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An anoxic event at the Albian–Cenomanian boundary: the Fish Scale Marker Bed, northern Alberta, Canada

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ABSTRACT

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The Fish Scale Marker Bed (FSMB) of the Shaftesbury Formation, which marks the Albian–Cenomanian boundary, is a regional stratigraphic marker in the Western Interior of Canada. At the outcrop studied on the Smoky River in northwestern Alberta, three major shale units can be distinguished in the FSMB and contiguous strata. The lowermost shale (Unit 1) is bioturbated and contains high-diversity dinoflagellate and moderate-diversity foraminiferal assemblages. It has dominantly Type III (terrestrial) organic matter (OM) and low total organic carbon content (TOC). The unit was deposited in an open-marine, neritic environment of normal salinity. The FSMB (Unit 2) represents a zone of condensed bioclastic accumulation composed of abundant fish remains. The dinoflagellate species diversity is drastically reduced in this unit and it lacks benthonic foraminifera and bioturbation. Unit 2 is characterized by mainly Type II (marine) OM and high TOC values. Unit 2A contains rippled sandstone related to either a shallowing or to deeper water currents. A fish-hash conglomerate making up Unit 2B can alternatively be interpreted as a bioclastic, condensed and winnowed deposit or as a transgressive lag. Unit 2C consists of black, platy shale with abundant fish remains and represents a minor peak of marine transgression during the deposition of FSMB, when the bottom waters were dominantly anoxic. Collectively, the features of Unit 2 suggest deposition under a stratified water column with moderate productivity of planktonic and nektonic organisms in the upper oxygenated layers but with anoxic bottom waters. Unit 3, overlying the FSMB, consists of blocky shale with reduced concentration of fish remains. Due to increased rate of sedimentation during its deposition, the organic-rich sediment of Unit 3 was progressively diluted by clastic material and there was an increase in the dissolved oxygen content of the bottom waters. The anoxic event at the FSMB is related to a relative rise in sea level and possibly to the mixing of waters of different salinities and temperatures from the Arctic Ocean and the Gulf of Mexico in the Western Interior seaway.

Introduction

The Fish Scale Marker Bed (FSMB) has a widespread distribution in the Western Interior of Canada from northeastern British Columbia to Manitoba. The base of the unit is used as a boundary between the Lower and Upper Cretaceous. The FSMB (also called "Fish Scales Sandstone", "Base of Fish Scales" and "Fish Scales Zone") commonly occurs as a persistent sandstone, or sandstone and siltstone bed, containing abundant fish remains (Price, 1964; Caldwell, 1984) and is extensively used as a stratigraphic marker in subsurface correlation. In the northwestern plains of Alberta and British Columbia, the FSMB is well developed in the Shaftesbury Formation and correlative strata. It is also quite prominent in southern Alberta. However, the base of the FSMB marks a regional paraconformity (Stelck et al., 1958; North and Caldwell, 1975) and it is missing

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in central Saskatchewan. Farther to the east, the FSMB reappears in the upper part of the Ashville Formation in the Manitoba Escarpment. Although FSMB per se has not been recorded from the northwestern interior of the United States, fish scales and bones are common in the upper sandy unit of the Bootlegger Member of Montana and the Mowry Shale of Wyoming. These units are of equivalent age and the uppermost Mowry Shale and FSMB contain the same species of ammonite (*Neogastroplites maclearni*).

Although of widespread occurrence and geological and commercial importance, the FSMB is poorly understood because it is exposed in only a few outcrops (Stelck and Armstrong, 1981) and is not commonly cored during hydrocarbon exploration. The purpose of this paper is to document an outcrop of this important organic-rich marine shale in the northwestern plains of Alberta and to interpret its depositional environment through an integrated study of its sedimentological, palynological, microfaunal, ichthyological and geochemical characteristics. In this paper, the FSMB is interpreted to represent sedimentation under a stratified water column with anoxic bottom waters. The widespread distribution of FSMB in other parts of the Western Canadian Basin and the fish remains in correlative beds in the northwestern interior of the United States may indicate an anoxic event at the Albian–Cenomanian boundary in certain parts of the Cretaceous Interior Seaway of North America.

The FSMB and encompassing strata examined for this study are exposed in the lower Shaftesbury Formation on the east bank of the Smoky River, near the confluence of the Smoky and the Peace rivers (Fig. 1) and below Judah Station, about 10 km south of the town of Peace River in northern Alberta. The outcrop is situated on a large rotational slump block (Fig. 2A), about one-third of the way up the bank of the Smoky River valley. In this paper, the FSMB is interpreted to represent sedimentation under a stratified water column with anoxic bottom waters. The FSMB in northern Alberta may be related to the Upper Mowry Shale and Aspen Formations (Cobban and Reeside, 1952; Gleddie, 1954) which also contain abundant fish remains.

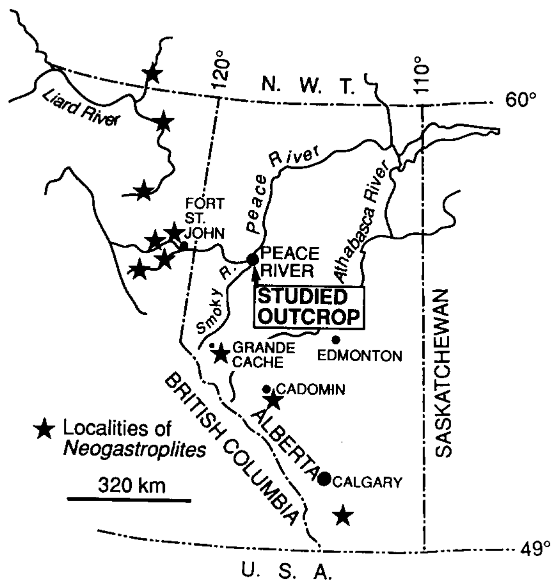


Fig. 1. Map of Alberta and eastern British Columbia showing the location of the studied outcrop of the Fish Scale Marker Bed (indicated by arrow) near Peace River town and localities of *Neogastroplites* (marked by stars) in northeastern British Columbia and central western Alberta. The co-ordinates of the studied outcrop of the Fish Scale Marker Bed are 56°9′ 20″N, 117°20′W (legal subdivision 12, section 35, township 82, Range 22, west of the 5th meridian).

Methods

Micropaleontological and geochemical samples were collected from outcrop in trenches dug at least 20 cm deep to remove most of the surficial weathered material. Samples were processed for palynofloral, microfaunal, organic and geochemical analyses. Fourteen samples were processed for calcareous nannofossils; however, they were all barren (T. Bralower, pers. comm., 1990).

Elemental analysis was determined by X-ray fluorescence (XRF). Sample preparation was by fusion with a lithium-tetraborate flux (Norrish and Hutton, 1969). Volatile content was determined by loss on ignition (LOI). Bulk mineralogy was determined by X-ray diffraction (XRD) on whole-rock powder mounts using CoKa radiation generated at 40 kV, 30 mA at 2.5 sec/0.05° 2θ from 4 to 65° 2θ. Total carbon (TC) and sulphur analyses were determined by induction furnace combustion with thermal conductivity and IR detectors, respectively (see Baedecker, 1987). Total organic carbon

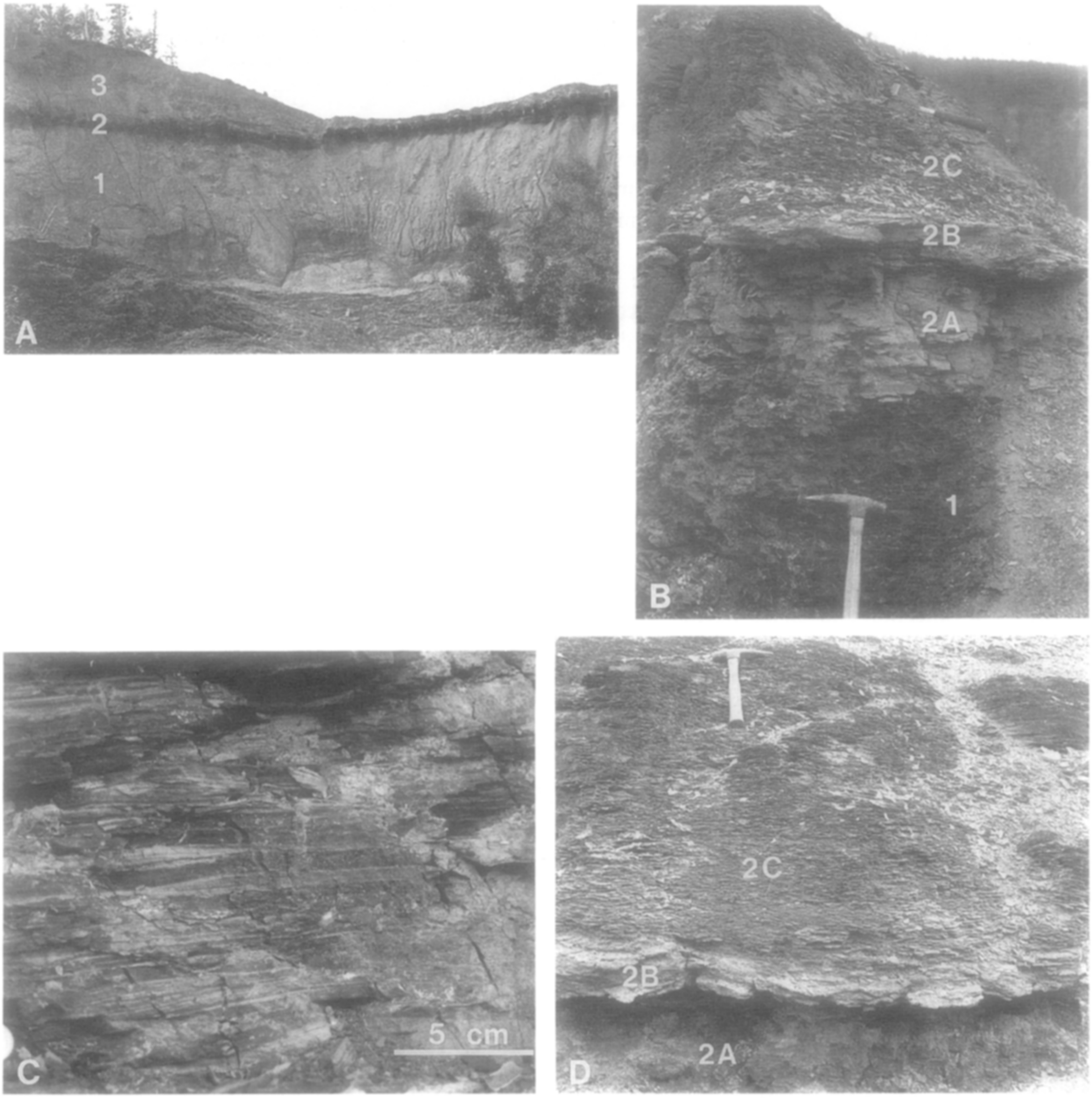


Fig. 2. Outcrop of the Fish Scale Marker Bed and contiguous strata below Judah Station on the Smoky River. A. Measured outcrop section. Numbers refer to units described in the text. Unit 2 is the Fish Scale Marker Bed. Person for scale below the number *1*. B. Sharp contact between Units 1 and 2. The upper hammer, above *2C* is in the bentonite making up Unit 2D. Numbers refer to units described in the text. C. Finely interbedded sandstone, siltstone and shale comprising Unit 2A. D. Unit 2 which makes up the Fish Scale Marker Bed.

(TOC), hydrogen and oxygen indices (HI and OI) and T_{max} were determined by Rock-Eval pyrolysis (Espitalié et al., 1985). TC from combusted, acid-leached samples were compared with Rock-Eval TOC to insure consistency between combustion and pyrolysis methods for carbon content. Total inorganic carbon (TIC) was calculated as the difference of TC and TOC.

Mineral modes were determined using the method of Pearson (1978) as modified by Bloch (1989) to document mineralogical changes through the section. In this method, elemental analyses are used as mass-balance constraints to calculate mineral modes. XRD data are used to define the mineral assemblage. Carbonate and sulphate mineral abundances were calculated by oxide mass balance with inorganic (carbonate) carbon and sulphur values. Silicate mineral abundances were calculated using simultaneous solution of mass-balance equations (Bloch, 1989) for five major oxides (SiO_2, Al_2O_3, FeO, MgO, K_2O).

The lack of compositional data on the clay minerals, and the complex assemblage of smectite, illite, kaolinite, chlorite, or mixed layer illite–smectite, kaolinite and chlorite, are potentially large sources of error in the determination of modal mineralogy from whole-rock chemistry. Clay-mineral composition was approximated by compositional data for smectite from Güven (1988), illite from Weaver and Pollard (1973) and chlorite from Foster (1962), analogous to a normative calculation. Consideration of compositional variation in smectite and illite, particularly for magnesium and aluminum, suggests that errors in clay-mineral abundances may approach 20 wt%. However, the calculation errors are systematic and do not affect an interpretation of the data based on relative differences. Sulphate and carbonate mineral abundances were determined by mass-balance of sulphur and inorganic carbon abundances and therefore have errors less than 1 wt% (weight percent).

Geological setting and the age of the Fish Scale Marker Bed

The Fish Scale Marker Bed (FSMB) is generally considered to mark the Albian–Cenomanian stage boundary in Western Canada (Warren and Stelck, 1969, p. 533). This interpretation was based on the succession of *Neogastroplites* spp., mainly in the Fort St. John area of northeastern British Columbia (Fig. 3), coordinated with the neogastroplitid zonation of Reeside and Cobban (1960) for the Western Interior of the United States. *N. maclearni*, which occurs within the FSMB in northeastern British Columbia and at Cadomin in central western Alberta (Fig. 1), was considered to be of latest Albian age. *N. maclearni* is accompanied by *Metengonoceras* in the Grand Cache area of central western Alberta (Warren and Stelck, 1969, fide Thorsteinsson, 1952, p. 30) with implication for an early Cenomanian age according to Cobban and Kennedy (1989, p. L9). *N. americanus* and *N. muelleri* (the latter from talus record only–Warren and Stelck, 1969, p. 532) were collected a few metres below the FSMB in the Fort St. John area. Cobban and Kennedy (1989) have implied that the Albian–Cenomanian boundary should be lowered at least to the base of the *N. americanus* Zone, based on the association of *Metengonoceras* faunas, closely resembling Early Cenomanian species from Texas, with the zones of *N. americanus* and *N. muelleri* in Wyoming and Montana. They also suggested that the order of these two zones be reversed from the original arrangement in Reeside and Cobban (1960) so that *N. americanus* precedes *N. muelleri*, as is shown in Fig. 3. As a few fragments of *Metengonoceras* were obtained from the underlying *N. cornutus* Zone in the U.S. Western Interior region, its age may well be early Cenomanian according to Cobban and Kennedy (1989, p. L9).

In contrast to the comparatively thick, proximal succession of sediments in northeastern British Columbia, with its well-documented faunal succession, the equivalent strata of the much thinner, condensed distal sequence exposed to the east in the northern Alberta plains near the town of Peace River have not yielded any ammonites. As a consequence, reliance is placed on microfossils and palynomorphs for confirming the age of the FSMB at the studied outcrop. Elements of the *Verneuilina canadensis* foraminiferal assemblage were recorded from the Shaftesbury Formation below the FSMB here as well as at other localities in the immediate area (Leckie et al., 1990, Nielsen, 1950). The *V. canadensis* Subzone corresponds to the beds directly below the *Neogastroplites haasi* Zone (Fig. 3) of late Late Albian age (Stelck and Koke, 1987, p. 2259). The other two younger subzones of the *Miliammina manitobensis* Zone, viz. *Haplophragmoides postis goodrichi* and *Bulbophragmium swareni*, recognized in beds subjacent to the FSMB in northeastern British Columbia, are not identifiable in northern Alberta, probably due to pinch out of the associated strata to the east (Fig. 3). Their disappearance along with the

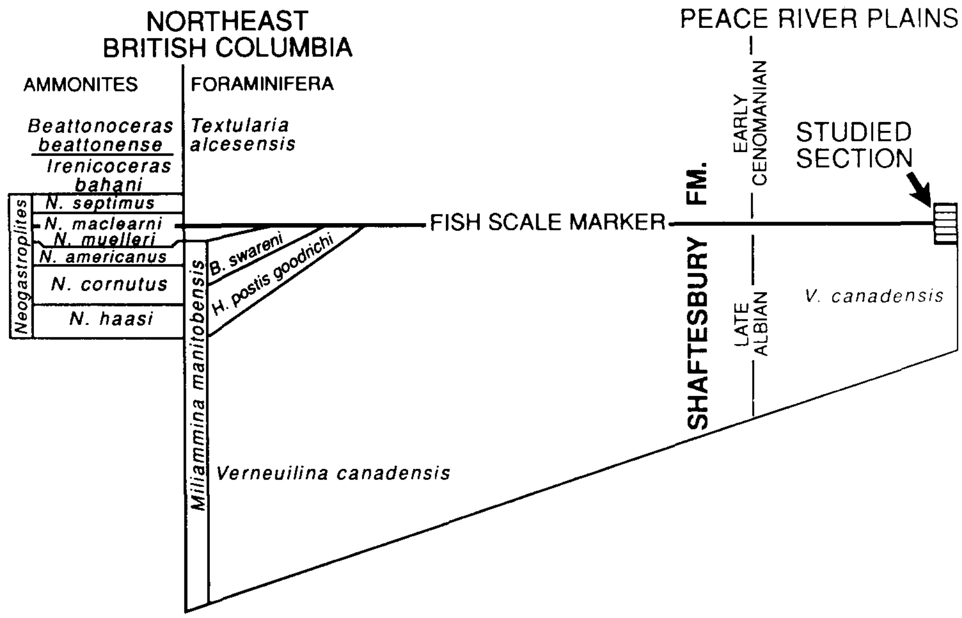


Fig. 3. Schematic cross-section from northeastern British Columbia to the Peace River plains showing the distribution of the ammonite and foraminiferal zones.

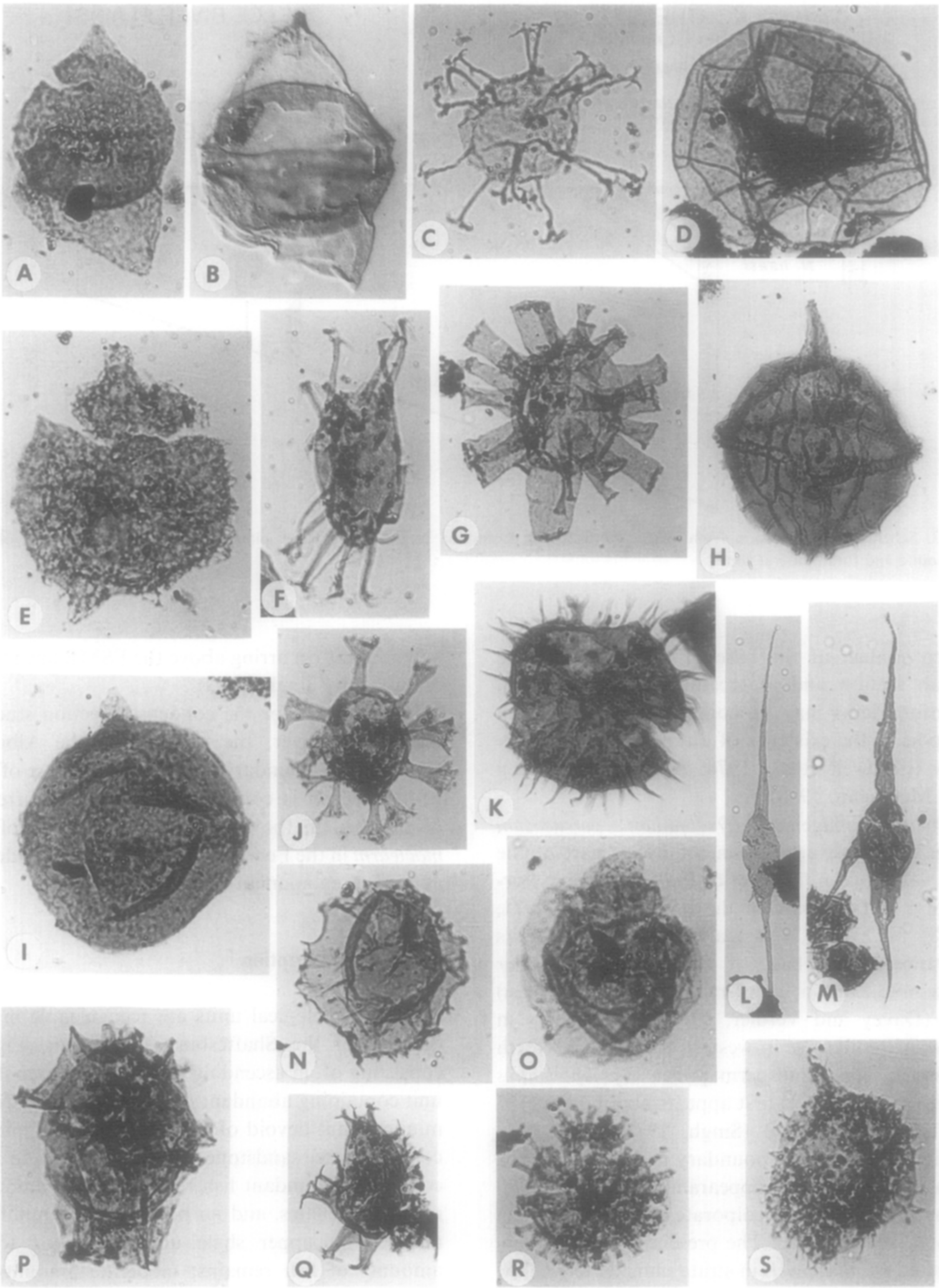
sharp contact at the base of the FSMB in the Judah section and at localities in the southern Interior Plains may be construed as evidence in support of the existence of a regional paraconformity (Caldwell et al., 1978; Arnott, 1987; Lang and McGugan, 1988).

The dinoflagellate *Ovoidinium verrucosum* (Fig. 4: A) first appears in the upper part of the interval between the base of the Shaftesbury Formation and the base of the FSMB (Singh, 1971, p. 28). In France, this marker species makes its entrance at the base of the *Stoliczkaia dispar* ammonite Zone of late Vraconian (latest Albian) age (Davey and Verdier, 1973) and appears in rocks of similar age in western Europe and North America. The angiosperm pollen *Nyssapollenites albertensis* (Fig. 5: I) first appears about 35 m (115 ft) below the FSMB (Singh, 1971, p. 28). The Albian–Cenomanian boundary in North America is marked by the first appearance of similar small, smooth, triangular, tricolporate angiosperm pollen (Singh, 1975, p. 379). The presence of *O. verrucosum* and *N. albertensis* in strata immediately below the FSMB indicates a latest Albian (Vraconian) age for this interval. The Lower Cenomanian palynofloras occurring above the FSMB have been discussed by Singh (1983).

In summary, for the condensed section studied on Smoky River, the position of the Albian–Cenomanian boundary is drawn at the base of the FSMB, which is compatible with the occurrence of this bed in the more complete section of *N. maclearni* in the Fort St. John area, now considered as Early Cenomanian in age.

Lithologic description

Three lithological units are recognizable in the outcrop of the Shaftesbury Formation (Fig. 6) consisting of, in ascending order: (1) a lower shale unit containing abundant dinoflagellates and foraminifera, but devoid of fish remains; (2) a middle conglomerate, sandstone, siltstone and shale unit containing abundant fish remains, lesser amounts of dinoflagellates, and no benthonic foraminifera; and (3) an upper shale unit containing lesser amounts of fish remains, moderate amounts of dinoflagellates and rare foraminifera, the last only at the top.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Unit 1 (0–12.65 m)

Description

Unit 1 consists of 12.65 m of non-fissile, apparently massive, slightly silty shale (Fig. 2A,B). No sedimentary structures are apparent, and the shale weathers blocky in the outcrop. The only trace fossils are horizontal, pyritized 1 mm-wide, filament-like traces of *Gordia* (?) and horizontal siltstone-filled burrows (*Planolites* ?) up to 4 mm wide. The base of the unit is not exposed.

Interpretation

Unit 1 represents pelagic sedimentation in an offshore-marine setting. The presence of bioturbation suggests a well-oxygenated water column, with the substrate inhabited by benthonic, burrowing organisms.

Fish Scale Marker Bed, Unit 2 (12.65–14.2 m)

The FSMB (Unit 2) forms a prominent resistant ridge on the outcrop (Fig. 2A) and is divided into four lithologically distinct subunits (Figs. 2B and 6).

Unit 2a (12.65–12.95 m)

Description. Unit 2A is 30 cm thick and consists of finely interbedded shale, siltstone, and very fine-

Fig. 4. Diagnostic species of dinoflagellates from strata within and adjacent to the Fish Scale Marker Bed. The species name is followed by a Geological Survey of Canada (GSC) type number which can be used to access permanent records giving the slide number and microscope coordinates for each specimen. μm indicates maximum dimension.

A. *Ovoidinium verrucosum* (Cookson and Hughes, 1964) Davey, 1970, GSC 99755 (77 μm).

B. *Luxadinium propatulum* Brideaux and McIntyre, 1975, GSC 99756 (77 μm).

C. *Oligosphaeridium tenuiprocessum* Singh, 1983, GSC 99757 (89 μm).

D. *Stephodinium australicum* Cookson and Eisenack, 1962, GSC 99758 (80 μm).

E. *Cyclonephelium vannophorum* Davey, 1969, GSC 99759 (85 μm).

F. *Bourkidinium psilatum* Singh, 1983, GSC 99760 (86 μm).

G. *Florentinia cooksoniae* (Singh, 1971) Duxbury, 1980, GSC 99761 (86 μm).

H. *Cribroperidinium intricatum* Davey, 1969, GSC 99762 (121 μm).

I. *Apteodinium reticulatum* Singh, 1971, GSC 99763 (96 μm).

J. *Oligosphaeridium totum* Brideaux, 1971, GSC 99764 (80 μm).

K. *Pervosphaeridium cenomaniense* (Norvick, 1976) Below, 1982, GSC 99765 (90 μm).

L. *Odontochitina singhii* Morgan, 1980, GSC 99766 (330 μm).

M. *Odontochitina costata* Alberti, 1961, GSC 99767 (285 μm).

N. *Catastomocystis spinosa* Singh, 1983, GSC 99768(60 μm).

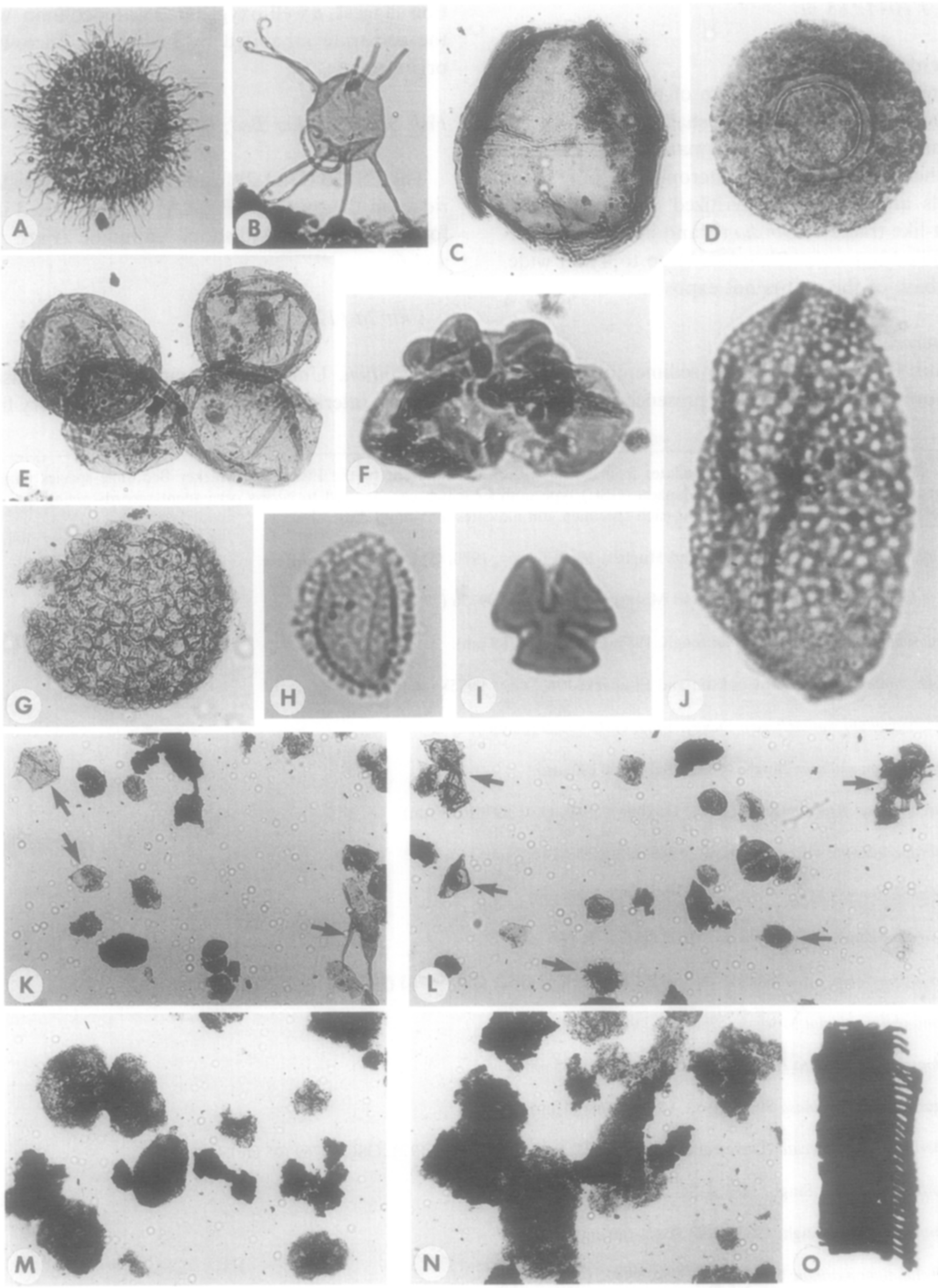
O. *Leberidocysta defloccata* (Davey and Verdier, 1973) Stover and Evitt, 1978, GSC 99769 (65 μm).

P. *Spiniferites aligerus* Singh, 1983, GSC 99770 (77 μ).

Q. *Spiniferites tripus* Singh, 1983, GSC 99771 (66 μm).

R. *Dapsilidinium marinum* Singh, 1983, GSC 99772 (49 μm).

S. *Aptea* sp., GSC 99773 (64 μm).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grained sandstone (Fig. 2C). Sandstone comprises about 40% of the unit. The basal contact is remarkably sharp. Bed thicknesses vary from millimetre-thick coarse siltstone and sandstone laminae within the shale to 4-cm thick sandstones. Many sandstone and siltstone beds are lenticular and pinch out laterally over 10–20 cm. Coarse siltstone beds are sharp based, graded or parallel laminated, and up to 2 cm thick. Sandstone beds are sharp based and contain parallel laminations and possibly bidirectional, wave-ripple stratification. The wave length of ripple crests is on the order of 22 cm, with a trough-to-crest amplitude of 16 mm. One set of ripple crests is oriented 3-183° and the dominant ripple-foreset direction dips towards the west. Some sandstone beds contain abundant millimetre-thick wisps of siltstone. There is no bioturbation.

Proportions of the kinds of fish remains are given in Fig. 7. The fish remains occur primarily as scales ranging from 3 mm to 2 cm in size (Fig. 8: A, D), with lesser amounts of bones (Fig. 8: B, C) and teeth, and are noticeable directly above the sharp basal contact. Counts of fish scales in a 100 cm^2 area show that the greatest concentrations occur on the coarse siltstone and sandstone laminae (0–51 scales/100 cm^2, averaging 38) with lesser amounts within the interbedded shales (0–9 scales/100 cm^2, averaging 5). Other bones, occurring mostly in the finer-grained layers, are biological aggregations (i.e., coprolites).

Interpretation. The rippled and parallel-laminated, coarse siltstones and sandstones are the deposits of currents having relatively low flow velocities. Sharp-based and graded or parallel-laminated siltstones resemble distal storm deposits described by Aigner (1984). The sandstones may have been

Fig. 5. Diagnostic species of dinoflagellates, acritarchs and pollen grains along with organic matter from strata within and adjacent to the Fish Scale Marker Bed. The species name is followed by a Geological Survey of Canada (GSC) type number which can be used to access permanent records giving the slide number and microscope coordinates for each specimen. µm indicates maximum dimension.

A. *Cometodinium whitei* (Deflandre and Courteville, 1939) Stover and Evitt, 1978, GSC 99774 (69 µm).

B. *Tubulospina circinata* Singh, 1983, GSC 99775 (77 µm).

C. *Ascostomocystis maxima* Singh, 1971, GSC 99776 (140 µm).

D. *Pterospermella* sp., GSC 99777 (79 µm).

E. A cluster of *Leiosphaeridia* sp., GSC 99778 (75 µm).

F. *Rugubivesiculites multisaccus* Singh, 1983, GSC 99779 (53 µm).

G. *Palambages* Form A Manum and Cookson, 1964, GSC 99780 (121 µm).

H. *Retimonocolpites textus* (Norris, 1967) Singh, 1983, GSC 99781 (19.5 µm).

I. *Nyssapollenites albertensis* Singh, 1971, GSC 99782 (15 µm).

J. *Liliacidites giganteus* Singh, 1983, GSC 99783 (50 µm).

K, L. Sample 12 (12.65 m): Showing a high density of dinoflagellates (indicate by arrows) with very little organic matter and representing strata deposited in well oxygenated environment with good water circulation below the Fish Scale Marker Bed X120.

M. Sample 13 (12.8 m).

N. Sample 20 (15.1 m): Showing abundant amorphous organic matter in strata deposited under anoxic condition with poor water circulation within and above the Fish Scale Marker Bed X120.

O. Sample 3 (5 m): Details of a tracheid (from land-derived wood) X400.

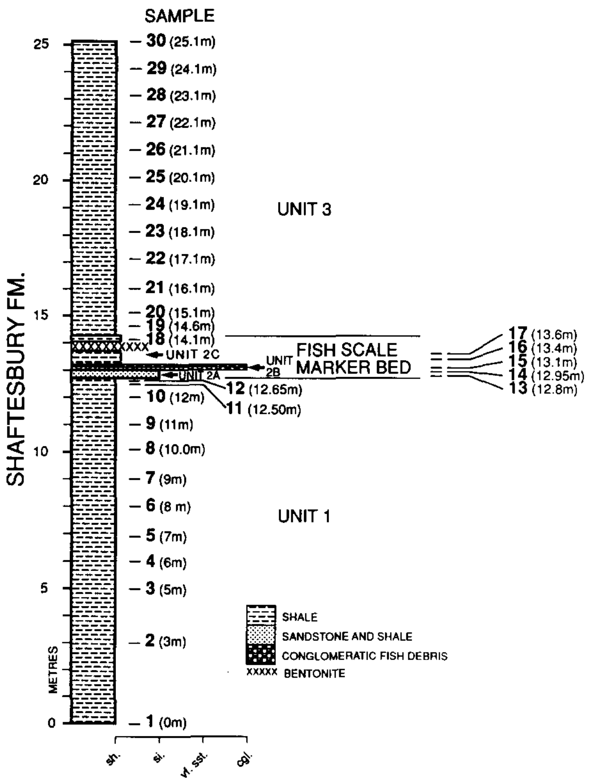


Fig. 6. Measured section of the Shaftesbury Formation adjacent to the Fish Scale Marker Bed showing the three lithological units and sample positions.

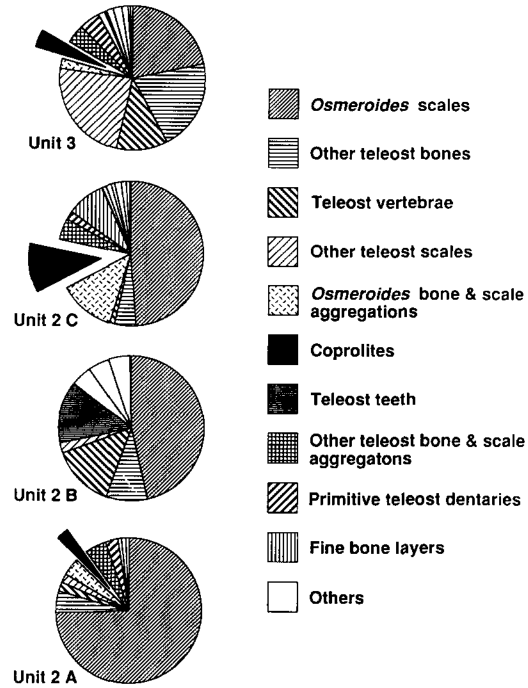


Fig. 7. Proportions of the kinds of fish remains in four units of the Fish Scale Marker Bed. *Osmeroides* scales are the dominant remains in all units except Unit 3, which has more bones of other teleosts. Coprolite fractions are highlighted because (a) they demonstrate the activity of predators feeding on fish, and (b) they cannot be reworked or transported. Coprolites might have been present also in Unit 2B, but would have been destroyed by abrasion or turbulence.

Fig. 8. Representative vertebrate fossils of Units 2A and 2B, Fish Scale Marker Bed, Shaftesbury Formation, Alberta. All specimens are deposited in the Laboratory for Vertebrate Paleontology, University of Alberta (UALVP). Scale bars = 5 mm.

Unit 2A:

A. Aggregation of fish scales, *Osmeroides transversus*, from the basal layers of Unit 2A. Note scales separated by thin layers of sediment.

B. Quadrate bone (jaw articulation) of a teleostean fish.

C. Aggregation of finely broken fish bones and scales.

D. Two isolated teleostean fish scales.

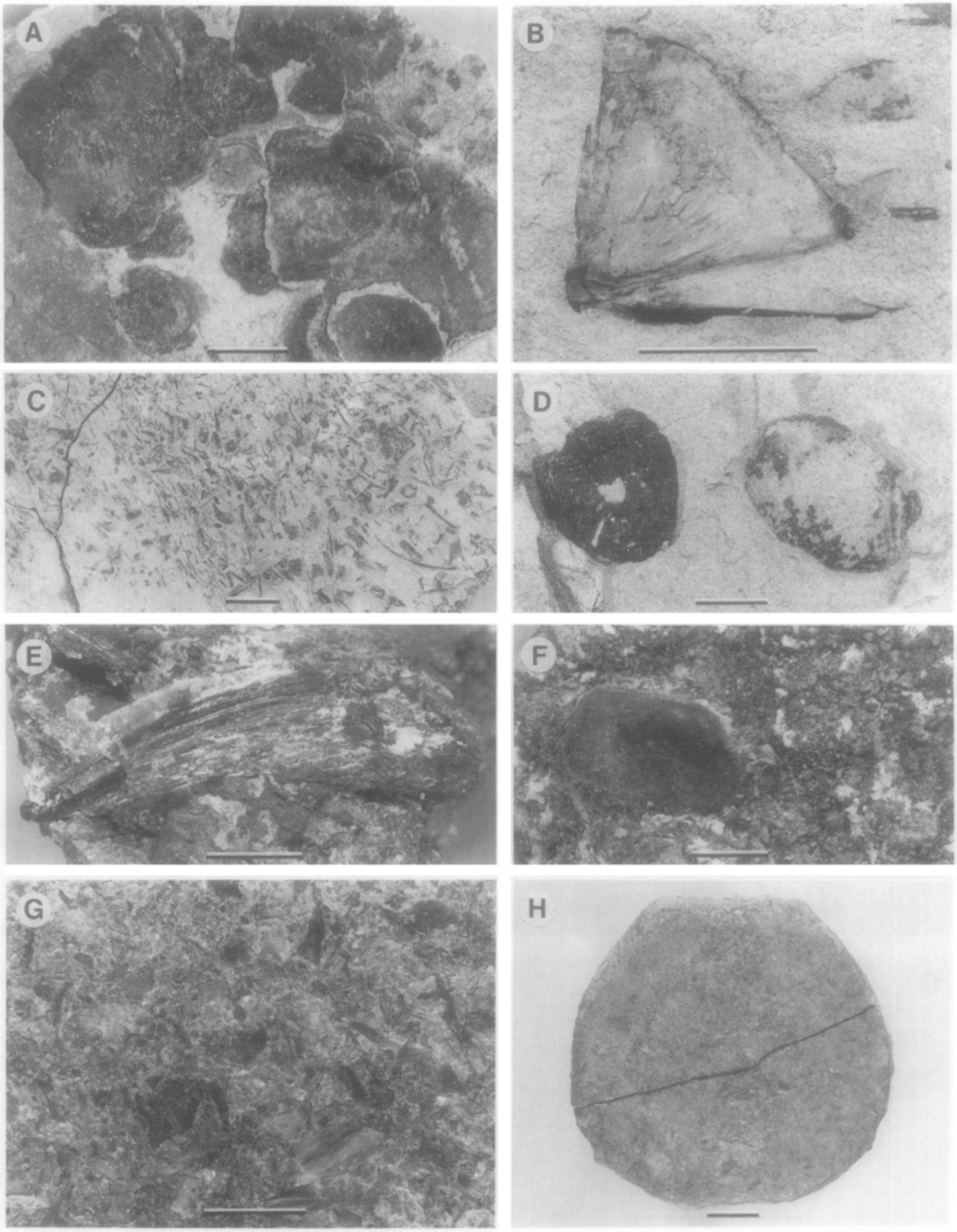
Unit 2B:

E. Tooth of a marine reptile in a matrix of small fragments of fish bones and scales.

F. Pebble in a matrix of small fragments of bones and scales.

G. Bedding plane in the bone bed covered with fragments of small bones and scales.

H. Caudal vertebra of an ichthyosaur (marine reptile) removed from the bone bed.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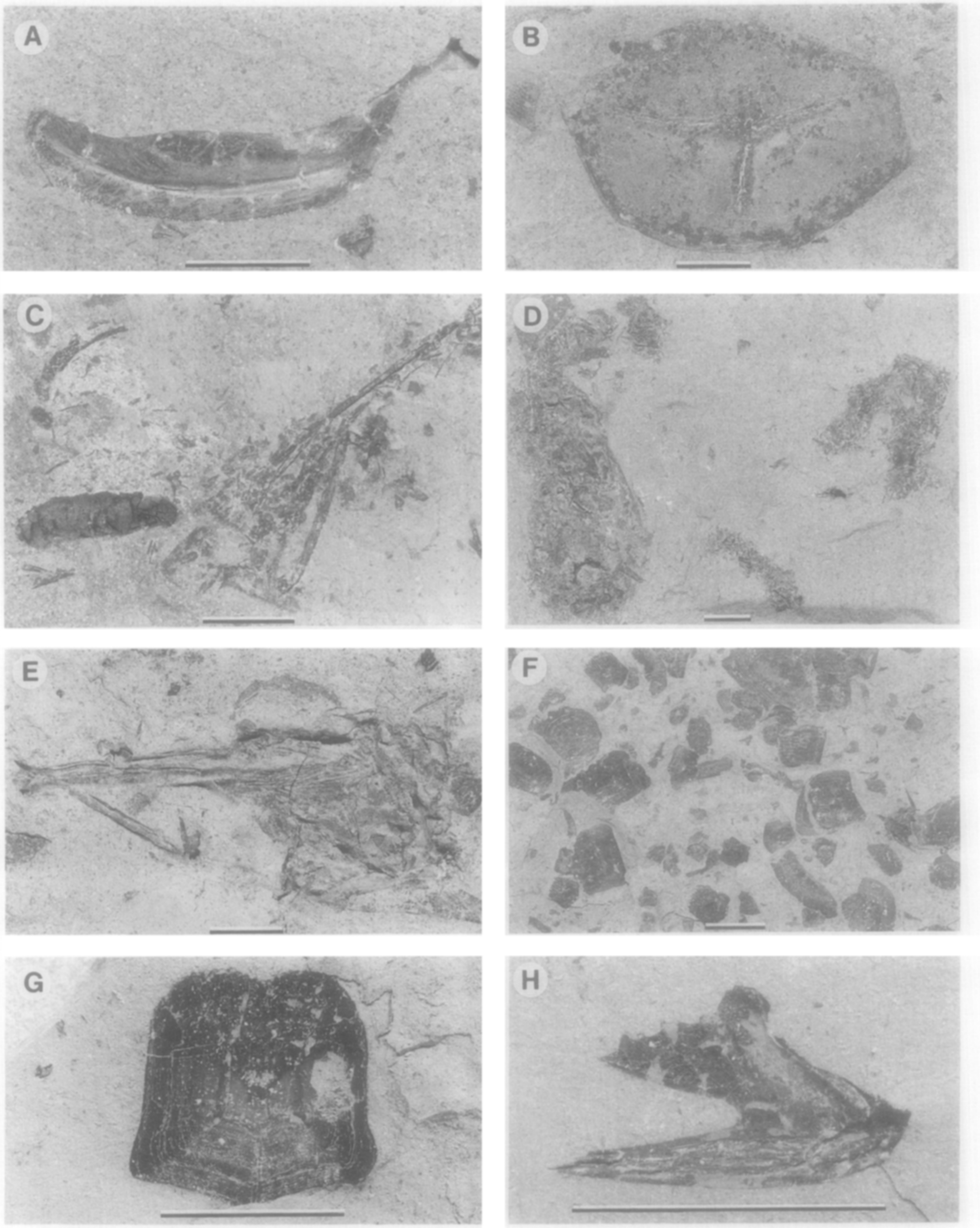
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transported to this area by storm-generated or fluvially generated density flows, although the possibility of semi-permanent ocean currents cannot be ruled out. Lenticular, rippled sandstones indicate that the sea floor was somewhat starved of sand. Siltstone laminae within some of the rippled sandstone suggest fluctuating currents. The well-preserved, fine lamination with no bioturbation indicates that the bottom waters and substrate were inhospitable to burrowing benthonic organisms.

The high concentrations of fish remains, particularly scales, associated with the siltstone and sandstone suggest that some of the bones were transported, or at least concentrated, by currents. The coprolites demonstrate that predators of fish were active in the area above the sediments during deposition of the fine-grained layers. The sharp basal contact to the unit suggests a sudden change in environmental conditions with possibility of a minor hiatus.

Unit 2b (12.95–13.03 m)

Description. This 8-cm thick unit consists of a phosphatic, bioclastic, fish-hash conglomerate that is well cemented and forms a resistant unit (Fig. 2B). The fish remains consist of fragments of scales and teeth. Tooth debris varies from a few millimetres to 1 cm in length (Fig. 8E). The maximum clast size is represented by a 5-cm diameter ichthyosaur vertebra and another comparably-sized reptile bone. Extraformational clasts are very rare as only three chert pebbles were found, with the largest being 1.5 cm in diameter. One clast of coalified-wood debris, 20 cm long and 1 cm thick, was found. Selenite crystals are abundant as is an unidentified, amber-coloured, resinous material having a rainbow-coloured fluorescence. X-ray diffraction analysis shows that the amber unit contains quartz, apatite, alunite and possibly barite.

Interpretation. The origin of Unit 2B is enigmatic. This unit, containing the coarsest debris in the outcrop, has many of the characteristics of a lag deposit. It appears to separate shallower-water sediments containing evidence of current activity (Unit 2A) from apparently deeper-water deposits of Unit 2C. As such, it is inferred to signify a deepening of the water column. The largest clasts (reptile bones, chert pebbles) need not have been transported very far by bottom currents because the reptiles were marine and some of the chert pebbles could represent gastroliths (stomach

Fig. 9. Representative fish fossils of Units 2C and 3, Fish Scale Marker Bed, Shaftesbury Formation, Alberta. All specimens are deposited in UALVP. Scale bars = 5 mm.

Unit 2C:

A. Maxilla (upper jaw bone) of a teleostean fish.

B. Scale of a large ichthyodectid teleostean fish.

C. Coprolites (fossil feces), small cylindrical one with amorphous contents of digested bone, large diffuse one with contents of broken fish bones.

D. Three coprolites with contents of broken fish bones.

E. Partial skull of a teleostean fish in the family Enchodontidae.

Unit 3:

F. Aggregation of scales of the teleostean fish *Osmeroides transversus*.

G. Single scale of the teleostean fish *Osmeroides* sp.

H. Dentary (lower jaw bone) of a primitive teleostean fish.

stones). The abundance of sulphate minerals indicates weathering of an initially sulphide-rich sediment. A sediment containing abundant sulphide and phosphate is consistent with elevated concentrations of preserved organic material.

Unit 2c (13.03–14.2 m)

Description. Unit 2C consists of 1.17 m of black, platy shale containing abundant fish remains with a 20 cm bentonite bed 76 cm above the base. The shale weathers into fissile plates a few millimetres thick and 1–15 cm in diameter and forms a resistant ledge along the length of the outcrop (Fig. 2B,D). Millimetre-thick wisps of coarse siltstone and very fine-grained sandstone are dispersed throughout the shale, and no burrowing traces were observed. Fish remains, including scales, bones and biological concentrations of these (i.e., coprolites and/or gastric residues) generally lie horizontal. The largest scales are 3 cm in size (Fig. 9B). Counts of fish scales within the shales show that they occur with an average frequency of 29 scales/100 cm^2 (range of 2–107 scales/100 cm^2). Fish scales occur in greater abundance on the siltstone and sandstone laminae, with an average frequency of 148 scales/100 cm^2 (range of 118–176 scales/100 cm^2). Several partially articulated fish skulls (Fig. 9E) and a partial tail were found. One piece of coalified wood debris, 30 cm long and 0.5 cm thick, was also found.

A 20-cm thick, grey, sanidine-bearing bentonite occurs 76 cm from the base of Unit 2C. A 2.5-cm diameter, circular pyritic concretion was found within the bentonite. The bentonite comprises largely discrete smectite with quartz, jarosite, and minor gypsum. Chemical analysis of a Na-saturated smectite separate from this bentonite indicates that this smectite is a Wyoming-type montmorillonite (Grim and Kublicki, 1961).

Interpretation. The wisps of coarse siltstone and very-fine sandstone may be the result of sediment transported to this part of the basin as a result of distant storms, or possibly the result of very weak but persistent ocean currents. The greater concentration of fish scales on the siltstone and sandstone laminae indicates that current activity is partially responsible for transporting and concentrating some of the platy fish scales. Another large fraction of the fish remains was obviously deposited here as coprolites.

The bentonite represents an altered volcanic ash probably derived from central British Columbia in the Omineca Belt and Western Rocky Mountains where Armstrong (1988) has documented that there was considerable volcanic activity during the Middle Cretaceous.

Unit 3 (14.2–25.1 m)

Description

Unit 3 (Fig. 2A) consists of 10.9 m of shale which is not as fissile and weathers more blocky than the underlying shale of Unit 2C. Millimetre-thick, faint parallel laminations are locally evident in some of the shale and there is no apparent bioturbation. Scales are the most abundant fish remains, followed by fish bones and coprolitic concentrations. Scales are flat-lying and occur with an average concentration of 6 scales/100 cm^2 (range of 0–17 scales/100 cm). The top of Unit 3 is vegetated and highly weathered.

Interpretation

The concentration of fish scales decreases upward from Unit 2D to Unit 3. If it is assumed that the rain of fish debris was constant over time (see discussion below), then the decreasing concentration of fish scales upwards may be due to an increased rate of sedimentation. If this is the case, then the shale of Unit 3 may represent the beginning of a progradational event, which may be expressed as a downlapping surface overlying the condensed section. This interpretation is consistent with regional wire-line log cross-sections through northwestern Alberta (J. Bhattacharya, pers. comm., 1990), which indicate that clinoforms downlap onto the FSMB.

Fish remains

Stratigraphic distribution

Fish scales and bones are abundant on most bedding planes throughout the FSMB (Unit 2).

They occur in somewhat decreasing frequency in the lower 3.5 m of shales overlying the Fish Scale Marker (Unit 3) and are absent from Unit 1. The shale occurrences are not unlike fossil fish assemblages elsewhere, including the Mowry Shale in Colorado (Cockerell, 1919) and the Kanguk Formation on Banks Island (Wilson, 1978). The distribution of fish debris is consistent with a nearly continuous rain of fish remains onto the sea floor over a long period of time (perhaps tens to hundreds of thousands or even millions of years).

Unit 2B consists of nearly 100% fish-bone "hash", made up of small bone, tooth and scale fragments. This bone-bed concentration may be a lag deposit. Similar bone beds occur in the Kaskapau Formation near Watino, Alberta (Wilson and Chalifa, 1989) and at the base of the Shaftesbury Formation near Peace River town (Leckie et al., 1990; Leckie and Singh, in press), although sharks' teeth are more prominent in those samples than they are in the FSMB.

Taxonomy

At least four kinds of fish are represented (Fig. 7), all of them typical of Albian to Turonian fish assemblages of the interior of North America. *Osmeroides transversus* is by far the most abundant species. It occurs in the Kanguk Formation of Banks Island (Wilson, 1978) and the Mowry Formation of the western United States (Cockerell, 1919). *O. transversus* is represented in the FSMB by its scales, which are the most common skeletal fossils in both the siltstone and the shales, as well as by other bones, of which superficial skull bones are the most common and most readily identified. Other taxa include Ichthyodectidae (Bardack, 1965; Wilson and Chalifa, 1989), represented by several large scales and a toothed dentary bone in Unit 2C, and Enchodontiformes (Bardack, 1965; Wilson and Chalifa, 1989), represented by a single partial skull in Unit 2C. Reptiles are represented by vertebral centra of ichthyosaurs in Unit 2B. Units 2C and 3 also contain a few bones and scales of a very small acanthomorph teleost. Overall, the taxa represent pelagic or nektonic species rather than obviously benthonic forms.

Taphonomy

Most of the fish fossils are preserved as isolated scales and bones (Figs. 7–9). The most common bones are superficial bones of the skull, with pectoral-girdle and vertebral elements somewhat less common as isolated elements. A few aggregations of bones and scales appear to represent single skeletons, since they are closer to each other than they would be if randomly distributed over a bedding plane. These commonly include aggregations of vertebrae and scales as well as skull bones and fin-ray fragments which are nearly completely disarticulated. Several partial skulls are also present in Unit 2C.

The preservation of almost completely disarticulated fish bones and scales in the shale beds of Units 2A and 2C of the FSMB and Unit 3 means either that articulated fish did not settle to the bottom, or else that they settled out but were subsequently disturbed by scavengers, either vertebrate or invertebrate, attacking fish carcasses and scattering the bones (Elder and Smith, 1988). However, lack of epifauna and infauna suggests that the water column above the substrate (and the mud itself) was anoxic or otherwise inhospitable to animals, thus excluding benthonic scavengers.

Alternative mechanisms, other than scavenging, which are capable of producing assemblages of disarticulated fish bones and scales include flotation-decay, whereby bloated, floating carcasses drop bones and scales to the sea bottom (Elder and Smith, 1988; Schäfer, 1972; Wilson, 1988); predation, resulting in undigested bones from feces or gastric residues (Wilson, 1987; Wilson, 1988); and wave agitation or current disturbance (Elder and Smith, 1988).

The actual bone dispersal mechanism can be distinguished in many cases by the arrangement of bones on the substrate. In the flotation-decay mechanism, superficial bones and scales are randomly distributed over bedding planes, interspersed with fragmentary and partially disarticulated skeletons that lack many of the superficial elements (Wilson, 1987). In the scavenging mechanism, partially articulated skeletons may be recognized, around which the superficial bones, especially those of the skull, are scattered in random directions but still more closely associated with the remains of the skeleton than in the flotation-decay model (Elder and Smith, 1988). In the predation mechanism, partially dissolved, disarticulated bones are randomly arranged but spatially concentrated within coprolites or gastric residues, some of them including bones of more than one individual or species in a single aggregation (Wilson, 1987). In the current-dispersal mechanism, partially articulated skeletons occur, with the superficial bones, scales and fin rays aligned in the down-current direction (Elder and Smith, 1988). In the FSMB, the main problem in discriminating among these mechanisms is the paucity of articulated skeletal fragments against which to compare the distribution of the isolated bones.

The fish fossils in shale of Units 2C and 3 show minimal evidence of current disturbance whereas fish remains in Unit 2A appear to be concentrated in the siltstone and sandstone beds. Many or most bones and scales appear to be distributed at random over bedding planes, as in the flotation–decay model. A few examples resemble scavenged skeletons because of the proximity of the disarticulated superficial elements to what may be the remnants of a source skeleton. A few others are in loose aggregations somewhat more like predator concentrations.

In summary, the fish remains represent an abundant fish community, including predators, with complete decay of soft tissues following the death of the fish. The fish were primarily pelagic and nektonic. The FSMB may denote a slow accumulation and preservation of fish remains in anoxic bottom waters over a long period of time, rather than a sudden mass mortality.

Palynofacies

The strata from Unit 1 below the FSMB [samples 1 (0.0 m) to 12 (12.65m)] have a high dinoflagellate diversity (20–43 species) and count (114–361 specimens) (Table 1) indicating deposition in an open-marine, outer-neritic environment of normal salinity. The dinoflagellate assemblage is dominated by a single species, *Luxadinium propatulum* (Table 2). The sample immediately below the FSMB (sample 12, 12.65 m) has the highest dinoflagellate species diversity (43 species) and count (361 specimens). The offshore nature of Unit 1 is also indicated by the paucity of the continental palynoflora. Throughout the interval, the organic matter present in the slides is low (Fig. 5: K, L) and consists mainly of black pieces of coal (vitrinite), tracheids (Fig. 5: O) and leaf cuticles. All these factors indicate a stable, well-oxygenated environment with good water circulation during the deposition of the strata below the FSMB.

There is a marked reduction in the dinoflagellate species diversity and count within the FSMB [Unit 2: samples 13 (12.8 m) to 18 (14.1 m)], especially in the upper part (Table 1). This is accompanied by changes in each sample in the dominant dinoflagellate species indicating an unstable chemical environment (Table 2). This is also true of the interval above the FSMB [Unit 3: samples 19 (14.6 m) to 24 (19.1m)]. Changes in the water chemistry (e.g., salinity, pH, oxygen content and chemical nutrients) and physical environment (temperature

TABLE 1

Distribution, frequency and species diversity of microspores, pollen and dinoflagellates adjacent to the Fish Scale Marker Bed in the Shaftesbury Formation.

			Microspores and pollen*		Dinoflagellates		Environment
	Sample	Depth	No. of species	No. of specimens	No. of species	No. of specimens	
	24	(19.1m)	4	18	16	113	Anaerobic with poor water circulation
	23	(18.1m)	6	13	21	242	
Unit 3	22	(17.1m)	4	9	20	189	
	21	(16.1m)	4	10	20	180	
	20	(15.1m)	5	5	20	152	
	19	(14.6m)	5	21	21	135	
Fish Scale Marker Bed, Unit 2C	18	(14.1m)	2	7	17	77	Anoxic peak
	17	(13.6m)	5	6	8	48	
	16	(13.4m)	0	0	13	53	
	15	(13.1m)	5	6	12	29	
Fish Scale Marker Bed, Unit 2A	14	(12.95m)	7	16	20	148	
	13	(12.8m)	3	3	16	94	
	12	(12.65m)	13	26	43	361	Well oxygenated with good water circulation
	11	(12.5m)	10	12	34	306	
	10	(12.0m)	6	8	34	225	
	9	(11.0m)	9	13	34	279	
Unit 1	8	(10.0m)	9	14	37	254	
	7	(9.0m)	9	16	36	263	
	6	(8.0m)	10	13	29	198	
	5	(7.0m)	10	22	28	182	
	4	(6.0m)	11	14	29	188	
	3	(5.0m)	5	10	29	190	
	2	(3.0m)	8	12	31	204	
	1	(0.0m)	10	16	20	114	

*Excluding conifer pollen

TABLE 2

Distribution and frequency of the dominant dinoflagellate and acritarch species adjacent to the Fish Scale Marker Bed in the Shaftesbury FORMATION.

	SAMPLE DEPTH		*LUXADINIUM PROPATULUM*	*OVOIDINIUM VERRUCOSUM*	*ODONTOCHITINA OPERCULATA - COSTATA*	*CRIBROPERIDINIUM INTRICATUM*	*PALAEOPERIDINIUM CRETACEUM*	*APTEA* sp.	*APTEA EISENACKII*	*CYCLONEPHELIUM VANNOPHORUM*	*PSEUDOCERATIUM EXPOLITUM*	*LEIOSPHAERIDIA* sp.	*PTEROSPERMELLA* spp.
	24 (19.1m)	UNIT 3	1	17	17	2	1	-	34	8	18	12	54
	23 (18.1m)		8	30	17	6	3	-	5	85	30	16	43
	22 (17.1m)		-	65	23	4	1	-	-	39	22	16	32
	21 (16.1m)		8	34	30	12	-	-	17	-	-	41	5
	20 (15.1m)		4	35	41	10	12	-	7	-	-	42	5
	19 (14.6m)		1	30	47	2	10	-	6	-	-	41	19
FISH SCALE MARKER BED	**18** (14.1m)	UNIT 2C	1	23	13	5	3	-	10	-	-	34	10
	17 (13.6m)		-	34	1	1	4	-	4	-	-	17	5
	16 (13.4m)		-	6	6	1	20	-	10	-	-	22	1
	15 (13.1m)		-	-	5	2	2	1	6	-	-	-	3
	14 (12.95m)	UNIT 2A	28	28	4	2	-	41	8	-	-	-	3
	13 (12.8m)		15	25	1	3	6	17	1	-	-	-	3
	12 (12.65m)	UNIT 1	65	28	38	10	15	-	24	-	-	-	-
	11 (12.5m)		58	23	26	4	38	-	15	-	-	1	-
	10 (12.0m)		44	15	12	11	25	-	7	-	-	-	1
	9 (11.0m)		52	22	12	32	20	-	8	-	-	1	1
	8 (10.0m)		54	24	24	6	19	-	13	-	-	-	3
	7 (9.0m)		53	26	14	9	16	-	10	-	-	1	1
	6 (8.0m)		59	28	17	9	9	-	2	-	-	-	-
	5 (7.0m)		47	21	11	10	12	-	2	-	-	1	2
	4 (6.0m)		41	17	24	10	13	-	2	-	-	-	-
	3 (5.0m)		43	18	23	10	16	-	-	-	-	1	2
	2 (3.0m)		39	20	18	7	17	1	3	-	-	3	1
	1 (0.0m)		27*	6	10	5	6	3	1	-	-	1	2

*** Circled figures indicate the dominant species in a sample**

and the effect of turbidity on available light for photosynthesis) can probably favor one species of dinoflagellate over others. Marshall and Batten (1988) found similar variations in the Cenomanian to Turonian palynofacies of "black shale" sequences of northern Europe related to the changes in the lithofacies and the amount of oxygen levels in the water column. In the FSMB (Unit 2), the changes in the dinoflagellate population are accompanied by an enormous increase in brown, spongy or granular amorphous organic matter (Fig. 5: M, N). This suggests that the FSMB (Unit 2; Fig. 6) and the strata above (Unit 3) were deposited under anoxic conditions with poor water circulation (Table 1). The anoxic peak was probably reached in the upper part of the FSMB [samples 15 (13.1 m) to 18 (14.1 m)], which has the lowest dinoflagellate species diversity (8–17 species) and count (29–77 specimens). The reduction in the dinoflagellate population in Unit 2 was not caused entirely by the unfavorable environmental conditions; it is at least partially due to the dilution effect of the high amount of organic matter preserved in the sediments along with the dinoflagellates. Thus, the low dinoflagellate count may indicate very high accumulation of organic matter which decays very slowly at this level as a result of highly anoxic conditions.

In samples 19 (14.6 m) to 24 (19.1 m) from Unit 3, the dinoflagellate species diversity (16–21 species) and count (113 to 242 specimens) are moderate, indicating an increase in the dissolved oxygen content of depositional water and some reduction in the amount of organic matter preserved in the sediments (Table 1). However, the persistence of a generally unfavorable environment is indicated by the dominance of just a few species. For example, although 242 specimens of dinoflagellates were counted in sample 23 (18.1 m) (Table 1), more than half belong to three species (Table 2) viz. *Cyclonephelium vannophorum* (85 specimens), *Pseudoceratium expolitum* (30 specimens) and *Ovoidinium verrucosum* (30 specimens). Some reduction in the salinity of the surface waters and stratification of the water column may be indicated by the predominance of the marine green algae *Leiosphaeridia* sp. and *Pterospermella* spp. (Table 2) in the upper part of the FSMB and the strata above [samples 16 (13.4 m) to 24 (19.1 m)]. Samples 25 (20.1 m) to 30 (25.1 m) were not included in this study as they were badly weathered.

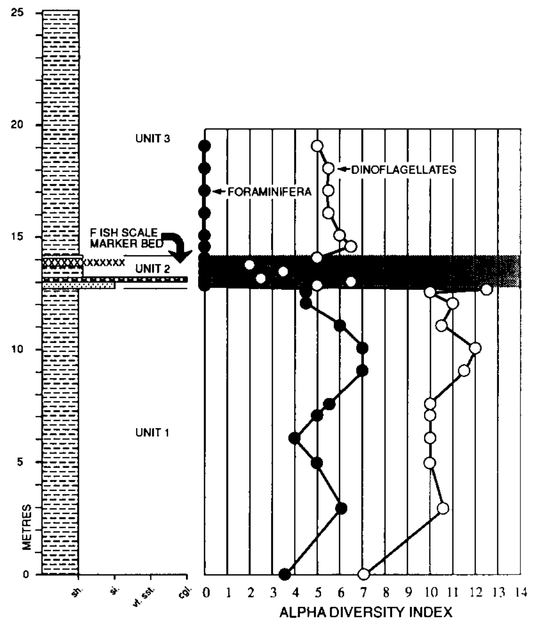

Fig. 10. Distribution and diversity indices of foraminifera and dinoflagellates in the Fish Scale Marker Bed and the contiguous strata of the Shaftesbury Formation.

Micropaleontology

The interval from Unit 1 below the FSMB [samples 1 (0.0) to 12 (12.65 m)] contains a moderately-diversified assemblage of entirely arenaceous, benthonic foraminifera. The prominent elements of this assemblage are *Gravellina chamneyi*, *Uvigerinammina manitobensis*, *Ammobaculites fragmentarius*, *Miliammina manitobensis* and related species, which are assignable to the late Late Albian *Verneuilina canadensis* Subzone of the *Miliammina manitobensis* Zone (Fig. 3; Stelck, 1975; Caldwell et al., 1978, p. 515).

Fisher alpha-diversity indices for the foraminifera and dinoflagellates (Fig. 10) were plotted for each sample, based on a graph in Murray (1973, p. 9). Murray (1973, p. 239, 240, fig. 101) has shown that in modern settings alpha values of 5 or higher indicate normal marine environments, whereas those of less than 5 signify abnormal hyposaline or hypersaline conditions. As the indices for a majority of the pre-fish scale foraminiferal assemblages are 5 or above, and most of the others are only marginally lower (Fig. 10), it is assumed that the foraminifera recovered from Unit 1 lived on an open-marine shelf of moderate depth and normal salinity. Since calcareous foraminifera were not recovered, it is difficult to make comparisons with modern oceanic shelf environments, where this group usually predominates. The application of alpha-diversity indices to assess ancient environments is limited by the concept of a fossil species, particularly among arenaceous foraminifera, being very subjective. Moreover, the salinity of the Cretaceous epeiric sea may well have been less than that of modern oceans. Although the dinoflagellates are planktonic and much more diverse than the benthonic foraminifera, there is a broad similarity in their distribution trends with some divergence just below the FSMB, where the dinoflagellates show a marked increase (Fig. 10).

The base of the FSMB (Unit 2) marks the onset of highly unfavorable bottom-water conditions. The absence of benthonic foraminifera above this level (Fig. 10) suggests that the dissolved-oxygen content of bottom-waters may have been too low for these organisms to survive. Only planktonic forms are represented above this level. Stelck et al. (1958, p. 24) recorded rare specimens of the planktonic foraminifera *Hedbergella* (listed as *"Globigerina"*) and *Heterohelix* (listed as *"Guembelina"*) from the FSMB. However, these were not encountered in the samples collected for the present study. Pelagic algal cysts [*Leiosphaeridia* sp., *Campenia* sp. (?) and cf. *Lancettopsis lanceolata* Mädler, 1963] are abundant within the FSMB (Fig. 12: A–C) and continue in the overlying 5 m of strata of Unit 3 in reduced numbers. These algae commonly occur in organic-rich marine shales, deposited under anoxic conditions (e.g., Shale Facies 2 of Leckie et al. 1990, p. 107, Fig. 7). A radiolarian, *Theocorys* sp. (Fig. 11: D–F), is extremely abundant in the upper part of the FSMB [samples 16 (13.4 m) and 17 (13.6 m)] and is present through about 4 m of suprajacent strata in Unit 3. Modern radiolarians are planktonic and live at all depths in the water although the bulk are found in the upper few hundred metres (Kling, 1978, p. 212). The upper levels of water also seem to have been adversely affected, as shown by the steep decline in the dinoflagellate species diversity in the FSMB (Fig. 10). There is some improvement in the dinoflagellate diversity index in the overlying strata indicating slightly less anoxic conditions.

Geochemistry

Mineralogy

X-ray diffraction (XRD) on whole-rock samples indicates that the mudstones of Units 1–3 are composed dominantly of mixed-layer illite/smectite (MLC) and quartz (Fig. 12). Some discrete smectite and illite are present. Additional silicate constituents include potassium feldspar, kaolinite and trace amounts of chlorite. Jarosite is a major component in all units and trace amounts of gypsum and siderite consistently are present. Macroscopic selenite is common in Unit 2C.

Unit 1 consists dominantly of MLC and quartz with jarosite and kaolinite generally accounting

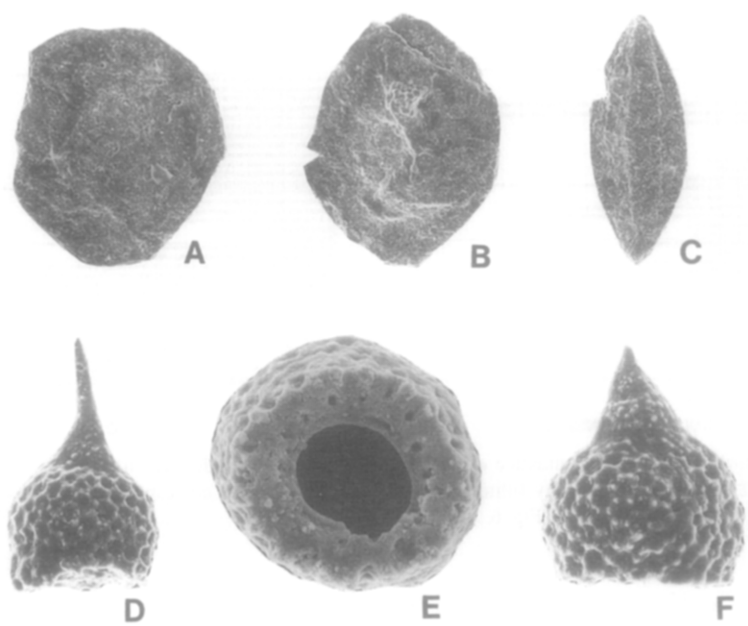

Fig. 11. Scanning electron photos of algal cysts and radiolarians from the Fish Scale Marker Bed, samples 15 (13.1 m) and 16 (13.4 m), respectively. µm indicates maximum dimension except for E which is width at base.

A. *Leiosphaeridia* sp., GSC 98238 (390 µm).

B. *Campenia* (?) sp., GSC 98239 (492 µm) with partial radiolarians incorporated in upper middle area.

C. cf. *Lancettopsis lanceolata* Mädler 1963 GSC 99754 (540 µm). D, E, F. *Theocorys* sp., GSC 98235, 98236, 98237 (171 µm, 89 µm, 125 µm).

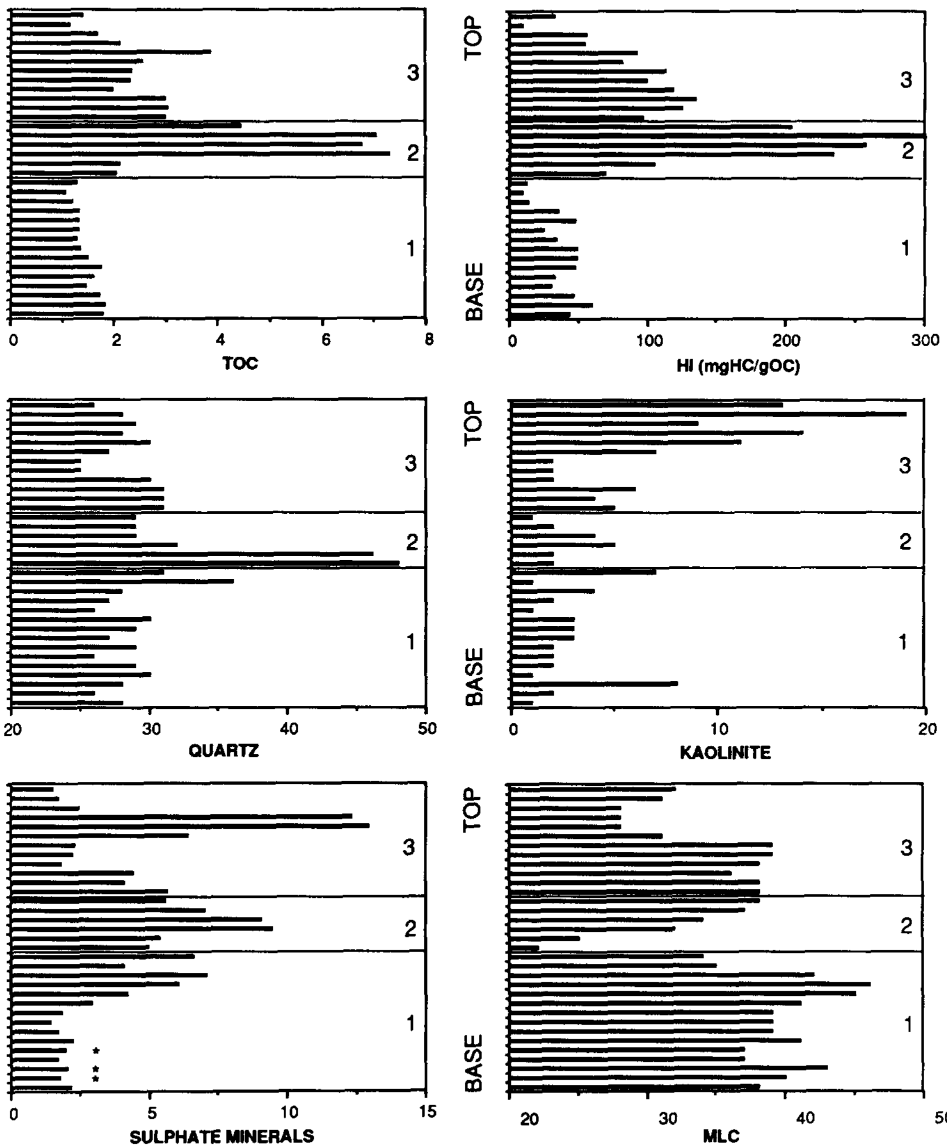

Fig. 12. Stratigraphic distribution of the abundance of major constituents, as weight percent, and Hydrogen Indices (HI). TOC is total organic carbon, MLC is mixed layer clay (illite/smectite). Sample locations correspond to those shown in Fig. 6. The three samples indicated by the * are not included in Fig. 6.

for less than 5 wt% (Fig. 12). Feldspar and chlorite are present as minor constituents whereas siderite, rutile, and apatite occur in trace amounts. Gypsum is ubiquitous in trace amounts, except in sample 14 (Unit 2A), where it makes up 2.5 wt% of the sample.

The abundance of quartz increases at the top of Unit 1 and is the major constituent in Unit 2A. Beginning 4 m below and continuing into Unit 2, there is a pronounced increase in the abundance of jarosite, up to approximately 8 wt%, in Unit 2C. Alunite occurs in unit 2C up to 1.5 wt%. The large increase in quartz reflects the coarse nature and increased sand content of the sediment in unit 2A (Fig. 12).

The lower half of Unit 3 shows a rapid decrease in jarosite abundance and is otherwise similar in composition to that of Unit 2. There is an increase in kaolinite content in the upper 5 m (Fig. 12). The greatest abundance of jarosite (approximately 12 wt%) also occurs in the upper 5 m of Unit 3. Overall, MLC abundance decreases up section and kaolinite content increases.

Organic matter

Rock-Eval data indicate that much of the organic matter (OM) is apparently Type III with possibly some Type II (Fig. 13) and that the OM of each facies is distinct. Unit 2C is the most reactive and presumably has the highest abundance of Type II OM. Unit 1 is dominantly Type III and Unit 3 contains both Type III and II OM. Unit 3 samples with high OI values are from the upper 5 m of the section that is highly weathered (see below). Weathering can lower the total organic carbon content and HI of outcrop samples (Leythaeuser, 1973) as do diagenesis and thermal maturation. All TOC values most likely reflect minor carbon loss and OM degradation attributable to these processes (see below). However, four samples from Unit 2C show elevated HI values (>200 mg

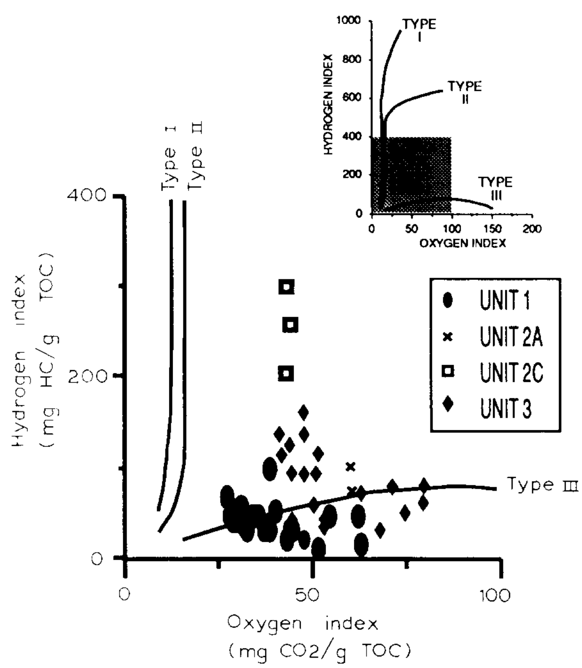

Fig. 13. Cross plot of Oxygen Index (OI) and Hydrogen Index (HI) from Rock-Eval data which shows the distinct groupings of organic matter from each of the shale units.

HC/g OC) as well as high TOC values of about 4–7 wt% that indicate abundant reactive organic matter is still present in this unit.

The temperature at which the maximum yield of pyrolyzable hydrocarbons occurs during pyrolysis is defined as T_{max}, which provides an approximation of thermal maturity (Teichmüller and Durand, 1983). Generally, in other Lower Cretaceous strata of the region, T_{max} values below 430°C indicate immature OM at or above the top of the oil window (Leckie et al., 1988). Because T_{max} is sensitive to the type of organic matter in the sample, it should be calibrated with other thermal maturation parameters such as vitrinite reflectance (R_0). In the absence of other thermal maturation data however, T_{max} values for Shaftesbury Formation samples at this location, generally below 435°C, suggest that the OM is marginally mature to immature. This is consistent with R_0 values of 0.36–0.42 from coal samples from the underlying Paddy Member which were obtained from 30 km north of the present study site (W. Kalkreuth, pers. comm., 1989).

Discussion

OI and HI values show distinct stratigraphic zonations (Fig. 13) and there is a high degree of correlation between TOC and HI (Fig. 12). These two factors, when considered with the palynological and sedimentological data, suggest that the preservation of Type II OM was enhanced in Unit 2C, most likely due to anoxic conditions in the depositional environment. The relatively low TOC and HI values of Unit 1 indicate a dominance of Type III OM. The constancy of HI and TOC values in Unit 1 suggest a stable, depositional environment that would have received a mixture of marine and terrestrial OM. The occurrence of terrestrial plant debris in palynological residues confirms Type III input into the marine depositional environment. Palynological and micropaleontological data indicate a well-oxygenated depositional environment with good circulation that would have preferentially oxidized the less refractory Type II OM, resulting, in part, in the observed TOC and HI values. T_{max} values are generally less than 435°C suggesting minimal thermal alteration and therefore, minor alteration and OM loss during burial.

The increase in TOC ($m=4.57$, range of 2.02–7.27 wt%) and HI ($m=170$, range of 69–254 mg HC/g OC) values in Unit 2 is attributable to an anoxic depositional environment which is consistent with the other data for this unit, including the abundance of the marine pelagic algal cysts (cf. *Lancettopsis lanceolatta* Mädler, 1963) and marine green algal forms of the Prasinophyceae, viz. *Leiosphaeridia* sp. and *Pterospermella* spp. The greatest increase of TOC and HI occurs in Unit 2C, suggesting a peak in preservation and perhaps productivity of OM in Unit 2C. Anoxic conditions evidently persisted during deposition of the lower portion of Unit 3 sediments as significant abundances of OM are present. HI are also somewhat elevated relative to Unit 1 (Figs. 12 and 13), suggesting a greater proportion of Type II OM than Unit 1, but less than Unit 2. This could result from an increase in sedimentation rate which would dilute a constant OM contribution.

Mineralogy

The minerals alunite and jarosite form a solid solution series that is generally considered to result from the alteration of iron sulphide minerals under oxidizing, slightly-acidic conditions (Brophy et al., 1962). The absence of detectable amounts of pyrite suggests that the abundant jarosite, alunite and gypsum in the outcrop were derived primarily from the weathering of pyrite. Pyrite formation in organic-rich marine sediments results from early diagenetic, bacterially-mediated sulphate reduction. Sulphate-reducing bacteria are anaerobes and pyrite formation therefore is enhanced by anoxic conditions at the sediment–water interface. An increase in bacterial sulphate reduction and subsequent pyrite formation, now present dominantly as jarosite, would be expected in Unit 2C because of the increased Type II OM content of the sediment. Considering the abundance of sulphate minerals as a crude proxy for sulphides, the systematic increase then decrease in sulphate mineral abundance within Unit 2 is consistent with a gradual change in the dissolved oxygen content of the depositional waters, with an inferred peak in anoxia occurring in Unit 2C.

Weathering has most likely affected the distribution of sulphur within the section and it is probable that some sulphur was lost during the oxidation of pyrite. The occurrence of macroscopic selenite indicates mobilization of sulphur on a local scale. Carbon–sulphur systematics, while not conclusive, may indicate major sulphur depletion within Unit 2C (Fig. 14). C–S values from Units 1, 2A and 3 are generally within the range considered to be "normal marine" (Sweeney, 1972; Leventhal, 1983; Berner and Raiswell, 1984) in contrast to values for Unit 2C. Despite the inferred sulphur depletion, Unit 2C samples still contain a relatively high abundance of sulphur.

Alternatively, the reduced S/C values in Unit 2C may result from iron limitation (Raiswell and Berner, 1985; Davis et al., 1989) or brackish-water conditions. Iron limitation is consistent with a "condensed section" hypothesis where terriginous input would be at a minimum. The low number of dinoflagellate species in Unit 2C could be attributed to brackish-water conditions but this is inconsistent with the reduced numbers of microspores and pollen that indicate a more distal, and therefore deeper-water, environment.

A more rapid change to, and perhaps more intense period of, anoxia is suggested by the large increase in sulphate mineral content (dominantly jarosite) in Unit 3. However, the location of Unit 3 near the present soil horizon, the poor preservation of organic matter and dinoflagellates, and the rapid increase in kaolinite content suggest that the sulphate mineral content in Unit 3 results from

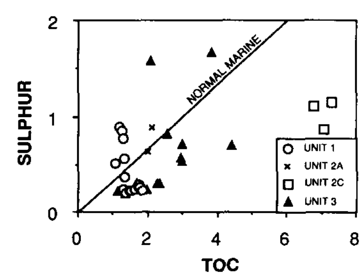

Fig. 14. Carbon–sulphur plot (weight percent) showing that C/S values for Units 1, 2A and 3 are within the range generally considered representative of normal marine values. Unit 2C shows elevated C relative to sulphur. See text for discussion.

recent weathering processes. Additional work on unweathered strata in the subsurface, correlative to Unit 3, may determine if this zone represents a primary anoxic signature or recent weathering.

Interpretation and discussion

The high and moderate diversities and counts of the dinoflagellates and arenaceous, benthonic foraminifera (Table 1, Fig. 10) in Unit 1, below the FSMB, indicate an open-marine, neritic environment of normal salinity. The arenaceous nature of the foraminifera indicates moderate depth, but the paucity of the continental palynoflora points to considerable distance from a land mass. Most of the OM is Type III, derived from terrestrial sources. The low levels of organic matter in Unit 1 signify a stable, well-oxygenated environment with good water circulation.

Unit 2A, which represents the lowest subunit of the FSMB, is inferred to represent a shallowing upwards from the deeper water represented by sediments of Unit 1. This interpretation is based on the presence of rippled sandstone which is coarser than the underlying Unit 1. Some of the characteristics of Unit 1 show a slight change upwards towards the base of Unit 2; for example, the upper five samples of Unit 1 show a decreasing HI, increasing quartz content, increasing sulphate mineral content and decreasing foraminiferal diversity (Figs. 10 and 12) which would be consistent with a distal progradational event.

The origin of the fish-hash conglomerate making up Unit 2B is enigmatic. Two alternative and speculative interpretations are offered here and further work is needed. The first alternative is that the shale of Unit 1 represents continuous deepening. In this scenario, Unit 2B was deposited during the maximum extent of marine transgression and the coarse organic debris was concentrated when clastic detritus was trapped in estuaries and in the coastal zone. Deep-water currents may may have enhanced the winnowing and could also account for the rippled sandstones in Unit 2A. In favour of this interpretation, we note that the dinoflagellates in Unit 2A are open-marine varieties, although their numbers are reduced. The largest clasts consisting of reptile bones and very rare chert pebbles were possibly locally derived as the pebbles could represent gastroliths from marine reptiles. Unit 2C would then represent continued deepening but the rate of sea-level rise had decreased and there was a gradual influx of fine clastic sediment at toes of progradational clinoforms.

An alternative interpretation of the fish-hash conglomerate of (Unit 2B) is that it represents a lag deposit overlying a marine disconformity. If this is the case, then the water depths under which it was deposited had to have shallowed to less than a few tens of metres such that the sea floor was affected by high-energy wave and current processes (Demarest and Kraft, 1987; Nummedal and Swift, 1987). To invoke a marine disconformity and lag deposit also requires the existence of a ravinement surface or a marine erosional surface situated seaward of the ravinement surface (Thorne and Swift, in press). This, in turn, requires the conclusion that a shoreline was seaward of this area, which was subsequently transgressed. On regional grounds though, we see no support of this interpretation of a shoreline east of the Smoky River outcrop. Yet, at the same time, this interpretation is consistent with observations by North and Caldwell (1975), Caldwell et al. (1978) and Caldwell (1984) who have argued on biostratigraphic grounds that a paraconformity exists between the Albian and Cenomanian in western Canada and that Late Albian sedimentation was interrupted by a period of non-deposition, and possibly even subaerial or submarine erosion. This latter interpretation is also in agreement with observations from northern Montana, where the beds equivalent to the FSMB represent an unconformity which separates the Lower Cretaceous Bootlegger Member from the Upper Cretaceous Floweree Member (Arnott, 1987) or is near to that boundary (Lang and McGugan, 1988). The presence of shelfal sandstones in correlative Upper Mowry shale in Wyoming further suggests a regional progradational event (Davis, 1987). Davis suggested that sandstone deposition resulted from a relative sea level fall, then rise. Sandstone deposition was diachronous, younging from south to north, and resulted in a shingling of discrete sandstone units. This (these) event(s) may be related to FSMB deposition.

Unit 2C of the FSMB represents a zone of condensed bioclastic accumulation in an interval somewhat starved of clastic detritus. Regionally, a rise in sea level is indicated by the presence of the radiolarian *Theocorys* sp. within the FSMB. The appearance of planktonic foraminifera (Eicher, 1965) in the uppermost Mowry Shale of Wyoming (*N. maclearni* Zone), of equivalent age, also confirms a rise in sea level. A further indication of rising sea level and the inundation of the barrier between Gulfian and Boreal seas is the occurrence in abundance of the Early Cenomanian ammonite *Metengonoceras* from Texas with *Neogastroplites americanus* and *N. muelleri* in Wyoming and Montana (Cobban and Kennedy, 1989). This barrier appears to have been intact up to *Neogastroplites cornutus* time (Figs. 3 and 15) preceding the FSMB.

The base of Unit 2C coincides with a major environmental change related to the rise in sea level and the onset of anoxic conditions. There is an enormous increase of amorphous organic matter of algal marine origin (Type II organic matter), a dearth of benthonic foraminifera and a marked decrease in the diversity and population of dinoflagellates (Table 1, Fig. 10) within and above the FSMB. The higher TOC content of Unit 2C may also be the result of reduced clastic sediment input during the relative peak of a marine transgression as sediment depocentres were shifted landwards towards the west. The anoxic peak was probably reached in the upper part of the FSMB (Unit 2C) which has a high total organic carbon content (Fig. 12), Type II OM (Fig. 13) and low dinoflagellate count and diversity (Table 1 and Fig. 10). The onset of the anoxic phase led to the disappearance of the benthonic foraminifera, which could not survive in oxygen-depleted waters and are absent above the base of the FSMB (Fig. 10). Only abundant radiolarians, which can survive in the surface waters, are present above this level. The drastic reduction in the dinoflagellate population and diversity and the disappearance of benthonic foraminifera at the base of the FSMB (Fig. 10) may not only represent an onset of the anoxic phase but may also reflect a hiatus or paraconformity at this level. The apparent rapid change in the dinoflagellate species association and the dominant species (Table 2) within and above the FSMB may be related to slow rate of sedimentation. In condensed sections, thin intervals represent long periods of time during which the species association and the dominant species can change many times due to alterations in the chemical and physical environments. There is a predominance of pelagic algal cysts (cf. *Lancettopsis lanceolata*) and marine green algal forms of Prasinophyceae vis *Leiosphaeridia* sp. and *Pterospermella* spp. in the upper part of the FSMB and the overlying strata (Table 2). These algae commonly occur in anoxic settings (Leckie et al., 1990) in organic-rich marine shales (Combaz, 1967; Madler, 1963) and indicate reduced salinity in the surface waters of a stratified water column.

Numerous hypotheses have been proposed to explain Cretaceous oceanic anoxic events. These expound the nutrient-rich upwelling of oceanic bottom waters (Jarvis et al., 1988, p. 84), a salinity stratified water column (Tyson et al., 1979), and the formation of an oxygen-minimum layer at the sediment–water interface (Schlanger and Jenkyns, 1976) as causes. Although a nutrient-rich upwelling mechanism may not be the cause of the anoxic FSMB, limited amounts of nutrient-rich upwelling for the northern Western Interior Seaway during the Middle Cretaceous have been predicted from recent climate model predictions by Kruijs and Barron (1990). Their model simulation predicted low values of coastal upwelling but these have not yet been substantiated by data. More likely however, the FSMB is the result of a stratified water column and concomitant formation of an oxygen-minimum level. A major rise in sea level beginning in the Late Albian (Greenhorn marine cycle) has been documented within the foreland basin (Caldwell, 1984) and globally (Haq et al., 1987). Global sea level during latest Albian to earliest Cenomanian time may have been 225 m higher than at present (Haq et al., 1987). During their study of the Cenomanian–Turonian oceanic anoxic event in southeastern England, which coincides with a major eustatic transgressive pulse, Jarvis et al. (1988; figs. 31 and 32) have recorded a sharp drop in the diversity and population of the dinoflagellate cysts and benthonic foraminifera with the onset of the anoxic phase, similar to that which occurs at the base of the FSMB. The anoxic event related to Unit 2C of the FSMB may have been caused by a rise in sea level and the mixing of waters of very different salinities and temperatures from the Arctic Ocean and the Gulf of Mexico in the Western Interior seaway (Fig. 15). The Arctic and Gulf seas may have been connected by *N. cornutus* to *N. americanus* time (Figs. 3 and 15; C.R. Stelck, pers. comm., 1990). Habib et al. (1988, p. 240) have linked palynofacies containing abundant amorphous organic matter to marine transgression and Hay (1989, p. 362) has suggested that the mixing of waters from different climatic zones can produce organic carbon-rich deposits in epicontinental seas. The high amount of total organic carbon is inferred to be the result of accumulation under anoxic conditions. The abundance of pelagic algal material may indicate periods of high production of organic matter. The introduction of Arctic waters of lower salinity is likely to have produced a stratified water column, inhibiting water circulation and creating anoxic conditions in the bottom waters. This mechanism could explain the regional expression of the FSMB that may extend from northern Alberta to Wyoming..

Unit 2C of the FSMB has many of the characteristics of condensed sections as defined by Loutit et al. (1988), but some features are missing (Table 3). Unit 2C is characterized by high total organic-matter content, high HI, high radioactivity, pelagic algae indicated by the abundant presence *Lancettopsis*, *Leiosphaeridia*, *Ptermospermella*, fish remains and the radiolarian *Theocorys* sp., a bentonite bed, and is associated with the base of prograding clinoforms (J. Bhattacharya, pers. comm., 1990). A major difference between condensed sections defined by Loutit et al. (1988) and the FSMB is the paucity of pelagic or benthonic foraminiferal microfossils within the latter. They noted that condensed sections are characterized by abundant and diverse suites of pelagic and benthonic microfossils as a result of reduced sedimentation rates during the peak of marine transgression. The FSMB contains abundant pelagic microfossils consisting of algae and radiolaria. A second difference is the absence of burrowed and bioturbated surfaces, which Loutit et al. (1988) suggest are commonly associated with condensed sections. The absence of benthonic foraminifera and burrowed surfaces are inferred to be due to the anoxic bottom waters.

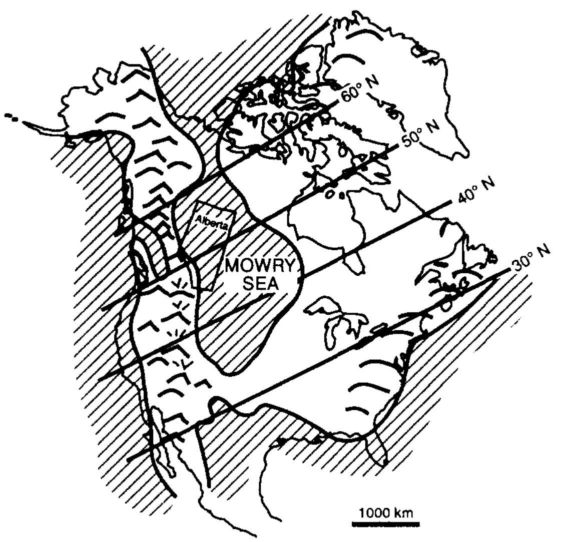

Fig. 15. Map showing extent of the late Late Albian sea at the time of *Neogastroplites cornutus* (after Williams and Stelck, 1975; Cretaceous paleolatitudes from Habicht, 1979).

Conclusions

The Fish Scale Marker Bed (FSMB) is a regional stratigraphic marker at the Albian–Cenomanian

TABLE 3

Comparison of the characteristics of condensed sections (from Loutit et al., 1988) and those of the Fish Scale Marker Bed.

CHARACTERISTICS OF CONDENSED SECTIONS	FISH SCALE MARKER BED	
THIN		YES
PELAGIC TO HEMIPELAGIC SEDIMENTS		YES
AREALLY EXTENSIVE		YES
ASSOCIATED WITH MARINE HIATUSES		(?)
BURROWED, LITHIFIED BED (MARINE HARDGROUND)	NO	
ABUNDANT AND DIVERSE PLANKTONIC AND BENTHIC MICROFOSSIL ASSEMBLAGE	NO FORAMINIFERA	
AUTHIGENIC MINERALS (GLAUCONITE, PHOSPHORITE, SIDERITE)		?
HIGH ORGANIC MATTER CONTENT		YES
BENTONITES		?
ASSOCIATED WITH MAXIMUM WATER DEPTHS		YES
ASSOCIATED WITH BASE OF PROGRADING CLINOFORMS		?
INCREASED RADIOACTIVITY		YES

boundary which occurs in marine sediments throughout a large part of western North America. Sedimentological, palynological, microfaunal, ichthyological and geochemical analysis of an outcrop near Peace River town, Alberta show that the FSMB and contiguous strata can be divided into 3 lithological, biostratigraphical and geochemical subunits. The shale of Unit 1, below the FSMB, is characterized by moderate foraminiferal and high dinoflagellate species diversities and numbers, low TOC content, predominance of terrestrial (Type III) organic matter and no preserved fish remains. Unit 1 was deposited in an open-marine, neritic environment having normal salinity. Overall, the FSMB (Unit 2) is characterized by absence of benthonic foraminifera, low dinoflagellate diversity, lack of bioturbation, higher TOC values, and marine (Type II) OM. The origin of the fish-hash conglomerate comprising Unit 2B is enigmatic and can alternatively relate to a shallowing or represent the peak of marine transgression. Unit 2C represents continued deepening and probably maximum anoxia. The fossil suite preserved in Unit 2 was derived from pelagic organisms (fish, reptiles, algae, radiolaria, foraminifera and dinoflagellates) most of which could have only survived in the upper well-oxygenated waters. These features are interpreted to represent deposition in anoxic bottom waters of a well-stratified basin with high productivity in the oxygenated portions of the water column. Following deposition of the FSMB, the deposition of organic-rich sediment was progressively diluted by clastic material and the dissolved oxygen content of bottom waters increased. The anoxic event related to the FSMB may have been caused by a rise in sea level and the mixing of waters of different salinities and temperatures from the Arctic Ocean and the Gulf of Mexico in the Western Interior seaway.

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