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EFFECTS OF MIDDLE TO LATE ALBIAN SEA LEVEL FLUCTUATIONS IN THE CRETACEOUS INTERIOR SEAWAY, WESTERN CANADA

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ABSTRACT

The late Middle to Late Albian was generally a period of overall sea level rise, punctuated by higher frequency episodes of sea level fall. The effects of these fluctuating sea levels is variably preserved in the sedimentary record of the Joli Fou, Viking, Boulder Creek and Peace River formations of western Canada as stacked progradational shoreline sequences, incised valleys, and subsequent valley-fills, unconformable surfaces, condensed sections of marine shelf deposits, erosional shoreface notches, and paleosols. Sea level falls resulted in valley incision into the Cadotte Member and Joli Fou Formation. The Cadotte incision reduced sedimentation rates on the old floodplain resulting in the formation of several superposed paleosols within the correlative Boulder Creek Formation. When sea level subsequently started to rise, the incised valleys became filled with estuarine sediments of the Paddy and Viking formations. Factors such as variations in sediment supply, shoreline paleogeography and paleotopography (all tectonically controlled) contributed to the formation of progradational (shoreline regressive) sequences, in near juxtaposition, or only a few tens of kilometres from, vertically-accreting valley-fill, or transgressive estuarine-fill deposits.

RESUME

De la fin de l'Albien moyen à l'Albien supérieur prédominait une période de baisse globale du niveau de la mer ponctuée par des épisodes de plus haute fréquence de baisse du niveau de la mer. Les effets de ces variations de niveau de la mer se voit préservés et enregistrés stratigraphiquement dans les formations de l'ouest canadien de Joli Fou, de Viking, de Boulder Creek et de Peace River où se trouvent des séquences entassées de rivage progradé, de vallées enfoncées et remblayées postérieurement, de surfaces de discordance, de coupes condensées de dépôts marins de plate-forme, de cannelures infratidales et érosionnelles, et de paléosols. Des baisses de niveau de la mer ont abouti à l'enfoncement de vallées dans le membre de Cadotte et ont réduit les taux de sédimentation sur l'ancienne plaine inondable, ce qui menait à la formation de plusieurs paléosols superposés à l'intérieur de la formaion corrélative de Boulder Creek. Ensuite, lorsque le niveau de la mer commençait à remonter, les vallées enfoncées se remplissaient de sédiments estuariens des formations de Paddy et de Viking. Des facteurs tels que la variation de la charge de sédiments, la paléogéographie et la paléotopographie littorales (tous contrôlés de façon tectonique) ont contribué à la formation des séquences progradées (de côtes d'abrasion) qui sont en quelque sorte soit juxtaposées soit localisées, à quelques dixaines de kilomètres des remblayages de vallée d'accrétion verticale ou à des dépôts transgressifs de remblayage estuarien.

INTRODUCTION

The Cretaceous basin of the Western Interior of North America is one of the largest foreland basins in the world, extending from the Gulf of Mexico, northward to the Arctic Ocean, and from eastern British Columbia to western Ontario (Williams and Stelck, 1974). The basin formed as a result of major collisional events to the west, which caused thrust-sheet loading and flexural subsidence of the foreland basin. These tectonic events provided a source of detritus, a gradient to transport sediment and a basin in which to deposit it. Sedimentation within the basin consisted primarily of westerly derived, thick, largely continental clastic wedges, alternating with sequences of marine shales (Stott, 1982). These clastic wedges prograded into the basin, likely as a result of major orogenic events further to the west as is the case for the Lower Albian Fort St. John Group (Leckie, 1986b). However, during the Middle-Albian (approximately 105 Ma), a major episode of global sea level rise had begun, and the foreland basin became flooded by marine waters extending north, from the Gulf of Mexico, and south from the Arctic. By Late Albian times, the total length of the basin was flooded by this shallow, epicontinental Western Interior Seaway (Williams and Stelck, 1974).

The major sea level fluctuations which affected the Western Interior Seaway in the early Cretaceous have been widely discussed (Kauffman,1977, Weimer, 1983, and Caldwell,1984) and several higher frequency, transgressive-regressive cycles have been identified in strata of the southern Interior Plains. Most pertinent to this paper are the two transgressive-regressive cycles of Albian age described by Caldwell (1984). These are the Kiowa-Skull Creek Marine Cycle which contains three to four secondary transgressive-regressive couplets, and the overlying Greenhorn Cycle which contains one or two secondary couplets. Caldwell suggested that the Kiowa-Skull Creek and Greenhorn transgressions were strongly influenced by global eustasy, but that local and/or regional tectonics controlled all secondary couplets of the transgressive phases.

Caldwell (1984) further implied that in order to resolve the relative roles of eustasy and tectonism in controlling transgressions and regressions, it would be necessary to examine, in detail, specific regions of the basin. The primary purpose of this paper is to do just that with the Middle to Late Albian cycles in the south-central and northwest interior plains of Alberta, and in northeastern British Columbia. Previously, the major transgressive-regressive cycles have been documented on a continent-wide scale, largely on the basis of regional biostratigraphic and lithostratigraphic correlations. The higher frequency, second order cycles (secondary couplets) perhaps hold the key to understanding the role of tectonic events in influencing cycles of sedimentation on a regional, as opposed to a basinwide scale. Secondary cycles are manifest in the sedimentary record in several ways, including stacked progradational shoreline sequences, incised valleys and subsequent valley-fills, unconformable surfaces, condensed sections of marine shelf deposits, and paleosols. In this paper, we will utilize sedimentological facies-sequence observations, supplemented by biostratigraphic correlations, to examine the influence of sea level fluctuations on sedimentation patterns in the following Middle to Late Albian formations: the Peace River Formation of northwest Alberta, the Boulder Creek Formation of northeastern British Columbia and the Viking Formation of southern and central Alberta (Fig. 1). Detailed facies and environmental aspects are not elaborated upon here, other than for substantiating the transgressive-regressive relationships and cyclicity displayed by the individual depositional sequences.

A secondary objective of this paper is to resolve the correlative relationship of the Lower Colorado Group (including Viking and Joli Fou formations) in the central plains of Alberta, with the Peace River Formation (Paddy and Cadotte members) of northwestern Alberta, and the Boulder Creek Formation in northeastern British Columbia. The stratigraphic correlations of these Middle to Late Albian units have been the subject of much debate (Stelck and Koke, 1987; Stott, 1968). It will be shown here that the correlations put forward by Stelck (1958), Koke and Stelck (1984; 1985) and Stelck and Koke (1987) are compatible with the biostratigraphic correlations and with the models of transgressive-regressive cyclic sedimentation presented in this paper.

STRATIGRAPHY

Regional Setting

Middle to Late Albian correlations within the Western Canadian foreland basin have been the subject of controversy for many years

(Stelck and Koke, 1987; Stott, 1968; Oliver, 1960; Workman, 1959). The primary dispute involves the Peace River Formation in northwestern Alberta and how its members correlate with the Viking and Joli Fou formations in the subsurface of the central Alberta plains (Figs. 1 and 2). For example, the Harmon shale has been correlated with the Joli Fou Formation by Smith *et al.* (1984) and Workman (1959), but shown to be slightly older by Stelck (1958) and Jackson (1984). Similarily, the Viking Formation is shown to be stratigraphically equivalent to the Paddy Member by Stelck (1958) and Koke and Stelck (1984), but equivalent to the Paddy and Cadotte members by Workman (1959). As pointed out by Stelck and Koke (1987), these diverse opinions are still being incorporated into correlation charts, even though it can be shown by foraminiferal evidence that the Cadotte Member is of Middle Albian age, whereas the Viking sands are Late Albian in age.

In this paper, we adhere to the latest correlations of Stelck and Koke (1987), which have been incorporated in the nomenclature and stratigraphic chart shown in Figure 2. Before discussing the rationale for these detailed correlations it is necessary to review briefly the regional stratigraphic framework of Middle to Upper Albian strata as it evolved in the early literature. The regional stratigraphy of the Lower Colorado and Fort St. John Groups has been discussed in detail by Glaister (1959), Rudkin (1964) and Stott (1968; 1982). The Lower Colorado Group in the central plains includes the Joli Fou Formation (Stelck, 1958), Viking Formation (Slipper, 1918) and overlying Lower Colorado shales, all considered to be marine deposits. In southern Alberta, the Lower Colorado includes the "basal Colorado sands", the Bow Island Formation and the overlying shale interval.

In central Alberta, the dark gray, marine shales of the Joli Fou Formation are 18 to 36 m thick, but thin rapidly westward until the overlying Viking Formation merges with the Mannville Group to form the Blairmore Group of the Foothills (Mellon, 1967). Southward, the Joli Fou becomes indistinguishable from the Viking, and both formations grade laterally into the Bow Island Formation. The Viking Formation ranges from 15 to 30 m thick over most of central Alberta, increasing to over 45 m in southern Alberta where it merges with part of the Bow Island Formation. The Viking Formation becomes progressively thinner to the east and northeastern until it "shales-out" completely in the vicinity of St. Paul, Tp. 58, Rg. 9W4M (Gammell, 1955).

As mentioned above, many of the early workers correlated the Viking Formation with the Paddy and Cadotte members of the Peace River Formation in the northwestern plains (Rudkin, 1964). Stelck (1958), however, basing his comments on micro- and macrofaunal evidence, suggested that the Viking was not equivalent to either the Cadotte Member or the top of the Blairmore Group. Rather, Stelck postulated that the Viking Formation was deposited during an erosional hiatus which occurred between the Upper and Lower Blairmore of the southern Foothills, and between the Mountain Park and Blackstone formations of the central Foothills. He further suggested that a hiatus lies between the Cadotte and Paddy members and that only the Paddy is correlative in part with the Viking. The relationship between the Paddy and Cadotte members was also thought to be unconformable by Wickenden (1951) and Oliver (1960). Oliver further suggested that the Joli Formation onlapped northwards onto an eroded Cadotte surface. These correlative relationships between the Viking and Peace River formations have been thoroughly documented in recent papers (Koke and Stelck, 1984; Stelck and Koke, 1987) using biostratigraphic relationships. It is the intention of this paper to clarify and elaborate some of the detailed correlations.

Biostratigraphy and Age Correlation

The stratigraphic chart presented in Figure 2 is based primarily on biostratigraphic zonation, supplemented by lithostratigraphic correlations (Figs. 3, 4 and 5) and radiometric dating. The Harmon and Hulcross shales represent the southerly limit of a marine boreal incursion which extended only as far south as the northern Interior Plains (Oliver, 1960; Stott, 1982; Caldwell, 1984). The Hulcross Formation at Monkman Pass correlates lithostratigraphically with the Harmon Member near the town of Peace River and both units lie within the *Pseudopulchellia* Zone (Stott, 1982; Stelck and Koke,, 1987; Stelck and Leckie, in press). The Harmon microfauna at Peace River belongs to the *Haplophragmoides multiplum* Subzone (Wickenden, 1951; Caldwell *et al.*, 1978; J. Wall, pers. comm., 1987). Biotite crystals in a volcanic ash from the middle Hulcross have been dated at 102 +- 1 Ma (Yarnegi *et al.* in press) indicating a Middle to Late Albian age. The Harmon Member is conformably overlain by the sandstones of the Cadotte Member at Peace River town, and the Hulcross Formation by the Boulder Creek Formation in the British Columbia foothills. Strata correlative to the Cadotte and Harmon Members are not precisely known farther south in central Alberta (Fig. 2).

Shaly lithofacies of the Cadotte Member contain microfauna which correspond to the *Ammobaculites* sp. Subzone (Caldwell *et al.*, 1978; J. Wall, pers. comm., 1987). At the confluence of Peace and Cadotte Rivers, a shaly lithofacies of the Cadotte contains the *Gastroplites* fauna (Wickenden, 1951). Also, at the town of Peace River, *Inoceramus cadottensis* (C. Stelck, pers. comm., 1987) occurs within sandstone float of the Cadotte Member. The dinoflagellate *Spinidinium vestitum* makes its entrance level in the uppermost Cadotte (Singh, 1971; Brideaux, 1971) and also occurs at the base of the Joli Fou Formation in central Alberta (well 7-29-55-21 W4M; C. Singh, pers. comm.). Singh (pers. comm., 1987) states that "based on the entrance level of *S. vestitum*, the Joli Fou cannot be older than the uppermost 10 feet of the Cadotte Member and is most likely much younger".

The upper part of the Boulder Creek Formation at Monkman Pass has been dated, using chara, palynoflora, and megaflora, as middle Middle Albian to lower to middle Upper Albian (Stelck, pers. comm., 1987). Strata correlative to the Boulder Creek is missing in the Peace River town and in central Alberta.

The only fossil recovered from the Paddy Member is *Inoceramus altifluminis* McLearn at the type section (Stelck, 1958) which

Wickenden (1949) also observed in upper Joli Fou shales on the Athabasca River. A more precise age for the Paddy Member has not yet been determined due to the lack of suitable fossil recovery (Wickenden, 1951; Singh, 1971; J. Wall pers. comm., 1987).

The basal portion of the Hasler Formation at Monkman Pass contains suites representative of the *Trochammina depressa* and *Trochammina umiatensis* Subzones (C.R. Stelck, pers. comm., 1987) which are subdivisions of the upper part of the *Haplophragmoides gigas* Zone (Stelck and Koke,1987). The Joli Fou Formation in west-central Alberta also belongs to the *Haplophragmoides gigas* Zone (Caldwell *et al.*, 1978), and contains bentonites radiometrically dated at approximately 98 Ma (Tizzard and Lerbekmo, 1975). Shales directly overlying the conglomerate beds of the Viking Formation in west-central Alberta contain foraminiferal assemblages of the *Verneuilina canadensis* and*Haplophragmoides postis goodrichi* Subzones of the *Miliammina manitobensis* Zone.

In the basal Shaftesbury Formation at Peace River town, shales above a regionally extensive fish bone bed (described below) contain a foraminiferal assemblage equated to the *Verneuilina canadensis* Subzone of the *Miliammina manitobensis* Zone (J. Wall., pers. comm., 1987). Unnamed black shales of the Colorado Group above the Viking Formation in the Caroline area of west-cental Alberta, also contain foraminiferal suites of the *Verneuilina canadensis* Subzone (P. Sherrington, pers. comm., 1983; J. Wall, pers. comm., 1987)

Results of the biostratigraphic and age dating analyses (Fig. 2) discussed above, and lithostratigraphic correlations (Figs. 3, 4 and

5), can be summarized as follows: 1) the basal sandstone of the Boulder Creek Formation is correlative with the Cadotte Member in the Peace River area, and both are significantly older than the Viking Formation of the central Plains; 2) the Joli Fou Formation in central Alberta is younger than both the Hulcross Formation of northeastern British Columbia and the Harmon Member of the northwestern Alberta plains, 3) strata correlative with the Joli Fou Formation in the Peace River town area may be lost in the unconformity between the Paddy and Cadotte members, and; 4) the Paddy Member in northern Alberta is probably correlative with the Viking Formation farther south.

PEACE RIVER FORMATION, NORTHWESTERN ALBERTA

Outcrop

The Peace River Formation is well exposed in outcrops near the town of Peace River, Alberta along the Peace and Heart Rivers (Figs. 1 and 6). The Harmon Member, 16 m thick, consists of finely interbedded, marine sandstones, siltstones and shales (Fig. 6). Sandstones are wave-rippled and hummocky cross-stratified. In the upper 5 m of the Harmon Member, sandstones increase in frequency and thickness upwards. The overlying Cadotte Member is about 15 m thick and composed of very fine- to fine-grained sandstone dominated by hummocky and swaley cross-stratification. The Harmon and Cadotte members can be traced westwards for more than 300 km to the foothills where they outcrop as the correlative Hulcross and basal Boulder Creek formations, respectively (Fig.2). The Harmon and Cadotte members are conformable and are interpreted as the deposits of a progradational wave-dominated coastline. The upper boundary of the Cadotte Member is sharp and when traced laterally, exhibits several metres of relief; it locally contains *Skolithos* burrows. Strata directly above the Cadotte contact contain siderite nodules (5 to 10 cm in diameter), with concentrations of wood debris and molds of *Inoceramus cadottensis*. The upper Cadotte Member does not represent a normal progradational nearshore succession because the top has been truncated. In the area of Peace River town, this truncated surface is interpreted as an unconformity formed through downcutting and valley incision (discussed below).

The overlying Paddy Member is subdivided into three units (Fig. 6). The lowermost unit consists of approximately 7 m of medium grained, crossbedded sandstone containing abundant comminuted carbonaceous debris and shell of *Inoceramus cadottensis*. This sandstone merges laterally over a few tens of metres with horizontal to low angle inclined (10 to 18^{o}), rhythmic couplets of sand and carbonaceous mud (Fig. 7B) similar to the inclined heterolithic stratification described by Thomas *et al.* (1987). These sand-mud couplets are centimetres to decimetres thick, contain millimetre scale mud couplets (Fig. 7C), tidal bundles, reactivation surfaces and a low diversity assemblage of trace fauna (*Trichichnus* and small *Skolithos*). The low angle dipping, sand-mud couplets grade laterally into a carbonaceous mudstone interval, 4 to 5 m thick and up to 50 m wide, with a concave-up lower contact (Fig. 7A). The distal margin of the mudstone plug is sharp and erosional.

This lowermost interval is interpreted as tidally influenced point bars and channels, probably deposited in an upper to middle estuarine setting. The trace fossils suggest a marine influence, but the low diversity indicates a stressed environment as would occur in an upper estuarine setting (Dorjes and Howard, 1975; Frey and Howard, 1986).

The middle portion of the Paddy Member is approximately 3 m thick and consists of centimetre scale, interbedded fine sandstones, siltstones and shales (Fig. 6). The sediments contain ripple laminated sandstones, flaser beds, linzen beds, synaeresis cracks and a low diversity *Trichichnus* and *Skolithos* assemblage. Some of the sediments are rooted and locally consist of current-reworked bentonitic siltstone. This interval is interpreted as tidal flat to bay-fill deposition. The bentonitic material probably represents an ash fall reworked by tidal currents.

The upper unit of the Paddy Member is 3 to 6 m thick and exhibits substantial lateral and vertical variation. The lower 2 to 3 m is a wave-rippled and swaley cross-stratified(?) fine-grained sandstone. The upper part, ranging from 0.30 to 3 m thick, is a medium to coarse-grained, variably pebbly, sandstone which is predominantly planar tabular crossbedded with mud drapes on toesets. Measurements of 36 bed sets show the dominant paleoflow to the northeast with rare, superposed reversing sets (Fig. 7D). Compound crossbeds and reactivation surfaces are locally present. Trace fossils include mud-filled *Arenicolites*, *Terebellina*, *Skolithos* and *Teichichnus*. The upper unit of the Paddy Member is interpreted as a tidally-influenced, estuary-mouth deposit. The increased trace fossil diversity may indicate an environment which was less stressful on the organisms, such as would occur at the entrance of an estuary and the swaley facies may also represent a bar or spit at the mouth. The cap of coarser crossbedded sandstone probably represents the transgressive surface overlain by inner-shelf sands.

The Paddy Member is abruptly overlain by shales of the Shaftesbury Formation. The lower 5 to 8 m of the Shaftesbury Formation contain a brackish water equivalent of the *Miliammina manitobensis* foraminiferal assemblage dominated by *Ammotium* (J. Wall, pers. comm., 1987). These basal shales also contain a high proportion of large, subcircular to elliptical algal cysts, have up to 6% dispersed total organic carbon content, and exhibit high radioactivity as indicated on gamma ray logs from nearby wells (Fig. 3). A wave-rippled bed, 20-30 cm thick and consisting of fish teeth, fish vertebrae and chert pebbles, occurs at approximately 3 to 5 m above the base of the Shaftesbury Formation. A similar layer of fish remains can be traced along the Peace River for 75 km, and has been reported 260 km to the east on the Athabasca River (Wickenden, 1949; 1951).

The overall sequence within the Paddy Member, near the town of Peace River, represents a deepening transgression as follows. Estuarine channel-fill is overlain by intertidal flat deposits, which, in turn, are followed by deeper-water, estuary mouth-shoal to inner shelf deposits. The vertical section in Figure 6 is similar to that of estuaries along the Georgia coast (Frey and Howard, 1986). The succession was dominated by tidal processes during the relative sea level rise. The radioactive, basal Shaftesbury shales may represent an episode of reduced sedimentation at the peak of the lower Shaftesbury transgression.

Subsurface

In the subsurface of northern Alberta, an incised valley system 5 to 15 km wide, in the Paddy and Cadotte Members has been mapped in Townships 67-71, Ranges 10-13 W6 Meridian (Fig. 8). The valley system is reflected in the gamma ray logs by the truncated and abnormally thin Cadotte sandstones. In Figure 8, the "normal or regional" Cadotte log pattern occurs on both sides of the cross section. The log pattern shows an upwards coarsening, interbedded sandstone and shale (serrated pattern of the Harmon Member), overlain by 16 to 23 m of blocky sandstone of the Cadotte Member. The gamma ray logs in the central part of the section show a truncated and abnormally thin Cadotte interval. In the 10-2-69-13W6 well, the Cadotte Member is only 7 m thick and is overlain by a 12 m thick fining upwards unit, interpreted as channel-fill sequence. The highly radioactive "kick" at the top of the fining upwards sequence occurs at a similar stratigraphic position within the valley-fill deposit to that of the bentonitic tidal flat deposits in the Peace River outcrop. The radioactive interval does not occur outside of the valley-fill deposits in the surrounding "regional" facies of the Paddy Member.

BOULDER CREEK FORMATION, MONKMAN PASS AREA

The description of the Hulcross and Boulder Creek formations in the Monkman Pass area of northeastern British Columbia (Fig. 9) is based on the measurement of a continuous coal exploration core. The upper Hulcross Formation consists of interbedded sandstones, siltstones and shales. The sandstones are dominantly wave-rippled and hummocky cross-stratified and increase in frequency and thickness upward. The very fine- to fine-grained sandstone of the basal Boulder Creek Formation consists of 24 m of coarsening-upward, hummocky cross-stratified sandstone overlain by high angle crossbedded sandstone and conglomerate. The basal Boulder Creek, similar to the correlative Cadotte Member, is interpreted as the deposit of a progradational, wave-dominated shoreline.

Fifteen superposed paleosols and paleosol complexes are concentrated in the top 90 m of the Boulder Creek Formation (Figs. 2, 9). The interval containing the paleosols can be traced northwards for 250 km along the Rocky Mountain Foothills and eastward into the subsurface for at least 70 km. The paleosols have been described in detail by Leckie *et al.* (in press). Individual paleosols are 0.5 to 1.5 m thick with some paleosol complexes (multiple stacked paleosols) up to 7.1 m thick. The paleosols are characterized by their grey colour, pedogenic slickensides (cutans), vertical roots, preserved peds, spherulitic siderite and absence of primary sedimentary structures. Carbonaceous material in some of the larger root traces has been oxidized and replaced by illuviated clays. The grey drab coloration, manganese mottling and abundance of siderite nodules and spherulites within the soils indicates that they were periodically waterlogged and poorly aerated. Siderite-filled shrinkage cracks suggest intermittent drying with a lowering of the water table followed by a subsequent water table rise.

The Boulder Creek paleosols formed on floodplain alluvium derived from the Cordillera to the southwest. The climate was warm humid to subhumid with periodic dry intervals. The gley nature of the soils does not necessarily indicate high rainfall but could result from poorly-drained soils on a low relief plain with broad gentle divides. Leckie *et al.* (in press) compared biotite weathering in one of the paleosol profiles with modern biotite degradation in warm humid climates from New Zealand (Mokma *et al.*, 1973; Birkeland, 1984), and concluded that some of the individual soils may have taken at least 10,000 yr to form.

The significance of the paleosols lies in their abundance, thickness and high degree of development. In the underlying nonmarine portions of the Gates Formation, Gething Formation, Cadomin Formation and Minnes Group, paleosols are common, but are very thin and poorly developed. They can be considered as immature soils, deposited in highly aggradational, depositional regimes. In contrast, the paleosols in the Boulder Creek Formation represent subaerial disconformities, formed in a stable environment when sedimentation rates were reduced (Leckie and Foscolos,1986; Leckie *et al.*, in press). Leckie *et al.* (in press) attributed the soil formation to an episode(s) of lower relative sea level which caused incisement of fluvial channels into the floodplain, thereby reducing the rate of sedimentation and lowering the water table. Evidence of correlative incised channels and paleovalleys has been found at the boundary between the Paddy and Cadotte members, as discussed previously.

DEPOSITIONAL MODEL: PEACE RIVER AND BOULDER CREEK FORMATIONS

The relationship between the paleosols, incised channels, and relative sea level fluctuations of the Boulder Creek Formation and Paddy and Cadotte members is shown in Figure 10. During Stage 1, relative sea level was stable or falling slowly, resulting in progradation of the Cadotte (and basal Boulder Creek) shoreline, which became capped by a coal. In Stage 2, rapid sea level fall created a new base level. The rate of sea level fall was greater than the rate of subsidence and thus the old floodplain was incised, creating a valley system. The incised valley acted as a conduit, flushing sediment through the old floodplain to a new shoreline, reducing the rate of sedimentation on the floodplain. After the episode of downcutting, the landscape of the old floodplain became stabilized, the rate of sedimentation and erosion virtually ceased and soils formed. If the amount of sea-level fall was not large, then significant relief would not have developed and, consequently, the "erosional truncation" as predicted by Haq *et al.* (1987) would be minimal. Although perhaps 10 to 15 m of incisement took place, the floodplain was not totally cut off from sediment supply. Some of the paleosols, after as much as 10,000 yr of non-deposition were probably buried by a flooding event of large magnitude (i.e., possibly 500, 1000, 5000 yr event). During Stage 3, relative sea level rose and the incised valleys became filled with estuarine (and fluvial) materials. Soils continued to develop on the interfluves until they were covered by the rising sea. If, as in Stage 4, there were higher frequency sea level fluctuations during the overall relative sea level rise, there may have been multiple incisement and fill events while the paleosols continued to form. The Stage 4 scenario, with multiple incisions, is not strictly conjectural, because Smith *et al.* (1984, Fig 31) show a 22 m thick sandstone at the top of the Paddy Member. Subsurface mapping indicates that this sand forms a linear, shore-perpendicular trend, which cuts into surrounding Paddy deposits. It may represent a second downcutting and valley-fill event. In Stage 5, the incised valley system became filled with estuarine and tidal flat sediments. In the Peace River outcrop, the top of the fill is represented by bar, spit or tidal shoal sands which are sharply capped by a transgressive layer of coarse-grained crossbedded sands. In the Monkman core, the transgression is represented by a decimetre-thick pebble conglomerate (Fig. 9). Shales directly above the transgressive surface are radioactive (Fig. 3) and may represent an episode of reduced sedimentation during the final phase of flooding. The preservation of the thick, tide-dominated Paddy interval may be due to a high rate of sea-level rise as postulated by Fischer (1961).

VIKING FORMATION, SOUTH AND CENTRAL ALBERTA

The geological setting and regional stratigraphy of the subsurface Viking Formation in south and central Alberta received much attention in the early literature (Jardine, 1954; Edie, 1955;

Love, 1955, 1960a,b; DeWiel, 1956; Roessingh, 1959; Beach, 1962; Tizzard and Lerbekmo, 1975; Lerand and Thompson, 1976; Alho *et al.*, 1977; Koldijk, 1976). This is because the Viking sandstones have proven to be favourable reservoirs for the accumulation of oil and gas. Some of this literature dealt with facies sequences and depositional patterns, but only in general terms. More recent papers documented detailed facies relationships and depositional environments of specific areas (Beaumont, 1984; Reinson *et al.*, 1983; Reinson, 1986; Reinson and Foscolos, 1986; Reinson *et al.*, 1988; Leckie, 1986a; Hein *et al.*, 1986). All of these studies interpret the Viking sandstones as having formed in some type of marine environment ranging from coastal-shoreface to inner shelf settings.

Stratigraphic Sequence: Gilby-Joffre to Caroline Transect

Detailed lithostratigraphic correlations between Caroline and the Gilby-Joffre trend situated to the NNE (Fig. 1), suggest that the Viking Formation in this region represents an asymmetrical transgressive-progradational cyclic succession within which two major progradational sequences are recognizable (Fig. 11). For descriptive purposes, these are termed the "regional shelf-shoreface cyclic" and "Caroline" sequences.

Regional Shelf-shoreface Cyclic Sequence

The lowermost prograding cycle (Fig. 11) is typical of the Viking Formation throughout most of north-central and central Alberta, consisting of an interbedded succession, 20-30 m thick, of mudstone, sandy mudstone, interbedded sandstone-mudstone, bioturbated muddy sandstone, sandstone and coarse-grained conglomeratic sandstone (Beaumont, 1984; Reinson *et al.*, 1988). The lithofacies are arranged in a series of coarsening-upward units with mudstone or bioturbated sandy mudstone at the base and bioturbated muddy sandstone and sandstone being sequentially superimposed (Figs. 5, 12). Mudstone and sandy mudstone represent offshore-transitional deposits, while the bioturbated muddy sandstone (Fig. 13) and sandstone lithofacies represent the lower shoreface deposits resulting from progradation of the shoreface sediment wedge. In south-central Alberta, the Viking Formation consists of two to four of these cyclic segments (Fig. 12) which constitute the "regional shelf-shoreface" progradational sequence described by Reinson *et al.* (1988). The regional shelf-shoreface succession is always truncated at the top by a thin veneer of coarse-grained to granular sandstones (Fig. 14b) over a broad region of the basin. Locally, this coarse-grained detritus forms thick linear trough crossbedded, bar-type deposits (Fig. 13a) such as the Gilby-Joffre trend (Figs. 1, 5 and 11). The thin conglomerate lag is interpreted as a ravinement deposit which records initial transgression of the Lower Colorado Sea, while the thicker linear deposits are thought to be tidally generated, inner-shelf sands formed under sustained transgressive conditions (Reinson *et al.*, 1983).

Caroline Sequence

In contrast to the regional shelf-shoreface sequence, the Viking Formation in the Caroline area is approximately 45-50 m thick (Figs. 1, 5 and 11). Detailed log correlations and core analyses indicate that this thickness differential can be accounted for by the presence of an overlying progradational shoreface wedge (cycle 2) comprised of a sequence of lithofacies distinct from that which constitutes the regional shelf-shoreface cyclic succession (Figs. 13, 14 and 15). This upper facies was discussed in detail by Leckie (1986a), Hein *et al.* (1986) and Reinson *et al.* (1983). The Caroline progradational sequence is characterized by a single, continuous, coarsening-upward cycle consisting, from base to top, of laminated to bioturbated shale-sandstone, interbedded sandstone-shale, and fine-grained cross-bedded sandstone (Fig.15). Sedimentary structures, such as hummocky cross-stratification, wave-ripple lamination, sole marks and shale rip-up clasts are prevalent in the coarsening-upward sequence, suggesting a storm-dominated, nearshore environment (Leckie, 1986a). Cycle 2 is interpreted as a shoreline-attached, prograding shoreface-sediment wedge that formed in a wave-dominated environment receiving an abundant supply of fine-grained sand detritus (Reinson *et al.*, 1983; Leckie, 1986a).

The uppermost sandstones are invariably truncated, and overlain by conglomerates and conglomeratic sandstones, some of which are encased in Lower Colorado shales (Figs. 11, 14a). The conglomerates have a sheetlike geometry with gentle relief. Internally, they contain high-angle crossbeds, compound crossbeds and abundant mud drapes. The sedimentary structures and mudstone intercalations suggest fluctuating energy conditions, indicating that tidal influences were prevalent during time of deposition of the unit

(Leckie, 1986). A shale interval from between two of the conglomerates contains a "dwarf" assemblage of low species diversity consisting of *Ammodiscus*, *Miliammina*, *Haplophragmoides collyra* and rare *Verneuilinoides*. The small size of the individuals and low diversity suggest a stressed, brackish or marginal marine depositional setting. In contrast, shales overlying the conglomerate beds contain "normal" agglutinating foraminiferal assemblages of the *Verneuilina canadensis* and *Haplophragmoides postis goodrichi* Subzones of the *Miliammina manitobensis* Zone probably indicating neritic conditions of about 25-100 m water depth (P. Sherrington, pers. comm., 1983). This biostratigraphic data combined with sedimentary stuctures indicative of tidal influence, suggest that the multiple conglomerate beds record the onset of a basinwide rise in sea level related to the lower Colorado transgression.

Depositional Model

Figure 11 illustrates that the Viking Formation is thickest at Caroline (50 m) and thins to 25 m in a step-wise fashion towards the north-northeast. Detailed isopachs of the Viking Formation reflect the two step-wise "breaks" in thickness such as illustrated on this diagram. Isopach maps also show that these "breaks" are oriented roughly east-west to northwest-southeast corresponding to the approximate zero edge of the lower-middle shoreface facies wedge and to the zero-edge of the shoreface-transitional sediment prism (Figs. 5 and 14). Cores 2 and 3 (Fig. 14) demonstrate the overstepping of shelf-transitional deposits of the "regional shelf-shoreface cyclic" sequence by the prograding shoreface sediment prism of the "Caroline" sequence. The occurrence of coarse-grained to conglomeratic sandstone deposits situated below the laminated to bioturbated shale-sandstone lithofacies would suggest there exists a major depositional break (transgressive event) between cycles 1 and 2. Reworking of coarse-grained, granular detritus by tidal-currents seaward of the shoreface must have continued during the north-northeastward progradation of cycle 2. This contributed to the formation of linear, inner shelf bars oriented parallel to depositional strike of the shoreface sediment prism.

The uppermost conglomeratic lithofacies overlying the "Caroline" sequence reflects a final basin-wide inundation, which resulted in erosion of prograding cycle 2 deposits in the southwest, with deposition and reworking by tidal currents into transgressive sheet sands and shelf bars north-northeastward. Beyond the limit of the "Caroline" sediment prism, the upper boundary of the the Viking Formation probably represents a major break in deposition due to the coincidence of two unconformable surfaces (Fig. 11).

The interpreted sequence of deposition and resultant patterns of transgression and regression for the Viking Formation in the Caroline-Gilby region of south-central Alberta is illustrated in Figure 16. The formulation of this model is derived from the combined works of Reinson *et al.* (1983), Leckie (1986a) and Reinson *et al.* (1988). The accumulation of the Viking Formation is thought to have occurred under the following sequence of events or stages as follows:

Stage 1. At the end of Joli Fou time, a progradational stage of deposition began which corresponded to the initiation of Viking deposition. Cyclic prograding shelf-to-shoreface sediment wedges accumulated in response to one, or both, factors of variable input in sediment supply and relative sea level fluctuations, resulting from local tectonic activity or sediment loading.

Stage 2. This oscillating but generally progradational event of Stage 1 was terminated by a major drop in relative sea level which led to erosion and removal of a portion of prograding cycle 1 (Figs. 11 and 16). Subsequent rise in sea level initiated a reworking of previously deposited sediments by tidal currents. This led to the formation of coarse-grained to granular, linear bar deposits situated in inner-shelf settings, but oriented parallel to the transgressing strandline.

Stage 3. A period of progradation again ensued in response to a stable, or slowing falling, relative sea level, and under the influence of a high but constant input of sediment. This resulted in the deposition of prograding cycle 2 (Figs. 11 and 16), a single, continuous, coarsening-upward succession dominated by nearshore, wave-generated processes, and capped by the coal-marsh deposits of the prograding coastal plain.

Stage 4. A rapid rise in sea level terminated prograding cycle 2, resulting in transgression, erosion and reworking of upper shoreface-coastal plain deposits, and deposition of coarse-grained to conglomerate sheets and undulating bar-forms. As mentioned above, this transgression is thought to have been basinwide, reflecting inundation by the Lower Colorado sea. The sheet and bar deposits were formed by oceanic and tidal currents in a shelf setting.

Stage 5. During the overall transgression, minor oscillations in relative sea level occurred, probably in response to local tectonically-induced factors. This led to the deposition of three conglomeratic intervals (6 to 20 m thick) having sharp boundaries with, and encased in, Lower Colorado shales.

Stratigraphic Sequence-Crystal Area

Detailed studies in the Crystal Field area (Figure 1), indicate that the cyclic shelf-shoreface deposits of the regional Viking succession are deeply-incised by a major unconformable valley (Reinson, 1985; Reinson *et al.*, 1988), in which a 30 m thick, complex sand body is situated (Figs. 17, 18). The sandstone body is thought to be a multistage, tidal channel-fill deposit which formed within a larger estuarine channel-bay complex. A major lowstand of relative sea level that occurred approximately 97 Ma ago may be responsible for incisement of the initial valley, which subsequently became estuarine and progressively filled under transgressive conditions (Reinson *et al.*, 1988). Reinson *et al.* considered that the estuarine deposits probably accumulated over an extended time period due to the stacking of stillstand units formed during sequentially higher stands of the sea. Similar to the regional shelf-shoreface succession present basinwide, the Crystal Viking deposits are truncated by a thin transgressive-lag sequence which resulted from rapid inundation of the Lower Colorado sea.

Viking Relationships - Crystal and Caroline areas

The depositional model for the Crystal Viking succession, as postulated by Reinson *et al.* (1988) is illustrated diagrammatically in Figure 19). The model indicates the presence of a major valley-fill deposit bounded by unconformities and encased in predominantly muddy shelf-lower shoreface facies. This model also points to two major depositional breaks, within and at the top of, the Viking Formation, respectively. Either, or both, of these breaks could reflect eustatic controls of sea level. A major worldwide sea level drop was reported to have occurred approximately 97 Ma by Hancock (1975), Vail *et al.* (1977) and Weimer (1983). Further, Weimer (1983) recognized a major valley unconformity in the equivalent sandstone of the Denver Basin, and Reinson *et al.* (1988) suggested that this unconformity could be the same one that forms the incised valley surface in the Viking Formation at Crystal.

When the two sea level curves and stages of deposition of the Crystal and Caroline areas are compared, there are a number of important differences between the two successions. These differences are possibly caused by variations in sediment supply and topographic configuration of each depositional basin segment. For example, cross-section C-C' (Fig. 5) substantiates that stage 1 deposits are the same in both areas and are truncated by the same unconformity. Thus the incised valley at Crystal (Fig. 19) is equivalent to the unconformable surface of stage 2 at Caroline (Fig. 16). Further, the stepped stillstand configuration of the sea-level curve at Crystal (stage 3) may equal that portion of the Caroline curve expressed as stage 3 in Figure 16. That is, prograding cycle 2 is interpreted to have been deposited during a relative sea level rise, but in an embayed, wave-dominated setting subjected to high sediment supply. The high sediment input would counteract the effects of relative sea-level rise leading to a progradational situation at the same time that sequential transgressive fill of the estuary at Crystal was taking place (Fig. 19, stage 3). Stage 4, at both Caroline and Crystal are also equivalent, the difference being that the transgressive lags (or ravinement deposits) are separated by prograding cycle 2 at Caroline, but superimposed in the Crystal area. Thus, beyond the edge of the prograding sediment wedge of cycle 2, a double unconformity occurs at the top of the Viking over large areas of the basin where incised valleys did not form.

The transgressive-regressive model proposed by Beaumont (1984) for the Viking Formation in central Alberta is similar in some ways to that postulated here. Beaumont considered that the Viking was deposited during an overall transgression punctuated by minor regressions or stillstands, and that the formation consists of a series of overlapping sediment sheets that became progressively younger westward toward the paleoshoreline. Hence, he considered this to be a retrogradational shelf sedimentation rather than prograding shoreface sedimentation. It is suggested here, that the Viking was deposited during an overall transgression, but that the sequences of prograding cycle 1 (regional shelf-shoreface cyclic deposits, Fig. 11) actually "young" away from the paleoshoreline (Fig. 4) and are therefore progradational. In contrast, prograding cycle 2 appears to be a retrogradational sequence relative to the lower Viking Formation. The step-wise breaks-in-slope depicted in Figure 11, are in accordance with the retrogradational shelf model postulated by Beaumont. However, the regressions and stillstands that punctuated the overall transgression were much more prolonged, in terms of sediment accumulation, than Beaumont (1984) would have them. In fact, some of the regressions triggered substantial progradational events, especially in the lower part of the Viking Formation.

DISCUSSION

Both regional stratigraphic correlations (Fig.2) and sedimentologic analyses indicate that the Middle to Late Albian in Western Canada was a time of multiple unconformities and depositional hiatuses. It was also a time of several eustatic sea level fluctuations (Kauffman, 1977; Weimer, 1983; Caldwell, 1984; Haq *et al.*, 1987). The effects of these sea level fluctuations have been preserved in the sedimentary record of the Viking, Boulder Creek and Peace River formations as shown above.

In all of these formations, the regressive shoreline sequences (basal Boulder Creek Formation, Cadotte Member and lower Viking Formation) are characterized by coarsening-upward sandstones dominated by hummocky cross-stratification and wave ripple lamination in the lower shoreface and high angle cross-stratification in the upper shoreface. The thickness of the shoreface sandstones, their extensive lateral continuity and predominance of wave-formed sedimentary structures all indicate progradation of a high energy, wave-dominated coastline with no preserved evidence for tidal activity.

However, when sea level started to rise, the character of preserved sedimentation changed markedly. Evidence of wave activity is only rarely preserved and tidally-modified sedimentation predominated. The lowermost unit of the Paddy Member consist of laterally accreting, bioturbated sand-mud couplets commonly taken to indicate fluvially-influenced, estuarine sedimentation (Thomas *et al.*, 1987). Tidal sedimentation is further indicated by flaser and linzen beds, synaeresis cracks, mud-draped, high angle foresets, mud couplets, tidal bundles and compound cross-stratification and the trace fossil assemblages. The Viking Formation at Crystal contains mud couplets (Reinson *et al.*, 1988) a structure diagnostic of tidal sedimentation (Visser, 1980). At Caroline, the transgressive Viking facies contains large-scale, trough, planar and compound cross stratification alternating with mud drapes on foresets and compound crossbeds which Leckie (1986a) interpreted as evidence of tidal activity in a shelf setting. The change in character of sedimentation between regressive and transgressive phases must reflect a change in basin configuration. In general, modern tide-dominated deposits are most commonly preserved in coastal embayments and semi-enclosed shelves, whereas wave-dominated deposits are more representative of open coastlines (Davis and Clifton, 1987). This is also the case for the Middle to Late Albian sequences documented above.

The correlations in the cross sections (Fig. 3, 4 and 5) and in Figure 2 indicate three major unconformities within the Middle to Late Albian succession. These are: 1) the incised valley surface that occurs at the base of the Paddy Member in northwestern Alberta and at the correlative unconformity at the base of the Joli Fou in central Alberta (Fig. 10), 2) the incised valley surface that marks the base of the Viking sandstone deposit in the Crystal area of central Alberta (Fig. 19) and, 3) the transgressive lag surface which marks the top of the Viking Formation throughout most of south and central Alberta. It was shown that all three of the unconformable surfaces can be related to sharp fluctuations in relative sea level. Whether these sea level drops are the result of worldwide eustasy is difficult to resolve but is speculated upon above.

The unconformity at the base of the Paddy Member (Figs. 3 and 4), may be, in part, correlative with the major disconformity between the Joli Fou Formation and underlying Mannville Group in the central Alberta plains (Fig. 2; Caldwell *et al.*, 1978). The fifteen well-developed, superposed paleosols in the Boulder Creek Formation of northeastern British Columbia (Leckie *et al.,* in press) may also reflect some aspect of this major hiatus. The paleosols are diastems which cumulatively may represent episodes of non-deposition totalling several tens of thousands of years. The time gap between the Paddy and Cadotte Members is in part correlative with that of the Boulder Creek diastems and may represent much of the upper Middle Albian. This hiatus, in the Peace River area, was terminated by deposition of Joli Fou shales which marks the transgressive phase of the Kiowa-Skull Creek marine cycle (Caldwell, 1984). While Joli Fou shales were deposited throughout the central plains, estuarine deposits were being deposited along the northwestern margin of the transgressive sea (Paddy Member). Caldwell (1984) and Kauffman (1977) consider this transgression and the subsequent regressive phase (Kiowa-Skull Creek cycle) to have been controlled, or substantially influenced, by continent wide, eustatic sea level fluctuations. Caldwell suggests that the transgressive peak of this cycle probably marks the highest stand of sea level in Early Cretaceous time.

The regressive phase of the Kiowa-Skull Creek cycle is represented by Viking sands in the interior plains (Caldwell, 1984). We have shown that the Viking consists of two major depositional phases separated by an unconformity (Figs. 11, 16, 19). The lower regressive phase (prograding cycle 1) probably corresponds to the regressive phase referred to by Caldwell. The cyclical perturbations of prograding cycle 1 may reflect the influence of local and/or regional tectonics, or autocyclic processes which could have affected variations in sediment supply.

The Crystal unconformity that terminates prograding cycle 1 (Figs. 16, 19) is thought to represent a basin-wide drop in sea level, because it appears to correspond with correlative strata in the Denver Basin in which a similar unconformable incised valley system occurs (Weimer, 1983). Weimer considered this unconformity to represent a worldwide low-stand of sea level that occurred approximately 97 Ma (Vail *et al.*, 1977; Hancock, 1975). This basinwide drop in sea level, if not eustatic, certainly has to represent a major tectonic event of some magnitude.

We have documented a major transgressive phase following the "middle Viking" unconformity in northeastern British Columbia, and in northwestern and central Alberta (Figs. 10, 16 and 19). The fact that this transgressive phase may be tectonically-controlled is reflected in the progradational nature of the Caroline sequence (prograding cycle 2, Fig. 16) which is thought to be correlative with the cyclical stillstand-transgressive estuary-fill sequence at Crystal (Fig. 19; Reinson *et al.*, 1988). As mentioned earlier, extremely high input of sediment in the Caroline region effected progradation of cycle 2 even under relative sea level rise. Tectonic influences on basin and shoreline configuration, depositional gradient and resultant sediment availability could lead to such a situation (Fischer, 1961).

The uppermost unconformity at the top of the Viking Formation-Paddy Member equivalents represents another relative drop in sea level which extended at least over the Alberta-B.C. part of the basin (Fig. 16). Major downcutting and coastal plain dissection created a conduit for the supply of coarser grained detritus which was subsequently reworked across the entire basin during the ensuing major transgression of the lower Colorado sea. Here again, if the basinwide transgression is not eustatic, it would have to reflect a major episode of crustal uplift and adjacent subsidence. It is likely that this major inundation records the onset of the Greenhorn transgression described by Caldwell (1984). Minor sea-level fluctuations, caused by regional and/or local structural movements, are reflected in the conglomeratic sediment pulses which were encased in basinal muds early in the transgressive phase (stage 5, Fig. 16).

CONCLUSIONS

The findings and interpretations presented in this paper indicate that there are major stratigraphic breaks within the Middle to Late Albian Viking, Peace River and Boulder Creek formations of Alberta and northeastern British Columbia. These major breaks occur within what appears to be an overall basinwide transgressive phase. At least from upper Viking and basal Paddy time onward, relative sea level was rising steadily, but punctuated by at least two lowstands. Local and regional tectonic effects contributed to divergent sequences in different areas of the basin. Factors such as variations in sediment supply, shoreline paleogeography and paleotopography (all tectonically controlled) contributed to the formation of progradational (shoreline regressive) sequences, in near juxtaposition, or only a few tens of kilometres from, vertically-accreting valley fill, or transgressive estuarine-fill deposits.

At this time it is still not possible to resolve the relative roles of eustasy versus tectonic factors as the dominant force in governing transgressive-regressive cyclicity in the Lower Cretaceous of the Western Interior plains. However, we are able to highlight the occurrence of basinwide (Alberta and British Columbia) stratigraphic breaks within the Middle to Late Albian succession, which, heretofore, have gone unrecognized. Eustasy must have played a major role in the occurrence of these stratigraphic breaks, but the overprinting of local and regional tectonics is clearly seen within the preserved facies sequences and lateral relationships.

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FIGURES

Figure 1. Location map showing areas studied in this paper and locations of cross section shown in Figures 3, 4, 5, and 11. Location of major oil-bearing Viking sandstone reservoirs are outlined on the enlarged south-central Alberta map.

Figure 2. Stratigraphic terminology and correlations. The radiometric date for Hulcross Formation is from the Hudson Hope area. See details in text.

Figure 3. Gamma ray cross section AA'. Location shown in Figure 1.

Figure 4. Gamma ray cross section BB'. Location shown in Figure 1.

Figure 5. Gamma ray cross section CC'. Location shown in Figure 1.

Figure 6. Complete measured section of the Harmon, Paddy and Cadotte Members of the Peace River Formation in the Peace River area. The composite section is based on outcrops along the Peace and Heart Rivers near the town of Peace River. Location of section shown in Figure 1.

Figure 7. A) Erosional surface of Paddy (P) on the Cadotte (C) indicated by dashed line. The lower sandstone unit of the Paddy Member is replaced to the right by a carbonaceous, muddy channel fill. Upper recessive interval is the basal Shaftesbury Formation. Location is along the Heart River. B) Bioturbated sand-mud couplets. Top sandstone bed contains mud drapes on foresets. Scale bar is 15 cm long. C) Crossbedded sandstone with carbonaceous muddy drapes on foresets. Location is along the Peace River. Scale bar is 15 cm long. D) Bidirectional, planar

tabular crossbeds. Location is along the Heart River. Scale bar is 15 cm long.

Figure 8. A) Subsurface gamma ray cross-section showing incised valley system of Paddy into the Cadotte. Asterisk is a radioactive "kick" referred to in text. Location of cross section is shown in B. B) Subsurface map showing distribution of wells having a truncated or abnormal Cadotte log character. The patterns define an incised valley (stippled) cutting into the "regional" Cadotte facies. The area contains 112 wells through the interval.

Figure 9. Measured section of the Hulcross and Boulder Creek Formations from continuous coal-exploration in the Monkman Pass area. The section is based on measurement of continuous coal core MDD 80-08.

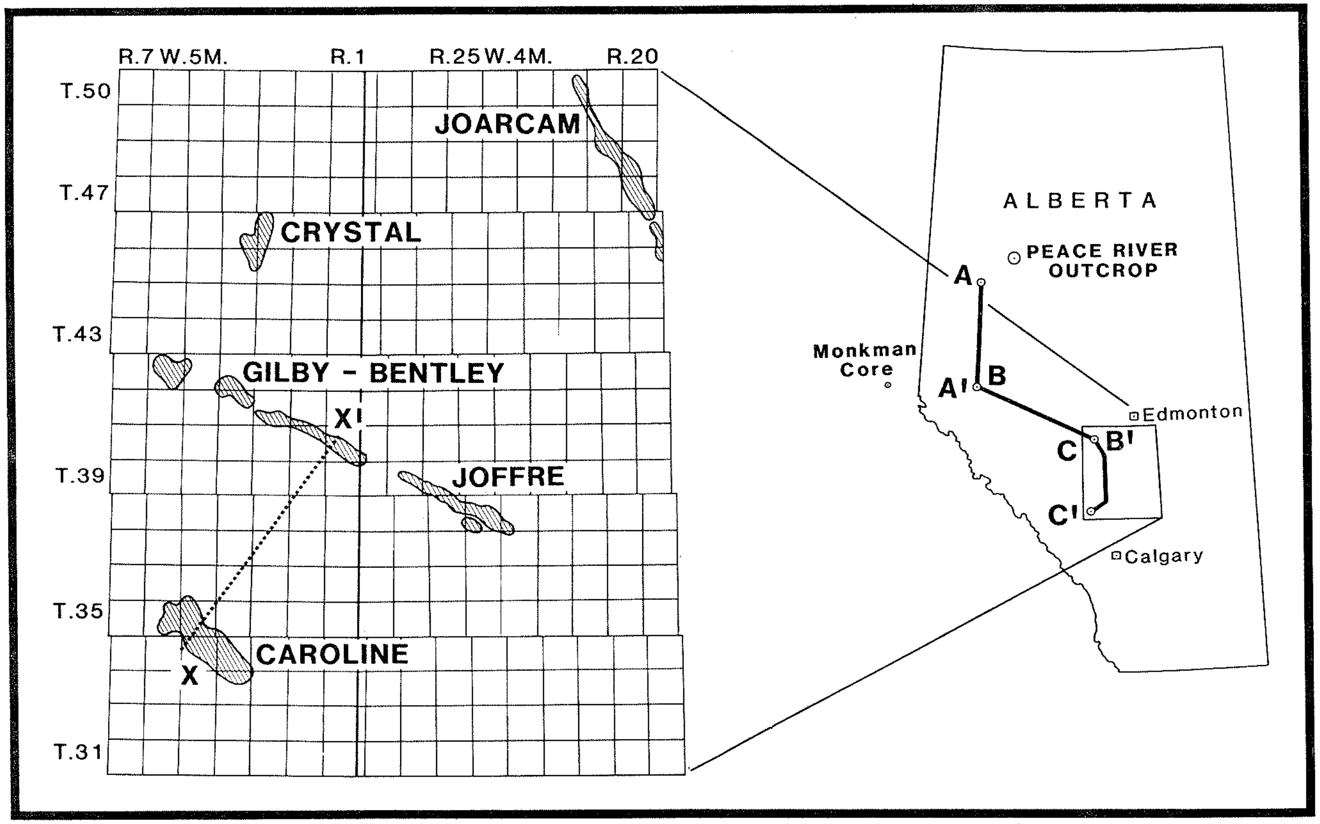
Figure 10. Schematic model relating paleosols to incised valleys and relative sea level fluctuations.

Figure 11. Generalized schematic cross section extending form the Caroline oil-field in the southwest, northeastward to the Gilby-Joffre oil-bearing trend. Location of cross section shown in Figure 1.

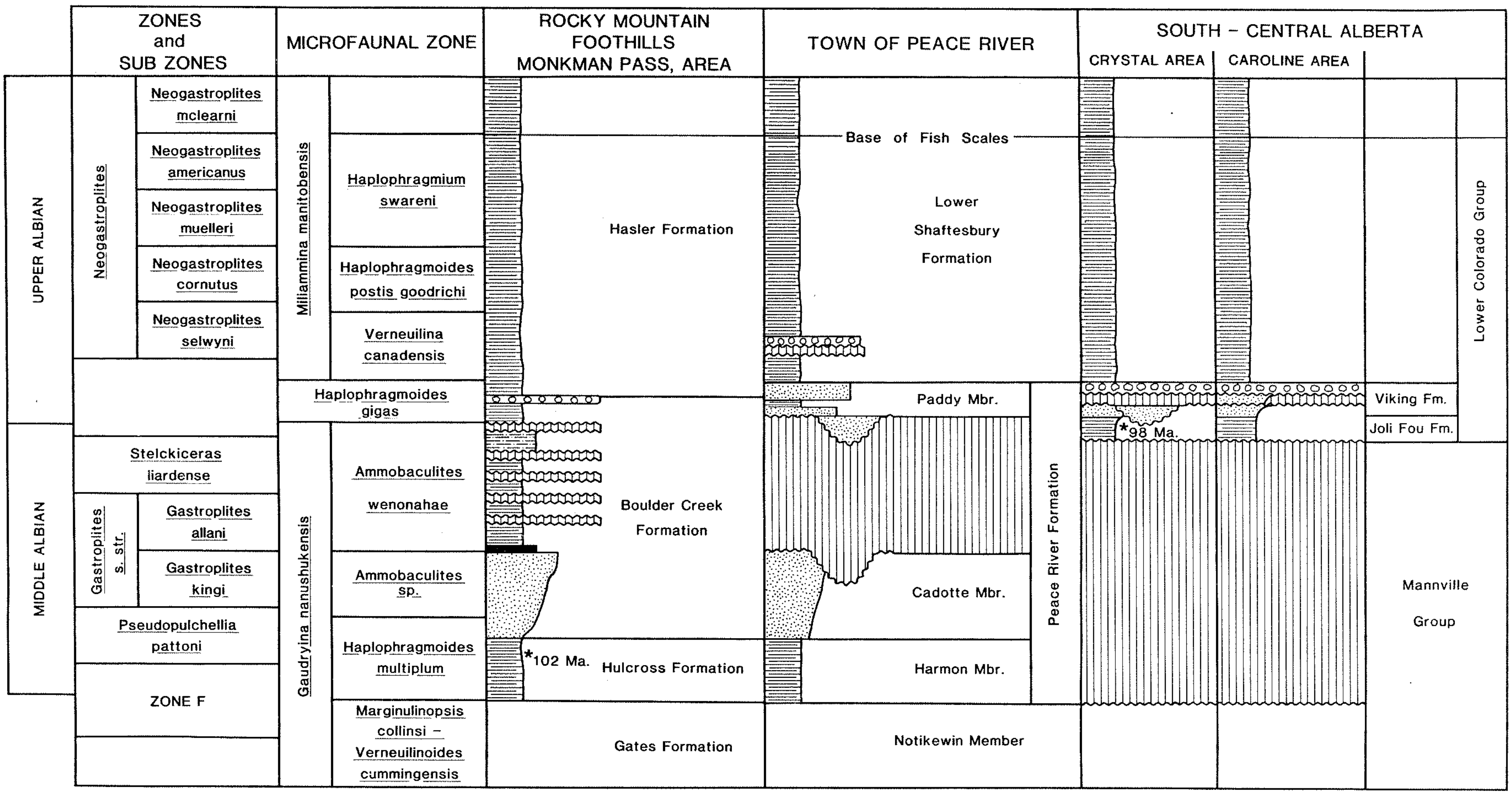
Figure 12. Cored facies-sequence of prograding cycle 1 in the Viking Formation,13-5-46-3W5 borehole, Crystal area, Alberta (modified from Reinson *et al.*, 1988).

Figure 13. A) Bioturbated muddy sandstone of the Viking "regional shelf to shoreface cycle". Note the large *Skolithos* burrow filled with coarse-grained sand. Flattened *Terebellina* also visible (6-

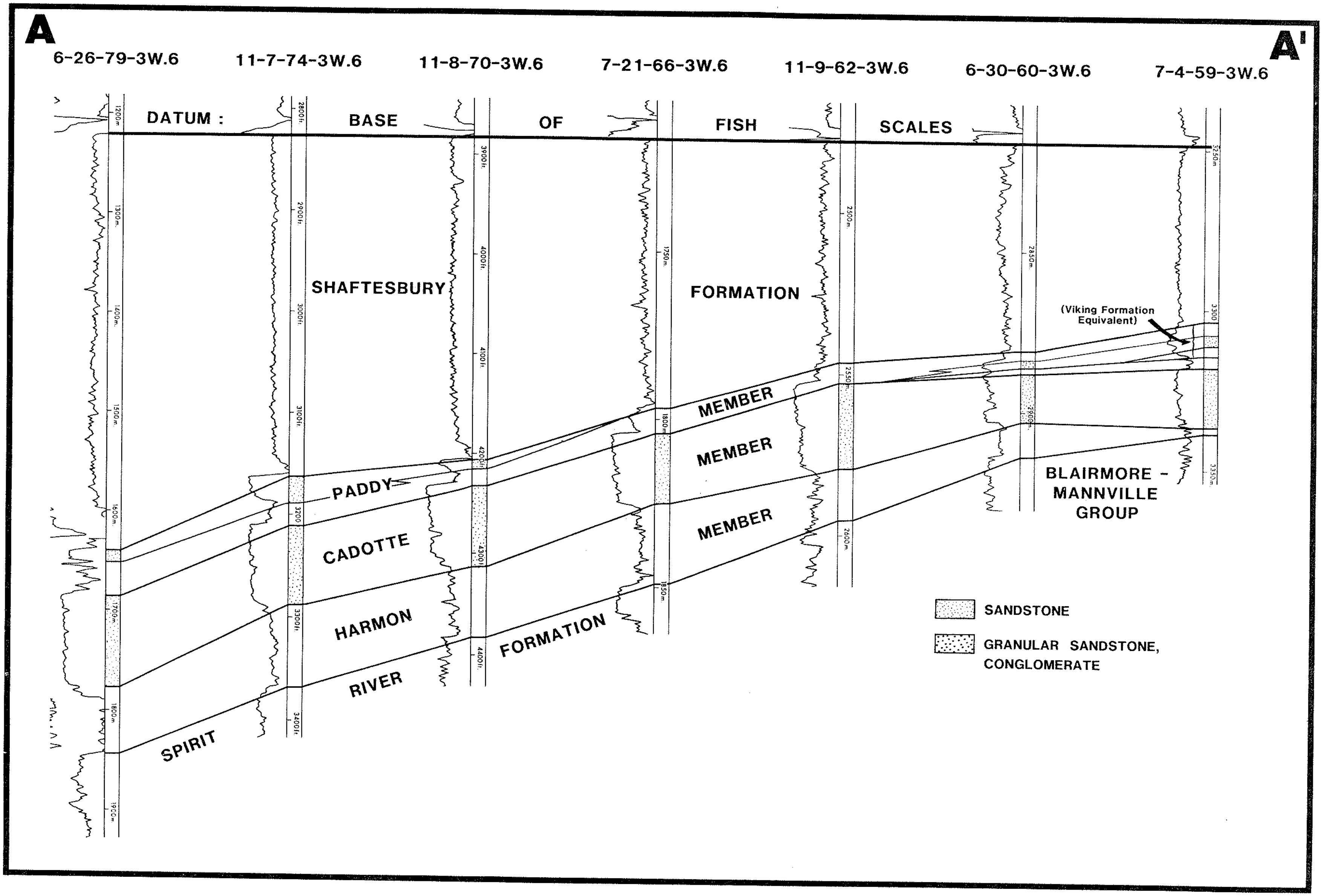
4-38-24W4, 4544.5 ft). B) Coarse-grained, trough crossbedded sandstone of the tidally-generated transgressive shelf facies (12-7-39-26W4, 4958 ft.).



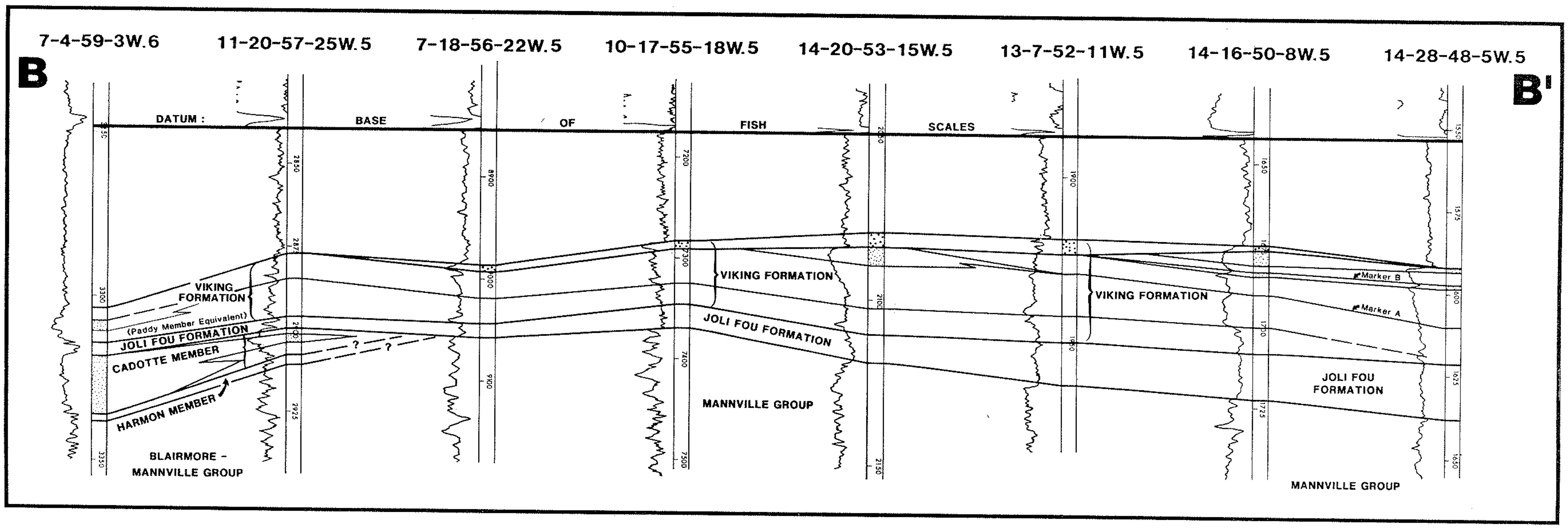
Leckie + Reinson
Fig 1



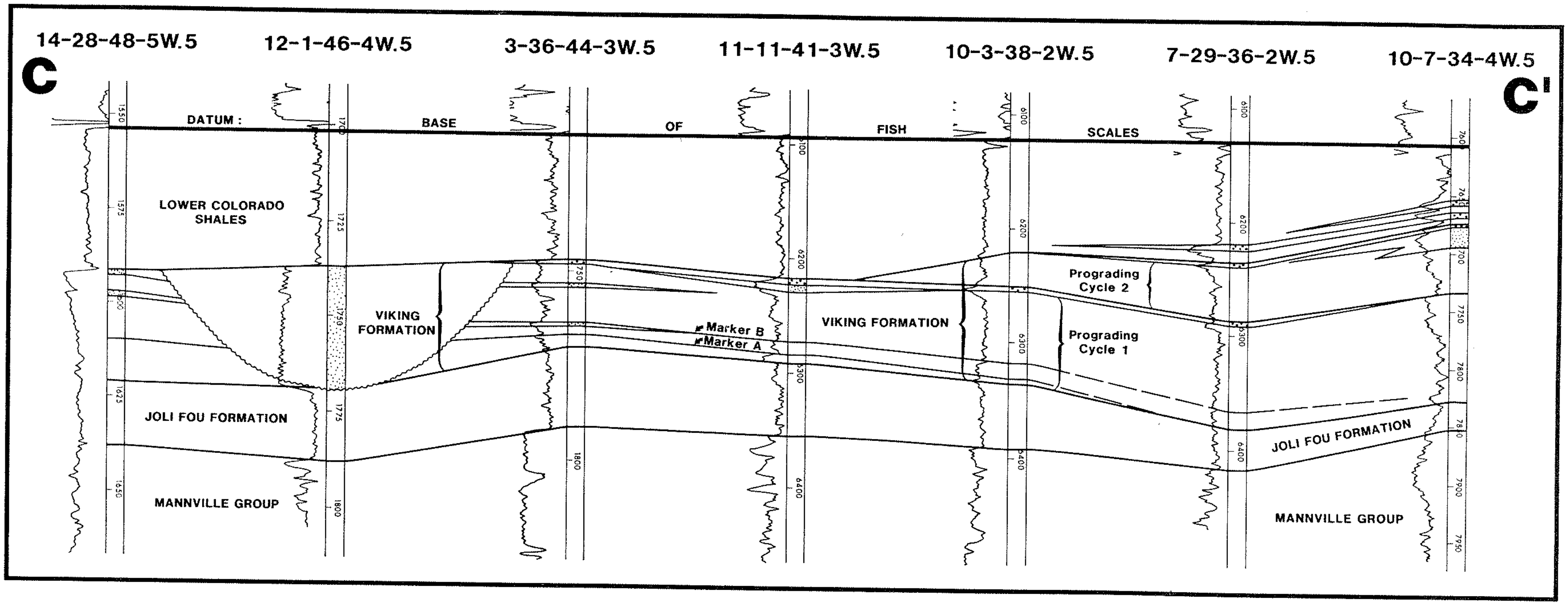
Leckie-Reinson Fig 2



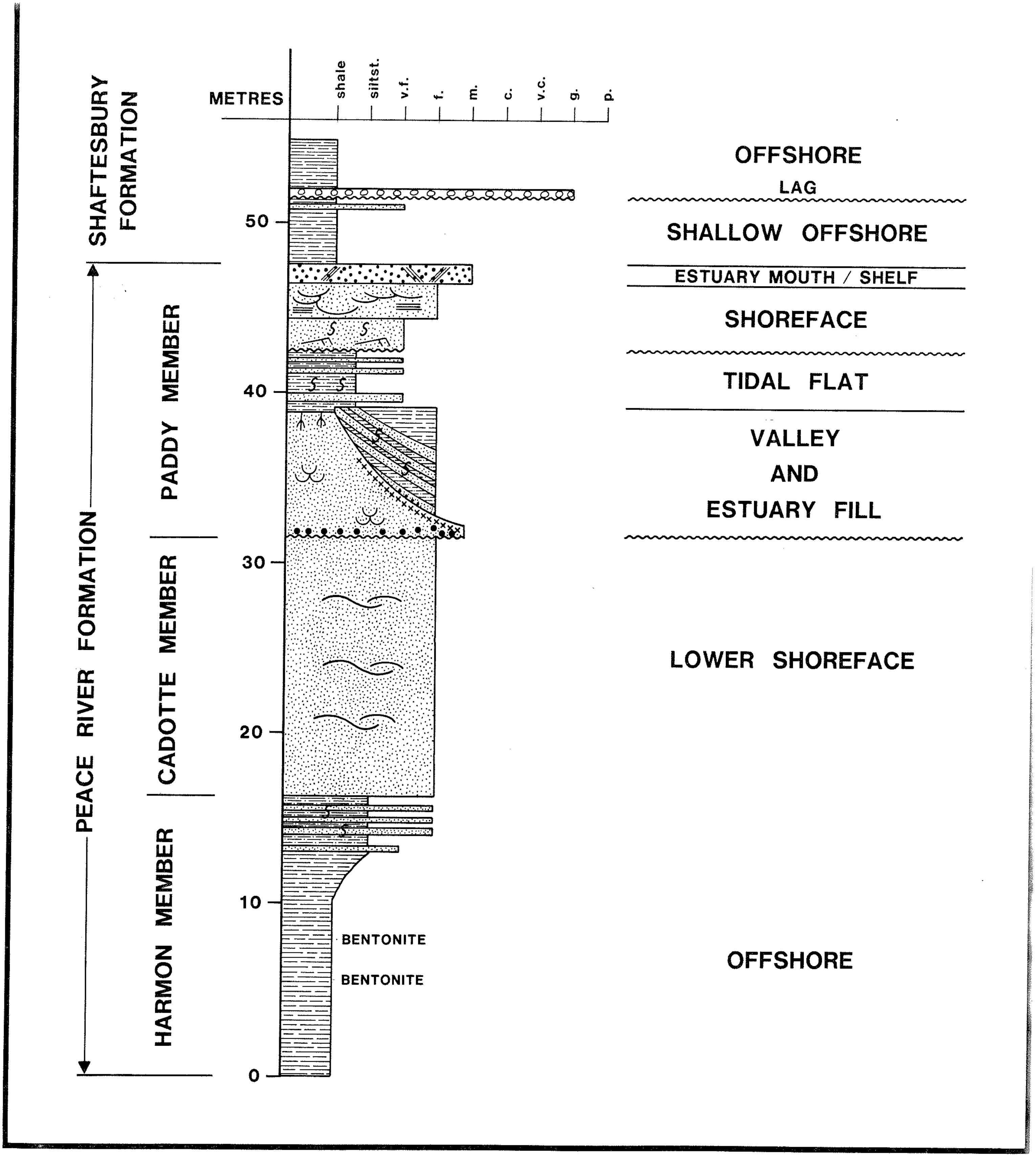
Leckie + Reinson
Figure 3



Leckie-Reinson Fig 4.



Leckie + Reinson
Figure 5

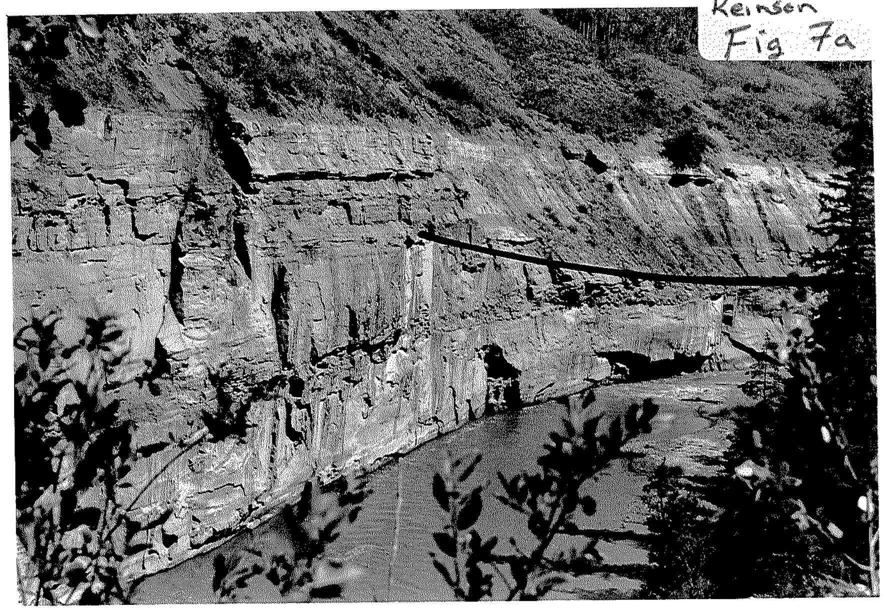


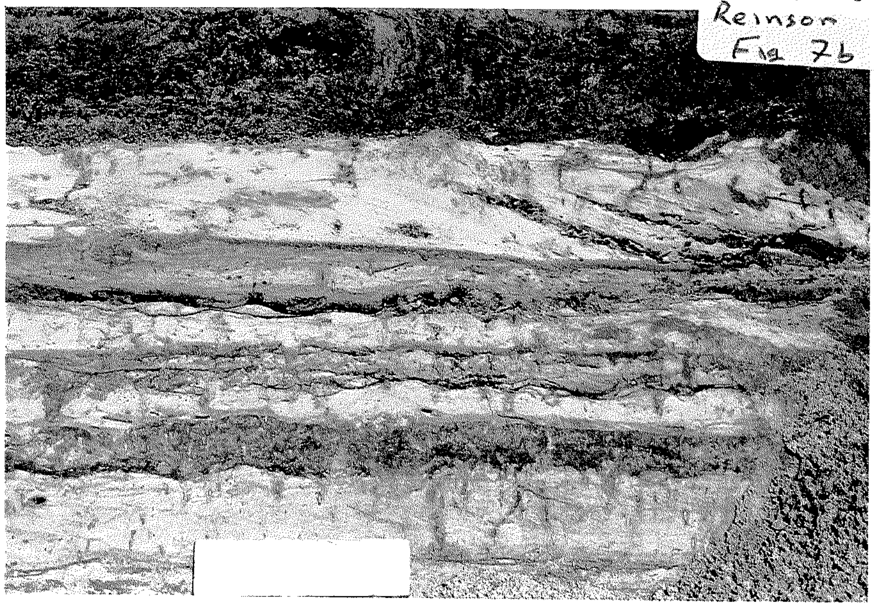
Leckie & Reinson Fig 6a

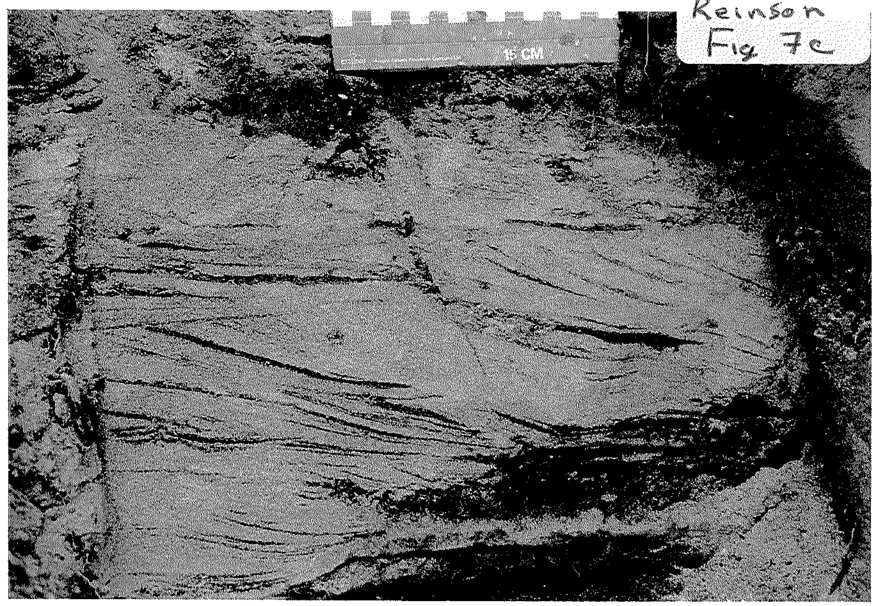
LEGEND

- CONGLOMERATE
- COARSE – GRAINED TO GRANULAR SANDSTONE
- VERY FINE TO MEDIUM – GRAINED SANDSTONE
- SILTSTONE
- SHALE
- COAL
- XX – FERRUGINOUS NODULES , BANDS, CONCRETIONS
- CLAY CLAST
- PLANAR CROSS – BEDDING
- TROUGH CROSS – BEDDING
- HUMMOCKY CROSS – STRATIFIED
- PARALLEL LAMINATION
- WAVE RIPPLE CROSS – LAMINATION
- CURRENT RIPPLE CROSS – LAMINATION
- BIOTURBATION
- ROOTS
- CONTORTED, DISRUPTED BEDDING

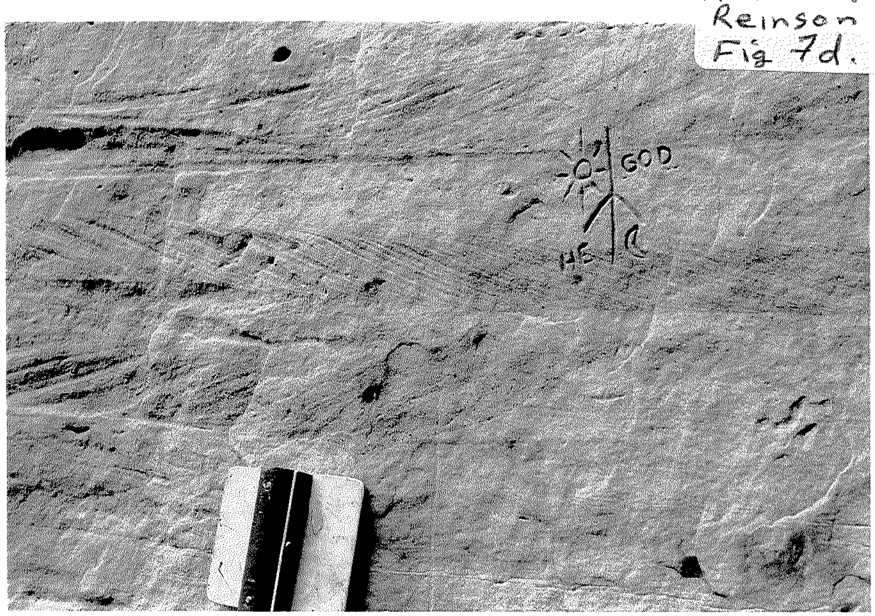
Leckie & Reinson Fig 6b


Leckie and Reinson Fig 7a

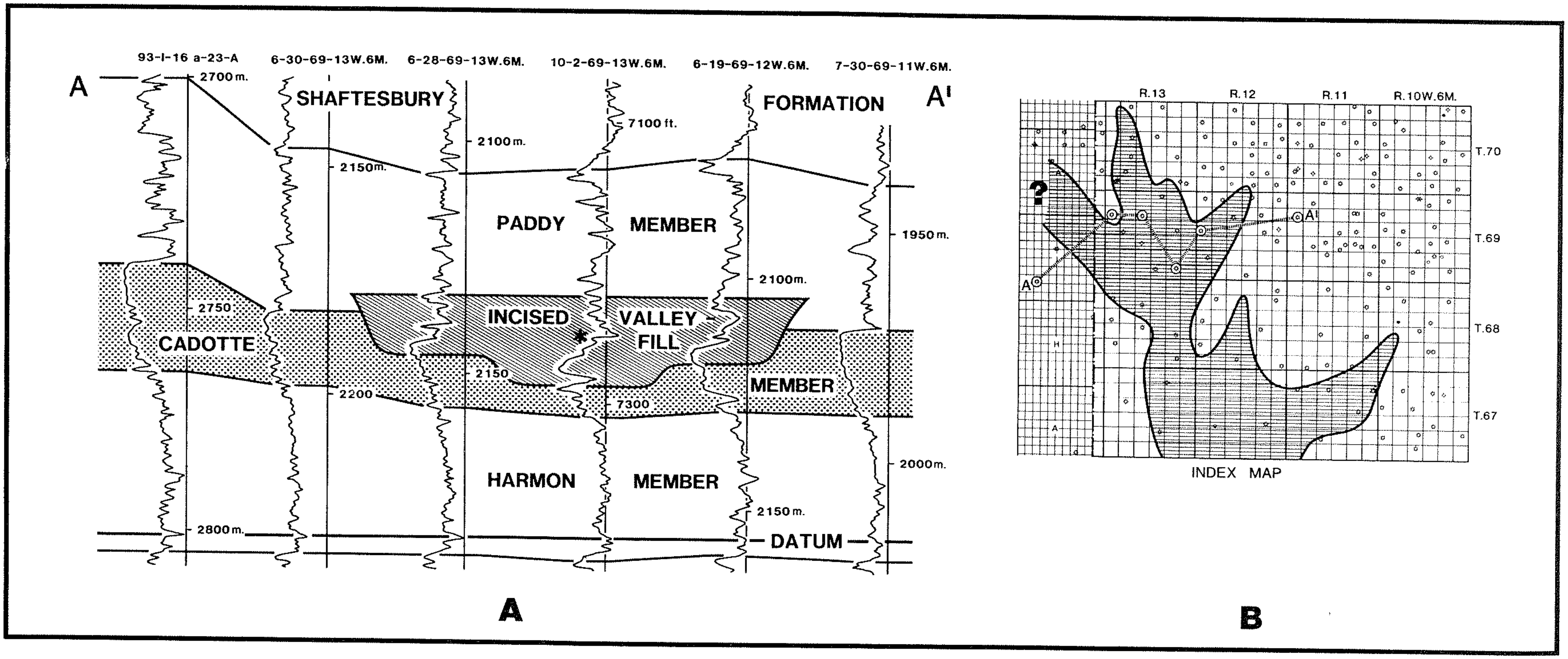

Leckie & Reinson Fig 7b



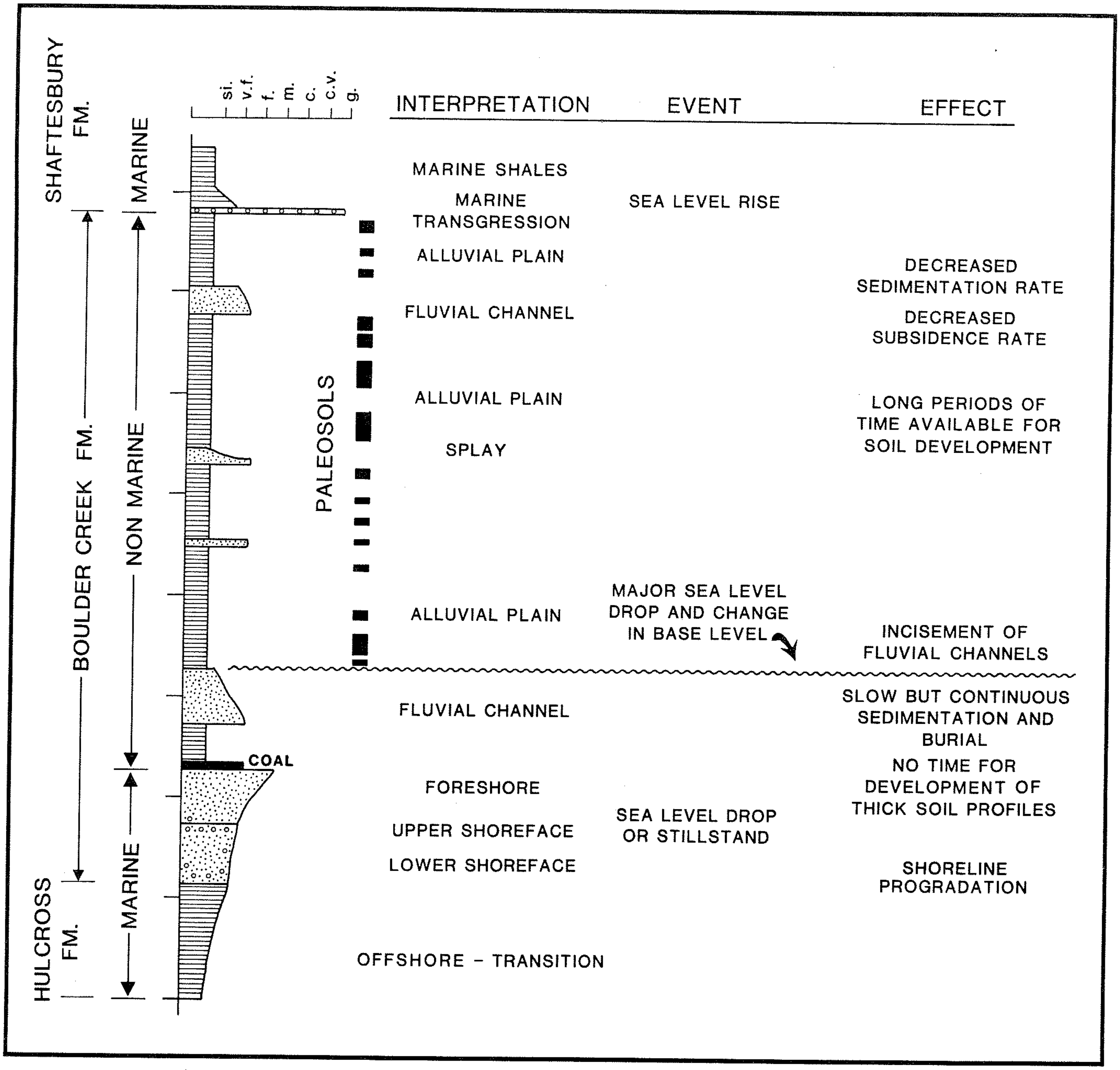
Leckie & Reinson Fig 7c



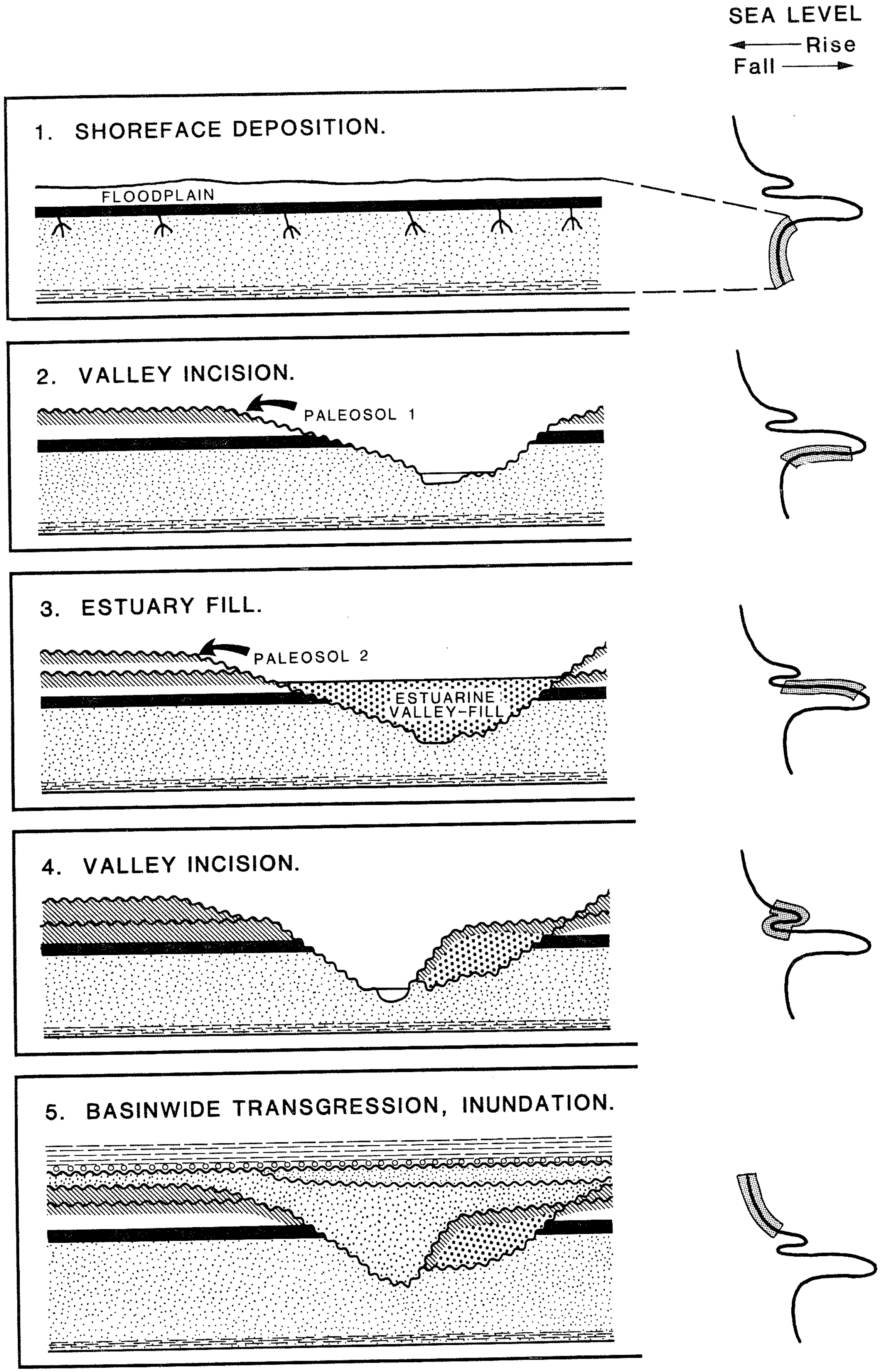
Leckie & Reinson Fig 7d.



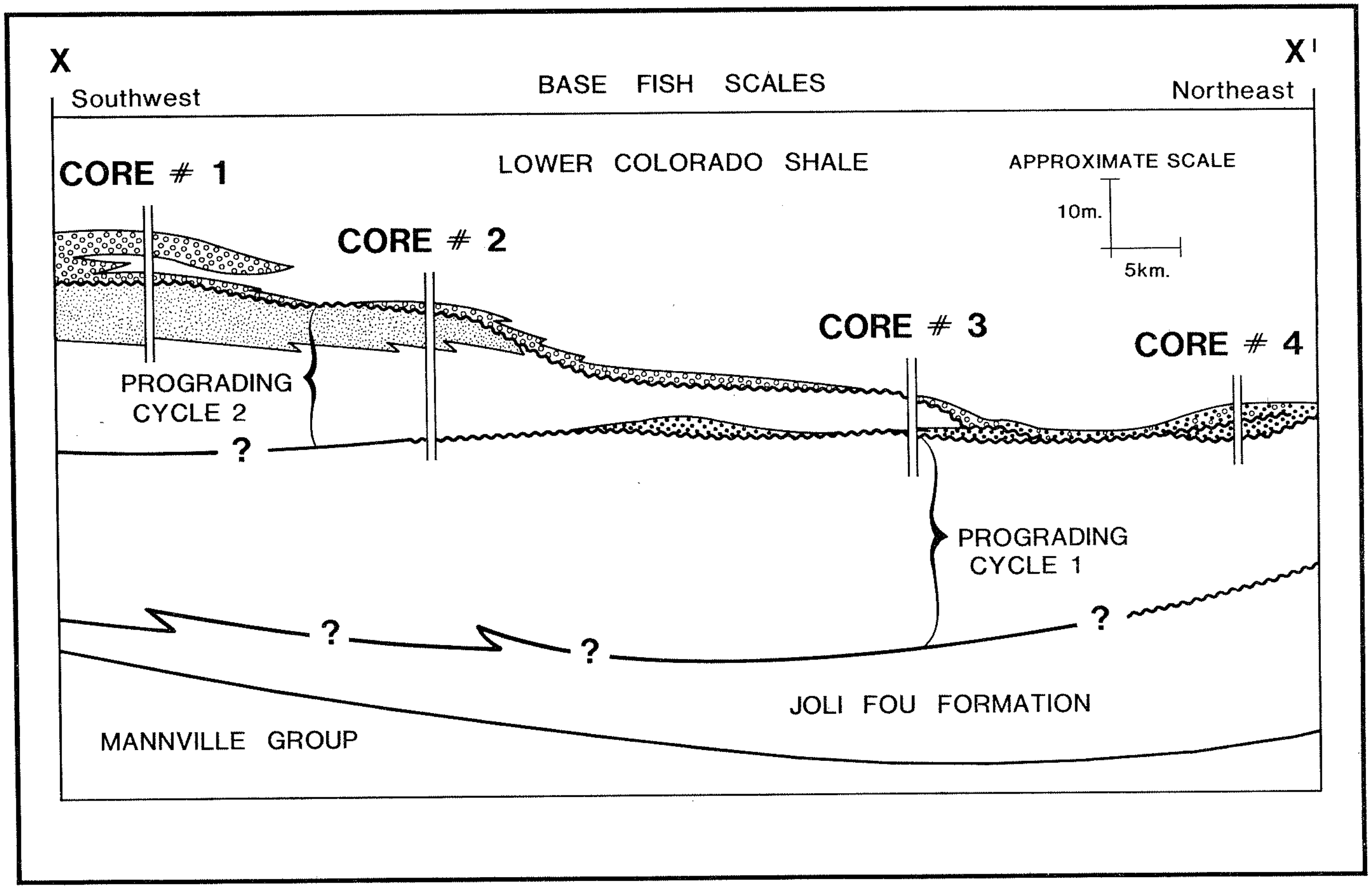
Leckie + Reinson
Figure 8



Leckie & Reinson
Fig 9

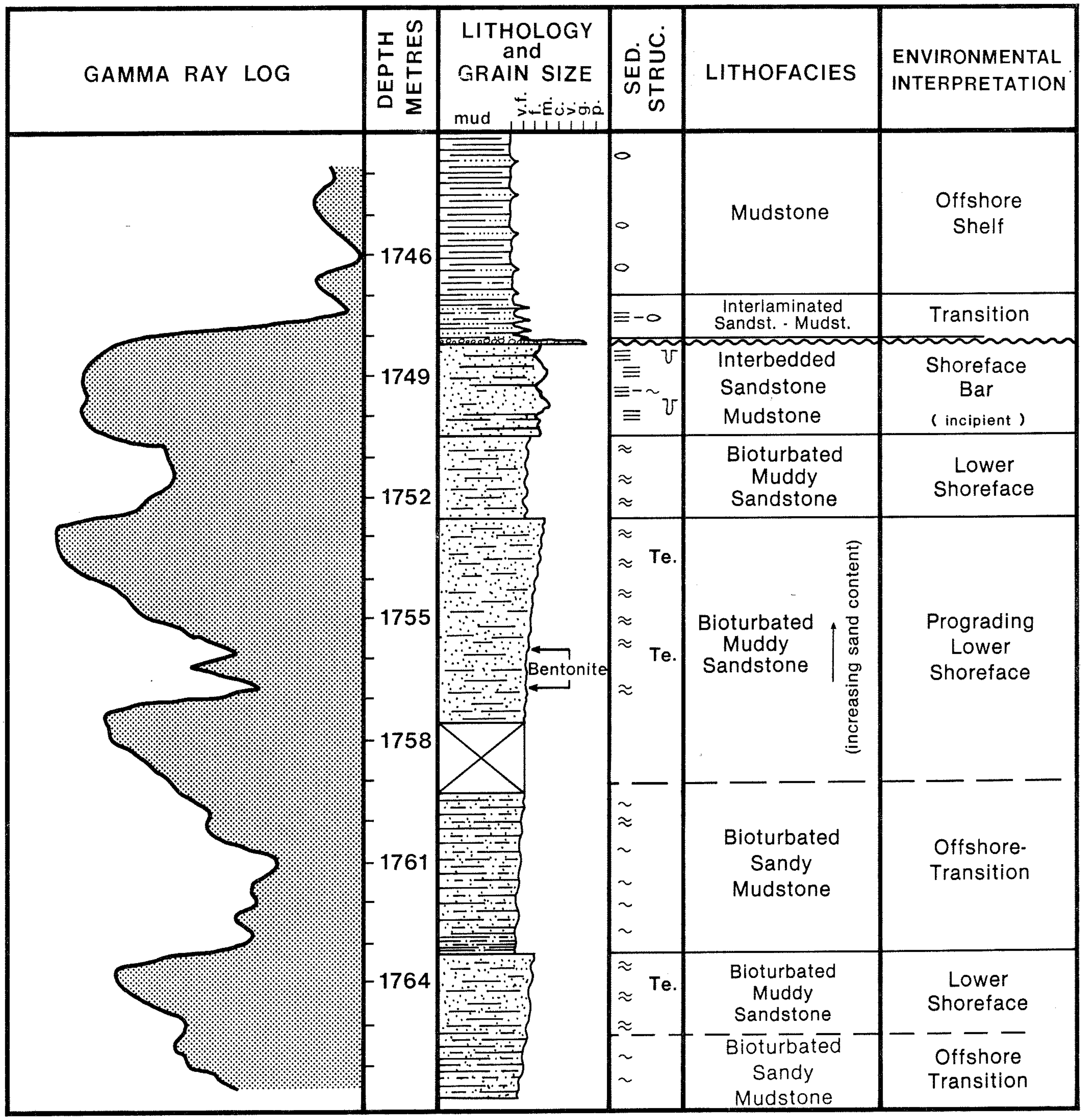


Leckie + Reinson
Figure 10



Leckie
Reinso
Fig 11

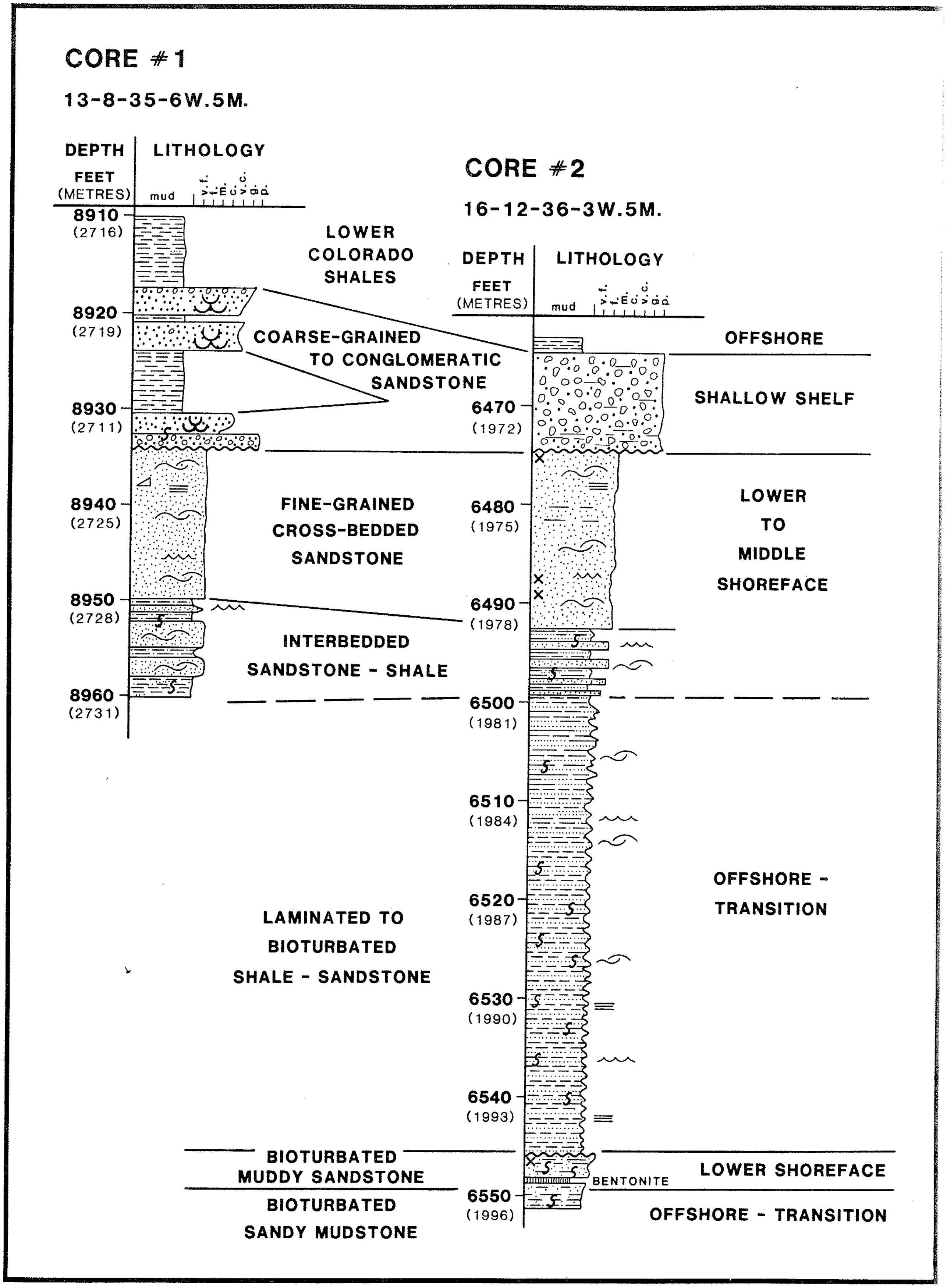
CRYSTAL 13-5-46-3W.5M.



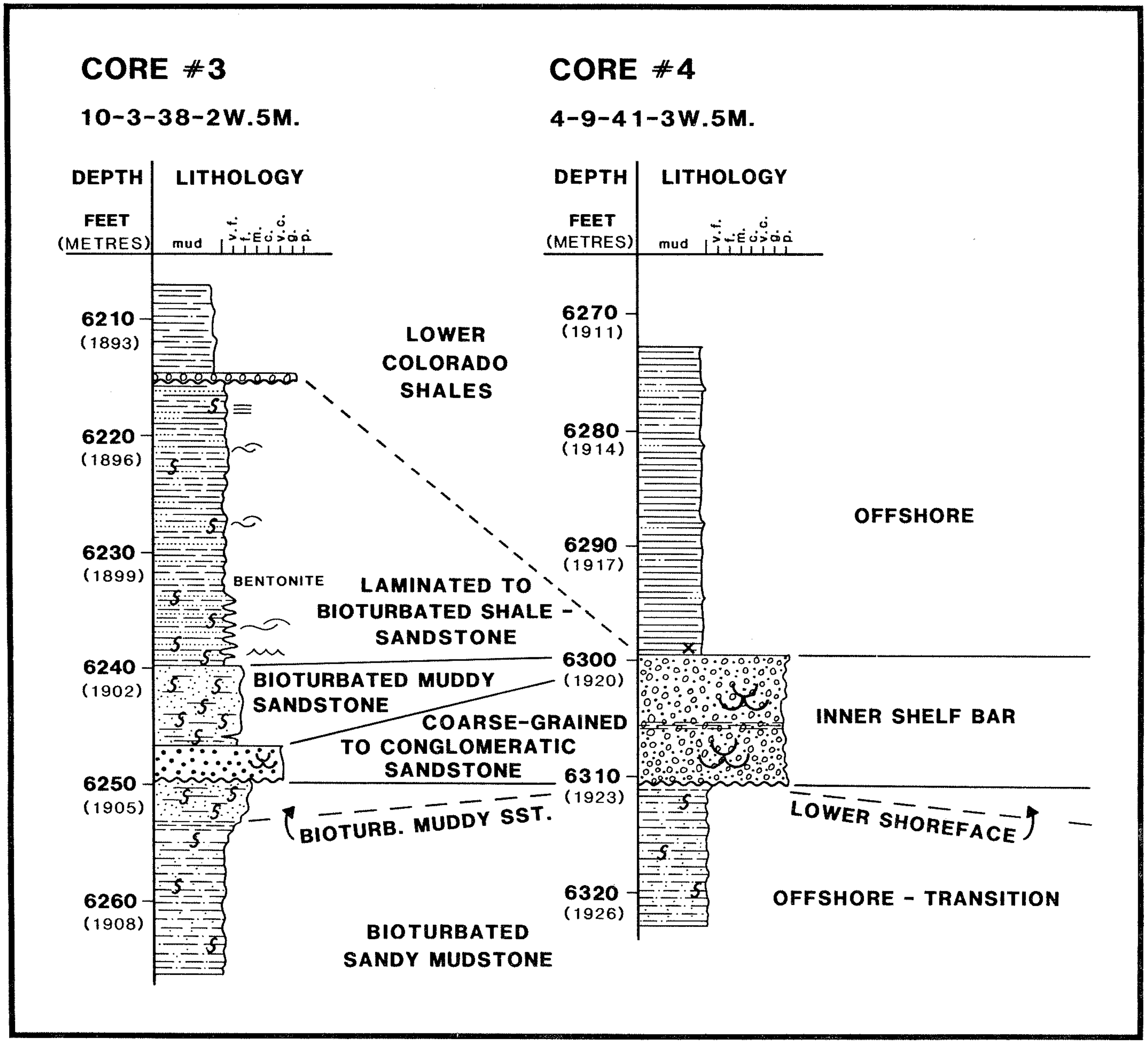
Leckie & Reinson
Fig 12

Leckie and Reinson Fig 13a

Leckie and Reinson Fig 13b

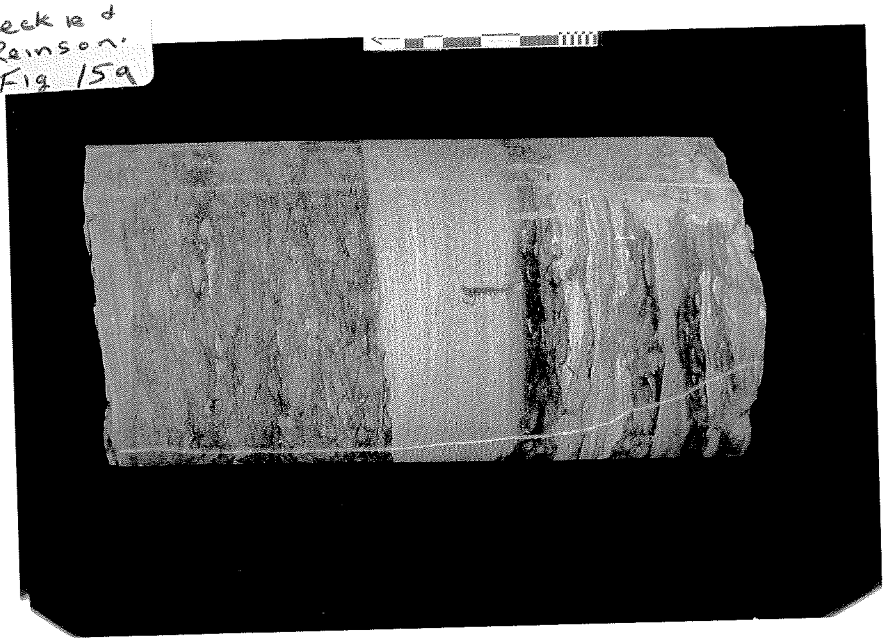


Leckie & Reinson Fig 14 Left

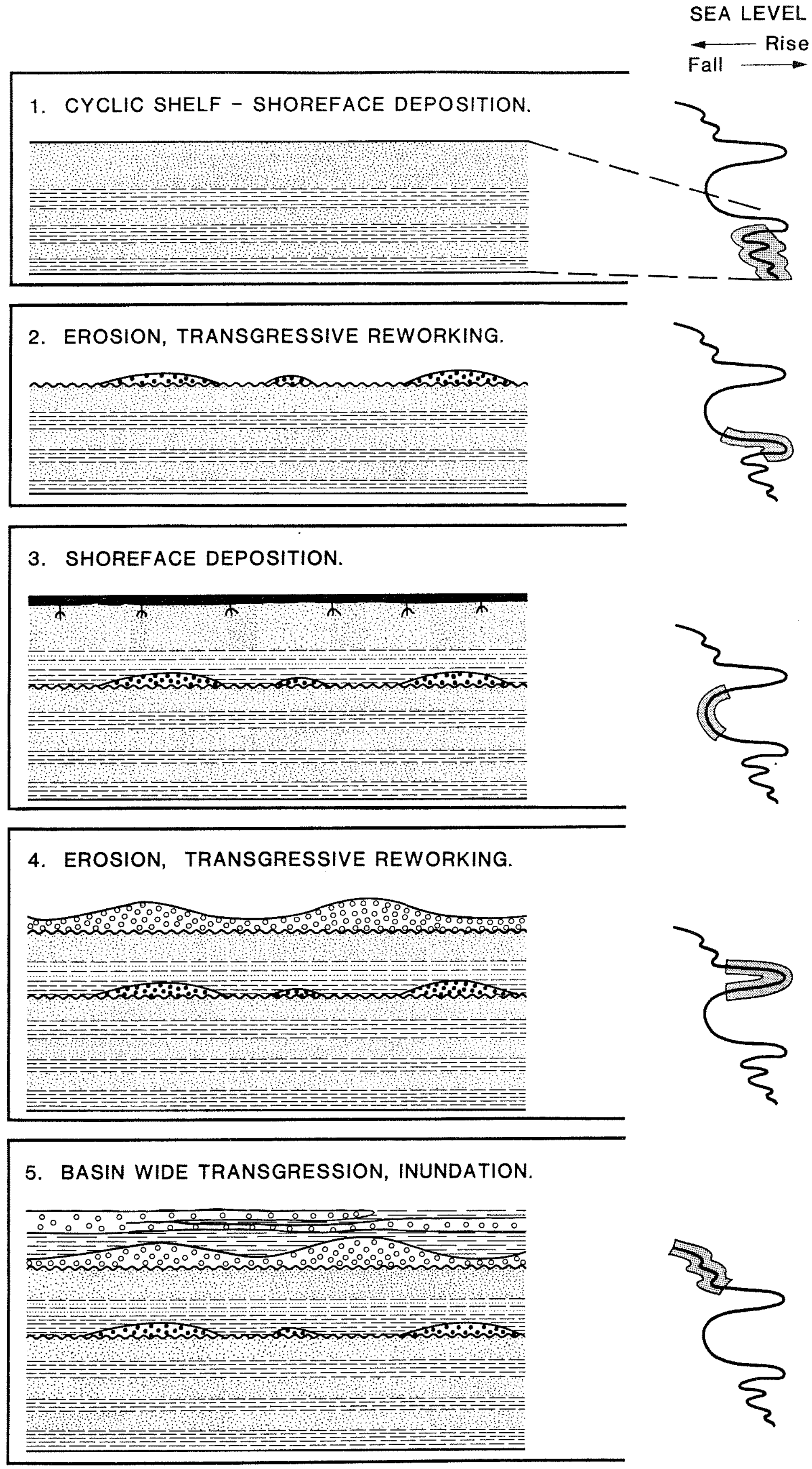


Leckie + Reinson
Figure 14 'Right'

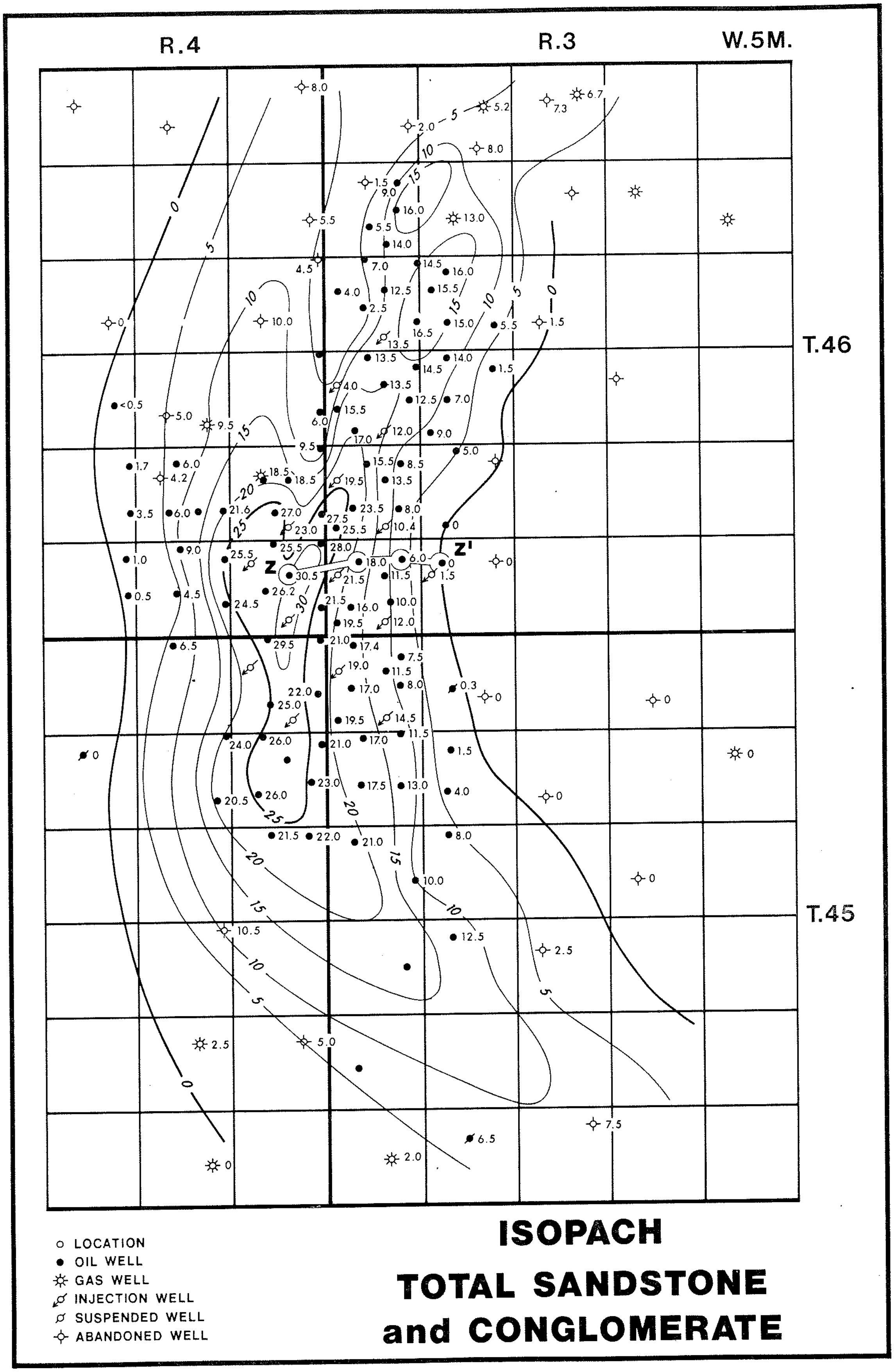
Leckie & Reinson. Fig 15a



Leckie & Reinson Fig 15b.



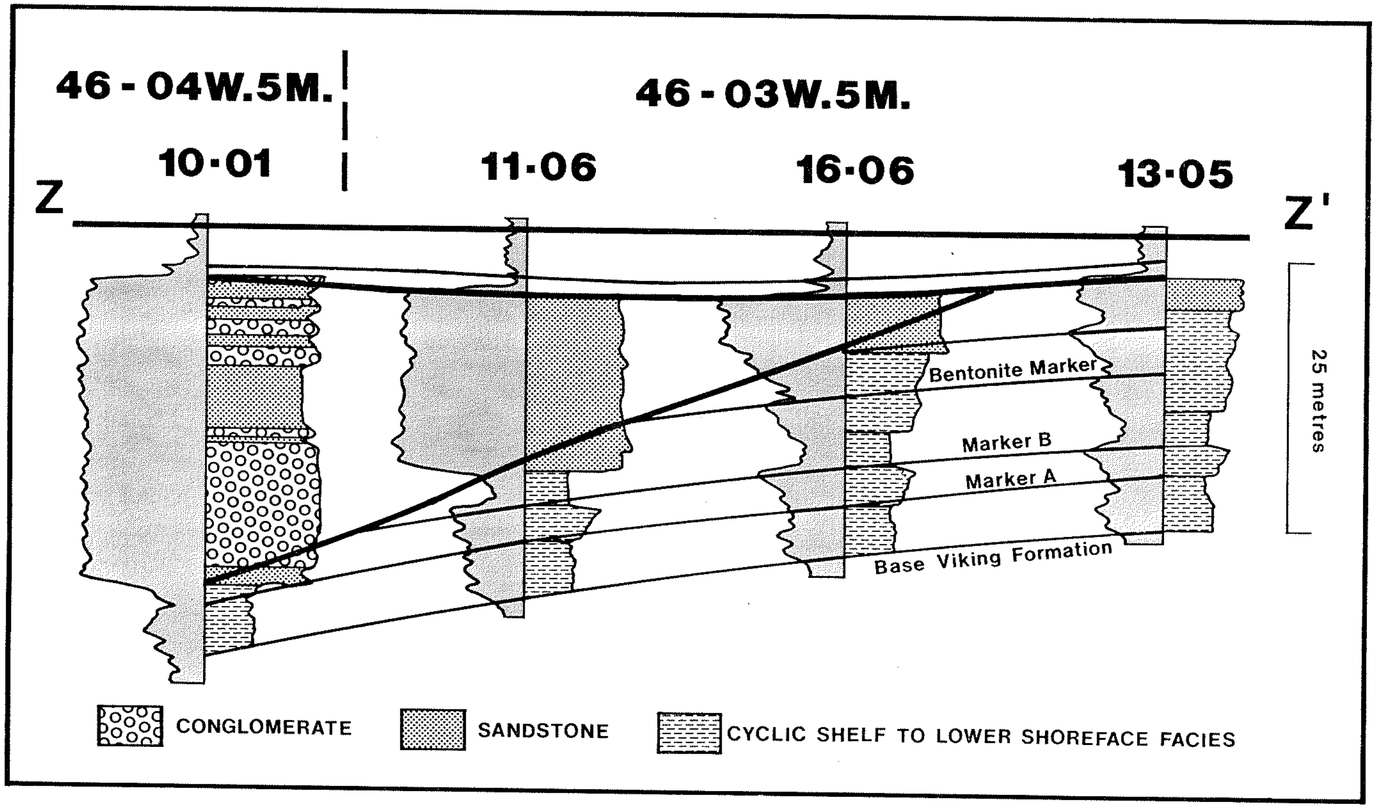
Leckie & Reinson Fig 16

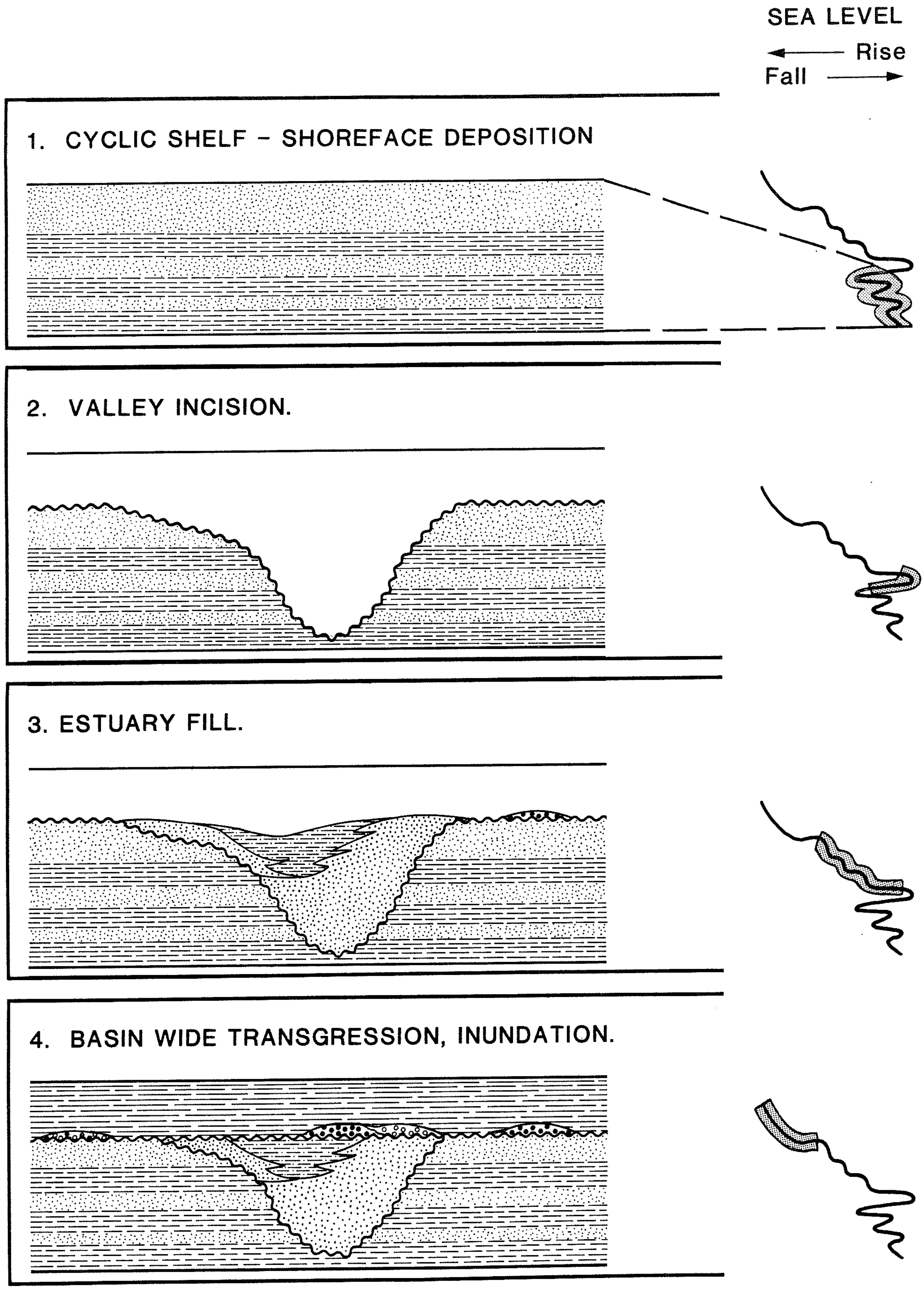


ISOPACH TOTAL SANDSTONE and CONGLOMERATE

Leckie & Reinson.
Fig 17

17


46 - 04W.5M.
46 - 03W.5M.
10·01
11·06
16·06
13·05
Z
Z'
25 metres
Bentonite Marker
Marker B
Marker A
Base Viking Formation
CONGLOMERATE
SANDSTONE
CYCLIC SHELF TO LOWER SHOREFACE FACIES



Leckie & Reinson. Fig 19.