SEDIMENTARY ROCKS OF THE ELLSWORTH–THIEL MOUNTAINS RIDGE AND THEIR REGIONAL EQUIVALENTS

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Abstract. Sedimentary rocks of the Ellsworth–Thiel mountains ridge are divided into three major units: a volcaniclastic unit, a red sandstone unit and a mixed carbonate–clastic unit. The units are correlated with neighbouring Cambrian successions and are related to an intracontinental extensional environment. The volcaniclastic unit occurs within the Thiel Mountains, is formally defined as the Mount Walcott Formation and was deposited in a deepening shoreline–shelf–outer shelf or base of slope marine setting bordering volcanic islands. The mixed carbonate–clastic unit of the Nash and Martin hills, termed the Nash Hills Formation, represents shallowing upwards events in a shallow, storm-influenced shelf adjacent to a productive clastic shoreline. The red sandstone unit, termed the Mount Johns Formation, was deposited by alluvial processes and may represent a widespread regression. If the correlations are correct, tectonic events can now be matched between Greater and Lesser Antarctica during the Cambrian period.

INTRODUCTION

Sedimentary rocks form a significant part of the scattered groups of nunataks exposed along the Ellsworth–Thiel mountains ridge (ETMR), the prominent sub-ice topographic high that extends across Lesser Antarctica (Figs 1 a, b) from the base of the Antarctic Peninsula to the Transantarctic Mountains (Bentley and Ostenso, 1961; Jankowski and others, 1983). The ridge is located in one of the most tectonically important parts of Antarctica. Although partially dissected by rifts it is the only continuous topographic feature to straddle the major tectonic provinces of Greater and Lesser Antarctica. The ridge also impinges against the western margin of Greater Antarctica at a major gap in outcrop in the Transantarctic Mountains (Fig. 1 a). Thus the scattered nunataks of the ETMR lie at the centre of a triangle with well-exposed areas at its apices: the Ellsworth, Pensacola and Horlick–Queen Maud mountains. These three areas have undergone different strato-tectonic development (Fig. 2) and an understanding of the rocks of the ETMR is crucial to understanding the evolution of this part of Antarctica.

This paper is a description of some aspects of the sedimentology and stratigraphy of the least deformed and thermally altered sedimentary rocks of the ETMR. It is based on field observations by BCS and laboratory work by both authors. BCS was a member of the recent joint UK–US Lesser Antarctica Tectonic Project that visited the area during the 1983–84 austral field season (Dalziel and Pankhurst, 1985).

REGIONAL SETTING

The Transantarctic Mountains bordering Greater Antarctica contain thick greywacke-shale sequences (e.g. Patuxent, La Gorce and Goldie formations) deposited in one or more Precambrian basins and deformed during the late Precambrian Beardmore orogeny (Grindley and McDougall, 1969). These rocks were unconformably overlain by Cambrian shallow marine clastic rocks, local silicic volcanic rocks and

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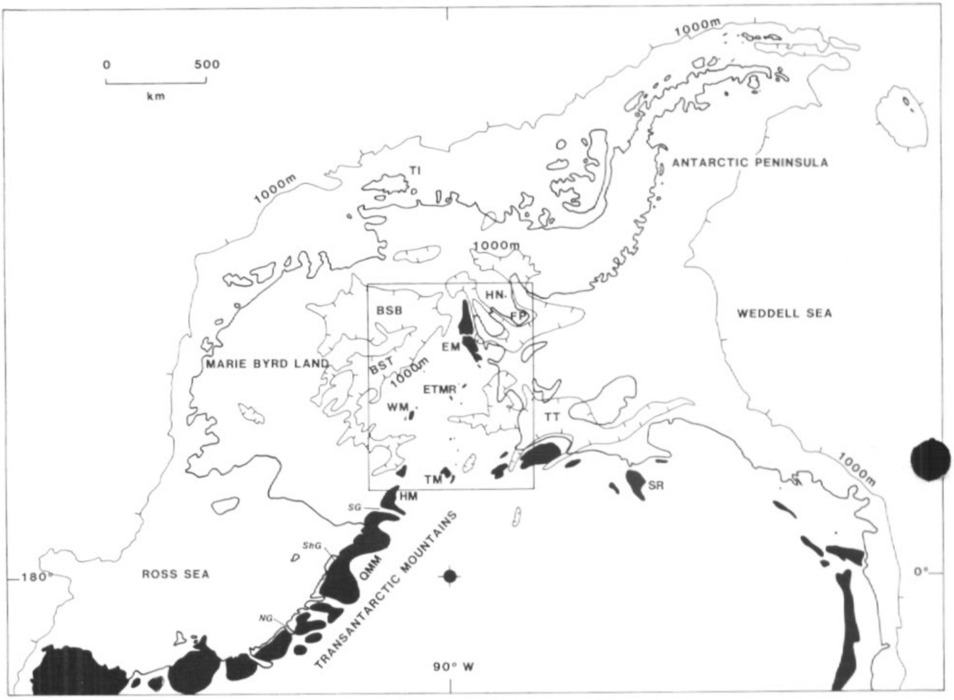

Fig. 1(a). For legend see opposite.

archaeocyathid-bearing limestones (Byrd and Liv groups) all deposited in an epicontinental sea (Elliot, 1975). In the late Cambrian–Ordovician these rocks were deformed during the Ross orogeny and intruded by granitic plutons, the Granite Harbour Intrusives 540–450 Ma (Faure and others, 1979). Subsequent to this, much of Greater Antarctica behaved as a stable shield area, accumulating a Devonian–Triassic platform cover sequence (Beacon Supergroup, Barrett and others, 1972), and undergoing vertical tectonism.

In contrast, the conformable Cambrian–Permian sedimentary succession of the Ellsworth Mountains, within Lesser Antarctica, was deformed during the Permo-Trias Ellsworth orogeny about north-west–south-east trending fold axes (Craddock and others, 1964). The lowest stratigraphic unit is the Heritage Group (Craddock, 1969; Webers and Sporli, 1983). It is a mixed clastic assemblage that contains volcaniclastic conglomerates and lava flows, and was deposited under fluvial, deltaic and shallow marine conditions. The Minaret Formation, overlies the Heritage Group and is composed almost entirely of shallow marine limestone that contains a Middle Cambrian fauna (Webers and Sporli, 1983). The Cambrian sequence is overlain by a 5–6 km thick series of ?Ordovician–Permian strata: the Devonian Crashsite Quartzite, which consists of well-sorted medium- to coarse-grained, thick-bedded quartzite; the Whiteout Conglomerate, a massive dark-grey formation of late Palaeozoic glaciomarine origin; and the Polarstar Formation, which consists of interbedded sandstone-shale sequences that contains some coal beds. It contains Permian *Glossopteris* leaves, the diagnostic fossil of the cover sequence that links different parts of the supercontinent Gondwanaland (Du Toit, 1937).

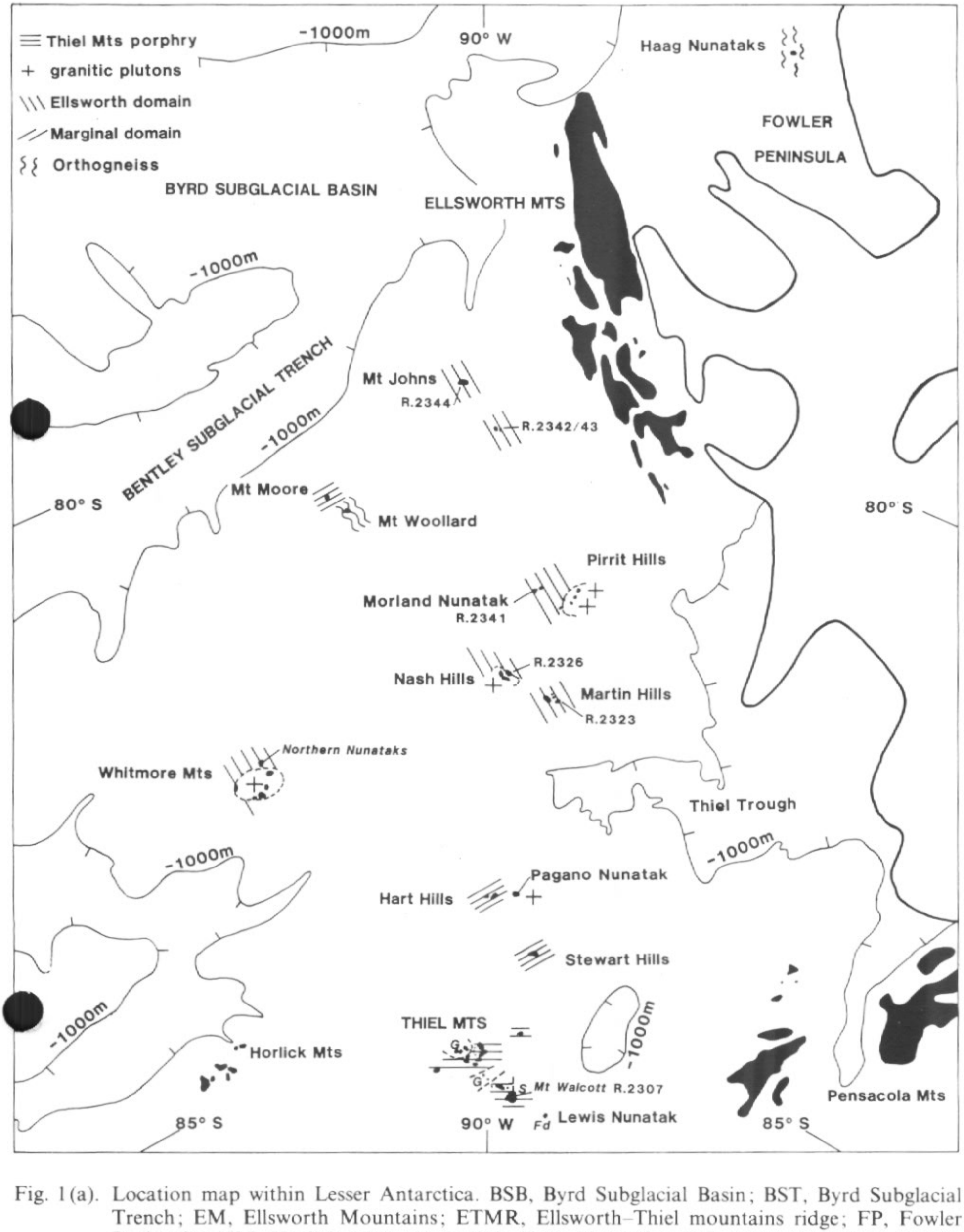

Fig. 1(a). Location map within Lesser Antarctica. BSB, Byrd Subglacial Basin; BST, Byrd Subglacial Trench; EM, Ellsworth Mountains; ETMR, Ellsworth–Thiel mountains ridge; FP, Fowler Peninsula; HM, Horlick Mountains; HN, Haag Nunataks; NG, Nimrod Glacier; QMM, Queen Maud Mountains; SG, Scott Glacier; ShG, Shackleton Glacier; SR, Shackleton Range; TI, Thurston Island; TT, Thiel Trough; TM, Thiel Mountains. (b) Geological sketch map of the Ellsworth–Thiel mountains ridge illustrating the main tectonic provinces.

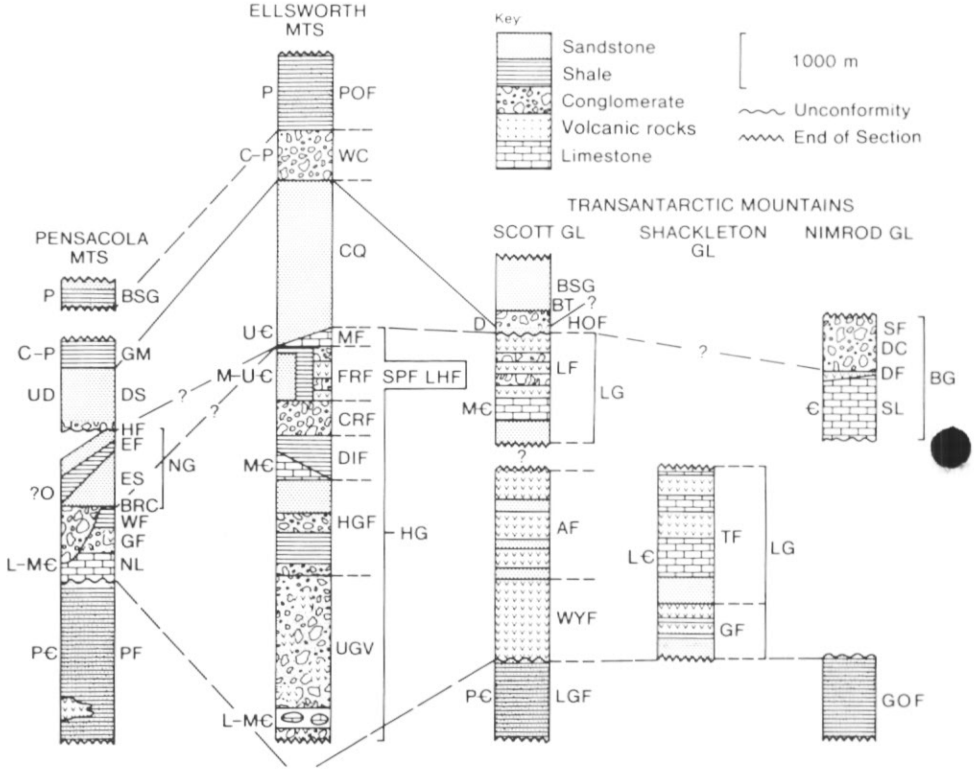

Fig. 2. Correlation chart of representative stratigraphic columns, from Pensacola Mountains (Schmidt and Ford, 1969), Ellsworth Mountains (Craddock, 1969; Webers and Sporli, 1983) and Transantarctic Mountains (Cooper and Grindley, 1982; Stump, 1983; Stump and others, 1986; Rowell and others, 1987). PENSACOLA MOUNTAINS; PF, Patuxent Formation; NL, Nelson Limestone; GF, Gale Formation; WF, Wiens Formation; BRC, Brown Ridge Conglomerate; ES, Elliot Sandstone; EF, Elbow Formation; HF, Heiser Formation; DS, Dover Sandstone; GM, Gale Mudstone; NG, Neptune Group; BSG, Beacon Supergroup. ELLSWORTH MOUNTAINS: UGV, Union Glacier Volcanics; HGF, Hyde Glacier Formation; DIF, Drake Icefall Formation; CRF, Conglomerate Ridge Formation; LHF Liberty Hills Formation; SPF, Springer Peak Formation; FRF, Frazier Ridge Formation; MF, Minaret Formation; HG, Heritage Group; CQ, Crashsite Quartzite; WC, Whiteout Conglomerate; POF, Polarstar Formation. TRANSANTARCTIC MOUNTAINS; LGF, La Gorce Formation; WYF, Wyatt Formation; AF, Ackerman Formation; LF, Leverett Formation; HOF, Horlick Formation; BT, Buckeye Tillite; GF, Greenlee Formation; TF, Taylor Formation; LG, Liv Group; SF, Starshot Formation; GOF, Goldie Formation; SL, Shackleton Limestone; DF, Dick Formation; DC, Douglas Conglomerate; BG, Byrd Group. PЄ, Precambrian; LЄ, Lower Cambrian; MЄ, Middle Cambrian; UЄ Upper Cambrian; O, Ordovician; UD, Upper Devonian; C, Carboniferous; P, Permian.

The Pensacola Mountains (Schmidt and others, 1965, Schmidt and Ford, 1969) lie within the Transantarctic Mountains and have similarities with both Greater and Lesser Antarctica; the late Precambrian Patuxent Formation was folded and deformed during the Beardmore orogeny. Unconformably overlying Cambrian carbonates and silicic volcanics (Nelson Limestone, Gambacorta Formation and Wiens Formation) are correlated with similar successions within the Transantarctic Mountains. They were deformed at the same time as the Ross orogeny and unconformably overlain by the Neptune Group, an Ordovician to Devonian marine transgressive and regressive conglomerate-sandstone sequence. A discontinuity separates the Neptune Group from Devonian to Permian sequences of the Beacon Supergroup. This part of the Beacon Supergroup was deformed during the Weddell orogeny, a correlative of the Ellsworth orogeny.

Ellsworth–Thiel Mountains Ridge

The Thiel Mountains at the southern end of the ETMR (Fig. 1b) contain a flat-lying sequence of sedimentary rocks intruded by a quartz–monzonite porphyry; both units were thought to be of late Precambrian age (Schmidt and Ford, 1969) and may be part of the Transantarctic Mountains province (Storey and Dalziel, in press). The remaining nunataks between the Ellsworth and Thiel mountains (Fig. 1b) are predominantly formed of deformed sedimentary rocks, some of which (Nash Hills, Pirrit Hills, Martin Hills and Whitmore Mountains) are intruded by a consanguinous suite of Middle Jurassic granitic plutons. Pagano Nunatak is entirely formed of granite and large gabbro sills intrude the sedimentary rocks at Hart Hills.

The sedimentary rocks of the ETMR have been correlated with various tectonic units. The boundary between Greater and Lesser Antarctica has been drawn in the narrow gap between the Hart and Stewart hills (Jankowski and others, 1983) and on the north side of the Hart Hills (Craddock, 1983), and Schmidt and Rowley (1986) have postulated a major strike-slip boundary through this zone. Craddock (1983) correlated the Stewart Hills with the Precambrian Patuxent Formation of the Pensacola Mountains. He suggested that the sedimentary rocks of the Nash Hills resemble the Heritage Group, and that the Pirrit Hills and Mount Johns resemble the Crashsite Quartzite of the Ellsworth Mountains. Webers and others (1983) suggested the Hart Hills may be part of either the Ellsworth or an older orogen.

The affinities of part of the Ellsworth Mountains succession with the Beacon Supergroup led Schopf (1969) to suggest that the Ellsworth Mountains were originally part of the Transantarctic Mountains and that they originated within the Weddell Sea embayment.

Storey and Dalziel (in press) have drawn attention to the structural boundary between the undeformed sedimentary rocks of the Thiel Mountains and highly deformed sedimentary rocks of the Stewart Hills, and have incorporated the entire area between the Thiel Mountains and Haag Nunataks within the Ellsworth–Whitmore mountains crustal block (EWM). They divided the crustal block into two structural domains; the Ellsworth and Marginal domains. The sedimentary rocks of the Ellsworth domain were deformed by north-west–south-east trending structures whereas in the Marginal domain the fold history is more complex with trends orientated north-east–south-west. The Marginal domain may be part of the Ellsworth orogen or may contain elements of an earlier orogen.

In the present study, the sedimentary rocks are divided into three major sedimentary units: a volcaniclastic unit, a red sandstone unit and a mixed carbonate-clastic unit. The volcaniclastic unit is only found within the southern part of the Thiel Mountains; the red sandstone unit crops out at Mount Johns, at a series of unnamed nunataks (79° 58′ S, 89° 37′ W) between Mount Johns and the Ellsworth Mountains and at Morland Nunatak, 20 km west of the Pirrit Hills; the mixed carbonate-clastic unit forms the metamorphic aureole in the Nash and Martin hills. The sedimentary rocks of the northern nunataks of the Whitmore Mountains and Lewis Nunatak, on the southern side of the Thiel Mountains are also briefly described. The sedimentary units are compared with the successions within the adjoining tectonic provinces, and the bearing of palaeoenvironmental interpretations on the tectonic history of this part of Lesser Antarctica is discussed.

The sedimentary rocks of the Hart Hills, Stewart Hills, Pirrit Hills, Whitmore Mountains and Mount Moore are not included in this study; the Hart Hills rocks are highly deformed and have been described by Webers and others (1983); the Pirrit Hills and Whitmore Mountains, with the exception of Northern Nunataks, contain scattered, deformed and hornfelsed rafts on the margins of large plutons and both the Stewart Hills and Mount Moore are moderately deformed.

VOLCANICLASTIC UNIT

Stratigraphy

Sedimentary rocks form a minor, but important part of the Thiel Mountains. They crop out in the south-eastern part at Mount Walcott and Mount Wrather (3 km south-west of Mount Walcott). In both sections the sequence is dominated by volcaniclastic sandstone, pebbly sandstone and siltstone, with subordinate mudstone and rare breccia and limestone.

The two outcrops are considered to be separate exposures of a single sedimentary unit, here formally defined as the *Mount Walcott Formation* (MWF). The type section is on the east face of Mount Walcott (R.2307), where there is a well-exposed section 100 m thick (Fig. 3).

Fig. 3. Mount Walcott, type locality of the Mount Walcott Formation, Thiel Mountains (locality R.2307). The sedimentary section is about 100 m thick.

At both localities the formation is faulted against the porphyry of the Thiel Mountains. A dacite sill is intruded into the lower part of the sedimentary section on Mount Walcott and the top of the accessible section is marked by a thick porphyry intrusion. These are most likely part of the same magmatic episode as the Thiel Mountains porphyry. However, at the base of the Mount Walcott section a thick

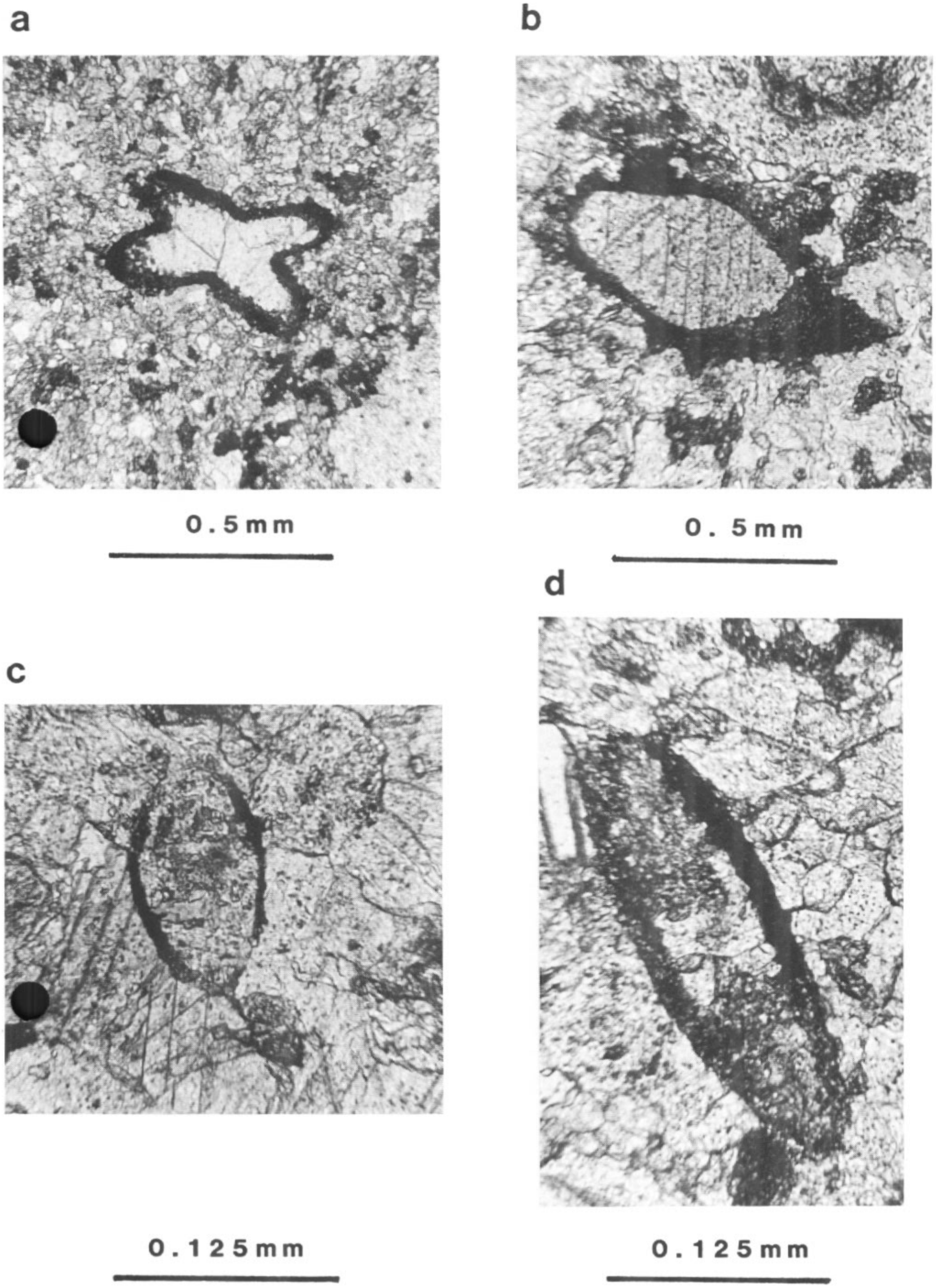

Fig. 4. Fossils within a limestone (R.2307.4) of the Mount Walcott Formation. (*a*) Possible sponge spicule. (*b*) Fragment of an echinoderm plate. (*c*) and (*d*) Unknown organic structures.

brecciated porphyry lava is interbedded with the sedimentary rocks, and the large amount of fresh detrital volcanic material within the volcaniclastic sandstone suggests that the MWF is coeval with the Thiel Mountains porphyry.

Radiometric dating from the Thiel Mountains porphyry (670–530 Ma, Ford and others, 1963; Aaron and Ford, 1964; Faure and others, 1979) led previous workers (Schmidt and Ford, 1969; Craddock, 1983) to consider the sedimentary rocks to be of Precambrian age, but it is clear from several lines of evidence that they are Phanerozoic.

(i) In specimen R.2307.4 from Mount Walcott there are abundant fragments of echinoderm plates.

(ii) In the same specimen there are a number of enigmatic structures 0.1–0.2 mm in diameter. They consist of a coarsely crystalline (or even single crystal) core with a very thin marginal zone of either clear or finely crystalline epidotised calcite. They are commonly circular or oval, with some elongate ovals up to 0.5 mm, but there is a variety of other shapes: lozenge and heart shapes are common (Fig. 4). The variety of shapes is probably the result of different sections through some tubular fossil which changes form along its length. Although undoubtedly organic, their origin and affinity is uncertain (S. Conway Morris, pers. comm.). A single cruciform structure (Fig. 4) resembles the sponge spicule *Protospongia fenestrata* described from the Cambrian Nelson Limestone by Tröger and Weber (1985).

(iii) Specimen R.2311.1 contains a cluster of small siltstone-filled oval burrows, possibly representing the ichnogenus *Chondrites*.

(iv) A loose block from the scree below Mount Walcott contained a simple tubular burrow of the ichnogenus *Planolites*.

(v) New Rb-Sr radiometric dating of the Thiel Mountains porphyry, although not conclusive, suggests an age close to 500 Ma (R. J. Pankhurst, pers. comm.). This is considerably younger than previous estimates of the age of the porphyry and the age range (600–530 Ma) of the Cambrian–Precambrian boundary (Cowie and Johnson, 1985; Odin and others, 1985) and confirms a Cambrian age for the porphyry and sedimentary rocks.

Lithology

The *sandstones* are predominantly volcanic lithic arenites which display a complete spectrum of sandstone grain sizes, although medium-coarse grades are most common. Most are packstones, and moderately-sorted. Quartz, often embayed, forms 30–40% of most sandstones and is of volcanic origin. Lithic clasts form 40–60% and include a variety of volcanic rock types, principally felsite and quartz-andesite; some felsite clasts include deeply embayed or very well-rounded quartz phenocrysts. Minor amounts of highly altered more angular alkali and plagioclase feldspar make up the balance of the clast population. Trace quantities of detrital sphene, zoisite, tourmaline, zircon and magnetite are also present in some samples.

Pebbly sandstones and *siltstones* contain a similar range of clast types to the sandstones.

Mudstones form a small part of the succession. They are very dark grey to black shales, and are chertified in places.

Volcaniclastic *breccia* is only found at the base of the section at Mount Walcott. It is a quartz feldspar porphyry with a rhyolitic matrix showing flow lamination and felted texture. Quartz phenocrysts are partially resorbed, feldspars are altered to sericite and calcite with some chlorite, and original ?glassy material is now all chlorite.

Limestone is rare in the succession but, where present, forms distinctive pale bands.

Most limestones are highly impure, interbedded with calcareous siltstone or very fine sandstone on a cm scale. Limestones are almost entirely formed of sugary-textured ferroan calcite with little hint of previous textures, though in one sample there is, as previously described, a variety of bioclasts.

Facies association

The section at station R.2307 on Mount Walcott falls neatly into five units which are also distinct facies associations. These are described and discussed from base to top of the section.

Unit 1 (7 m thick) consists of brecciated porphyry with clasts up to 20 cm in diameter set in a matrix of very coarse sand to granule grade volcaniclastic arenite. Much of the unit is a product of *in situ* brecciation but there are areas where there seems to be a crudely-developed cross bedding, suggesting that some of the material has been transported. It is conformably overlain by Unit 2.

Unit 2 (7 m thick) comprises cross-bedded volcaniclastic sandstones which vary from medium–very coarse sand grade. Most cross strata are in tabular sets 10–50 cm thick, arranged in cosets up to 1.5 m thick. Interbedded with these are sets of parallel-laminated sandstone, or of low-angle lamination. Sorting is relatively good in this unit.

The junction with the overlying Unit 3 is obscured by a 15 m thick dacite intrusion.

Unit 3 (10 m thick) consists of thin-bedded sandstone, interbedded with subordinate silty mudstones. Limestone beds occur within this unit. Bases of sandstone beds are sharp and flat while tops are sharp and generally slightly undulating. Sandstone beds are 5–15 cm thick and either plane or cross-laminated. Cross laminae occur in sets 3–5 cm thick, mostly with a trough-like form. There are round-topped symmetrical ripples at the top of some beds; ripples are mostly discordant with the internal lamination but in a very few beds there are 0.5–1 cm thick sand drapes concordant with the ripple forms. A detached slump fold nose was found within a 7 cm mudstone, which is slightly thicker than most fine intervals in this unit. The boundary with the overlying unit is transitional, and the facies of Unit 3 persists into the overlying association.

Unit 4 (55 m thick) comprises thick-bedded sandstones, pebbly sandstones and conglomerates (which only occur as lenses within pebbly sandstones). Beds are tabular, with sharp, occasionally slightly erosive bases and sharp flat-undulating tops. Thicknesses vary from 60 cm to 1.5 m, and bed amalgamation is common. Pure sandstone beds are generally thinner than pebbly sandstones; sandstone beds are either structureless or normally graded, while pebbly beds are inverse–normally graded. The contact with Unit 5 is abrupt.

Unit 5 (5 m thick) is dominated by dark silty mudstone with thin silty sandstone beds and abundant carbonate concretions. Mudstone beds are structureless. Sandstones are 1–5 cm thick, structureless or slightly graded.

The section on Mount Wrather is shorter and less well-exposed. Although the facies are broadly comparable to those seen on Mount Walcott a detailed correlation of the section is not possible. Two associations are recorded:

(i) There is a 10 m thick unit of parallel-laminated sandstone with occasional cross-lamination. This could be a mud-deficient form of Unit 3, or an expansion of the type of parallel lamination found in the cross-bedded Unit 2.

(ii) Several units comprise 2–5 cm thick symmetrical ripple sets showing vertical up-building.

Environmental interpretation

The section on Mount Walcott clearly represents a deepening event. The *in situ* brecciation of the porphyry of Unit 1, coupled with the evidence of later transport of some material implies formation at a shoreline. The flow broke up on entering the water, and suffered some later reworking. The well-sorted cross-bedded and parallel laminated sands that form Unit 2 are tractional deposits, in a high energy environment. They resemble the facies recorded from shoreface settings, either on a barrier island, a beach or in nearshore bars (Reinson, 1985).

Unit 3 was clearly deposited within wavebase, in a setting where there was episodic sand sedimentation by erosive decelerating flows. It most likely represents a shelf area with periodic incursions of sand from storm-induced flows. This is the only unit with unequivocal evidence of deposition in a marine setting. Unit 4 contains a variety of mass-flow deposits, principally structureless and graded sandstones and inverse to normally graded pebbly sandstones. These can all be referred to deposition from high-density turbidity currents (Lowe, 1982). The position of this unit immediately overlying the shelf sandstones of Unit 3, is problematical. They could either [illegible] deposited in a shelf setting by flows generated up slope, probably on land, or represent deposition in a small slope fan after rapid foundering of a shelf area.

The mudstones and thin sandstones of Unit 5 would then represent either an outer shelf or base of slope deposit.

However one interprets Units 4 and 5, it is clear that the Mount Walcott Formation is the product of the inundation of a volcanically active land area. Relative sea level was rising and there was coeval volcanicity.

Regional correlation

Felsic and mafic volcanic and hypabyssal igneous rocks of late Precambrian and early Palaeozoic age are widespread throughout this part of Antarctica (Fig. 2) and are reviewed for correlative purposes. In the upper Precambrian Patuxent Formation of the Pensacola Mountains there are mafic pillow lavas, basaltic flows, diabase and felsic sills dated at 809 ± 38 (Gorecki rhyolite) (Faure and others, 1979) and 784 ± 55 (diabase sill). In the central part of the Transantarctic Mountains a massive silicic porphyry (Wyatt Formation) and associated interbedded shallow marine sediments and pyroclastic breccias (Ackerman Formation), several thousand metres thick (Stump, 1983), are considered Precambrian (633 ± 13, Faure and others, 1979). Cambrian ages from the Wyatt Formation (543 ± 47) are interpreted as equilibrati[illegible] ages during the Ross orogeny (Faure and others, 1979; Stump and others, 1986).

The Union Glacier Volcanics at the base of the Heritage Group of the Ellsworth Mountains, contain limestone clasts of early to middle Cambrian age and are a 3000 m succession of basaltic volcanic diamictite with volcanic bombs and flattened pumice clasts (Webers and Sporli, 1983). A geochemical analysis of some igneous rocks described as pre-Middle Cambrian by Hjelle and others (1982) may be correlatives of the Union Glacier Volcanics and are continental tholeiites and Na- and K-alkaline rocks characteristic of a block-faulting regime. In the Queen Maud Mountains the upper part of the Middle Cambrian Leverett Formation consists of over 1000 m of interbedded rhyolite and conglomeratic sandstone (Laird and Bradshaw, 1982). The Gambacorta Formation of the Pensacola Mountains overlies the Middle Cambrian Nelson Limestone. It consists of 0–1000 m of red brown and light green rhyolitic flows, volcanic breccias, tuffs and volcaniclastic sandstone and conglomerate (Schmidt and Ford, 1969).

Volcanism persisted into the late Cambrian in the Ellsworth Mountains where the Liberty Hills Formation represents localized basaltic volcanism with 1000 m of basaltic lavas and associated sedimentary rocks (Webers and Sporli, 1983). On the basis of a geochemical analysis, the basalts are considered to be continental within plate basalts emplaced in an extensional environment (Vennum and others, in press).

The Thiel Mountains porphyry is petrographically and geochemically similar to the late Proterozoic porphyry of the Wyatt Formation. However, the discovery of the echinoderm plates and possible sponge spicules, and the new radiometric dating of the Thiel Mountains porphyry indicates a Cambrian age for the MWF and the coeval porphyry. Consequently the Cambrian ages obtained both from the porphyry of the Thiel Mountains and the Wyatt Formation may be crystallization ages and not, as previously interpreted, reset ages. The porphyry may represent, together with the Ackerman Formation, an episode of peraluminous volcanism and a contemporaneous marine transgressive sequence bordering a zone of Cambrian crustal extension. The Union Glacier Volcanics within the Ellsworth Mountains are likely to represent associated volcanism within the axial zone undergoing extension.

RED SANDSTONE UNIT

Stratigraphy

Red sandstones and mudstones of a red sandstone unit crop out at Mount Johns, at a series of small unnamed nunataks nearby, and at Morland Nunatak (Fig. 1b) 150 km farther south. These are considered to be separate exposures of a single sedimentary unit, here formally defined as the Mount Johns Formation (MJF). The type section of this formation is on the north face of Mount Johns (locality R.2344) where there is partial exposure of a 120 m thick section, with the lowest 40 m well-

Fig. 5. Mount Johns, type locality of the Mount Johns Formation (R.2344). The lowest part of the section is about 40 m thick.

exposed and easily accessible (Fig. 5). At localities R.2342 and R.2343 the exposure is poor and no long sections are measurable, but at Morland Nunataks (R.2341) there is a continuous section of 50 m. Neither base nor top of the formation is exposed and there is no information on its relationships with any other rock unit.

Lithology

The major lithology is sandstone, varying from very fine to medium grain-size in a variety of colours: pale grey, greenish grey, reddish brown, pink and red. There are minor associated red mudstones and reddish brown and red siltstones. Some of the grey and green sandstones have a mottling of reddish brown, and all contain intraclasts of red mudstone; red sandstones commonly display green reduction spots.

The sandstones are composed of very well sorted, subangular grains of quartz with subordinate feldspar (dominantly plagioclase with some alkali feldspars) and muscovite. Grains are coated by a thin layer of clay with disseminated haematite. Texturally the sandstones are either grainstones, cemented by irregular plates of calcite which appear to have corroded margins, or packstones with a sericitized matrix.

There is no discernible variation in the petrography between any of the localities and in a cathodoluminescence study sandstones from Mount Johns and Morland Nunatak showed identical patterns of quartz luminescence.

Facies

In both the Mount Johns and Morland Nunatak sections the rocks are well-bedded on a scale of 50 cm–2 m with beds laterally persistent across the width of the exposure (*c*. 120 m in the case of Mount Johns).

There are seven major facies (A–G) in two facies associations. Five of these facies (A–E) are found at all localities while F and G are only found at Morland Nunatak.

Facies A comprises tabular cross-bedded sandstone in individual sets 0.3–2 m thick. Sets are either solitary, with laminated sand above and below or occur as cosets with at most two other sets. Foresets are planar-tabular, commonly enhanced by trains of small irregular mudstone intraclasts.

Facies B is formed of trough cross-bedded sandstone with individual sets 30–40 cm thick. Sets are rarely solitary and are commonly found as cosets up to 1 m thick. This facies either occurs above, and transitional from, massive units, or is bounded above and below by parallel laminated sandstone.

Facies C, parallel-laminated sandstone, occurs in units 0.1–2 m thick and commonly contains tabular intraclasts of red mudstone up to 5 cm thick by 10 cm long. The style of lamination is highly variable, from sharply defined laminae 1–5 mm thick to an interlamination of fine and very fine sandstone on a scale of 1–3 cm. There are rare massive units up to 15 cm thick scattered throughout the laminated units.

Facies D units are massive sandstone beds with slightly erosive bases (basal erosion of 15 cm was recorded in one instance). Beds are 30–60 cm thick and tend to have sharp flat tops. Internally, beds are structureless or display an irregular wispy lamination; they can pass upwards either into trough cross-bedded sandstone of Facies C or into a crude parallel lamination.

Facies E comprises very thin rippled layers of very fine sandstone or siltstone on the upper surface of units of other facies. The ripples are preserved as form sets, never more than 1 cm thick; they are symmetrical with slightly rounded crests and in plan they are straight-crested with rare tuning-fork junctions. Ripple height varies from 0.5–1 cm and spacing is 1–2 cm (ripple index 1–4). In some cases there are weaklydeveloped ladder ripples running across the troughs. Internally the ripples show dominant transport in one direction with an even drape of siltstone 0.5–1 mm thick mantling the whole ripple topography.

Facies F, red mudstone with cross laminated very fine sandstone, is only present *in situ* at Morland Nunatak but is found as intraclasts in the other areas. Facies units can be up to 2 m thick and consist in roughly equal proportions of structureless deep red mudstone and paler siltstone and very fine sandstone, interbedded on a scale of 1–10 cm. The coarser units are sharp-based and completely cross-laminated throughout. Sandstone and siltstone also occur as infills in desiccation cracks which cut through the mudstone units. This facies is overlain either by the massive sandstones of Facies D or by Facies G; it can overlie any other facies.

Facies G is characterized by units of cobble-grade mudstone intraclasts that overlie erosion surfaces. The intraclast horizons are no more than 15 cm thick and the erosion surfaces tend to be subhorizontal, with a maximum relief of 20–30 cm. Intraclasts are supported in a matrix of medium sandstone which passes upwards into structured sandstone of one of Facies A–C. At one locality the erosion surface is directly into Facies F mudstones and it is clear that the size of the intraclasts is controlled by the vertical thickness of the mudstone layer and the spacing of desiccation cracks.

Facies A–D form a single sandstone-rich facies association, representing the dominant style of sedimentation. A second, fine grained association is represented by the mudstones of Facies F and the intraclasts present in most other facies. Although the rippled very fine sandstones and siltstones of Facies E are associated with Facies A–D, and as such should probably be counted with the sandstone association, their finer grain size and rippled structure point to a similar genesis to Facies F.

Environmental interpretation

Any interpretation of the environment of deposition of the MJF is hampered by the small scattered nature of the exposure and the lack of a proper lithofacies log. However, a reasonably detailed interpretation can be made on the basis of the information available. Firstly, it is clear that the whole formation has been red-coloured in the past and the grey and green sandstones merely represent reduction of red sandstones along zones of high permeability. The red colour and total lack of fossils imply deposition in a continental environment.

Within this context the seven facies are amenable to a process interpretation (Table I) and fit well into the standard lithofacies scheme for fluvial sediments proposed by Miall (1978). Recently Miall (1985) suggested a system of *architectural element analysis*, fitting standard lithofacies into eight major elements of fluvial systems (equivalent to facies associations). These eight elements can be combined in a variety of ways to allow precise description of any ancient fluvial system. In the MJF most rocks belong to Miall's Sandy Bedform (SB) Element (our Sandstone Association), perhaps interbedded with minor amounts of Elements LS (laminated sandsheets) and SG (sediment gravity flows). Minor amounts of Element OF (overbank fines) were deposited, but these were extremely susceptible to later erosion. The main morphology is sheet-like and there are no obvious large-scale channels or lateral accretion surfaces.

The evidence suggests that deposition was in essentially unchannelized flows dominated by sandy bedforms with rare overbank deposits, typical of distal ephemeral braid plains (Williams, 1971; Miall and Gibling, 1978). The presence of sediment gravity flow deposits suggests that the environment could have been a sheet flood alluvial plain subject to highly flashy discharge (Miall, 1985) or the distal portion of an alluvial fan (Bull, 1972; Collinson, 1978), where similar facies can accumulate

Table I. Process interpretation of the seven facies of the Mt Johns Formation and the equivalent facies in the standard scheme of Miall (1978)

Facies	*Description*	*Equivalent facies of Miall* (1978)	*Depositional process*
A	Planar cross bedded sandstone	Sp	Tractional deposits of transverse bars or sandwaves. Lower flow regime.
B	Trough cross bedded sandstone	St	Tractional deposits of subaqueous dunes. Lower flow regime.
C	Parallel-laminated sandstone	Sh	Planar bed flow in either the upper or lower flow regimes.
D	Massive sandstone	No equivalent	Deposits of sandy debris flows or sheet floods. Miall's closest equivalent is Facies Gms.
E	Rippled very fine sandstone	Sr or Fl	Wind-driven wave ripples in very shallow pools.
F	Mudstone and cross-laminated sandstone	Fl or Fm	Overbank deposits: mudstones deposited from suspension with periodic desiccation, sandstones represent waning flood deposits.
G	Erosion surface with intraclasts	Se	Scour fill.

(McGowen and Groat, 1971). The lack of any rudaceous material is surprising and could imply that the MJF was of great lateral extent with conglomeratic material trapped nearer source.

Regional correlation

All of the Cambrian sections within bordering successions (Fig. 2) contain red bed units representing a possible Middle Cambrian regression. The Hyde Glacier Formation of the Heritage Group in the Ellsworth Mountains includes a 280 m thick unit of red and buff polymict conglomerate and quartzite with large-scale channels (Webers and Sporli, 1983). There are also terrestrial intervals within the Union Glacier Volcanics at the base of the Heritage Group, where there is a 390 m thick fluvial conglomerate with clasts of grey Lower–Middle Cambrian limestone (Webers and Sporli, 1983), and in the Middle–Upper Cambrian Springer Peak Formation at the top of the Heritage Group. The fluvial sedimentary rocks of the Springer Peak Formation are also associated with volcanics.

In the Queen Maud Mountains there is a 300 m thick sequence of red cross-bedded sandstone, overlain by 100 m of red pebbly mudstone at the base of the Middle Cambrian Leverett Formation (Laird and Bradshaw, 1982).

The situation is more complex in the Pensacola Mountains where there are three possible correlatives of the MJF within the Lower Palaeozoic succession. At the base of the Lower–Middle Cambrian Nelson Limestone there is a 26 m thick red sandstone and conglomerate member; the Wiens Formation, which occurs higher in the same conformable succession, comprises 300 m of dark green and red brown shale, siltstone, and very fine sandstone of presumed middle–late Cambrian age (Schmidt and Ford, 1969). The third possibility is the 1–2 km thick Neptune Group which consists of a thick terrestrial sequence probably representing proximal alluvial fan-coastal plain environments. This sequence is of unknown age and rests with pronounced unconformity on the ?Cambrian Nelson, Gambacorta and Wiens formations (Schmidt and others, 1965).

There are also possible correlatives higher in the succession, above the mid-Palaeozoic unconformity. In the Queen Maud Mountains, there is a thin red sandstone unit (Horlick Formation) of Devonian age, while in both the Ellsworth Mountains (Crashsite Quartzite) and Pensacola Mountains (Dover Formation) there are thick sequences of cross-bedded sandstone of presumed Devonian age, albeit not red and of unknown depositional environment.

The final possible correlation is with the rocks of the Beacon Supergroup (of the Queen Maud and Pensacola mountains) or the equivalent Polarstar Formation of the Ellsworth Mountains. All these rocks are of Permian age, and have been interpreted as fluvial-deltaic deposits (Barrett and others, 1972; Collinson and others, in press). However they are not red, all contain plant fossils and far more fine material than the MJF. In a recent paper Barrett and Fitzgerald (1985) suggested that fluvial facies rocks of the Ohio Range (eastern Queen Maud Mountains) represented the upper part of a Permian drainage basin feeding deltas in the Ellsworth Mountains area. This would imply Permian drainage over the whole Mount Johns area and a Permian age for the MJF must remain an outside possibility.

[illegible] conclusion the MJF, which represents the deposits of braided, probably ephemeral streams or distal alluvial fans, most likely correlates with Middle Cambrian red beds of the Hyde Glacier Formation (Ellsworth Mountains), Leverett Formation (Queen Maud Mountains) and the Wiens Formation or Neptune Group (Pensacola Mountains). It may represent a widespread regression some time in the middle of the Cambrian. It could also be correlated with Devonian or Permian clastic sediments in the region, but this is considered less likely.

MIXED CARBONATE-CLASTIC UNIT

Stratigraphy

A distinctive association of limestone, sandy limestone, calcareous sandstone and argillite crops out in the Nash and Martin hills. In both areas the succession consists of pale carbonate-rich units, tens of metres thick, interbedded with thicker, dark, dominantly siliciclastic units.

The rocks of both areas are identical in facies and mineralogy and are considered to be a single formation, here formally named the *Nash Hills Formation* (NHF). The type section, 350–400 m thick (Fig. 6) of this formation is at station R.2326 on the northern side of the Nash Hills. Neither base nor top of the formation is exposed and it is not in contact with any other sedimentary unit. In the Martin Hills about 300 m of hornfelsed strata are exposed and intruded by undated felsite dykes and a small rhyodacite plug. In the Nash Hills there are a number of isolated hornfelsed exposures of sedimentary rocks around the northern and western sides of a large Middle Jurassic granite pluton (Millar and Pankhurst, in press). The presence of echinoderm and shell fragments and of trace fossils implies a Phanerozoic age.

Lithology

There are 5 main lithologies within the mixed carbonate-clastic unit:

1. *Dark argillite* is a minor but significant constituent of the unit. It is black, very dark grey and dark olive mudstone and calcareous mudstone that comprises silt-grade quartz and detrital muscovite set in a matrix of epidote and clay. Calcite is occasionally present as small clots and stringers; in some samples calcite is possibly dispersed throughout the matrix.
2. Dark-weathering grey and green *calcareous sandstones and siltstones* form 30–

Fig. 6. Nash Hills, type locality of the Nash Hills Formation (locality R.2326) illustrating the cyclic mixed carbonate-clastic unit, intruded by Middle Jurassic granite on left.

40% of the unit. They are mainly coarse silt or very fine sand grade aggregates of quartz with subordinate feldspar and abundant chloritized mica. Grains are sutured and grain margins appear strongly corroded. Residual porosity is filled with coarsely crystalline ferroan calcite and epidote. In some samples the calcite is absent.

3. The commonest lithology comprises highly *calcareous sandstone and sandy limestone* interbedded on a scale of 1–3 cm. This rock type is very distinctive and presents an unusual appearance in the field, with stripes of interbanded brown-weathering calcareous sandstone and grey limestone. The sandy limestone comprises very fine sand grade quartz grains and stubby laths of muscovite floating in a coarsely crystalline carbonate matrix. The carbonate is ferroan calcite and although it is crystalline in irregular plates up to 0.2 mm across, there are abundant circular patc[illegible] of the same order of size of slightly finer-grained ferroan calcite, generally with very fine-grained margins; these are probably recrystallized ooids. Ragged-margined plates of echinoderm detritus are also common, and there are rare, recrystallized shells. The calcareous sandstone consists of very fine sand to coarse silt grade quartz grains and plates of muscovite in a packstone texture with recrystallized clay matrix. Dispersed throughout are areas of ferroan calcite up to 0.1 mm across, that are commonly crudely lozenge-shaped. These could be pseudomorphs after dolomite. The bands are very difficult to distinguish in thin section, and are only brought out by staining with Alizarin Red-S and Potassium Ferricyanide (Dickson, 1966). Cathodoluminescence also enhances the distinction, with all the ferroan carbonate luminescing dull orange except the margins of allochems which show a brighter yellow-orange colour. This outer band corresponds to a very thin rim on the allochems which does not take up either stain and may be dolomite. Both staining and cathodo-

Fig. 7. Flat-pebble conglomerate within the Nash Hills Formation. A pencil is shown for scale.

luminescence show that the boundaries between the two lithologies are no more than 2 grain diameters.

Some of the grey limestone bands display thin orthogonal cracks infilled by the darker material suggesting that the limestone underwent earlier diagenesis than the calcareous sandstone.

4. *Flat-pebble conglomerate* is a very minor constituent but is unusual enough to warrant special mention (Fig. 7). It comprises subangular cuboidal clasts of light grey sandy limestone set in a matrix of darker calcareous sandstone. Clasts vary from 0.5 cm to 25 cm long and can be up to 15 cm thick. In general their long axes lie parallel to bedding although some of the smaller clasts are in more random orientations. The two constituents of the flat-pebble conglomerate are remarkably similar to the two lithologies in the banded sandy limestone: they are clasts of quartzose bio-oosparite in a matrix of calcareous silty sandstone. This also suggests early cementation of the limestone.

5. Pure *limestone* is a minor constituent of the unit, comprising no more than 10% overall. Most of the limestones are oolitic or pisolitic with trace quantities of shell and echinoderm material; allochems are set in a coarse clear spar. There are rare dispersed clasts of silt-grade quartz and occasional thin laminae of recrystallized micrite, but most of the rocks can be classified as oosparites. The ooids and pisoliths vary from 0.5 to 3 mm in diameter and are obviously recrystallized. Most of these consist of only 4–5 large irregular calcite crystals, with a darker rim of fine-grained calcite which probably reflects the former presence of a micritic envelope. This coating luminesces brighter than the uniform dull orange of the rest of the rock, a similar pattern to that found in the sandy limestones. Staining reveals that while the whole rock comprises ferroan calcite, the allochems are less iron-rich than the cement.

Facies association

Although no detailed sections were measured, four major associations have been identified. These correspond broadly to the lithologies identified above and are organized in cycles.

Association A comprises structureless mudstone with subordinate thin beds of sandstone and calcareous sandstone (some containing ooids). These beds are 5–15 cm thick and are graded, or, more rarely, graded and horizontally laminated. Bed bases are commonly load-cast, and in some cases the beds are merely represented by discrete load balls or pseudonodules (Fig. 8). Small carbonate concretions occur within the sandstone beds. There are rare trace fossils comprising irregularly undulose subcylindrical unbranched burrows with a fill only slightly coarser-grained than the host sediment. These are referable to the ichnogenus *Palaeophycus* and resemble the form ?*P. tubularis* (Pemberton and Frey, 1982).

The association represents sedimentation of clastic material from suspension with minor inputs of coarser clastic and carbonate material as small mass flows. These flows could either be gravity or storm generated.

Association B consists of massive-bedded greenish sandstone, calcareous sandstone and siltstone interbedded with rare, thin mudstone beds. Individual sandstone beds have sharp, flat bases and tops and may reach 1 m in thickness; they are commonly structureless or faintly parallel-laminated. Mudstone beds are structureless and generally only 5–15 cm thick. Mudstone is also present as clusters of intraclasts within sandstone, forming lensoid bodies from a few tens of cm to 1 m wide and up to 30 cm thick. The sandstone and siltstone commonly have small irregular nodules of grey carbonate. Some beds are rather more clearly structured and show sharp scoured bases with overlying graded divisions passing upwards into undulating parallel lamination, slumps or convolute lamination. In one such case in the Martin Hills the base of the bed is erosive into the slumped top of an underlying bed.

It is likely that much of this association was deposited by erosive-based episodic flows. The massive appearance is probably due to bed amalgamation. It is not clear whether the flows were gravity- or storm-driven.

Association C is formed of cross-bedded calcareous sandstone and sandy limestone with subordinate units of flat-pebble conglomerate and thin interbeds of mudstone. The cross strata have an unusual and distinctive striped appearance due to the interlamination of sandy limestone and calcareous sandstone (Fig. 9). Cross set thickness varies from 30 cm to 1 m. Coset thicknesses can be as much as 10–20 m although 5 m is more typical and there appears to be a hierarchy within cosets with smaller, more obviously trough-shaped sets overlying larger, tabular sets. There are also subordinate beds of flat-laminated striped limestone and structureless calcareous sandstone, some with straight-crested symmetrical ripples, with a spacing of roughly 2 cm, on their top surfaces. The flat-pebble conglomerate beds are 20–30 cm thick, erosive-based and appear graded (Fig. 7). Intraclasts occur both in lensoid, presumably channelled, units and in beds separating sets of cross-strata (Fig. 10). Mudstone interbeds tend to be quite thin, only a few tens of cm. There are thicker mudstone units which resemble Association A, except that they contain both flat-pebble conglomerate beds and isolated cross-stratified beds of sandy limestone. Rare hummocky cross-stratified beds are found throughout the association.

The main part of this association was deposited in a migrating sandwave and dune field in a shallow marine environment. The mixture of siliciclastic grains and ooids suggest that the area was open to both clastic and carbonate supply. Fine-grained sediments and early lithified carbonate-rich sands provided material for various types

Fig. 8. Load structures within the Nash Hills Formation. The hammer handle is 60 cm long.

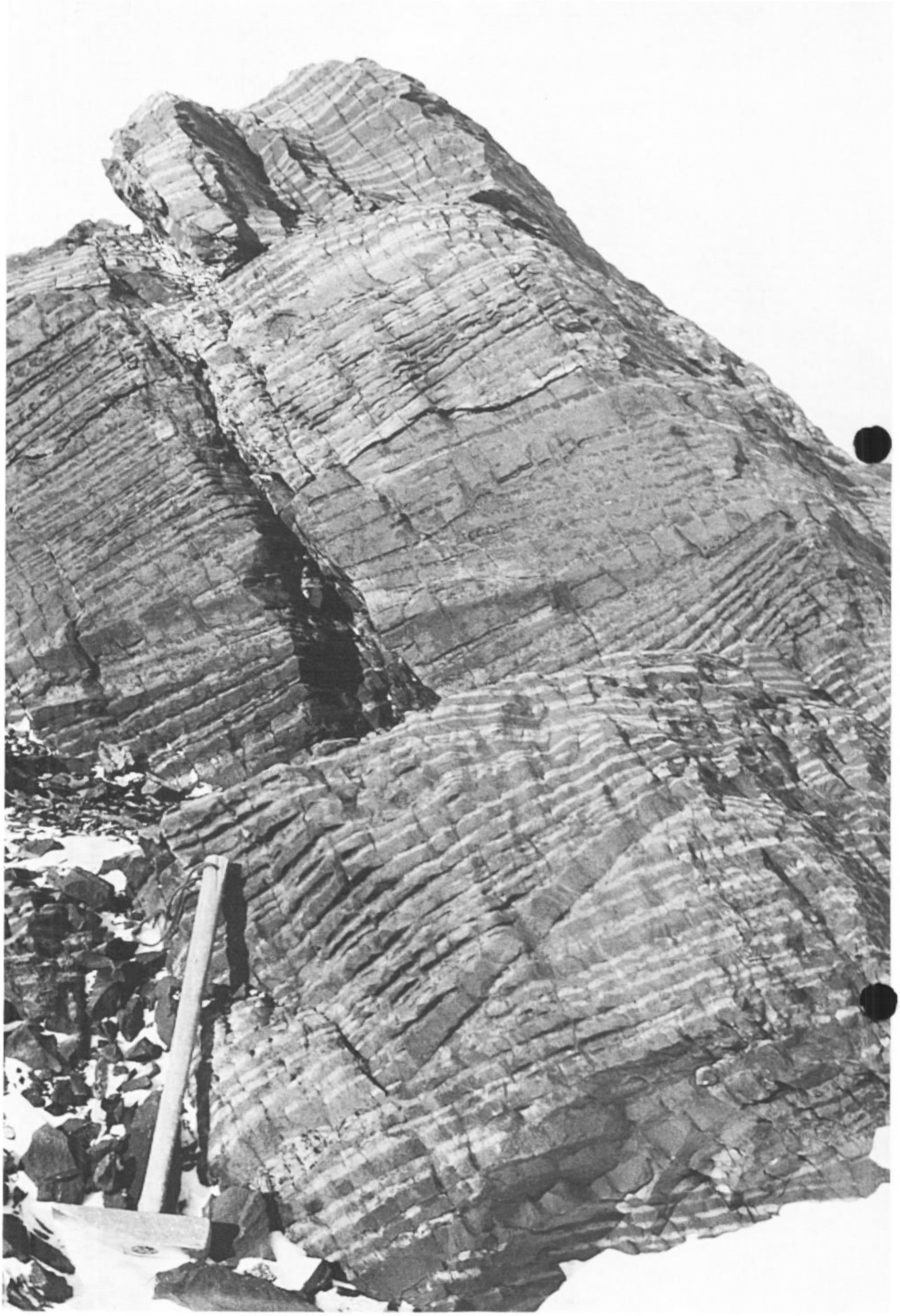

Fig. 9. Cross-bedded calcareous sandstone and sandy limestone of the Nash Hills Formation. The hammer handle is 60 cm long.

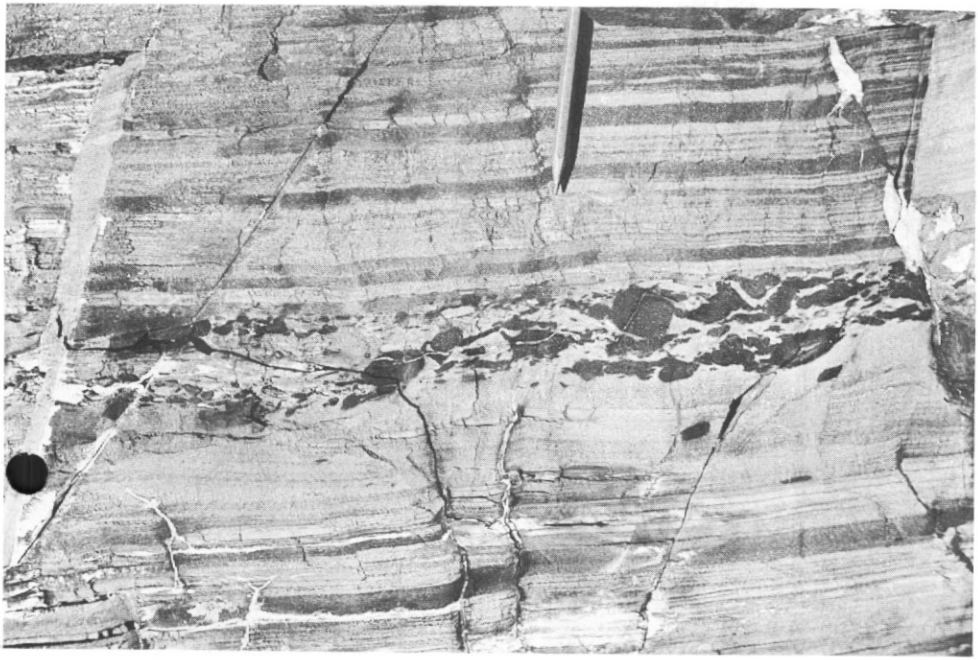

Fig. 10. Mudstone intraclasts within the Nash Hills Formation.

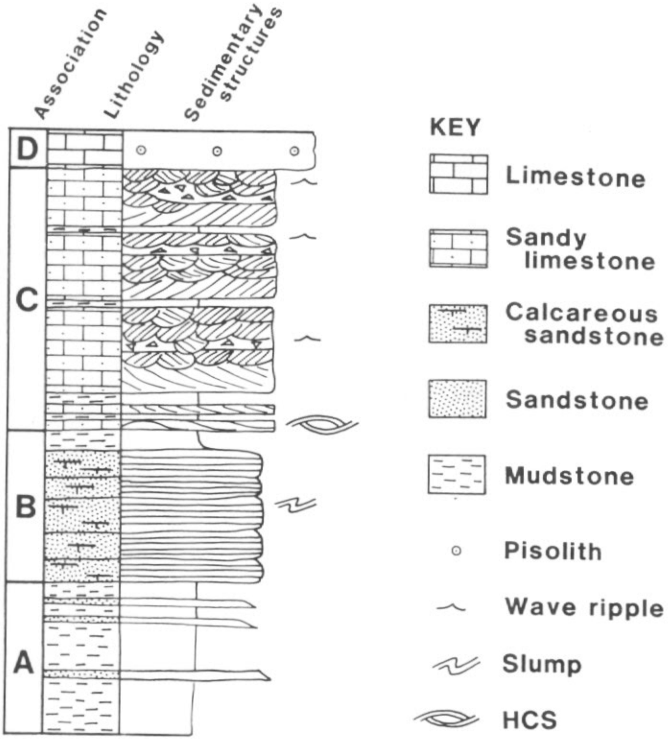

Fig. 11. Idealized clastic-carbonate cycle of the Nash Hills Formation. Such cycles can vary from 50–130 m thick.

of intraclastic deposit which were probably due to very high-energy erosional currents. Mudstone-rich parts of the association, where there are discrete sets of cross strata probably represent areas marginal to the main dune field (cf. Anderton, 1976; Johnson, 1978). The presence of wave ripples suggest that at least parts of the association were deposited in water of only a few metres depth, while the hummocky cross stratification implies periodic reworking by storm waves.

Association D comprises pure oolitic and pisolitic grainstones. These occur in structureless beds up to 4 m thick. Since rocks of this facies seem to be more prone to deformation than the more siliciclastic lithologies, it is possible that any sedimentary structures have been obscured. Despite the lack of internal structure, it is possible that this association represents an ooid shoal.

Facies organization. The four associations are organized into dramatic coarsening and cleaning-upward cycles (Fig. 11). Only at the base of each cycle is there pure clastic material, and only at the top, pure carbonate. The boundaries between each association are gradational but cycles have very sharp tops. In the type section in the Nash Hills cycles are up to 130 m thick, with the coarse clastic part (Associations B, C and D) varying from 50–70 m. In the Martin Hills the basal mudstones of Association A are only 3–5 m thick and the coarse clastic part of the cycle is 50–60 m.

Environmental interpretation

There is comparatively little work on the interpretation of mixed carbonate-clastic units. Generally the onset of clastic deposition inhibits carbonate production and deposition (Mount, 1984; McCave, 1985). Most of the literature concerning mixed carbonate–clastic deposits deals with very large-scale associations and thick cycles. Attention has focused on the quartzite–dolomite association of the Cambro–Ordovician of the North Atlantic area (Swett, 1969), on the 'depositional grand cycles' of the Cambrian of the Rocky Mountains (Aitken, 1978; James, 1984), and on the sandstone–limestone–shale belts of the Cambro–Ordovician of the southern Appalachians (Markello and Read, 1981, 1982; Walker and others, 1983). In each of these cases an element of tectonic control is envisaged: generally variation in the rate of subsidence and clastic sedimentation. Smaller-scale associations of sandstone and limestone have been reviewed by Mount (1984) and ascribed to four major processes, of which punctuated mixing (by storms for instance) and mixing at facies belt boundaries are of relevance to this study. In the latter case, most published examples display a fairly abrupt transition between the clastic and carbonate parts of the cycle (Mount, 1984). Shallowing-upward regressive shoreline deposits seem to be common, with limestone marking the *base* of the cycle and the clastic part being very near-shore or terrestrial (Bowman, 1979; Markello and Read, 1981; James, 1984). In most cases there appears to be little mixing of the silicic and carbonate clasts, although Driese and Dott (1984) described calcareous sandstone from the central part of limestone–sandstone cycles.

The cycles in the NHF clearly record shallowing upward events (Fig. 11). However the clastic Association A represents the deepest environment and the carbonate-rich Association D the shallowest. In this example, as in other shallowing-upward cycles (Bowman, 1979; James 1984; Aitken, 1978; Markello and Read, 1981) there are common facies elements: flat-pebble conglomerates, cross-bedded ooid grainstones, and carbonate-rich flow deposits. However, all these examples culminate in stromatolitic or algal mat peritidal facies, which seem to be entirely absent from the NHF.

It is likely that deposition of the NHF occurred well offshore on a shallow storm-influenced shelf adjacent to a productive clastic shoreline. Clastic material removed from this shoreline was incorporated into sand shoals within wave base where ooids were intermittently produced on shoal tops but which were frequently reworked, resulting in the removal of material into relatively deeper water and mixing of carbonate and clastic material. The juxtaposition of Associations A and B (containing erosive-based graded beds, which could be storm beds or turbidites) with the obviously shallow marine Associations C and D, suggests that the graded beds were produced by storm currents. Associations A and B probably represent marginal areas which received sediment swept off the prograding sand/ooid shoal complex. The slumps in Association B only record local depositional slopes.

Since the principal control was probably storm currents, this would represent the 'punctuated' class of carbonate/clastic deposits of Mount (1984). However later reworking of the shallowest areas was also important. Dune fields in the shoal areas migrated under the influence of tidal or meteoric currents resulting in alternating 'clean' and 'dirty' layers. The former underwent early diagenesis and were commonly reworked as flat-pebble conglomerates while the dirty layers remained incompetent. [illegible] whole unit was later recrystallized in an episode of ferroan calcite diagenesis, perhaps under deep-burial conditions

Regional correlation

Limestones occur in the Ellsworth, Pensacola and Queen Maud mountains (Fig. 2); all are of Cambrian age.

In the Pensacola Mountains the 0–450 m thick Nelson Limestone (Weber and Fedorov, 1980) is of Middle Cambrian age and consists of a lower part interbedded with sandstone and an upper, purer part. The formation has a basal red conglomerate member and is overlain by volcanic conglomerates of the Gambacorta Formation and ?terrestrial sediments of the Wiens Formation. Deposition probably occurred during a transgressive–regressive cycle.

In the Queen Maud Mountains the central part of the Middle Cambrian Leverett Formation is a limestone unit which grades up from a calcareous mudstone into a relatively pure limestone (Laird and Bradshaw, 1982). Again there are red sandstones below and volcanics above this unit, and a comparable setting to the deposition of the Nelson Limestone is envisaged.

There are three major occurrences of limestone within the Cambrian succession in the Ellsworth Mountains:

(*a*) Within the Union Glacier Volcanics at the base of the Heritage Group there is [illegible] 90 m thick sequence of limestone conglomerate, supposedly deposited under fluvial conditions (Webers and Sporli, 1983). Buggisch (1983) suggested that the clasts were derived from a Lower to Middle Cambrian shelf limestone.

(*b*) The lower part of the Drake Icefall Formation (middle Heritage Group) consists of a sequence of grey limestone varying from 5 to 200 m thick. This unit overlies nearshore clastics, is in turn overlain by dark argillite, and probably represents a major transgression.

(*c*) The Minaret Formation separates the Heritage Group from the Crashsite Quartzite; it varies from 0 to 600 m thick and contains an Upper Cambrian fauna (Webers and Sporli, 1983). Buggisch (1983) described onco- and biosparites, pelmatozoan sparites, oolites and mudstones from the Minaret Formation, and suggested an open, shallow marine setting for deposition. There are distinctly silty intervals in some parts of the Minaret Formation (Craddock, 1969) and also pisolitic intervals (Hjelle and others, 1982).

Correlation of the Nash Hills Formation is difficult, since there is no evidence about strata above or below. Given the rich fauna and comparative purity of the Minaret Formation, correlation with this, and hence a late Cambrian age, is unlikely. There was widespread carbonate deposition during the Middle Cambrian with the Nelson Limestone and parts of the Leverett and Drake Icefall Formations being deposited during a marine transgression and regression. None of these formations is described as being cyclic, but all are associated with clastic strata and this is certainly a possible correlation. The NHF could equally well represent the *in situ* equivalent of the limestone conglomerate within the Union Glacier Volcanics; this would imply an early to middle Cambrian age for the formation.

REMAINING NUNATAKS

1. *Northern nunataks, Whitmore Mountains*

There is a narrow exposed ridge of interbedded fine–very fine subarkose and silty mudstone. Sandstone beds are 20–30 cm thick, parallel-sided, with sharp bases [illegible] tops. Bed bases display groove, prod and flute casts, and internally they are gra[illegible], with flat and cross lamination. Bouma (1962) T_{ac} and T_{abc} beds have been recognized and it is clear that these are turbidites. They belong to the Facies Association C–D spectrum of Walker and Mutti (1973) and are probably part of a much larger turbidite fan system.

2. *Lewis Nunatak*

At the base of the massive dolerite sill of the Jurassic Ferrar Supergroup at Lewis Nunatak there is a partially exposed sequence of flat-lying sedimentary rocks up to 10 m thick. The rocks are interbedded laminated dark silty mudstones, green sandstones and very thick poorly sorted green-grey pebbly sandstones. The thin-bedded mudstones occasionally contain single pebbles up to 2 cm in diameter and the pebbly sandstones may contain isolated granite-gneiss, granitoid and carbonate boulders up to 1 m in diameter. The sandstones are sub-arkoses and contain well-rounded quartz, subordinate mottled feldspar and fine-grained volcanic lithic clasts and accessory rounded garnet, biotite, chlorite, muscovite and zircon. Some of the volcanic clasts with embayed quartz phenocrysts resemble the nearby Thiel Mountains porphyry.

The occurrence of single pebbles within laminated sandstone and mudstone suggests that these are glacial dropstones and that the strata may be lateral equivalents of Permian glacial strata within the Beacon Supergroup; the Buckeye Tillite of [illegible] Horlick Mountains, the Gale Formation of the Pensacola Mountains and the White[illegible] Conglomerate of the Ellsworth Mountains.

PALAEOCURRENTS

The only palaeocurrent information recorded in this area was the orientation of wave ripple crests. These data come from three units: the red sandstone at Mount Johns (5 readings) and Morland Nunatak (1); the mixed carbonate–clastic unit at the Martin (4) and Nash (1) hills; and the volcaniclastic unit in the Thiel Mountains (8). The data are shown on Fig. 12. All 19 data points lie in the range 073–150°.

At all three localitities the mean orientation lies roughly east–south-east–west–north-west. All the ripples are small, shallow-water structures, probably the results of wind-driven waves. In the case of the red sandstone unit they probably formed in shallow ephemeral pools; in the other two units they are marine.

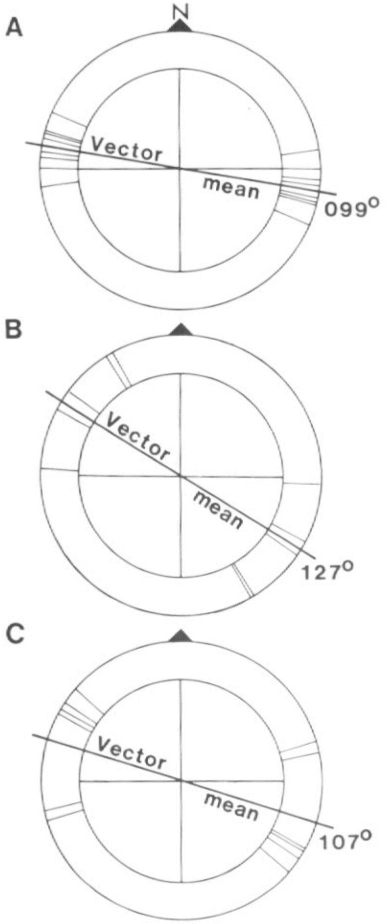

Fig. 12. Orientation of wave ripple crests for A, volcaniclastic unit, $n = 8$; B, carbonate-clastic unit, $n = 5$; C, red sandstone unit, $n = 6$.

Although the total number of measurements is low the small spread of data within each unit, and between the three units has interesting implications:

(i) The ripples were formed in a fairly constant wind regime, with either north–north-east or south–south-west directions.

(ii) If all three units are Cambrian, as seems likely, either the coincidence of directions is fortuitous or it may suggest there has been no major rotation of the EWM relative to Greater Antarctica since the Cambrian.

Obviously these suggestions are tentative, and a much more extensive sampling program would be needed to confirm the ideas, but the approach could be used to test the rotation hypothesis.

DISCUSSION

The stratigraphic correlations of the sedimentary rocks of the Ellsworth, Pensacola and Transantarctic mountains are summarized in Fig. 2. With the exception of Lewis

Nunatak and the northern nunataks of the Whitmore Mountains, the sedimentary rocks of the ETMR can be correlated with the neighbouring Cambrian successions. The thickest Cambrian succession occurs within the Ellsworth Mountains which may, as indicated by the chemistry of the Cambrian volcanic rocks (Hjelle and others, 1982; Vennum and others, in press) have been deposited in an intracontinental extensional basin. Although carbonate horizons are present within the Cambrian Ellsworth Mountains succession the main platform carbonates occur within the Transantarctic Mountains including the Pensacola Mountains. Here, they are associated with widespread silicic volcanic rocks.

The Thiel Mountains porphyry and the associated volcaniclastic rocks of the MWF were, prior to this study, believed to be late Precambrian in age. However the occurrence of the fossil (echinoderm and ?protospongia) fragments and the radiometric studies suggest a Cambrian age. We would also suggest that these rocks together with the Wyatt and Ackerman formations represent a period of Cambrian, peraluminous S-type volcanism (Vennum and Storey, in press) bordering the extensional zone within the Ellsworth Mountains. Their correlation with the volcanic rocks of the Gambacorta Formation and Liv Group, the petrogenesis and tectonic setting of which is unknown, is at present uncertain. It is possible that they all represent part of the one Cambrian magmatic suite.

If the above correlations are correct then both stratigraphic and tectonic events can be correlated between Greater and Lesser Antarctica during the Cambrian; the present day boundary may represent the boundary between the extended continental crust of the EWM and the bordering carbonate platform and emergent volcanic islands of the Transantarctic Mountains. The main contrast in tectonic development occurred subsequent to the Cambrian; the Ellsworth and Pensacola mountains continued to be subsiding basinal zones infilled by thick ?Ordovician to Permian successions and deformed during the Permo-Triassic Ellsworth and Weddell orogenies; the Cambrian strata of the central Transantarctic Mountains were deformed during the Cambro-Ordovician Ross orogeny and intruded by the Granite Harbour Intrusive Suite (Faure and others, 1979) prior to deposition of Devonian to Triassic platform sediments. However the Thiel Mountains porphyry and the MWF have remained for the most part undeformed. This is puzzling and may be partly due to the lithological control of the massive porphyries and partly due to their geographical location marginal to the main zones of both Ross and Ellsworth deformation.

CONCLUSIONS

The sedimentology of some of the scattered nunataks of the Ellsworth–Thiel mountains ridge is correlated with the known sedimentary history of this part of the Antarctic during the Cambrian period. It can be related to a Cambrian intracontinental extensional environment and is consistent with a more or less autochthonous origin for the Ellsworth–Whitmore mountains crustal block. The Mount Walcott Formation of the Thiel Mountains is a Cambrian volcaniclastic unit deposited in a deepening shoreline–shelf–outer shelf or base of slope marine setting bordering peraluminous volcanic islands along the margins of the extensional rift zone. The mixed carbonate–clastic unit of the Nash and Martin hills represents shallowing upwards events and formed well offshore in a shallow, storm-influenced shelf adjacent to a productive shoreline. The red sandstone unit of the Mount Johns Formation was deposited by braided ephemeral streams or distal alluvial fans and may represent part of a widespread regressive event in the Cambrian.

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