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River- and wave-dominated depositional systems of the Upper Cretaceous Dunvegan Formation, northwestern Alberta

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ABSTRACT

This paper documents the detailed sedimentological aspects of the Dunvegan Formation based on examination of about 130 core and 500 well logs. Nineteen facies have been grouped into 7 successions. In combination with sand isolith maps, these facies successions are further linked into lithofacies assemblages that define distinct, large-scale depositional systems.

Facies Successions 1, 2, and 3 coarsen upward and represent the progradation of storm-dominated shorefaces, river-dominated delta lobes, and mixed-influence deltaic lobes, respectively. Facies Successions 4, 5, and 6 fine upward and comprise the deposits of fluvial-dominated distributaries, estuaries, and barrier inlets. Facies Succession 7 is irregular and comprises the deposits of the delta plain, including interdistributary bays and lagoons.

Facies Successions 2, 4, and 7 define the river-dominated deltaic depositional systems, which show lobate geometries fed by channelized shoestring sands. The wave-dominated deltas also show lobate geometries but are characterized by a linkage of Successions 1, 5, and 7, which show more marine influence. The wave-influenced deltas are characterized by a linkage of Successions 3, 4, and 7 and are intermediate in shape and facies between the wave-dominated and river-dominated end members. The wave-dominated barriers are elongate and oriented shore parallel, and are characterized by a linkage of Successions 1, 6, and 7.

The Dunvegan Formation cannot be characterized as a single delta. Rather, it is interpreted here as a stacked series of different types of depositional systems. These prograded to the southeast, with shorelines trending approximately northeast–southwest. Overall there apppears to be a decrease in the importance of fluvial processes upward.

RÉSUMÉ

L'exposé qui suit donne une description sédimentologique détaillée de la formation Dunvegan, basée sur l'examen d'approximativement 130 carottes et 500 diagraphies de forage. Dix-neuf faciès ont été groupés en 7 successions de faciès. En association avec des cartes isolithes, ces successions de faciès sont à leur tour regroupées en assemblages de lithofaciès qui définissent dans un cadre plus large des ensembles de milieux sédimentaires distincts.

Les successions de faciès 1, 2 et 3 montrent une granulométrie qui augmente vers le haut et représentent la progression vers la mer de zones infratidales dominées par les tempêtes, des lobes deltaïques dominés par les forces fluviatiles, et des lobes deltaïques à influence multiple, respectivement. Les successions de faciès 4, 5 et 6 montrent une granulométrie qui diminue vers le haut et comprennent les sédiments d'effluents dominés par les forces fluviatiles, d'estuaires, et de chenaux d'entrée de crêtes d'avant-plage émergées. La succession de faciès 7 est irrégulière et comprend les sédiments de la plaine deltaïque, incluant les baies et les lagunes situées entre les effluents.

Les successions de faciès 2, 4, et 7 définissent les ensembles de milieux sédimentaires deltaïques dominés par les forces fluviatiles, qui montrent des formes de lobes nourries par des grès en lacet déposés dans des chenaux. Les deltas dominés par la vague ont aussi des formes de lobe mais sont caractérisés par un lien des successions 1, 5, et 7, qui accusent une plus forte influence marine. Les deltas influencés par la vague sont caractérisés par un lien des successions 3, 4, et 7 et sont de forme et de faciès intermédiaires entre les extrêmes dominés par la vague et par les forces fluviatiles. Les crêtes d'avant-plage émergées dominées par la vague sont allongées et orientées parallèles à la ligne du rivage et sont caractérisées par un lien des successions 1, 6, et 7.

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La formation Dunvegan ne peut pas être décrite comme formant un seul delta. Elle est plutôt interprétée ici comme une série de différents ensembles de milieux sédimentaires empilés les uns sur les autres. Ceux-ci progressent vers la mer en direction sud-est, avec les lignes de rivage ayant une orientation approximative de nord-est/sud-ouest. En géné ral, il semble y avoir une diminution de l'importance des processus fluviatiles vers le haut.

Traduit par Marc Charest.

Introduction

This paper presents the first systematic documentation and illustration of facies and facies successions in sedimentary rocks of the Dunvegan Formation in the Alberta subsurface. These facies successions are in turn interpreted as components of rather different depositional systems ranging from river-dominated deltas to wave-dominated shorelines.

Depositional systems were defined by Fisher and McGowen (1967) as three-dimensional lithofacies assemblages that are genetically linked by similar processes and environments of deposition. In this study, separate depositional systems are recognized and mapped on the scale of individual allostratigraphic units here termed "shingles" and defined below (Bhattacharya, 1989a, Bhattacharya and Walker, *this volume*). These shingles are of a smaller scale than those recognized in studies by Fisher and McGowen (1967).

Dunvegan Formation Stratigraphy and Previous Work

Sediments of the Upper Cretaceous (Middle Cenomanian) Dunvegan Formation comprise a complex series of interbedded marine to nonmarine sandstones and shales deposited in an actively subsiding foreland basin. These interfinger with the shales of the overlying Kaskapau Formation and underlying Shaftesbury Formation. We have defined seven allomembers, A through G, within the Dunvegan Formation, each of which is bounded by major marine flooding surfaces (Fig.1). Each allomember consists of several sandy shingles, most of which are grouped onto offlapping sets (Fig.1). Shingles are defined as regionally discontinuous, lens-shaped, heterolithic sedimentary units arranged in an en echelon or offlapping pattern within a given allomember as shown in Figure 1, and are bounded by marine flooding surfaces (MFS) and/or regressive surfaces of erosion (RSE). The details of this allostratigraphic scheme are given in Bhattacharya and Walker (*this volume*).

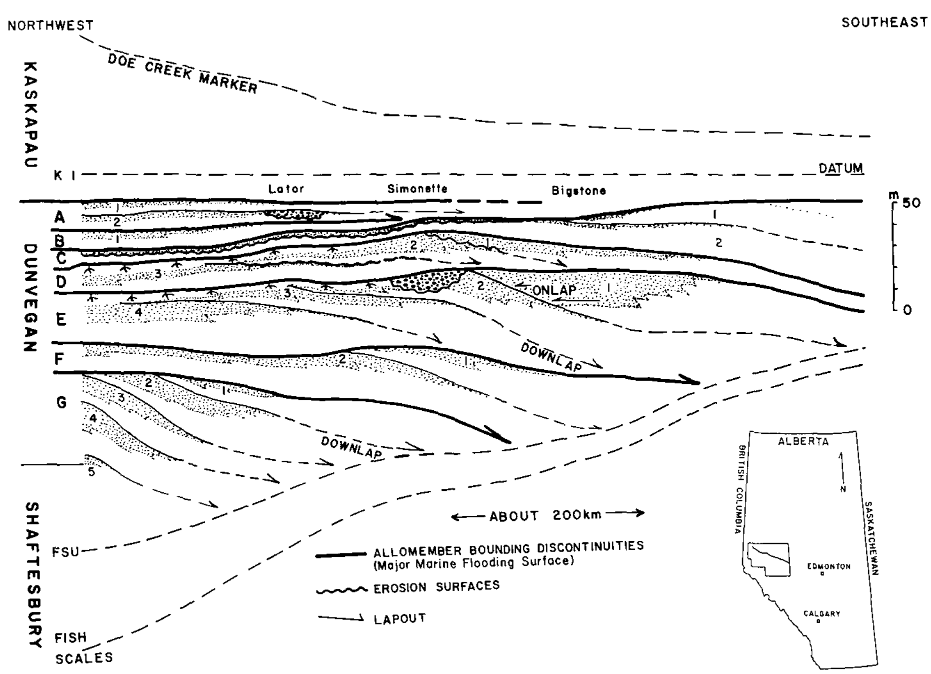


Fig. 1. Schematic allostratigraphy of the Dunvegan Formation. The cross-section emphasizes the downlapping nature of Dunvegan sediments onto the FSU marker. This supports the interpretation of the FSU marker as a condensed section. Letters indicate allomembers whereas the numbers indicate the offlapping shingles within the allomembers. Light stipple indicates largely marine sandstone, heavy stipple indicates channelized units, root symbols indicate generally nonmarine facies. Inset location map shows study area and location of cross-section. (based on Bhattacharya and Walker, Fig. 4, *this volume*).

Previous workers (McLearn, 1919; Stelck *et al.*, 1958; Tater, 1964; Stott, 1982) have interpreted the Dunvegan Formation as "deltaic", and have often referred to it as "The Dunvegan Delta". Their interpretations were based on the general recognition of a marine to fluvial transition in outcrop sections and on the fact that the Dunvegan Formation is largely confined to northwestern Alberta and therefore defines a relatively large lobate body of sediment. Use of the term "Dunvegan Delta" by previous workers implies that the Dunvegan clastic wedge was fed by a single major river, although most of their interpretations predated the application of modern deltaic facies models (*e.g.*, Coleman and Wright, 1975; Miall, 1984; Elliott, 1986, and Alexander, 1989).

The only previous subsurface study of the Dunvegan is that of Burk (1963). He presented a cumulative isolith map for all sandstones within the formation, showing a general southeastward thinning. The broad scope of his study did not permit stratigraphic subdivision of the formation, and no core descriptions or detailed sedimentological aspects of the formation were presented.

Purpose of This Study, Methods and Database

This study was conducted in order to determine the nature of Dunvegan depositional systems in the subsurface and to answer the following questions. Does the Dunvegan Formation represent a single large deltaic complex or is there more than one shoreline system present? If the Dunvegan is deltaic, what is the nature of this delta and how does it compare with existing deltaic facies models (Elliott, 1986; Miall, 1984; Coleman and Wright, 1975)?

This study involved the correlation of about 500 well logs, and incorporated facies description and interpretation of about 130 cores over an area of about 30,000 km^2 (T51 to 67, R15W5 to R10W6, Fig. 1). The gross sandstone isolith maps presented below are based on the cumulative gross sandstone thicknessess between the bounding discontinuities used to define the shingles. They give an indication of sand body geometry, which was then compared with existing facies models (Miall, 1984; Elliott, 1986; Weise, 1979; Coleman and Wright, 1975).

Our results are presented in hierarchical order beginning with the smallest units of observation (facies) and building up to the recognition of the large-scale depositional systems at the scale of shingles and allomembers. The broader tectonic and stratigraphic implications of this work are discussed in the companion paper (Bhattacharya and Walker, *this volume*).

Facies Descriptions

During core measurement, facies were differentiated on the basis of lithology (particularly the nature of interbedding of shale and coarser material), grain size, primary sedimentary structures, type and degree of burrowing, and special constituents (such as fossils, nodules, plant remains and diagenetic material such as siderite). This led to the description and illustration of 21 facies (Bhattacharya, 1989a). In this paper, we present a revised scheme of 19 distinct facies grouped into six main categories.

Category 1: Unstratified Shaly Mudstone

Facies 1 - Unstratified shaly mudstone

This facies consists of massive, black shaly mudstone that is commonly pervasively bioturbated (Fig. 2A), although there is normally insufficient silt to make distinct burrow forms or spreite visible. Marine fauna include foraminifers, dinoflagellates, pelecypods (including *Inoceramus*) and fish scales. Facies 1 typically lies immediately above allomember-bounding major marine flooding surfaces.

We interpret Facies 1 as having formed in a quiet setting, deep enough to be consistently below wave base.

Category 2: Stratified Mudstone, Siltstone and Sandstone

Four varieties of interbedded mudstone, siltstone and sandstone can be distinguished on the basis of lithology, sedimentary structures and style of interbedding. The percentage of sandstone may vary from 30 to 60 per cent. None of the facies is extensively bioturbated.

Facies 2A - Stratified silty mudstone

This facies consists of gray mudstone, with abundant cm-scale, sharp-based graded siltstone or very fine grained sandstone beds (Fig. 2B). It may be up to 7 m thick and may contain *Helminthopsis* (Fig. 2C) and *Inoceramus*. The sandier beds within Facies 2A may be laminated (Fig. 2D). Facies 2A may be cut by gutter casts filled with hummocky cross-stratified sandstone (Fig. 6B), and scattered synaeresis cracks.

We interpret the silty mudstones as having been deposited below fairweather wave base. The synaeresis cracks (and perhaps the lack of bioturbation) suggest fairly rapid deposition (Plummer and Gostin, 1983), and the graded beds indicate sediment emplacement by sudden, waning density underflows.

Facies 2B - Rippled silty mudstones

This facies consists of brownish gray, sideritic silty mudstone containing abundant mm-scale, very fine grained, biscuit-shaped, wave-rippled, silty to sandy beds (Fig. 3A, B, C). Facies 2B ranges from a few tens of cm up to 3 m in thickness and may exhibit soft sediment deformation (Fig. 3B). Rare trace fossils include *Skolithos*, ?*Trichichnus* (Fig. 3C), and pyritized to carbonaceous *in situ* root casts up to 5 mm in diameter. Macrofossils include *Corbula sp.* and *Unio dowlingi* (a nonmarine pelecypod; McLearn, 1945). The facies may also contain carbonaceous debris with some perfectly preserved fern leaves on bedding planes.

The presence of root traces, nonmarine bivalves, and abundant starved wave ripples is interpreted as indicating deposition in a brackish to nonmarine, shallow water setting. Siderite is common in modern salt water marsh environments (Pye, 1981; Postma, 1981) and similar sideritic sediments have been documented in cores from Atchafalaya Bay in the modern Mississippi delta plain (Ho and Coleman, 1969).

Facies 2C. Rippled sandy mudstones

This facies contains irregularly interbedded (mm-to cm-scale), black, carbonaceous mudstone and fine to medium grained sandstones (Fig. 3D). In contrast to 2A and 2B, Facies 2C contains very little siltstone, imparting a more black and white appearance. It ranges from a few tens of cm to a few metres in thickness. Sandstone interbeds have very sharp bases and tops without indications of grading, and starved wave and current ripples are common. Synaeresis cracks (Fig. 3D) are ubiquitous, and nodular to bedded siderite is common. Rare burrows include *Planolites, Chondrites* and *Teichichnus.*

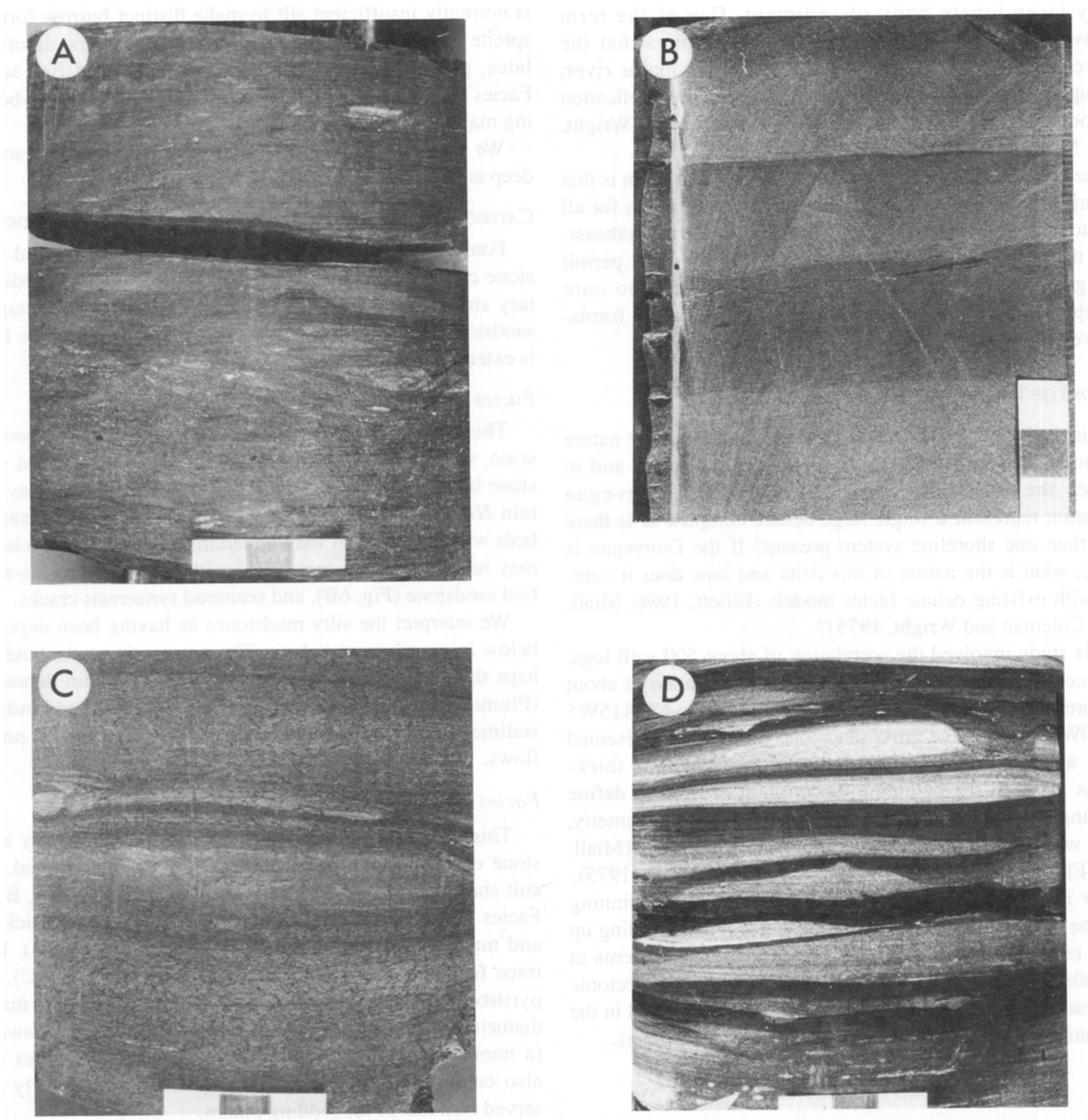


Fig. 2. **A**. Facies 1, unstratified shaly mudstone. The siltier bioturbated material in the lower 4 cm marks the transgressive facies preserved at the base of allomember C. (From well 6-22-62-3W6, 2527 m). Scale is 3 cm. **B to D.** Facies 2A, stratified silty mudstone **B.** cm-scale graded beds (from well 10-20-65-23W5, 1359 m, allomember C). **C.** stratification is disrupted by abundant *Helminthopsis* burrows in an example of Facies 2A (from well 16-1-61-22W5, 1897 m, allomember E). **D.** sandier example of Facies 2A showing biscuit-shaped, very fine grained sandy interbeds truncated by small-scale scours and rare burrows (from well 6-11-62-3W6, 2538 m, allomember D).

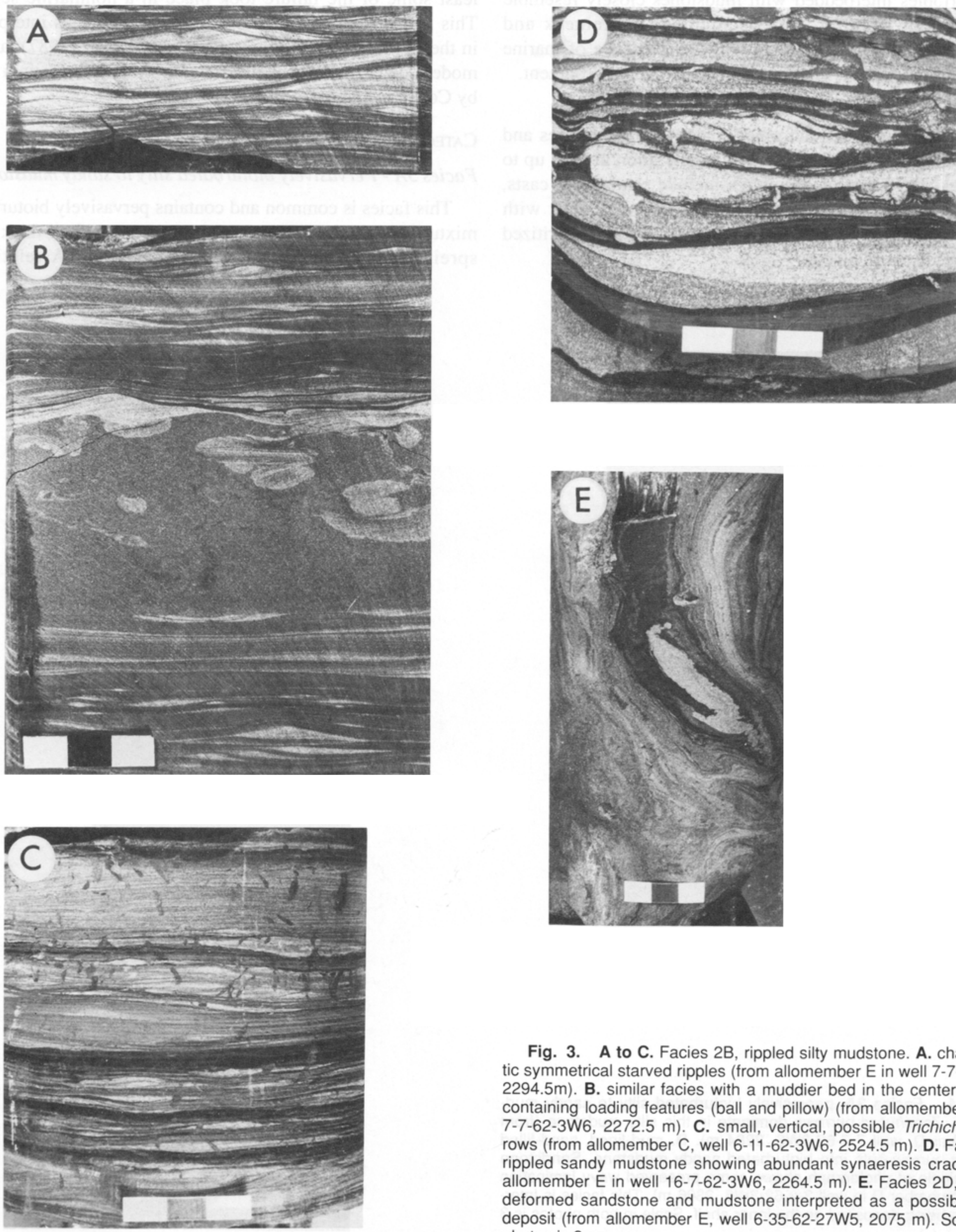


Fig. 3. **A to C.** Facies 2B, rippled silty mudstone. **A.** characteristic symmetrical starved ripples (from allomember E in well 7-7-62-3W6, 2294.5m). **B.** similar facies with a muddier bed in the center of photo containing loading features (ball and pillow) (from allomember C, well 7-7-62-3W6, 2272.5 m). **C.** small, vertical, possible *Trichichnus* burrows (from allomember C, well 6-11-62-3W6, 2524.5 m). **D.** Facies 2C, rippled sandy mudstone showing abundant synaeresis cracks (from allomember E in well 16-7-62-3W6, 2264.5 m). **E.** Facies 2D, massive deformed sandstone and mudstone interpreted as a possible slump deposit (from allomember E, well 6-35-62-27W5, 2075 m). Scale in all photos is 3 cm.

The sharply bounded sandstone beds were probably deposited suddenly and episodically in an environment normally receiving carbonaceous mudstone. The abundant synaeresis cracks probably result from salinity changes and may indicate periodic fresh water influx (Burst,1965). The starved ripples interbedded with mudstones closely resemble the lenticular bedding (linsenschichten) of Reineck and Wunderlich (1968). This, along with the presence of marine trace fauna, suggests a shallow marine subtidal environment.

Facies 2D - Massive deformed sandstone and mudstone

Facies 2D comprises deformed intermixed sandstones and silty mudstones with rare preserved stratification in beds up to 3 m thick. Deformation structures include sandy load casts, ball and pillow structures, and highly deformed beds with sharp, irregular upper and lower contacts (Fig. 3E). Pyritized root traces occur in places.

We interpret the loading to be a result of rapid deposition of sand onto a water-rich, soupy substrate. Where there is abundant disseminated organic material, trapped methane formed during decay may have helped to raise the pore fluid pressure, triggering failure. The *in situ* roots suggest that at least some of the failure took place in a nonmarine setting. This facies is similar to ancient nonmarine facies interpreted in the Cardium Formation by Plint and Walker (1987), and to modern delta front facies illustrated from the Mississippi delta by Coleman and Prior (1982).

Category 3: Bioturbated Silty to Sandy Mudstone

Facies 3A - Pervasively bioturbated silty to sandy mudstone

This facies is common and contains pervasively bioturbated mixtures of sand, silt and mud in units up to 3 m thick with spreite usually clearly visible (Fig. 4A, B). A relatively

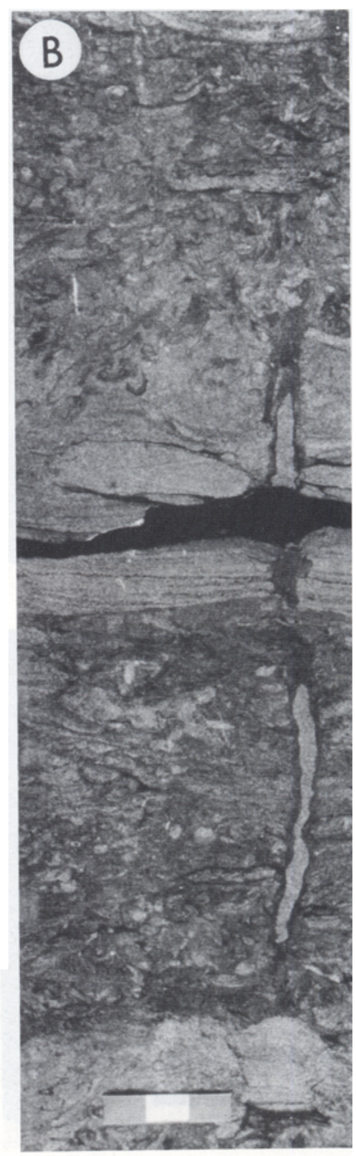


Fig. 4. Facies 3A, pervasively bioturbated silty to sandy mudstone. **A.** *Zoophycos* burrows dominate in this silty mudstone (from allomember D, well 7-7-62-3W6, 2284 m). **B.** mud-lined, sand-filled *Skolithos* burrow cuts into bioturbated sandy mudstone. Sandstone bed in middle of photograph shows some preserved wavy lamination (from allomember D in well 3-9-62-3W6, 2366 m). This facies is interpreted as being deposited on the inner shelf. Scale in both photos is 3 cm.

diverse marine trace fauna includes *Zoophycos, Rhizocorallium, Planolites* and *Terebellina* (belonging to the *Zoophycos* ichnofacies; Frey and Pemberton, 1984). In sandier occurrences, mud-lined *Skolithos*, *Paleophycos*, *Asterosoma*, and *Ophiomorpha* with burrow diameters less than 1 cm are common (Fig. 4B) and are more indicative of the *Skolithos* ichnofacies (Frey and Pemberton, 1984). Facies 3A may be gradational with Facies 4H (Fig. 9A).

We interpret these bioturbated sediments as having formed in a shallow, open marine environment. The replacement of the *Zoophycos* ichnofacies by the shallower water *Skolithos* ichnofacies may suggest shallowing. Overall, sedimentation rates were probably relatively low.

Facies 3B - Burrowed, poorly stratified mudstone and sandstone

This facies is gradational with Facies 2C, but is much more burrowed (Fig. 5A,B). It ranges from a few cm up to a few metres in thickness. Up to about 50 per cent of the rock may be disturbed by traces that include *Planolites, Teichichnus, Rhizocorallium* and *Terebellina*. Synaeresis cracks occur in places.

The trace fauna are interpreted as belonging to the *Cruziana* ichnofacies, which was described as sublittoral by Frey and Pemberton (1984). Beynon *et al.* (1988) have described similar ichnofacies as typical of brackish water environments. Although gradational, it appears to have a more marine character than Facies 2C but is probably more restricted than Facies 3A.

Category 4: Sandstones

Facies 4A - Hummocky to Swaley Cross -stratified Sandstones

This facies consists of very fine grained laminated sandstone beds in units a few tens of cm to a few metres in thickness. Individual beds are invariably sharp based, and the inter-

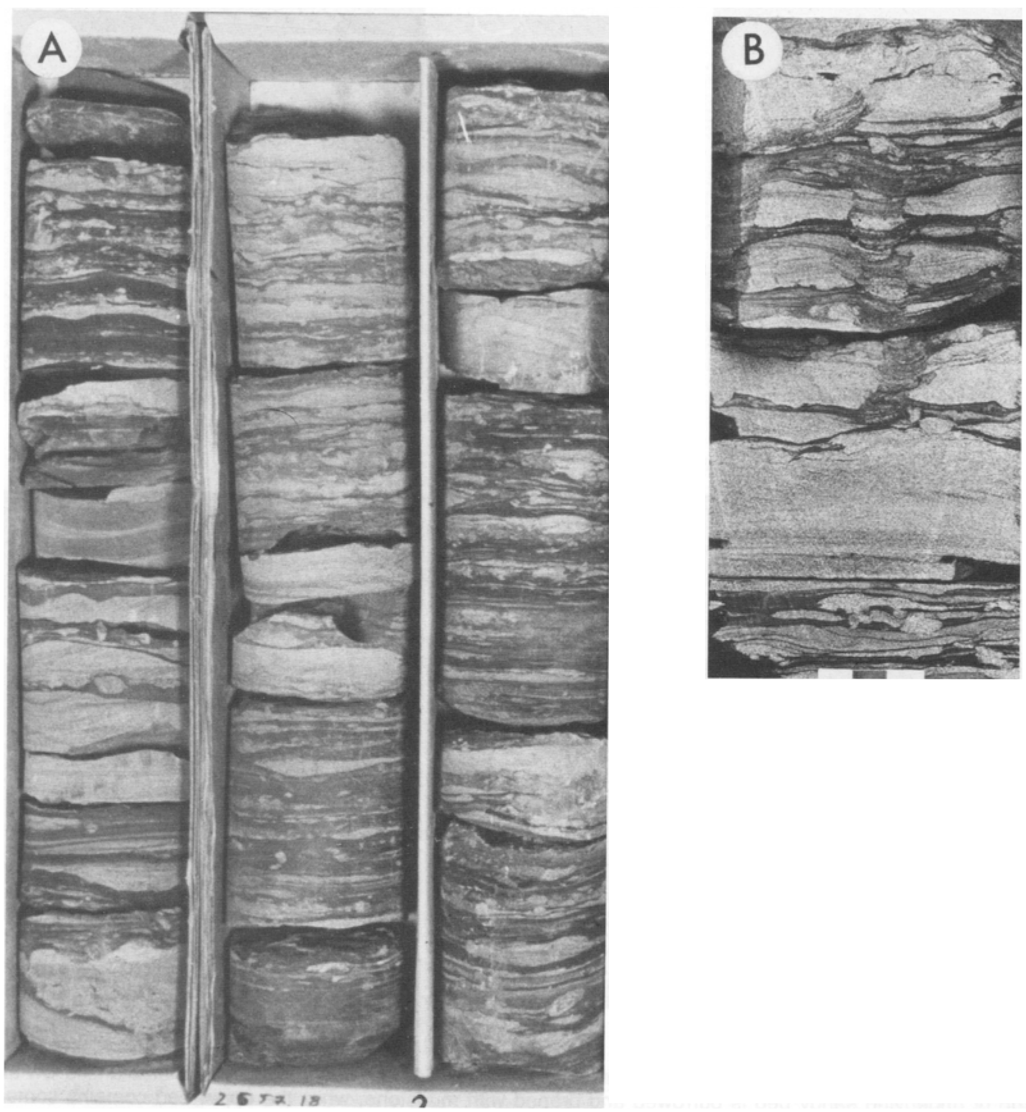


Fig. 5. Facies 3B, burrowed, poorly stratified mudstone and sandstone. **A.** transition from Facies 2C (rippled sandy mudstone) into the more highly burrowed sediments of Facies 3B above. Top is at upper right (4" diameter core from allomember E in well 6-11-62-3W6, 2656-2658 m). **B.** well developed *Teichichnus* burrow in the middle of the photo. A current rippled sand bed lies below and probable synaeresis cracks are above the scale (3 cm). Photo is from allomember E, well 8-35-62-3W6, 2145 m.

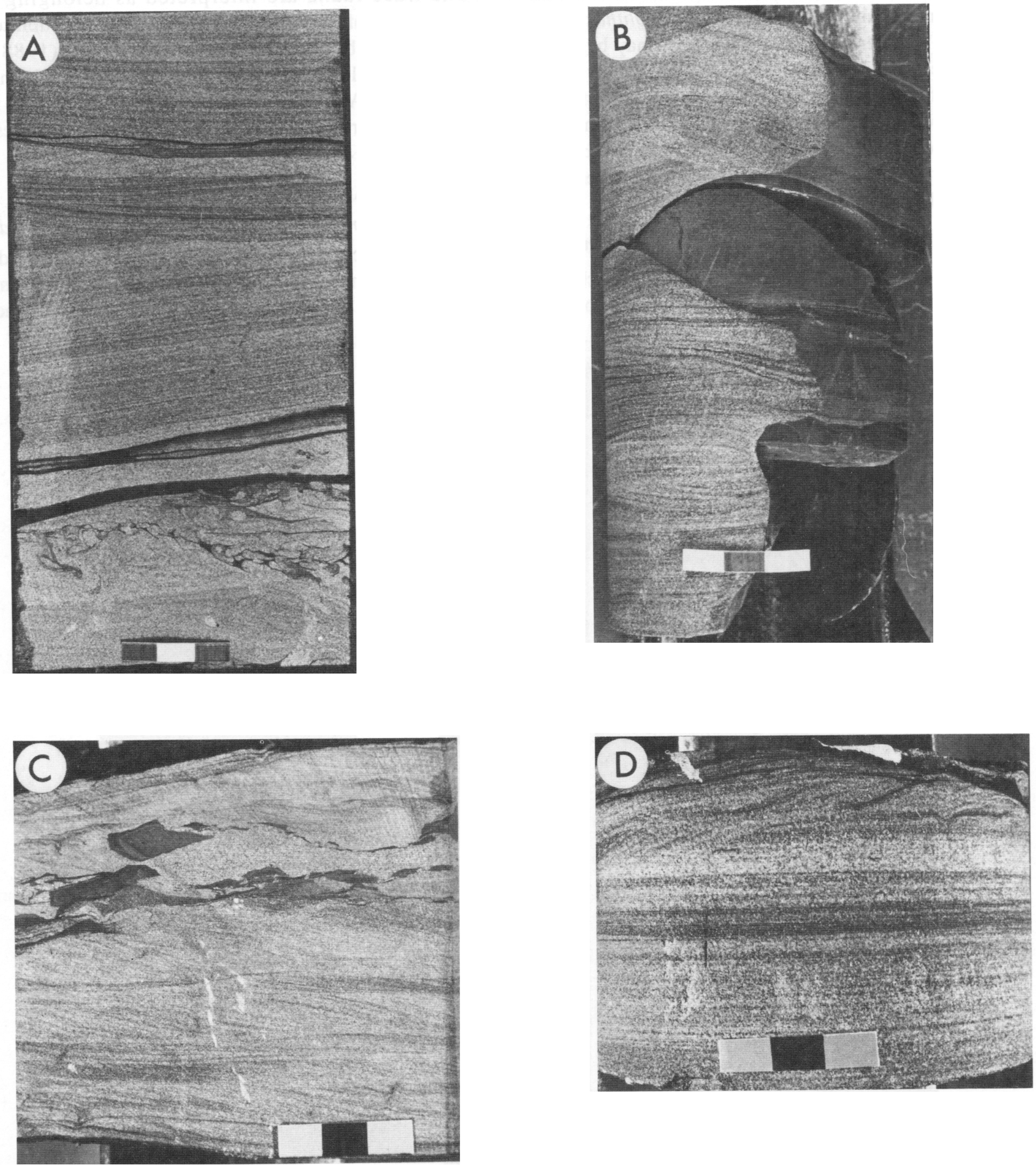


Fig. 6. **A, B.** Facies 4A, Hummocky to swaley cross-stratified sandstone. **A.** sharp-based beds with characteristic low-angle curved to intersecting laminae. Top of underlying sandy bed is burrowed and draped with mudstone, while the upper bed contains some wave ripples (from allomember D, well 8-35-62-3W6, 2140 m). **B.** shows sandy gutter cast cutting into Facies 2A. The overhanging portion in the middle is a sideritized layer. The sand is dominantly wave rippled (from Allmember D in well 14-6-63-26W5, 1947 m). **C, D.** Facies 4B, Current rippled sandstone, **C.** ripple cross-laminated sandstone containing sideritized mud chips (from allomember D, well 7-7-62-3W6, 2295 m). **D.** a unit that passes from flat-laminated sandstone into current rippled sandstone indicating a waning flow (from well 4-11-65-2W6, allomember E, 1764 m). Scale in all photos is 3 cm.

nal laminae typically intersect and truncate at low angles, and may be very gently curved (Fig. 6A). These structures, observed in core, likely represent hummocky cross-stratification (HCS; Harms *et al.*, 1975). The tops of the beds are wave rippled and/or bioturbated, and may be capped by thin silty drapes (Fig. 6A). Individual beds may amalgamate upsection, such that their sharp-based, episodically emplaced aspect is lost; thus HCS grades into swaley cross-stratification (SCS; Leckie and Walker, 1982). Facies 4A may also occur as isolated sand-filled gutter casts, up to 50 cm thick (Fig. 6B).

We interpret the sharp-based HCS sandstones as having been emplaced in a shallow marine environment, where storm waves formed the HCS but depths were too great for subsequent modification by fair weather currents. The SCS appears to be typical of the lower shoreface (McCrory and Walker, 1986; Rosenthal and Walker, 1987).

Facies 4B - Parallel-laminated to current rippled sandstone

This facies comprises very fine to fine grained sandstones with current ripple crosslamination, and may contain siderite and mud rip-up clasts (Fig. 6C,D). Cosets are up to a few cm in thickness and commonly climb. Individual beds may begin with several cm or more of plane parallel lamination that grades up into ripple crosslamination (Fig. 6D). This is descriptively similar to the BC portion of a Bouma turbidite sequence (Bouma, 1962).

The parallel laminated to rippled beds may be interpreted as having been deposited from episodic waning flows. Where the ripples are climbing, there is a high rate of deposition from suspension, giving local hydrodynamic conditions similar to those of a waning turbidity current.

Facies 4C - Crossbedded sandstone

This facies comprises fine to medium grained sandstone characterized by planar tabular and trough crossbedding in sets 10 to 50 cm thick (Fig. 7A). Individual foresets are commonly not well defined in core. The bases of sets may contain clasts of mudstone (commonly sideritized), shell fragments and coalified woody material.

The crossbedding most likely resulted from the migration of two- or three-dimensional dune forms. Dunes can occur in many environments, and further interpretation depends on the context of the facies.

Facies 4D - Crossbedded to rippled sandstone with mud couplets

This facies comprises dominantly trough crossbedded, fine to medium grained sandstone, characterized by numerous mm-scale carbonaceous or muddy parting (Fig. 8A,B). Sets average a few tens of cm thick and occurrences of the facies are up to 3 m thick. The muddy partings, which vary in thickness and number upward, may be distinctly arranged into pairs (couplets, Fig. 8A), may encase thinner biscuit-shaped sandy layers (Fig. 8B), and may disappear upward. Also, the dip of the crosslaminae may decrease upward rather than steepening (Fig. 8A). Through a thickness of a few metres, there can be alternations of muddier, laminated and rippled, to more massive sandstone.

We interpret the well-defined couplets as suggesting a tidal influence (Visser, 1980; Allen and Homewood, 1984), and the upward flattening of laminae suggests sigmoidal crossbedding (Kreisa and Moiola, 1986), also reflecting a tidal origin.

Facies 4E - Flat laminated sandstone

This facies comprises fine to medium grained calcite-cemented sandstone in units up to 2 m thick. The dominant sedimentary structure is flat lamination (Fig. 7B), which is commonly penetrated by *in situ* root casts. The laminae may also be defined by macerated carbonaceous debris. This facies commonly lies above marine SCS sandstones of Facies 4A.

This combination of features is typical of swash and backwash on a beach.

Facies 4F - Structureless sandstone

This facies comprises very fine to medium grained, massively bedded sandstone displaying no sedimentary structures, and hence appearing structureless in core (Fig. 7C). In one core (well 11-19-59-3W6), this facies reaches a thickness of about 10 m (Bhattacharya, 1989a). In places, a crude bedding may be suggested by layered mudstone rip-up clasts, siderite clasts, or by shale partings. Elsewhere, rare wispy-looking zones of cleaner sand, on the order of 1 mm or less in thickness, may possibly represent a *Macaronichnus*-like burrow (Krause and Mattison, pers.comm.), although the forms are very indistinct. In coarsening-upward facies successions, Facies 4F is commonly associated with deformed sandstone (Facies 4G, Fig. 7D).

Interpretation of these sandstones, associated with sediments that are interpreted as broadly deltaic, is problematic. The structureless sandstones may have been deposited very rapidly, without the formation of equilibrium bedforms and hence stratification. Rapid deposition and powerful currents are suggested by the mudstone and siderite clasts, especially if the facies is at the base of a fining-upward succession. Alternatively, sandstones can lose primary structures by bioturbation from animals or plants. Massive, structureless sandstones of the Basal Belly River Formation have been similarly interpreted as the result of bioturbation by a *Macaronichnus*-like organism (Power, 1989).

Sandstones may also lose their structure as a result of liquefaction or dewatering. Where associated with deformed sandstones, this may be the case, although other classic dewatering features (*e.g.*, pipes and dish structures) were not observed.

Facies 4G - Deformed sandstone

This facies comprises very fine grained sandstone characterized by soft sediment deformation structures, commonly in the form of high angle, oversteepened to vertical stratification (Fig. 7D). Occurrences of the facies reach 1 m in thickness. This facies may also occur interbedded with Facies 2D. Neither body nor trace fossils were observed.

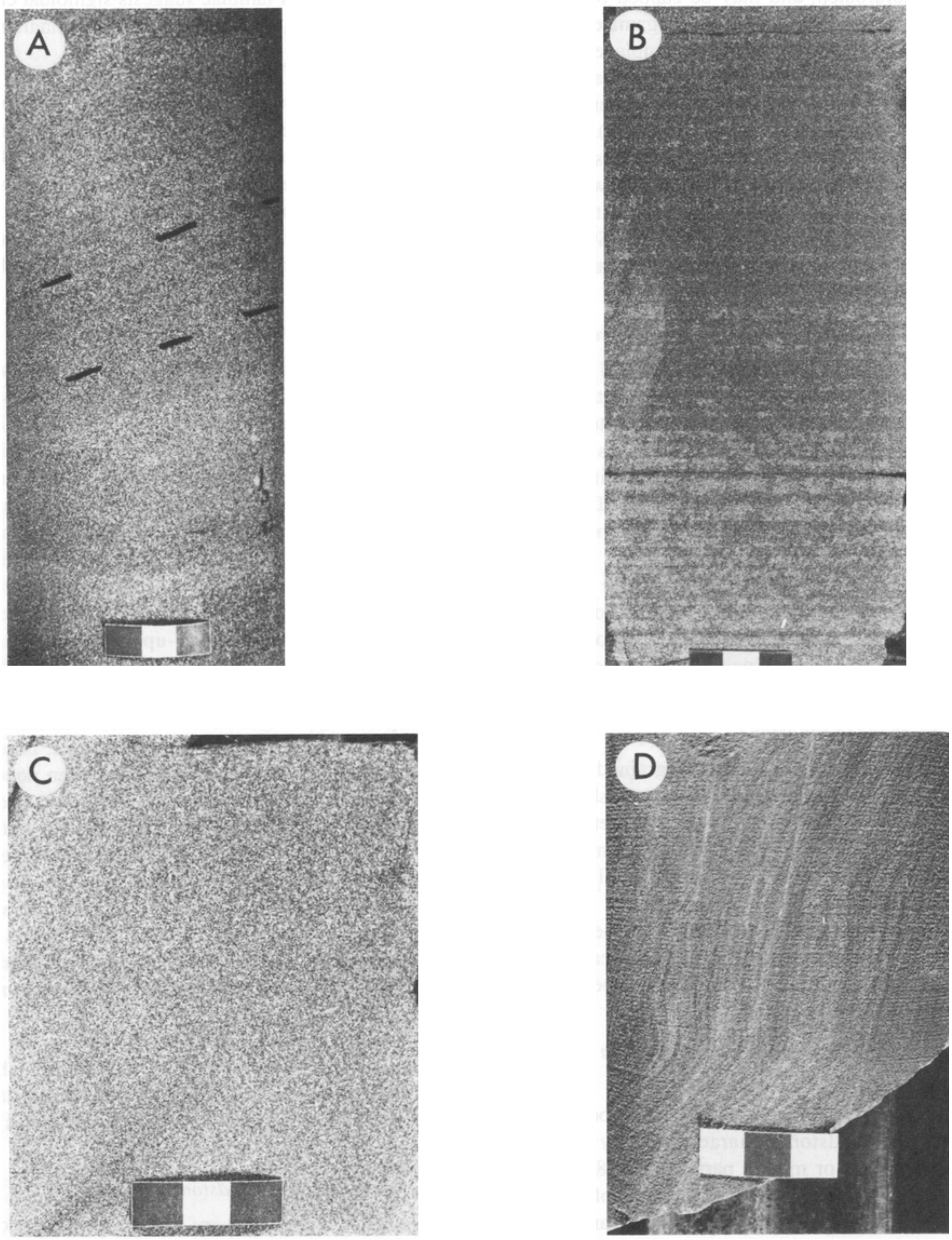


Fig. 7. **A.** Facies 4C, crossbedded sandstone. Rather massive sandstone passes up into indistinctly crossbedded sandstone, highlighted with black marker (from allomember D, well 11-19-59-3W6, 3031 m).

B. Facies 4E, flat laminated sandstone, defined by differences in calcite cement and interpreted as typical of beach stratification (from allomember D, well 8-35-62-3W6, 2127 m). **C.** Facies 4F, structureless sandstone (from well 11-19-59-3W6, 3038 m, allomember D). **D.** Facies 4G, deformed sandstone showing nearly vertical dip to the original laminae (from allomember E, well 7-11-60-22W5, 2065 m). Scale is 3 cm.

We interpret the oversteepened stratification as the result of very high rates of deposition, with fluid trapping between sand grains leading to a weak or almost cohesionless deposit.

Facies 4H - Pervasively bioturbated muddy sandstone

This facies comprises muddy, very fine to medium grained sandstone in beds a few tens of cm to about 2 m thick. Any primary stratification has been disrupted, mainly by large (1 to 2 cm diameter) *Ophiomorpha* burrows (Fig. 9A,B). These burrows lose their lining and take on the form of *Thalassinoides* when they penetrate into underlying mudstones.

The trace fauna in the sandstones are interpreted as typical of the *Skolithos* ichnofacies (Frey and Pemberton, 1984). This ichnofacies is believed to indicate relatively high energy, shallow marine environments with shifting substrates. The contact with the underlying mudstones may represent the *Glossifungites* ichnofacies (Frey and Pemberton, 1984; MacEachern *et al.*, 1990).

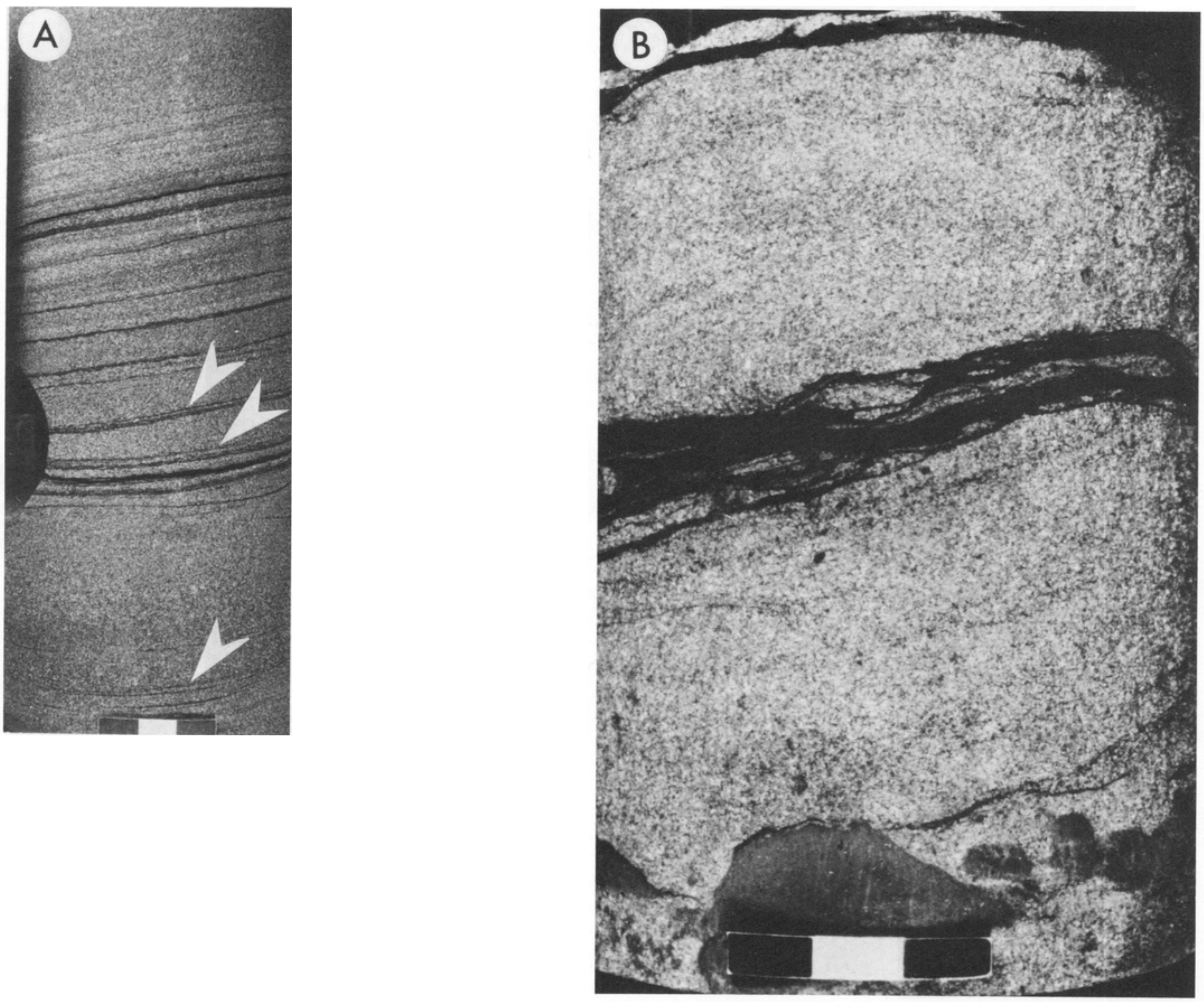


Fig. 8. Facies 4D, crossbedded to rippled sandstone with mud couplets, **A.** well-defined twinned carbonaceous layers (arrows) define crossbedding in this sandstone. These are interpreted as tidal in origin (from allomember E, well 4-26-62-26W5, 1887 m). **B.** Crossbedded sandstone contains siderite clasts at the base and a thin, shaly parting that contains biscuit-shaped sandy interlayers (from allomember C, well 16-23-65-21W5, 1260 m). Scale is 3cm.

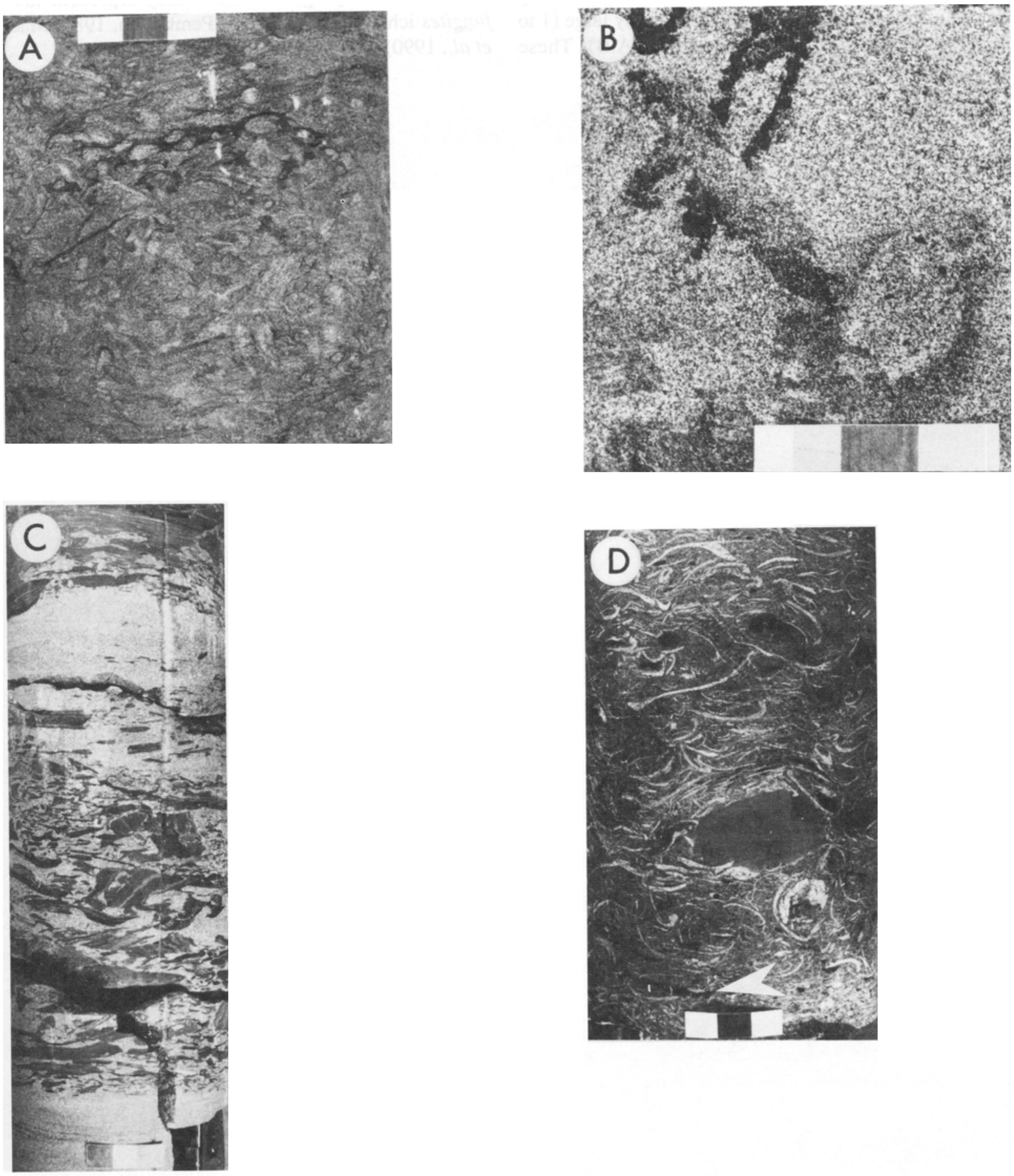


Fig. 9. **A, B.** Facies 4H, pervasively bioturbated sandstone. **A.** dominated by small diameter *Ophiomorpha* (from allomember D, well 6-11-62-3W6, 2536 m). **B.** Larger diameter *Ophiomorpha nodosa* burrows (from allomember C, well 6-11-62-3W6, 2522.5 m). **C, D.** Facies 5, lag. **C.** primarily ripped-up angular mudstone clasts typical of channelized units (from allomember D, well 11-19-59-3W6, 3028 m). **D.** Another typical channel lag containing shell debris, coalified woody material (arrow) and large siderite clasts (from allomember E, well 11-5-63-26W5, 1949 m).

CATEGORY 5: LAG

Facies 5 - Lag

This facies comprises siderite-clast and shell-rich lags; two types were identified. The first is characterized by angular to rounded ripped up mudstone clasts and large coalified wood fragments, with or without shelly material, and can be up to 30 cm thick (Fig. 9 C, D). The second type is thinner (up to 10 cm); the mudstone clasts are commonly sideritized, smaller, and more rounded, and coaly material is uncommon (Fig. 10A).

We interpret the first type of lag as having formed at the base of a channel; this is its typical stratigraphic context. The second type is associated with abrupt transitions from coarser clastic facies into marine mudstones, and suggests an origin as a transgressive lag.

CATEGORY 6: COAL, COALY MUDSTONE AND PALEOSOLS

Facies 6A - Coal and coaly mudstone

This facies comprises coal, or black, crumbly, highly carbonaceous mudstone, normally in beds thinner than 1 m.

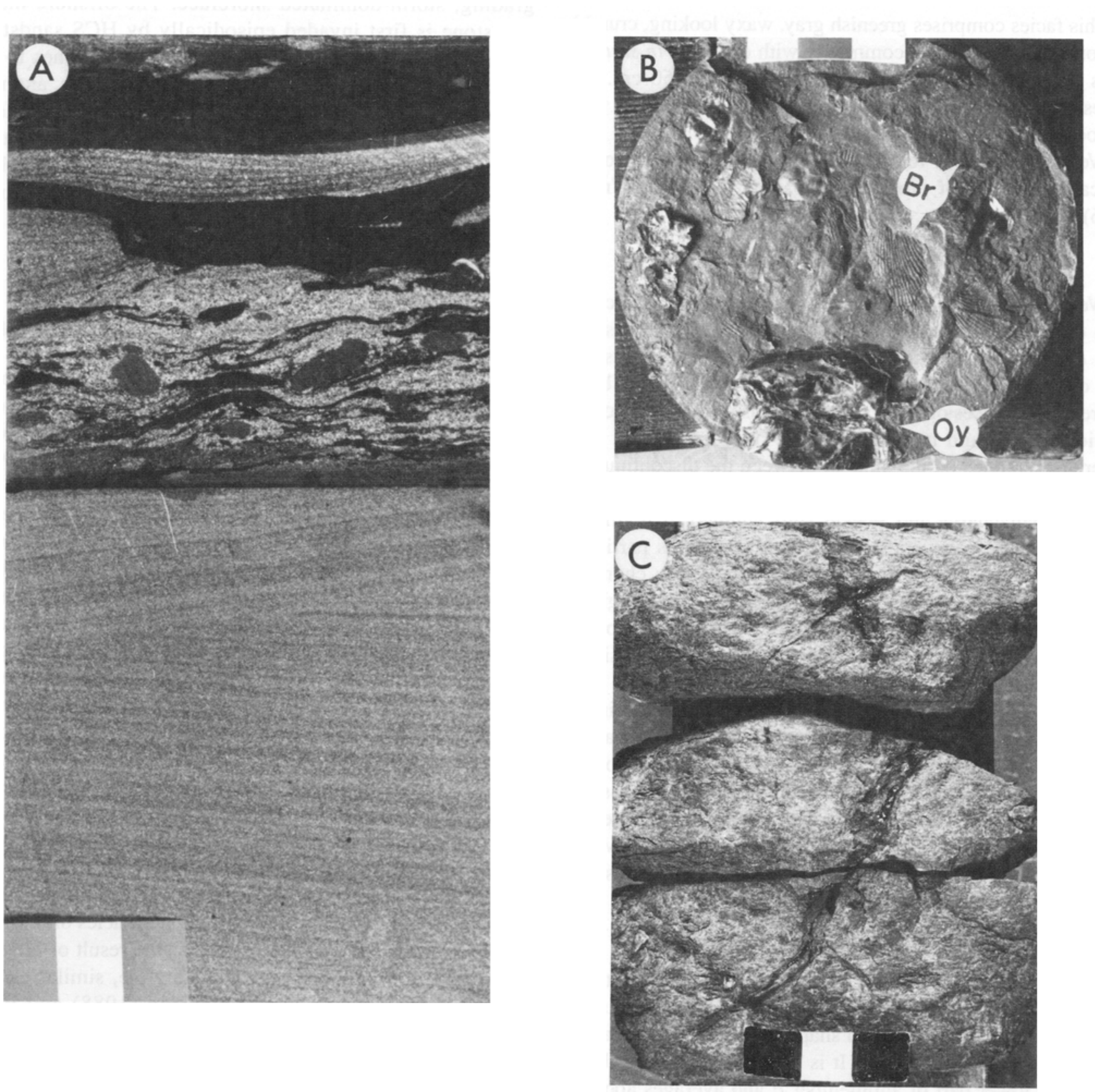


Fig. 10. **A.** Facies 5, thinner (transgressive) lag containing smaller rounded siderite clasts in medium grained sand (from allomember D, well 7-10-63-1W6, 1978 m). **B.** Facies 6A, carbonaceous mudstone containing a brackish water fauna including oysters (Oy) and *Brachydontes* (Br) (from allomember E, well 10-13-63-2W6, 2093 m). **C.** Facies 6B, waxy grey paleosol containing *in situ* root traces (from allomember E in well 6-26-67-10W6, 1781 m).

Associated body fossils include *Corbula, Brachydontes* and *Unio*, together with gastropods (*Melania*) and oyster beds (Fig. 10B).

These faunal assemblages are interpreted as brackish to nonmarine, like those described elsewhere in the Western Interior Seaway (Kauffman, 1969; Plint and Walker, 1987). The coals and coaly mudstones indicate dominantly nonmarine to paralic environments, and the assemblage of features therefore suggests a distal coastal plain with swamps, standing bodies of water, and abundant vegetation.

Facies 6B - Paleosols

This facies comprises greenish gray, waxy looking, crumbly carbonaceous mudstone, commonly with coalified *in situ* root casts (Fig. 10C). Maximum thickness is about 50 cm. The facies is confined to the northwestern part of the study area, and occurs only rarely in the subsurface.

We interpret these features as characteristic of paleosols, indicating periods of prolonged subaerial exposure (Wright, 1986).

Facies Successions

We use the term *facies succession* for a stratigraphic column of facies with gradational contacts between facies, but with discontinuities at the bases and tops of the successions. The discontinuities include sharp, erosional channel bases (regressive surfaces of erosion-RSE), transgressive surfaces of erosion (TSE), and marine flooding surfaces (MFS). This paper concentrates on the units in between the discontinuities. The nature and the significance of the discontinuities are dealt with in Bhattacharya and Walker (*this volume*). It is implied that the facies are genetically related inasmuch as particular sedimentological characteristics are progressively changing throughout the succession; for example, grain size might be gradually increasing, and there might be a change upward from dominantly biologically formed structures to physically formed ones.

Seven distinct successions have been recognized in the Dunvegan, and they follow three basic patterns: 1) coarsening-upward (or sandier-upward) successions; 2) erosionally based fining-upward successions; and 3) irregular successions, which commonly contain nonmarine indicators. The interpretive titles of the successions are discussed in the individual descriptions below. These interpretations are further substantiated by the isopach maps and sand body geometries.

Facies Succession 1 - Storm Dominated Shoreface

In core, this succession shows a gradual and relatively smooth upward increase in the proportion of sand. This is also indicated by the smooth funnel shape in the associated gamma log response (Fig. 11, upper). It is common in allomember D and in the lower part of allomember E and averages about 10 to 15 m thick.

The succession begins with 1 to 3 m of pervasively bioturbated shaly mudstone (Facies 1) or sandy mudstone (Facies 3A). These become interbedded upward with HCS sandstones (Facies 4A), which in turn amalgamate upward. The episodic aspect of HCS deposition gives way to more continuous sandstones interpreted as swaley cross-stratified (SCS: Facies 4A). The SCS sandstones are overlain by up to 3 m of fine grained, crossbedded sandstone (Facies 4C), which in turn are overlain by up to 2 m of fine grained, flat laminated sandstone (Facies 4E). This upper sandstone may contain *Skolithos* burrows and *in situ* root casts, giving a mottled or structureless appearance. In places, a thin coal or coaly mudstone (Facies 6A) may cap the succession.

Succession 1 may be interpreted as the deposit of a prograding, storm-dominated shoreface. The offshore marine mudstone is first invaded episodically by HCS sandstones deposited during storms. As the shoreface continues to prograde, more and more storm events affect the beds, and more deposits are preserved, culminating in the SCS sandstones of the lower shoreface. The crossbedding is more likely to be preserved in the upper shoreface, and is overlain by flat lamination (produced by swash and backwash) characteristic of the beach. Nonmarine facies, including root traces and coals, indicate final emergence.

Facies Succession 2 - River-Dominated Delta Front

In core, Facies Succession 2 also coarsens upward (Fig.12) but in contrast to Succession 1 it is more irregular and contains a greater proportion of interbedded mudstone throughout. This is also indicated by the more serrated appearance of the associated gamma-ray log trace (Fig.12). It is common in the upper parts of allomember E (Bhattacharya, 1989a, *in press*) and may reach up to 30m in thickness.

In contrast to Facies Succession 1, the basal mudstones are stratified (Facies 2A) and show very little burrowing except for rare zones of *Helminthopsis*. Soft sediment deformation is ubiquitous, and results in massive, deformed silty mudstone beds (Facies 2D). Upward the mudstones contain interbedded, ripple crosslaminated sandstones (Facies 4B). These grade upward into fine to medium grained, crossbedded sandstone (Facies 4C), often containing shaly partings or beds, and mudstone rip-up horizons. Structureless (Facies 4F) to convolute-laminated sandstones (Facies 4G) may also occur throughout the succession. The sandstones, in general, are characterized by a lack of wave-formed sedimentary structures, in direct contrast to Facies Succession 1. The trace fauna is limited to the *Skolithos* ichnofacies (Frey and Pemberton, 1984). The upper part of the succession may contain *in situ* root traces, overlain by a thin coal or coaly mudstone (Facies 6A).

We interpret Facies Succession 2 as the result of progradation of a river-dominated deltaic shoreline, similar to those described by Moslow and Pemberton (1988) and Elliott (1986). The offshore shales are overlain by stratified silty mudstones of the distal prodelta. More proximal conditions are recorded by the increase of sandstone and deformed mudstones. Finally, crossbedded sandstones indicate progradation of the distributary mouth bar. Unlike Succession 1, there is little evidence of strong wave reworking and winnowing and concentration of sand at the shoreline. The abundance of

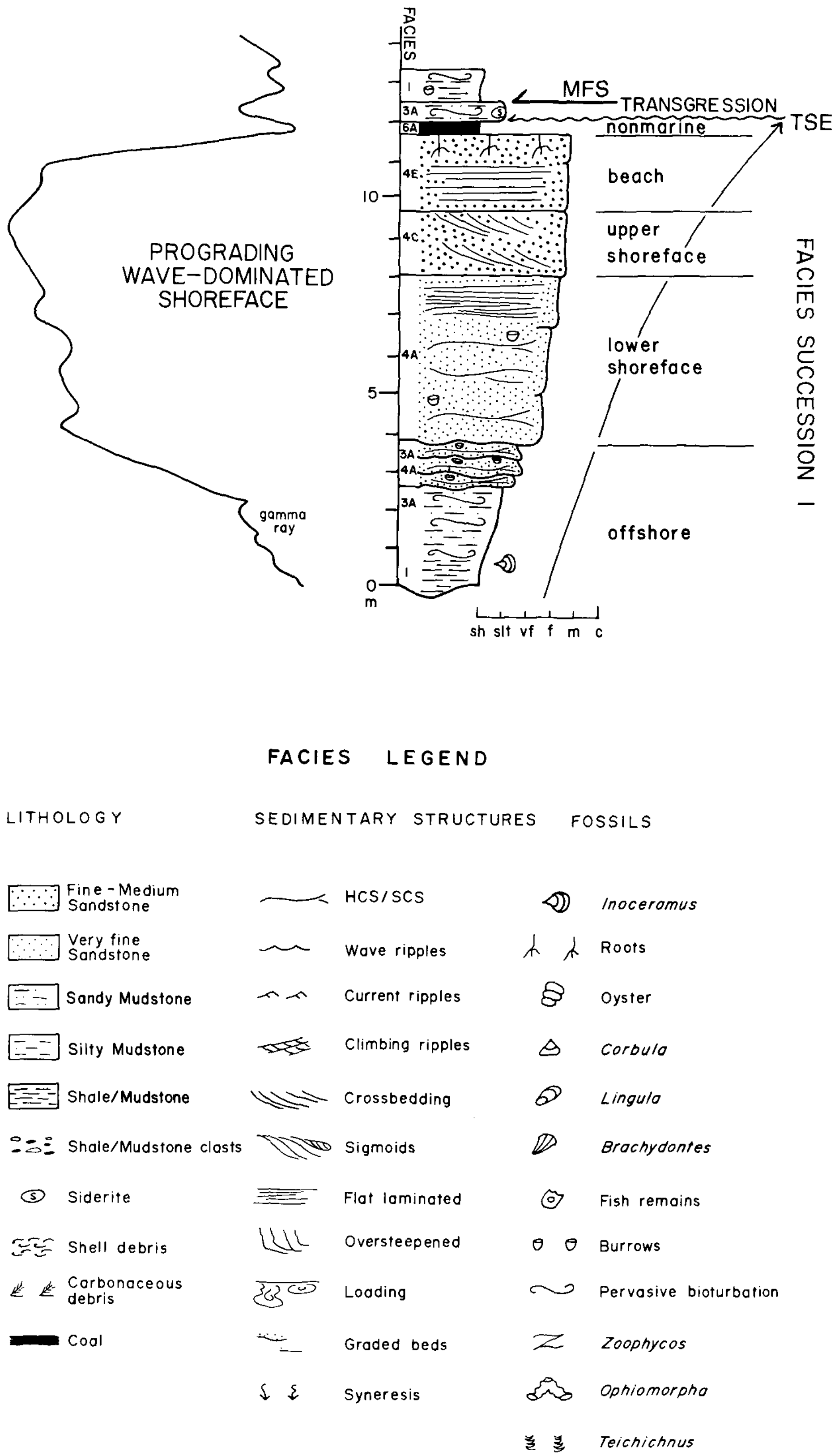


Fig. 11. ***(Upper)*** Facies Succession 1, characteristic of the deposits of a wave-dominated prograding shoreface (see text for description and interpretation). The coarsening-upward succession is capped at 12 m by a transgressive unit (Facies 3A) underlain by a transgressive surface of erosion (TSE) and overlain by a marine flooding surface (MFS). Figure is an idealization based largely on core and well log from allomember D in well 7-10-63-1W6 and shown in Bhattacharya (1988, Fig. 6, p. 30). ***(Lower)*** Facies Legend for Figures 11 to 16.

climbing ripples (Facies 4B) and soft sediment deformation (Facies 2D) suggest high sedimentation rates.

The irregular coarsening-upward and abundant shaly interbeds probably reflect variable fluvial discharge. Sand isolith maps (*e.g.*, Fig. 18) show that Facies Succession 2 is associated with sand bodies that have in plan view a deltaic morphology, and that they are associated with updip channels interpreted as distributaries (Bhattacharya, 1988, 1989a, and *in press*).

Facies Succession 3: Wave-Influenced Delta

Facies Succession 3 shows characteristics of both Successions 1 and 2 (Fig. 13). It occurs in the lower parts of Allomembers D and E, and characterizes Allomember G. It displays a fairly smooth and regular coarsening-upward character (similar to Succession 1), also indicated by a fairly smooth funnel shape on the gamma-ray log, and reaches thicknesses of 30 m.

Facies Succession 3 normally begins with several metres of stratified silty mudstone (Facies 2A), similar to the basal part of Succession 2. In contrast to that succession, however, soft sediment deformation features are rare in Succession 3, and the mudstones become interbedded upward with HCS sandstone (Facies 4A). The HCS sandstones first appear as isolated gutter casts, but become thicker and more continuously bedded upward. As the succession coarsens, the HCS is replaced by crossbedded sandstone (Facies 4C), in places with ripped-up mudstone clasts. This passes upward into flat laminated sandstones (Facies 4E) which may be capped by coals (Facies 6A).

Facies Succession 3 is interpreted as the result of the progradation of a wave-influenced deltaic shoreline. Elements of Successions 1 and 2 are present; wave influence is suggested by the HCS sandstones, but the lack of bioturbation in the underlying mudstones may suggest slightly higher rates of deposition than Succession 1.

Facies Succession 4 - Distributary Channel Fill

Facies Succession 4 is invariably underlain by a regressive surface of erosion (RSE), and fines upward (Fig 14). The regressive surface of erosion is defined as an erosional surface across which there is evidence of a seaward shift in the position of the shoreline. It is usually caused by a relative fall of sea level, which results in fluvial incision in the position of the channel, and subaerial exposure in interfluve areas. The gamma-ray log response commonly shows a bell-shaped profile, although where this succession is dominantly sandy it may appear more blocky (Bhattacharya, 1988 and *in press*). It is commonly found within sand bodies that map as elongate "shoestring" isolith patterns (Fig. 18), and it is commonly 12

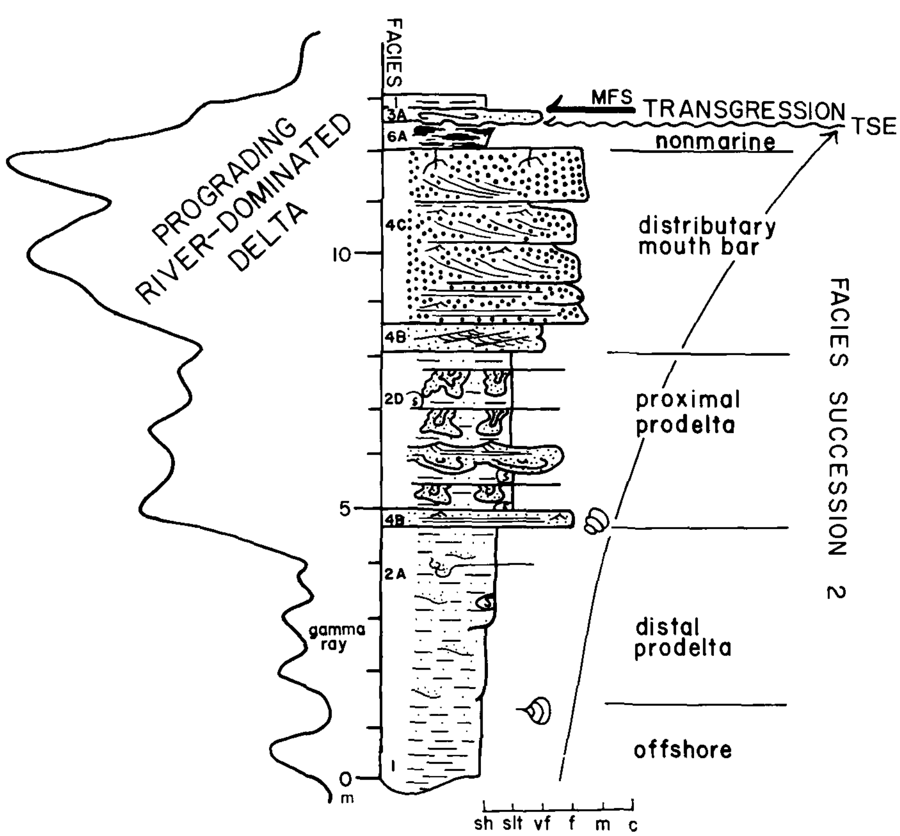


Fig. 12. Facies Succession 2, characteristic of the deposits of a prograding river-dominated delta front (see text for description and interpretation). The coarsening-upward succession is capped by a thin transgressive unit bounded by a transgressive surface of erosion below and a marine flooding surface (MFS) above. Figure is an idealization based largely on core and well log from allomember E in well 15-31-62-25W5 in Bhattacharya (1988, Fig. 4, p. 29).

to 20 m thick. A maximum thickness of 35 m was observed in Allomember D (well 11-19-59-3W6).

The lower erosional contact is commonly overlain by a lag (Facies 5) up to 30 cm thick. This is followed by several metres of massive fine to medium grained crossbedded (Facies 4C) to structureless sandstone (Facies 4F). These sandy facies alternate, but tend to be replaced upward by parallel-laminated to current-rippled sandstone (Facies 4B). Convolute laminated sandstones may also be present (Facies 4G). Any one succession can contain several fining-upward "sub-cycles" of crossbedded to ripple crosslaminated sandstone. Thin mudstone beds can occur throughout the succession. In places, the succession grades upward into several metres of interpreted nonmarine mudstones and shales of Facies 2B, 2D, or 6A, while elsewhere the succession may be dominantly sandy.

We interpret Facies Succession 4 as a channel fill. This is suggested by the overall fining upward, the erosional base with a lag, and the plan view shoestring geometry of associated sand bodies (Bhattacharya, 1988, 1989a, and *in press*). The lack of marine facies indicates that the channel is fluvial-dominated. The sub-cycles within the overall succession suggest channel filling by a series of waning flows, perhaps associated with flood stages of the river.

Facies Succession 5: Estuarine Channel Fill

Facies Succession 5 also fines upward, but contains a much higher proportion of marine facies than Succession 4 (Fig. 15). These marine facies are also more irregularly distributed and the gamma-ray log tends to be more serrated than that of Succession 4 (Fig. 15). The succession may reach up to 20 m in thickness (Bhattacharya, 1989b). Above the basal erosion surface, the sandy portion of the succession begins with fine to medium grained crossbedded to rippled sandstone, with mud couplets on some of the foresets (Facies 4D). Synaeresis cracks may be present. Shell debris and eroded mudstone clasts are also present, in places comprising a thicker lag (Facies 5). The sandstones may pass upward into as much as 10 m of interbedded rippled to bioturbated mudstone and sandstone (Facies 2C, 3B, 3A) containing wave- and combined-flow rippled sandstones and, in places, synaeresis cracks. A marine trace fauna includes *Teichichnus, Planolites, Rhizocorallium* and *Terebellina*. *Inoceramus* also occurs in places. The succession may be capped by very fine grained HCS or flat laminated sandstone (Facies 4A or 4E). In places, the upper parts of the succession may be dominantly sandy, although the sands are commonly burrowed and commonly contain muddy partings.

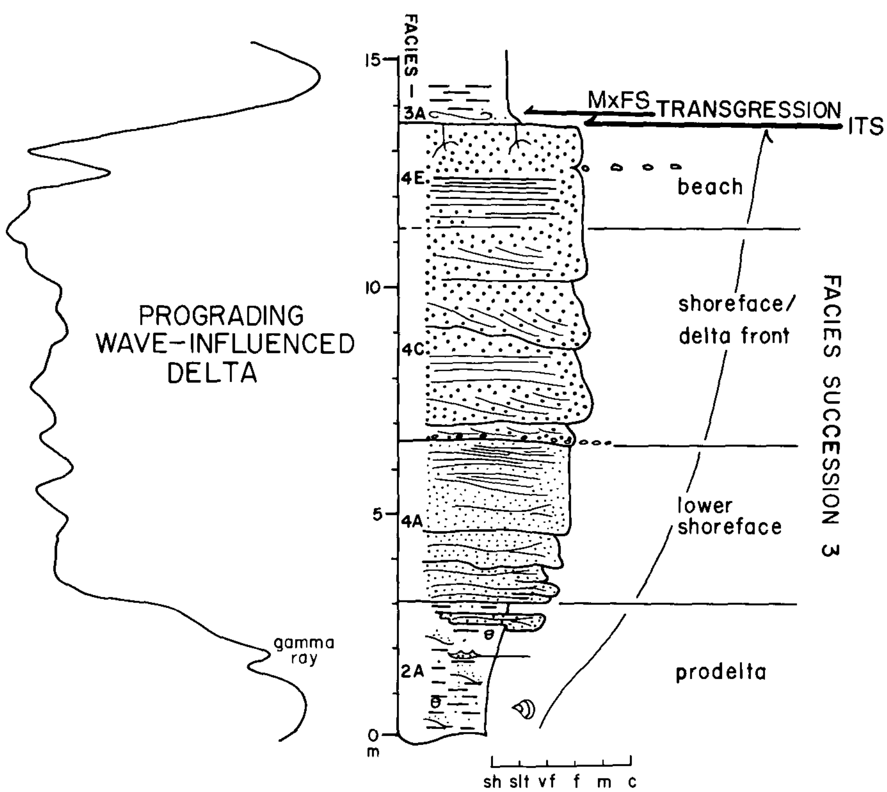


Fig. 13. Facies Succession 3 represents the deposits of a wave-influenced prograding delta and is environmentally in between Successions 1 and 2 (Figs. 11, 12). See text for further explanation. Coarsening-upward facies succession is capped by a thin transgressive unit (Facies 3A); ITS , initial transgressive surface; MFS, maximum marine flooding surface. Figure is partly based on cores from allomember G (Bhattacharya, 1989a, Fig. 9-5b, p. 448). Gamma trace is from allomember E in well 12-21-61-9W6 (Bhattacharya, ibid).

Facies Succession 5 is common in the upper parts of the allomembers, and tends to occur immediately below allomember-bounding major marine flooding surfaces, particularly in Allomembers D, C, B and A (Bhattacharya, 1989b; Bhattacharya and Walker, *this volume*).

We interpret Facies Succession 5 as a channel fill, but the increasing marine aspect upward suggests an estuarine rather than fluvial setting. We use the concept of an estuary as a drowned river valley in which tidal processes are prominent (Barrell, 1912). The mud couplets suggest a tidal influence within the estuary, and the presence of synaeresis cracks probably indicates fluctuations in salinity (Burst, 1965). Where present, the HCS indicates a deeper marine environment as the transgression continues. The estuarine interpretation (Bhattacharya, 1989b) is also consistent with the stratigraphic position of the successions within the allomembers, immediately below the bounding major marine flooding surface.

Facies Succession 6 - Barrier Inlet Fill

Facies Succession 6 also fines upward but is considerably thinner than Succession 4 or 5 and is dominantly sandy (Fig. 16). It is the least common of all of the facies successions defined and is restricted to Allomember D, where it averages about 5 m in thickness. Above the basal erosion surface, the sandy portion of the succession begins with fine to medium grained crossbedded to rippled sandstone, with thin mud couplets on some of the foresets (Facies 4D), similar to Succession 5, but without a basal lag. Succession 6 lacks the thick burrowed mudstones of Succession 5, although the sands may be moderately burrowed. The sands may show a transition upward from dominantly crossbedded sand (Facies 4C,4D) into parallel laminated to rippled sand (Facies 4B). In Allomember D, Facies Succession 6 lies within a shore-parallel, linear sand body interpreted as a barrier sand (Figs. 20, 22).

The presence of a channellized sand body within a barrier island is interpreted as a tidally influenced barrier inlet fill. The presence of tidally produced crossbedding (Facies 4D) and a marine trace fauna support this interpretation.

Facies Succession 7 - Interdistributary Bay/Lagoon

This facies succession is very irregular, and is dominated by various types of stratified mudstones, siltstones and sandstones that may be cut by fining-upward channel fills (Facies Succession 4). The gamma-ray log commonly shows a highly serrated character (Fig. 17). The order of the facies is variable, although locally, thin fining- and coarsening-upward trends occur. In any given occurrence of the succession, nonmarine facies usually become predominant upward. Succession 7 is

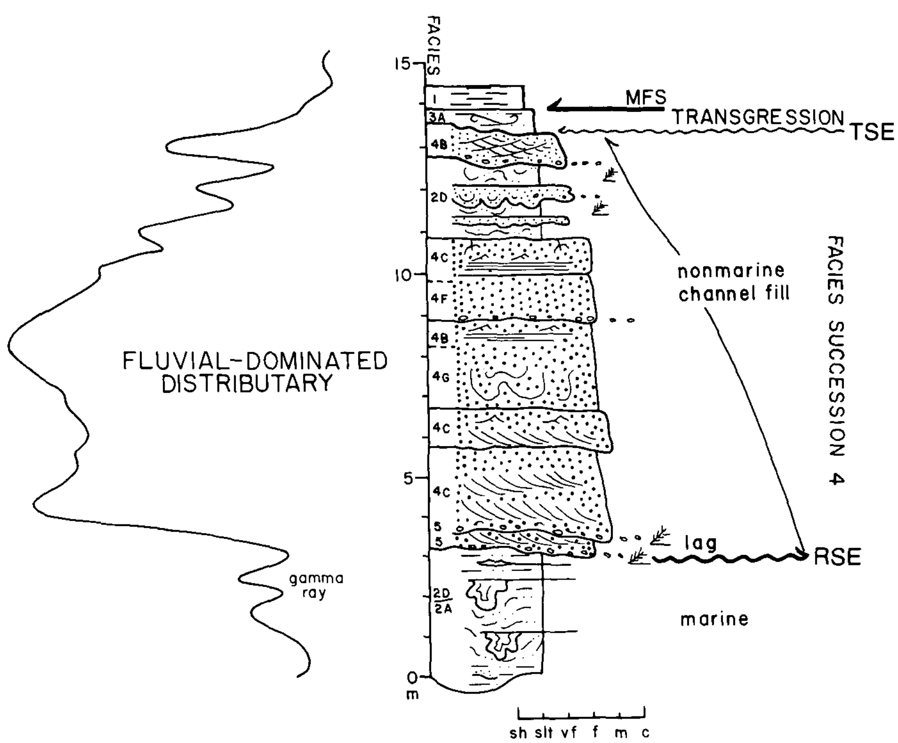


Fig. 14. Facies Succession 4, interpreted as a fluvial-dominated distributary channel fill. Channel base correlates with a regressive surface of erosion (RSE). The channel is filled with nonmarine facies truncated by a thin transgressive unit (Facies 3A), underlain by a transgressive surface of erosion (TSE), and overlain by a marine flooding surface (MFS). Figure is an idealization based largely on core and well log from allomember E in well 2-1DU-63-26W5 (1804-1817.5 m). Root traces were not noted in this well, however.

largely restricted to the northwestern part of the study area where nonmarine facies predominate.

Figure 17 illustrates a typical example of Facies Succession 7 from allomember E in well 3-9-62-3W6. Marine stratified, silty mudstones (Facies 2A) pass up into sideritic, rippled, silty mudstones (Facies 2B). Rippled, sandy mudstones containing abundant synaeresis cracks (Facies 2C) also occur. They may be interbedded with burrowed stratified mudstones and sandstones of Facies 3B. The interbedded muddier facies are cut by 1 m of fine grained current rippled sandstone (Facies 4B) which fines upward. This sandstone is followed by more interbedded mudstones and sandstones, which are in turn capped by coaly mudstones (Facies 6A). These contain a brackish water fauna (oyster beds, *Brachydontes sp., Corbula sp.*) and *in situ* root traces. Coals (Facies 6A) and waxy gray paleosols (Facies 6B) may also occur in this facies succession.

Facies Succession 7 is common in Allomember E, where it reaches a thickness of 10 m.

We interpret Facies Succession 7 as having been deposited in low energy, shallow marine to nonmarine environments on the distal fringes of coastal plains similar to those interpreted by Plint and Walker (1987) and Elliott (1974). The environments probably include low energy interdistributary bays, lagoons, deltaic and fluvial floodplains, and shallow ponded bodies of water. Thicker sandstone beds may fill crevasse channels and splays. A prograding low energy coastal plain or interdistributary bay is suggested in cases where Succession 7 begins with silty marine mudstones (Facies 2A) and passes upward into nonmarine facies, as in the example shown here (Fig. 17). The distinction between lagoon and bay fill will depend on the nature of the depositional system in which it is contained as indicated by the associated maps.

Discussion of Facies Successions

The vertical facies successions we have recognized above are based on observations of repeated and systematic facies relationships in core. Some facies are mutually exclusive, whereas others tend to occur together, giving the distinctive aspect of each succession. In this sense, the facies successions described above represent distinct two-dimensional lithofacies assemblages. These facies and facies successions are the basic descriptive units of the Dunvegan Formation.

Equally important is the possibility that very similar facies successions exist elsewhere; this is known to be the case for Succession 1 (the prograding, storm-and wave-dominated sandy shoreface), which has been recognized in the Jurassic Passage Beds (Hamblin and Walker, 1979), the Lower

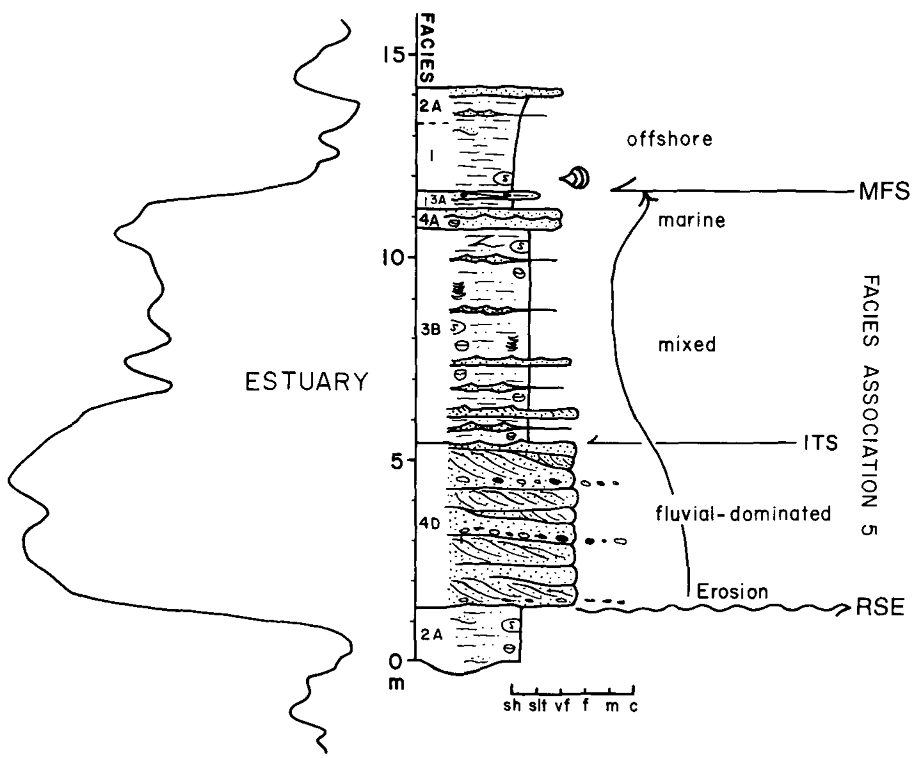


Fig. 15. Facies Succession 5, interpreted as a transgressive estuarine channel fill. The channel base (RSE) was cut by fluvial processes, although the overlying facies indicate an increasingly marine influence upward. The RSE may have been modified by marine processes. The contact between Facies 4D and 3B marks the first significant initial transgressive surface (ITS). A major marine flooding surface (MFS) terminates the succession at 11.5 m. See text for further explanation. This figure is based largely on core and well log from well 7-21-64-23W5, 1472-1487 m.

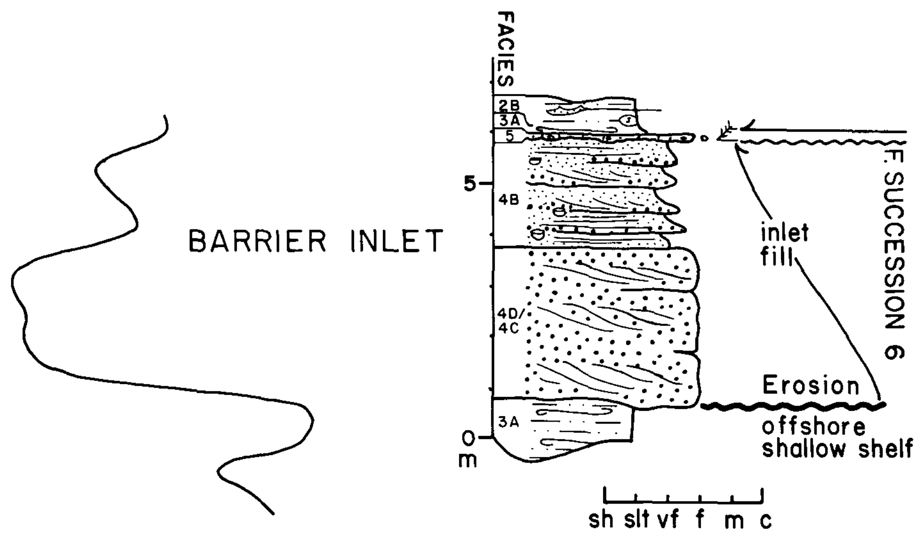


Fig. 16. Facies Succession 6, interpreted as representing a tidal inlet fill. The basal erosion surface is interpreted as resulting from inlet migration. A thin transgressive lag (Facies 5) caps this fining-upward succession. See text for further explanation. Figure is based on core and well log from allomember D in well 13-28-61-2W6 (2420-2441 m) shown in Bhattacharya (1989a, Fig. 5-8B, p. 352).

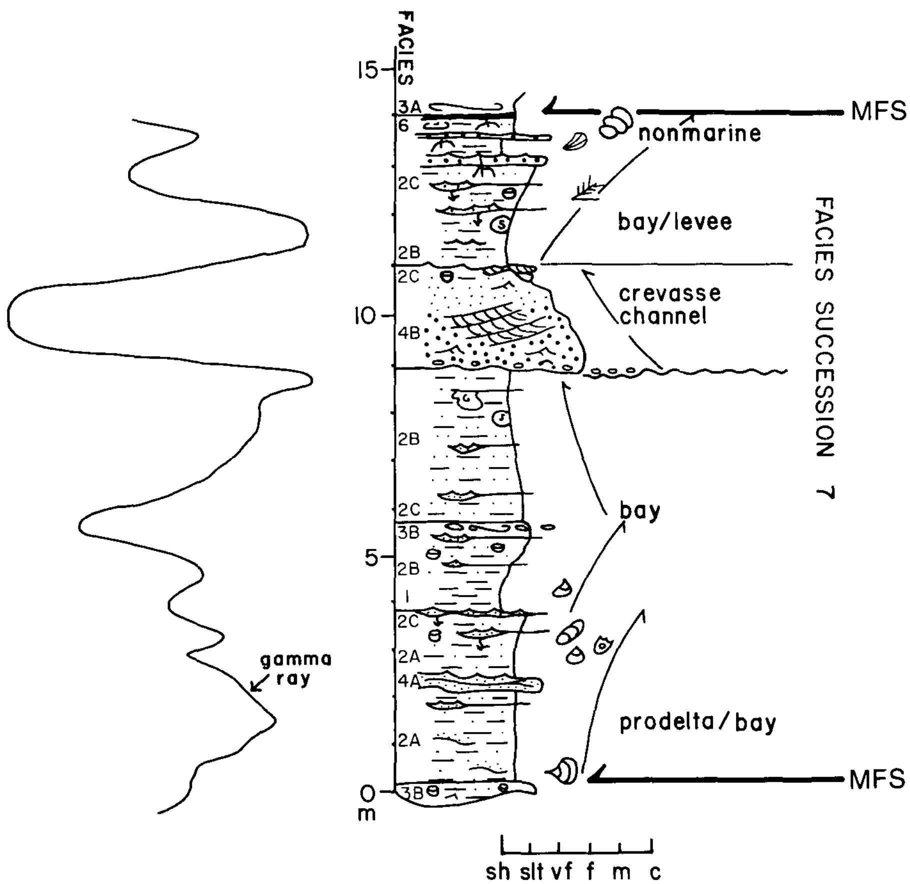


Fig. 17. This example of facies Succession 7 is interpreted as representing a shallowing-upward interdistributary bay fill bounded by a marine flooding surface (MFS) above and below. See text for further interpretive details. Figure is based on core and well log from allomember E in well 3-9-62-3W6 (2373-2386 m) shown in Bhattacharya (1989a, Fig. 4-14b, p. 284).

Cretaceous Viking Formation (Hein *et al.*, 1986), the Upper Cretaceous Cardium Formation (Plint and Walker, 1987) and the Upper Cretaceous Chungo Member of the Wapiabi Formation (McCrory and Walker, 1986; Rosenthal and Walker, 1987).

Succession 2 (the river-dominated delta) is similar to facies successions through other modern river-dominated deltas (*e.g.*, Coleman and Prior, 1982) and has been found in many ancient successions (see review by Elliott, 1986). Moslow and Pemberton (1988), and Van Wagoner *et al.* (1990) also presented criteria for distinguishing similar shoreface successions (our Succession 1) from deltaic successions (our Succession 2).

Succession 4, the fluvially dominated, fining-upward succession, is also widely recognized (review by Walker and Cant, 1984). The estuarine fining-upward succession (Succession 5) is similar to that in James Bay, Virginia, described by Nichols *et al.* (1989), and is characteristic of wave-dominated estuaries modelled by Zaitlin and Schulz (1990). Other ancient estuarine complexes have been described from the Viking Formation by Reinson *et al.* (1988).

Ancient tidal inlet successions have been recently described from the Western Interior Seaway by Cheel and Leckie (1990) and are similar to modern tidal inlet successions described by Kumar and Sanders (1974). Fine grained, distal flood plain deposits (Succession 7) have been described by Walker and Harms (1971), Plint and Walker (1987), and Elliott (1974).

Depositional Systems

Relationship of Facies Successions

Mapping and correlation of the facies successions adds the third dimension and indicates that some facies successions tend to occur together while others are mutually exclusive (Bhattacharya, 1989a, 1989b, *in press*). These associations or linkages of specific facies successions define distinct depositional systems, which are related to deposition within one shingle or allomember in the Dunvegan Formation.

Several different types of depositional system can be recognized in the Dunvegan, including: 1) river-dominated deltas, 2) wave-dominated deltas, 3) wave-influenced deltas and 4) wave-dominated barrier island systems. An example of each is discussed below.

River-Dominated Deltas, Allomember E

River-dominated deltaic depositional systems in allomember E are characterized by the three-dimensional linkage of Facies Successions 2, 4, and 7 (Bhattacharya, *in press*). Allomember E contains four offlapping shingles (Fig. 1). Bhattacharya (*in press*) showed that each shingle contains channels, lobes and interlobe areas that were interpreted as being similar to the shoal water deltas of the modern Mississippi delta plain.

An example of the sand body geometry in shingle E1 is shown in Figure 18. It shows a major shoestring shaped sand body in the northwest (Simonette channel) which splits to the southeast where it feeds a large, multilobate sand body. The shape is characteristic of a river-dominated system (Coleman and Wright, 1975). Cores through the shoestring are typical of Facies Succession 4, and it is therefore interpreted as a major distributary channel. Cores through the lobes are typical of Facies Succession 2, which was interpreted above as deposits of a river-dominated prograding sandy delta front. Core through the interlobe areas are typical of Facies Succession 7, and are interpreted as the deposits of interdistributary bays.

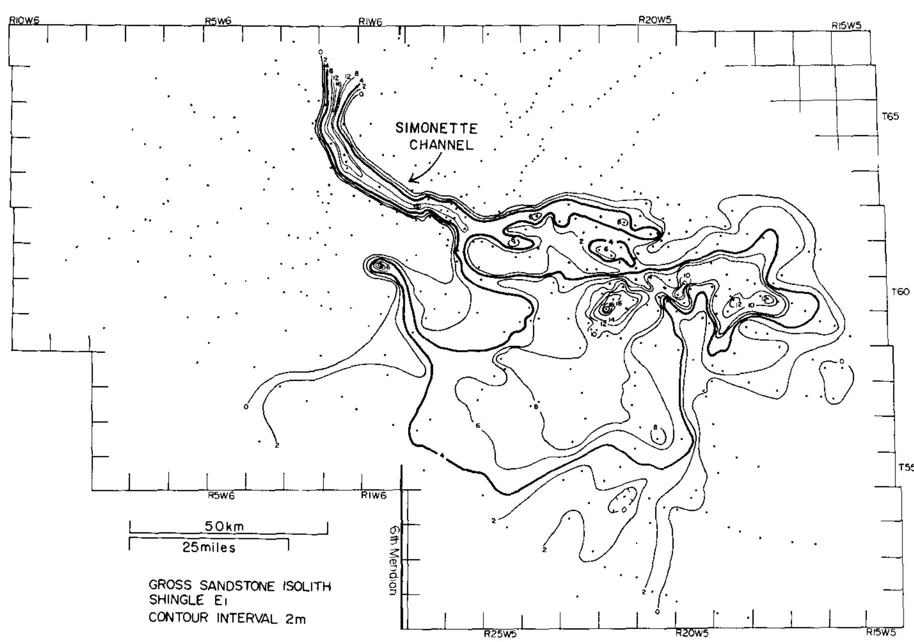


Fig. 18. Sand body geometry, Shingle E1. Dots indicate data points. (After Bhattacharya, *in press*).

The paleogeographic reconstruction of shingle E1 combines the sand body geometry with the observed facies successions, and shows the delta prograding to the southeast (Fig. 19). The lateral variability of facies successions within allomember E, as well as additional maps of the other deltas in shingles E2, E3, and E4, are documented in detail in Bhattacharya (*in press*).

Wave-Dominated Delta, Allomember D

The wave-dominated delta in shingle D1 of allomember D is characterized by a linkage of Facies Successions 1 and 5. The sand body isolith map of allomember D shows the D1 lobe and the linear D2 barrier (Fig. 20). The lobe in the southeast correlates with shingle D1. It appears to narrow to the northwest in the Waskahigan area where it correlates with a major channel. Cross-sectional relationships clearly indicate that the channel cuts into shingle D2 (Bhattacharya, 1989b). The geometry of the delta front is interpreted as being cuspate in shape (Fig. 21) and is similar to the cuspate, wave-dominated deltas documented by Weise (1979) and Coleman and Wright (1975). This contrasts with the rather more digitate lobes of the river-dominated deltas in allomember E (Fig. 19).

Cores through the lobe are typical of Facies Succession 1 and indicate that delta front sandstones are characteristically reworked into wave- and storm-dominated shorefaces. Cores through the channellized sand in the Waskahigan area are characteristic of Facies Succession 5 and indicate a marked estuarine character. An example of the lateral facies variability through this estuary is documented in Bhattacharya (1989b).

In contrast to the fluvial-dominated deltas, distributary mouth bar sandstones have not been identified and the lithofacies do not directly reflect fluvial influences. Without the accompanying sandstone distribution map (Fig. 20) the delta front facies succession would be practically indistinguishable from sandy wave- and storm-dominated strand plain deposits not associated with deltaic outbuilding.

Wave-Dominated Barrier, Allomember D

The wave-dominated barrier in shingle D2 of allomember D is characterized by a linkage of Facies Successions 1, 5, 6, and 7 (Fig. 22). The overall geometry of this sand body is totally

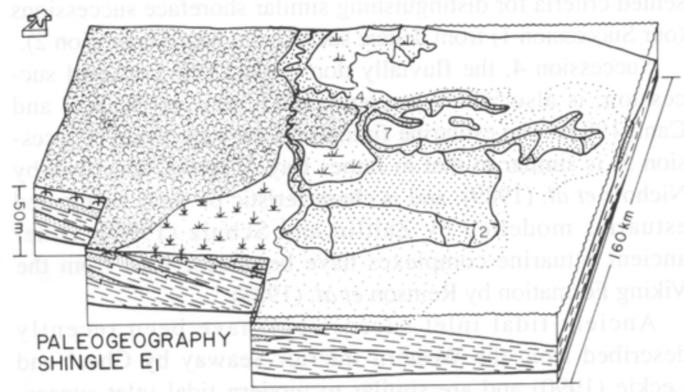


Fig. 19. Paleogeographic reconstruction illustrating typical relationships in river-dominated deltaic depositional systems in the Dunvegan Formation. This is based on the sand body geometry shown in Figure 18 and on the facies successions observed in core. Position of Facies Successions 2, 4, and 7 with respect to the lobes, channels and interlobes are shown. White areas indicate prodelta shale, fine stipple indicates subaqueous prodeltaic sandstones, coarse stipple indicates delta front and distributary channel sandstones, swamp pattern indicates interdistributary bays, forest pattern indicates alluvial plain (area of nondeposition). Additional data about allomember E are presented and discussed in detail in Bhattacharya (1989a, and *in press*).

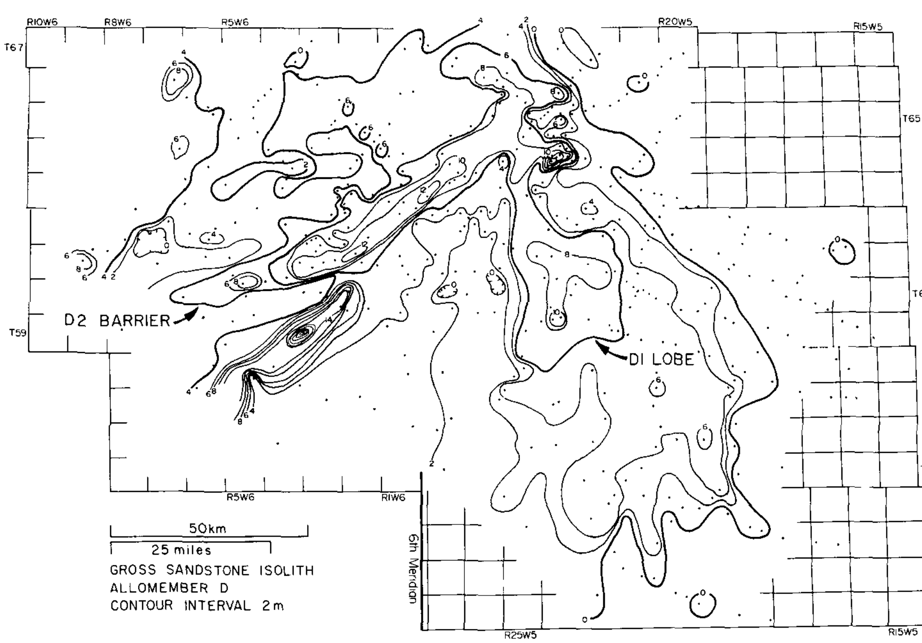


Fig. 20. Sand body geometry, allomember D. All three shingles are mapped together. Dots indicate data points.

different from that for the river-dominated deltas (Fig. 19). It is linear, oriented parallel to overall Dunvegan shoreline trends (northeast–southwest), and has a relatively smooth seaward margin. The maximum sandstone thickness within this depositional system is about 10 m (Fig. 20) compared to a maximum of about 18 m for delta front sands in river-dominated delta systems (Fig. 18).

The main components of this barrier island depositional system include the sandy barrier bar with a lagoon to the northwest and an open shelf to the southeast (Fig. 22).

Facies through much of the barrier bar coarsen upward and are typical of Facies Succession 1 indicating a progradational shoreface. Other facies successions fine upward and are typical of Succession 6. These are interpreted as tidal inlets within the barrier. The deposits behind the barrier are characteristic of Facies Succession 7 and include flood-tidal deltas adjacent to the tidal inlets. We have assumed that the tidal range is on the same scale as the thickness of preserved foreshore (*i.e.*, beach) deposits, which in the best example is about 2 m (Bhattacharya, 1989b). This marks the transition between micro- and mesotidal environments.

The paleogeographic reconstruction (Fig. 22) shows that a major distributary channel probably fed this barrier bar at its northeastern end and sand was apparantly transported to the southwest by longshore drift. Comparison with the models presented by Reinson (1984) and Niedoroda *et al.* (1985) suggests that this depositional system represents a microtidal to mesotidal, regressive, barrier-spit.

A relative sea level fall, following deposition of the D2 barrier, resulted in incisement of the Waskahigan channel and deposition of the D1 lowstand delta described above (Fig. 21).

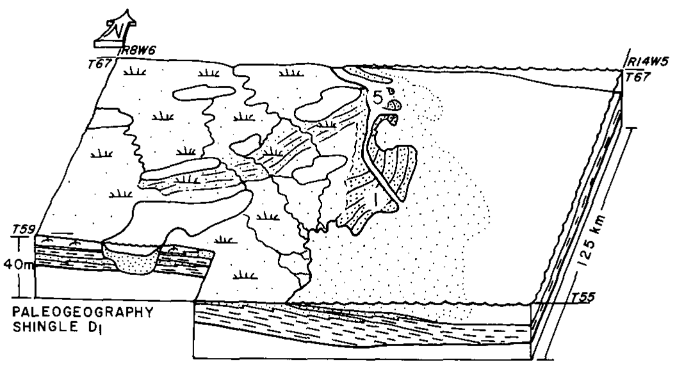


Fig. 21. Paleogeographic reconstruction of shingle D1 based on the sand body geometry shown in Figure 20 and on the facies successions observed in core. Shingle D1 is interpreted as a wave-dominated delta fed by a channel to the north. Position of Facies Successions 1 and 5 are shown. White areas indicate shale-dominated environments, light stipple indicates subaqueous sandy facies, heavy stipple indicates emergent areas characterized by coarser sands, and marsh symbol indicates coastal plain environments. Additional data are presented in Bhattacharya (1989a,b).

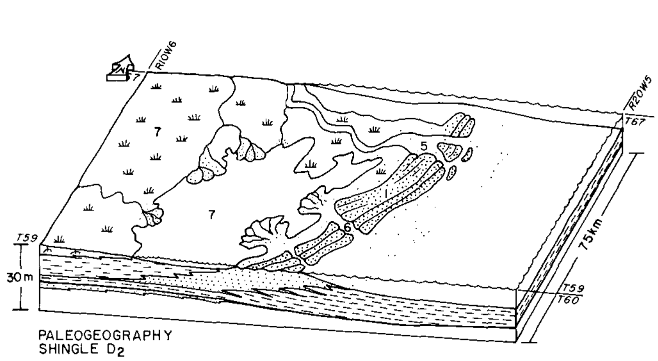


Fig. 22. Paleogeographic reconstruction of a barrier island depositional system based on shingle D2 in allomember D. Position of Facies Successions 1, 5, 6, and 7 are shown. Facies legend same as Figure 21. Additional data are presented in Bhattacharya (1989a,b).

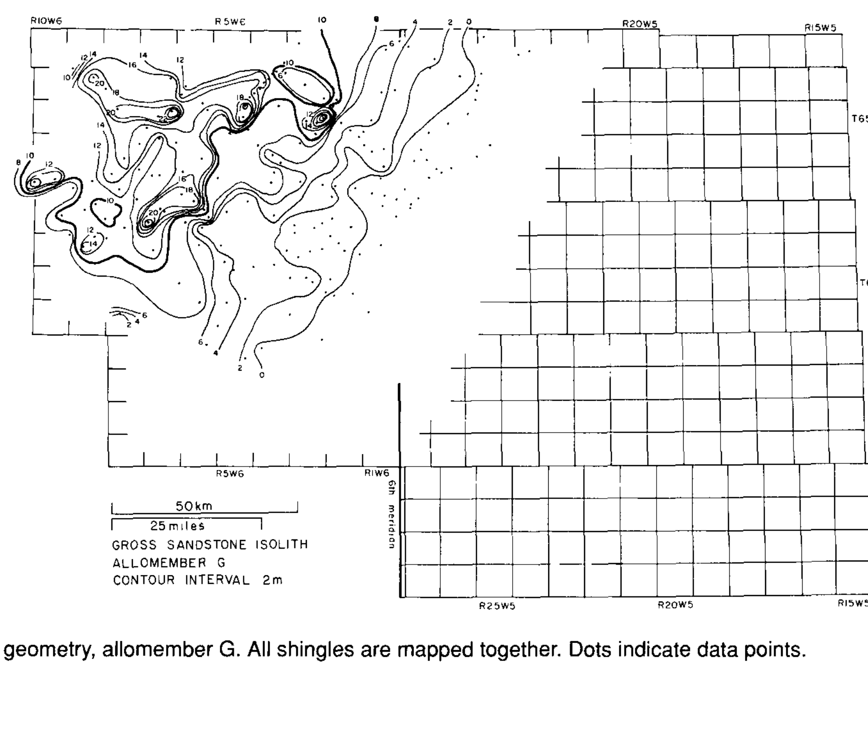


Fig. 23. Sand body geometry, allomember G. All shingles are mapped together. Dots indicate data points.

Wave-influenced deltas, allomember G

Wave-influenced deltas in allomember G are characterized by a linkage of Facies Successions 3, 4, and 7. They display characteristics of both wave- and river- dominated deltas.

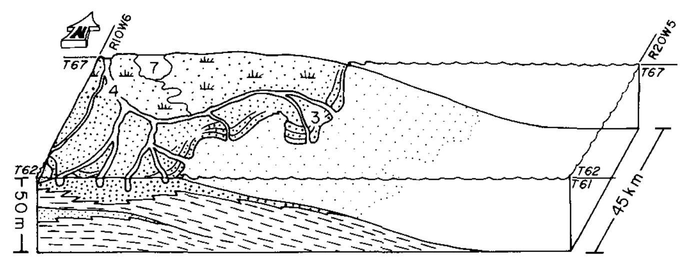
Allomember G comprises 5 offlapping shingles (Fig. 1) which are collectively mapped in the sand isolith map (Fig. 23). The sand bodies show a rather irregular seaward geometry, suggesting the presence of several overlapping delta lobes. Cores through the lobes are typical of Facies Succession 3, which were interpreted above as being intermediate between successions 1 and 2. Some of the lobes are truncated by distributary channels (Bhattacharya, 1989a). Cores through these channels are more typical of Facies Succession 4, suggesting fluvial dominance. Using the terminology of Fisher *et al.* (1969) these deltas could also be classified as high-constructional, wave-influenced deltas. Similar ancient wave-influenced deltaic systems have been described by Pulham (1989).

Transgressive depositional systems

All of the depositional systems described above have one essential characteristic. They all contain coarsening-upward facies successions, which indicate progradation or regression of environments. Regressive depositional systems dominate the Dunvegan Formation.

Preserved transgressive deposits, in contrast, comprise a much smaller proportion of the preserved stratigraphic record. The exception occurs when channels are transgressed and considerably thicker successions of estuarine deposits may be preserved, such as in the Waskahigan channel in allomember D.

The best example of a transgressive sheet sandstone is the sandstone that caps allomember C. The geometry and facies of this sandstone are different from any of those depositional systems described above. Well defined lobes, shoestring sands or linear shore-parallel sand bodies are absent and the sandbody geometry is that of an irregular ragged sheet (Fig. 25). In cores, the sandstone is sharp-based and is dominated by abundant *Ophiomorpha* burrows and rarer crossbedding in places. Similar transgressive sandstone facies were observed re-working and partly eroding the tops of sandy deltaic successions in the San Miguel Formation, Texas (Weise, 1979). It is clear that these deposits are not primary. They are essentially sandy lags produced by erosion of the underlying substrate. Probably



PALEOGEOGRAPHY, ALLOMEMBER G

Fig. 24. Paleogeographic reconstruction of wave-influenced deltas in allomember G, based on sand body geometry shown in Figure 23 and on facies successions observed in core. Positions of Facies Successions 1, 3, 4, and 7 are shown. White areas represent prodelta shales, light stipple indicates prodelta sands, heavy stipple indicates delta front areas and marsh pattern indicates delta plain. Geometry of delta front is considerably smoother than in Figure 19. Additional data are presented in Bhattacharya (1989a).

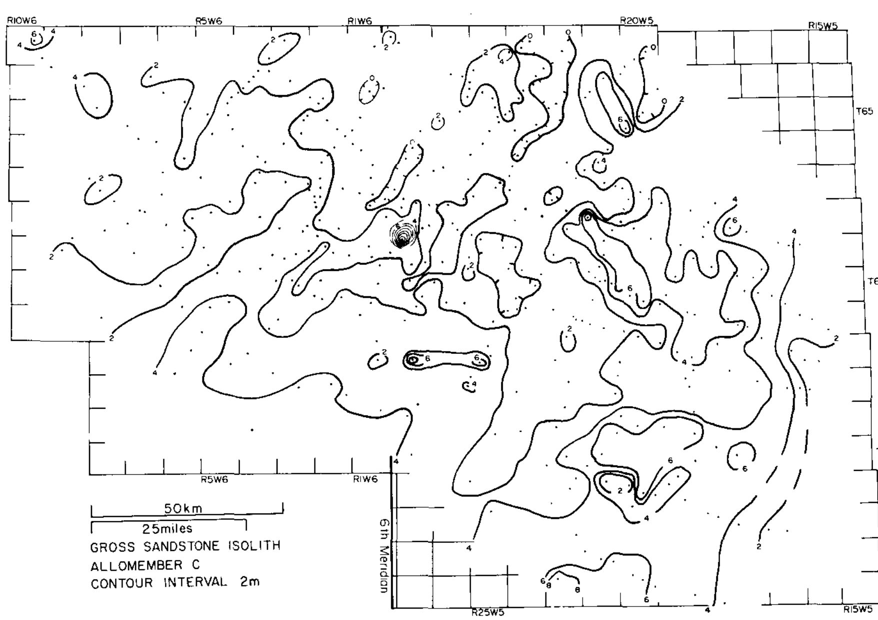


Fig. 25. Sand body geometry of allomember C indicating a rather irregular sand sheet, typical of a transgressively reworked barrier sand. Dots indicate data points. The sand is dominantly pervasively bioturbated, with very few original sedimentary structures or stratification preserved.

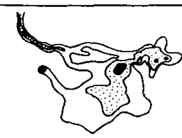
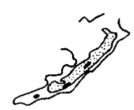
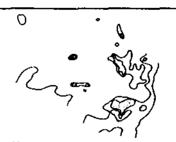
Depositional systems	Sand body geometry	Facies successions	Occurrence
River-dominated delta		2, 4, 7	Shingles E1, E2, E3; Allomember G
Wave-influenced delta		3, 4, 7	Allomember G Allomember F Shingle E4
Wave-dominated delta		1, 5, 7	Shingle D1
Barrier island		1, 6, 7	Shingle D2
Transgressive barrier		1, 6, 7 Incomplete	Allomember C

Fig. 26. Summary of depositional systems in the Dunvegan Formation. Facies successions in the transgressive barrier are largely homogenized by burrowing, chiefly *Ophiomorpha*, and are usually incomplete.

the best understood mechanism of marine erosion during transgression is marine shoreface retreat (Niedoroda *et al.*, 1985). This sheet sandstone was probably deposited as a series of en echelon sandy barrier bar sands as a result of erosional shoreface retreat at the end of allomember C deposition.

Relationships of Depositional Systems

Our data clearly show that the Dunvegan comprises a series of stacked depositional systems. These show a wide range of environments from river-dominated deltas to wave-dominated barrier islands. These depositional systems are summarized in Figure 26. In the companion paper (*this volume*) we show, in an allostratigraphic context, how these stacked depositional systems are related to transgressive and regressive episodes.

In general, Dunvegan depositional systems show a distinct evolution through time and show an overall decrease in fluvial dominance upward (Bhattacharya, 1989a). Depositional systems within the lower allostratigraphic units (allomembers G and F) are characterized by the highly progradational, but wave-influenced deltaic depositional systems (Fig. 24). The middle portion of the Dunvegan (allomember E) is characterized by the highly river-dominated depositional systems (Fig. 19). Finally, the upper portion of the Dunvegan (allomembers D, C, B, and A) comprises facies belonging to the wave-dominated and tide-influenced depositional systems and have a more "transgressive" character, marked by a much greater degree of reworking by basinal processes including an overall increase in the degree of bioturbation. We speculate that this overall upward decrease in fluvial dominance may reflect a decrease in sedimentation rate as uplifted highlands to the northwest were progressively eroded. This pattern of erosion was indicated by Tater (1964). A similar pattern of an upward decrease in fluvial dominance has also been documented in other deltaic clastic wedges (Galloway, 1975; Duncan, 1983). Other factors, however, such as relative sea level change or changes in basin energy, may also be important. Wave-influence in the deltas in the lower part of the Dunvegan may relate to deposition during a relative highstand of sea level (Bhattacharya and Walker, *this volume*).

Conclusions

1. Nineteen facies can be recognized and described in the sediments of the Dunvegan Formation.
2. These were grouped into a series of seven commonly occuring, vertical facies successions. These were interpreted as: 1) storm-dominated shoreface, 2) river-dominated delta front, 3) wave-influenced delta front, 4) fluvial-dominated distributary channel, 5) estuarine channel fill, 6) barrier-inlet fill, and 7) interdistributary bay/lagoon.

3. Mapping and correlation within allostratigraphic units indicated that the facies successions could be further linked into assemblages that defined distinct depositional systems. These range from highly river-dominated deltaic systems linking facies successions 2, 4, and 7, to wave-dominated, tide-influenced barrier island systems linking facies successions 1, 5, 6, and 7. The different depositional systems are characterized by unique sand body geometries. The various facies successions occur in specific places within these sand bodies.
4. The Dunvegan Formation can not be characterized simply as a single delta. It consists of a series of stacked depositional systems that show an overall decrease in fluvial dominance upward.

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