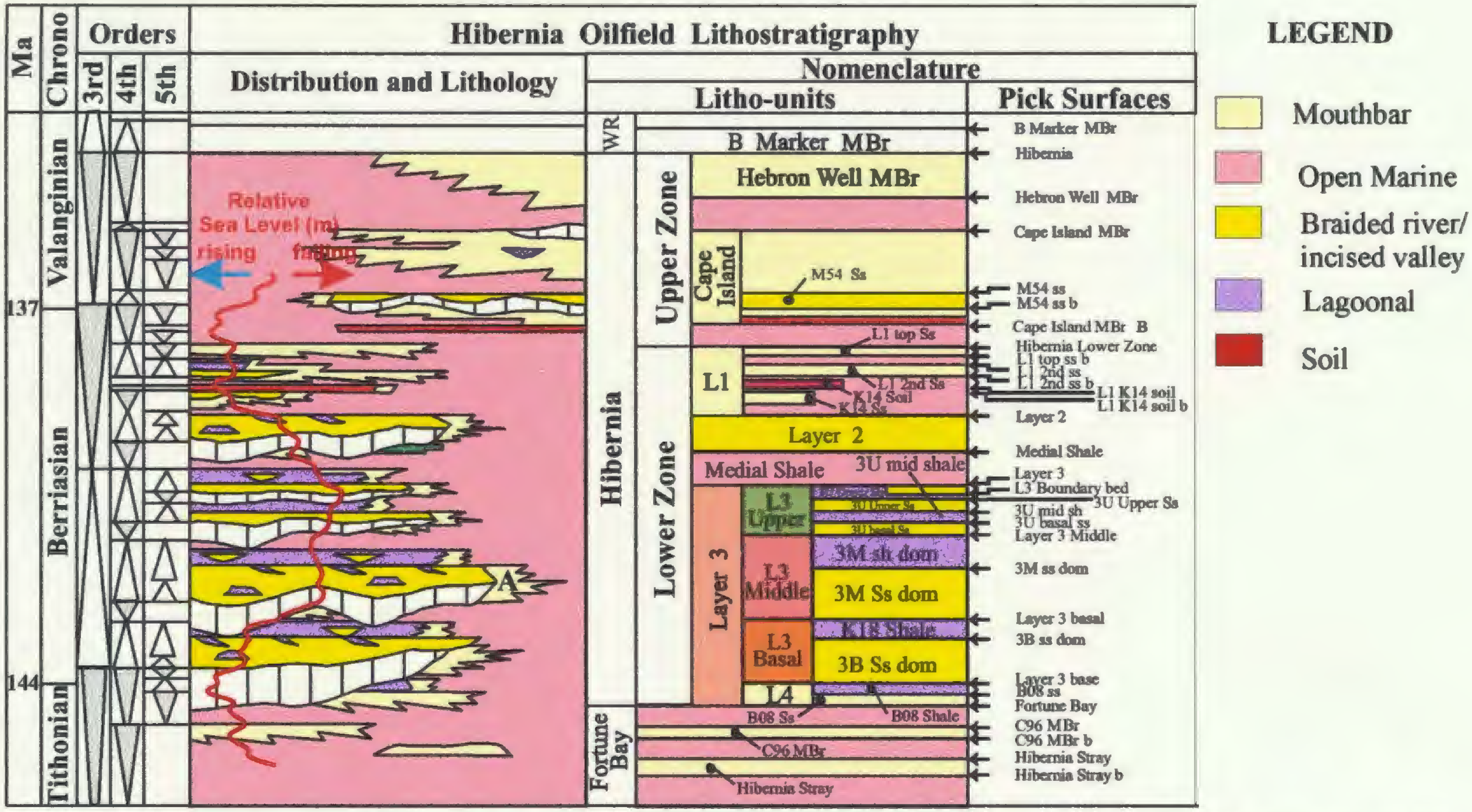


Figure 5.2. Lithostratigraphy and sequence stratigraphy of the Hibernia Oilfield. Third-, fourth-, and fifth-order cycles are present throughout the Hibernia Formation. Layer 3 is interpreted as a complete third-order composite sequence and can be further subdivided into fourth- and fifth-order cycles. Fifth-order cycles are only present in the upper Portion of Layer 3, due to this being the turnaround point in the third-order cycle from falling to rising sea-level. Fifth-order cycles are likely breached by fourth-order incised valley systems in the lower portion of Layer 3, and are not observed. White triangles represent different orders of LST to TST while inverted triangles represent Periods of HST. Lowstand shorefaces denoted by the letter A on this figure were identified in other cores by HMDC (Modified from Flint and Sinclair, 2001).

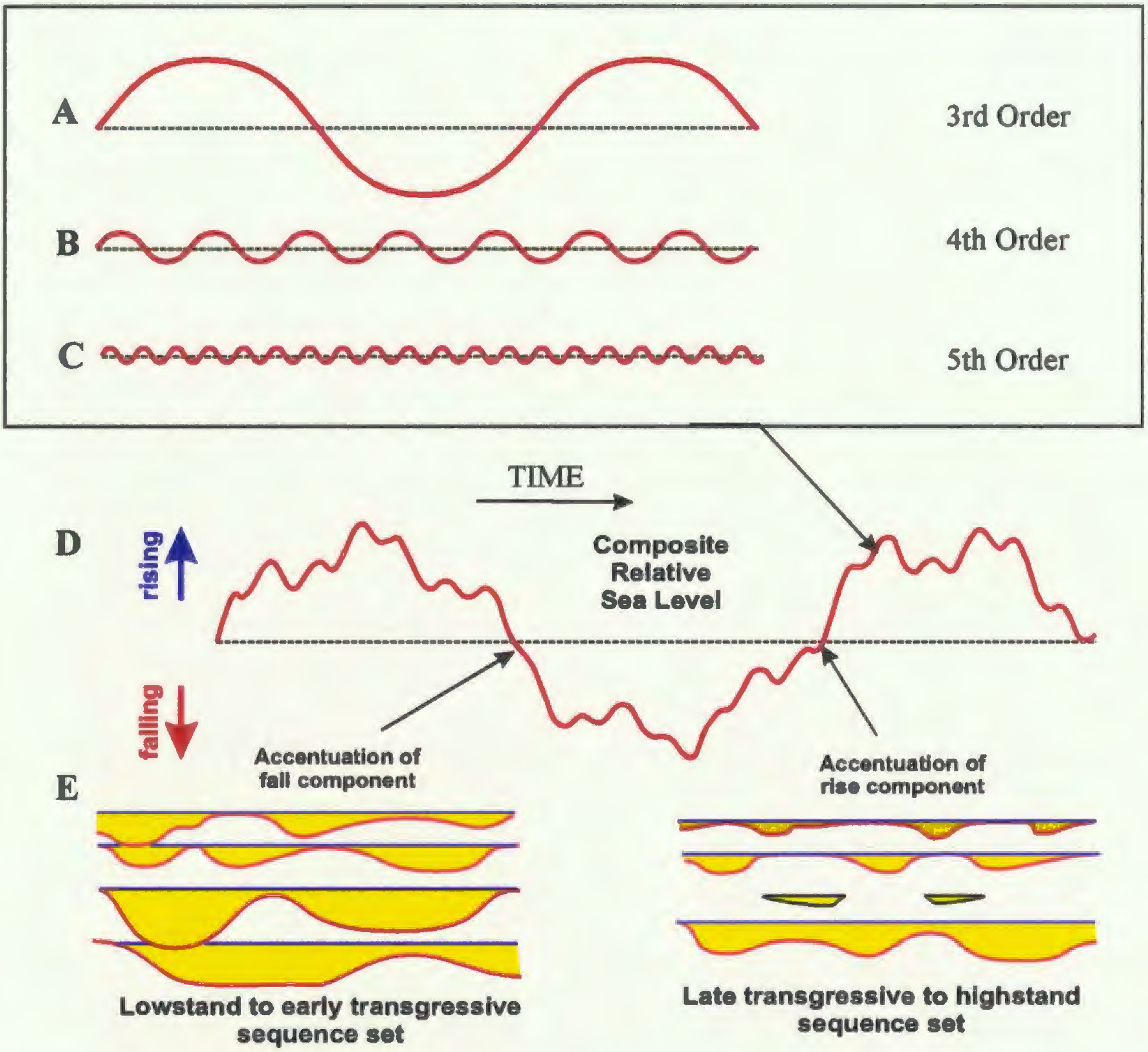


Figure 5.3. Varying frequencies of relative sea-level cycles. **A).** High amplitude, low frequency third-order relative sea-level curve. **B).** High frequency, lower amplitude fourth-order relative sea-level curve. **C).** Low amplitude, high frequency fifth-order relative sea-level curve. **D).** Composite third-, fourth-, and fifth-order relative sea-level curve. This composite sea-level curve controls the distribution of high and low net sandstone intervals and the creation of accommodation throughout the, Hibernia Formation. **E).** The left side represents the early LST to early TST during which time valley systems achieve their maximum erosive potential. This results in multistorey sandbodies as seen in the lower portion of Layer 3. The right side represents the late TST to HST, during which time the erosive potential of valley systems is reduced and single storey sandbodies develop, such as those in the upper portion of Layer 3.

by Emery and Myers (1996) and Aitken and Flint (1995) for the placement of a third-order sequence boundary.

The valley fill of Layer 3 is interpreted to belong to a late LST to early TST. In the LST, the overall rate of sediment supply is greater than the rate of creation of accommodation. Sediment bypass to the shelf, in conjunction with a base-level fall, results in erosion and the creation of new accommodation space through incision. The incision creates a valley system (Figure 5.4) (Shanley and McCabe, 1993). In the early TST, reduced rates of base-level fall and a change to a slowly rising base-level results in amalgamated fluvial channel deposits (Shanley and McCabe, 1993). Stacking patterns observed through such amalgamated deposits are similar to those observed throughout the lower portion of Layer 3 in the B-16-2 well (Figure 5.4). Eventually, in the late TST, the rate of base-level increases because of a rise in relative sea level; this results in the development of isolated and tidally influenced deposits. This progression from amalgamated to isolated and tidally influenced sandstones implies a transgression and is characteristic of the late TST (Shanley and McCabe, 1993).

The top of Layer 3 is marked by an abrupt landward shift in facies. This abrupt contact signifies an increase in water depth and is the first significant flooding surface in the sequence. A *Glossifungites* (firmground) trace-fossil assemblage characterizes this surface in the B-16-4 and B-16-17 wells (Figure 3.17). The presence of this surface implies colonization of a firm substrate by organisms as the ravinement surface is

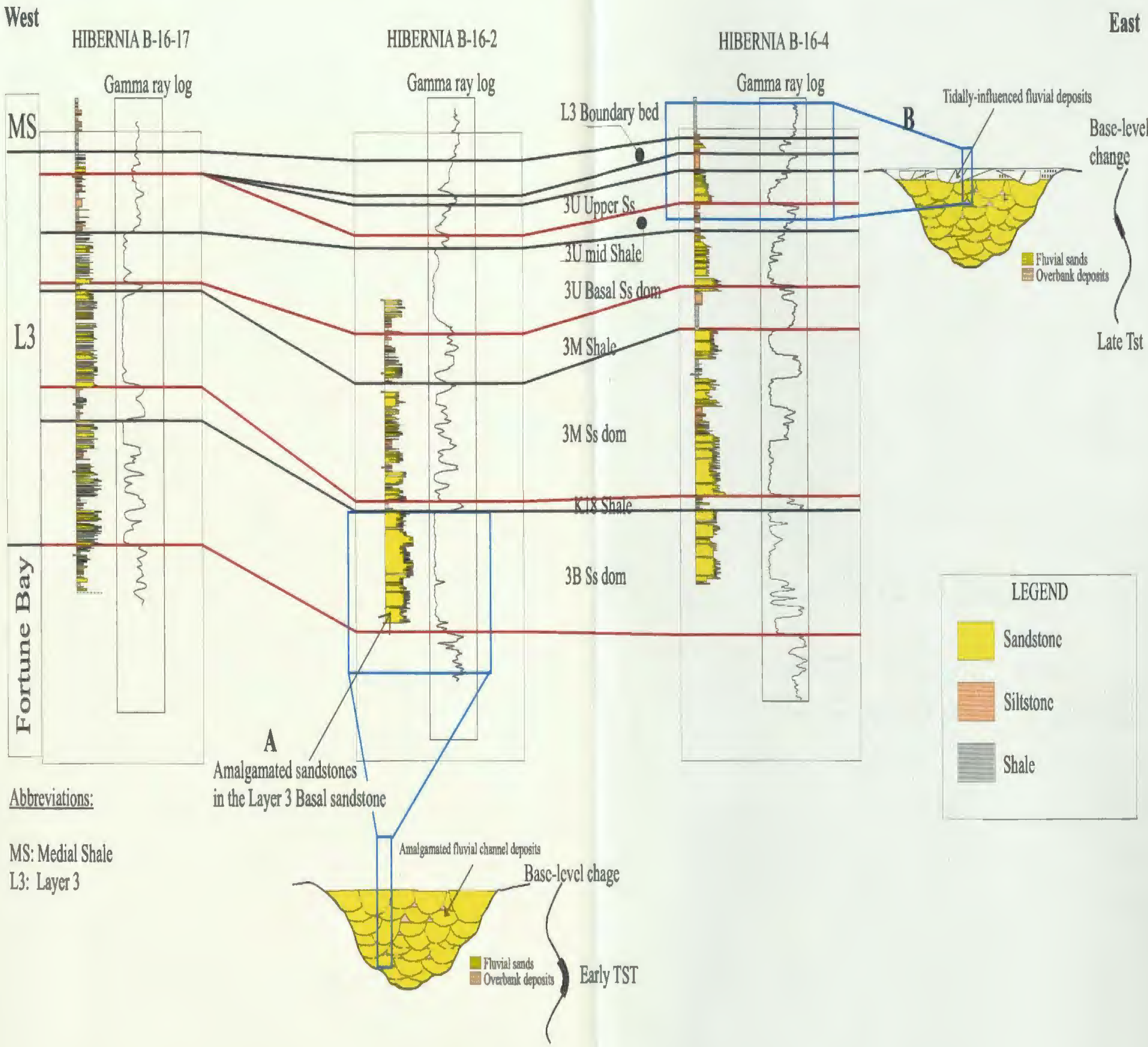


Figure 5.4. Amalgamated sandstones comprise the third-order cyclicity throughout Layer 3. **A)** In the early TST, reduced rates of base-level fall result in amalgamated sandstones being deposited. **B)**. In the late TST, the rate of base-level rise increases and results in the development of isolated tidally influenced, fluvial deposits. This stacking pattern is observed throughout the upper Portion of Layer 3, below the Medial Shale. Fluvial architectures as a function of base-level change have been modified from Shanley and McCabe (1994).

excavated, and prior to deposition of the overlying sediment (Pemberton et al., 2001). The *Glossifungites* assemblage suggests that this is a surface of erosion as opposed to a normal flooding surface. Therefore the contact between Layer 3 and the Medial Shale is interpreted as a third-order transgressive marine ravinement surface and marks the base of the third-order maximum flooding zone. During this third-order sea-level rise, the incised valley system of Layer 3 becomes completely sealed by a field-wide marine shale.

The upper Medial Shale through to Layer 1 represents the HST. The HST throughout the Hibernia Formation is characterized by a reduced rates of base-level rise that are balanced by rates of sedimentation (Shanley and McCabe, 1993). This results in initial aggradational stacking patterns through the upper Medial Shale and later progradational stacking patterns in Layer 2 through to Layer 1. Facies architecture will initially be similar to that of the TST; however, as progradation begins and the rate of base-level and relative sea-level rise decreases, tidal influence will decrease and overbank/lagoonal facies will become less prevalent (Emery and Myers, 1996). This results in channel sandbodies becoming more common and connected as seen in the sandstones throughout Layer 2. Oxidized shales in Layer 1 are consistent with low water table conditions during the HST (I. Sinclair, pers. commun., 2001). The top of the HST is marked by a sequence boundary. The development of the sequence boundary results in erosion of the underlying highstand strata and initiates a period of non-deposition and bypass of sediment.

5.2.2 Fourth-order cyclicity

Careful examination of the correlated well data indicates that multiple levels of cyclicity are present within the Hibernia Formation. This cyclicity is also apparent from analysis of the stacking patterns. Lagoonal or marine shales deposited during repeated drowning of the fluvio-deltaic system overlie each valley system.

Layer 3 is comprised of three major sandbodies; the lowermost two are interpreted as major incised valley fills, while the third can be further subdivided into two smaller valley systems (Figure 5.1). The application of high-frequency sequence stratigraphy is required to better document and understand this cyclicity. The high-frequency sequence stratigraphy will be discussed with respect to high and low net sandstone intervals.

This cyclicity is apparent in the stacking patterns recognized in the Hibernia cores. The stacking patterns in the sandstone reservoir intervals at Hibernia (Layer 3 Basal, 3 Middle, 3U Basal and 3U Upper Sandstone-dominated intervals) are summarized below:

1) Stacked, upward fining, coarse to fine grained sandstones characterized by trough crossbedding at the base pass upwards through planar crossbedded to current rippled sandstones at the top;
2) The moderate to well sorted sandstones have an average size of medium sand, but range from fine sand to granule size;
3) Erosive-based sandstones are defined by siderite lags and/or carbonaceous debris (transported material);

4) Thin bedded silty shales are preserved as erosional remnants within the sandstones.

The sandstone reservoir intervals are repeatedly separated by non-reservoir, fine-grained siltstones and shales (K18, 3M, 3U Middle and 3U Upper shales respectively) (Figure 3.21). Their stacking patterns and characteristic attributes are summarized below:

1) The deposits consist of interbedded shales, siltstones and very fine grained sandstones;
2) Brackish water to fully marine trace-fossil assemblages are characteristic;
3) Lagoonal facies grade upwards into rooted siltstones and thin bedded coals.

The fine-grained, non-reservoir facies occur truncated below and gradationally above the braided river sandstones of facies association VII. The siderite nodules and carbonaceous debris of the fine-grained deposits were commonly reworked during valley incision and occur as lag deposits at the base of the braided river sandstones.

In the correlated well data, this cyclicity is shown by alternating high and low net sandstone intervals throughout the Hibernia Formation (Figure 5.1).

5.2.2.1 High net sandstone intervals

The sand-rich Layer 3 can be further subdivided into three fourth-order sequences. Fourth-order sequences are attributed to a low amplitude, high frequency relative sea-level curve (Figure 5.3b). The superposition of fourth-order relative sea-level fluctuations on a third-order curve results in a complex composite relative sea-level curve which controls the distribution of the high net sandstone intervals throughout the

Hibernia reservoir (Figure 5.3e). The composite sea-level curve retains the basic shape of the third-order curve, but shows the oscillations of higher frequency, fourth-order cycles (Mitchum and Van Wagoner, 1991). The high net sandstone intervals in the lower portion of Layer 3 (3 Basal and 3 Middle Sandstone-dominated intervals) are interpreted as two separate fourth-order incised valley systems. Placement of fourth-order sequence boundaries at the base of each valley system is based on the criteria provided by Emery and Myers (1996), Aitken and Flint (1995) and Zaitlin et al. (1994). The base of each valley system is marked by an abrupt basinward shift in facies resulting in the erosional juxtaposition of proximal, non-marine, braided river sandstones over more distal deposits. The valley systems erode most deeply during the early LST (Figure 5.3e). This accounts for the significant erosion of both the Fortune Bay Formation below the 3 Basal Sandstone-dominated interval, and the upper portion of the TST and all of the HST below the 3 Middle Sandstone-dominated interval. The *Glossifungites* (firmground) trace-fossil assemblage provides further evidence for a fourth-order sequence boundary at the base of the 3 Basal Sandstone-dominated interval. The recognition of a pebble lag across the field in addition to the erosional juxtaposition of more proximal facies over more distal facies demonstrates a fourth-order sequence boundary at the base of 3 Middle Sandstone-dominated interval.

The incision of both valley systems at the base of Layer 3 occurred during the early LST and subsequent fill occurred during the late LST to early TST. The *Glossifungites* assemblage indicates a hiatus between the erosional event in the early LST and deposition of the valley fill, so it is possible that the valley fill accumulated entirely in the late LST to early TST. At Hibernia, the *Glossifungites* assemblage is found below the valley in the underlying delta-front deposits of the Fortune Bay Formation.

The valley fills show both initial valley incision and amalgamated stacking patterns. In the B-16-17, B-16-2 and B-16-4 development wells, stacking patterns in the 3 Basal Sandstone-dominated interval suggest that sediment supply was greater than the rate of creation of accommodation (Figure 5.5). This resulted in valley incision and amalgamated sandstones. Fine-grained facies within this interval in the B-16-17 well attest to the preservation of fine-grained facies between the braided river sandstones (Figure 5.5). Sandstone-dominated stacking patterns are observed farther east in the B-16-2 and B-16-4 wells. Similar amalgamated stacking patterns are evident in the 3 Middle Sandstone-dominated interval. This interval in the B-16-17 development well produces a blocky gamma ray response, and in core exhibits numerous internal erosional contacts (Figure 5.6). The absence of fine-grained facies in the B-16-17 well suggests that the well was cored through the sand-rich portion of the amalgamated stacking pattern; however, eastward towards the center of the valley system, fine-grained facies are observed in the B-16-2 and B-16-4 wells (Figure 5.6). The thickening of the 3 Middle Sandstone-dominated interval towards the east, in addition to the increase in fine-grained facies basinward suggest that the B-16-4 well was cored towards the center of the valley system and that the axes of the valley systems were shifting across the field during the deposition of the Hibernia Formation.

The final fourth-order sequence occurs in Layer 2. The Layer 2 incised valley formed due to a fourth-order base-level fall during a third-order highstand. This valley

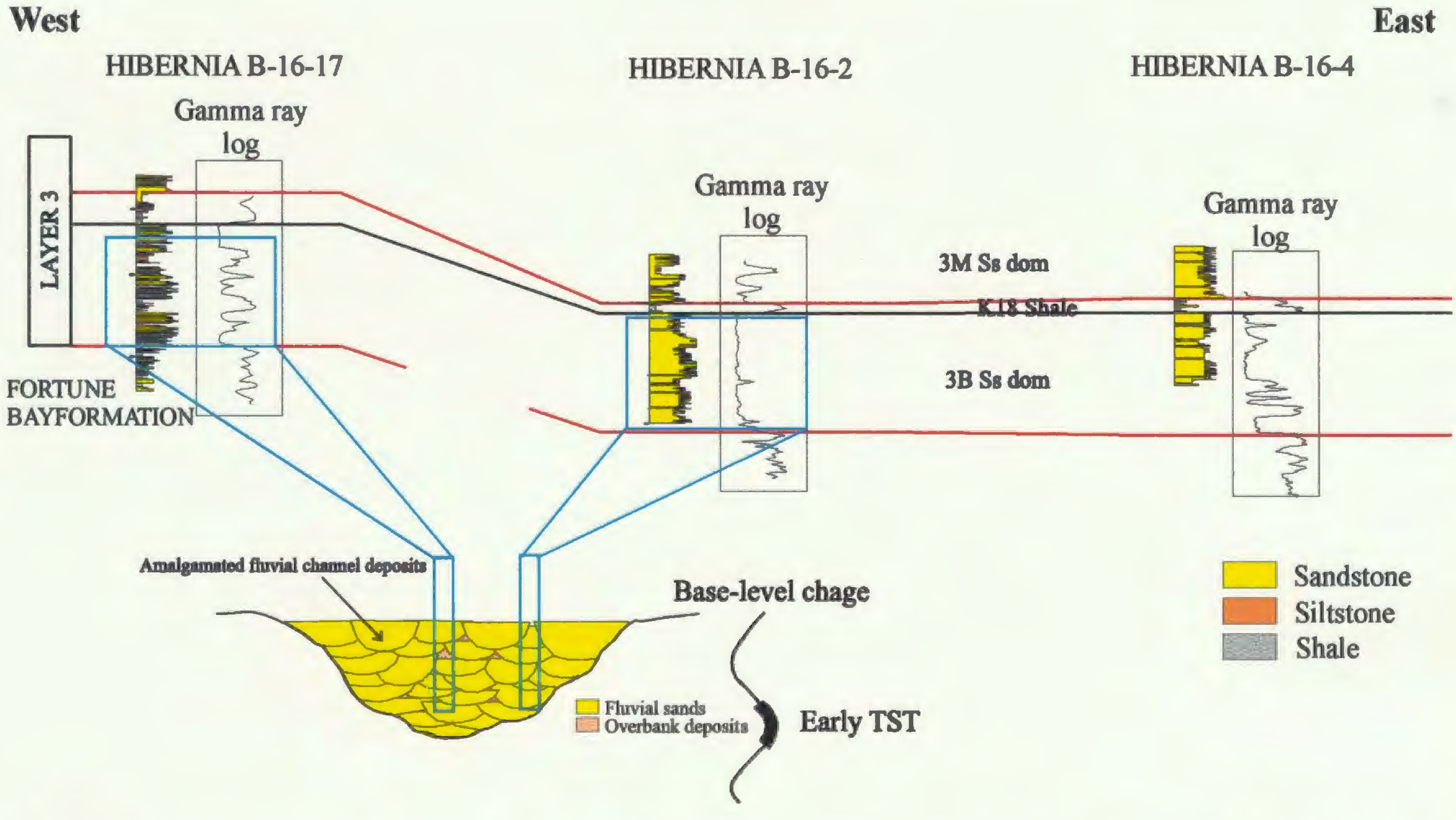


Figure 5.5. Amalgamated sandstones in the Layer 3 Basal Sandstone-dominated interval at Hibernia. Sandstone-dominated stacking patterns are observed in the B-16-2 and B-16-4 wells, whereas fine-grained facies are evident basinward in the B-16-17 well. Fluvial architectures as a function of base-level change have been modified from Shanley and McCabe 1994.

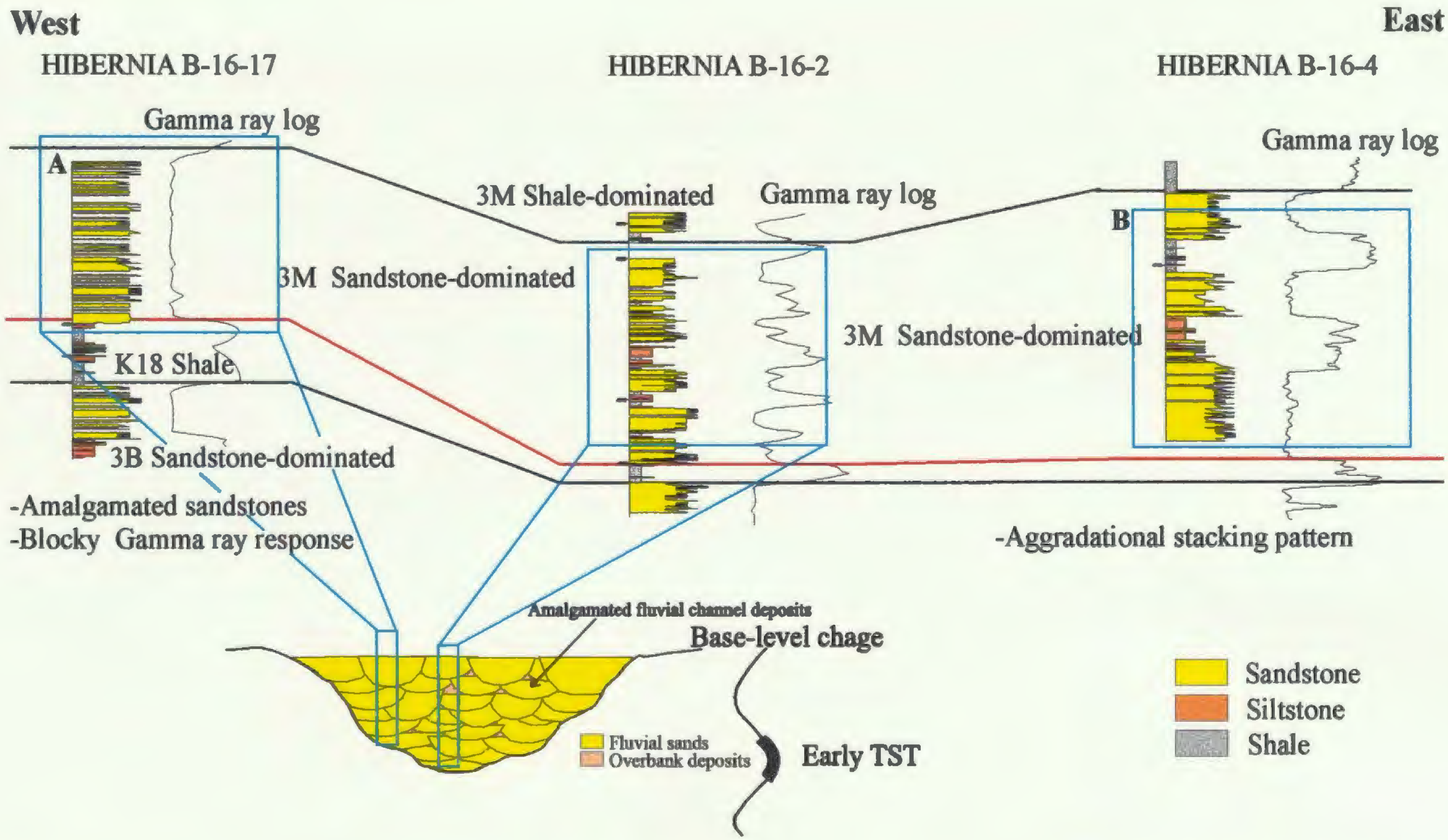


Figure 5.6. Variations in stacking patterns observed field-wide through the 3M Sandstone-dominated interval. The correlation shows the presence of amalgamated sandstones in the 3M Sandstone-dominated interval in the B-16-17 development well, however shows the absence of deposits further east in the B-16-4 development well. Fluvial architectures as a function of base-level change have been modified from Shanley and McCabe 1994.

system is very similar to those in the lower portion of Layer 3. Recognition of a fourth-order sequence boundary at the base of Layer 2 is based on an ironstone pebble lag and an abrupt basinward shift in facies. However, the incised valley system that characterizes Layer 2 did not achieve its maximum erosive potential. The superposition of a fourth-order sea-level fall on a third-order sea-level rise accounts for the minimal depth of incision, and preservation of the field-wide Medial Shale.

5.2.2.2 Low net sandstone intervals

The low net sandstone intervals represented by marine shales and lagoonal facies include the K18 Shale, the 3M Shale, the 3U Middle Shale, the 3U Upper Shale and the Medial Shale. Transgressive surfaces define the base of each low net sandstone interval.

The low net sandstone intervals vary in thickness throughout the Hibernia Formation. The K18 Shale ranges in thickness from 2-9 m. The thinness of the K18 Shale in the east is due to a decrease in accommodation space and erosion by the overlying valley system (Figure 5.1). The 3 Middle Shale-dominated interval increases in thickness from west to east, which suggests an increase in the creation of accommodation space in that portion of the field. The absence of the upper TST and all of the HST in both shale units in the three wells suggests that the finer-grained deposits were likely breached by erosion beneath the 3Basal and 3Middle Sandstone-dominated fourth-order incised valleys (Figure 5.2).

The Medial shale was deposited during a time of third-order maximum flooding (Figure 5.1). The base of the Medial Shale is marked by a *Glossifungites* assemblage and is interpreted as a transgressive marine ravinement surface. However, the maximum flooding surface is difficult to position within the Medial Shale. Therefore, the lower Medial Shale is interpreted as a maximum flooding zone. The distinctive marine trace-fossil assemblage and bioclast-rich shale overlying interdistributary bay deposits in the B-16-4 and B-16-17 development wells are a record of a marine ravinement caused by the landward passage of a transgressive, wave-dominated coastline across the lower delta-plain (Figure 5.7).

5.2.3 Fifth-order cyclicity

The uppermost fourth-order sequence in Layer 3 can be further subdivided into two, fifth-order incised valley systems. Fifth-order cycles are associated with a low amplitude, high frequency sea-level curve (Figure 5.3c). The recognition of fifth-order sequence boundaries at the base of the 3U Basal and 3U Upper Sandstone-dominated intervals is based on basal pebble lags and the erosional juxtaposition of proximal facies over distal facies. These intervals belong to the late LST to early TST, while the late TST is represented by the 3U Middle and 3U Upper Shale-dominated intervals, respectively (Figure 5.2). The interfluve to the topmost of these smaller valley systems has been identified in core from the B-16-17 development well at 3999.25 m.

The 3U Upper Sandstone-dominated interval pinches out laterally to the west (Figure 5.1), where the sequence boundary at the base of this sandstone passes laterally into a correlative interfluvial sequence boundary. Van Wagoner et al. (1990) state that, adjacent to incised valleys, the erosional surface passes into a correlative subaerial

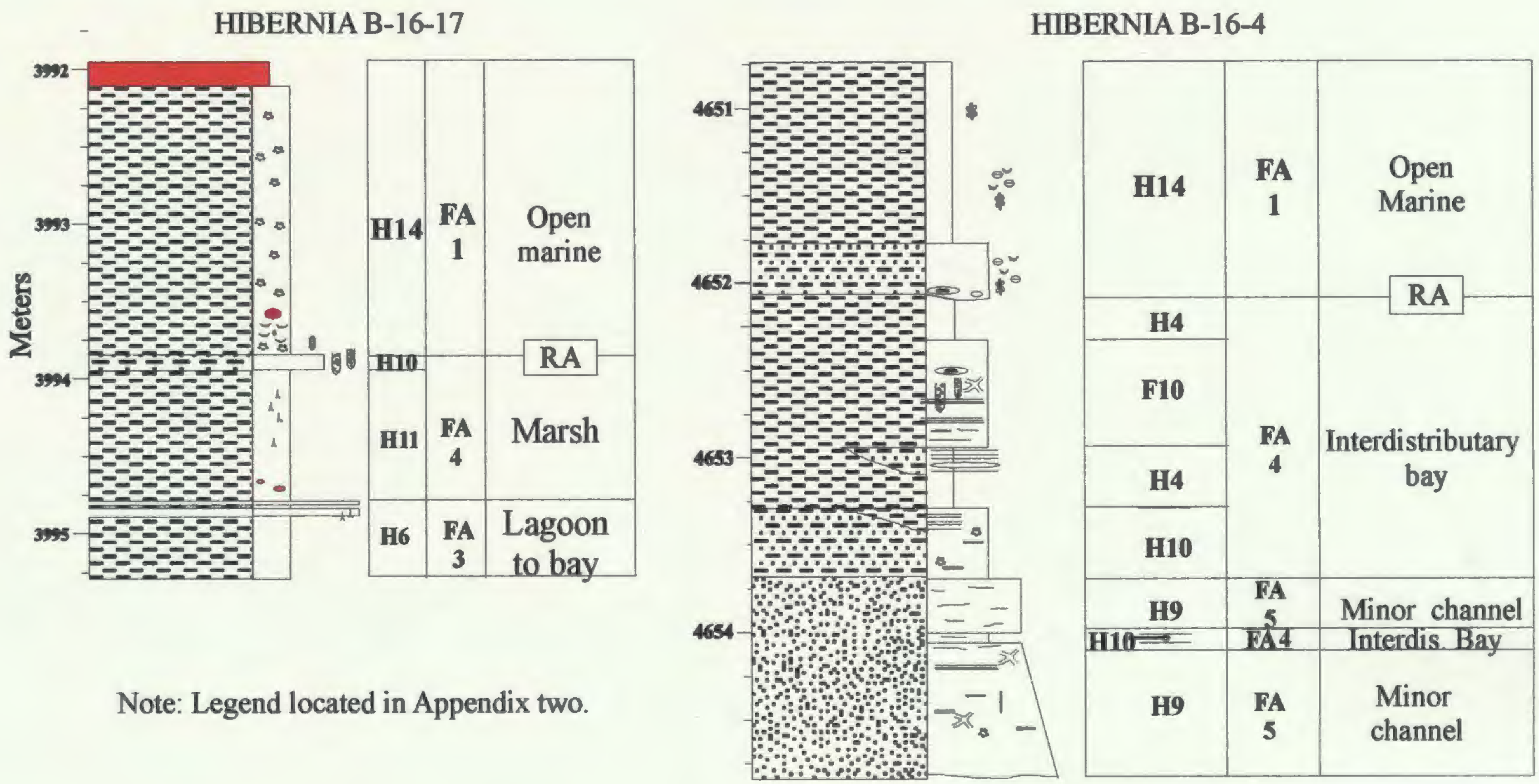
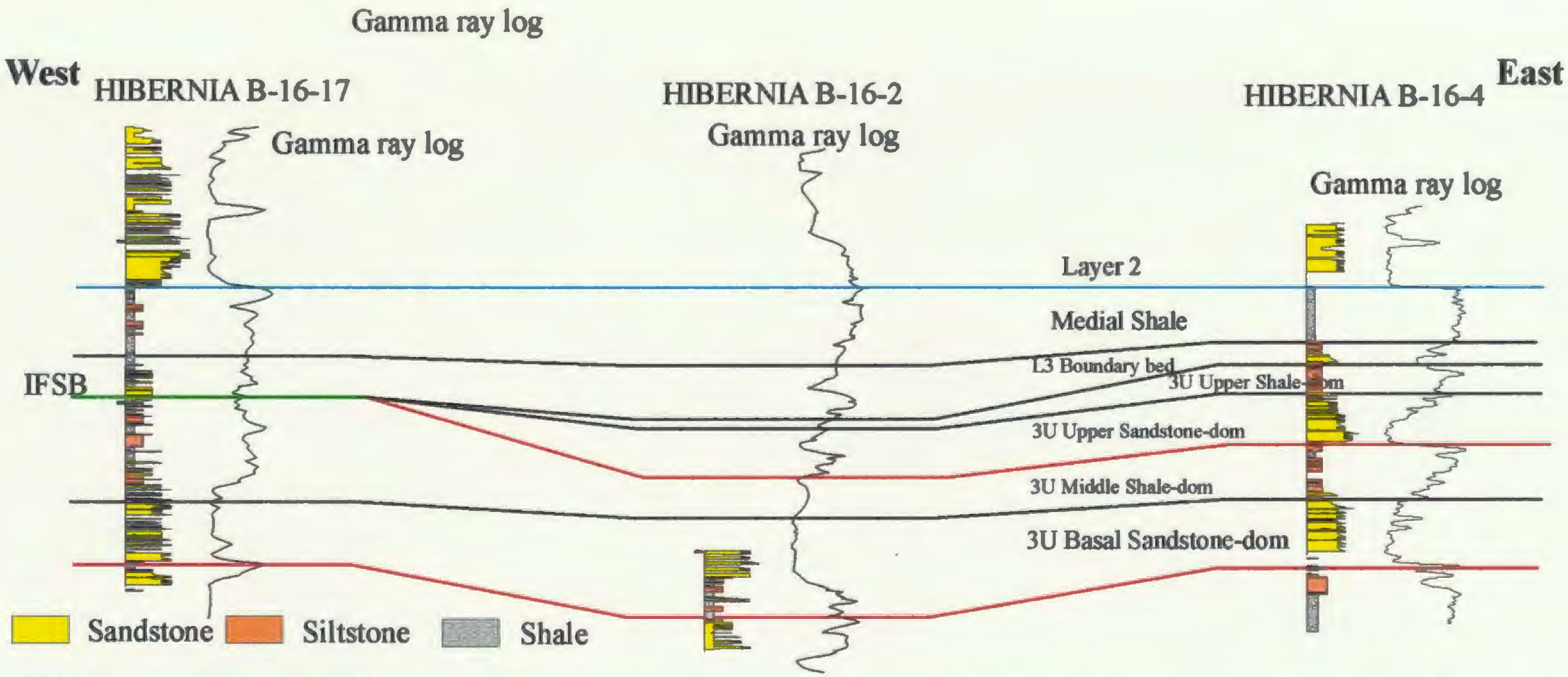
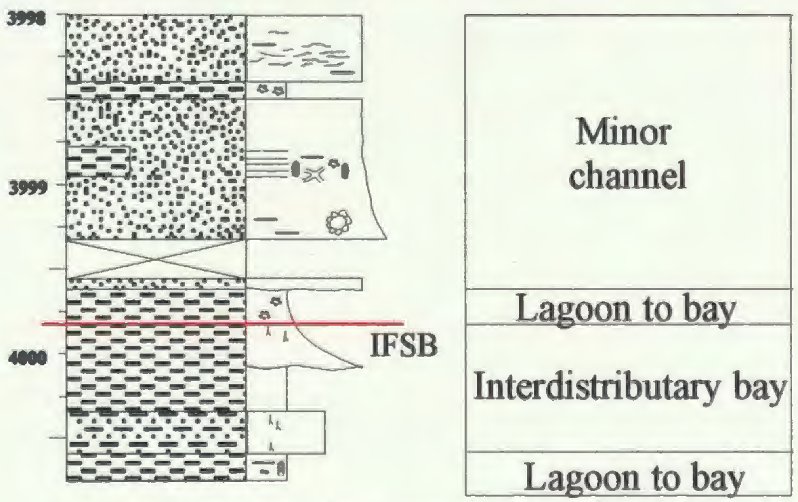


Figure 5.7. The Medial shale interval in both the B-16-17 and B-16-4 development wells. A distinctive marine trace-fossil assemblage and bioclast-rich shale overlies the interdistributary bay deposits in both wells. This supports the interpretation of a marine ravinement (RA) caused by the passage of a transgressive coastline across the lower delta plain. The *Glossifungites* assemblage at the base of the Medial Shale in the B-16-4 development well indicate erosion and exhumation of the underlying lower delta plain deposits.

exposure surface marked by soils or rooted horizons. The presence of interdistributary bay deposits with root penetrations overlain by bioturbated lagoonal shales characterize the interfluvial sequence boundary in the B-16-17 development well (Figure 5.8). The Layer 3 boundary bed at the top of Layer 3 (Figure 5.2) represents the HST. The preservation of the fifth-order cycles at the top of Layer 3 is due to this being the turnaround point in the third-order cycle from falling to rising relative sea level, contributing to an increase in accommodation space. The superposition of a fifth-order fall on a third-order rise reduces the erosive potential of the valley systems during the early LST (Figure 5.3e). This also accounts for the thickness variations between the braided river sandstones in the lower and upper portions of Layer 3 (Table 5.1).

The fifth-order cycles are also revealed by a change in fluvial geometry within Layer 3. The 3 Basal and 3 Middle Sandstone-dominated reservoir intervals are composed of multistorey braided river sandstones as opposed to the stacked single storey fluvial sandstones at the top of Layer 3 (Figure 5.1). The reduced fluvial incision, and increased accommodation space accounts for the preservation of thin HST and reduced connectivity of sandstones. This difference in fluvial geometry suggests that these sandstones are of higher frequency than those in the lower and middle portions of Layer3.





Note: Legend located in Appendix 2

Figure 5.8. Interfluvial sequence boundary (IFSB) at the base of the Layer 3 Boundary bed in the B-16-17 development well is highlighted in green. The 3U Upper Sandstone-dominated interval pinches out laterally, and the sequence boundary passes laterally into a correlative subaerial exposure surface marked by root penetrations. These interdistributary bay deposits are directly overlain by lagoonal deposits with common *Chondrites* traces. The contact between the deposits is interpreted as a interfluvial sequence boundary.

Table 5.1: Thickness variations of the Layer 3U Upper sandstone-dominated interval across the Hibernia field. These variations result from the superposition of a fifth-order sea-level fall on a third-order sea-level rise.

HIBERNIA FORMATION			
Sandstone Interval	B-16-17 Well	B-16-2 Well	B-16-4 Well
Layer 2	11.75 m	N/A	9.3 m
Layer 3U Upper Sst	**N/A**	**5.0 m**	**7.25 m**
Layer 3U Basal Sst	12.15 m	4.70 m	10.18 m
Layer 3 Middle Sst	21.94 m	8.0 m	14.1 m
Layer 3 Basal Sst	30.29 m	30.3 m	15.88 m

5.3 SEQUENCE STRATIGRAPHIC FRAMEWORK OF THE BREATHITT GROUP

Sequence stratigraphic concepts can also be used to better understand the depositional systems and the distribution of potential reservoir sandstones throughout the Breathitt Group. Sequence stratigraphic interpretations are based on correlated well data using the top of the Magoffin Shale as datum; the Magoffin Shale is the most laterally extensive marine shale in the Breathitt Group.

Using the criteria provided by Emery and Myers (1996) and Aitken and Flint (1995), six type 1 sequence boundaries are interpreted to be present throughout the study area in the Breathitt Group. Two types of sequence boundaries are identified throughout the Breathitt Group. These are characterized by:

1) A basinward shift in facies resulting in the erosional juxtaposition of high net sandstone intervals over low net sandstone intervals;
2) Interfluvial sequence boundaries identified by highly rooted, oxidized and bleached soil horizons.

Multistorey, braided river sandstones (facies association VII) constrained within incised valleys characterize the LST within the Breathitt Group. Van Wagoner et al. (1988) state that the LST is bounded at the top by the transgressive surface. However, such surfaces are rarely developed throughout the Breathitt Group. Instead, many of the incised valley systems are capped by regionally extensive coals, which formed in response to a water table rise and termination of clastic sediment supply during the initial transgression. As a result, the upper surface of each of these coals is interpreted as a transgressive surface.

Single-storey channels and crevasse splays (facies association V) within a framework of fine-grained overbank deposits (facies association IV) represent the base of the TST. These deposits pass upwards into marine deposits (facies association I & II) and/or lagoonal deposits (facies association III). Estuarine deposits indicating tidal influence are present, but are not widely developed throughout the Breathitt Group. Therefore, maximum flooding surfaces are difficult to detect. Channel fills in the TST have a heterolithic fill (Aitken and Flint, 1995). This is evident at Roadgap, where a mud-filled channel truncates the upper portion of the Elkins Fork Shale (Figure 5.9, Appendix 4). This channel is filled with black silty shale with siderite stringers.

The base of the HST is difficult to detect throughout the Breathitt Group. Like the TST, the HST is also characterized by single storey channel fills, crevasse splays, fine-grained lower-delta plain deposits and coals. Soil horizons and bleached and rooted zones are commonly associated with the HST.

The sequence stratigraphy of the Breathitt Group will be discussed with respect to third-, fourth- and fifth-order cyclicity. Fourth-order cycles will be discussed in terms of stacking patterns and high and low net sandstone intervals.

5.3.1 Third-order cyclicity

Previous studies conducted by the Kentucky Geological Survey show that the major marine members (Betsie, Kendrick and Magoffin marine members) are estimated

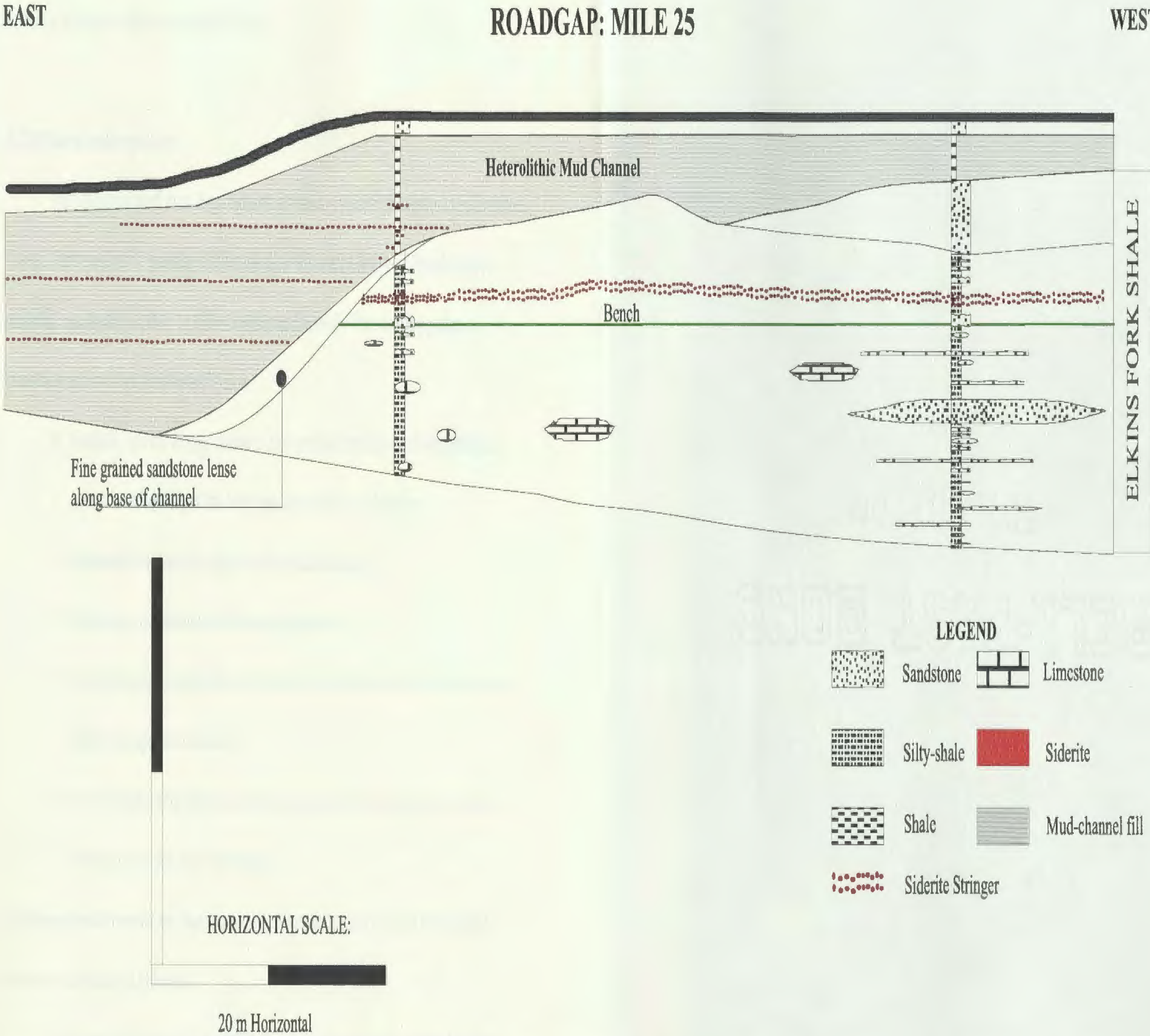


Figure 5.9. Mud-filled channel at Roadgap. This channel truncates the upper portion of the Elkins Fork Shale towards the west end of the outcrop. **(A)**The channel is filled with black silty shale and siderite stringers and represents the TST. **(B)** Fine grained sandstone lense along the channel margin. The green line represents a bench along the outcrop.

to have occurred at 2.5 million year intervals, which equates with the third-order cyclicity proposed by Vail et al. (1977b) (Aitken and Flint, 1995). This implies that a third-order cyclicity is present within the Breathitt Group.

5.3.2 Fourth-order cyclicity

The correlated well data show multiple levels of cyclicity throughout the Breathitt Group. This cyclicity is manifested by sandstone-dominated intervals (braided-river deposits) repeatedly overlain by shale-dominated intervals. The stacking patterns of the sandstone intervals are summarized below:

1) Stacked, upward fining, coarse to fine grained sandstones characterized by trough crossbedding at the base pass upwards through planar crossbedded to current rippled sandstones at the top;
2) Sandstones are predominantly medium grained;
3) Erosive-bases of sandstones are defined by siderite lags and/or carbonaceous debris (transported material);
4) Thinly bedded silty shales and coals are preserved as erosional remnants within the braided river sandstones.

The fine-grained intervals are characterized by deposits similar to those between the reservoir sandstones at Hibernia.

Correlated well data of the Breathitt Group reveals alternating intervals of high and low net sandstone intervals (Figure 5.10).

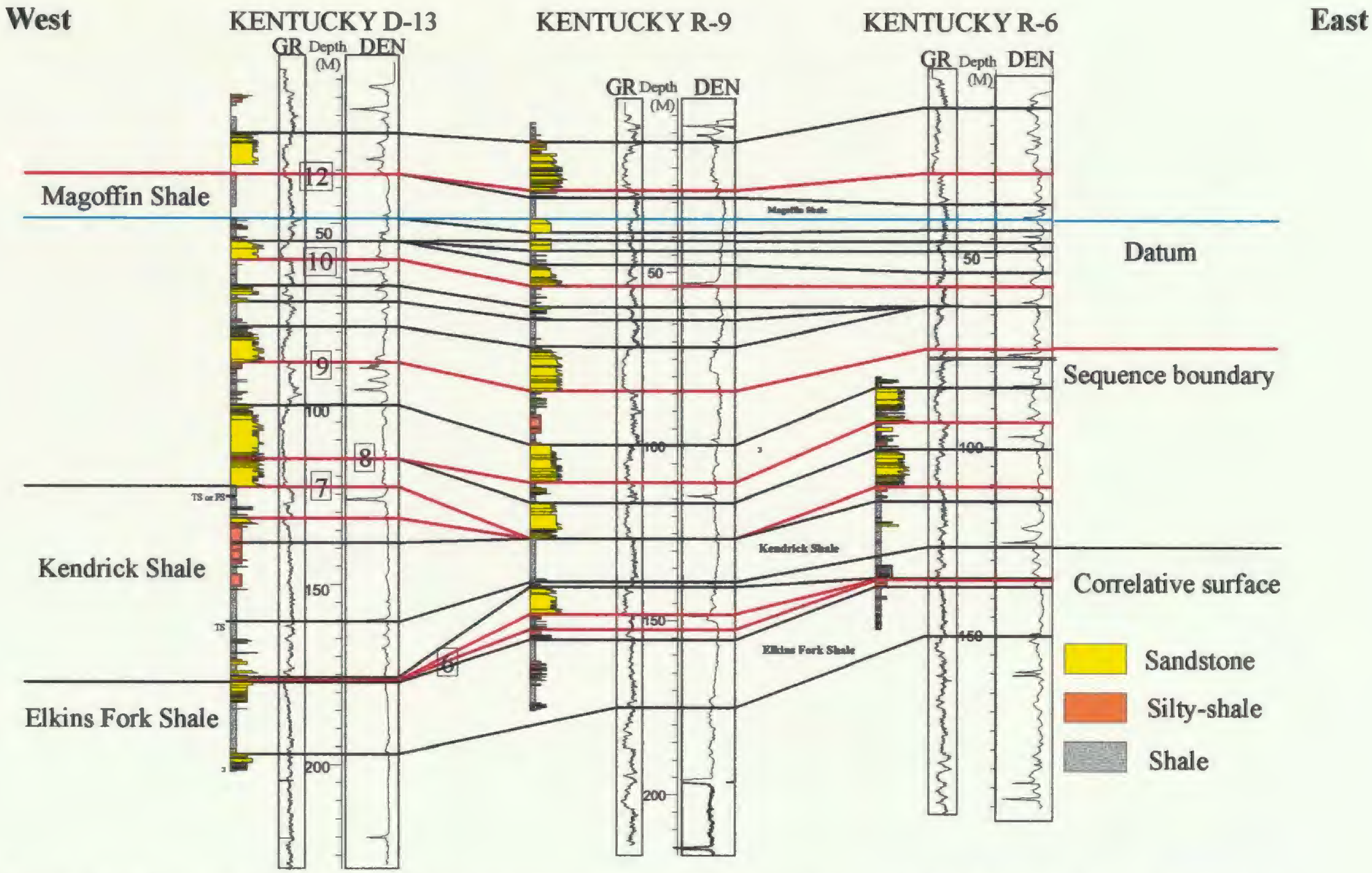


Figure 5.10. Correlated Kentucky well data, constructed using the base of the Magoffin Shale as a datum. Sequence boundaries in red occur at the base of each sandstone interval. The correlation shows alternating high and low net sandstone intervals throughout the Breathitt Group, as well as thickness variations of the Kendrick and Magoffin Shale members. Sequence boundaries have been interpreted by the author.

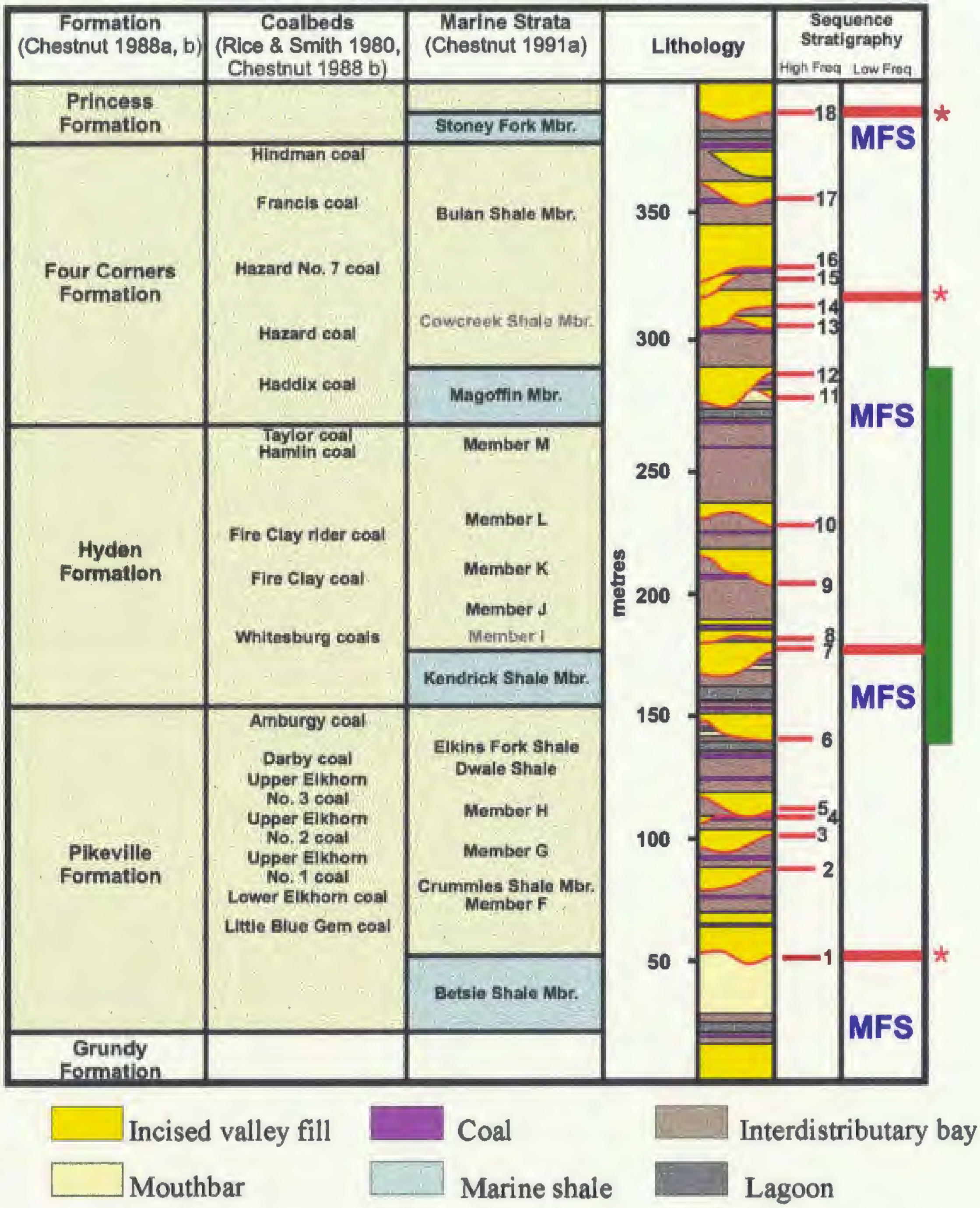


Figure 5.11. Lithostratigraphy and sequence stratigraphy of the Pikeville, Hyden and Four Corners formations (modified from Aitken and Flint, 1994). Note the number of marine intervals throughout the fluvial-deltaic complex. Sequence boundaries (SB) are numbered 1 to 18. The interval to be used as an analogue for the Hibernia reservoir is from SB6 to SB12 and is marked by a green bar.

5.3.2.1 High net sandstone intervals

The third-order cycle through the Pikeville, Hyden and Four Corners formations can be further subdivided into six fourth-order cycles, numbered 6 to 12 after Aitken and Flint (1994) (Figure 5.11). The high net sandstone intervals are dominant away from the Pine Mountain Overthrust, where the creation of accommodation was less, and the depth of incision was at a maximum (Figure 5.12).

The first fourth-order cycle is bounded at its base by sequence boundary 6 and overlies the Elkins Fork Shale (Figure 5.10). Recognition of the sequence boundary at the base of this valley system is based on the abrupt basinward shift in facies, abrupt increase in vertical sandstone thickness and an increase in mean grain size. This valley system formed in response to a fourth-order base level fall and is considerably smaller than the overlying valley systems in the Breathitt Group. The valley fill accumulated in the late fourth-order LST to early TST.

The remaining high net sandstone intervals are comprised of braided-river sandstones constrained within fourth-order late LST – early TST incised valley systems. The lower contacts of the valley systems are defined by sequence boundaries 9, 10, and 11. Each of these valleys was filled during the early stages of the ensuing transgression.

Throughout the valley systems, fine-grained lower delta-plain and lagoonal deposits are locally preserved. Where preserved, they occur as minor siltstone and shale partings within the late LST – early TST incised valley fills and are interpreted as the erosional remnants of lower delta-plain depositional settings. The majority of the late TST has been removed by the overlying valley system. These fine-grained deposits occur

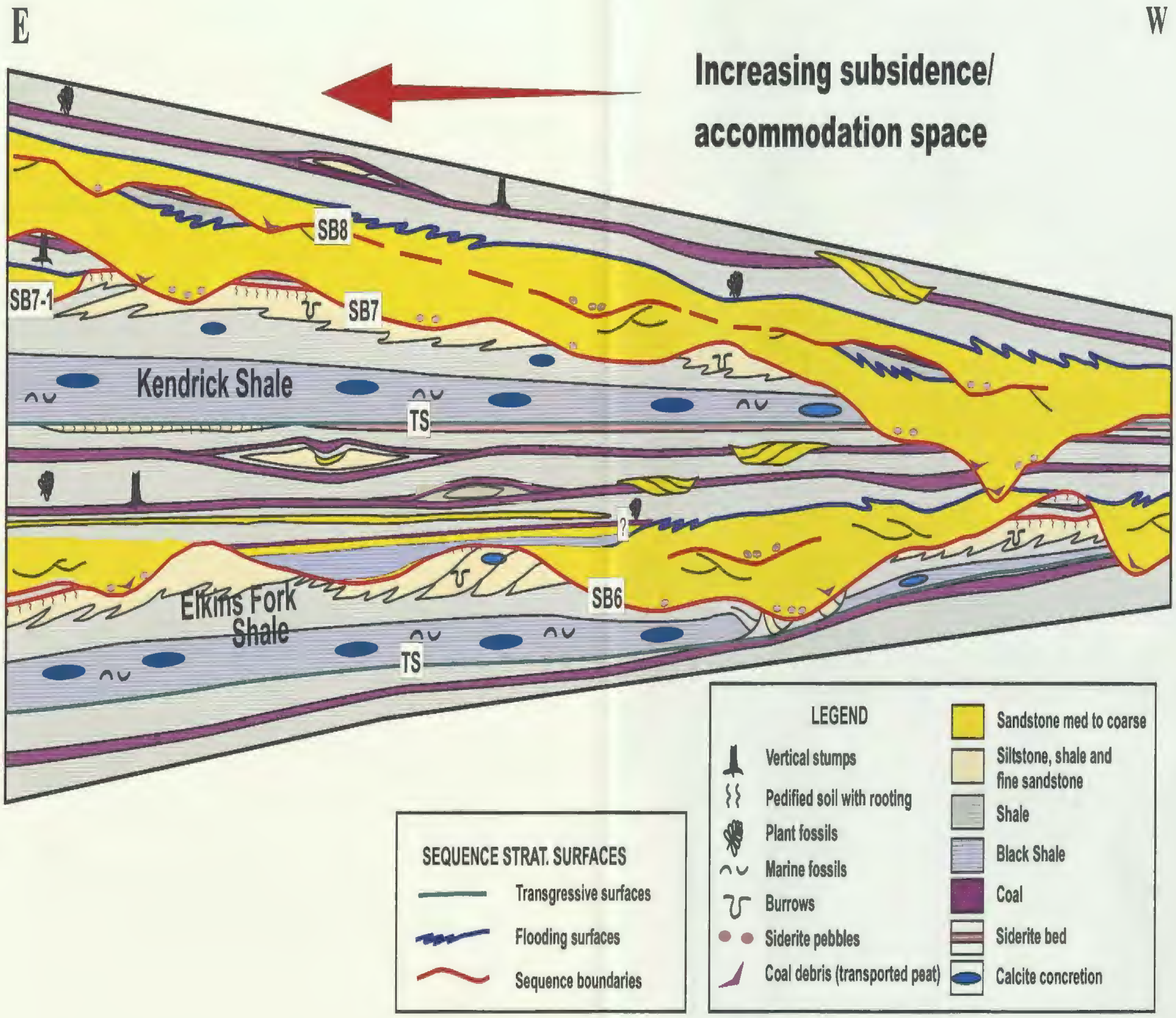


Figure 5.12. West to east (left to right) strike section through the Elkins Fork to Amburgy Coal Zone of the Breathitt Group. Increasing subsidence towards the Pine Mountain Overthrust fault in the east results in an increase in the rate of creation of accommodation. The increase in accommodation and decrease in incision depth towards the east, results in the preservation of low net sandstone, shale-dominated intervals, such as the Kendrick Shale. Away from the Pine Mountain Overthrust, a decrease in accomodation results in high net sandstone intervals where incision is at a maximum. (Modified from HMDC, 2001).

mostly towards the top of the valley fills and signify the retreat of the lower delta-plain up the valley. These deposits are characterized by isolated, single channels, as seen in the region above sequence boundary 10 below the Magoffin Shale (Figure 5.10). The preservation of these single storey channels in the R-9 and R-6 wells is due to an increase in accommodation towards the east.

5.3.2.2.Low net sandstone intervals

The low net sandstone intervals are composed of marine silty shales of the Elkins Fork, Kendrick and Magoffin Shale members. These intervals increase in thickness towards the Pine Mountain Overthrust in the east. The increased deposition and preservation of shale-dominated strata in the east is due to an increase in the rate of creation of accommodation along the Pine Mountain Overthrust, and an associated decrease in the depth of incision (Figure 5.12).

The Elkins Fork Shale in both core and outcrop is characterized by a series of upward coarsening successions of interlaminated to interbedded shale, siltstone and very fine to fine grained sandstone (Figure 3.18). Each succession coarsens upwards through prodelta/delta-front to mouthbar deposits. The contact between each upward coarsening succession is interpreted as a parasequence boundary. The top of each upward coarsening succession is marked by an abrupt facies change. The top of each succession is marked by a fine-grained sandstone overlain by a black shale. This abrupt contact represents a deepening or flooding of the mouthbar succession, on top of which prodelta/delta-front deposits accumulated. The upward coarsening successions in the Elkins Fork Shale are preserved at Roadgap and in the D-13 well.

The Kendrick Shale is a fairly widespread marine unit and was deposited in response to a third-order relative sea-level rise. The Kentucky Geological Survey has interpreted this unit as an upwards coarsening marine shale. However, the upward coarsening succession is only preserved in the D-13 well and locally at Roadgap. In the D-13 well, the transgressive surface at the base of the Kendrick Shale is interpreted at the top of a coal bed at 160.10 m and marks the base of the maximum flooding zone. The upper portion of the Kendrick Shale in the D-13 well represents the late TST and HST. The preservation of the HST in the D-13 well is due to increased accommodation space at the time of deposition. In the R-9 and R-6 wells, most of the late TST and all of the HST have been completely removed by the overlying valley system.

The Magoffin Shale is the most laterally extensive marine shale in the Breathitt Group. The base of the Magoffin Shale is defined by a series of limestone concretions that are in turn overlain by a black, fossiliferous shale. The lower contact is interpreted as a marine transgressive surface which developed in response to a third-order base-level rise. This marks the base of the TST. However, since fourth-order cyclicity does not disappear, the influence of the fourth-order when added to the third-order would produce a more widespread and prolonged drowning of the basin. Above this black shale, the Magoffin Shale passes up into a light grey silty shale which grades up into thin-bedded fine-grained sandstones. The contact between the black shale and grey silty shale is interpreted as the maximum flooding surface and marks the base of the HST. The Magoffin Shale is truncated in both core and outcrop by the overlying braided-river sandstones.

Preservation of the Magoffin highstand deposits is variable throughout the Breathitt Group. The correlated well data show an upward coarsening succession in the D-13 well, but no evidence for such a cycle in the R-9 or R-6 wells. This variability is also evident in the outcrop at Hye 23 (Figure 5.13 Appendix V). Significant erosion beneath the overlying valley system increases to the east at Hye 23. This results in thinning of the HST in the upper portion of the Magoffin Shale towards the east.

5.3.3 Fifth-order cyclicity

Increased accommodation towards the Pine Mountain Overthrust fault in the east, results in the preservation of a local fifth-order early LST to late TST interval within the fourth-order early to late LST incised valley fill (Figure 5.10). The fifth-order valley fills in the Whitesburg Coal Zone are bounded at their base by sequence boundaries 7 and 8 (Figure 5.10). In the D-13 well, sequence boundary 7 is at 121.65 m and is marked by a basinward shift in facies placing non-marine braided- river sandstones with a sandstone dominated, amalgamated stacking pattern on top of lagoonal deposits of the Kendrick Shale (Appendix 4). Incision occurred in response to a fifth-order base level fall during a fourth-order LST. A siderite pebble lag at 112.30 m depth marks the base of the overlying fifth-order incised valley system and has been interpreted as sequence boundary 8. This results in two fifth-order valley systems stacked directly on top of one another in the D-13 well. Both fifth-order valley systems were completely filled during

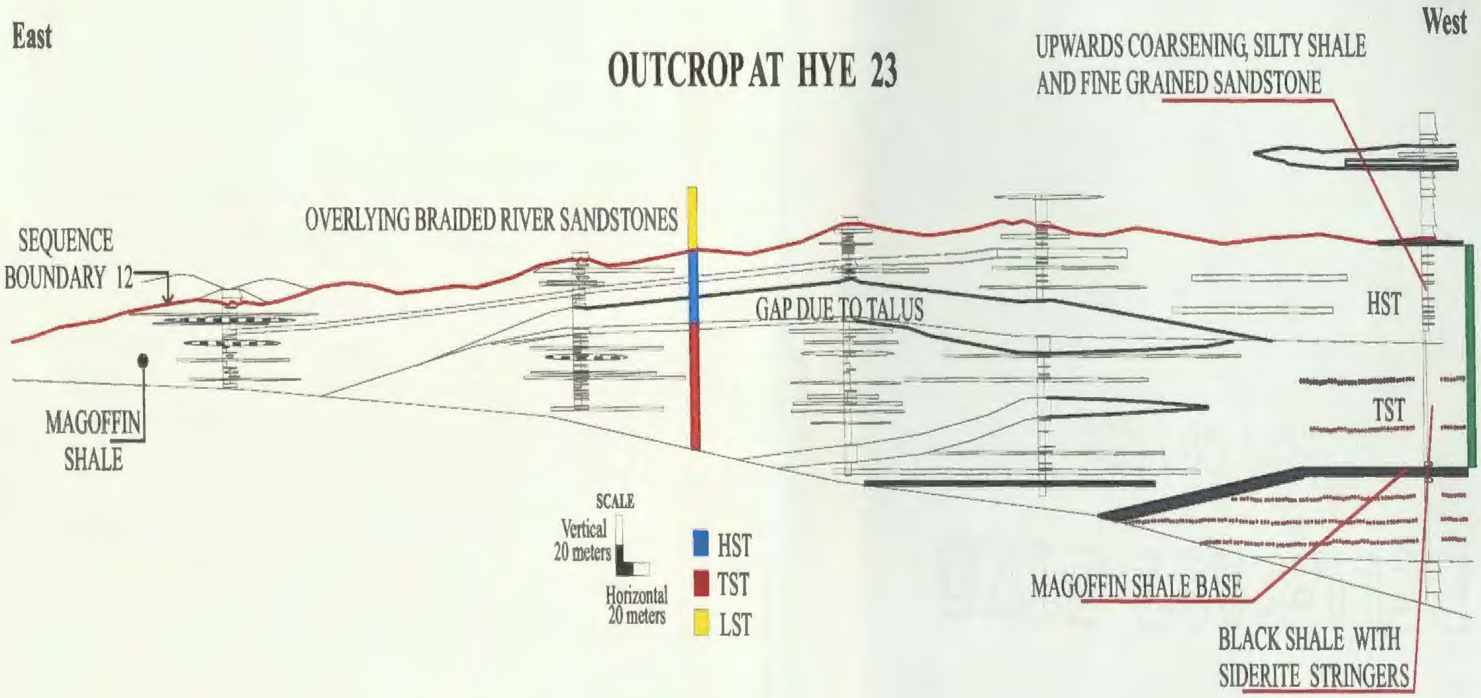


Figure 5.13. The preservation of the Magoffin Shale at Hye 23 varies from west to east. The base of the Magoffin Shale is at the top of a coal bed and is defined by limestone concretions. The depth of incision by the overlying valley system increases to the east. This results in the thinning of the HST deposits in the upper portion of the Magoffin Shale towards the east end of the outcrop. The Magoffin Shale is interpreted as a maximum flooding zone because it is rather difficult to accurately position the contact between the TST and HST throughout much of the Breathitt Group. However, the contact between the black shale with siderite stringers and the overlying upwards coarsening silty shale to fine grained sandstone could be interpreted as the contact between the TST and the HST. The maximum flooding zone is marked by the green vertical bar.

the ensuing transgression, during which time a series of prominent coals were developed within the TST deposits. The increase in accommodation towards the east results in the preservation of fine-grained TST deposits the R-9 and R-6 wells. Fifth-order TST deposits are truncated in both wells by sequence boundary 8 (Figure 5.10). The absence of the fifth-order TST deposits and presence of the sandstone-dominated, amalgamated stacking pattern in the D-13 well suggest a decrease in accommodation space towards the west, away from the Pine Mountain Overthrust fault.

5.4 Sequence Stratigraphic Comparisons and Analogue Potential

The Hibernia Formation and the Breathitt Group are both interpreted as third-order composite sequences that are composed of higher order fourth- and fifth-order cycles. The upward coarsening successions bounded by maximum flooding surfaces in the Elkins Fork Shale are analogous to the upward coarsening successions bounded by maximum flooding surfaces in the Fortune Bay Formation at Hibernia (Figure 3.18). Gamma ray logs in the B-16-2 and B-16-4 development wells at Hibernia show potential upward coarsening delta-front/mouthbar deposits in the Fortune Bay Formation. The Elkins Fork Shale to Amburgy Zone in the Breathitt Group is considered analogous to the upper portion of Layer 3, from the 3U Middle Shale-dominated interval to the Layer 3 Boundary bed (Figure 5.14). The Elkins Fork to Amburgy interval at Roadgap preserves an upward coarsening succession as the overlying fourth-order incised valley fill, bounded at its base by sequence boundary 6, pinches out laterally. This valley system

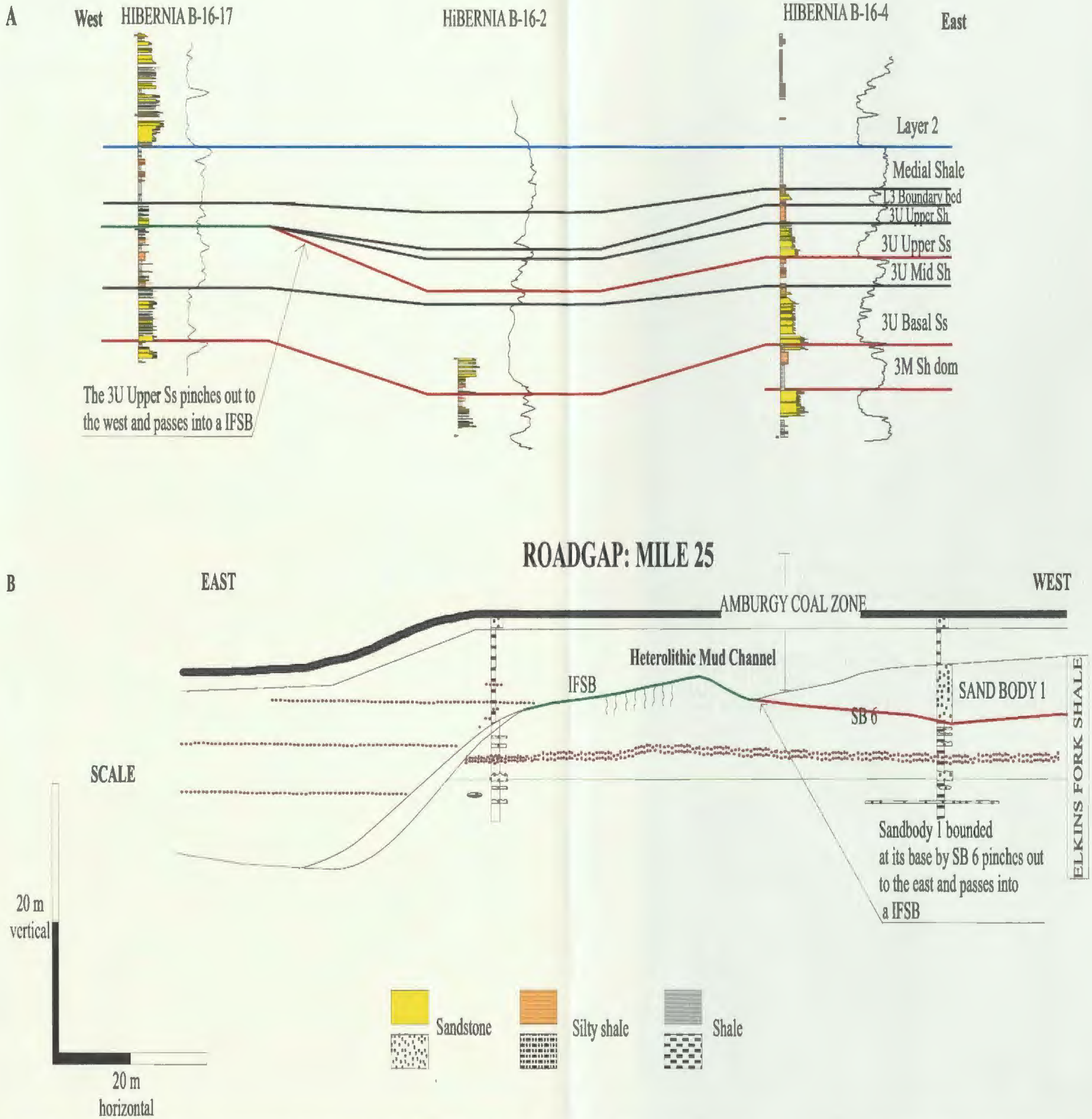


Figure 5.14. The Elkins Fork Shale to Amburgy Coal Zone interval in the Breathitt Group is analogous to the 3U Middle Shale-dominated to L3 Boundary bed interval in the Hibernia Formation. A). The 3U Upper Sandstone-dominated interval at Hibernia pinches out and the sequence boundary at the base passes into a correlative subaerial exposure surface interpreted as a interfluvial sequence boundary (IFSB highlighted in green). B). The upper sandstone in the Elkins Fork Shale bounded at its base by SB 6, passes laterally into a IFSB. Therefore this Interval does provide a reasonable analogue to the upper portion of Layer 3 at Hibernia.

passes laterally into an interfluvial sequence boundary (IFSB) characterized by a rooted and bleached sandy siltstone. The Layer 3U Upper Sandstone-dominated interval at Hibernia is analogous to this valley-filling sandstone above sequence boundary 6 in the Breathitt Group. It pinches out laterally and the sequence boundary passes laterally into a correlative IFSB observed in the B-16-17 development well.

The Elkins Fork Shale to Amburgy interval provides an opportunity to understand the lateral continuity of the late TST to HST and the potential of these deposits to act as flow and pressure barriers within Layer 3. The IFSB at Roadgap is assigned to these systems tracts and confirms that such deposits can be sufficiently well preserved and continuous to act as hydrodynamic barriers. The same situation is predicted for the upper portion of Layer 3 at Hibernia. Factors such as increased subsidence and increased rate of creation of accommodation prevent erosion by overlying valley systems and permitted preservation of the fifth-order cycles at the top of Layer 3.

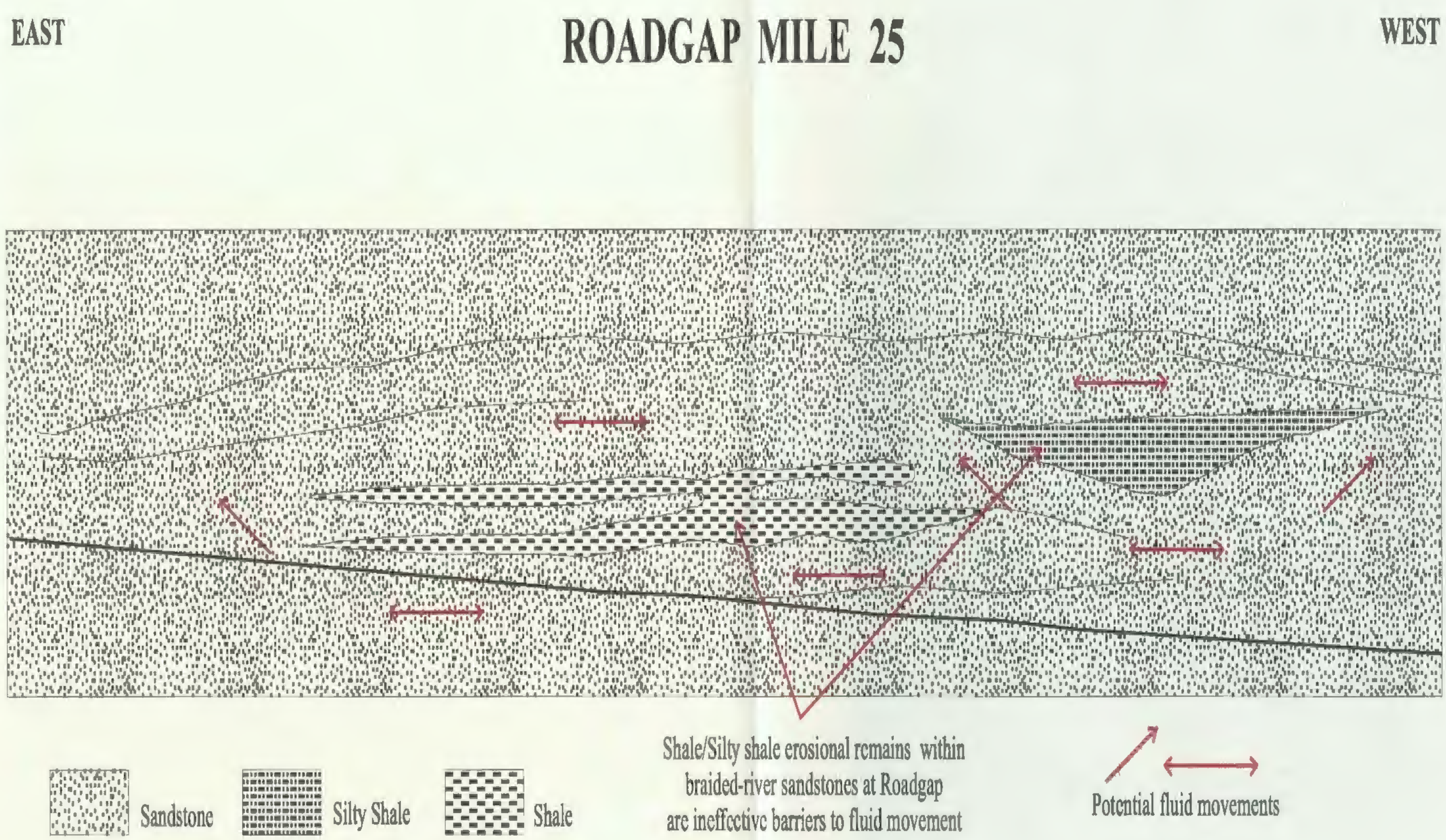
5.4.1 High net sandstone intervals

The high net sandstone intervals of the Hibernia Formation and the Breathitt Group are also analogous to one another. The valley systems in both regions are defined at their base by fourth-order sequence boundaries that formed in response to fourth-order base-level fall during the early lowstand. The incised valleys in both regions were completely filled during the late lowstand to early transgression. They are capped by crevasse splays, channel sandstones and fine-grained lower delta-plain deposits that represent the late TST and locally preserved HST. The most common heterogeneities within the incised-valley fills are erosive channel bases and siltstone partings. Channel bases in both regions are defined by siderite lags, coalified peat and woody debris. Outcrop data show that these features are discontinuous along each channel base and therefore should lead to only local reductions in permeability. Shale and siltstone erosional remains within the incised-valley fills tend to be truncated laterally, and therefore are ineffective vertical barriers to fluid flow. Instead they simply help direct the fluid flow through the braided river sandstones (Figure 5.15).

5.4.2 Low net sandstone intervals

The low net sandstone intervals in the Breathitt Group (Elkins Fork, Kendrick and Magoffin Shale members) are analogous to the low net sandstone intervals in the Hibernia Formation (K18 Shale, 3 Middle Shale, 3U Middle Shale and 3U Upper Shale-dominated intervals, respectively). These fine-grained, brackish-water to marine shales are bounded at their base by transgressive surfaces that mark the initial flooding event. The transgressive surfaces in the Breathitt Group are more difficult to detect and many occur at the top of coal beds. Preservation of the low net sandstone intervals is dependent on the rate of creation of accommodation and the erosive potential of the overlying valley systems. Preservation of the late TST and HST deposits is rare in both regions. Such deposits are locally preserved at the top of the Kendrick Shale in the D-13 well. However, these late TST and HST facies are uncommon in the lower portion of Layer 3 at Hibernia, suggesting that any fifth-order shale-prone strata were likely stripped away by erosion within the 3B and 3M sandstone-dominated fourth-order incised valleys.

The Magoffin Shale is considered analogous to the Medial Shale at Hibernia. The abrupt shift to open marine conditions at the base of the Magoffin Shale is similar to the



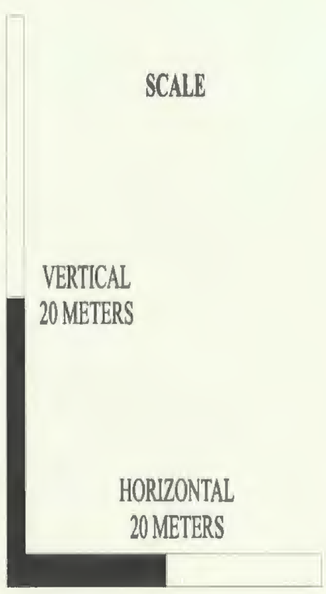


Figure 5.15. Shale and silty-shale remains within the braided-river sandstones at Roadgap. These fine-grained partings act as ineffective barriers to fluid movement and will actually direct flow through the reservoir sandstones. This movement is represented by the red arrows.

abrupt shift to open marine conditions at the base of the Medial Shale. Shell debris and the trace-fossil assemblages observed at the base of the Magoffin Shale in the D-13 well are similar to the shell debris and trace-fossil assemblages at the base of the Medial Shale observed in the B-16-17 and B-16-4 development wells. The bases of both marine intervals is interpreted as a marine transgressive surface that formed during a third-order base-level rise.

The correlated well data from both regions show similar stacking patterns below the Magoffin and Medial shales. Both the Fire Clay to Taylor Zone in the Breathitt Group and the Layer 3 Middle Shale-dominated to Layer 3 boundary bed interval at Hibernia are characterized by retrogradational stacking patterns. The preservation of TST and HST deposits in both regions is due to increases in the rate of creation of accommodation. Predominantly fine-grained, single-storey strata, deposited during a rise in base-level, characterize the TST and HST of the Fire Clay to Taylor Zone and the 3U Middle Shale-dominated to Layer 3 Boundary bed interval.

Based on similar sequence stratigraphic architecture, the Pikeville through Four Corners interval in the Breathitt Group is a good analogue for the Hibernia Formation. The detailed geometry of fourth-order late LST to early TST incised valley fills separated by shale-dominated intervals, acquired from Kentucky outcrops, can therefore be incorporated into existing reservoir models for the Hibernia Formation. This would represent a further step, and is beyond the objectives of this thesis.

5.5 IMPLICATIONS FOR EXISTING MODELS AT HIBERNIA

The sequence stratigraphic framework presented above has several implications for the interpretation of the Hibernia Formation. The laterally extensive coal zones throughout eastern Kentucky are predicted to have little impact on modeling techniques at Hibernia. Extensive coals throughout the Breathitt Group are a common updip expression of transgressive marine flooding surfaces and can form pressure barriers. Any reservoir study of the Breathitt Group would require the regional modeling of coals and associated silty-shale intervals as potential hydrodynamic barriers. In the Hibernia Formation, where coals are less common, parameters in reservoir models can be adjusted to specify less effective or lithologically different updip pressure barriers.

The data from Roadgap provide a unique opportunity to understand how low-permeability horizons (coals) can channel fluids through potential reservoir sandstones and act as potential hydrodynamic barriers. The Whitesburg Coal Zone at Roadgap consists of three distinct coal beds. The two lowermost coal beds are interpreted as fifth-order coals; they are truncated towards the east end of the outcrop. In contrast, the uppermost fourth-order coal is laterally extensive across the outcrop (I. Sinclair, pers. comm., 2002) (Figure 5.16). Braided-river channels truncate the lower two coal beds and the sandy channel fill thickens towards the east. This breaching results in the connection of the braided-river sandstones to the channel sandstones that overlie the Kendrick Shale (Figure 5.16). Initially, the lower two coals might be interpreted as potential hydrodynamic barriers to the distributary channel sandstones overlying the Kendrick Shale. However, the termination of these fifth-order coals to the east and subsequent

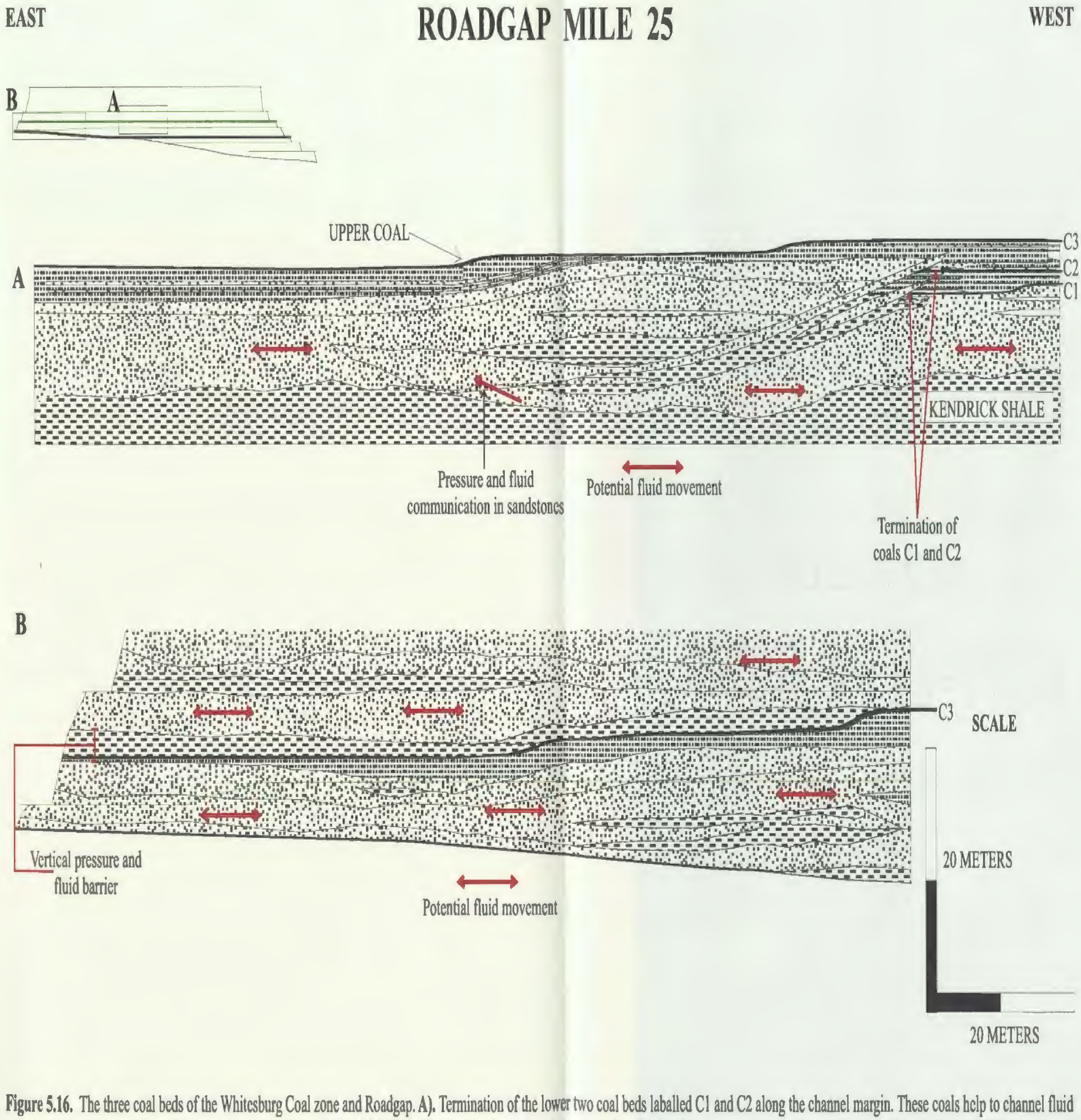


Figure 5.16. The three coal beds of the Whitesburg Coal zone and Roadgap. **A).** Termination of the lower two coal beds laballed C1 and C2 along the channel margin. These coals help to channel fluid movement through the sandstone overlying the Kendrick Shale. Erosion by channel sandstones result in fluid and pressure communication as shown by the red arrows. **B).** The upper coal Bed C3, is continuous across the outcrop, and acts as a pressure and fluid barrier between potential reservoir intervals.

communication of the distributary channel sandstones with laterally adjacent sandbodies show that, in fact, these coals can channel fluids into potential reservoir sandstones. The uppermost fourth-order coal and shale interval is a more extensive hydrodynamic barrier, as it appears to completely separate two horizons of braided-river deposits (Figure 5.16). The integrity of extensive fourth-order hydrodynamic barriers, combined with breaching of fifth-order coal intervals at Roadgap, is similar to the breaching of fifth-order, fine-grained facies in the lower portion of Layer 3 at Hibernia. The breaching of fifth-order deposits throughout the lower portion of Layer 3 allows laterally extensive, fourth-order hydrodynamic barriers such as the K18 and 3 Middle Shale-dominated intervals to separate reservoir intervals. In summary, there are six major implications for modeling that result from research presented in this thesis.

1) Marine flooding surfaces commonly form intraformational seals. The flooding surfaces at the base of the K18, 3M, 3U Middle and 3U Upper Shale-dominated intervals at Hibernia act not only as extensive barriers to fluid flow, but also as pressure seals. They are interpreted as intraformational seals. The marine flooding surfaces at the base of the Kendrick and Magoffin Shale members are interpreted as potential intraformational seals in a depositional setting similar to the Hibernia Formation.
2) Sequence boundaries can often define flow-unit boundaries. Integrated log and core data allow flow units to be correlated throughout the Hibernia

Formation. Similar correlations in more accessible outcrops show the geometry of such flow units in the analogous Breathitt Group.

3) Erosion of the marine tops of fifth-order cycles within the Breathitt Group can be used to model the breaching of fifth-order cycles in the lower portion of Layer 3 at Hibernia. The breaching of such fifth-order cycles can result in fluid and pressure communication within the reservoir.

4) Shales and siltstones should be expected to interfere with hydrocarbon production from interbedded sandstones in late TST to HST deposits.

5) Incised-valley systems with preserved interfluves may laterally compartmentalize the braided-river sandstones at Hibernia.

6) The base of both the Medial and Magoffin shales are transgressive marine flooding surfaces that, respectively, form the base to a field-wide vertical permeability barriers in the Jeanne d'Arc Basin , and the base of a regionally extensive shale in the central Appalachian Basin.

CHAPTER SIX

CONCLUSIONS

The upper Breathitt Group strata of eastern Kentucky provide an attractive analogue for stacking patterns throughout the reservoir and non-reservoir intervals of the Hibernia Formation. Braided-river and distributary-channel sandstones that were deposited in broad, episodically developed incised valleys dominate high net sandstone intervals throughout both the Breathitt Group and Hibernia Formation. These high net sandstone intervals in both regions are vertically separated by low net sandstone, fine-grained, lower delta-plain, delta-front, and open-marine facies. Characteristics of these intervals are summarized in table 6.1. Facies and stacking patterns through the high and low net sandstones in the upper Breathitt Group strata are analogous to those in the Hibernia Formation.

Sequence boundary expression and systems tract preservation throughout the Breathitt Group are very similar to those at Hibernia. The Hibernia Formation is interpreted as a complete third-order sequence formed of three fourth-order cycles. The uppermost fourth-order cycle within Layer 3 can be further subdivided into two fifth-order cycles. Preservation of these fifth-order cycles occurred at the turn-around point in a third-order cycle from falling to rising relative sea-level. Each of the late lowstand to early transgressive reservoir intervals at Hibernia is separated by shale-dominated intervals that developed in response to fourth-order base-level rises. Shale-dominated fifth-order cycles are likely breached throughout the lower portion of Layer 3 by fourth-

Table 6.1. Facies characteristics for high and low net sandstone intervals.

INTERVAL	CHARACTERISTICS	HIBERNIA FORMATION	BREATHIT GROUP
High net sandstone	-upward fining, very coarse to very fine grained sandstone, centered on medium grain size	●	●
	-planar and trough crossbedded sandstone	●	●
	-braided river sandstones defined by erosive bases, siderite pebbles, mud rip-up clasts and carbonaceous debris	●	●
	-current rippled very fine to fine grained sandstones	●	●
	-bioturbated medium to very fine grained channel sandstones	●	●
	-very fine grained sandstones exhibit convolute lamination	not present	●
Low net sandstone	-interlaminated to interbedded shale, siltstone and very fine grained sandstone	●	●
	-marine and marginal-marine trace-fossil assemblages	●	●
	-seat earths, rooted and bleached horizons underlie thick coals	●	●

order incised valley systems. Similar breaching of fifth-order strata and the development of laterally extensive fourth-order shale-dominated intervals separating potential reservoir intervals is observed in outcrop at Roadgap in eastern Kentucky.

The transgressions and regressions responsible for the stratigraphic architecture in the two study areas can be explained by changes in (a) subsidence rate, (b) rate and direction (up or down) of eustatic sea-level change, and (c) rate of sediment supply. The high-frequency cycles that characterize many ancient successions are generally attributed to either high-frequency eustatic changes (e.g., as produced by glacial-interglacial cycles at a Milankovitch rhythm), or high-frequency changes in extensional/compressive stresses promoting equally rapid changes in regional subsidence/uplift (Cloetingh, 1986). The mix of controlling factors was likely substantially different for the Carboniferous Breathitt Group as compared to the Cretaceous Hibernia Formation, because the climate state of the globe was profoundly different at these two times. In the Carboniferous, the Earth was in an "icehouse" condition (Murphy and Nance, 1999, p.621); so high-frequency glacial-interglacial eustatic sea-level changes (like in the Quaternary) would have been the norm (Crowley and Baum, 1991; Maynard and Leeder, 1992; Heckel, 1994; Olszewski and Patzkowsky, 2003). In contrast, the Early Cretaceous was a time of global "greenhouse" conditions (Barron, 1983; Murphy and Nance, 1999, p.621), so high-frequency relative sea-level changes were more likely the result of fluctuating tectonic stresses in the extensional Jeanne d'Arc Basin (e.g., Sinclair, 1993).

The database for this thesis does not permit the unraveling of the eustatic and tectonic components of the relative sea-level curves for the two areas. However, the combination of factors a-c, above, appears to have created very similar histories of transgression and regression in the depositional areas for the Breathitt Group and Hibernia Formation, so that close comparisons of stratigraphic architecture can be successfully undertaken.

The abundance of coal throughout the Breathitt Group suggests a warm and humid climate. During the middle Carboniferous, the Appalachian Basin was at a latitude of 12-15 ^{0} S (Morel and Irving, 1978). In the nearby mid-continent area, Olszewski and Patzkowsky (2003) infer that climatic conditions fluctuated between humid and arid in response to fluctuations in global ice volume. Coal accumulation would have likely been enhanced during the more humid intervals. In contrast, the Jeanne d'Arc Basin during the Early Cretaceous was at a latitude of 32-35 ^{0} N (Irving, 1979), where atmospheric circulation resulted in a more dry average climate (deserts today cluster at $\pm$ 30 ^{0} either side of the equator). This may account for the paucity of coals in the Hibernia Formation.

Somewhat different subsidence rates are the likely cause of the different preservation of fine-grained units in the Breathitt Group verses the Hibernia Formation. The presence in Kentucky of thick low net sandstone intervals such as the Elkins Fork, Kendrick and Magoffin Shale members, particularly towards the east, is due to an increase in the rates of local subsidence and creation of accommodation along the Pine Mountain Overthrust, resulting in a decrease in the depth of incision. In contrast, the thin nature of the low net sandstone intervals throughout the Hibernia Formation suggest that local subsidence rates were lower than those experienced throughout the Appalachian Basin at the time of Breathitt Group deposition.

In spite of the minor differences in stratigraphic architecture noted above, the otherwise strong similarities in stacking patterns and sequence-stratigraphic frameworks in the two field areas justifies incorporation of numerical data from the upper Breathitt Group into the next generation of geocellular models for the Hibernia field. Sequence boundaries and coal zones recognized throughout the Breathitt Group form potential flow-unit boundaries and likely hydrodynamic barriers, respectively, and should be modeled accordingly in the Hibernia Formation reservoirs. Further quantification of the Breathitt Group analogue, although beyond the scope of this thesis, will significantly improve the understanding of fluid movement and hydrocarbon recovery in the Hibernia field. Such reservoir modeling was not an objective of this thesis, and needs to be addressed in a subsequent phase of analogue studies.

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APPENDIX I

DESCRIPTIVE NOMENCLATURE

Descriptive nomenclature

A bed is the smallest formal unit in the hierarchy of lithostratigraphic units. It is a lithologically homogenous sedimentary unit, which was initially deposited on a horizontal surface. Beds occur as tabular or lenticular layers of sedimentary rock with internal textural, lithological or structural unity. Bedding is defined as a sequence of parallel layers within a body of sedimentary rock and is classified according to thickness.

Lamina is the thinnest recognizable unit layer of original deposition in a sediment or sedimentary rock, which differ from each other with respect to color, grain size or composition on a scale of less than one cm.

Table A1: Summary of bed thickness values and terminology (Boggs, 1995).

<table>
<tr><th colspan="2">Thickness (cm)</th><th colspan="2">Bed Thickness Terminology</th></tr>
<tr><td colspan="2">100</td><td colspan="2">Very thick bed</td></tr>
<tr><td colspan="2">30-100</td><td colspan="2">Thick bed</td></tr>
<tr><td colspan="2">10-30</td><td colspan="2">Medium bed</td></tr>
<tr><td colspan="2">3-10</td><td colspan="2">Thin bed</td></tr>
<tr><td colspan="2">1-3</td><td colspan="2">Very thin bed</td></tr>
<tr><td rowspan="2">0-10 (mm)</td><td>3-10 (mm)</td><td rowspan="2">Lamina</td><td>Thick lamina</td></tr>
<tr><td>0-3 (mm)</td><td>Thin lamina</td></tr>
</table>

Massive bedding is defined as an apparent absence of any form of sedimentary structure in a sedimentary unit. Massive bedding is rare in sandstones, but may occur in well sorted sandstones where structures cannot be identified by textural variations. Massive bedding can result from the complete destruction of primary structures by intensive organic burrowing.