Palaeozoic microfossils from Orphan Knoll, NW Atlantic Ocean

Jan E. van Hinte & Alan Ruffman, with
Marinus van den Boogaard, Jan Jansonius, Theo M.G. van Kempen,
Michael J. Melchin & Theo H. Miller

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J.E. van Hinte, Centrum voor Mariene Aardwetenschappen (CMA), Vrije Universiteit, de Boelelaan 1085, 1081 HV Amsterdam, The Netherlands; A. Ruffman, Geomarine Associates Ltd, P.O. Box 41, Station M, Halifax, Nova Scotia, Canada B3J 2L4; M. van den Boogaard, Nationaal Natuurhistorisch Museum, Palaeontologie, Postbus 9517, 2300 RA Leiden, The Netherlands; J. Jansonius, Imperial Oil Resources Ltd, Calgary, now Institute of Sedimentary and Petroleum Geology, Geological Survey of Canada, 3303 3rd St. NW, Calgary, Alberta, Canada T2L 2A7; T.M.G. van Kempen, Centrum voor Mariene Aardwetenschappen (CMA), Vrije Universiteit, de Boelelaan 1085, 1081 HV Amsterdam, The Netherlands; M.J. Melchin, Department of Geology, St Francis Xavier University, Antigonish, Nova Scotia, Canada B2G 1C0; T.H. Miller, EPR Co., Houston, now 9008 Lake Union Hill Way, Alpharetta, GA 30201, USA.

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Orphan Knoll is an isolated, drowned continental fragment 550 km northeast of Newfoundland. The top of Orphan Knoll stands at 1800 to 2000 m and is marked by a series of protruding mounds. Dredging at the base of one of the mounds in 1971 obtained a suite of fossiliferous limestone pebbles that are interpreted to reflect nearby bedrock. The shallow marine limestone facies include mudstone, wackestone, packstone, and grainstone. The pebbles yielded Late Ordovician, Silurian and Devonian conodonts, as well as Ordovician/Silurian scolecodonts, chitinozoans and graptolites. Similarly, sponge spicules suggest the presence of Late Ordovician as well as Middle Devonian material including a *Silicunculus*-type of hexactinellid anchoring basalia and an octactine heteractinid spicule of *Ensiferites*, respectively. A Middle to Late Ordovician silicified ostracod fauna appears to be endemic at the species level including forms with both North American and North European affinities with a genus and two species that are new to science.
We conclude that the Upper Ordovician to Silurian and Devonian material is not ice-transported but reflects the bedrock of nearby mounds. Thus, the Ordovician marine intracratonic platform sediments were much more extensive than previously known and a marine re-entrant penetrated the Devonian Old Red Sandstone province in an area where marine limestones were previously unknown.

Contents

Introduction

Orphan Knoll is a submerged, isolated continental remnant lying in the southwestern Labrador Sea of the Northwest Atlantic Ocean, 350 km north of Flemish Cap, 550 km northeast of the island of Newfoundland and 50 km south of the Charlie Gibbs Fracture Zone (Fig. 1). The Knoll is kidney-shaped; it is c. 75 km in breadth and is elongated in a northwest-southeast direction between 49°55'N and 51°25'N over c. 150 km. The detailed interpreted bathymetry map, made from collected soundings, that appeared in Laughton et al. (1972), and in Ruffman & van Hinte (1973) is still the best map of the feature (Fig. 2) and has been incorporated into Canadian Hydrographic Service (C.H.S.) Natural Resource Map 800A (Canadian Hydrographic Service, 1971) and the related 1:250,000 series (Woodside, 1988).

The Knoll appears to be separated into two parts (Fig. 2); the larger southern part rises to depths of less than 1800 m while the smaller northern extension only rises to depths of slightly less than 2400 m. The northeast margin falls directly to the abyssal plain at 4000 m and the feature is separated from the Labrador and Flemish Cap continental shelves by water 2800-3400 m deep. The northeast side has steep slopes of up to 30°; whereas the southwest slopes are more gentle, being in the range of 5-10°. The northeast margin is quite linear except for the southern extension where a very steep offshore seamount and two smaller features stand slightly seaward of the main body (Fig. 2). Parson et al. (1984) have suggested that the three abyssal peaks are composed of fault-bounded pre-Jurassic blocks. The western margins of the Knoll are broadly semicircular in outline with a canyon-like feature incised into the southern flank (Fig. 2).

Orphan Knoll was surveyed and drilled by D/V GLOMAR CHALLENGER on Leg 12 of the Deep Sea Drilling Project (DSDP) as Site 111 from June 24 to 28, 1970 and the Knoll's status as a continental remnant was established (Laughton et al., 1972; Ruffman & van Hinte, 1973). In May, 1971, the USNS LYNCH, cruise 7/11/71 of the U.S. Naval Oceanographic Office (Ruffman, 1971) dredged on the pronounced bathymetric highs (mounds) found to the northeast of DSDP Site 111. These mounds rise over 300 m above the flat plane of the upper surface of the Knoll.

The Atlantic Geoscience Centre of the Geological Survey of Canada visited Orphan Knoll in 1978 and did a line of seismic refraction work. Two dredge stations were attempted with significant recoveries of rock in both cases (Keen, 1978). The British Institute of Oceanographic Sciences worked over the Orphan Knoll area in 1979 and 1981 on M/V STARELLA and M/V FARNELLA respectively, gathering a few six-channel seismic reflection profiles, GLORIA sidescan sonograms and echo-sounder data (Parson et al., 1984; 1985). Other than the above field work and a few other papers (Hart, 1976; van Hinte et al., 1975; Hacquebard, 1981; Hacquebard et al., 1981; Woodside & Verhoef, 1989; Nederbragt, 1989) little attention has been paid to Orphan Knoll since the drilling by the DSDP in 1970.

A 1972 manuscript by Ruffman & van Hinte reporting the 1971 dredging of

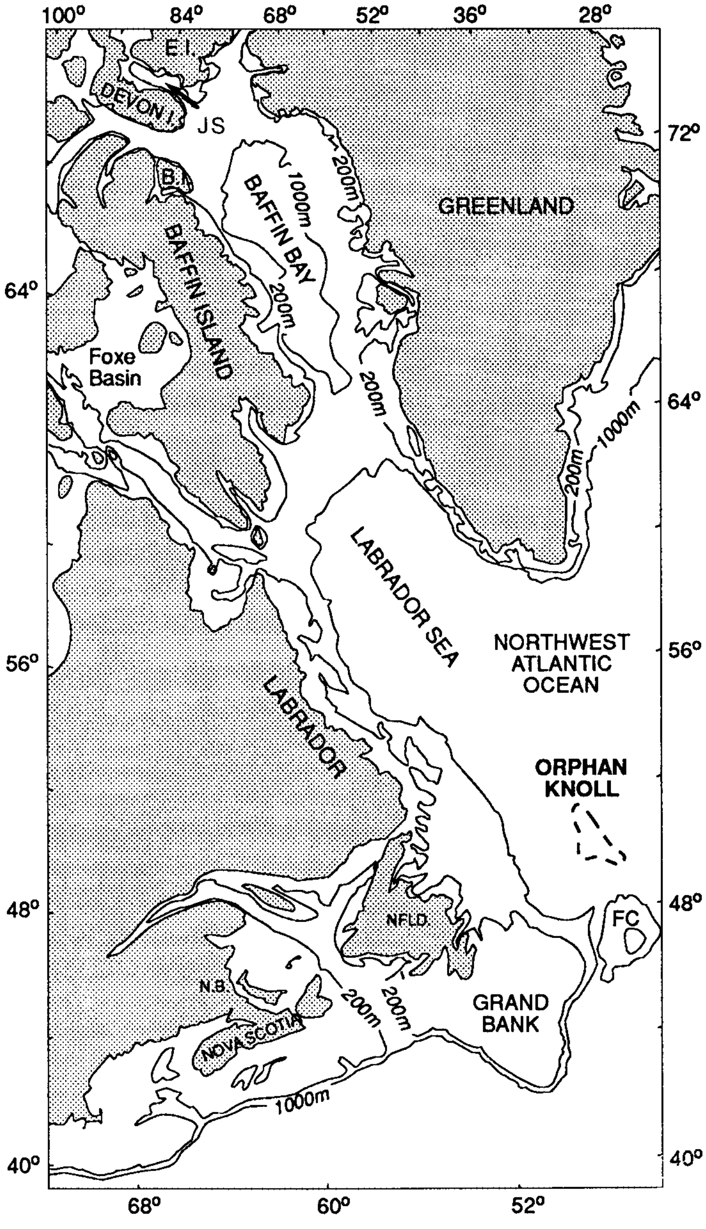


Fig. 1. Index map showing the location of Orphan Knoll (outlined by the dashed approximate 2000 m depth contour) relative to the east coast of Canada and the 1000 m depth contour. Possible ice-transported sedimentary rock could be generated by glaciers in East Greenland, West Greenland, SE coast of Ellesmere Island (EI), Jones Sound (JS), eastern part of Devon Island, Bylot Island (BI), east coast of Baffin Island or by pack-ice from Hudson Bay or Foxe Basin. FC - Flemish Cap, NFLD - Island of Newfoundland, NB - New Brunswick.

marine Palaeozoic rocks from the mounds on top of Orphan Knoll was rejected by Nature; the editors' reviewer apparently felt the material could only be ice-transported debris from a northern locality. It remained 'published by Xerox' until 1989 when it appeared as part of Open File 2065 of the Geological Survey of Canada (Ruffman & van Hinte, 1989). The preparation of Open File 2065 prompted the authors to initiate a reexamination of the 1971 dredge material.

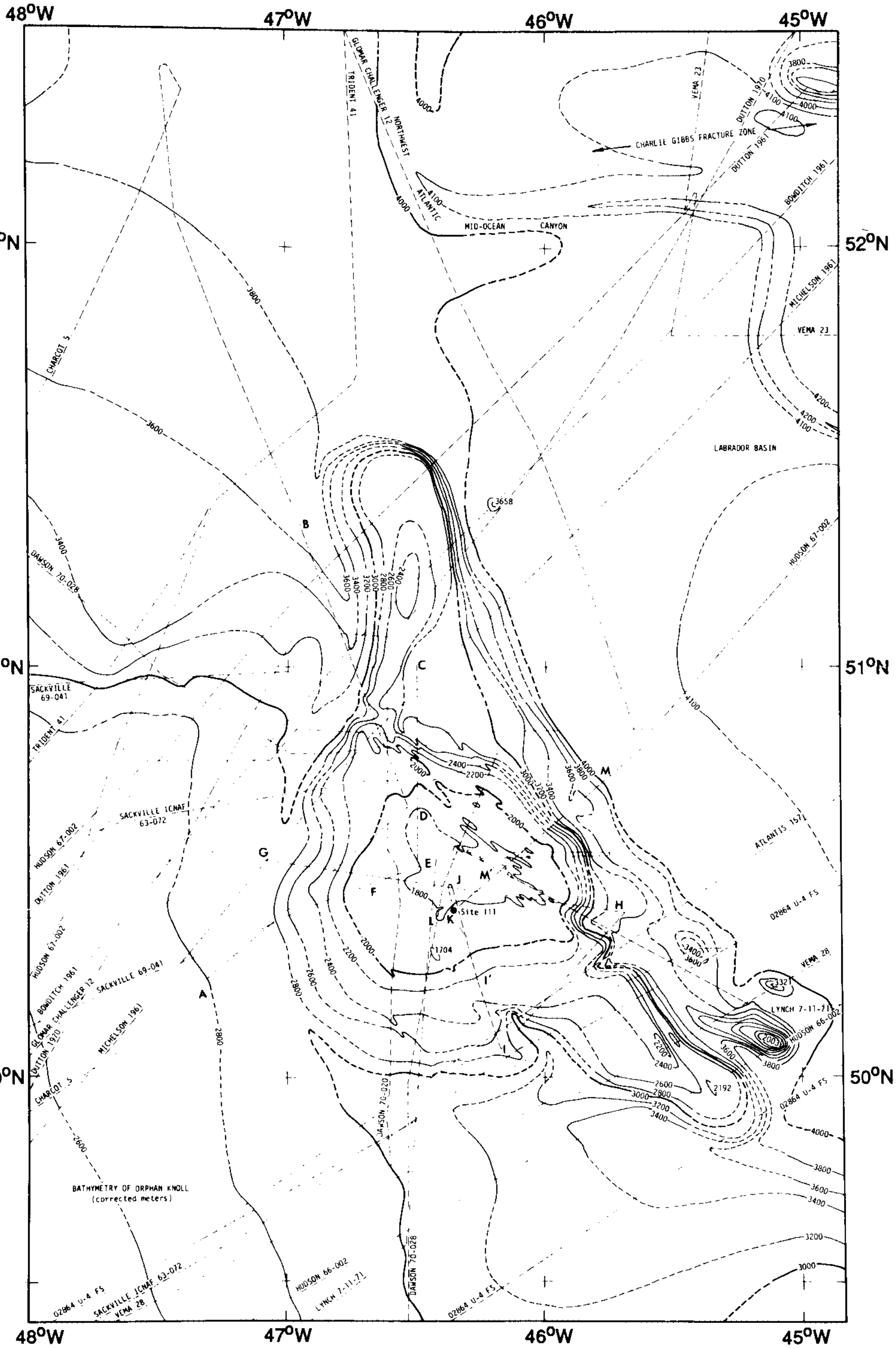
Mounds of Reflection Unit 2

The top of the northeastern part of Orphan Knoll is marked by a series of pronounced bathymetric highs that are seen, on almost every seismic profile or bathymetric transect of the Knoll, to protrude through the cover of younger sediments (Fig. 3) and to stand up to 300 m above the generally smooth upper surface of the Knoll. They were first mapped by CHARCOT 5 in 1969 (LePichon et al., 1971) and by C.N.A.V. SACKVILLE in 1969 on its 69-041 cruise (Laughton et al., 1972). Laughton et al. (1972) referred to these structures as 'layer 2' in their DSDP Site 111 seismostratigraphy (Fig 3). These bathymetric highs are of very short 'wave length' and appear to be quite sharp projections from the seafloor on the seismic profiles with very high vertical exaggerations.

Laughton et al. (1972) and Ruffman & van Hinte (1973) interpreted these features as 'narrow ridge structures' or a 'tight series of linear ridges'. Ruffman & van Hinte (1973) also noted that any single 'hill' was less than 3 km wide. Parson et al. (1984) referred to these features as 'mounds'. Keen (1978) and Legault (1982) called them 'pinnacles', perhaps having been influenced by the severe vertical exaggeration of circa 25:1 seen on continuous seismic and echosounder records.

Parson et al. (1984, p. 62) noted that 'Neither seismic reflection profiles nor precision echo soundings accurately delimit the vertical cross-sectional shape of the mound-like features, due to the interference of hyperbolae and abundant side echoes on the records.' They used GLORIA (Geological LOng Range Inclined Asdic) sidescan sonograms in conjunction with subbottom profiling data to find that most of the mounds had a 'vertically flattened conical form, with a range in height between 115 and 320 m above sea floor' and that some of the partially-buried mounds 'probably exceed 600 m in total height and have a basal width of 3-4 km. The flanks of these features thus slope at angles of around 15 to 20°.' The present authors interpret some

Fig. 2. From Laughton et al. (1972, fig. 2). Bathymetry of Orphan Knoll in corrected metres. Contour interval 200 m except over the Labrador Basin where the interval is 100 m. Solid contours indicate that the contour is defined, while presumed contours are shown as broken lines. The sources of information are indicated by ships' tracks. Tracks indicated only by figures are from the U.S. Navy collected sounding sheets and the quality is completely unknown. The exact northwest and southeast extension of the feature is unknown though the 1979 cruise of M/V STARELLA and the 1981 cruise of M/V FARNELLA have done an additional line in the two areas respectively. The minimum soundings to the top of some of the more pronounced mounds are indicated. Letters shown refer to profiles referenced in the Deep Sea Drilling Project text from Leg 12 and in one of the following figures (Fig. 3 - Line GH).
In the 1972 interpretation of the bathymetry the pronounced 'peaks' on top of Orphan Knoll were interpreted as a series of linear ridges; they are now known to be isolated features or groups of features and are better referred to as 'mounds'.


48°W
47°W
46°W
45°W
52°N
51°N
50°N
LABRADOR BASIN
CHARLIE GIBBS FRACTURE ZONE
NORTHWEST ATLANTIC MID-OCEAN CANYON
Site 111
BATHYMETRY OF ORPHAN KNOLL
(corrected meters)

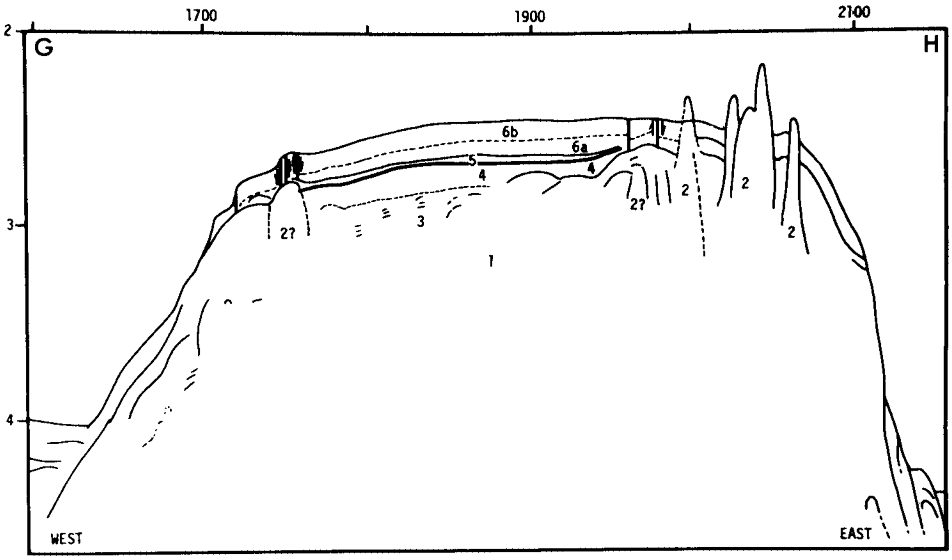


Fig. 3. After fig. 7 from Laughton et al. (1972) showing a line interpretation of the west to east seismic profiling traverse of Orphan Knoll by GLOMAR CHALLENGER 12 (line G-H, Fig. 2). Vertical exaggeration about 25:1. The buried structure on the left (seismostratigraphic Unit 2?) is a buried mound of the southwest zone of mounds. Differential compaction over the westernmost feature has caused some normal faulting and a small topographic high is found on the Knoll's upper surface over the buried feature.
The seismostratigraphic units are those used in Laughton et al. (1972). The unknown basement (Unit 1) is overlain by dipping non-marine Jurassic (Bajocian) sandstone rich in anthracite fragments (Unit 3). An Albian-Cenomanian shallow marine section overlays the unconformity on top of the Jurassic (Unit 4) and a Maastrichtian chalk overlays a hardground on top of the Cenomanian with an overlying deep Palaeocene section (Unit 5). Orphan Knoll sank to its present depth beginning at the end of the Cretaceous and the 180 m Cenozoic deep marine section is draped over the top of the Knoll (Units 6a, 6b). The Palaeozoic mounds (Unit 2) or reactivated diapirs appear to originate in the unknown basement and penetrate all horizons to outcrop on top of the Knoll.

of the features they have examined to have slopes of up to 30°, and suspect that slopes are even steeper locally.

Parson et al. (1984) mapped close to 250 individual mounds on the cruises of M/V STARELLA in 1979 and M/V FARNELLA in 1981 on the northeastern part of the upper surface of Orphan Knoll (Fig. 4). They found the mounds to be discrete and grouped in a generally NW-SE trending zone along the northeast margin. They saw no evidence of the earlier-suggested NW-SE trending ridge-like character (Laughton et al., 1972; Ruffman & van Hinte, 1973).

There is a second zone of very low or buried mounds along the southwestern side of Orphan Knoll shown in Laughton et al. (1972) to the southwest of a small Cretaceous basin (Fig. 5). Most of these Unit 2 features are buried as seen on the left of Fig. 3. Very few break the surface of Orphan Knoll, as seen on the south-north portion of the LYNCH 7/11/71 profile (Fig. 7 to the left of the arrow at Site 111) and on the GLOMAR CHALLENGER June 25, 1970 line at 0320 local time (fig. 9 of Laugh-

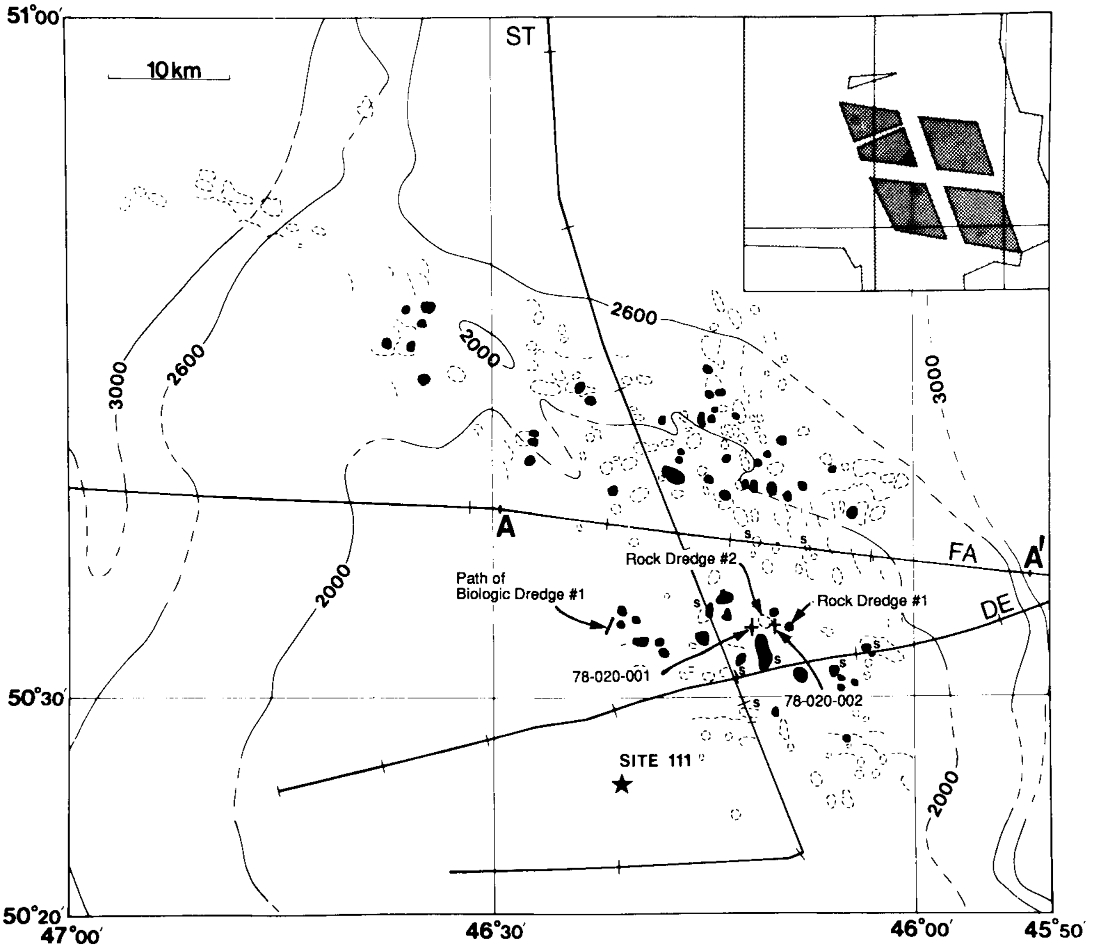


Fig. 4. After Parson et al.'s (1984) fig. 4, showing a schematic interpretation of the distribution of the northeast zone of mounds on top of Orphan Knoll, superimposed on a simplified bathymetry. The black shaded features are mounds definitely located on two GLORIA sonographs recorded from perpendicular tracks. The unshaded features were observed from only one direction. S = mounds observed on both a seismic profile and on the GLORIA sonograph. The inset map shows the extent of sonograph coverage in the main figure; darker shading indicates double coverage, and the unshaded area inside the limits has only single swath coverage. Only the southeast and southwest corners and the northeast margin of the area were not insonified at all. ST = M/V STARELLA line in 1979, FA = M/V FARNELLA line in 1981 and DE represents a deep seismic line operated by Seiscan Delta.
DSDP Site 111 is shown west of the mounds. The locations of the 1971 LYNCH Rock Dredge #1 and #2 are shown along with the track of the 1971 LYNCH Biologic Dredge #1 which is the subject of this paper. Both the HUDSON 78-020 rock dredge hauls appear to have been from the same mound as the LYNCH's attempted Rock Dredge 2.

ton et al., 1972). In this last case, Reflection Unit 2 (the mound) is protruding through shallowly-dipping Jurassic non-marine sandstone (Reflection Unit 3 on Fig. 3) and through flat-lying Albian-Cenomanian shallow water carbonates. Generally the mounds seem to mark the edge of the Albian-Cenomanian basin or to flank it, suggesting a possible structural relationship (compare Fig. 4 to Fig. 5).

Dredging the mounds

Two attempts to dredge the pronounced bathymetric highs on the top of Orphan Knoll have occurred. The first was by Alan Ruffman on the USNS LYNCH cruise 7/11/71 on May 23, 1971 (Ruffman, 1971), and the second was by the HUDSON 78-020 cruise in 1978 (Keen, 1978).

The first 1971 rock dredge station was unsuccessful, but the second recovered 4.1 kg of pebbles [Rock-dredge No. 2, LYNCH Station D2-7-11-71, 50°33.2'N, 46°10.7'W, depth c. 1600 m (Ruffman, 1971), Fig. 4]. At the third dredge station (Figs. 4, 6), which was just to the west of the zone of mounds (Fig. 7), the Canadian National Museum of Natural Sciences' specially designed 'Arctic Dredge' (Clarke, 1972), was used to collect a biologic mud sample. This was LYNCH Station D3-7-11-71 (Bio-dredge No. 1), average position 50°33.3'N, 46°21.9'W, depth 959.5 fm uncorrected or 1775 m corrected, at c. 0140 GMT May 23, 1971 (slightly adjusted from the 0130 time and position used in Ruffman & van Hinte, 1989). Unlike Clarke (1974), we consider that the averaged satellite position midway during the bottom time of the dredge haul is the most reasonable position to use.

The biologic dredge slowly dragged over about 1.0 km of ocean floor in an 010° direction during its 50 minutes of bottom time as LYNCH was allowed to drift. The dredge yielded a suite of 6.41 kg of pebbles, 2.5 kg of which, or 39.2% by weight, were somewhat angular light grey-buff limestone with numerous borings, or limestone with a weathered dark surface (Pl. 14, figs. 1, 2). The Arctic Dredge was designed to exclude larger rocks and to collect mainly mud with its entrained biologic samples (Clarke, 1972). The chain bag would not have dug more than 5-10 cm into the ocean floor as it dragged along. The mud and the pebbles collected in the bag of the biologic dredge therefore were deposited within the past 1000 years (assuming

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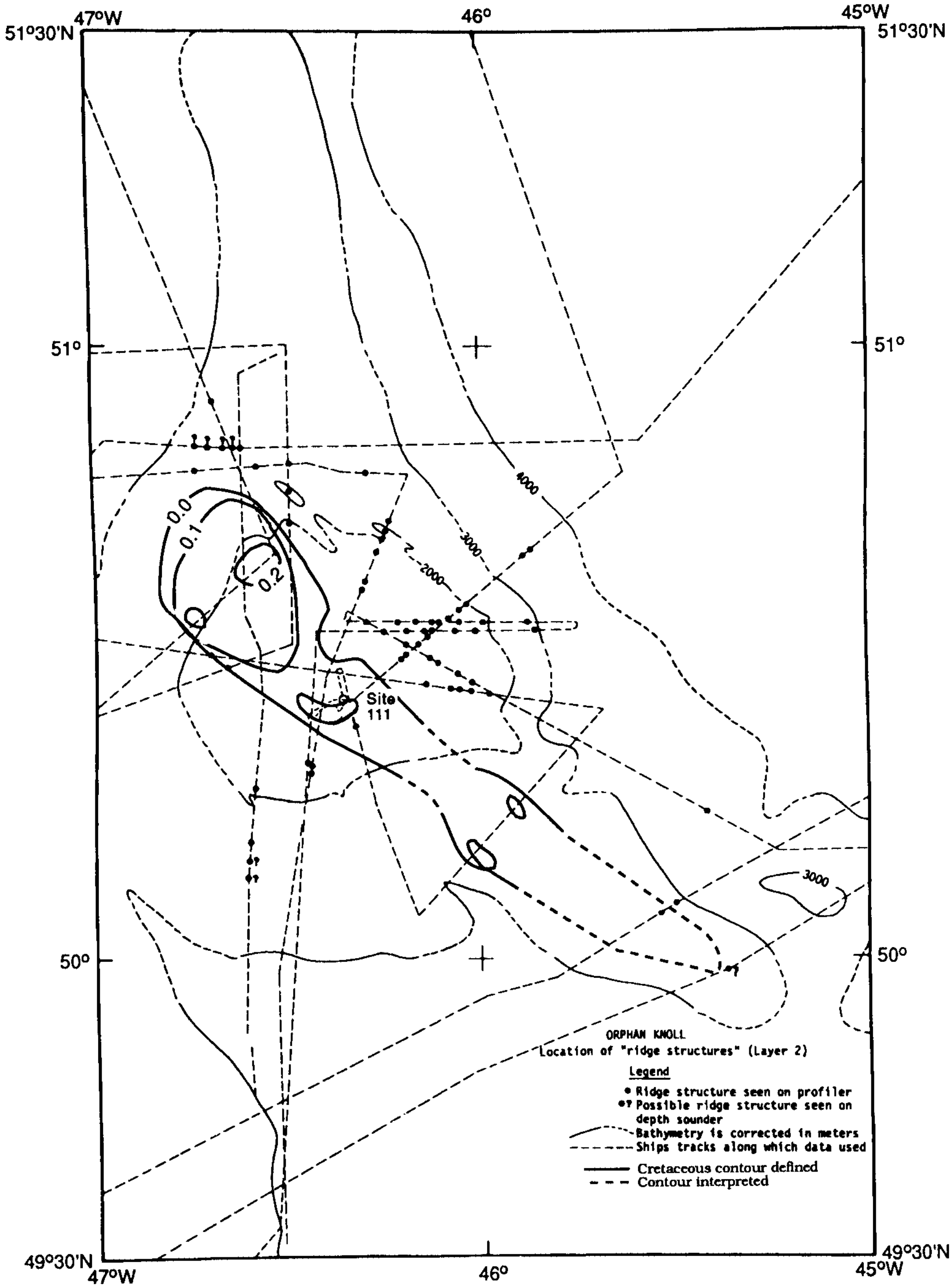
Fig. 5. Map of seismostratigraphic Unit 2 mounds as they were known in 1972 superimposed on a simplified bathymetry map of Orphan Knoll. This is fig. 23 from Laughton et al. (1972) modified to add the nearly-buried Unit 2 feature that outcrops on the GLOMAR CHALLENGER profile I-I'-J (Fig. 2) to the south-southeast of Site 111. This is the only mound presently known to penetrate the rocks of the small Cretaceous basin. The mounds are shown predominantly along the northeast margin of the upper surface of Orphan Knoll with a second, less dense (or less known), series along the southwest margin of the Knoll which are buried by Tertiary-Quaternary pelagic sediment. The small Albian-Cenomanian basin of flat-lying carbonates (Unit 4) tends to lay between the two zones of Unit 2 mounds and strikes NW-SE (see fig. 25 in Laughton et al., 1972). The Albian-Cenomanian sediment thickness is shown in the superimposed heavier contours in units of 0.1 s of two-way travel time from seismic profiles (Laughton et al. , 1972). The small basin contained a shallow sea with carbonates deposited between the two zones of Ordovician-Devonian mounds; the two zones may have been subject to subaerial erosion during the Albian-Cenomanian though no evidence of Palaeozoic erosion products was reported in Laughton et al. (1972).


47°W
46°
45°W
51°30'N
51°30'N
51°
51°
50°
50°
49°30'N
49°30'N
47°W
46°
45°W
0.0
0.1
0.2
4000
3000
2000
3000
Site 111
ORPHAN KNOLL
Location of "ridge structures" (Layer 2)
Legend
Ridge structure seen on profiler
? Possible ridge structure seen on depth sounder
Bathymetry is corrected in meters
Ships tracks along which data used
Cretaceous contour defined
Contour interpreted

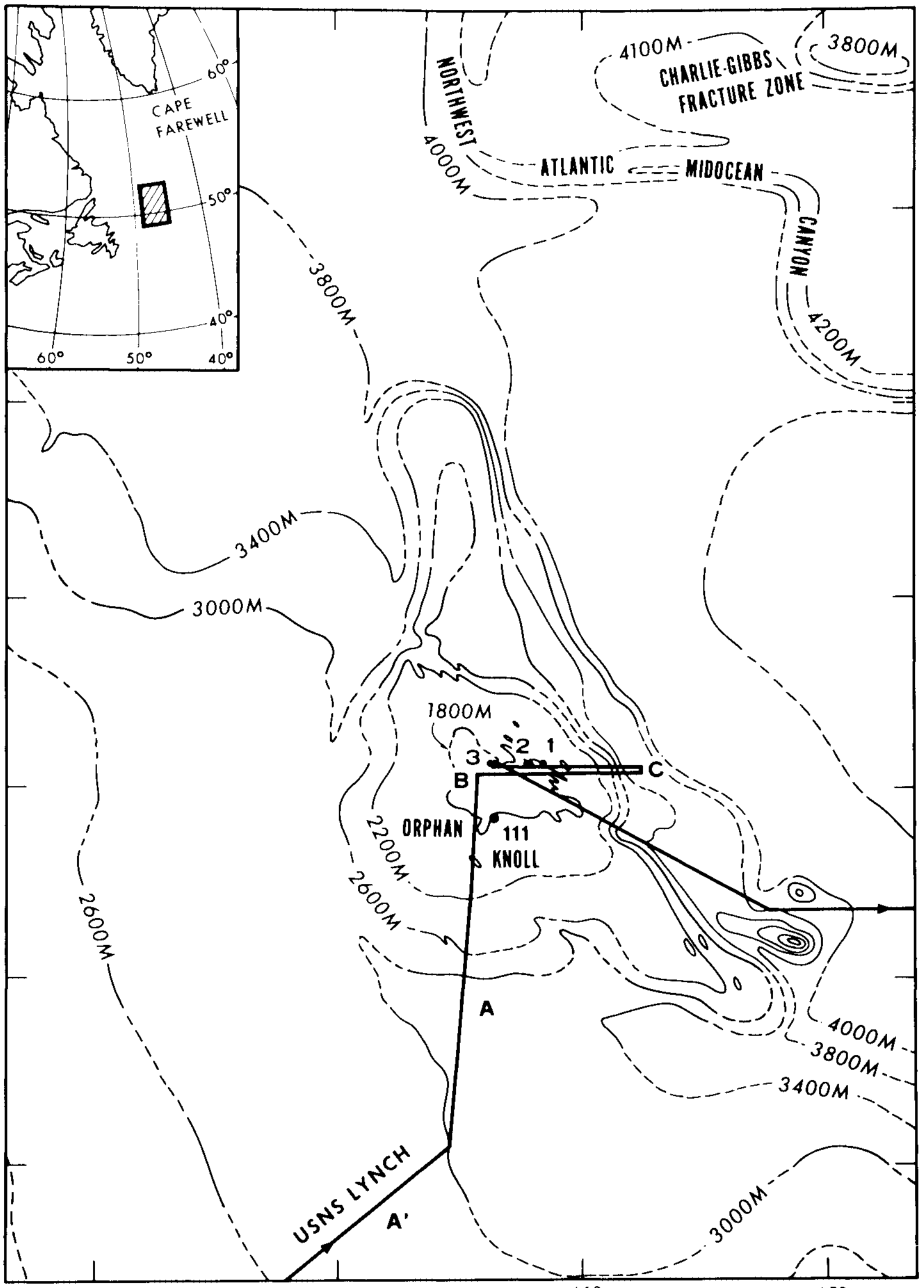


Fig. 6. Map showing 1971 track of USNS LYNCH, superimposed on simplified bathymetry, as it came up over Orphan Knoll and proceeded eastward across the northeast zone of mounds (track BC) then returned to the west to dredge unsuccessfully at Rock Dredge Station Nos. D1-7-11-71 and D2-7-11-71 (1 and 2 on the map). Biologic Dredge Station No. 1 was obtained at LYNCH Station No. D3-7-11-71 (No. 3 on the map). The bathymetry is in corrected metres; solid contours are defined and the dashed contours are interpreted. DSDP Site 111 is shown.

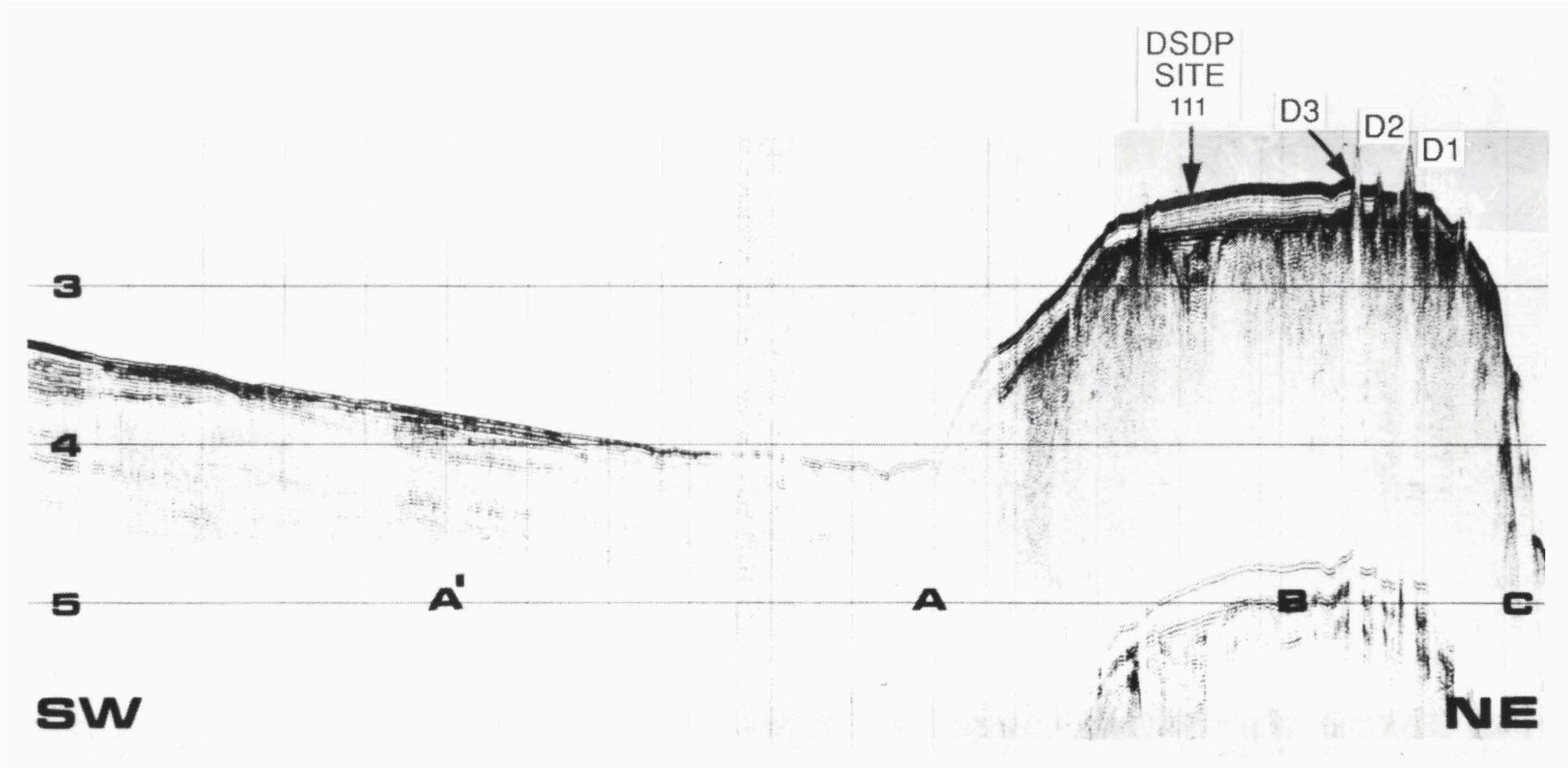


Fig. 7. Continuous seismic reflection profile A'ABC of the 30 kJ sparker of USNS LYNCH cruise 7/11/71 showing the long continental rise of northeast Newfoundland slowly deepening to a depth of 2800 m (A) on a track northeast from the Newfoundland shelf edge (for location see Fig. 6). Orphan Knoll (B) abruptly rises to depths of less than 1800 m before sharply dropping off to the northeast to the abyssal plain at 4000 m (C). The profile shows the northeast zone of mounds rising up from the 'basement' of the Knoll (Unit 1) and penetrating through all formations to stand as topographic highs as much as 300 m above the top of the feature. One mound from the generally buried southwest zone is also shown south (to the left) of the arrows. LYNCH's rock dredge stations were attempted at D1 and D2 on two mounds while the Biologic Dredge Station No. 1 was at D3 just to the west at the base of a prominent mound. The second arrow marks the approximate location of DSDP Site 111. The differing sediment levels between the mounds on the northeast indicate ponding of sediment between the mounds and may reflect differential, periodic slumping of Quaternary pelagic sediment off the mounds. This mechanism may have carried the talus from nearby mound outcrops to LYNCH Station D3-7-11-71.

the 10 cm/ka sediment accumulation rate found from DSDP Site 111; Laughton et al., 1972) and certainly within the past 5 ka. The dredge only yielded extant biota (Clarke, 1973; 1974) and examination of the mud showed modern Pleistocene/Holocene coccoliths with no reworked forms (pers. comm., K. Perch-Nielsen). Thus, if the pebbles were transported to Orphan Knoll from a distant northern source, then this occurred via modern pack ice or iceberg processes.

The other dredge work done on the mounds of Orphan Knoll was by the Atlantic Geoscience Centre HUDSON 78-020 cruise on July 10, 1978 with two dredge hauls (Keen, 1978). These two attempts on opposite sides of a nearby mound (Fig. 4) resulted in 16.3% and 19.1% (by weight) limestone, skeletal limestone and dolomite, or, 36 and 57 pieces of carbonate, at Dredge Stations 78-020-001 and 78-020-002, respectively (Ruffman & van Hinte, 1989).

Palynological slides of one cobble of Dredge Station 78-020-001 [50°33.0'N, 46°11.6'W, 890 fm (1628 m) uncorrected depth] were studied by Jocelyn A. Legault for acritarchs and chitinozoans. Legault (1982, p. 1854) concluded that 'The age of some of the Paleozoic bedrock in the area of Orphan Knoll,...is Late Ordovician.... This is in accord with a previously-determined age of Caradoc for strata at southeastern Baffin Island to the north of this locality (MacLean et al., 1977). That age determination was based on a coral, scolecodonts, and chitinozoans.' The bedrock nature of this sample has been questioned by Grant in Parson et al. (1984) and by Grant (1988). Grant (1988) and Ruffman (1989), who reexamined the dredge, both point out that the single sample examined by Legault could have been transported by glacial or pack ice from southeast Baffin Island and note that none of the other limestones from the 1978 dredge haul have yet been examined.

While the 1978 dredge haul of HUDSON still requires more work, the 1971 dredge haul of LYNCH has now had exhaustive work done on it and has yielded some most interesting faunas and conclusions that merit reporting at this time. This paper concerns the fauna found in the 2.5 kg of limestone pebbles of Bio-dredge No. 1, LYNCH Station D3-7-11-71.

All microfaunal slides, washed residues and thin sections, as well as four of the original, unprocessed, limestone pebbles with a combined weight of 15.1 g (Pl. 14, fig. 1), two tiny hard limestone pebbles of 1.0 g and the remaining 3.9 kg of rounded glacial erratics of granitic and metamorphic rocks have been archived at the 'Nationaal Natuurhistorisch Museum' in Leiden (collection nrs. RGM 414 000 - 414 111 and 414 132 - 414 149), along with five similar erratic crystalline rocks, one 110 g pebble of dark and light laminated micrite from Rock-dredge No. 2, LYNCH Station D2-7-11-71 and a detailed listing of the LYNCH 1971 samples (van Hinte & Ruffman, 1990).

Lithologies and sample treatment

Lithology

Twenty of the larger limestone pebbles (total c. 500 g) of Bio-dredge No. 1, and one pebble of Rock-dredge No. 2, were macroscopically grouped under eight rock types.

Facies 1 (Pl. 15, figs. 1-6).
Light to medium grey, buff wackestone.
Microfacies: micritic-skeletal limestone with abundant crinoid fragments, common ostracods, some bryozoans, brachiopods, bivalves and rare sections of trilobites, gastropods, conodonts, corals, and sponge spicules; skeletal remains may show some sorting.
Depositional environment: low energy, shallow marine.
Material: 7 pebbles, thin sections JV340-344, JV346, JV352.

Facies 2 (Pl. 16, fig. 2).
Light to medium grey, buff grainstone.
Microfacies: sparitic, skeletal-detrital burrowed limestone with rounded, slightly coated grains. Many gastropod fragments, some crinoids and brachiopods.
Depositional environment: high energy, shallow marine.
Material: 1 pebble, thin section JV345.

Facies 3 (Pl. 16, fig. 5).
Light grey, buff mudstone.
Microfacies: dense micrite with rare fragments of ostracods, brachiopods, trilobites, and bryozoans.
Depositional environment: low energy, shallow marine.
Material: 2 pebbles, thin sections JV347, JV349.

Facies 4 (not illustrated).
Light grey, buff mudstone.
Microfacies: dense micrite without fossils.
Depositional environment: low energy, shallow or deep marine.
Material: 3 pebbles, thin sections JV348, JV354 and JV359.

Facies 5 (a: Pl. 14, fig. 4; Pl. 16, fig. 3; b: Pl. 14, figs. 3 and 5; Pl. 16, fig. 6).
Light grey, buff, (a) homogeneous or (b) laminated fine, sugary dolomitic mudstone.
Microfacies: recrystallised calcareous dolomite, dolomitic micrite or dolomitic wackestone in which the skeletal remains are not identifiable because of recrystallisation. One pebble and the Rock-dredge No. 2 pebble show lamination because of a parallel arrangement of tiny, brown, flaky plant remains.
Depositional environment: low energy, shallow marine (lagoon).
Material: (a) 3 pebbles, thin sections JV350, JV356 and JV357; (b) 2 pebbles, thin sections JV351 and JV430 (from Rock-dredge No. 2).

Facies 6 (not illustrated).
Grey, non-calcareous, sandy mudstone.
Microfracies: very fine, subangular, micaceous sandstone with composite grains.
Depositional environment: non-diagnostic, possibly deltaic floodplain.
Material: 1 pebble, thin section JV353.

Facies 7 (Pl. 16, fig. 1).
Medium grey, buff skeletal mudstone.

Microfacies: skeletal pelloidal packstone; the skeletal elements are large, unbroken brachiopod shells, ostracods, gastropods, and crinoids.
Depositional environment: low energy, outer (?) carbonate shelf.
Material: 1 pebble, thin section JV355.

Facies 8 (Pl. 16, fig. 4).
Light grey packstone.
Microfacies: crinoidal limestone with some ostracods and a solitary coral or bryozoan.
Depositional environment: medium energy, shallow marine.
Material: 1 pebble, thin section JV358.

Sample treatment

Two thin sections (one covered, one uncovered) were made of each of the 20 Biodredge No. 1 pebbles used for the facies description (thin sections JV340- JV359), and of the micrite and a non-carbonate erratic from Rock-dredge No. 2 (thin sections JV430 and JV360, respectively). The remains of eight larger pebbles were then processed for conodonts (samples B3273 - B3280 of Table 1). Initially, six of the larger pebbles were saved for archiving, but, because we were eager to find more fossils, two were later processed for conodonts and palynomorphs (samples B3291 and B3292 of Table 1), and so was half the micrite pebble of Rock-dredge No. 2 (sample B3295 of Table 1).

All other samples are composites of small to very small pebbles from the various bags in which the material had been shipped. On initial receipt of the dredge haul material, six large composite samples were processed for conodonts (samples B3259 - B3264 of Table 1): samples B3259, B3260 and B3263 were made up of macroscopically selected skeletal limestone, micrite and unidentifiable coated pebbles, respectively; sample B3261 had siliciclastic pebbles while those of samples B3262 and B3264 were too small to be macroscopically identified. Two additional bulk samples were crushed and washed for calcareous microfossils (samples 48337 and 48338 of Table 1), their washed residues were picked and then processed for conodonts (samples B3349 and B3350, respectively, of Table 1). Finally, the finest material left in the sample bags and the tiny remains of thin sectioned pebbles, were combined and processed for conodonts and palynomorphs (samples B3293, B3294 of Table 1).

Microfauna and age of the limestone pebbles

The standard acid processing for conodonts not only yielded phosphatic and some larger organic walled microfossils, but also gave well preserved silicified ostracods and sponge spicules. No attempt was made to identify the fish bone and scale remains or the fragments of bryozoans, crinoid stems and gastropods that were also found in these sample preparations. The few microfossils recovered from the crushed-and-washed samples are poorly preserved.

Table 1 records the microfossil distribution in these sample preparations and in those thin sections that were made from the same pebbles. The fossil content of other thin sections is recorded in the microfacies description of the lithology section above.

Table 1. Microfossil distribution in samples and thin sections.

sample number	A	B	barren	conodonts	fish fragm.	siculae	Chitinozoa	scolecodonts	ostracods	sponge spicules	gastropods	crinoid fragm.	Bryozoa	brachiopods	trilobite fragm.	bivalves
single pebbles																
B3273	1	JV340	-	1	-	-	-	2	x	2	-	x	1	x	x	x
3274	1	343	-	x	1	-	-	-	x	-	-	x	-	x	x	x
3275	2	345	-	-	-	-	-	-	-	-	x	x	-	x	-	-
3276	3	347	-	1	2	-	-	-	x	-	-	-	x	x	x	-
3277	4	348	o	-	-	-	-	-	-	-	-	-	-	-	-	-
3278	6	353	o	-	-	-	-	-	-	-	-	-	-	-	-	-
3279	7	355	-	-	-	-	-	-	>25	1	x	x	-	x	-	-
3280	8	358	-	-	-	-	-	-	x	3	-	x2	x	-	-	-
3291	5a	*	-	-	-	-	-	1	-	-	-	-	-	-	-	-
3292	5b	*	o	-	-	-	-	-	-	-	-	-	-	-	-	-
3295	5b	*430	-	-	-	+	+	-	-	-	-	-	-	-	-	-
mixed pebbles																
B3259	1	-	-	29	1	-	-	2	-	6	1	-	-	-	-	-
3260	5	-	-	9	-	1	-	3	-	14	2	2	1	-	-	-
3261	m	-	o	-	-	-	-	-	-	-	-	-	-	-	-	-
3262	m	-	-	6	-	-	-	-	2	12	1	12	4	-	-	-
3263	m	-	-	9	-	-	-	-	-	15	-	9	3	-	-	-
3264	m	-	-	-	2	-	-	-	-	5	-	6	-	-	-	-
48337	m	-	-	-	-	-	-	-	1	-	-	2	-	-	-	-
48338	m	-	-	-	-	-	-	-	2	-	-	5	1	-	-	-
3349	m	-	-	-	-	-	-	-	-	5	-	-	-	-	-	-
3350	m	-	-	1	1	-	-	-	-	-	-	-	-	-	-	-
3293	m	-	o	-	-	-	-	-	-	-	-	-	-	-	-	-
3294	m	-	-	1	2	-	+	-	-	15	-	2	-	-	-	-

A = facies type, m-mixed; B = thin section number; * = photograph
x = present in thin section; + = present in palynologic preparation

Unfortunately, we made only five palynological preparations of which two have become misplaced over our 23-year old endeavour.

Conodonts (Pls 1-3)

Although many of the conodonts recovered are non-diagnostic (damaged or juveniles), some could be identified. *Pterospathodus celloni* (Walliser, 1964) indicates a Late Llandovery age for pebble B3276. Most of the Panderodontida of composite samples B3259, B3262 and B3263 (Pl. 1) appear to belong to the long ranging (M. Ordovician - M. Devonian) genus *Panderodus*. However, T.T. Uyeno (pers. comm. Dec. '91) indicates for sample B3263 that Pl. 1, fig. 5 may be a species of *Besselodus* or *Dapsilodus obliquicostatus* (Branson & Mehl, 1933); without the critical *Oistodus*-like, or *Acodus*-like element, respectively, it is difficult to distinguish the two. The combined range of these taxa is Late Ordovician to Early Devonian (cf. Nowlan & McCracken, 1988). The composite sample B3259 yielded the Early Devonian species *Ozarkodina remscheidensis remscheidensis* (Ziegler, 1960), a specimen of *Ozarkodina excavata excavata* (Branson & Mehl, 1933) which ranges from Ludlow into Emsian, and a juvenile *Icriodus*-like conodont also indicating marine Devonian.

The '*Icriodus*' resembles *I. expansus* (Branson & Mehl, 1933) but because the only specimen is a juvenile with an incomplete basal rim it cannot be identified; it may not even belong to *Icriodus* and be a juvenile of the middle Eifelian species *Steptotaxis macgregori* Uyeno, 1990. *O. excavata* s.s. was also found in composite sample B3294.

The Ordovican phosphatic problematicum *Milaculum* was recovered from sample B3260.

All these species are known from fauna recovered from the eastern islands of the Canadian Arctic Archipelago (Uyeno, 1990). The Orphan Knoll material has a CAI (Conodont Alteration Index, an index for thermal maturity) of c. 1.5, which is comparable with the conodonts from the Arctic Archipelago (CAI = 1 to 2, Uyeno, 1990, p. 13). Thus, neither the nature of the conodont faunules, nor their degree of thermal maturity offer any argument against their transport from the Arctic Archipelago. However, as we show later, it is difficult to impossible to transport these rocks by ice or icebergs from their presently known outcrops.

Sponge spicules (Pls 4-6)

Nine of the conodont-processed samples yielded a most interesting collection of sponge spicules (Table 2). With the exception of a sole lithistid desma, the spicules originate from two classes of sponges viz. Hexactinellida, which in life had a spicular skeleton of opaline silica, and Heteractinida, an extinct group of Palaeozoic Calcarea which had solid, calcium-carbonate spicules (Rigby, 1983; Reitner, 1992). Most of the diagenetically altered and recrystallised spicules are broken and incomplete; yet,

Table 2. Sponge spicule distribution and types in samples.

Sample	Hexactinellid spicules				Heteractinid spicules			
	n	common	n	particular	n	common	n	particular
B3259	6	hexacts/pentacts				octacts & deriv.		
B3260	7	idem	3	pinules			2	acanthous with
			1	anchor basalia				7 + 2 rays
B3262	5	idem			5	idem, 2 sexirad.	1	polyactine
B3263					10	idem, 3 sexirad.	1	?*Ensiferites*
B3264	2	1 idem, 1 desma			2	sexiradiates	1	*Ensiferites*
B3279/80	2	idem			3	2 sexirad., 1 undet.	1	polyactine
B3294	8	7 idem, 1 acant.	1	unknown	1	sexiradiate		
	1	undeterm.	5	anchor basalia				
B3349	3	hexacts/pentacts	1	uncinate				

acant. = acanthohexact; deriv. = derived forms; n = number of spicules some have chronostratigraphic value.

X-ray analyses with an Energy Dispersive Spectrometer and experiments with 10% acetic acid and hydrofluoric acid on different spicule types, showed 1) that the heteractinid spicules are either entirely composed of calcium carbonate or are wholly silicified, 2) that the hexactinellid spicules are wholly siliceous, and 3) that some octactine-based spicules have a siliceous exterior covering a calcareous core that effervesced while being acid-treated.

Hexactinellida

All smooth hexactine, or pentactine, megascleres are of a generalised type lacking diagnostic features (i.e. Pl. 5, fig. 2). The smooth-rayed pentact with gradually attenuating rays (Pl. 5, fig. 6) as well as the spinose hexact (Pl. 5, fig. 1) also are indistinctive. Comparable forms have been reported from the Lower Jurassic of Austria (Mostler, 1990) and similar, but smaller, acanthohexacts occur as dermal and gastral spicules in the extant lyssacine sponge *Aulosaccus tuberculatus* Okada (Okada, 1932).

Three similar, incomplete hexactine pinules were recovered from sample B3260 (Pl. 5, fig. 3). Their expanded pinular ray, which is situated immediately on the ray junctions, lacks its upper part. The basal parts of its spines are closely set and resemble imbricated scales. The pinules vertically measure 0.31- 0.46 mm. Pinules are common skeletal elements occurring in various families of extant Hexasterophora and Amphidiscophora. Different forms and sizes of pinules may be found in the same sponge, depending mostly on their location in the body i.e. dermal or gastral. Pinules date as far back as the Early Cambrian (Bengtson, 1986; Mostler, 1990) and a rich diversity of forms has been reported from the Alpine Triassic and Jurassic of Austria and northern Italy (Mostler, 1976; 1980; 1990).

The spinose spicule fragment seen in Pl. 5, fig. 4 may be part of an uncinate. Uncinates are common parenchymal megascleres in extant hexactinellids and also are described from the Alpine Lower Jurassic (Mostler, 1990) and the Middle Silurian of Arctic Canada (Rigby & Chatterton, 1989).

The fully silicified hexactinellid(?) spicule shown in Pl. 5, fig. 5 is an unusual and unknown form. It superficially resembles the spinose heteractinid spicules of Pl. 6, figs. 4-5, but the six adaxially bending, lateral rays at the head of the spicule are devoid of thorn-like protrusions on their inner side and show an upward inclination with respect to the vertical central ray, whereas the lateral rays of heteractinid spicules are at right angles to the vertical rays. This spicule also resembles the peculiar scopules of the extant sponge *Sclerothamnus clausii* Marshall (Schulze, 1887) and those reported from Austrian Lower Jurassic pelagic sediments (Mostler, 1990). However, even the larger known scopules are slender, small megascleres (scopular head diameter < 0.16 mm), whereas the Orphan Knoll spicule is 0.78 mm high, has a shaft length of 0.51 mm and a maximum diameter of its cluster of apical rays of 0.50 mm. The closest resemblance is with a spicule described by Webby & Trotter (1993 p. 38, fig. 7: 12) from the Upper Ordovician of New South Wales. It is about the same size as the Orphan Knoll specimen, but is smooth-rayed and has a collar of small spiny extensions around the base of the shaft. The cluster of apical rays on the Australian example is less symmetric and does not have its central ray in line with the shaft.

Most remarkable are the siliceous hexactinellid anchoring basalia found in several samples (Pl. 4, figs. 1-6). These particular forms were first reported from the Upper Cambrian Mungerebar Limestone of Queensland and were assigned to a new form genus *Silicunculus* by Bengtson (1986). Later, Webby & Trotter (1993) found *Silicunculus* anchoring basalia in the Upper Ordovician Malongulli Formation of New South Wales and proposed a second form genus *Chelispongia*. The Orphan Knoll material cannot be assigned to either genus because the diagnostic proximal parts of the spicules are missing. However, in almost all morphological aspects and dimensions our basalia seem identical to the Australian material. The incomplete, smoothly curving, cylindrical shafts can be as long as 1.6 mm and 0.11 to 0.24 mm wide at the often somewhat oval distal end.

The recurving hooks or straight spines which form the expanded spicule's distal tip, arise either directly at the base of the shaft (Pl. 4, fig. 3a) or typically as a palmate structure (Pl. 4, fig. 4a). The axial canal extends throughout the shaft and terminates distally as a swelling with incipient, knob-like outgrowths where the shaft merges into the sharply bent, multiple spined tip. Consequently, the palmate extensions and the spines or hooks are solid and devoid of axial canals.

Heteractinida

Most heteractinid spicules are of a generalised type, only permitting the assumption that they originate most likely from astraeospongiids. Plate 5, fig. 8 shows a lumpy, more or less intact, sexiradiate, stellate spicule. The crudely textured mass is wholly calcareous. Its six tangential rays are short and stout and probably were of unequal length; they uniformly taper into more or less bluntly rounded tips. The spicule has a maximum diameter of 0.50 mm and fits Rigby's (1976) description and illustrations of the Emsian astraeosponge *Stellarispongia*.

The diagnostic, solidly recrystallised, calcareous, octactine spicule shown in Pl. 6, fig. 1 has six, somewhat compressed, horizontal rays and two stout, cylindrical, vertical rays; none of the rays is complete. The specimen is 0.50 mm high; the horizontal rays are 0.065 to 0.075 mm wide at their base. The more robust vertical rays have a 0.08 mm diameter. The shorter, distal ray splits above the central junction in three supernumerary, upward and outward inclining branches. Such morphology is typical for spicules of the Middle to Upper Devonian *Ensiferites* Reimann, 1945 (Rigby et al., 1979; Rigby, 1983).

The smooth-rayed spherical polyactine of Pl. 6, fig. 3 is a solid megasclere with rays that radiate in all directions from a common centre. The gradually tapering rays are cylindrical and straight and originally were of unequal length. The overall diameter of the incomplete spicule is 0.56 mm; its rays measure 0.075 to 0.085 mm at their base. Two of the three EDS measuring points on the siliceous spicule showed a minor Ca peak, suggesting advanced silica replacement of a previously calcareous phase.

The similar, but smaller (max. diameter 0.135 mm) and more irregular polyactine stellate spicule of Pl. 6, fig. 2 has short and sturdy, steeply attenuating rays that radiate from a common centre. Two of the rays are disproportionally long; the curved one is hollow which suggests the former presence of an axial canal. However, the cavernous nature is an artifact of fossilisation that also shows in other spicules of undoubted heteractinid origin (e.g. Pl. 6, fig. 5). Rietschel (1968) discusses such preservational artifacts of originally solid calcareous spicules.

Both of the above polyactine spicules resemble forms that characterise the Wewokellidae from the Lower Carboniferous of Scotland and Belgium (genus *Asteractinella* Hinde, 1888; Vandercammen, 1950), the Lower Pennsylvanian of Missouri (Bailey, 1935), the Lower Permian *Talpaspongia* of central Texas (King, 1943) and the north Australian Middle Cambrian *Jawonya gurumal* Kruse (Kruse, 1990; Rigby, 1991a-b; Reitner, 1992). Thus, there appears to be an Ordovician-Devonian gap in the record of wewokellids into which our polyactines may fit somehow.

Plate 6, figs. 4-5 show two similar, octactine-based, spinose, completely silicified heteractinid spicules of a hitherto unknown form. They have seven, equally spaced, tangential rays normal to a pair of vertical rays, which form a large, flat central disc where their bases join. The rays bear widely and irregularly spaced, short thorns which tend to form ridges between them; this gives the spicules a jagged and angular appearance. Thorns also occur on the distal side along the outer rim of the central disc at the junctions with the ray bases. The proximal ray is the most prominent (0.24 mm long; Pl. 6, fig. 4b) and with its 0.1 mm diameter it is more than twice as thick as the distal ray. The two spicules have horizontal diameters of 0.47 mm, and total heights of 0.43 and 0.37 mm. Two broken tangential rays seen in the centre of Pl. 6, fig. 5b show circular hollows and central fillings. These spicules differ from any presently recorded types. Deviation from the usual number of six tangential rays is not uncommon and in itself does not suffice as a criterion for the recognition of taxa, unless it can be shown that spicules with seven tangential rays are the predominating form in this particular type of skeleton. However, also apart from having seven, instead of the general six, tangential rays, these spicules represent distinctive morphotypes which will be useful in further research on spicular material from this region.

The sponge spicules of Orphan Knoll probably are of Ordovician and Devonian origin and seem to represent a previously unknown faunal province.

Ostracods (Pls 7-11)

An intriguing, silicified ostracod fauna was recovered from the dredge samples. SEM photographs and specimens of some 20 species in open nomenclature were passed to Gerhard Becker (Frankfurt) who kindly described 13 forms (Becker & Adamczak, 1993; Becker, 1994) with the others remaining indeterminate due to their simple morphology, state of preservation or small number of specimens.

Becker (1994) identified four undescribed species of the palaeocopid genera *Anticostiella, Bromidella?, Ectoprimitoides*, and *Ordovizona*, and nine undescribed podocopids. The material allowed for the *Ordovizona* species to be described as new. The nine smooth podocopids also are new to science; they represent *Elliptocyprites?, Shenandoia, Uthoernia?, Pseudorayella?, Macrocyproides?, Baltonotella?*, two bairdiocypridid species, and *Aboilia blessi* described by Becker & Adamczak (1993) as a new species of a new genus.

Becker (1994) could not identify and did not describe further, *Monoceratella?* sp. A, palaeocopids PA-A and PA-B, and podocopids PO-A, PO-B, PO-C and PO-D, all illustrated on Pls 8-11.

Practically all the ostracods were recovered from the single-pebble sample B3279 (thin section JV355, Pl. 16, fig. 1); the Ordovician *Ectoprimitoides* sp. A and *Macrocyproides?* sp. A were also found in composite sample 48338, and a bairdiocyprid occurs in composite sample B3262.

The generic composition of this fauna indicates a Middle to Late Ordovician age and an open marine shelf depositional environment showing affinities with North American as well as with North European faunal provinces (Becker, 1994). On the species level, the fauna is unique and apparently endemic to a, hitherto undiscovered, Palaeozoic province of the Northern Hemisphere outcropping in the mounds of Orphan Knoll (Becker, 1994).

Scolecodonts (Pl. 3)

The few scolecodont jaws recovered from Orphan Knoll are all damaged. The two illustrated specimens from pebble B3273 give rise to the following remarks. The jaw of fig. 4 is of MIs position; its damaged external margin (left side of specimen in dorsal view) was possibly broadly rounded. The presence of a knob-like projection at its posterior termination makes the jaw quite similar to the MIs of *Polychaetaspis tuberculatus* Kielan-Jaworowska, 1966. It also shows a general resemblance to *Polychaetaspis warkae* Kozlowski, 1956. *Polychaetaspis* is characteristically abundant in Middle to Upper Ordovician strata, but may range up into the Silurian.

The jaw of fig. 6 is severely damaged. Its gross morphology indicates that it occupied a MId position, such as in *Kalloprion triangularis* Kielan-Jaworowska, 1966 (M. Ordovician), or a MIId, as in the Silurian *Paulinites polonensis* Kielan-Jaworowska, 1966 and *P. burgensis* Martinsson, 1960.

The specimens from composite sample B3259 also seem to be of Middle or Late Ordovician origin. Fig. 5 is closely similar to *Paleoenonites circumscriptus* Eller, 1945, but damage to the anterior denticulation of this right basal plate precludes precise identification. Its lightly fused individual denticles give the jaw of fig. 7 a primitive character; it could not be compared to any published form other than the poorly illustrated *Ungulites aculeatus* Stauffer, 1933.

The scolecodonts suggest the limestone pebbles to be of Middle to Late Ordovician age (Jansonius & Craig, 1971).

Chitinozoa (Pl. 13)

The five samples processed for palynomorphs (B3291-3295) have the brown, translucent appearance of the Ordovician Viola and Fernvale Formations of northern Oklahoma. Two samples are barren and one only has a few indeterminate chitinozoan remains. However, the pebble sample B3295 has numerous specimens of *Rhabdochitina minnesotensis* Stauffer, 1933 (= *Conochitina minnesotensis* of Eisenack, 1965, p. 126, pl. 10, figs. 7, 8; Laufeld, 1967 and Jenkins, 1969). The mixed sample B3294 has few, but well preserved, chitinozoans, including *Ancyrochitina* sp. and *Conochitina* sp.

The suggested age for the two samples is Middle to Late Ordovician.

Graptolites (Pls 12-13)

One juvenile graptolite (GS-a, sicula with theca beginning to bud on right-hand side) was recovered from the 'conodont preparation' of composite sample B3260 (Pl. 12, fig. 3); it has been provisionally identified as the Late Ordovician '*Glyptograptus*' *hudsoni* Jackson (cf. Jackson, 1971, textfigures 1C and 1E). It could, however, belong to other 'advanced' orthograptids which range from Caradoc to mid-Ashgill. A similar form was found in the single-pebble 'palynological preparation' B3295 (Pl. 12, figs. 6-7). If the imperfectly preserved specimen of Pl. 13, fig. 2 is unbroken it must be *Akidograptus ascensus* from the earliest Llandovery *acuminatus* Zone; if it is broken then it probably belongs to a Llandovery *Glyptograptus* species (sensu Melchin & Mitchell, 1991).

Thus, we have Late Ordovician and Early Silurian representatives. The nearest place the Early Silurian graptolites could have come from is Cornwallis Island in the interior of the Canadian Arctic Archipelago. Graptolites similar to the Ordovician forms have been found on Akpatok, Southampton, and southern Baffin Islands of Hudson Strait. We demonstrate in a later section that it is unlikely that material from Cornwallis Island has been ice- or iceberg-transported to Orphan Knoll in the modern day.

Age

The single-pebble samples B3273, B3276, B3279, and B3295, and the mixed samples B3260, B3262, 48338, and B3294 yielded Late Ordovician to Early Silurian fossils (conodonts, sponge spicules, ostracods, scolecodonts, chitinozoans, and graptolites). The fauna recovered from the three other fossiliferous mixed pebble samples B3259, B3263 and B3264 is dominated by Early to Middle Devonian fossils (conodonts, sponge spicules).

Nearby bedrock source versus ice-transported material

The limestone samples dredged from the base of the Orphan Knoll mounds in 1971 are interpreted to reflect nearby bedrock on the mounds rather than ice- or iceberg-transported glacial debris from a more northerly source. A brief review of the arguments for this conclusion was given in Ruffman & van Hinte (1993). We detail our argument here and note that this conclusion derives from a number of avenues which reinforce each other and strengthen our finding:

A) The mounds on top of Orphan Knoll appear to be bedrock highs on all high resolution seismic profiles, and on many profiles the mounds appear to be diapiric and to penetrate and cut all other horizons (Figs. 3 and 7). In some cases younger beds appear to be bent upwards adjacent to the mounds (Fig. 7).

B) Orphan Knoll has stood as an isolated, drowned, topographic high since at least the end of the Cretaceous. The continental- and shelf-derived turbidity currents of the past 60 Ma have flowed around Orphan Knoll into the abyssal plain, thus the rocks of the breakup escarpment have not been buried. The top of Orphan Knoll has only been subject to loading from the rain of pelagic sediment and to increased hydrostatic pressure from the sinking of c. 1800 m. The sediment loading and the increased hydrostatic pressure may provide a mechanism for the reactivation of salt diapirs in tight formations and for the protrusion of the mounds above the top of Orphan Knoll some time after the Cretaceous.

C) The sediment levels between some of the mounds are at different elevations (Fig. 7), suggesting that periodic slumping of at least Quaternary pelagic sediments off the mounds is differentially ponding between groups of mounds. This provides a logical mechanism for bedrock-derived talus from the exposed mounds to be moved downslope to the area at the base of the mounds where the 1971 biologic dredge picked it up (Figs. 4, 6, 7). In such a process one would expect a mix of nearby in situ bedrock sources (and ages) plus any ice-transported debris that has rained down in the Plio-Pleistocene.

D) The unique Ordovician assemblage of ostracods in the 1971 dredge haul is endemic at the species level and contains two new species and one newly identified genus with eleven other new forms left in open nomenclature (Becker & Adamczak, 1993; Becker, 1994; this paper). This material does not come from any other presently-known location in Canada, Greenland, or Europe and strongly suggests a local source (Becker, 1994).

E) The ostracods found have both North American and North European affinities, indicating that the provinciality of ostracod faunas between North America and Europe was breaking down during the latter part of the Ordovician, and that the fossil assemblage originates from an intermediate position (Becker, 1994). Orphan Knoll's geographical position at the time of breakup fulfils the latter requirement.

F) The Ordovician basalia sponge spicules are again not from any presently-known source in Canada, Greenland, or Europe and bear a close resemblance to Australian forms; they are in fact forms almost unknown from the literature. The 1971 Orphan Knoll dredge samples also contain Devonian heteractinid skeletal material which is difficult, to almost impossible, to move over Orphan Knoll from any known location by modern ice- or iceberg-transport.

G) The finding of Devonian conodonts in the 1971 dredge material again suggests a local nearby bedrock source since there are no presently-known sources of marine Devonian rocks in northern Canada (and none whatsoever in Greenland) that are accessible to local glaciers that debouche into Baffin Bay or into Jones Sound to create icebergs.

H) The finding of Early Silurian graptolites again suggests a local nearby bedrock source. The only other possible source is on Cornwallis Island and this source is not considered accessible to local glaciers that create icebergs.

I) It is virtually impossible for modern shore-fast, or near-shore, yearly, pack ice to freeze onto pieces of marine Silurian and Devonian limestone, then to pass over Orphan Knoll to melt and to drop them on top of the Knoll. Earlier we noted that the shallow bite of the Arctic Dredge used in 1971 meant that the dredge collected sediment and ice-rafted debris that had been deposited within the last 1000 (or possibly 5000) years. Any glacially-transported pebbles which were dropped from icebergs within the past 5000 years would have involved ocean current, wind, glacier, and iceberg processes, and bedrock sources which were very similar to those of today.

There is almost no opportunity for modern glaciers in Canada to create icebergs to transport marine Devonian rocks to Orphan Knoll; there are no known marine Devonian rocks on Greenland. Marine Devonian rocks are not in the modern glacial 'ice-shed' of Baffin Bay, and with one minor exception all glaciers that cross marine Devonian outcrops find their way northwestward into the Arctic Ocean or westward into the interior of the Arctic Islands; these icebergs do not then enter Baffin Bay or the Labrador Sea. A similar argument can be made for the Lower Silurian of Cornwallis Island.

J) Furthermore, it is considered statistically impossible to have present-day glacial ice in Canada, in Greenland, or elsewhere in the North Atlantic sampling quite unknown marine Ordovician, Silurian and Devonian outcrop areas, then producing icebergs, which then would drift across Orphan Knoll while melting and which would drop their entrained rocks randomly to give, in one small area on top of Orphan Knoll, the unique Ordovician ostracod assemblage, and the unique Ordovician spicule assemblage, and the Early Silurian graptolites, and the Devonian conodonts, and the Devonian spicules. The probability of this coincidence is considered vanishingly small. A nearby in situ bedrock source higher up on the mounds is much more likely.

K) Nelson, Hacquebard, Bloxam & Kelling, and Pocock (all 1972; all in Laughton et al. 1972), Hacquebard (1981), and Hacquebard et al. (1981) looked at the nonmarine Jurassic sandstone from DSDP Site 111 at Orphan Knoll and identified reworked Palaeozoic palynomorphs and coal, thus giving indirect evidence for at least a Late Palaeozoic section in the area of Orphan Knoll. The Freydis B-87, Indian Harbour M-52, Hopedale E-33, and Robertval K-92 wells on the southern Labrador Shelf all penetrated through the Mesozoic into Lower Palaeozoic limestones that are dated as Ordovician (Bell & Howie, 1990). Papers by MacLean et al. (1977) on the Ordovician of the southwest Baffin Island continental shelf and by Bergström et al. (1974) on the Ordovician platform sediments of western and north-central Newfoundland suggest a widespread area of Ordovician platform sediments in a large intracratonic Palaeozoic sea that could well have extended east from the southern Labrador Shelf to the Orphan Knoll area.

L) Similarly, there is also evidence for Devonian rocks in the lower part of the sedimentary section on the Grand Banks or off Labrador. Grant (1988) noted that Williams (1987) has, 'described recycled Devonian palynomorphs in Cretaceous and Tertiary sediments from exploratory wells on the Labrador Shelf, and noted the possibility that Devonian rocks may occur somewhere in the Labrador Sea as an element of [the] basement to the Mesozoic-Cenozoic section.' Devonian rocks were found at the Gannet 0-54 well on the Grand Banks (Barss et al., 1979). In addition, Devonian rocks have been identified below 2456.7 m (8060 ft) in the Phalarope P-62 well on the Grand Banks (Sedley Barss, Atlantic Geoscience Centre, pers. comm., February 17, 1989, referring to a 1976 internal report of W.A.M. Jenkins). It is, therefore, not unreasonable that marine Devonian rocks were also laid down in the Orphan Knoll area. The probable presence of an original Devonian section supports a possible exhumed Devonian section as the origin of some of the mounds on Orphan Knoll.

M) The 1971 dredge haul had a high 39%, by weight, of limestone pebbles versus other erratic metamorphic or granitic crystalline material. This high percentage indicates a nearby bedrock source. In addition, the pebbles were somewhat angular and showed no sign of glacial or subglacial transport such as soling or rounding (Pl. 14).

N) The marine Ordovician material in the 1971 dredge haul agrees with the marine Ordovician finding in the 1978 dredge haul on a different mound (Legault, 1982) even though we recognise that her finding was made on only one of 93 carbonate samples dredged in the two 1978 dredge hauls (Ruffman & van Hinte, 1989; Ruffman, 1989).

O) The finding of a large amount of the modern ahermatypic coral *Desmophyllum cristagalli* in the same 1978 dredge haul (78-020-001) on which Legault worked (Ruffman, 1989) strongly suggests that the dredge was dragged through a coral debris pile just below a vertical or overhanging wall of outcrop since that is this coral's preferred habitat (S. Cairns, Smithsonian Institution, pers. comm., 1989). Radiocarbon and U/Th dating showed the coral debris to be 76 ka to 4 ka and 50 years old (Ruffman & Mudie, 1994; Smith, 1993; Smith & Risk, 1993). While this observation speaks only to the 1978 dredge haul No. 78-020-001, it does support the finding from seismic profiling and the GLORIA work that the mounds comprise outcrop with slopes of 15° to 20° (Parson et al., 1984) or even up to 30° (Ruffman & van Hinte, 1989).

All the evidence points towards a nearby, in situ bedrock source for the limestone pebbles recovered in the 1971 LYNCH Biologic Dredge No. 1. The carbonates probably reflect the bedrock geology of the mounds just to the east of the dredge site; the carbonates moved downslope with modern pelagic sediment in a series of slumps.

Origin of the mounds

At the time the mounds were first discovered by the D/V GLOMAR CHALLENGER as it did a brief pre-site survey (Fig. 3), it was hypothesised that the mounds on any one profile represented crossings of linear ridges of outcropping bedrock. The bathymetry map published in the Site 111 report was made by Ruffman during the LYNCH 7/11/71 cruise, and the mounds were interpreted as long, linear ridges striking northwest-southeast (Fig. 2). Laughton et al. (1972) interpreted the 'ridges' to be possible dyke material that had subaerially weathered high before the Knoll had subsided. However, the mounds had no magnetic signature. The 1971 LYNCH cruise and the dredging were completed before the DSDP Leg 12 volume went to press, and an addendum was added to Laughton et al. (1972, p. 80) to suggest that the mounds represented ridges of dipping resistant, massive, sedimentary strata that had been deformed by folding, then subaerially eroded to stand high prior to the sinking of Orphan Knoll.

The 1979 M/V STARELLA and 1981 M/V FARNELLA survey of Orphan Knoll using GLORIA showed that the mounds are generally discrete circular features and not resistant linear beds weathering high (Fig. 4). Alan Grant (1988) and Parson et al. (1984) have interpreted their GLORIA discovery as evidence that the mounds on the northeast upper surface of Orphan Knoll, 'may be remnants of reefal mounds on an exhumed Devonian landscape' (Grant, 1988). In their paper, they noted, 'that upper Paleozoic reefal limestones, which are widespread in North America, ... may give rise to high relief erosional topography particularly those limestones of Devonian and Carboniferous age.' (Grant, 1988).

An example was cited of Spanish Saharan reefs that have been exposed by recent subaerial erosion to form topographic highs 100 m in elevation and 2 km in diameter

(Dumestre & Illing, 1967). Another onshore example was found by Parson et al. (1984) and Grant (1988) in the Lower Carboniferous reef knolls of Yorkshire, northern England where reefal bodies up to 600 m thick and 1000 m in diameter have differentially eroded to, 'form a series of conspicuous isolated hills, or knolls, which rise abruptly 200 to 300 ft (60-90 m) above the general level of the surrounding country (Edwards & Trotter, 1954).' In the latter case, the 'country rock' surrounding the patch reefs is quite hard, and it has eroded subaerially relatively slowly so that the contrast in elevations is minimal (Parson et al., 1984).

Grant (1988) also noted that during the Devonian Orphan Knoll was in a favourable palaeogeographic position, at c. 15° S, to foster reef growth. Grant cites a personal communication from G. P. Smith, of Chevron Canada Resources Ltd, Calgary, Alberta noting that the mounds on Orphan Knoll, 'compare most closely with Leduc pinnacles [reefs] east of Edmonton, '...they have a higher height to width ratio than most typical Devonian reefs'.' The possibility of the Orphan Knoll mounds being Devonian pinnacle reefs is attractive, since it suggests such features might be found buried elsewhere in the sedimentary section of Eastern Canada or offshore Ireland where they might serve as excellent hydrocarbon reservoirs as they do in Alberta. There is no evidence to suggest that the seabed mounds are modern bioherms or lithoherms similar to those found by Hovland et al. (1994) off western Ireland, though the dimensions are similar.

Ruffman & van Hinte (1989) also noted that the height to width ratios of the Orphan Knoll mounds, whether buried or partially exposed above the sea floor, are much higher than those for the Spanish Saharan or Yorkshire onshore examples and the ratios are higher than most typical Devonian reefs. The cover of Geology for December, 1978 (Drake, 1978) suggested another possible origin of the mounds on top of Orphan Knoll as did the cover photo on Episodes for June, 1988 (Anonymous, 1988); both show Chinese karst topography near the city of Kweilin on the Li River developed in uniform Devonian, through Lower Carboniferous, limestones overlying Lower Devonian clastic sediments.

Karst topography in a limestone terrane can lead to the higher height to width ratios seen for the features on the top of Orphan Knoll and could be an explanation for the mound-like features seen. The mound fields on top of Orphan Knoll appear to closely resemble 'tower karst' in a field of 'aggregated peaks' (Drake,1979a,b; Ruffman & van Hinte, 1989). Orphan Knoll has been in the correct palaeogeographic zone in post-Ordovician times to have experienced high rainfall in a warm sub-tropical climate (Zonenshayn & Gorodnitskiy, 1977), and karst topography could well have developed in the limestones as a consequence. The spacing of the two possible karst fields along the northeast and southwest sides of Orphan Knoll thus may reflect Ordovician to Devonian structure or basinal geometry with the intervening area having weathered even lower to form a later basinal area first for the deposition of the Bajocian fluvial sediments found in DSDP Hole 111, and still later for the deposition of the Albian to Cenomanian shelf carbonates.

In either case, if one argues that the mounds reflect erosional remnants of a patch reef or pinnacle reef environment, or of a mature karst topography, then the 'pinnacles' must have stood as erosional highs during a period of subaerial erosion and deposition during Bajocian times and then stood as exposed islands in the Late Cretaceous and Early Tertiary sea as Orphan Knoll subsided about the time of continental breakup (Ruffman & van Hinte, 1989). Then as subsidence continued for the Orphan Knoll block, further Tertiary and finally Pleistocene sedimentation slowly rained down on the Knoll to completely bury some of the mounds and to leave others as the isolated mounds and groups of pronounced bathymetric highs seen in the two zones on top of Orphan Knoll today. The implication is that the mounds stood as, and survived as, islands over a 10-15 Ma period without being eroded to sea level and peneplaned. This is not possible.

The Aptian(?)-Albian-Cenomanian sea may well have been very shallow and confined to the known small sedimentary basin between the two zones of mounds (Fig. 5). However, erosion products and Palaeozoic indicators were not found in the Cretaceous sediment at Site 111 (Laughton et al., 1972). During the Maastrichtian when 10 m of chalk was deposited, the sea must have been deeper and the mounds would have had to survive as quite small islands for in the order of 2 to 5 Ma while Orphan Knoll sank, even if it sank quickly. This survival of the mounds as islands for 2 to 5 Ma seems very unlikely. While detailed bathymetry is not available, the minimum depths of the mounds appear to be quite variable, and their minimum elevations do not appear to form a peneplane (Fig. 4). The authors now favour a diapiric origin for the mounds which was originally suggested and dismissed in Laughton et al. (1972).

To propose halokinesis as the origin of the Orphan Knoll mounds one must have pre-Middle Ordovician salt in the area. While there is no trouble finding Carboniferous (Windsor Formation), Upper Triassic (Osprey Formation) and Lower Jurassic (Argo Formation) evaporites and diapirs on the eastern Canadian continental shelf (Wade & MacLean, 1990; Grant & McAlpine, 1990), Lower Palaeozoic evaporites have not been identified off the east coast of Canada. Silurian salt is found in the Michigan Basin and Devonian salt is found in the intracratonic areas of western Canada (Rose et al., 1968; Little et al., 1968). Zharkov (1981) shows Cambrian evaporites in the Michigan Basin and a multitude of small Ordovician-Silurian evaporite basins in North America. It seems reasonable to suggest an Lower Palaeozoic evaporite deposit in the area of Orphan Knoll. The diapirs on Orphan Knoll could also be caused by mobile shale rising up through the section, but not with such a long history of repeated movement.

We would propose that there was (pre-)Jurassic halokinesis and subsequent erosion during at least Bajocian times. The dipping nature of the non-marine sandstone beds in Reflection Unit 3 (Fig. 3) suggests a second, post-Jurassic erosion period with again a state of salt equilibrium reached and a cessation of diapir growth. As the Knoll sank to a shallow marine depth in the Cretaceous, a 58 m section of limestone and eventually 10 m of chalk were laid down (Laughton et al. , 1972). The Cretaceous sediment loading, followed by major subsidence to about 2000 m in the Early Tertiary, along with further loading of a 35 m Tertiary pelagic sediment section (Laughton et al., 1972) provided the driving force for a reactivation of the earlier Jurassic (and possible pre-Jurassic) halokinesis. The final loading of a 145 m Plio-Pleistocene section (Laughton et al., 1972) then provided impetus for a further reactivation of diapir growth leading to the present, young mounds. Movement on some of the diapirs may continue to the present-day with faulting and warping seen in the most recent sediments over some of the buried mounds (Fig. 3).

On the northeast side of the Knoll where the evaporites may have been thicker, the diapirs have risen to their highest levels to stand over 300 m above the top of Orphan Knoll. To the southwest where perhaps the early evaporite sequence was thinner, the diapirs have seldom broken through the top of the Knoll and remain generally buried. At present we know of only one diapir that has clearly penetrated up through the Cretaceous basin (Fig. 5); generally the two diapir fields flank the basin (Fig. 4).

Palaeogeographic implications

All palaeogeographic reconstructions of the North Atlantic Ocean are constrained by the Charlie Gibbs Fracture Zone just to the north of the northern extension of Orphan Knoll (Fig. 8). While Laughton et al. (1972) took the liberty of jostling the small continental fragments about to make a convenient fit, when they are constrained by the fracture zones and known poles of rotation, a fairly logical map results (e.g. Srivastava et al., 1988a, b). This places Orphan Knoll (OK) adjacent to the southwest margin of Porcupine Bank at Anomaly K time (105 Ma) as seen on Fig. 9.

While the Triassic-mid Cretaceous pre-breakup palaeogeography around Orphan Knoll is fairly well known, it is not well understood for the Early to Middle Palaeozoic (Ziegler, 1988). Almost certainly Orphan Knoll was separated from the Labrador and northeast Newfoundland Shelf by a very early initial rifting process. Thus Orphan Knoll may have been a few hundred kilometres further west in the Palaeozoic.

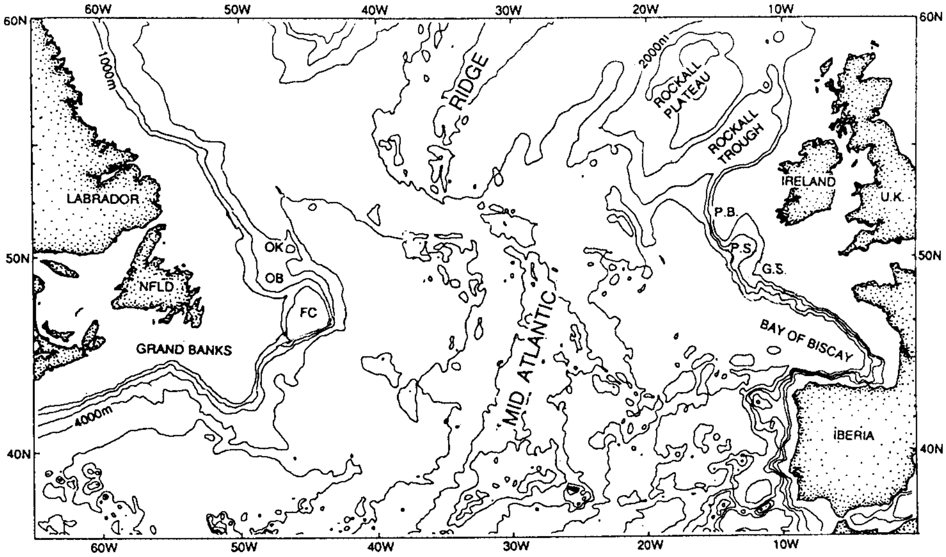


Fig. 8. General bathymetry of the North Atlantic Ocean slightly modified from the fig. 1 of Srivastava et al. (1988a). The 1000 m contour interval is based on the five minute digital data set of ETOPO5 (1986). OK - Orphan Knoll, FC - Flemish Cap, OB - Orphan Basin and on the conjugate margin, P.B. - Porcupine Bank, G.S. - Goban Spur, and P.S. - Porcupine Seabight.

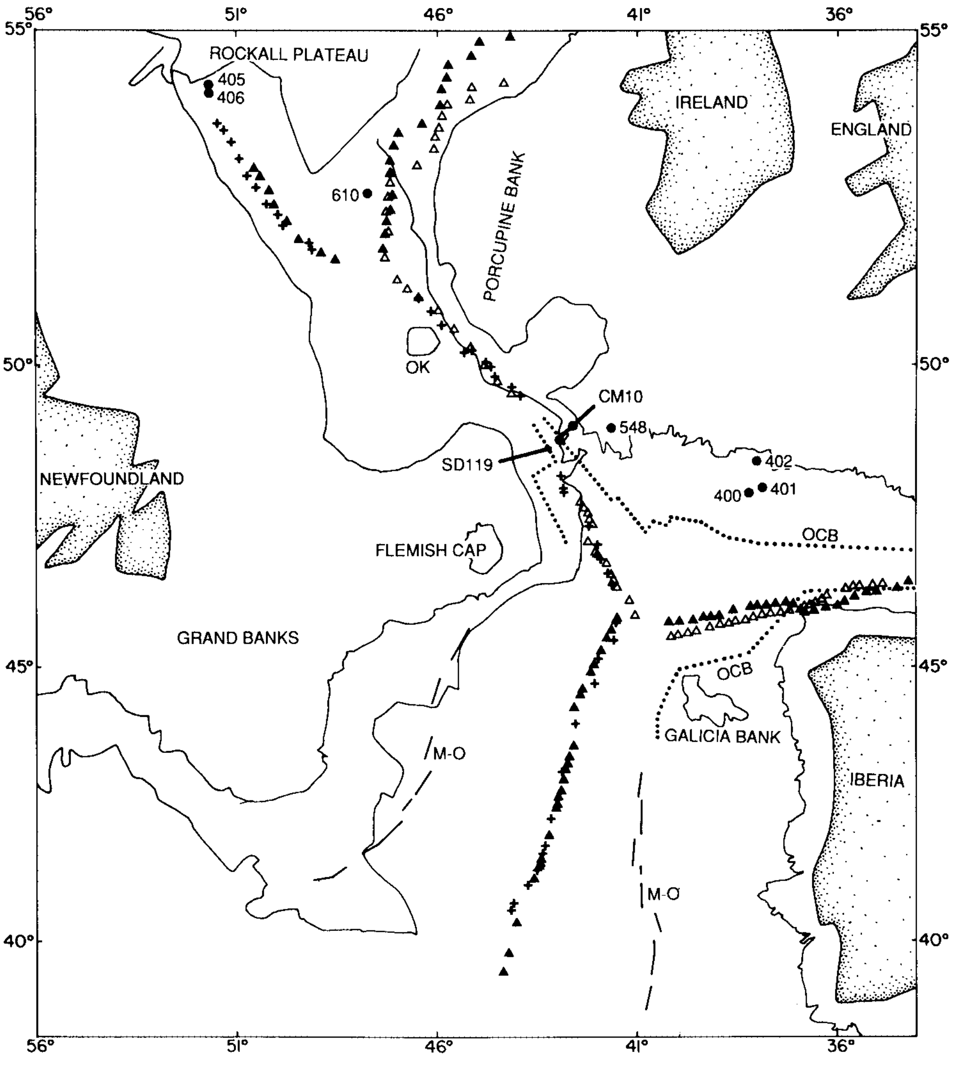


Fig. 9. Reconstruction of the North Atlantic Ocean at mid-Cretaceous magnetic Anomaly K time (105 Ma) with the geographic grid relative to North America. The figure and the following caption are slightly modified from Srivastava et al. (1988b). The reconstruction was obtained by first rotating the Rockall Plateau to the west to close the southern Labrador Sea, and then rotating Eurasia to close the region north of Flemish Cap as well as a portion of Rockall Trough. Locations of the ocean-continent boundary (OCB), north of Flemish Cap, are shown by plus signs for the North American Plate, by solid triangles for the Rockall Plate, and by open triangles for the Eurasian Plate. For the regions south of 50°N the rotated and unrotated positions of OCBs are shown by dotted lines. Positions of Anomaly K south of 48°N are shown by open triangles for the Porcupine (or Eurasian) Plate while for the Iberian and North American plates they are shown by solid triangles and plus signs respectively. Also shown are positions of anomalies M-0 on the North American and Iberian plates and of the two conjugate multichannel lines SD 119 and CM 10 used in Srivastava et al. (1988b). DSDP Site 111 is shown as Orphan Knoll (OK) and various other Ocean Drilling Program sites are shown as numbered black dots. The conjugate position of Orphan Knoll is directly adjacent to Porcupine Bank.

The present record of a marine shallow sea carbonate section in the Middle to Late Ordovician on Orphan Knoll, allows one to extend the known epeiric intracontinental sea from western Newfoundland and Anticosti Island through to the southern Labrador Shelf and right up to known similar deposits off southeast Baffin Island, in Foxe Basin, in East Greenland and at the Fossilik erratic location in West Greenland and out to the Orphan Knoll position in the Middle and Late Ordovician.

Considerable work has been done on the palaeogeography of the Devonian and the 'Old Red Sandstone' with special attention paid to the positioning of the marine and non-marine deposits and to the 'southern' shoreline of the land area (Friend, 1969; House, 1973; Oliver, 1973; Halstead & Turner, 1973; Johnson & Boucot, 1973). In most Devonian palaeogeographic reconstructions, Orphan Knoll falls within the 'Old Red facies'; the present record of marine Devonian on Orphan Knoll requires a marine reentrant during at least part of Devonian times, or significant post-Devonian strike-slip movement.

Conclusions

Reexamination of the 1971 dredged limestone material from Orphan Knoll has been shown to reflect nearby in situ bedrock from the mounds that mark the top of the Knoll. These mounds which in places stand more than 300 m above the top of the Knoll represent two fields of over 250 diapirs which were reactivated after Orphan Knoll sank at the time of the breakup of Europe and North America. The mounds are outcropping bedrock of Middle to Late Ordovician, Early Silurian and of Middle Devonian age, and were deposited in shallow marine, continental shelf conditions.

The presence of a marine Middle to Upper Ordovician section allows one to extend the intracratonic sea of these times eastward to the area of Orphan Knoll. Similarly our marine limestone finding in the Middle Devonian further constrains the southern shoreline of the 'Old Red Sandstone'.

The presence of an Ordovician to Devonian marine section on Orphan Knoll suggests that a similar section might be present beneath Porcupine Bank and other parts of the conjugate margin off Ireland and Rockall Platform. The unsedimented, northeast facing, break-up escarpment of Orphan Knoll offers one of the best opportunities to collect a suite of rocks that will reflect the Palaeozoic and pre-break-up succession out at the very edge of the zone of rifting.

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Manuscript received 23 July 1994.

Plate 1

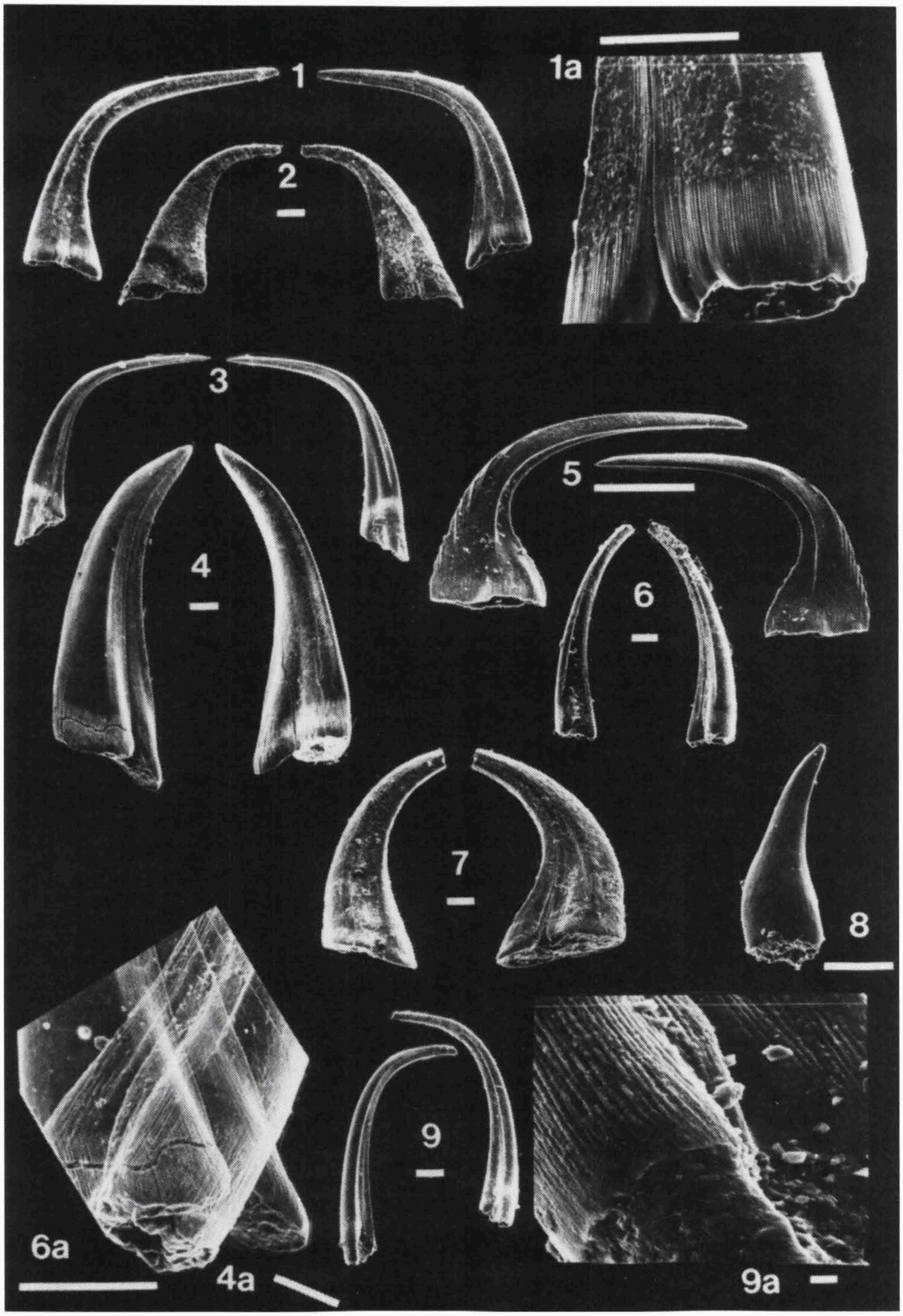
Conodonts. Scale bar is 100 µm, unless otherwise indicated.

Figs. 1-4, 6-7 and 9. Panderodontida.

1: Sample B3262 (RGM 414 140); 1a: close-up of basal portion; 2: sample B3262 (RGM 414 140); 3: sample B3263 (RGM 414 141); 4: sample B3259 (RGM 414 139); 4a: close-up of basal portion; 6: sample B3259 (RGM 414 139); 6a: close-up of basal portion; 7: sample B3259 (RGM 414 139); 9. Sample B3263 (RGM 414 141); 9a: close-up, oblique view of basal portion, scale bar is 10 µm.

Fig. 5. *Dapsilodus obliquicostatus* (Branson & Mehl, 1933)? or *Besselodus* sp., sample B3263 (RGM 414 141).

Fig. 8. Fish tooth (?), sample B3276 (RGM 414 138).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9a

Plate 2

Conodonts. Scale bar is 100 μm.

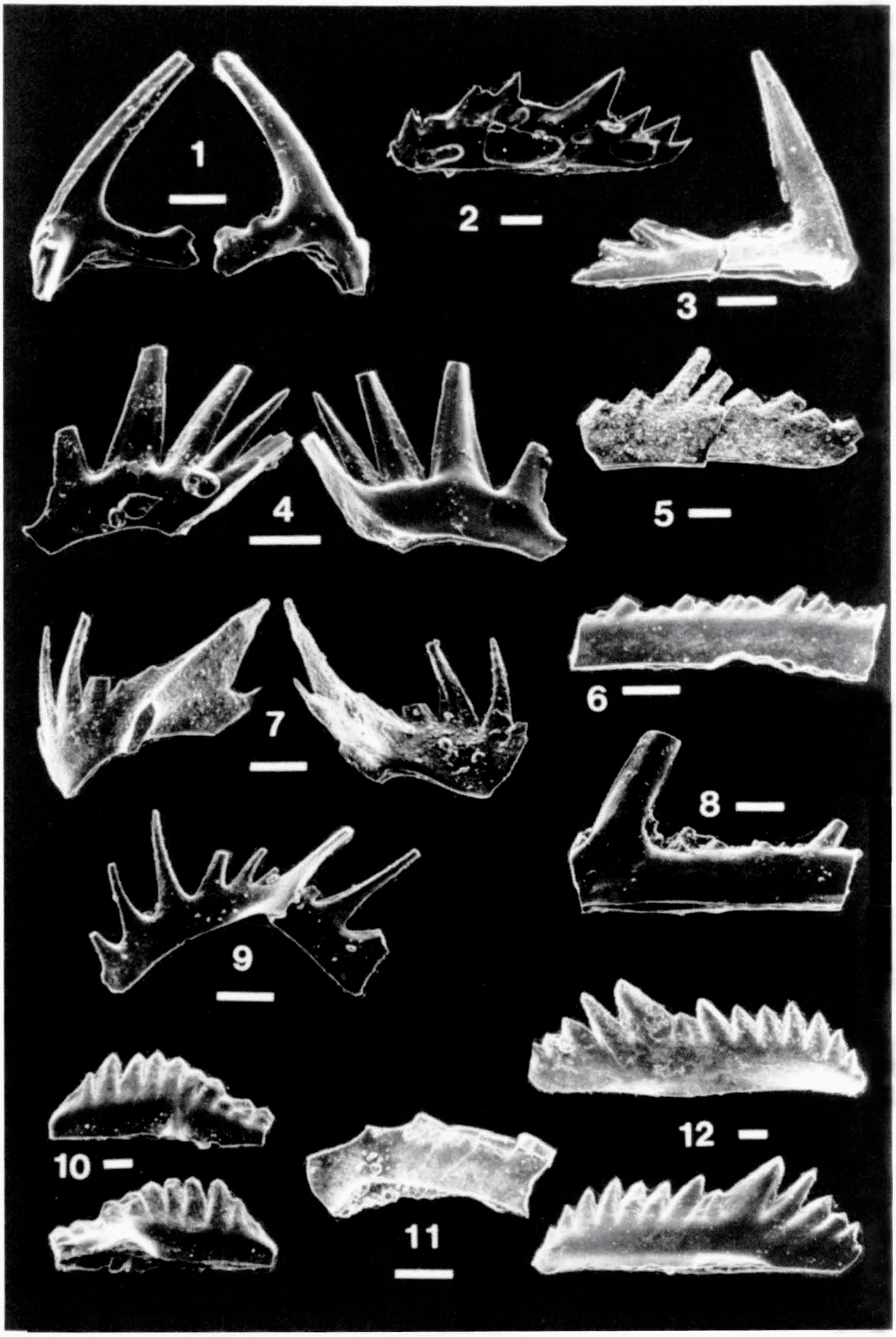
Figs. 1, 3-9 and 11. Unidentified ramiform conodont elements.

1: Sample B3259 (RGM 414 139); 3: sample B3263 (RGM 414 141); 4: sample B3263 (RGM 414 141); 5: sample B3259 (RGM 414 139); 6: sample B3259. (RGM 414 139); 7: sample B3262 (RGM 414 140); 8: sample B3259 (RGM 414 139); 9: sample B3263 (RGM 414 141); 11: sample B3273 (RGM 414 138).

Fig. 2. *Ozarkodina*? sp., sample B3263 (RGM 414 141).

Fig. 10. *Pterospathodus celloni* (Walliser, 1964), sample B3276 (RGM 414 138).

Fig. 12. *Ozarkodina excavata excavata* (Branson & Mehl, 1933), sample B3294 (RGM 414 138).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12

Plate 3

Conodonts and scolecodonts. Scale bar is 100 µm.

Fig. 1. *Ozarkodina excavata excavata* (Branson & Mehl, 1933), sample B3259 (RGM 414 139); a: side view; b: top view; c: basal view; d: close-up, basal view.

Fig. 2. *Icriodus* sp., sample B 3259 (RGM 414 139); a: top view; b: side view; c: basal view.

Fig. 3. *Ozarkodina remscheidensis remscheidensis* (Ziegler, 1960), sample B3259 (RGM 414 139); a: top view; b: side view; c: basal view.

Fig. 4. *Polychaetaspis* sp. cf. *P. tuberculatus* Kielan-Jaworowska, 1966, sample B3273 (RGM 414 136).

Fig. 5. *Paleoenonites* sp. cf. *P. circumscriptus* Eller, 1945, sample B3259 (RGM 414 136).

Fig. 6. Unidentified scolecodont jaw SJ-a, sample B3273 (RGM 414 136).

Fig. 7. Unidentified scolecodont jaw SJ-b, sample B3259 (RGM 414 136).

Fig. 8. Fish scale, sample B3264 (RGM 414 134).

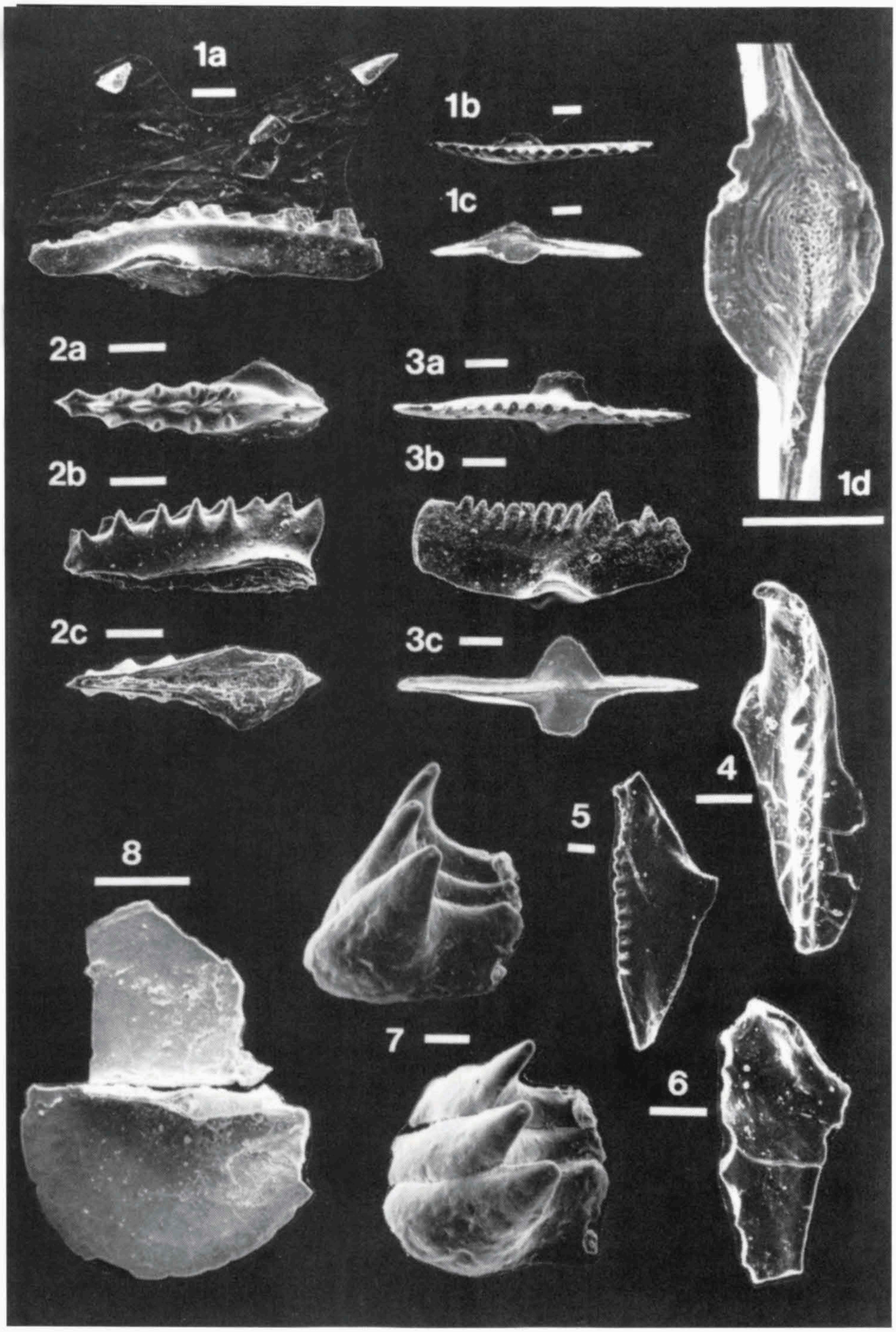
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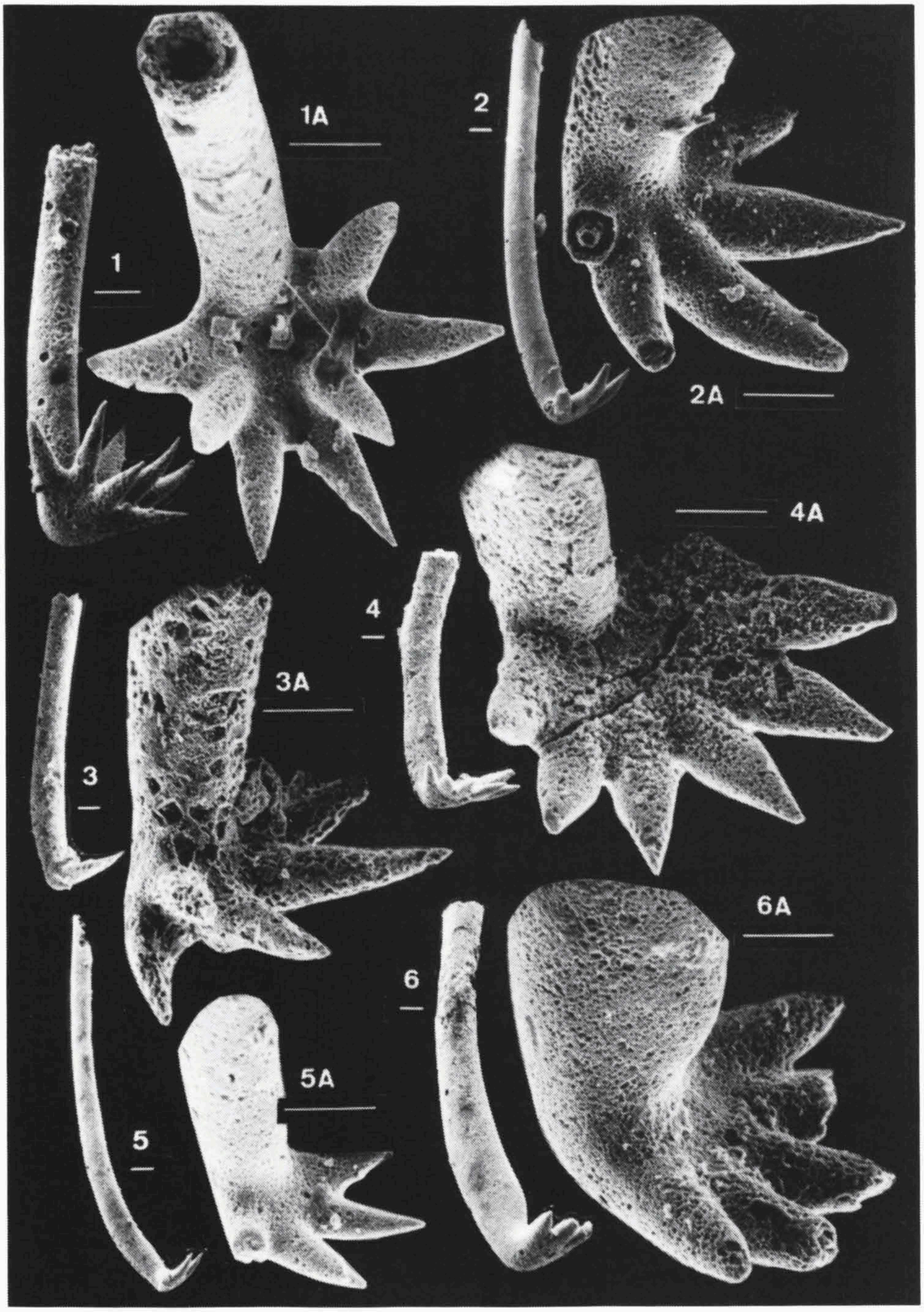
Plate 4

Sponge spicules. Scale bar is 100 μm.
Figs. 1-6. Hexactinellid anchor spicules showing close relationship with either the genus *Silicunculus* or *Chelispongia*. All specimens lack their distinctive, proximal part. The A-figures are enlarged views taken at a different angle; 1, 2, 4, 5-6: specimens from sample B3294 (RGM 414 099). For close-up of fig. 2 see Pl. 12, fig. 2; 3: specimen from sample B3260 (RGM 414 092); a 200 second EDAX X-ray analysis of 3A showed the main element to be silica.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2
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4A
4
3A
3
6A
6
5A
5

Plate 5

Sponge spicules. Scale bar is 100 µm.
Figs. 1-6. Hexactinellida.
1: Acanthohexact, sample B3294 (RGM 414 098); 2: common hexact, sample B3294 (RGM 414 098); 3: fragment of a hexactine pinule, sample B3260 (RGM 414 093); 4: small fragment of an uncinate, sample B3349 (RGM 414 100); 5: acanthous (?)hexactinellid spicule of hitherto unknown form, sample B3294 (RGM 414 098), 5a: side view, 5b: top view; 6: smooth surficial pentact, sample B3294 (RGM 414 098).
Fig. 7. Small desma of a lithistid demosponge, sample B3264 (RGM 414 096).
Figs. 8-10. Heteractinida.
8: Genuine planar sexiradiate spicule, sample B3264 (RGM 414 096); 9: octactine-based spicule of an astraeospongiid, sample B3263 (RGM 414 095), only one of the (broken) vertical rays is developed; 10: octact of an astraeospongiid, sample B3263 (RGM 414 095).

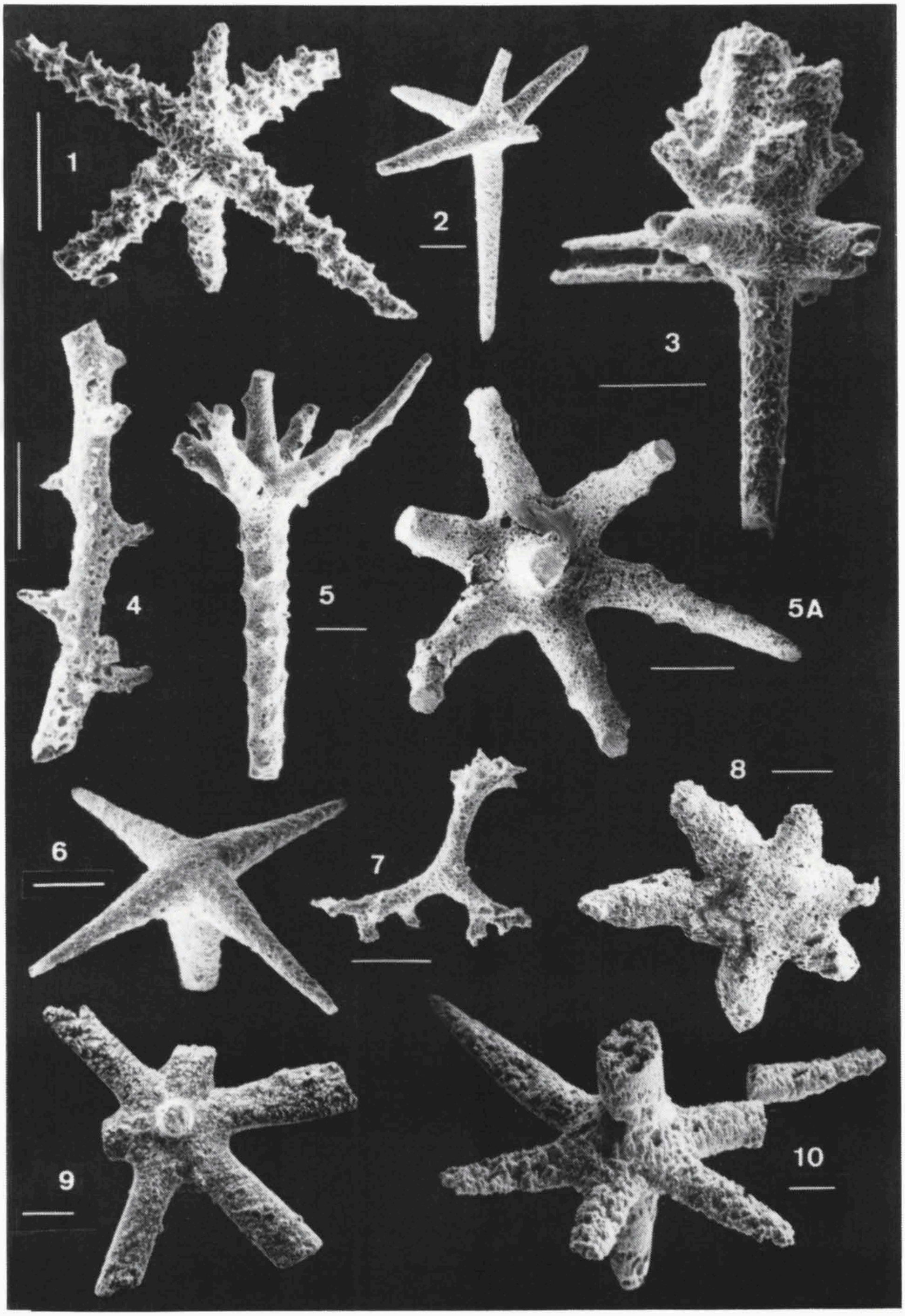
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Plate 6

Sponge spicules. Heteractinida. Scale bar is 100 μm, unless otherwise indicated.

Fig. 1. Spicule typical for the Devonian heteractinid genus *Ensiferites*: shown are five of the six horizontal rays and two vertical rays, sample B3264 (RGM 414 096), 1a: top view, showing the trifid nature of the distal ray; 1b: side view, showing the short (broken) distal ray with trifid termination, and part of the solid, simple, proximal ray.

Fig. 2. Minor, polyrayed ?wewokellid spicule, sample B3279/80 (RGM 414 097). Scale bar is 10 μm.

Fig. 3. Polyrayed, stellate megasclere presumably of a wewokellid (? *Asteractinella*), sample B3262 (RGM 414 094).

Figs. 4-5. Acanthous heteractinid spicules of hitherto unknown type; both specimens from sample B3260 (RGM 414 093); 4a: distal view, showing a large central disc and seven tangential rays (one broken off); 4b: side view, showing the distal and proximal rays at right angles to the tangential rays; 5a: distal view, showing the disc-like common centre and that three of the seven tangential rays are broken off; 5b: side view, showing the distal and proximal rays. Note that the hollows with a central filling at the fracture of two of the tangential rays are preservation artifacts of the originally solid calcareous spicule.

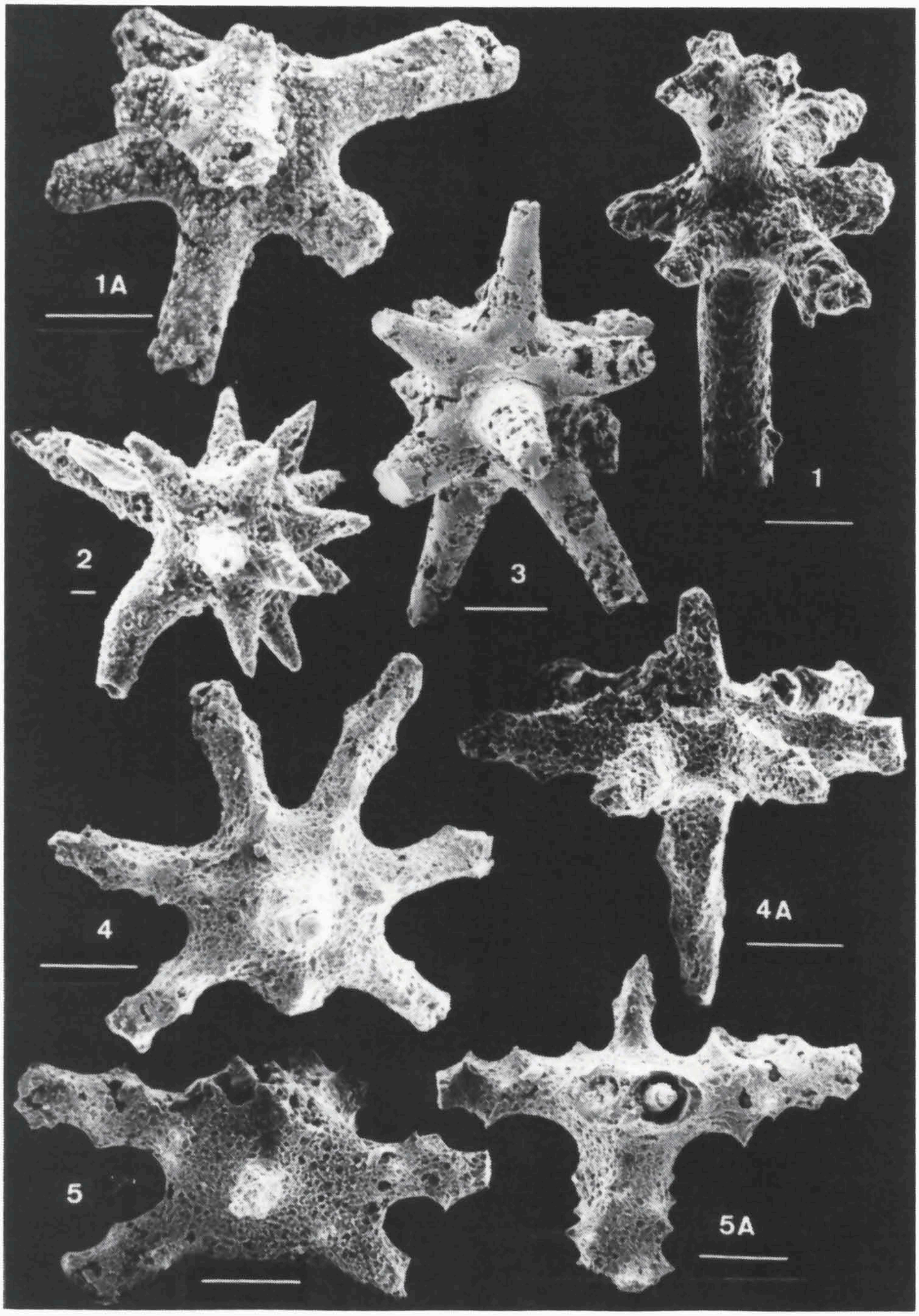
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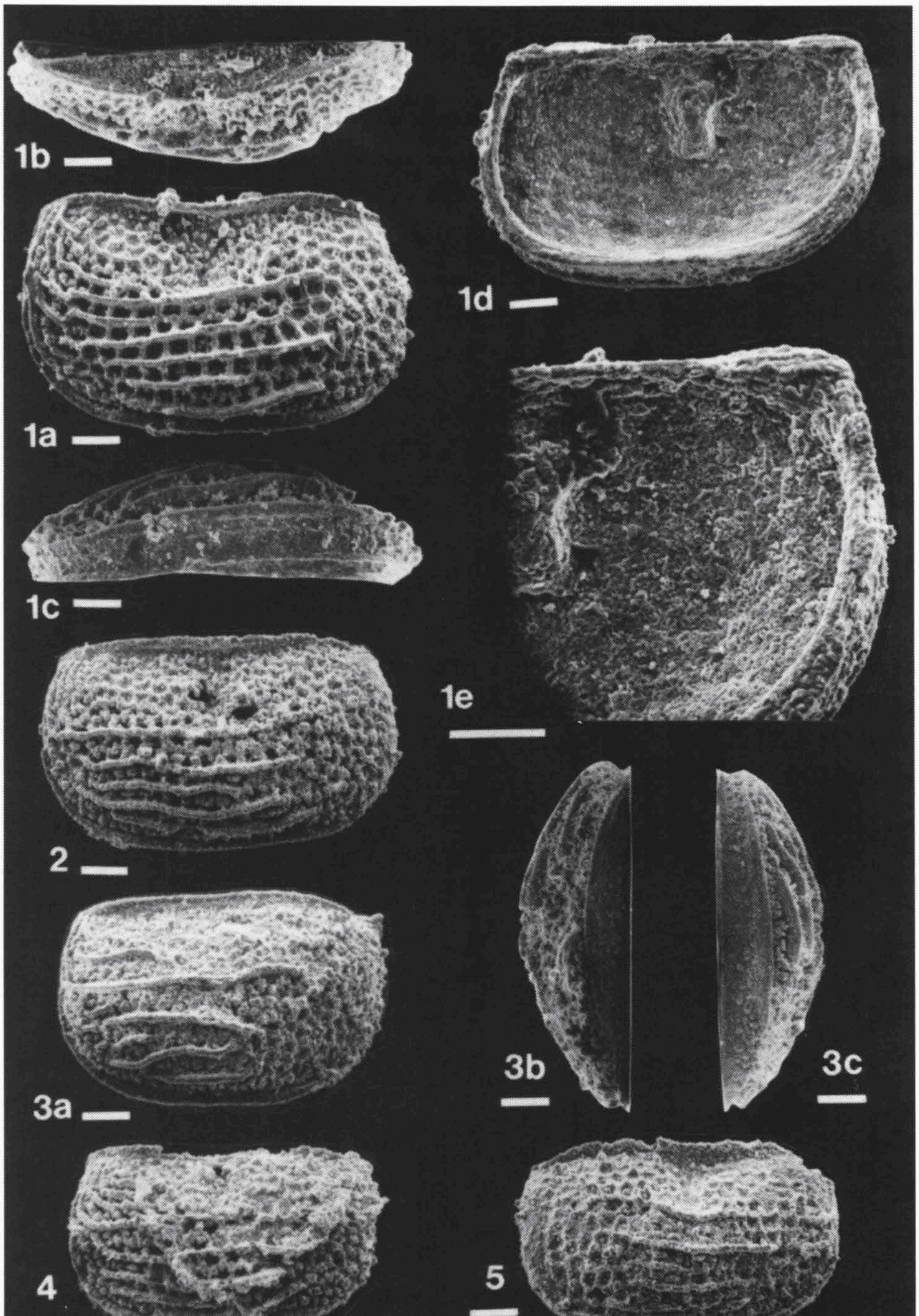
Plate 7

Ostracods. Scale bar is 100 μm. All specimens from sample B3279.
Figs. 1-5. *Ordovizona* sp. A.
1: Left valve (RGM 414 005); a: external lateral view; b: dorsal view; c: ventral view; d: internal lateral view; e: close-up of internal posterior; 2: juvenile left valve (RGM 414 006); external lateral view; 3: juvenile left valve (specimen lost); a: external lateral view; b: dorsal view; c: ventral view; 4: juvenile left valve (RGM 414 007); external lateral view; 5: juvenile right valve (RGM 414 008); external lateral view.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1c
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1e
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3c
5

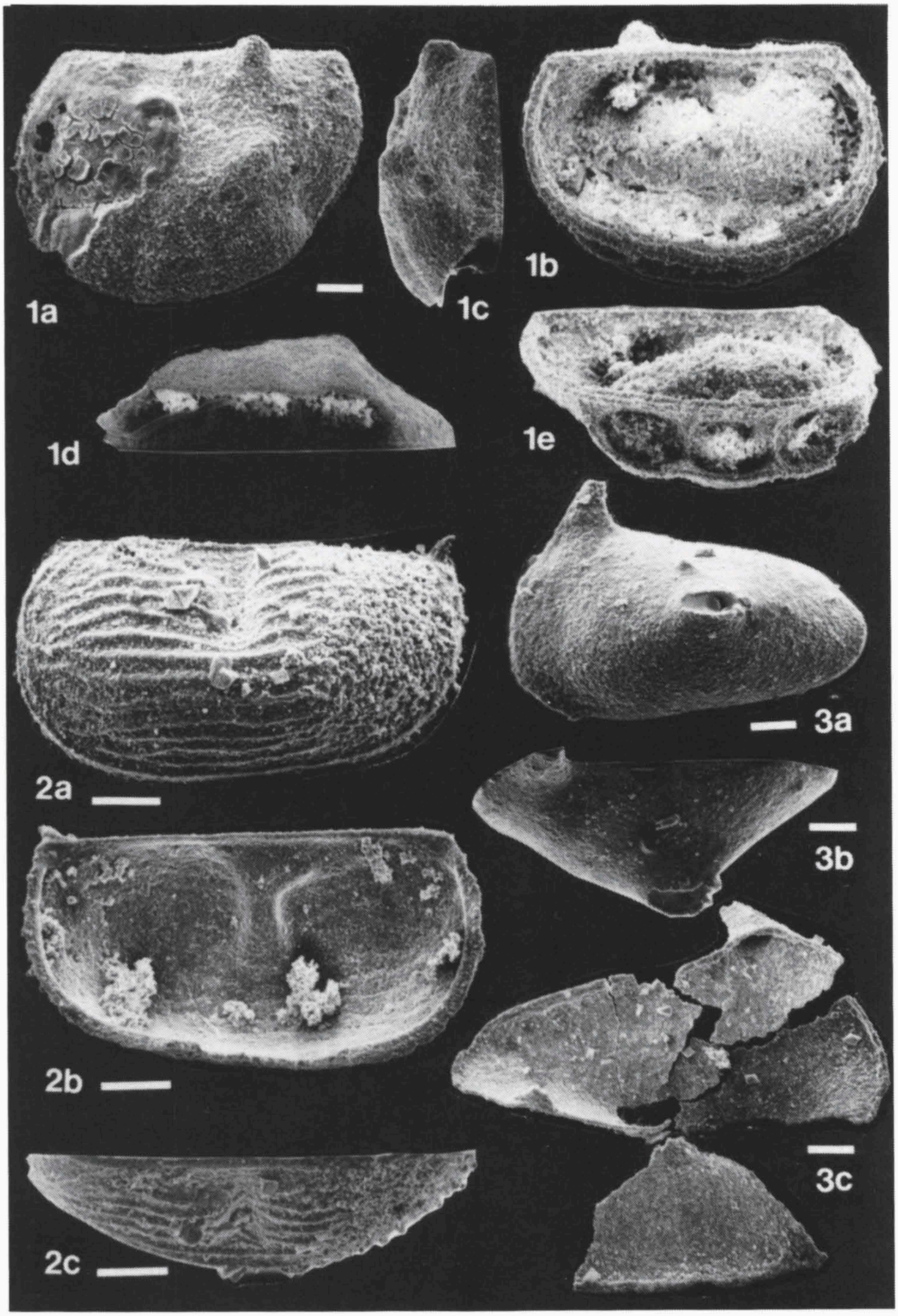
Plate 8

Ostracods. Scale bar is 100 µm. All specimens from sample B3279.

Fig. 1a-e. *Anticostiella* sp. A, heteromorphic left valve (RGM 414 000); a: external lateral view; b: internal lateral view; c: posterior view; d: ventral view; e: oblique internal lateral view.

Fig. 2a-c. *Ectoprimitoides* sp. A, left valve (RGM 414 003); a: external lateral view; b: internal lateral view; c: dorsal view.

Fig. 3a-c. *Monoceratella* ? sp. A, left valve (RGM 414 057), specimen shattered in remounting; a: external lateral view; b: dorsal view; c: internal view of broken specimen.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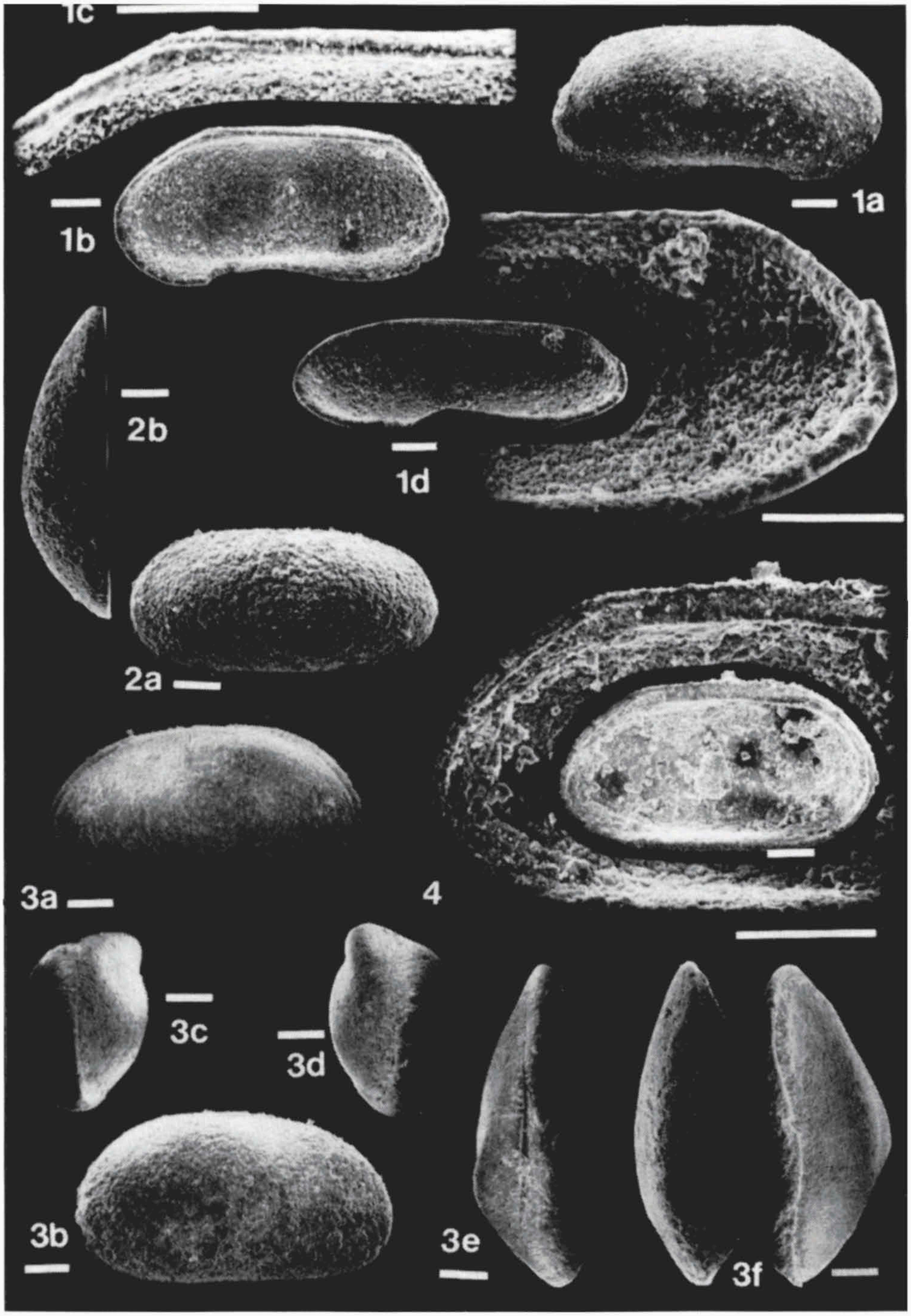
3a
3b
3c

Plate 9

Ostracods. Scale bar is 100 µm. All specimens from sample B3279.
Fig. 1a-d. *Uthoernia* ? sp. A, right valve (RGM 414 028); a: external lateral view; b: internal lateral view; c: internal close-up of hinge; d: oblique internal lateral view and close-up.
Fig. 2a-b. Left valve of podocopid ostracod PO-A (RGM 414 053); a: external lateral view; b: ventral view.
Figs. 3-4. *Aboilia blessi* Becker & Adamczak, 1993.
3: Carapace (RGM 414 010); a: left side external lateral view; b: right side external lateral view; c: anterior view; d: posterior view; e: dorsal view; f: ventral and tilted ventral views; 4: right valve (RGM 414 011); internal lateral view, with close-up.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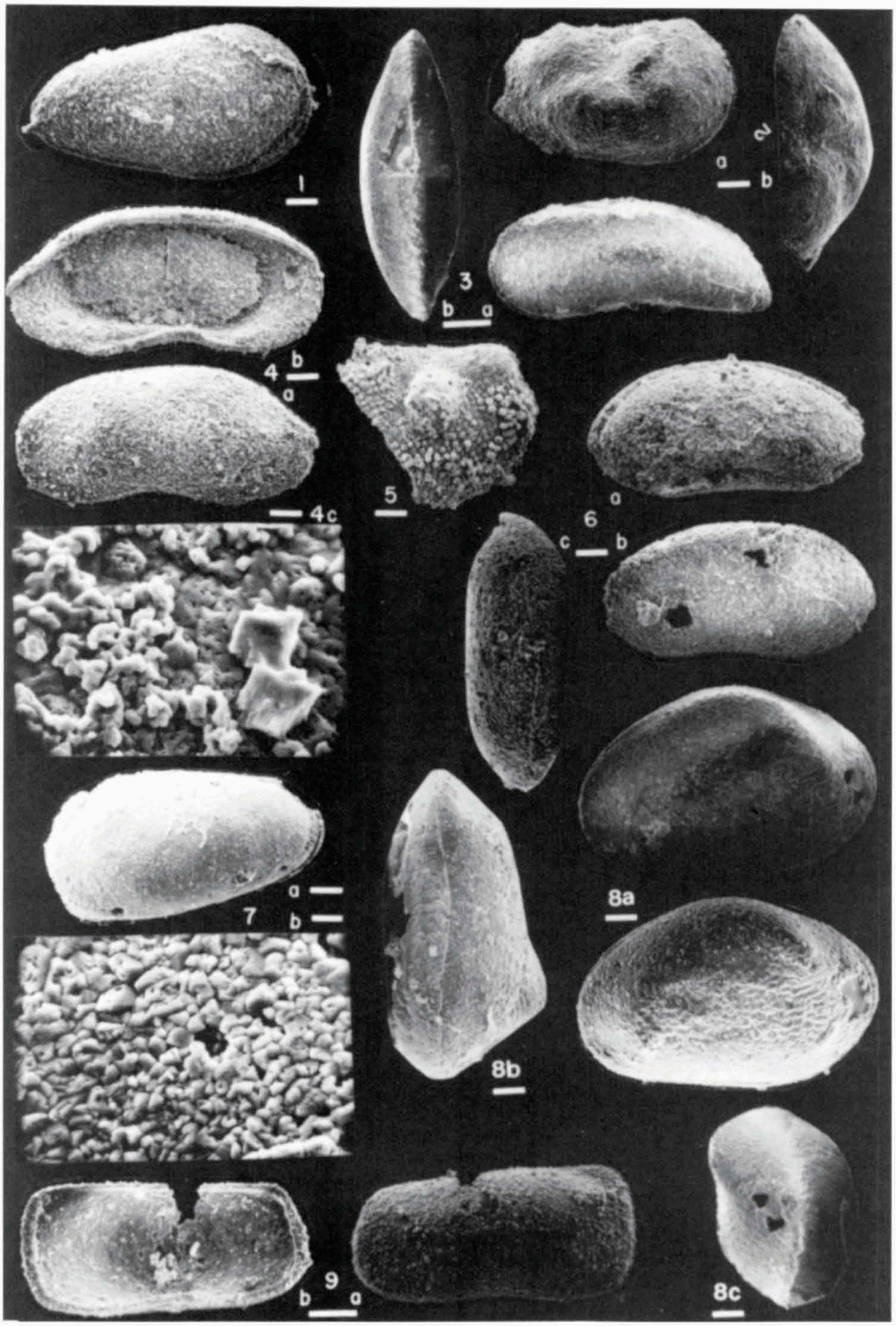
3f

Plate 10

Ostracods. Scale bar is 100 µm, unless otherwise indicated. All specimens from sample B3279.
Fig. 1. *Pseudorayella* ? sp. A; right-lateral view of carapace (RGM 414 040).
Fig. 2. *Anticostiella* sp. A; tecnomorphic right valve (RGM 414 001, posteriorly damaged); a external lateral view; b dorsal view.
Fig. 3. Carapace of podocopid ostracod PO-B (RGM 414 047); a: external left-lateral view; b: dorsal view.
Fig. 4. Left valve of bairdiocypridid ostracod BO-A (RGM 414 034); a: external lateral view; b: internal lateral view; c: close-up of posterocentral region, including spot for a 200 second EDAX x-ray analysis which showed the main element to be silica (scale bar is 10 µm).
Fig. 5. *Bromidella* ? sp. A; right valve (RGM 414 002, anterior fragment); external, lateral view.
Fig. 6. Carapace of bairdiocypridid ostracod BO-A (RGM 414 050); a: right-lateral view; b: left-lateral view; c: dorsal view.
Fig. 7. Carapace of palaeocopid ostracod PA-A (RGM 414 054); a: left-lateral view; b: close-up of central region of figure 7a, scale bar is 10 µm (a 200 second EDAX x-ray analysis of this view showed the main element to be silica).
Fig. 8. Carapace of *Aboilia blessi* Becker & Adamczak (holotype, RGM 414 009); a: two left-lateral views with different contrast; b: ventral view; c: posterior view.
Fig. 9. Left valve of palaeocopid ostracod PA-B (RGM 414 052); a: external lateral view; b: internal lateral view.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8c
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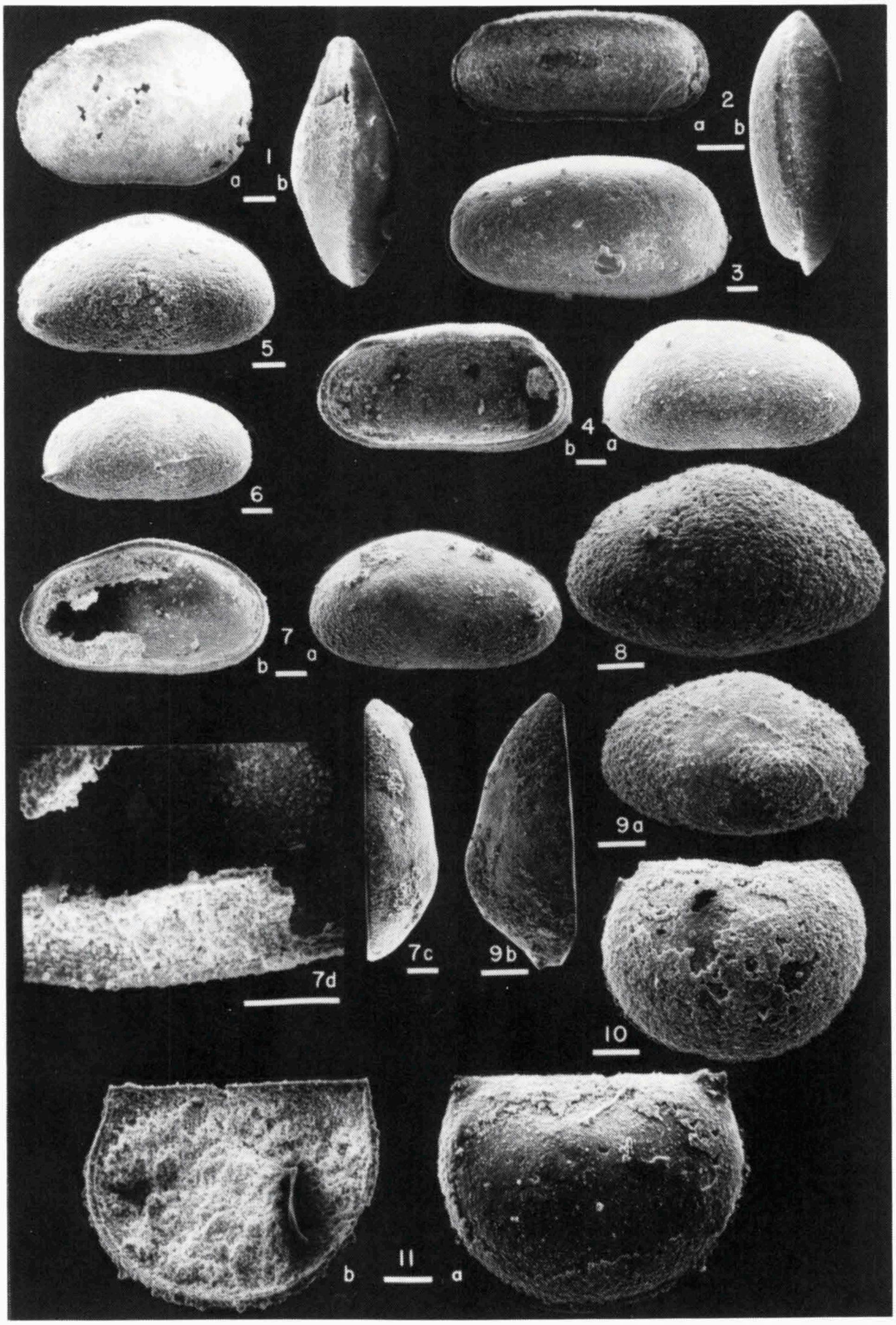
a

Plate 11

Ostracods. Scale bar is 100 µm. All specimens from sample B3279.
Fig. 1. *Macrocyproides* ? sp. A, carapace (RGM 414 042); a: left-lateral view; b: dorsal view with posterior end up.
Fig. 2. *Elliptocyprites* ? sp. A, carapace (RGM 414 022); a right-lateral view; b: dorsal view.
Figs. 3-4. *Shenandoia* sp. A.
3. Left valve (RGM 414 026); external lateral view; 4: right valve (juvenile) (RGM 414 025); a: external lateral view; b: internal lateral view.
Figs. 5-7. Bairdiocypridid ostracod BO-B.
5: Right valve (RGM 414 036); external lateral view; 6: juvenile right valve (RGM 414 037); external lateral view; 7: left valve (RGM 414 035); a: external lateral view; b: internal lateral view; c: dorsal view; d: close-up of internal view showing ventral margin.
Fig. 8. Left valve of podocopid ostracod PO-C (RGM 414 048); external lateral view.
Fig. 9. Left valve of podocopid ostracod PO-D (RGM 414 049); a: external lateral view; b: dorsal view.
Figs. 10-11. *Baltonotella* ? sp. A.
10: External lateral view of single valve (RGM 414 043); 11: single valve (RGM 414 044); a: external lateral view; b: internal lateral view.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9a
7c
9b
7d
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b a

Plate 12

Crinoid and graptolites. Scale bar is 100 μm, unless otherwise indicated.

Fig. 1a-b. Crinoid stem article, sample B3260 (RGM 414 146); a: general view; b: tilted close-up, scale bar is 10 μm; a 200 second EDAX x-ray analysis of the central part of this view showed the main element to be calcium.

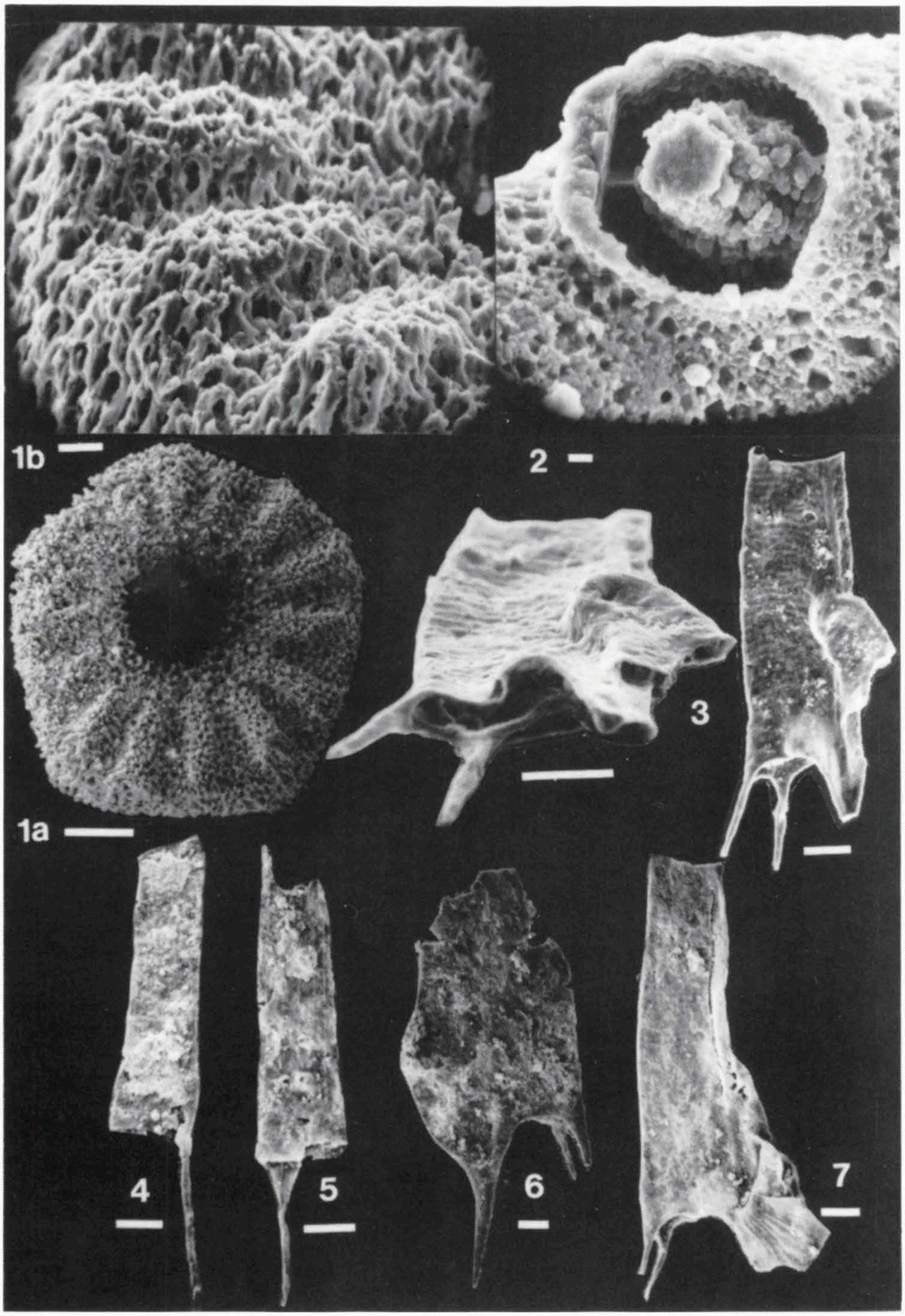
Fig. 2. Close-up of broken segment of the sponge spicule of Pl. 4, fig. 2; scale bar is 10 μm.

Fig. 3. Diplograptid sicula GS-a, family Orthograptidae (sensu Mitchell, 1987), with initial bud of protheca 1^1, ? = *'Glyptograptus' hudsoni* Jackson, 1971, sample B3260 (RGM 414 137); righthand figure, lateral view; lefthand figure, enlarged oblique apertural view.

Figs. 4-5. Graptoloid sicula GS-b, sample B3295 (specimen lost).

Fig. 6. Broken proximal end of diplograptid sicula GS-a, same species as fig. 3. Sample B3295 (specimen lost).

Fig. 7. Diplograptid sicula GS-a with initial bud of protheca 1^1 ('advanced' member of Orthograptidae, pattern F or K of Michell, 1987 or Melchin & Mitchell, 1991 respectively). Sample B3295 (specimen lost). Same species as fig. 3.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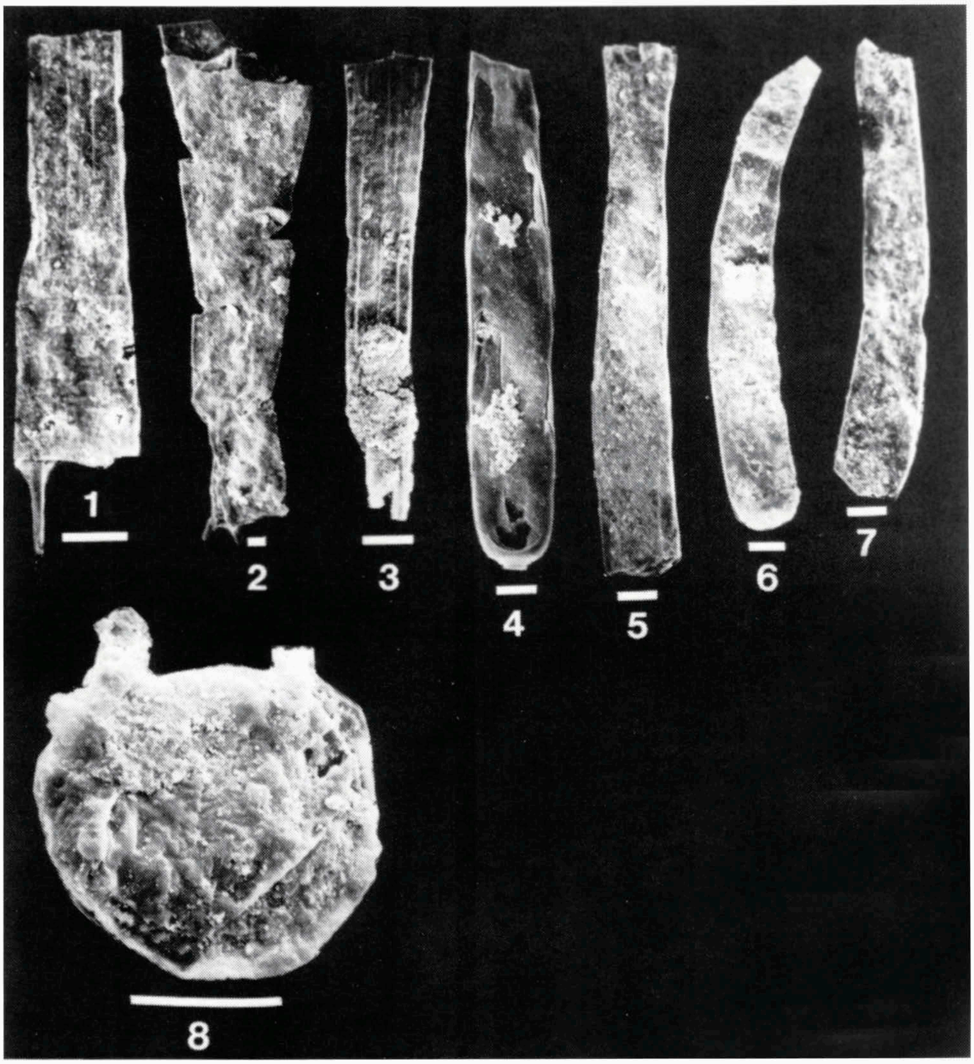

Plate 13

Graptolites and chitinozoans (specimens lost). Scale bar is 100 μm.
Fig. 1. Graptoloid sicula GS-b, sample B3295.
Fig. 2. Diplograptid sicula GS-c, broken proximal end of a *Glyptograptus* specimen (sensu Melchin and Mitchell, 1991), sample B3295.
Fig. 3. Graptoloid prosicula GS-d, sample B3295.
Figs. 4-7. Four specimens of the chitinozoan *Rhabdochitina minnesotensis* Stauffer, 1933, sample B3295.
Fig. 8. Unidentified sac-like form, sample B3295.

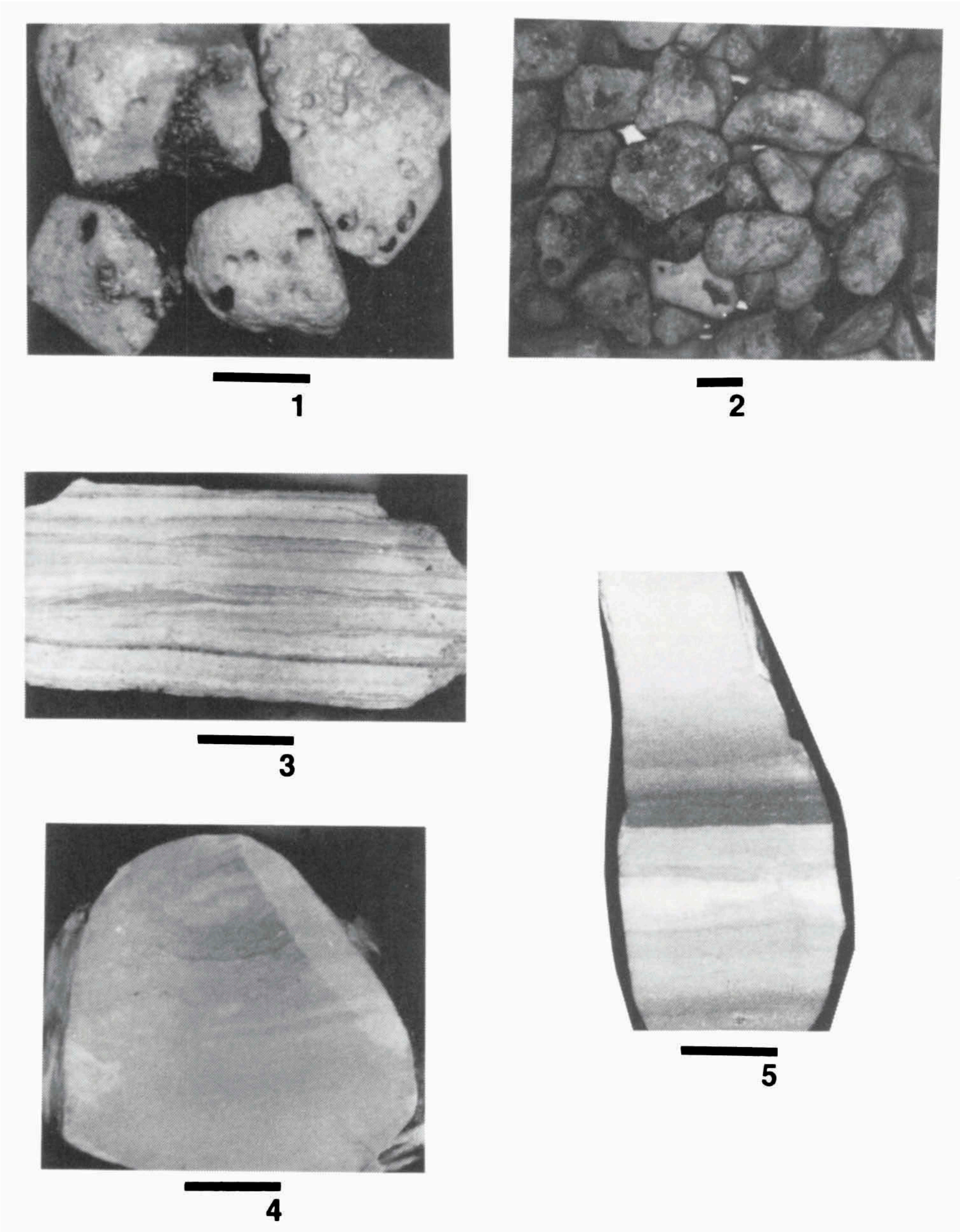

Plate 14

Carbonate pebbles. Scale bar is 1 cm.

Figs. 1-2. Bored, angular and subrounded limestone pebbles of Bio-dredge No. 1. The four pebbles of fig. 1 have been saved and filed under collection number RGM 414 063.

Fig. 3. Laminated micrite pebble of Bio-dredge No. 1. Facies 5b, processed as sample B3292.

Fig. 4. Algal, dolomitic micrite pebble of Bio-dredge No. 1. Facies 5a, processed as sample B3291.

Fig. 5. Laminated limestone pebble of Rock-dredge No. 2. Facies 5b, processed as sample B3295 and thin section JV430 (Pl. 16, fig. 6) (RGM 414 111).

Plate 15

Thin sections of carbonate pebbles Facies 1, Bio-dredge No. 1 (RGM 414 111). Scale bar is 2 mm.
Figs. 1-2. Positive prints of thin sections JV342 and JV341, respectively.
Fig. 3. Positive print of thin section JV340 of pebble processed as sample B3273.
Fig. 4. Negative print of thin section JV343 of pebble processed as sample B3274.
Figs. 5-6. Negative prints of thin sections JV344 and JV352 respectively.

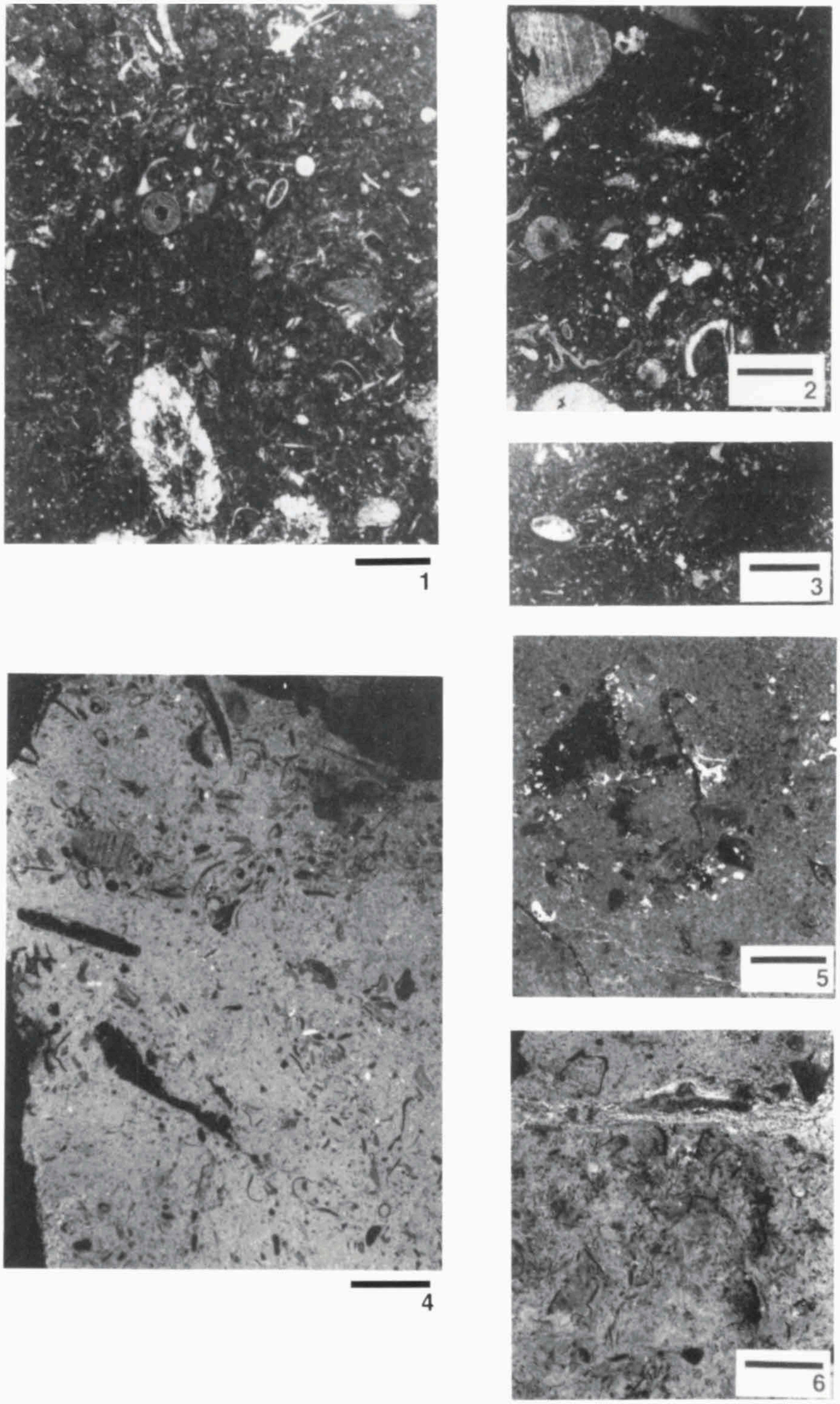
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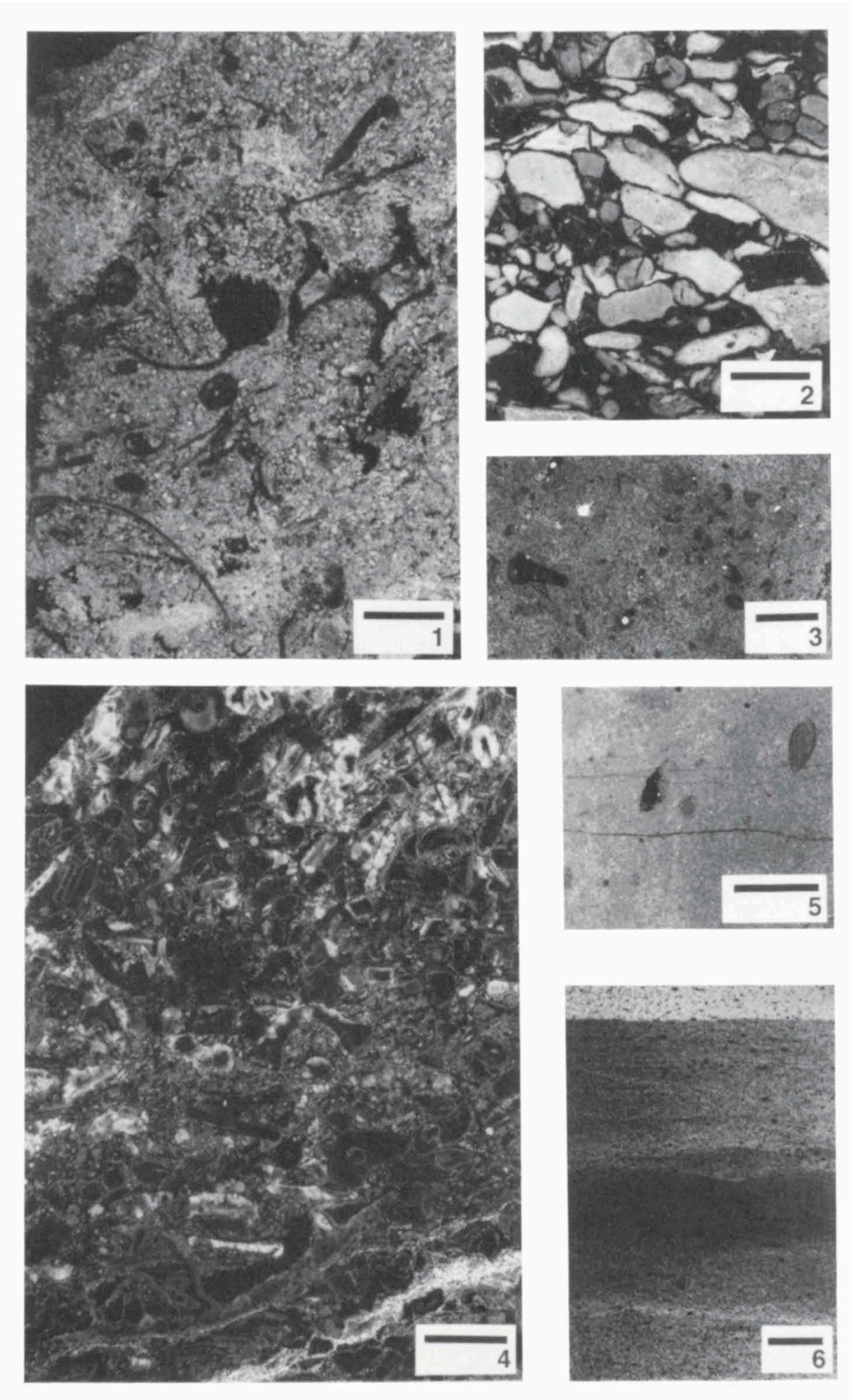
Plate 16

Negative prints of thin sections of carbonate pebbles Facies 2-8 (RGM 414 111). Scale bar is 2 mm.
Fig. 1. Section JV355, Facies 7, pebble of sample B3279, Bio-dredge No. 1.
Fig. 2. Section JV345, Facies 2, pebble of sample B3275, Bio-dredge No. 1.
Fig. 3. Section JV357, Facies 5a, Bio-dredge No. 1.
Fig. 4. Section JV358, Facies 8, pebble of sample B3280, Bio-dredge No. 1.
Fig. 5. Section JV347, Facies 3, pebble of sample B3276, Bio-dredge No. 1.
Fig. 6. Section JV 430, Facies 5b, pebble of Pl. 14, fig. 5, processed sample B3295, Rock-dredge No. 2.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