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Devonian depositional environments in the Darwin Mountains: marine or non-marine?

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Abstract: The depositional environment of the Devonian Taylor Group has been subject to considerable debate for over 30 years. The debate stems largely from a belief that the abundant and diverse trace fossils represent a marine ichnofauna, whereas sedimentary features, including palaeosols, desiccation polygons and red beds, are more typical of a non-marine setting. The debate is reconciled by a reinterpretation of the trace fossil assemblage which shows that the trace fossils comprise a typical fresh water (*Scoyenia* ichnofacies) assemblage, and their occurrence in the Taylor Group in the Darwin Glacier area is entirely consistent with deposition in a mixed fluvial-lacustrine-subaerial environment.

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Introduction

The use of trace fossils as palaeoenvironmental indicators for the Devonian of Antarctica has given rise to a debate over the marine or non-marine character of the Taylor Group (lower Beacon Supergroup) which has continued for nearly 30 years. Workers studying the trace fossils (eg. Vialov 1962, Webby 1968, Gevers *et al.* 1971, Bradshaw 1981, Gevers & Twomey 1982) have argued strongly for a shallow marine setting, whereas sedimentologists (eg. Barrett & Kohn 1975, Barrett 1979, McPherson 1978, 1979, Plume 1976, 1978) have largely favoured non-marine deposition.

Reviewing the Taylor Group trace fossils in southern Victoria Land, Bradshaw (1981) proposed that the lower half of the group was marine and the upper part non-marine based on the distribution of common trace fossils including; *Beaconites, Cruziana, Diplichnites, Rusophycus*, and *Skolithos* which Bradshaw believed to be marine. However, it has recently been demonstrated that these ichnogenera, which are commonly abundant in the Taylor Group in southern Victoria Land, represent a typical fresh water ichnofauna and that their occurrence in the Taylor Group is consistent with the apparent fluvial character of the sediments (Sherwood *et al.* 1989, Woolfe *et al.* 1989, Woolfe 1990).

A similar stratigraphical sequence and trace fossil assemblage to that described from southern Victoria Land (Bradshaw 1981, Woolfe 1990) occurs 400 km farther south in the Darwin Mountains (Fig. 1). Bradshaw *et al.* (1990) suggested that the lowermost Beacon Supergroup in the Darwin Mountains area (Fig. 2) was deposited in dominantly non-marine conditions with local marine incursions, and that fully marine conditions were only reached during the deposition of the Hatherton Sandstone. However, facies relationships and palaeocurrent measurements suggest that non-marine conditions persisted throughout this interval.

This paper re-examines the Devonian sequence in the Darwin Mountains in an attempt to resolve the apparent discrepancy between the trace fossils (suggesting marine deposition) and sedimentological evidence for non-marine deposition.

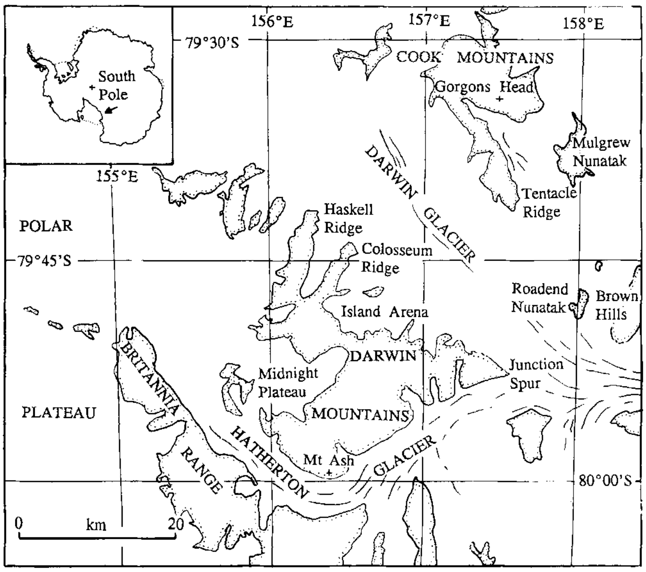

Fig. 1. Sketch map of the Darwin Glacier area showing the main localities mentioned in the text. Stippled margin denotes mostly ice-free mountainous areas.

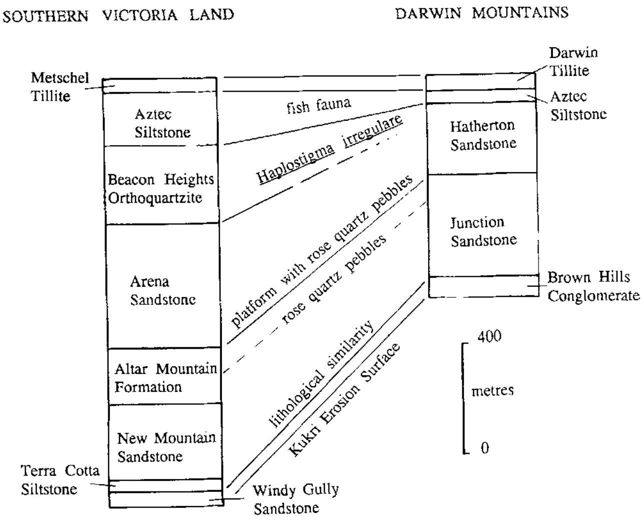

Fig. 2. Schematic stratigraphic column of the Taylor Group in southern Victoria Land and the Darwin Glacier area. Correlations between these two areas are shown along with the evidence on which the correlations are based (modified from Woolfe 1991).

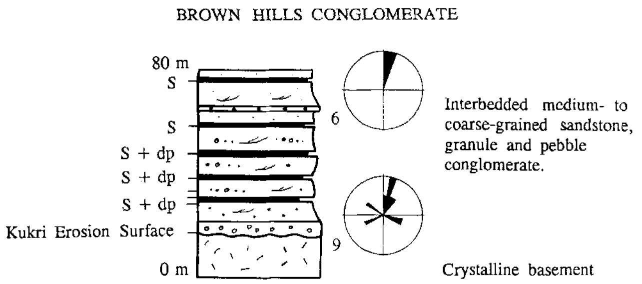

Fig. 3. Composite stratigraphic column for the Brown Hills Conglomerate, based largely on a section from Tentacle Ridge. Rose diagrams show palaeocurrent directions, the number to the lower left of each rose indicates the number of measurements. Measurements are visual averages of trough cross-bed axes taken from bedding plane exposures at Roadend Nunatak and Tentacle Ridge (Woolfe 1992). Principal *Skolithos* occurrences are noted to the left of the column (S), as are desiccation polygons (dp).

Stratigraphy and palaeoenvironment

Brown Hills Conglomerate

The Brown Hills Conglomerate is known to crop out on Tentacle Ridge and Gorgons Head in the Cook Mountains, at Roadend Nunatak and in the Brown Hills. Thicknesses are variable, ranging from 0 to 80 m, and the upper contact of the formation is locally gradational with the Junction Sandstone, making the boundary difficult to designate in some places. This led Bradshaw *et al.* (1990) informally to include the formation in the Junction Sandstone. However, the unit is treated here as a separate formation as originally described by Haskell *et al.*(1965).

Interbedded coarse-grained sandstone and pebble conglomerate beds, with lenses of dark brown mudstone, in the Brown Hills Conglomerate rest with striking unconformity on igneous and metamorphic rocks of the Lower Palaeozoic basement complex. In the east, towards Brown Hills (Haskell *et al.* 1965) and at Roadend Nunatak the lower part of the formation is dominated by pebble conglomerate, but, farther west, beds of pebble conglomerate are less common and the formation is mainly composed of coarse-grained sandstone and granule conglomerate.

The bulk of the formation (Fig. 3) is composed of well-cemented, medium- to coarse-grained, reddish-brown orthoquartzite. Planar-bedded units are strongly developed on a decimetre- to metre scale and are interbedded with trough cross-bedded units with cross-bed sets up to 0.5 m high. Fining upwards cycles are common in the planar-bedded facies and cycles are commonly capped by mud veneers; small asymmetrical and symmetrical ripples are also common and desiccation polygons are preserved in the upper portions of abundant dark reddish-brown mudstone lenses. The formation is well cemented and forms steep bluff-like exposures.

An excellent 80 m thick exposure through the entire formation occurs on the northern side of Tentacle Ridge. About 2 m of rolling relief is developed on the Kukri Erosion Surface which here separates the formation from underlying deeply weathered schist and foliated K-feldspar granite. Small lenses of angular conglomerate fill depressions in the erosion surface, clasts range in size up to 5 cm in diameter and are of mixed igneous and metamorphic lithologies. The lower 2 m of the formation is dominated by angular granule conglomerate containing both quartz and feldspar grains, with scattered well-rounded quartz pebbles up to 2 cm in diameter. This interval is pale pinkish-grey and forms a conspicuous pale layer when viewed from a distance. Up section, the unit grades into pale cream granule and pebble conglomerate, composed of subrounded quartz and feldspar grains up to 1 cm in diameter. Muddy veneers become common on the tops of decimetre-scale trough cross-bed sets and red-brown mudstone lenses (30 cm thick and up to 30 m wide) become widespread. This unit grades into a red-brown coarse- grained sandstone over about 5 m. Mudstone lenses and interbeds contain well-preserved desiccation polygons up to 20 cm in diameter and locally abundant *Skolithos*. The boundary with the overlying Junction Sandstone is marked by a strong break in slope.

Skolithos is by far the most abundant trace fossil; it occurs as straight unbranched, vertical or near-vertical burrows 1–3mm in diameter and ranging in length from 5 to 20 cm. Near the base of the formation it is most abundant in, and directly beneath lenses of dark reddish-brown mudstone containing well-preserved desiccation polygons (Fig. 4). Many of the burrows descend from within the mudstone lenses, showing that the trace makers either inhabited the ephemeral pools or burrowed into the sediment during periods of exposure and desiccation. Higher in the formation, *Skolithos* occurs in all lithologies, except the coarsest pebble conglomerate beds, and locally it is very abundant. Isolated sinuous trails occur on the surface of some mudstone lenses.

The most likely correlative of the Brown Hills Conglomerate in southern Victoria Land is the Windy Gully Sandstone (see Fig. 2), the closest known exposure being at Mount Kempe (300 km to the north), where the formation is 40 m thick (Plume 1976). The correlation with the Windy Gully Sandstone is based on its similar stratigraphical position (directly above the Kukri Erosion Surface) but, it is known that this method of correlating the basal formation of the Taylor Group can be problematic. This is because, in some parts of southern Victoria Land, the New Mountain Sandstone (and not Windy Gully Sandstone) rests unconformably on the crystalline basement complex (Bradshaw 1981).

No age determinations have be made from the Brown Hills Conglomerate and no material suitable for age determination has yet been recovered from the Windy Gully Sandstone. The top of the Windy Gully Sandstone is taken to be Early Devonian (Kyle 1977) on the basis of microfloral evidence from the overlying Terra Cotta Siltstone (no correlative of the Terra Cotta Siltstone has been identified in the Darwin Glacier area).

Bradshaw *et al.* (1990) interpreted the Brown Hills Conglomerate (their lower Junction Sandstone) as having been deposited by an extensive alluvial plain system. This interpretation is supported by the presence of abundant reddish-brown mudstone lenses containing well-preserved desiccation polygons, small-scale channels and mud-capped fining upwards cycles with desiccated tops which were observed during this study. Unidirectional palaeocurrent measurements obtained from trough cross-bed axes in the upper part of the formation (Fig. 3), together with the sheet-like geometry of the beds, suggest that the depositional system was probably braided.

Junction Sandstone

The Junction Sandstone crops out on both sides of the lower Hatherton Glacier and it is particularly well exposed adjacent to Junction Spur, from which it derives its name (Barrett 1971). The base of the formation, however, is not exposed here. Good exposures also occur on Mulgrew Nunatak but the top and bottom of the formation are not exposed. The only complete sections known occur on the northern side of Tentacle Ridge and to the south of Gorgons Head. At these localities the formation is 540 m thick (Fig. 5).

The Junction Sandstone is typically a strongly planar-bedded or cross-bedded, pale brown orthoquartzite. The lower contact is marked by a conspicuous slope break above the bluff forming strata of the Brown Hills Conglomerate. The basal unit is a pale cream or brown granule conglomerate which contrasts with the generally darker brown of the underlying Brown Hills Conglomerate. The lower part of the formation is dominated by trough cross-bedded and planar-bedded sandstone interbedded on a decimetre- to metre scale. Interbeds of red-brown shaly mudstone are widespread. Fining upwards cycles are common within planar-bedded units, with medium- to coarse-grained sandstone grading into medium- and locally fine-grained sandstone. Cycles are commonly capped by a dark mudstone veneer. Desiccation polygons are common and oscillation ripples are preserved on some surfaces. Isolated large tabular cross-beds up to 1.5m thick also occur.

Fig. 4. In-filled desiccation polygons in a mudstone lens in the lower part of Brown Hills Conglomerate at Tentacle Ridge. Note that *Skolithos* is common in the adjacent sandstone bed (top right corner of note book and lower right of photo). Notebook is 20 cm long.

Up section, the formation becomes dominated by decimetre-scale cross-bedded, medium- to coarse-grained sandstone with local occurrences of granule conglomerate. In fresh outcrop, the upper parts of the formation are pale brown, cream, pale green, dark red, maroon, or pink; outcrops are commonly weathered to a characteristic rusty red-brown. Decimetre- to metre-scale beds commonly define fining-upwards cycles, grading from granule conglomerate to fine-grained sandstone with many cycles capped by a thin red shale. Lenses of dark red or maroon shale, up to 2 m thick, are laterally continuous for several hundred metres. Desiccation polygons are preserved in many of the finer grained sediments. Ripples and ferruginous concretions of various sizes and shapes are scattered throughout the formation.

Beds of pale greenish sandstone ("green beds") up to 2 m thick are common and within these beds little or no internal lamination is preserved. Their lower contacts are always gradational on a centimetre- or decimetre-scale, with strongly developed cross- bedding in the underlying bed gradually becoming less distinct before disappearing completely within the "green bed". The upper contacts of the "green beds" are always sharp. Locally trough cross-bedded sandstone directly

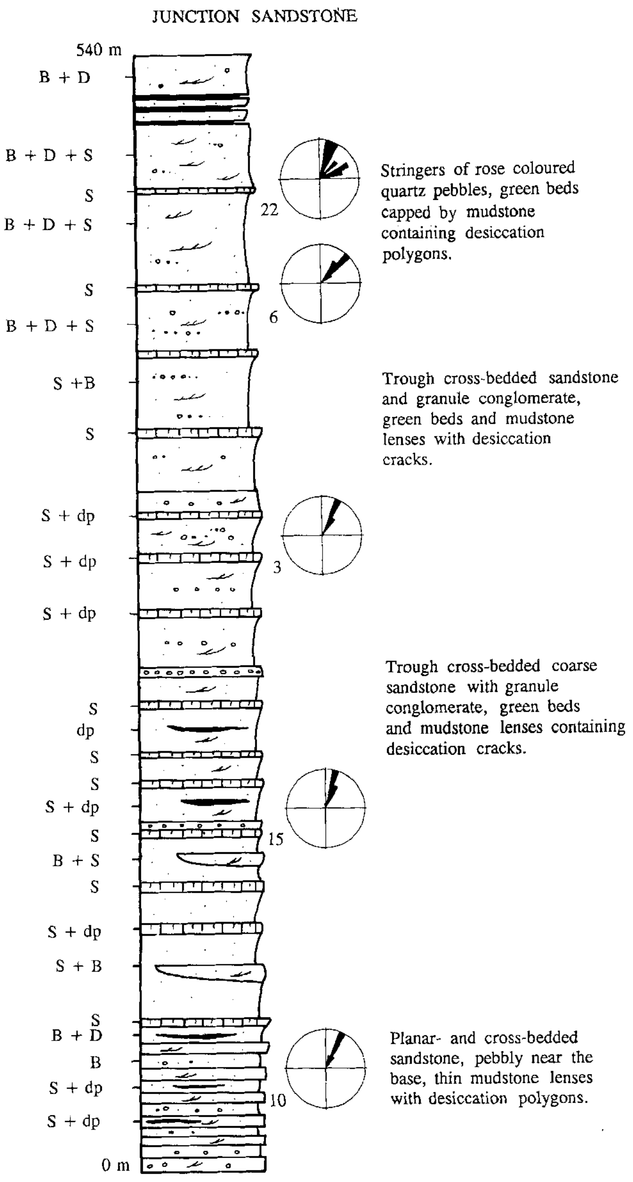

Fig. 5. Composite stratigraphic column for the Junction Sandstone. The column is compiled from sections measured at Tentacle Ridge, Gorgons Head and the lower Hatherton Glacier. Rose diagrams and abbreviations are the same as those used in Fig. 3. Additional trace fossil abbreviations are; *Beaconites* B and *Diplichnites* D, + indicates that the traces occur in the same bed or cross-bed set.

overlies the "green beds" with a scoured and irregular contact. Elsewhere the "green beds" are capped by a thin red-brown or black shale commonly containing well-preserved desiccation polygons. Where these thin mudstone lenses occur in association with *Skolithos*-rich "green beds", *Skolithos* is more abundant directly beneath the mudstone cap and many traces appear to descend into the "green bed" from near the base of the overlying mudstone. This suggests that the burrows were either formed in ephemeral ponds or during periods of subaerial exposure. Some beds (notably those containing only rare *Skolithos*) contain scattered pyrite nodules.

In the lower Hatherton Glacier area the top of the formation is composed of interbedded coarse-grained sandstone and granule conglomerate containing scattered rose quartz pebbles and siltstone intraclasts up to 5 cm in diameter.

On Gorgons Head, the lower part of the formation contains a well-exposed sequence of decimetre-scale trough cross-bedded sandstone, centimetre-scale planar-bedded sandstone, dark shale and "green beds" interbedded on a decimetre- to metre scale. Fining upwards cycles, up to 15 cm thick, are common and grade from coarse- to fine-grained sandstone. Many of the cycles are capped by mud veneers containing desiccation polygons, which also occur in the thicker shaly beds. *Beaconites* spp. occur in the planar-bedded intervals and *Skolithos* is common in the cross- bedded units as well as in the "green beds". *Skolithos* is the dominant trace fossil, forming "*Skolithos* beds" or "pipe rock" in which all other sedimentary structures have been completely destroyed by intense bioturbation. *Skolithos* is the only trace fossil observed in the "green beds" in which it commonly forms "pipe rock", especially in the lower Hatherton Glacier area. *Skolithos* is also locally abundant in decimetre- scale trough cross-bedded coarse-grained sandstone beds in the lower Hatherton Glacier area and at Mulgrew Nunatak. *Beaconites* spp. occur scattered throughout the formation and are locally the most abundant trace fossils. *Beaconites* is particularly widespread in a sequence of interbedded sandstone and shale near the top of formation north of Mount Ash. Trackways of *Diplichnites* occur throughout the upper part of the formation but were nowhere observed in abundance. Near Mount Ash three trackways were observed in the same coset as *Beaconites* indicating the coexistence of the trace-making organisms in the same depositional environment. It is possible that *Beaconites* and *Diplichnites* were formed by the same organism but no direct evidence to support this theory was observed.

The New Mountain Sandstone in southern Victoria Land is probably correlative with the lower half of the Junction Sandstone, but, the absence of the Terra Cotta Siltstone in the Darwin Glacier area makes this correlation only tentative in chronostratigraphical terms. The upper part of Junction Sandstone is probably best correlated with the Altar Mountain Formation. The incoming of rose coloured quartz pebbles near the top of the Junction Sandstone is matched by an influx of rose coloured quartz pebbles at a similar level in the Altar Mountain Formation, suggesting that direct correlation may be possible (see Fig. 2).

The lithological and morphological expression of the Junction Sandstone-Hatherton Sandstone boundary is strikingly similar to that of the Altar Mountain Formation-Arena Sandstone boundary in southern Victoria Land. This horizon provides a lithostratigraphical and possibly chronostratigraphical correlation between the Darwin Mountains and the Taylor Group in central southern Victoria

Land. The correlation is consistent with, but not as good as, that made on the basis of a well-preserved fish fauna in the Aztec Siltstone at Gorgons Head (Woolfe *et al.* 1990).

No datable material has been recovered from the formation. It is inferred to be Early–Middle Devonian based on its correlation with the New Mountain Sandstone in southern Victoria Land which conformably overlies Early Devonian sediments of the Terra Cotta Siltstone (Kyle 1977).

Many of the sedimentary features of the Junction Sandstone are similar to those found in the underlying Brown Hills Conglomerate, indicating a similar depositional environment. Palaeocurrent directions obtained from bedding-plane measurements of trough cross-bed axes are uniform (Woolfe 1992, p. 150–157) and indicate flow towards the north or north-east (Fig. 5). These, together with the sheet-like geometry of the trough cross-bedded sand bodies, suggest deposition by unconstrained, shallow braided channels. The "green beds", characteristic of the formation, are interpreted here as palaeosols on the basis of their gradational (replacive) lower boundaries and generally finer grain size. Desiccated mudstone caps on many of the "green beds" show that pools of standing water collected periodically on their surface. The carbon/sulphur geochemistry (after Berner & Raisewell 1984) of a dark red-brown shale 31 m below the top of the formation gave a C/S ratio of 59, a value indicative of fresh water deposition (Arnot 1991).

The *Skolithos–Beaconites* association described from the Brown Hills Conglomerate continues throughout the Junction Sandstone. *Diplichnites gouldi* becomes part the assemblage towards the middle of the formation. Bradshaw *et al.* (1990) argued that *Diplichnites* (and indeed *Skolithos*) represented a marine influence, but its occurrence within the same cosets as *Beaconites* suggests that it is part of the same non-marine *Skolithos–Beaconites* ichnofacies which occurs throughout the lower Junction Sandstone and Brown Hills Conglomerate.

Hatherton Sandstone

The Hatherton Sandstone crops out extensively in the Darwin Mountains, Cook Mountains and the Britannia Range. At most localities, the top of the formation is truncated by the Maya Erosion Surface and thicknesses range from 250–300m. The upper and lower contacts of the formation occur on Gorgons Head in the Cook Mountains, where the formation is 324 m thick (Fig. 6).

The Hatherton Sandstone is a generally homogeneous, slope-forming, clay-cemented, medium- to fine-grained, quartzose sandstone. Outcrop colour ranges from creamy white to yellowish grey, yellow-orange, pale green, or brown. Beds of "sugary", pale cream or white, strongly cemented quartz sandstone occur throughout, and these become locally abundant near the top of the formation. Thin beds of fine-grained green sandstone, pale pink granule conglomerate, and dark green shaly mudstone also occur. The lower contact of the formation is sharp, and a thin lag gravel is commonly developed; well-rounded quartz pebbles, up to 3 cm diameter, commonly weather out to produce a pavement litter which is diagnostic of this horizon.

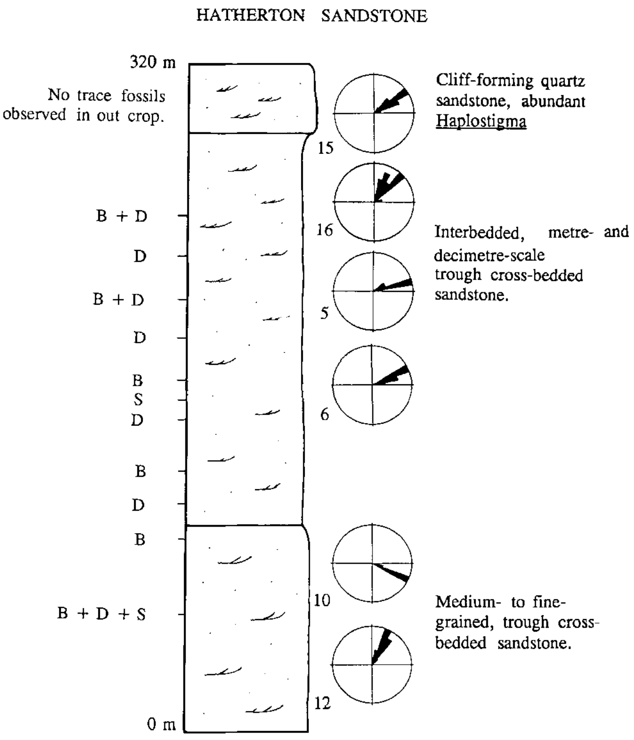

Fig. 6. Composite stratigraphic column and indicative palaeocurrent measurements from the Hatherton Sandstone. Data is drawn from exposures on Gorgons Head, the lower Hatherton Glacier and Colosseum Ridge. Legend as for Figs 3 and 5.

Bedding on a decimetre- or metre scale is generally defined by slight changes in colour and cementation. Cross- and planar- lamination is common, but the homogeneous nature of the sandstone makes these features less conspicuous than in underlying formations. Ripple marks are common, and desiccation polygons are locally preserved in shaly mudstone beds. Hummocky cross stratification (HCS) has been reported from a number of localities (Anderson 1979, Bradshaw *et al.* 1990). Small green or brown ferruginous nodules are widespread, generally occurring as diffuse specks within the sandstone. Dark brown, red, or green concretions of various shapes up to 3 m in diameter are scattered throughout the formation, nearly always in association with ripple-laminated sediments. Locally, these concretions are abundant, forming dark concretionary lenses within the generally paler sandstone. The formation locally weathers to produce a soft clay-rich sediment in which micro-karst features commonly develop.

The upper 30 m of Hatherton Sandstone at Gorgons Head is composed of strongly cemented, cliff-forming orthoquartzite containing abundant casts of the lycopod *Haplostigma* *irregulare* (Woolfe *et al.* 1990). Elsewhere the uppermost part of the formation is missing due to erosion across the Maya Erosion Surface.

Thick clay-cemented units weather to form rounded outcrops with surficial unconsolidated sand and clay deposits. The average grade of slope generally increases up-section from a regionally recognizable, broad platform immediately above the Junction Sandstone to steep slopes near the top of the formation.

The *Skolithos–Beaconites–Diplichnites* association persists throughout the Hatherton Sandstone (Fig. 6). In most localities one of these ichnogenera tends to dominate and high-density monoichnogeneric assemblages occur in many beds. *Skolithos* is less abundant than it is lower in the Taylor Group but both *Diplichnites* and *Beaconites* are significantly more abundant.

It has been argued that these three ichnogenera are not part of the same ichnofacies and that both *Diplichnites* and *Skolithos* represent a marine influence (Bradshaw *et al.* 1990). The abundance and close association of *Skolithos* and *Beaconites* in the lower Taylor Group is used here to argue that they form part of the same ichnofacies. This leaves only *Diplichnites*' position in the ichnofacies unclear and a *Skolithos–Beaconites–Diplichnites* association is demonstrable within the Hatherton Sandstone.

Numerous examples of *Beaconites* occurring in same cross-bed set as *Diplichnites gouldi* were observed on Colosseum Ridge and locally these occur on the same bedding plane. The most spectacular occurrence is at the northernmost end of the ridge, 14 m below the Maya Erosion Surface. There, abundant *Diplichnites gouldi* trackways, up to 40 mm across, and numerous undifferentiated foot prints and prod marks, up to 20 mm in diameter (Fig. 7), occur in a single 2 m high, steeply dipping (20°) cross-bed set, *Beaconites* also occurs in the same set. It appears unlikely that the *Beaconites* could have been introduced into the assemblage by animals burrowing down from sediment overlying the cross-bed set. This is because the *Beaconites*-producing animal would have had to descend nearly 2 m to reach the lower parts of the set, whereas all of the available field observations suggest that *Beaconites* was produced by a organism which burrowed only a few centimetres or a few tens of centimetres into the sediment. *Beaconites* and *Skolithos* occur within the same cosets and fining upwards cycles on the western side of Haskell Ridge. An association of *Beaconites*, *Diplichnites* and undifferentiated large foot prints is joined by bilobate resting traces, near the top of the formation in the upper Hatherton Glacier area (along Section J2, Barrett 1971).

Fig. 7. Undifferentiated large pits (foot prints and prod marks) along with trackways of *Diplichnites gouldi* in the Hatherton Sandstone at the northern end of Colosseum Ridge. Steep sided preservation of the pits suggesting formation in damp (cohesive) sand. Notebook is 20 cm long.

The Hatherton Sandstone is almost indistinguishable from the Arena Sandstone of southern Victoria Land (Fig. 2). The correlation between these two formations is strengthened by the similarity of their lower contacts (discussed above) and the presence of a 30 m thick sequence on Gorgons Head that closely resembles Beacon Heights Orthoquartzite. Bradshaw *et al.* (1990) made the correlation with the Beacon Heights Orthoquartzite directly, showing an upper and lower boundary to the formation, but such direct correlation is not made here. This is because the lower lithological boundary of the Beacon Heights Orthoquartzite at the type section (see McElroy & Rose 1987, p. 27) is defined by a change in secondary cementation and is therefore difficult to correlate.

Stems of the lycopod *Haplostigma irregulare* have been found at Gorgons Head (Woolfe *et al.* 1990) and at two localities in the Beacon Heights Orthoquartzite in southern Victoria Land (Harrington & Speden 1962, p. 715, McKelvey *et al.* 1977, p. 833). These indicate an early Middle Devonian age (Plumstead 1964 p. 639).

The Hatherton Sandstone has been previously interpreted as a marine unit on the basis of hummocky cross stratification (Anderson 1979, Bradshaw *et al.* 1990) and its trace fossil assemblage (Gevers & Twomey 1982, Bradshaw *et al.* 1990). Hummocky cross stratification is here discounted as a useful marine indicator because of;

a) its widespread occurrence in Permo-Triassic fluvial strata in southern Victoria Land (Woolfe 1989, 1992, new data).

b) its documented occurrence in fluvial sequences elsewhere in the world (discussed below), and

c) its occurrence in a sand-only sequence (discussed below).

The trace fossil assemblage (*Skolithos–Beaconites–Diplichnites*) is essentially the same as that found in the underlying units which together with the persistence of similar sandstone facies, suggests little or no change in sedimentary environment. Palaeocurrent directions are locally slightly more variable than in the underlying Junction Sandstone, but trough cross-beds axes indicate continuation of a north-easterly drainage (Fig. 6).

The Hatherton sandstone differs from the underlying units mainly because of its generally finer grain size and the near absence of mudstone. One explanation may be increased aridity causing a greater number of ephemeral events in the system and removal of much of the fine-grained material farther down stream. However, the continuation of the *Skolithos –Beaconites–Diplichnites* association, the north-easterly palaeocurrent direction and similar sandstone architecture suggests that only minor palaeoenvironmental changes occurred across the Junction Sandstone-Hatherton Sandstone boundary and that the Hatherton Sandstone was deposited in a sedimentary setting similar to that of the underlying units.

Aztec Siltstone

In the Darwin Glacier area, the Aztec Siltstone is known to crop out only on Gorgons Head in the Cook Mountains (Fig.8). At this locality the formation is truncated by the Maya Erosion Surface and reaches a maximum thickness of 120 m. Red and green shale fragments are common in the Darwin Tillite on Colosseum Ridge in the Darwin Mountains: it has been suggested that these were derived from the Aztec Siltstone south of the Darwin Glacier (Barrett & Kyle 1975) although no *in situ* exposures have been found south of the Darwin Glacier. The Aztec Siltstone consists of alternating mudstone and sandstone beds on a decimetre- to metre scale, with scattered lenses of intraformational conglomerate. Mudstone beds are typically red, green, brown or black. Palaeosols containing carbonate concretions, vein networks and strongly developed mottling are common. Some of the shaly beds contain abundant disarticulated fish remains (Woolfe *et al.* 1990). Sandstone beds are composed of fine- to medium- or coarse-grained sand, with decimetre-scale trough cross-beds. Planar-bedded sandstone and small tabular foresets also occur.

Trace fossils are rare in the Aztec Siltstone, scattered *Skolithos* was observed in some of the trough cross-bedded sandstone beds and *Beaconites* is preserved on isolated bedding planes.

The Gorgons Head exposure is believed to correlate directly with the Aztec Siltstone farther north (Woolfe *et al.* 1990). Fossil fish collected from Gorgons Head include phyllolepid placoderms and *Gyracanthides*, of the youngest biozone of the faunal succession described by Young (1988), and indicate an early Late Devonian (Frasnian) age for the formation (Woolfe *et al.* 1990).

Interbedded sandstone, granule conglomerate and mudstone suggest alternation between fluvial and lacustrine processes. Mottled mudstone with extensive vein networking, desiccation polygons and carbonate concretions indicate prolonged periods of soil formation. It is inferred that the Aztec Siltstone records a coexisting succession of rivers and lakes on a relatively low gradient flood plain. McPherson (1978) interpreted the formation, farther north in southern Victoria Land, as being deposited in a hot and seasonally wet and dry regime ('savanna climate' McPherson 1979) based on caliche and vein network development, pedochemical analogy to Australian 'savanna' soils and the presence of desiccation and syneresis polygons. It is likely that similar conditions prevailed in the Darwin Glacier area.

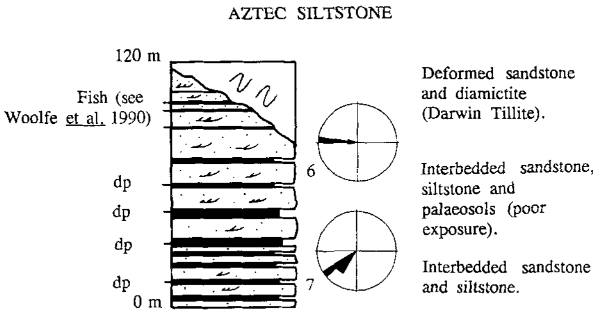

Fig. 8. Measured section through the Aztec Siltstone at Gorgons Head. Thicknesses are from surveying altimeter. See Figs 3 and 5 for explanation of rose diagrams and abbreviations.

Discussion

Trace fossils

Two ichnocoenoses have been previously described from the Taylor Group in the Darwin Mountains area (Bradshaw *et al.* 1990),

a) one containing *Beaconites barretti* and *B. antarcticus*, and

b) one containing *Diplichnites*, *Skolithos* and assorted large arthropod trackways.

These have been interpreted as indicating alternations of non-marine and marine deposition respectively (Bradshaw *et al.* 1990). However, as those authors commented, there is an apparent anomaly in the existence of *Beaconites* and *Skolithos* in close association within the sequence.

This "anomaly" appears to result from the belief that *Skolithos* is necessarily marine and that there are two distinct ichnocoenoses present in the sequence. Evidence presented here suggests that a single *Skolithos–Beaconites–Diplichnites* ichnofacies adequately describes the observed trace fossil associations. Furthermore, a review of the literature shows that *Skolithos* occurs widely in non-marine sediments (e.g. Stanley & Fagerstrom 1974, Bromley & Asgaard 1979, Ratcliffe & Fagerstrom 1980, Zawiskie *et al.* 1983, Ekdale & Bromley 1985, Pollard 1985, Fitzgerald & Barrett 1986, D'Alessandro *et al.* 1987, Sherwood *et al.* 1989, Woolfe 1990) and that its use as a marine indicator in this case cannot be justified. Bradshaw *et al.* (1990) also drew on the abundance of *Skolithos* (which they interpreted as being formed by suspension-feeding polychaetes) to infer a marine setting, arguing that marine waters are much more favourable to suspension feeders. The latter is undoubtedly true but, there is no evidence to suggest that *Skolithos* present in the Taylor Group (or elsewhere) was formed by suspension-feeding animals, and the abundance of *Skolithos* in some beds does not necessarily indicate that the *Skolithos*-producing organism was at any one time abundant. It is likely that many of the high-density trace fossil occurrences represent the activity of a comparatively small biological population over a significant period of time (years, decades, or possibly longer).

Within the Brown Hills Conglomerate and Junction Sandstone, *Skolithos* is closely associated with desiccated mudstone lenses, red-brown sandstone beds and palaeosols (Woolfe 1989), suggesting that it was produced by an organism that colonized either shallow pools of standing water or subaerially exposed sediments. The formation of the Darwin Mountains *Skolithos* by small terrestrial arthropods would be consistent with the available field evidence.

The association of a back-filled meniscate structure such as *Beaconites*, with *Diplichnites* and *Skolithos* is found throughout southern Victoria Land and the Darwin Mountains (Bradshaw 1981, Sherwood *et al.* 1989, Woolfe *et al.* 1989, Bradshaw *et al.* 1990, Woolfe 1990). This association has also been recorded from many places outside Antarctica and forms a diagnostic part of the *Scoyenia* ichnofacies which is widely recognized as a typical fresh water assemblage (Tevesz & McCall 1982, Ekdale *et al.* 1984). In this respect the trace fossil assemblage recorded by Bradshaw *et al.* (1990) is neither enigmatic nor does it require alternations of marine and non-marine strata. The large undifferentiated (arthropod) footprints and the very large trackways described by Bradshaw *et al.* (1990) are of particular interest. These trackways, up to 80 cm across, show preservation of steep sided pits and humps in clean, medium- grained sandstone (Fig. 6, see also Bradshaw *et al.* 1990, fig. 6). It is difficult to reconcile these features with a subaqueous setting. Saturated clean sand has insufficient cohesion to preserve steep impressions such as these and this makes it likely that the illustrated trackways, along with the more common but still large trackways of *Diplichnites gouldi*, were made in either damp (exposed) sand or sand which was bound by some form of algal mat or other cementing agent which has subsequently been removed. These giant arthropod trackways are truly remarkable whatever their palaeoenvironment, but, their occurrence in a mixed fluvial-lacustrine-subaerial environment is particularly significant as they may indicate the presence of land-based arthropods far larger than any previously recorded from the Early Devonian.

Hummocky cross stratification

Hummocky cross stratification (HCS) in the Hatherton Sandstone has been cited (Anderson 1979, Bradshaw *et al.* 1990) as evidence for marine deposition. The use of HCS as a palaeoenvironmental indicator within this sequence raises two questions which have recently received considerable coverage in the literature (for discussion see; Allen 1985, Allen & Underhill 1989, Sun 1990, Rust & Gibling 1990). The first question is largely unresolved and revolves around the definition and recognition of HCS, the second deals with its usefulness in palaeoenvironmental interpretations. Examples of non-marine HCS and SCS (swaley cross stratification) in southern Victoria Land have been reported from the Permian Weller Coal Measures at Allan Hills (Woolfe 1989) and similar structures have been observed in the Triassic Lashly Formation (Woolfe, new data).

The occurrence of HCS in a sand-only sequence (Hatherton Sandstone) is atypical of the type of HCS formed on the continental shelf. Storm-generated (shelf) HCS forms below fair-weather wave base and as a result hummocky sand layers are typically bounded by mud (see Leckie & Walker 1982). The absence of mudstone in the Hatherton Sandstone suggests formation by some other mechanism in either a near shore, fluvial or lacustrine setting and is inconsistent with the assertion of Bradshaw *et al.* that the HCS in the Hatherton Sandstone indicates a continental shelf setting.

Bidirectional palaeocurrents

The presence of bidirectional sets of tabular cross-beds has been used to infer a tidal influence during deposition (Bradshaw *et al.* 1990). This observation, while not inconsistent with a tidal regime, is not diagnostic and cannot be used on its own to infer a bimodal current direction. This is because tabular cross-beds can be formed by several mechanisms, including migration of isolated straight crested sand waves or mega ripples, migration of bars and progradation of deltas. Allen (1963) considered that migrating bars were the most common cause of this type of cross- bedding. As bars migrate across channels and grow outwards from channel margins, bimodal tabular cross-beds form commonly in unidirectional flows where bars grow outward from opposite margins of the channel or where different types are bars are preserved within the same sequence.

More reliable indicators of palaeocurrent direction are the axes of decimetre-scale trough cross-beds which are produced by small subaqueous dunes. In many vertical exposures of Hatherton Sandstone limbs of truncated trough cross-beds may appear to indicate bimodal flow directions and locally even look like hummocks. Measurements of trough cross-bed axes from platform exposures in the Hatherton Sandstone, Junction Sandstone and the Brown Hills Conglomerate in the Darwin Mountains (Woolfe 1992, p. 140–157) are all indicative of unidirectional flow regimes and show that a north to north-easterly drainage persisted throughout the deposition of these units.

Conclusion

The Taylor Group in the Darwin Glacier area was deposited in a relatively consistent palaeoenvironment. The stability of the system allowed a *Skolithos–Beaconites–Diplichnites* trace fossil association to persist throughout much of Devonian time. Sediment transport was to the north or north-east throughout the deposition of the Brown Hills Conglomerate, Junction Sandstone and the Hatherton Sandstone, indicating that little or no change in the regional tectonic regime occurred during that time. A mixed fluvial and lacustrine system is inferred to have deposited all of the Taylor Group formations in the Darwin Glacier area.

The marine–non-marine debate, which has dominated Taylor Group literature over recent years, is found to originate from a misinterpretation of the trace fossil assemblage. A re-interpretation of this suggests that a single non-marine *Scoyenia* ichnofacies persisted during the deposition of the Taylor Group. This reinterpretation resolves the enigma caused by the close association of "marine" and "non-marine" ichnotaxa reported by Bradshaw *et al.* (1990) and reconciles the previous discrepancies between the ichnology and sedimentology of the group. The interpretation also raises some exciting new possibilities as it is now apparent that the sequence may contain one of the earliest and best-preserved records of large land-based Devonian arthropods.

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