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Cambrian limestone erratics in the Tertiary glacio-marine sediments of King George Island, West Antarctica

ABSTRACT: The glacial and glacio-marine sediments of the Oligocene Polonez Cove and Early Miocene Cape Melville Formations on King George Island (South Shetland Islands, West Antarctica) yield numerous erratic boulders of limestone, in particular archaeocyathan-algal boundstone, oolite, onkolite, and biomicrite. Some of these boulders are fossiliferous and contain archaeocyathans, sponges, inarticulate brachiopods, monoplacophorans, gastropods, hyolithids, trilobites, ostracodes and such enigmatic fossils as: *Chancelloria, Coleolella, Dailyatia, Halkieria, Hadimopanella, Hyolithellus, "Lenastella", Mongolitubulus* and *Torellella.* The small shelly fauna appears to be Early Cambrian (Botomian) in age. The boulders of fossiliferous limestones resemble the rocks of the Shackleton Limestone unit in the central Transantarctic Mts. The lithological composition of the boulder assemblage brought to King George Island during the Tertiary glaciations suggests that the Cambrian outcrops around the Weddell Sea are the source of the erratics. The Antarctic Lower Cambrian fauna resembles its analogues in Australia and Asia.

Key words: Antarctica, glacial erratics, Cambrian fossils, paleogeography.

Introduction

On King George Island, Tertiary glacial and glacio-marine sediments are exposed in the southern cliffs, between Admiralty Bay and Melville Peninsula, as well as in isolated nunataks (Conglomerate Nunatak and Magda Nunatak) within the island's interior (Fig. 1). These deposits were investigated in 1978—1986 (*see* Birkenmajer 1980, 1982a,b; 1984, 1987, 1988) and have made the empirical basis for recognition of four Tertiary glaciations on King George Island; the Early Eocene Kraków Glaciation, Oligocene Polonez Glaciation, Late Oligocene Legru Glaciation, and Early Miocene

Melville Glaciation (Birkenmajer 1980, 1982a, 1988). The glacial and glacio-marine sediments of the two main glaciations have been attributed to the Polonez Cove and Cape Melville Formations, respectively, which are characterized by a large abundance of erratic blocks (Birkenmajer 1980, 1982a,b; 1984, 1987; Morycowa, Rubinowski and Tokarski 1982; Birkenmajer and Wieser 1985, Birkenmajer and Butkiewicz 1988;).

Petrografic characteristics of the igneous and metamorphic erratics in the Polonez Cove (Birkenmajer and Wieser 1985) and Cape Melville Formation (Birkenmajer and Butkiewicz 1988) are indicative of their source areas on the Antarctic continent and allow for a reconstruction of the paths of icestream movement and iceberg drift (Birkenmajer and Wieser 1985, Fig. 2—3). Fossiliferous limestone erratics may also be indicative of source areas on the continent (Morycowa, Rubinowski and Tokarski 1982; Gaździcki and Wrona 1982b, 1986; Wrona 1983, 1987, 1988).

A collection of several hundred limestone erratics has been taken from the glacial and glacio-marine sediments on King George Island during the Austral Summers of 1980—1981 and 1985—1986 (Gaździcki and Wrona 1982a, 1986). The fossils have been identified in thin sections or after chemical preparation. A dozen samples or so were analyzed for organic-walled microfossils, but no organic remains have been found.

The collection of erratic boulders, thin sections, and microfossils is housed at the Institute of Paleobiology of the Polish Academy of Sciences in Warsaw (abbreviated as ZPAL).

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Limestone erratics in the Polonez Cove Formation

The Polonez Cove Fm. is exposed between Admiralty Bay and King Georgy Bay (Fig. 1). These sediments were first described by Birkenmajer (1980, 1982b), and their sedimentology was recently studied by Porębski and Gradziński (1987). The formation is divided into four members: Krakowiak Glacier Mb., Low Head Mb., Siklawa Mb., and Oberek Cliff Mb.

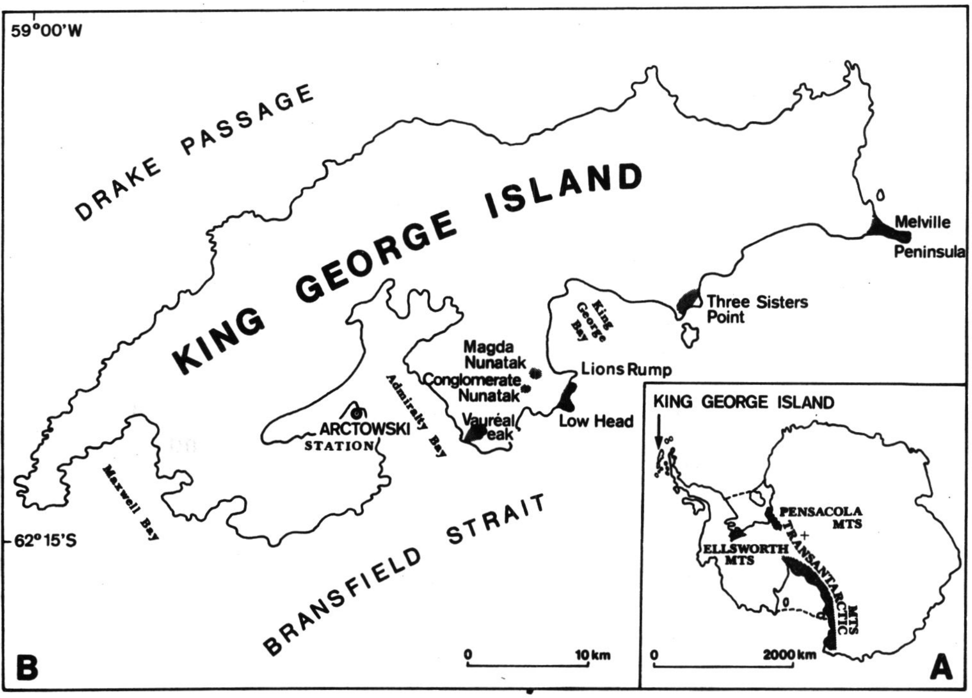

Fig. 1. Location map of King George Island in West Antarctica (A), and the extent of glacial and glacio-marine deposits (shaded) on the island (B)

The Oligocene age of the formation, and therefore also of the Polonez Glaciation, has been determined by the coccolith assemblage found in Low Head Mb. (Gaździcka and Gaździcki 1985; *see also* Birkenmajer, Dudziak and Tokarski 1989) and by radiometric (K—Ar) dating of volcanic lavas that directly overlay the Polonez Cove Fm. (Birkenmajer and Gaździcki 1986, Birkenmajer 1989, *this volume*).

Vauréal Peak

The tillites of Krakowiak Glacier Mb. and the glacio-marine conglomerates of Low Head Mb. occur close to the top and the middle of the western slope of Vauréal Peak (*see* Birkenmajer 1982b). These rocks were very poorly exposed in 1980—1981, and hence no more than a dozen small (up to 5 cm) erratics have been collected. They include rounded fragments of grey-greenish marly siltstone, black siltstone and lidites, and light-colored finegrained sandstones. All these blocks were macerated in acidic solutions but no fossils were found.

Low Head — Lions Rump

The steep cliff between Low Head and Lions Rump is the type locality of the Polonez Cove Fm. (for detail *see* Porębski and Gradziński 1987).

The tillites of Krakowiak Glacier Mb. include at Mazurek Point (Pl. 2, Fig. 1) a sequence of diamictites interbeded with sandstones (15 m in thickness) which yielded limestone erratics of the following kind:

Type 1 erratics. Black limestone, brown-grey when weathered; laminated biomicrite microfacies, with fragments of cryptalgal mats and stromatolitelike structure; erratic boulders ZPAL AE/M16, M23; ?Cambrian.

The Low Head Mb. sediments, in particular the fossiliferous rudites (*see* Gaździcki and Pugaczewska 1984, Pls 1—2; Porębski and Gradziński 1987) yielded erratics of the following kind:

Type 2 erratics. Blue-grey limestone with wavy lamination (Pl. 2, Fig. 2); laminated limestone microfacies, with interbeded layers of bituminous dark and silty micrite (Pl. 5, Fig. 4); erratic boulder ZPAL AE/LH2; ?Cambrian.

Erratics have also been collected from debris at the cliff's foot between Low Head and Lions Cove. These relatively large boulders seem to have primarily come from the Low Head Mb. In addition to the two types mentioned above, there are also specimens of the following kinds:

Type 3 erratics. Black-grey limestone; oomicrite microfacies, with particularly small-sized ooids; erratic boulders ZPAL AE/M1, M26; ?Cambrian.

Type 4 erratics. Dark-grey limestone with beige undertone; biomicrite microfacies, with blue-green algae *Girvanella* sp.: erratic boulder ZPAL AE/LH1; ?Cambrian.

Type 5 erratics. Light-colored limestone with archaeocyathan cups; archaeocyathan-algal boundstone microfacies, with blue-green algae *Epiphyton* sp. and archaeocyathans *Ajacicyathus* cf. *ajax* (Taylor), *Erugatocyathus* sp., and others (Pl. 6, Fig. 2); the archaeocyathan cups are crushed and often contain geopetal structures filled with blocky sparr; erratic boulder ZPAL AE/M10; Lower Cambrian.

Type 6 erratics. Light-grey limestone with archaeocyathan cups, trilobites, and blue-green algae at the weathered surface; biomicrite microfacies, with archaeocyathan, trilobite, and blue-green algae bioclasts; erratic boulder ZPAL AE/M15; Lower Cambrian.

Type 7 erratics. Dark-grey, fully recrystallized, nonfossiliferous limestone; erratic boulder ZPAL AE/M14; ?Cambrian.

Type 8 erratics. Green-grey, fully recrystallized limestone (?marble) with patches of calcite mineralization; erratic boulder ZPAL AE/LH13.

Three Sisters Point

Modern moraines in the vicinity of Three Sisters Point yielded erratic boulders that cover the range of Antarctic rocks typical of the Polonez Cove Fm. (Tokarski, Paulo and Rubinowski 1981; Morycowa, Rubinowski and Tokarski 1982). The limestone erratics are of the following kinds:

Type 9 erratics. Dark-grey limestone with archaeocyathans *Thalamocyathus trachealis* (Taylor); biomicrite microfacies, with archaeocyathans, trilobite debris, sponge spicules, echinoderm fragments and blue-green algae *Renalcis* sp. (*see* Morycowa, Rubinowski and Tokarski 1982); erratic boulder ZPAL AE/TS8; Lower Cambrian.

Type 10 erratics. Light-grey, nonfossiliferous marls with dark silstone intraclasts; erratic boulder ZPAL AE/TS4; possibly Meso- or Cenozoic.

Light-colored limestone of type 5; these erratic boulders (ZPAL AE/TS7) are so small, however, and the archaeocyathan cups are so fragmentary that they cannot be identified (*see also* Gaździcki and Wrona 1982b, Fig. 10); Lower Cambrian.

Limestone erratics in the Cape Melville Formation

Cape Melville is the easternmost part of King George Island (Fig. 1); it has no more than several dozens of meters in width in places, and its shores are inaccessible cliffs up to 200 m in height. Its icefree surface is a flat plateau (Pl. 1, Fig. 1).

The rocks exposed at Cape Melville belong to the Moby Dick Group, distinguished by Birkenmajer (1984) and subdivided into three formations. The Sherrat Bay Fm, is at the base; it encompasses basaltic lavas. The Destruction Bay Fm. contains crushed basalts and tuffs with marine fossils. It is discordantly and transgerssively overlain by the glacio-marine Cape Melville Fm., which represents a 200 m thick, almost horizontal sequence of rhytmically bedded grey, greenish, and black shales, siltstones, marls, and sandstones with a rich assemblage of Tertiary marine fossils alongside recyled Cretaceous coccoliths and belemnites (*see* Birkenmajer, Gaździcki and Wrona 1983, Gaździcki ed. *et al.* 1987) and erratics exotic to King George Island (Birkenmajer 1982b, 1984, 1987; Gaździcki and Wrona 1982a,b; 1986; Wrona 1987, Birkenmajer and Butkiewicz 1988). The Early Miocene age of the formation, and consequently of the Melville Glaciation, was determined by radiometric (K—Ar) dating (Birkenmajer *et al.* 1985, Birkenmajer 1989, *this volume*) and by biostratigraphic data (Biernat, Birkenmajer and Popiel-Barczyk 1985).

In the Cape Melville Fm., erratic boulders are generally distributed disorderly and in variable density (Pl. 1, Fig. 2), though they tend to occur more abundantly in the base part of the section. They are up to 2 m, but generally approximately 50 cm, in diameter, poorly rounded (Pl. 1, Fig. 2; Pl. 4, Fig. 1) to sharp-edged (Pl. 3, Fig. 1), with glacially-generated features (Pl. 3, Fig. 2). They are frost-cleft, sometimes secondarily cemented by surrounding sedimentary matrix (Pl. 5, Fig. 3). These boulders most commonly represent blocks of igneous, metamorphic, or clastic rocks, whereas limestone boulders account for some 5% of the total number. The largest boulders are solely igneous and metamorphic rocks, quartzites, and quartzitic sandstones (Birkenmajer and Butkiewicz 1988). The collection of limestone boulders derives entirely from the top surface of Melville Peninsula, which has been enriched by erosion in erratic boulders (Pl. 1, Fig. 1) that often present typical erosional forms (Pl. 3).

Some limestone erratic boulders have their surface bored by Miocene epibionts (erratic boulders ZPAL AE/Me75 and Me175). Most likely, they were bored in the Miocene sea by undetermined algae (Pl. 4, Fig. 2—4) and polychaetes (Pl. 4, Fig. 1).

The frequency and variability of erratic boulders are greater in deposits of the Melville Glaciation than in those representative of the Polonez Glaciation. Limestone erratics comprising small shelly fossils and boulders of oolite and onkolite occur solely in the Cape Melville Fm. Archaeocyathan limestone boulders also are more common and variable in the Cape Melville Fm. than in the Polonez Cove Fm. This pattern may be partly due to a sampling bias, since the erratic collection representative of the Melville Glaciation comes from the Melville Peninsula plateau, where erratic boulders have undergone erosional enrichment (Pl. 1, Fig. 1).

The limestone boulder collection from Melville Peninsula contains several hundred specimens, but they generally fall into a few lithological varieties which may represent each a single lithofacies or even bed. These limestone erratics are of the following kinds:

Type 11 erratics. Light-grey limestone with fragmented archaeocyathan cups, trilobites, phosphatic brachiopods, and algal crusts; biosparite (grainstone or packstone) microfacies, with archaeocyathans, brachiopods, trilobites, and blue-green algal dendritic or tubular form and laminae (Pl. 6, Fig. 1); erratic boulders ZPAL AE/Me67, Me94; Lower Cambrian.

Type 12 erratics. Dark-grey limestone; biomicrite (wackestone) microfacies, with trilobite debris, sponge spicules, and small fragments of archaeocyathan cups, and isolated radius of *Chancelloria* sp. (Pl. 6, Fig. 3); erratic boulder ZPAL AE/Me29; Cmbrian.

Type 13 erratics. Black limestone with hyolithids; intrabiomicrite (wackestone) microfacies, with hyolithid, mollusc (primarily gastropod), and inarticulate brachiopod shells and debris, sponge spicules, and *Chancelloria* sclerites. The shells often are filled up with a darker, allochthonous sediment (Pl. 6, Fig. 4), which indicates their redeposition or secondary phosphatization. Only 3 boulders of this type have been found, with their total weight of some 6 kg. They yielded numerous fossils (*see also* Gaździcki and Wrona 1986, Wrona 1987): archaeocyathan cups, sponge spicules (Pl. 7, Figs 5' and 7), inarticulate brachiopods *Lingulella*, monoplacophorans (Pl. 10, Fig. 2), gastropods *Pelagiella* (Pl. 10, Fig. 4), *Anabarella* and *Helcionella*, hyolithids, ostracodes *Hipponicharion*' and *Indiana*, corynexochid trilobites (Pl. 9, Figs 2—4), and problematic microfossils ?*Actinotheca*, *Chancelloria* (Pl. 8, Fig. 4), *Coleolella* (Pl. 7, Fig. 4), *Dailyatia* (Pl. 8, Figs 1, 5), *Halkieria* (Pl. 8, Fig. 3), *Hadimopanella* (Pl. 8, Fig. 7), *Hyolithellus* (Pl. 8, Fig. 2), *Mongolitubulus* (Pl. 8, Fig. 5), *"Lenastella"* (Pl. 8, Fig. 6) and *Torellella* (Pl. 8, Fig. 1). Erratic boulders ZPAL AE/Me32, Me33, Me66; Lower Cambrian (Botomian).

Type 14 erratics. Slightly bituminous limestone, black on fresh surface, grey when weathered; biomicrite microfacies, with blue-green algal mats and phosphatic brachiopods. Chemical treatment yielded a few isolated brachiopod shells (*Lingulella*) and *Hadimopanella* sclerites (*cf.* Wrona 1987); erratic boulders ZPAL AE/Me40, Me150; Lower Cambrian.

Type 15 erratics. Onkolitic limestone, with large, often multinuclear onkoids; onkosparite (grainstone) microfacies, with poorly sorted onkoids, pellets, and rare ooids; the onkoids and pellets often are multinuclear, coated, transitional to lumpstone (Pl. 5, Fig. 1); erratic boulders ZPAL AE/Me34, Me92, Me156, Me 158; Cambrian.

Type 16 erratics. Oolitic limestone, with laminar, fractionally graded arrangement of the ooids; oosparite (grainstone) microfacies, with regular, well sorted, densely packed ooids (Pl. 5, Fig. 2); erratic boulders ZPAL AE/Me1, Me83, Me93, Me95, Me173, Me200; Cambrian

Type 17 erratics. Dark-grey limestone without macroscopically discernible fossils; biomicrite microfacies, with sparse sponge spicule (Pl. 5, Fig. 3); erratic boulder ZPAL AE/Me112; Cambrian.

Type 18 erratics. Pink-whitish marble; erratic boulder; ZPAL AE/Me157.

Black limestone erratics of type 1. Laminite microfacies, in places cryptalgal in structure, with intralaminar voids, a terrigenous admixture, and sometimes also with stromatolitic structures; erratic boulders ZPAL AE/Me28, Me68, Me106; Cambrian.

Light-colored limestone of type 5 erratics with archaeocyathan cups encrusted by *Epiphyton* sp. and/or (less common) *Renalcis* sp. (Pl. 4, Figs 2—4; Pl. 6, Fig. 2). In places, synsedimentary calcification of coccoid blue-green algae resulted in free-standing structures of dendritic or tubular saccate or clotted form (*see* Pratt 1984); the spaces between these structures are either filled up with primary micrite, or with secondary, fine-grained micrite that shows laminar and fractional grading (Pl. 4, Fig. 4). Similar fills occur also within the archaeocyathan cups, which often contain also geopetal structures filled with blocky sparr; erratic boulders ZPAL AE/Me2, Me75, Me169, Me174, Me175; Lower Cambrian.

Cambrian fossils

What follows is a preliminary description of the assemblage of macro- and microfossils extracted chemically from the limestone erratics; this assemblage includes several representatives of the informal group Small Shelly Fossils (SSF), comprising by convention molluscs, hyolithids, protoconodonts and a variety of tubular forms, buttonlike and conical sclerites, and simple or rosettelike spicules (Matthews and Missarzhevsky 1975, Conway Morris 1987). Prior to the first appearance of trilobites, SSF have — in addition to archaeocyathans — much significance for definition and correlation of the base of the Phanerozoic (Missarzhevsky and Rozanov 1968, Cowie 1985, Brassier 1986).

Cyanobacteria. — Secondarily mineralized (phosphatized) blue-green algal filaments, often spirally coiled (Pl. 7, Fig. 6) meandering, probably encrusted the sediment surface, most commonly bioclasts (type 13 erratics). In some cases, they are arranged conically, presumably reflecting crusts covering hyolithid shells; they are then tubular, either void, or entirely filled inside: they resemble the genus *Spirellus*. Additionally, the genere *Epiphyton*, *Girvanella* and *Renalcis*.

Archaeocyatha. — This group is mostly represented by fragments of cups or their basal parts observed in thin sections. Types 11 and 13 erratics yielded also internal moulds that display the wall and septal structure and the pore arrangement. Their preservation, however, allows only for their identification with the *Ajacicyathus* cf. *ajax* (Taylor) and *Erugatocyathus* (ZPAL AE/M10), *Thalamocyathus trachealis* (Taylor) — (ZPAL AE/TS8), ?*Syringocnema* and ?*Putapacyathus* (ZPAL AE/Me67).

Siliceous sponges. — These fossils are rare and very poorly preserved. They include reduced stauract spicules (Pl. 7, Fig. 5) with secondarily changed internal structure (type 12, 13 and 17 erratics) as well as hexact spicules (Pl. 7, Fig. 7) which are better preserved and have their axial canals discernible. These spicules represent most probably the Protospongia.

Brachiopoda. — Abundant and well preserved phosphatic shells of the genus *Lingulella* (type 12, 13 and 14 erratics), some of them bored by some predators (?gastropods) and showing traces of regeneration. Such brachiopods are common and cosmopolitan in the Cambrian, though the genus *Lingulella* may include a variety of thin-shelled, elongated obolids.

Monoplacophora. — This group is hardly identifiable because represented exclusively by imprints and internal moulds of cup-shaped shells (Pl. 10, Fig. 2). They belong to at least two distinct genera, of which *Helcionella* is more common (type 13 erratics). The systematic position of these fossils is unclear. Some authors attribute them to the Gastropoda (Rozanov *et al.* 1969), whereas others regard them as cyrtonellid monoplacophorans (Runnegar and Pojeta 1974, Runnegar and Jell 1976).

Gastropoda. — Internal moulds of helically coiled shells (Pl. 10, Fig. 4) found in type 13 erratics are here interpreted as *Pelagiella* (*see also* Gaździcki and Wrona 1986, Fig. 7d), which may represent the oldest known gastropod taxon (Runnegar and Pojeta 1974, Matthews and Missarzhevsky 1975). This genus is in fact cosmopolitan in the Lower Cambrian.

Hyolithida. — Originally aragonitic but now calcitic shells of these organisms are the commonest fossils in type 13 erratics. They are clearly visible in the rock (Pl. 6, Fig. 4) but a chemical preparation only rarely yields their phosphatized shells and opercula. More commonly occur their internal moulds (Pl. 10, Fig. 1) or imprints that may preserve diagnostic elements of shell sculpture (*see also* Gaździcki and Wrona 1986, Fig. 7c).

Trilobita. — Recrystallized trilobite carapaces are clearly visible in thin sections (Pl. 6, Fig. 4); they undergo dissolution, however, during a chemical treatment. What is most commonly found are internal moulds of pygidia and glabellae (Pl. 9, Fig. 2); pyritized cephalons and pygidia occur less commonly (type 13 erratics); best preserved are phosphatized segments of corynexochid carapaces (Pl. 9, Figs 3—4). Isolated trilobite spines occur very abundantly.

Ostracoda. — Type 13 erratics (ZPAL AE/Me33 and Me66) contain few isolated phosphatic carapaces of primitive bradoriids, which are ancestral to the Ostracoda (Sylwester-Bradley 1961). The genus *Hipponicharion* is fairly well preserved (*see* Gaździcki and Wrona 1986, Fig. 7f), but the fragile carapaces of *Indiana* are poorly preserved. Some crushed carapaces may also belong to some other primitive ostracodes.

Incertae sedis

Chancelloria. — Rosettelike calcitic hollow sclerites, split into radial segments around the axial segment. A single rosette includes 3 to 12 (most commonly 6) radial segments. They all have a proximal foramen leading to the inner space of the sclerite. Type 13 erratics yield most commonly internal moulds of isolated radial segments (Pl. 8, Fig. 4). A few spacimens have also fragmentarily phosphatized walls (Gaździcki and Wrona 1986, Fig. 7a,b). These sclerites were initially attributed to sponges, but this interpretation has now been refuted beyond any doubt (Goryanskiy 1973, Bengtson and Missarzhevsky 1981). Their systematic position has nevertheless remained unclear. *Chancelloria* sclerites are very characteristic and cosmopolitan in the Cambrian. They were previously reported from Antarctica — from Middle Cambrian limestones that occur as erratic blocks in the moraines in Argentina Range (Solovjev and Grikurov 1979, Popov and Solovjev 1981).

"Lenastella". — Phosphatized (?originally calcitic) rosettelike spicules with fused radial segments as well as their inner spaces (Pl. 8, Fig. 6). The spicule wall is both externally and structurally close to that of *Chancelloria*, to which these fossils may be related. *Chancelloria* sclerites are in fact always associated with *"Lenastella"* spicules, which were first described by Missarzhevsky and Mambetov (1981) from Karatau, Asia. The Karatau specimens have no hollow spaces inside, but this may reflect their secondary mineralization. The Lower Cambrian specimens from Antarctica (type 13 erratics) have inner voids as in *Chancelloria* sclerites; they lack a "basal pore" or foramen, however, and this absence makes a difference from the star--shaped sclerites of *Archiastrella* Sdzuy (1969) which may indeed represent *Chancelloria* sclerites lacking their axial radii. The Antarctic specimens of *"Lenastella"* resemble most closely those from the Lower Cambrian of Australia (Laurie 1986, Fig. 10, G).

Dailyatia. – Well preserved phosphatic sclerites, more or less broad conical in shape, with radial folds (Pl. 9, Fig. 1, 5; *see also* Gaździcki and Wrona 1986, Fig. 7e). The external sculpture is particularly characteristic; it comprises densely spaced, concentric ridges with reticulate microornamentation in between (Pl. 9, Fig. 1'). Broken specimens show a lamellar structure of the wall. Whole specimens, and even some fragments, are identifiable as either mitral, or sellate forms. The Antarctic specimens are attributable to *Dailyatia ajax* Bischoff, described from the Lower Cambrian Ajax Limestone of southern Australia (Bischoff 1976). They are associated with massive tommotiid-like, but poorly preserved and hardly identifiable sclerites (Pl. 10, Fig. 3). *Dailyatia* was previously known solely from the Lower Cambrian (Atdabanian) of Australia (Laurie and Shergold 1985, Laurie 1986), but has recently reported also from Lower Cambrian erratics in Tertiary glacio-marine sediments of King George Island (Gaździcki and Wrona 1986, Wrona 1987; type 13 erratics) and from the Shackleton Limestone in the Transantarctic Mountains (Rowell, Evans and Rees 1988). These sclerites covered originally the body of animals attributed to the order Mitrosagophora (Bengtson 1970), which could have been related to the Paleozoic Machaeridia (Bengtson 1970, 1977a, Dzik 1986a).

Hadimopanella. — Button-shaped phosphatic sclerites, with their lower surface smooth and the upper surface covered with sharp tubercles (type 13 and 14 erratics; *see also* Gaździcki and Wrona 1986, Fig. 7g) have been described as *Hadimopanella antarctica* Wrona (1987). Such sclerites are widely distributed in the Cambrian of Europe, Asia, Spitsbergen, and Greenland. The Antarctic specimens differ in ornamentation from their congeners. The internal structure and external sculpture of *Hadimopanella* sclerites suggests they could have represented an animal body cover, in analogy to dermal sclerites of primitive chordates (Bengtson 1977b, Wrona 1982, 1987, Dzik 1986b). Recently, Bendix-Almgreen and Peel (1988) compared them to aragonitic ascidian spicules and interpreted *Hadimopanella* as an early Paleozoic relative of the ascidians.

Halkieria. — Sclerites in the form of minute, hollow, flat spines, approximately 1 mm in length, with a distinct base at the proximal end which also bears a foramen — the trace of attachment to an animal body (Pl. 8, Fig. 3). The sclerites occur as dextrally or sinistrally arched forms, sometimes also almost straight and usually longer spines. The upper surface is most commonly covered with longitudinal ribs, whereas the lower one is smooth; both the surfaces are also covered with delicate transversal lines. Presumably, *Halkieria* sclerites were originally calcitic; hence, a chemical treatment generally yields only internal moulds. Their secondarily phosphatized walls can be partially eatched in the course of chemical treatment

(Pl. 8, Fig. 3; *see also* Gaździcki and Wrona 1986, Fig. 7h) and they are then hardly identifiable (type 13 erratics). *Halkieria* sclerites are widely distributed (Fig. 2) in Lower Cambrian (no higher than the Atdabanian) of Europe, Siberia, Mongolia, Kazakhstan, Karatau, China, Iran, India, North America, and Australia (Missarzhevsky and Mambetov 1981, Bengtson and Conway Morris 1984). They appear to be closely related to *Wiwaxia* Walcott, known from the Middle Cambrian of British Columbia (Bengtson and Conway Morris 1984). Both *Halkieria* and *Wiwaxia* sclerites represented a dermal body cover and, similar to the Mitrosagophora Bengtson, could have been closely related to the Paleozoic Machaeridia (Dzik 1986a).

Hyolitellus. — Phosphatic or phosphatized, cylindric or slightly tapering tubes covered with transversal (?growth) lines (Pl. 7, Fig. 4, Pl. 8, Fig. 2) that are asymmetric and equally, in places variably, spaced. The Antarctic specimens (type 13 erratics) most closely resemble *H. isiticus* Missarzhevsky. Such forms are ubiquitous in SSF assemblages, and the specific sculpture provides some of their species with a biostratigraphic significance in the Lower Cambrian.

Torellella. — Phosphatic tubes, strongly tapering and usually arched in shape (Pl. 8, Fig. 1). They are subcylindric in crosssection at the arrow end but lenselike to ellipsoidal, strongly flattened at the wide end. The wall appears to be multilayered, covered with delicate growth lines. The aperture (whenever preserved) provided with two keels that are separated at the flat sides of the tube by a deep sinus, disappearing adapically and partly covered by a thin, translucent layer of the wall. Type 13 erratics. These fossils are cosmopolitan in the Lower Cambrian (Tommotian) of Asia (Siberia) and Europe.

Coleolella. — Primarily calcitic, cylindric to slightly tapering tubes. They are usually straight or very slightly bended, circular in cross-section, open at both the ends. The outer surface is covered with densely and evenly spaced, symmetric, transversal ribs, usually straight or weakly undulating (Pl. 7, Fig. 4). Type 13 erratics. This genus occurs in the Lower Cambrian (Tommotian) of Asia (Siberia) and Europe.

Mongolitubulus. — Conical phosphatic spines, straight to slightly arched, approximately 1 mm in length and 0.3 mm in diameter, covered with rhomboidal scales (Pl. 8, Fig. 5). The scales are inclined, separated distally from the spine surface, arranged spirally and at the same time alternately, thus forming a chesslike pattern. Broken specimens show a multilayered, fibroidal structure of the wall, similar to that observed by Bengtson (1983) in *Rhombocorniculum* spines. *Mongolitubulus* has been first described as tubus and assigned to the Hyolithelmintes (Missarzhevsky 1974, Missarzhevsky and Mambetov 1981, Rozanov 1986). The Antarctic specimens come from type 13 erratics and belong to *M. squamifer* Missarzhevsky, which has been thus far reported from the Lower Cambrian (Botomian) of Karatau and Mongolia and from the Middle Cambrian of Turkestan (Meshkova 1985), and more recently also from the Lower Cambrian of Greenland (Peel and Blaker 1988).

Tubular problematics. — A variety of tubular microfossils, most probably heterogeneous in nature, are attributed to the Hyolithelmintes. These are internal moulds of long, thin, cylindric or slightly conical tubes (type 13 and 14 erratics), lacking any external ornamentation that could be diagnostic and hence hardly identifiable (Pl. 7, Figs 1—3). They are usually interpreted as representative of the Annelida. They are very typical of SSF assemblages and widely distributed in the Cambrian (Rozanov 1986).

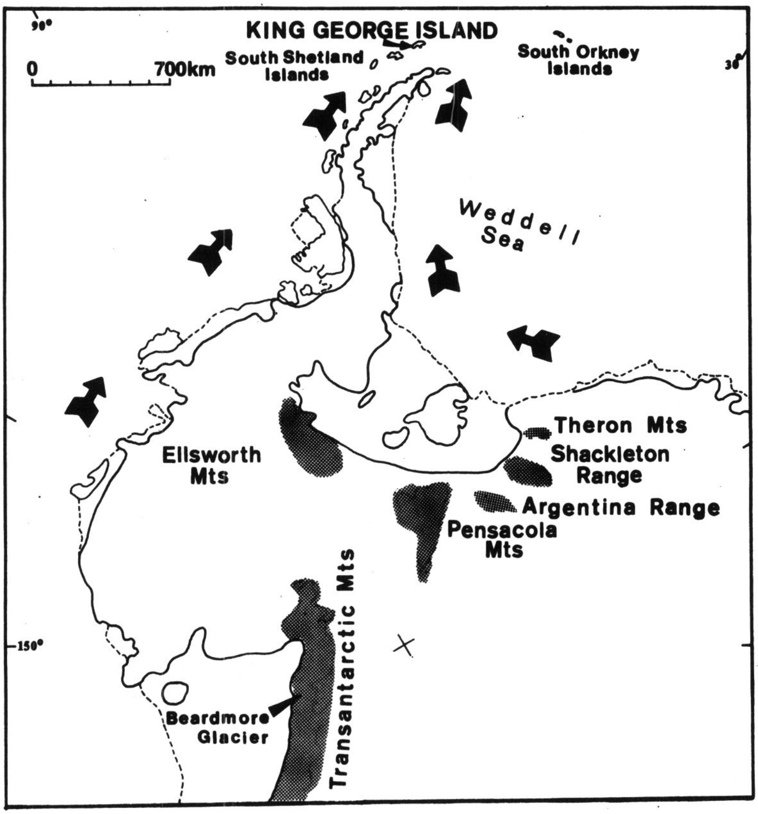

Fig. 2. Key map to West Antarctica: the extent of mountains with outcrops of fossiliferous Cambrian rocks (shaded). Arrows show the probable pathways of ice-rafting

Geological age and origin of the limestone erratic boulders

The most abundant group of limestone erratics in glacio-marine sediments on King George Island are light-colored archaeocyathan-algal limestones with, archaeocyathan cups and blue-green algae *Epiphyton* and/or *Renalcis*. They were in fact found by the pionieer expeditions to Antarctica; in modern moraines in the central Transantarctic Mountains (Shackleton's 1908—1909 British Antarctic Expedition, *see* Taylor *in*: David and Pristley 1914; and Scott's 1911—12 Expedition, *see* Debenham 1921) and as dropstones in modern glacio-marine sediments in the Weddell Sea (Scottish National Antarctic Expedition 1902—1904, *see* Gordon 1920). Isolated blocks of archaeocyathan-bearing limestone were also found in the Theron Mountains (Adie 1962), Which Way Nunataks (Hill 1964) and Argentina Range (Konyushkov and Shulyatin 1980). Archaeocyathan-bearing limestones in situ occur in the central Transantarctic Mountains — in the vicinity of Nimrod Glacier (Laird and Waterhouse 1962) and Beardmore Glacier (Grindley, McGregor and Walcott 1964). It appears very likely that the isolated blocks of these limestones found in the Transantarctic Mountains derived from the Lower Cambrian Shackleton Limestone, which is exposed between the Beardmore and Byrd Glaciers in the Holyoake Range (Debrenne and Kruse 1986). The archaeocyathan fossils indicate the Botomian age of these rocks. Their lithological and paleontological similarity to the erratics found in Tertiary glacio-marine sediments on King George Island suggests that the latter boulders may derive from the same source of Botomian age.

The fossil assemblage of type 13 limestone erratics found in the Cape Melville Fm., King George Island (Gaździcki and Wrona 1986, Wrona 1987), is indicative of their Early Cambrian age. The fragmented trilobite carapaces are attributed to Early Cambrian corynexochids (Pl. 9, Figs 3, 4). Some constituents of this fossil assemblage occur also in deposits geologically younger than the Lower Cambrian, but *Dailyatia* and *Halkieria* sclerites are confined to the Lower Cambrian and do not range beyond the Atdabanian. Therefore, the source rocks for these erratics seem to be Botomian in age.

Lower Cambrian small shelly fossils, including *Dailyatia* sclerites, have been recently described from the Shackleton Limestone exposed in the Transantarctic Mountains (Rees and Rowell 1985; Rowell, Evans and Rees 1988).

A Middle Cambrian assemblage, including *Chancelloria* sclerites, has been observed in moraine blocks in the Pensacola Mountains and in the vicinity of Ferrara Mt., Argentina Range (Popov and Solovjev 1981).

The most common lithologies of limestone erratics from Tertiary glacio-marine sediments on King George Island (archaeocyathan-algal boundstone, biomicrite, oolite and onkolite) resemble quite closely, both in microfacies and in the fossil content, the rocks of the Shackleton Limestone. This carbonate sequence, almost 2000 m in thickeness, was deposited in a variety of habitats on the shelf that was rimming the Antarctic paleocraton during the Early Cambrian (Rees and Rowell 1985; Rees, Pratt and Rowell 1989). Limestone members of this sequence, or their facies and age equivalents, folded at the edge of the Precambrian Antarctica build now the nunataks and mountain ranges between the Ross and Weddell Seas. It is most likely that some outcrops of those Lower Cambrian limestones in the vicinity of the Weddell Sea, which are presently unknown and/or covered by the icesheet, were the source of the limestone erratics found today on King George Island. This inference agrees with the interpretations of the source areas and transport directions applied previously to the erratics of igneous, metamorphic, and clastic rocks (Birkenmajer and Wieser 1985, Birkenmajer and Butkiewicz 1988).

The lithological and source area variation of the erratics found on King George Island is much greater than modern ice-rafed debris along the ice-shelf at the eastern shore of the Weddell Sea, as the lithology of this modern debris strongly depends on geology of the corresponding hinterland in Antarctica (Oskierski 1988). In the Tertiary, the ice-flow directions in West Antarctica (*see* Birkenmajer and Wieser 1985) probably were the same or similar as they are presently — generally centrifugal (Oskierski 1988, Fig. 4). Ice-stream transport selectively eliminates carbonate rocks and leads to enrichment of the resulting debris in more resistant blocks of igneous, metamorphic, and clastic rocks which underwent rather substantial diagenesis. Ice-rafting, in turn, leads to considerable mixing of various erratics, thus resulting in a wide lithological spectrum of erratics in the glacio-marine sediments on King George Island (*see also* Birkenmajer and Wieser 1985, Birkenmajer and Butkiewicz 1988).

Paleogeographic implications

Paleogeografic reconstructions of the land mass distribution at the Proterozoic/Phanerozoic boundary are achieved primarily by means of geophysical and geological data, but they need testing with paleontological informations on fossil faunas. Precambrian faunas, however, are few and poorly differentiated. They are largely represented by trace fossils and imprints of soft-bodied Metazoa. The Vendian faunas are nonskeletal organisms, such as the Ediacaran biota. The first Metazoa with mineralized skeleton are the enigmatic calcitic, tubular fossils *Cloudina*, known from the Vendian and Lower Cambrian of Gondwana (McMenamin 1982), namely from South America, South Africa, and Antarctica (Fig. 3). The Archǎeocyatha and Trilobita, which have been traditionally employed for biostratigraphy and

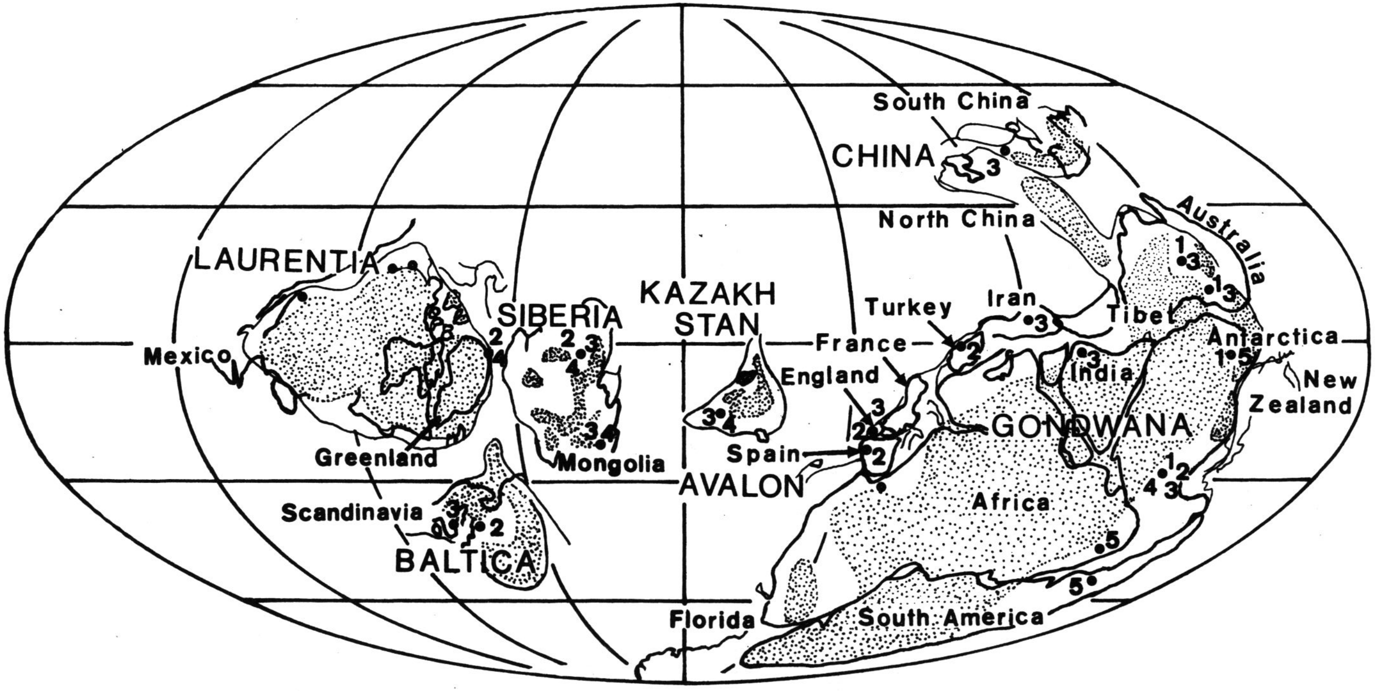

Fig. 3. Paleogeography of the world during the Early Cambrian (*after* Parrish *et al.* 1986), with the most important localities of earliest skeletal fossils (●) to show the proximity and probable similarities of SSF assemblages. Distribution of selected fossils: 1 — conical sclerites of *Dailyatia; 2 – button-shaped sclerites of Hadimopanella*; 3 — halkieriid sclerites; 4 — spinelike *Mongolitubulus*; 5 — vermiform tubes of *Cloudina*. Paleogeography: doted = land, light = shelf

paleogeography of the Lower Cambrian, have in fact only a limited potential. The small shelly fossils, however, which appeared later than the Ediacaran biota but earlier than trilobites, are a widely variable and almost cosmopolitan group. They may serve to trace the Precambrian/Cambrian boundary, or the base of the Tommotian (Cowie 1985).

The majority of SSF species found in Antarctica are distributed all over the world. The sclerites *Dailyatia ajax* Bischoff, however, occur exclusively in Australia and Antarctica. On both continents they occur in a similar carbonate facies (Ajax Limestone and Shackleton Limestone), associated with similar Botomian archaeocyathans (Debrenne and Kruse 1986).

Rich and variable SSF assemblages are apparently associated with warm-, shallow-, and rather quiet-water marine environments of carbonate deposition (Mount and Signor 1985, Gevirtzman and Mount 1986). The abundance of archaeocyathan-algal and SSF assemblages in the Lower Cambrian carbonates of Antarctica indicates their deposition on a warm and shallow shelf of Gondwana.

At the end of the Tommotian Stage, the SSF fauna undergoes explosive differentiation and reaches virtually all the continents; witness the Lower Cambrian assemblage from Antarctica which includes the cosmopolitan *Halkieria* (Bengtson and Conway Morris 1984) and receives at this point also *Mongolitubulus* and *Hadimopanella*, known previously from Asia and Greenland (Peel and Blaker 1988, Bendix-Almgreen and Peel 1988). The recent report from Botomian rocks of Greenland (Bendix-Almgreen and Peel 1988, p. 86, Fig. 4C) on sclerites which resemble very closely *Hadimopanella antarctica* Wrona also suggests that migration between Antarctica and Grrenland was rather easy at that time.

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Streszczenie

Bloki wapieni eratycznych zawierające liczne skamieniałości zostały zebrane z lodowcowych i morsko-lodowcowych osadów oligoceńskiej formacji Polonez Cove i mioceńskiej formacji Cape Melville na Wyspie Króla Jerzego w Antarktyce Zachodniej (fig. 1). Eratyki są głównie zrzutkami (pl. 1—4) z dryfujących gór lodowych i reprezentują kilkanaście typów litologicznych, z których najpospolitsze są: jasne wapienie archeocyjatowo-glonowe (pl. 4, fig. 2—4; pl. 6, fig. 1—2), oolity (pl. 5, fig. 2), onkolity (pl. 5, fig. 1) i czarne wapienie mikrytowe zawierające skamieniałości szkieletowe (pl. 6, fig. 4). Skamieniałości te reprezentują wiele typów świata zwierzęcego: archeocyjaty, gąbki, ramienionogi, jednopłytkowce i ślimaki, hyolity, trylobity, małżoraczki, a także organizmy o nieznanej pozycji taksonomicznej: *Chancelloria, Coleolella, Dailyatia, Halkieria, Hadimopanella, Hyolithellus, "Lenastella", Mongolitubulus* i *Torellella* (pl. 8—10). W oparciu o skamieniałości określono dolnokambryjski (botomski) wiek wapieni eratycznych. Główne typy litologiczne wapieni eratycznych są bardzo podobne do tych, które składają się na węglanową sekwencję Shackleton Limestone, odsłaniających się w centralnej części Gór Transantarktycznych. Analiza litologii wszystkich głazów przyniesionych na Wyspę Króla Jerzego podczas zlodowaceń Polonez i Melville pozwala sądzić, że obszarem źródłowym głazów na kontynencie antarktycznym były wychodnie skał kambryjskich w otoczeniu Morza Weddella (fig. 2).

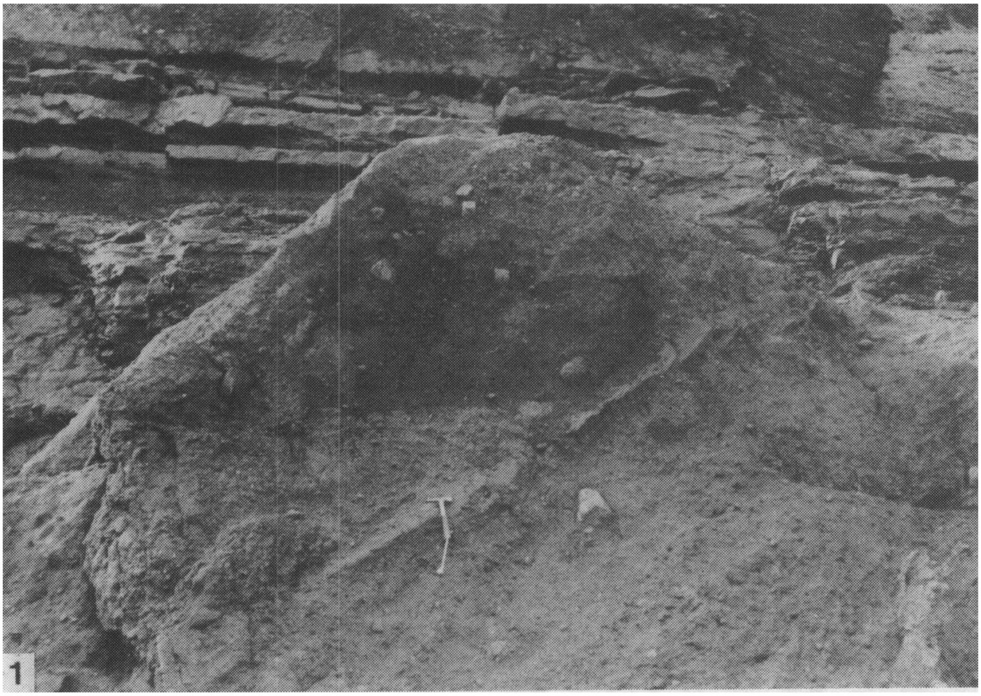
Pokrewieństwo odkrytych na Antarktydzie dolnokambryjskich zespołów faunistycznych do analogicznych zespołów znanych z Australii (wapienie Ajax) i Azji (Platforma Syberyjska i Mały Karatau) potwierdza paleogeograficzne rekonstrukcje wczesnokambryjskiego rozkładu kontynentów (fig. 3).

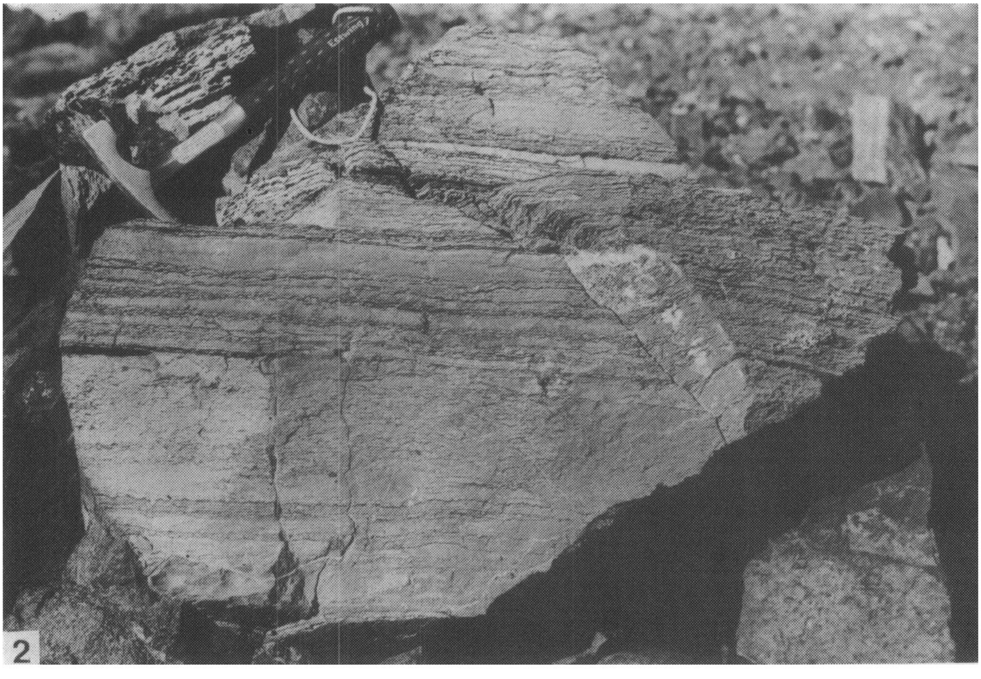
Pracę wykonano w ramach CPBP 03.03.

1

2

1. Erratic boulders as residual enrichment at the top of glaciomarine sediments of the Cape Melville Fm., Melville Peninsula. Mount Melville in background. Photo by R. Wrona, 1981
2. The lowermost part of glacio-marine sediments of the Cape Melville Fm., exposed in the north face of the Melville Peninsula cliff. Note dropstone distribution in the sediments. Photo by A. Gaździcki, 1986

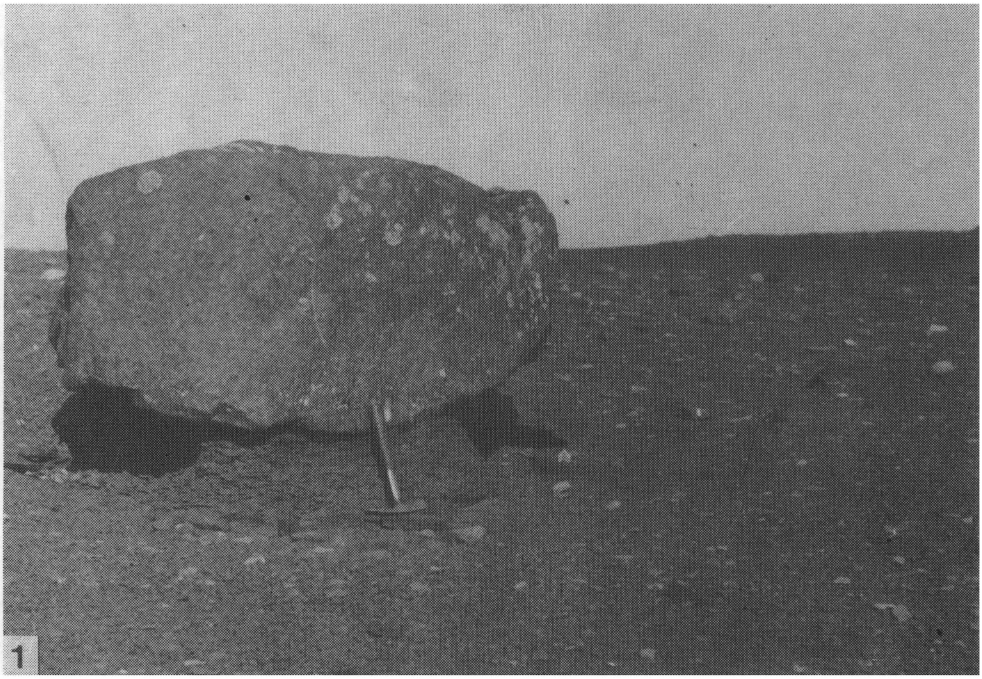




1. Exposure of diamictites of the Krakowiak Glacier Mb. at Mazurek Point. Note sandstone intercalations and chaotically scattered erratic boulders. Low Head Mb. sediments in the upper background

2. Dropstone within glacio-marine sediments of the Low Head Mb., blue-grey limestone with wavy lamination; ZPAL AE/LH2 (*cf.* Pl. 5, Fig. 4)

Photos by R. Wrona, 1981



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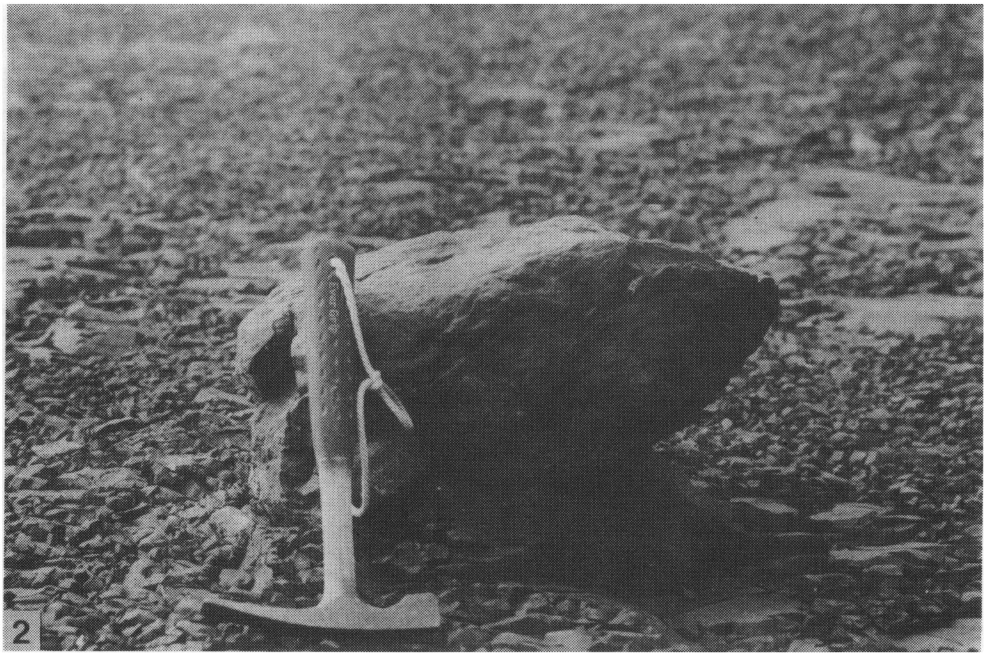
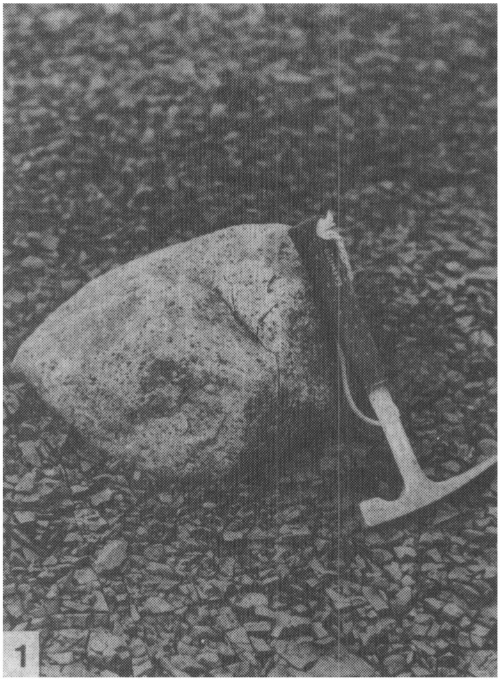


2

1. One of the largest dropstones
2. Striated and faceted dropstone. Both are residual boulders at the top of glacio-marine sediments of the Cape Melville Fm., Melville Peninsula
Photos by R. Wrona, 1981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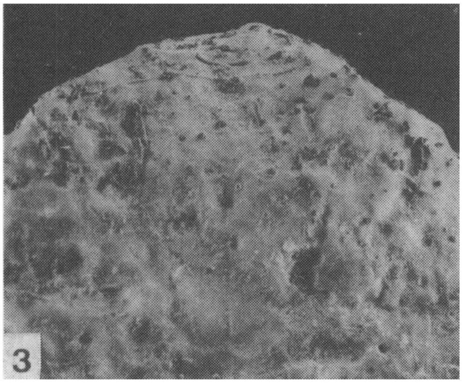
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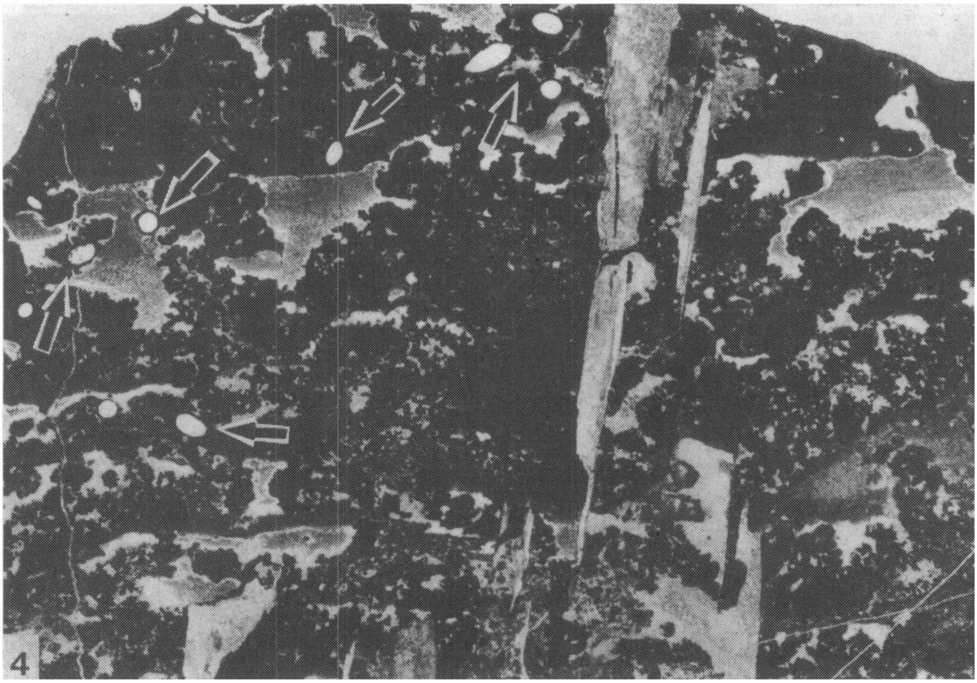
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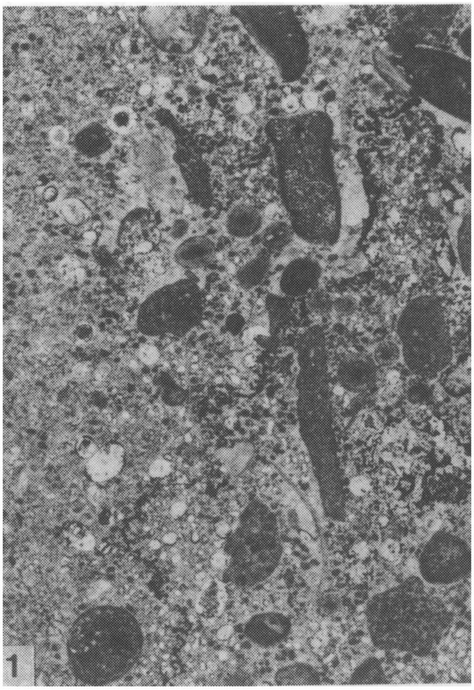
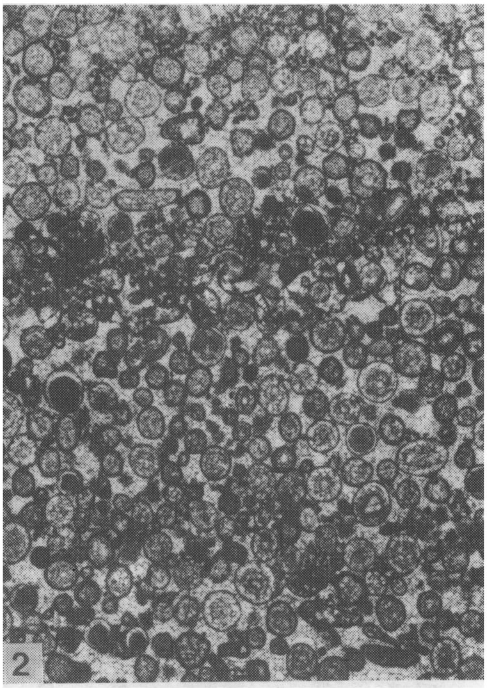
1. Dropstone bored by some Tertiary polychaetes

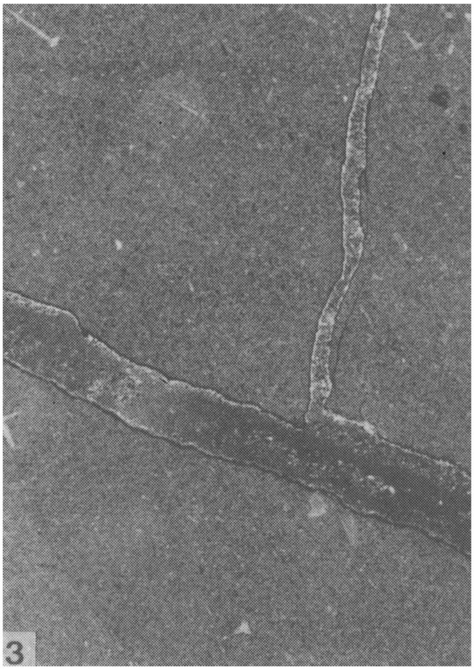
2—3. Dropstone of blue-green algal limestone bored by some Tertiary epibenthic algae. ZPAL AE/Me175, × 2

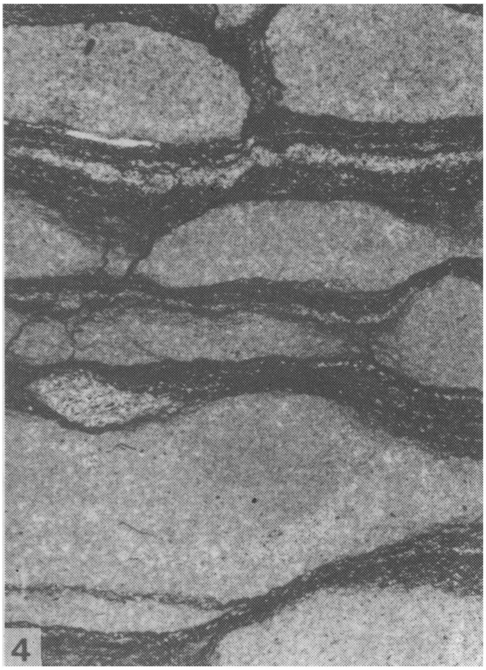
4. Thin section of the some limestone as in Figs 2—3. Note algal borings filled with sparry calcite and organic lining (arrowed). ZPAL AE/Me75, × 5

All boulders are from the Cape Melville Fm.





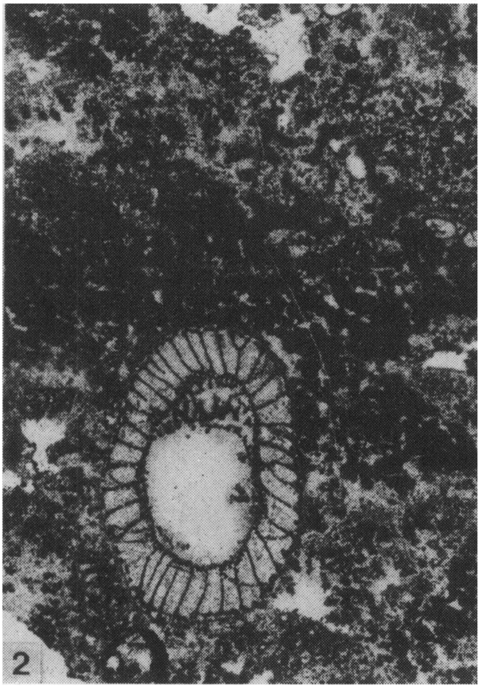




1. Intraonkobiosparite (packstone), ZPAL AE/Me111, × 5
2. Oosparite, ZPAL AE/Me1, × 5
3. Biomicrite with sparse sponge spicules; thin section of a frost-cleft dropstone with clefts infilled and cemented with sediment of the Cape Melville Fm., ZPAL AE/Me112, × 5
4. Laminated limestone (*cf.* Pl. 2, Fig. 2). Note light micrite layers alternating with bituminous silty and dark micrite layers, ZPAL AE/LH2, × 10

Figs 1—3 are from thin sections of dropstones from the Cape Melville Fm., Fig. 4 from the Low Head Mb.


1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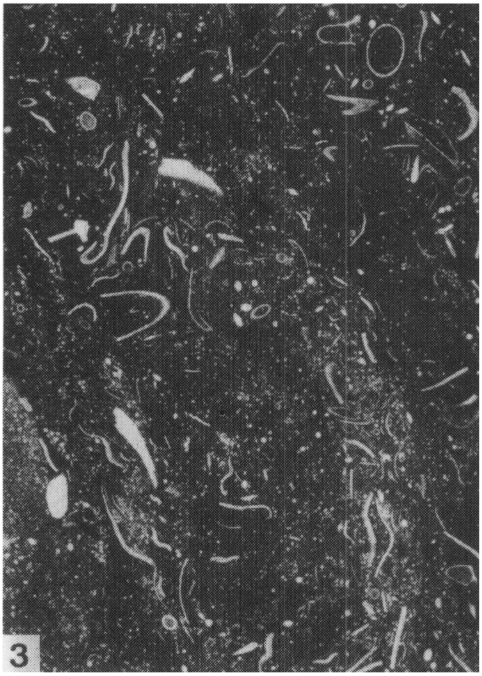
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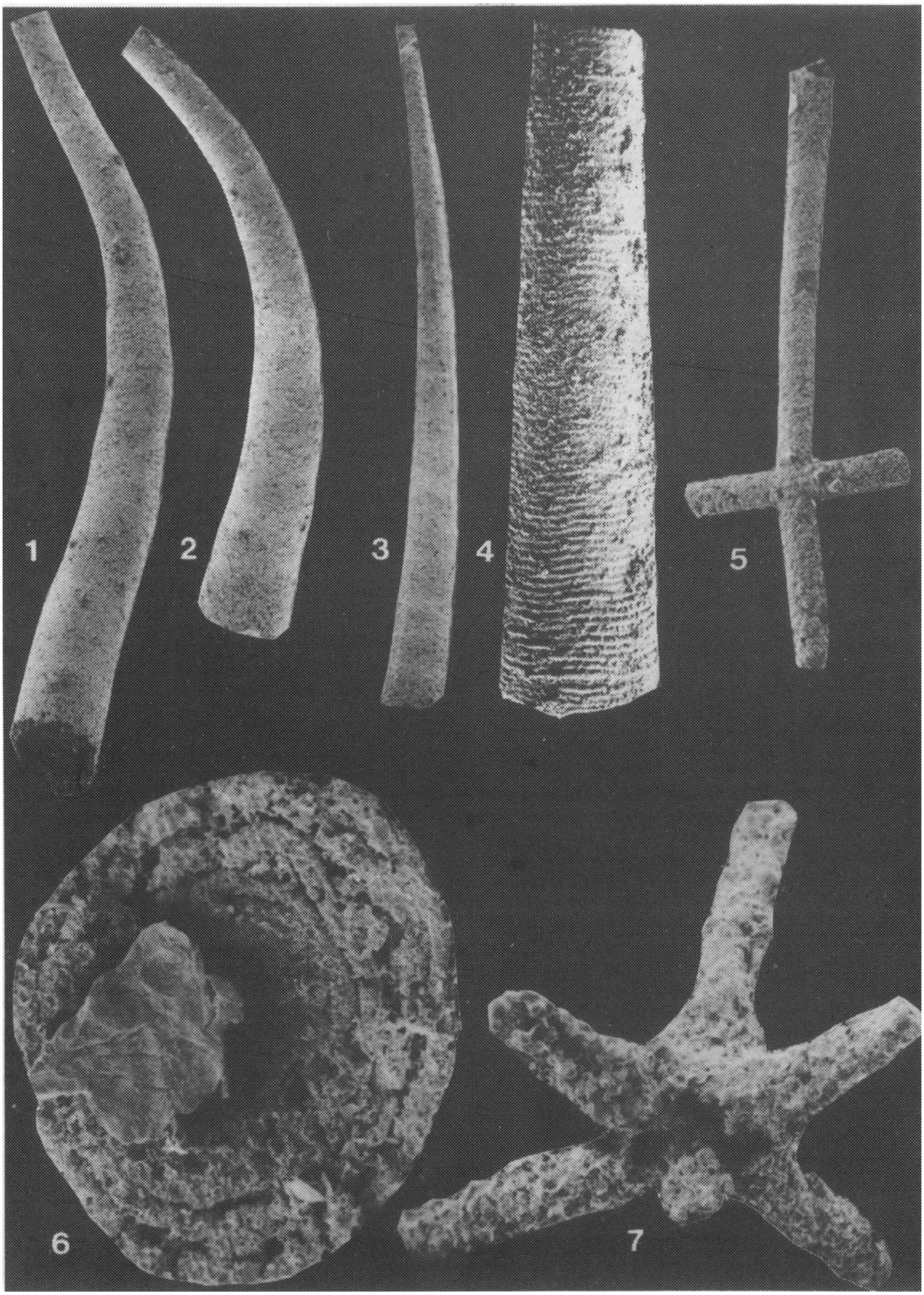
1. Biosparite (packstone) with fragmented archaeocyathan cups, trilobite and brachiopod shells and blue-green algal laminae, ZPAL AE/Me 67, × 5
2. Archaeocyathan-algal boundstone. Archaeocyathan cup encrusted by blue-green algae *Renalcis* sp., ZPAL AE/M10, × 5
3. Biomicrite with trilobite carapaces and sponge spicules ZPAL AE/Me29, × 5
4. Intrabiomicrite with hyoliths and trilobite spines, ZPAL AE/Me33, × 10

Figs 1—2, 4 are from thin sections of erratics from the Cape Melville Fm., Fig. 3 is from tillite of the Krakowiak Glacier Mb.



1—2. Phosphatic internal moulds of a tubular from ex. gr. Hyolithelmintes, Fig. 1 — ZPAL V.VI/26S6, × 10; Fig. 2 — ZPAL V.VI/25S3, × 60

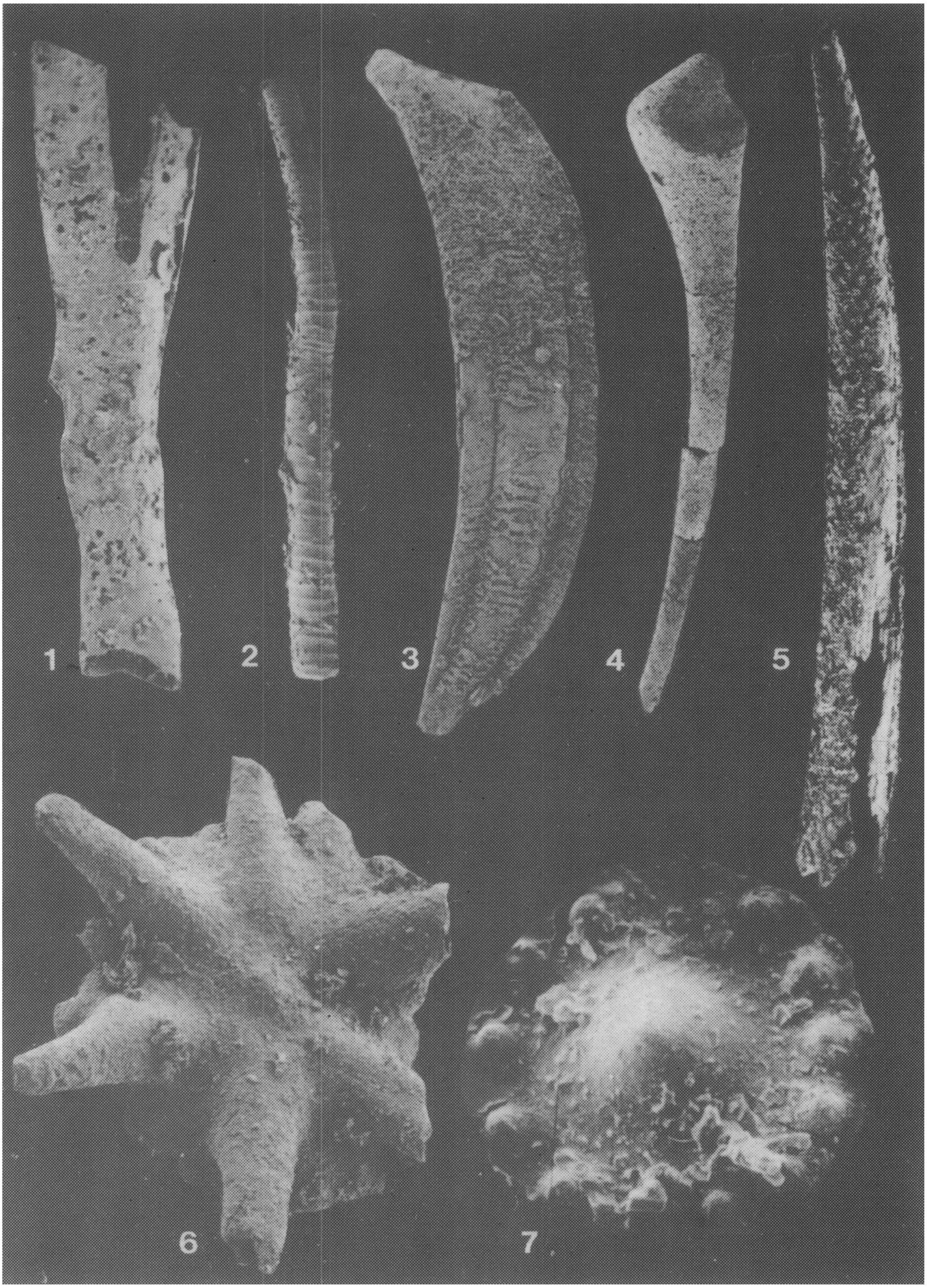
3. Phosphatic protoconodontiform spine, ZPAL V.VI/25S1, × 100

4. *Coleolella* sp. in lateral view, ZPAL V.VI/29S10, × 70

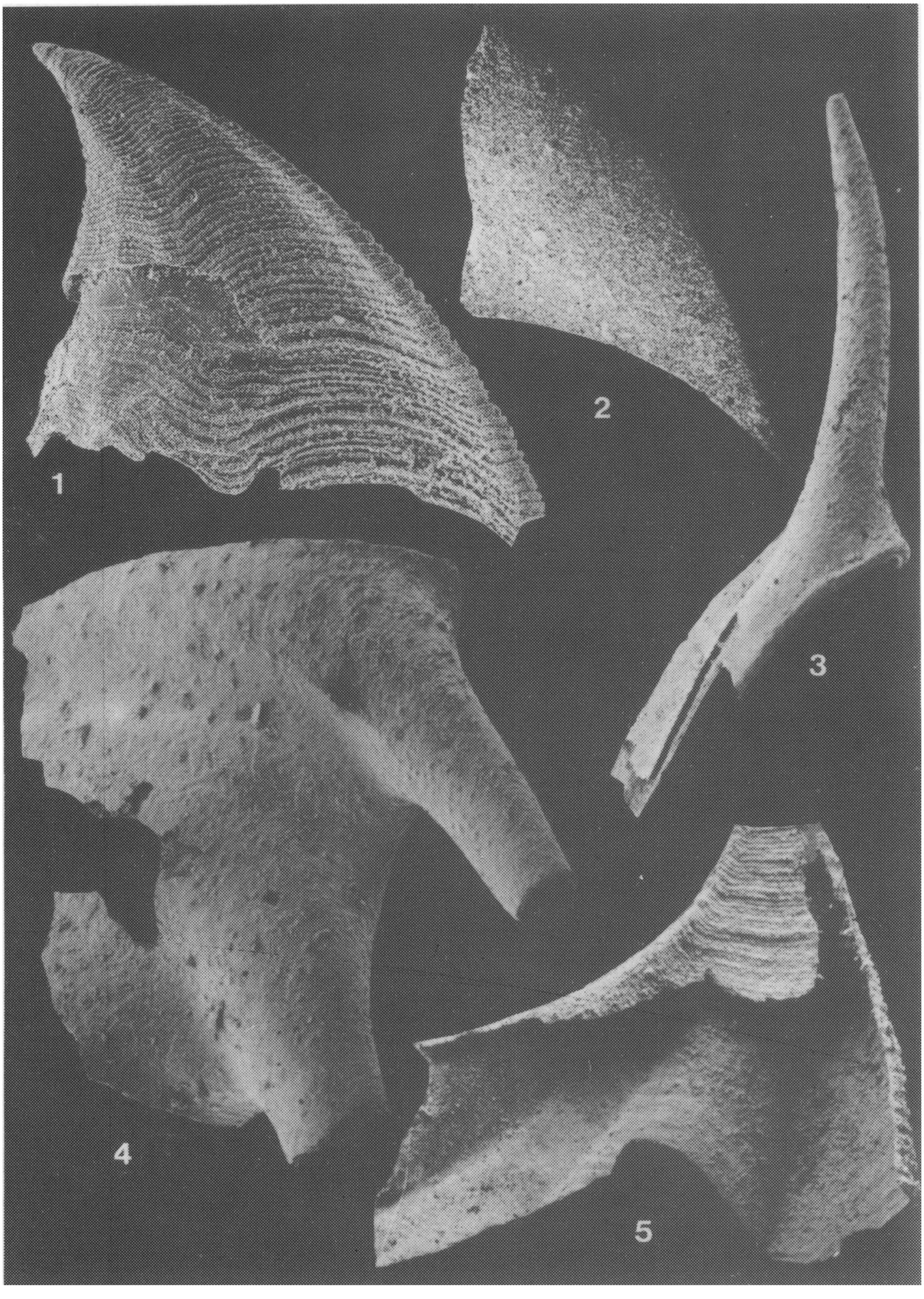
5. Stauract sponge spicule, ZPAL Pf.V/21 S7, × 120

6. *Spirellus* sp. secondarily phosphatized algal (cyanobacterial) filament, ZPAL V.VI/25S14, × 400

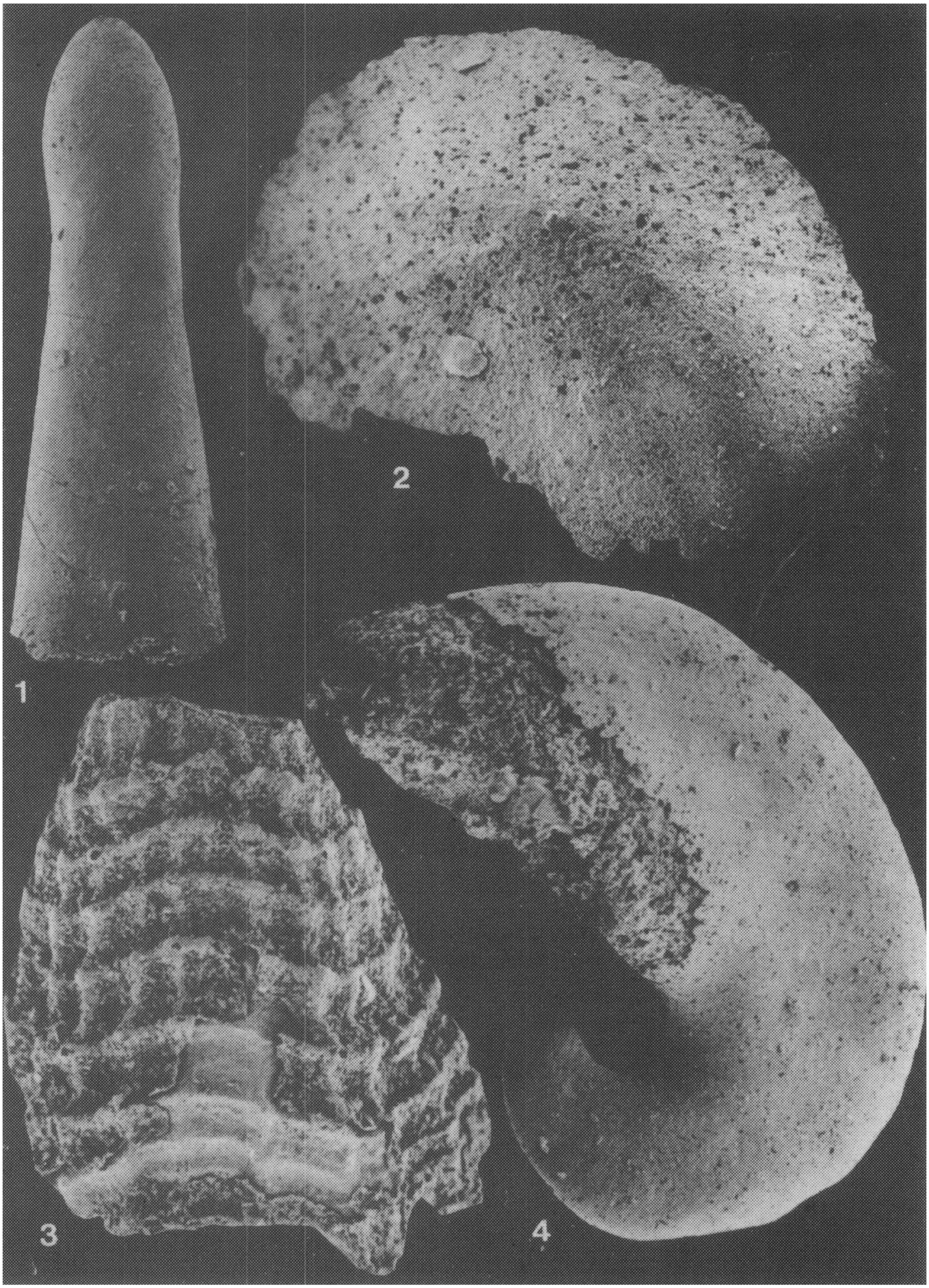
7. Hexact sponge spicule, ZPAL Pf.V/25S4, × 160



1. *Torellella* sp. in lateral view, ZPAL V.VI/22S27, × 70
2. *Hyolithellus* sp., a fragmentary specimen in lateral view, ZPAL V.VI/25S28, × 35
3. Isolated sclerite of *Halkieria* sp., complete internal mould with adhering sclerite wall, ZPAL V.VI/26S13, × 45
4. Internal mould of a radius of *Chancelloria* sp. in lateral view, ZPAL V.VI/22S14, × 60
5. Sclerite of *Mongolitubulus squamifer* Miss., ZPAL V.VI/28S28, × 75
6. Star-shaped sclerite of “*Lenastella*”, ZPAL V.VI/26S27, × 150
7. Button-shaped sclerite of *Hadimopanella antarctica* Wrona ZPAL V.VI/26S12, × 1000



1. Complete sclerite of *Dailyatia ajax* Bischoff, convex side in lateral view, ZPAL V.VI/29S3, × 75
2. Phosphatic internal mould of trilobite free cheek (librigenae), ZPAL Tr.V/22S16, × 50
3. Fragment of phosphatized corynexochid thoracic pleurae with spine, ZPAL Tr. V/21S8, × 50
4. Phosphatized corynexochid? pygidium with marginal spines, ZPAL Tr. V/21S19, × 70
5. Fragmented sclerite of *Dailyatia ajax* Bischoff, concave side in lateral view, ZPAL V.VI/26S28, × 60



1. Phosphatic internal mould of a juvenile hyolith conch, ZPAL V.VI/21S5, × 130
2. Phosphatic internal mould of a monoplacophoran shell. ZPAL Ga.V/22S3, × 150
3. Mitrosagophoran sclerite (tommotiid-like), convex side in lateral view, ZPAL V.VI/26S9, × 100
× 100
4. Phosphatic internal mould of a gastropod shell *Pelagiella* sp. in lateral view, ZPAL Ga. V/21S9, × 150