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The sedimentary geology, palaeoenvironments and ichnocoenoses of the Lower Devonian Horlick Formation, Ohio Range, Antarctica

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Abstract: Six ichnocoenoses in the clastic Devonian Horlick Formation (max. 56 m) confirm the nearshore marine character of eight of the nine lithofacies present. A basal sand sheet overlies a weathered granitic land surface (Kukri Erosion Surface) on Cambro–Ordovician granitoids. The level nature of this surface and the way it cuts across weathering profiles, suggests that the surface had been modified by marine processes prior to deposition. The basal sand sheet (Cross-bedded Sand sheet Lithofacies) contains tidal bundles, and at its top, abundant *Monocraterion* (*Monocraterion* Ichnocoenosis). The second sand sheet (*Pleurothyrella* Lithofacies) is heavily burrowed and shows alternating periods of sedimentation, burrowing, and erosion below wave base as the sea deepened (*Catenarichnus* Ichnocoenosis). With increasing transgression, finer sediments were deposited (Laminated Mudstone and Feldspathic lithofacies) in an unstable pattern of coarse sandbars and finer troughs (*Cruziana-Rusophycus* and *Arenicolites* ichnocoenoses) crossed by active longshore marine channels (Poorly-sorted Lithofacies, *Spirophyton* Ichnoocoenosis). Short-lived but powerful storms produced thin shelly tempestites (Shell-bed Lithofacies), whereas sporadic, very thin phosphate rich beds (Phosphatic Lithofacies) may have resulted from marine transgressions across the basin. The deepest water is probably represented by sediments of the *Spirifer* Lithofacies *(Rosselia* Ichnocoenosis). The Schulthess Lithofacies is regarded as fluvial, deposited in the lower reaches of a river draining a land area that lay towards Marie Byrd Land. Channels in the basal sand sheet indicate movement to the south-west, but orientation became more variable higher in the sequence. Four new measured sections are figured. The relationship of the Ohio Range to the rest of Antarctica during the Devonian is suggested.

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Key words: Beacon Supergroup, sedimentology, trace fossils, Transantarctic Mountains

Introduction

The Ohio Range is unique in that it is the only well documented locality in Antarctica where there is a record of fossiliferous marine sediment of Devonian age. Elsewhere in the Transantarctic Mountains the Devonian is represented either by a hiatus or by very limited fossiliferous outcrops (Ellsworth Mountains), or by nonfossiliferous sediment whose environmental interpretation is controversial, and whose age is uncertain.

In the Ohio Range the Horlick Formation constitutes the lowest formation of the Beacon Supergroup and overlies the level Kukri Erosion Surface cut across Cambro–Ordovician granitoids. The formation crops out along the northern face of the Ohio Range escarpment (Fig. 1), and preserved thickness varies from 0 to 56 m due to the relief on an overlying unconformity that is likely to have resulted from sub-glacial erosion during the late Palaeozoic. An Early Devonian age for the Horlick Formation is indicated by an abundant shelly fauna (Boucot *et al.* 1963, Doumani *et al.* 1965).

The sedimentology of the formation, based on 15 measured sections, was described in detail by McCartan & Bradshaw (1987), who interpreted the environments of deposition as sub-tidal inner shelf to shoreline, with storms producing an unstable pattern of coarse sand bars and finer troughs. A moderate tidal range of between 1–3 m is likely. The shoreline was low-lying with a wave cut platform that trimmed a deeply weathered and irregular land surface underlain by granitic rocks. The level trimming of a terrestrial landscape, followed by marine sediments, strongly suggests marine modification of the Kukri Erosion Surface in the Ohio Range. The source area for the Horlick Formation lay northwards towards Marie Byrd Land, and a westerly longshore drift carried detritus away from river mouth deltas. The sequence was described in terms of nine lithofacies (Table I), all but one of these being marine. Data from four additional sections measured during a later field visit are presented in Fig. 2.

The shelly fauna of the Horlick Formation is dominated by the brachiopod *Pleurothyrella antarctica* Boucot *et al.* (1963) and a variety of large Malvinokaffric bivalves that confirm shallow nearshore sedimentation (Bradshaw &

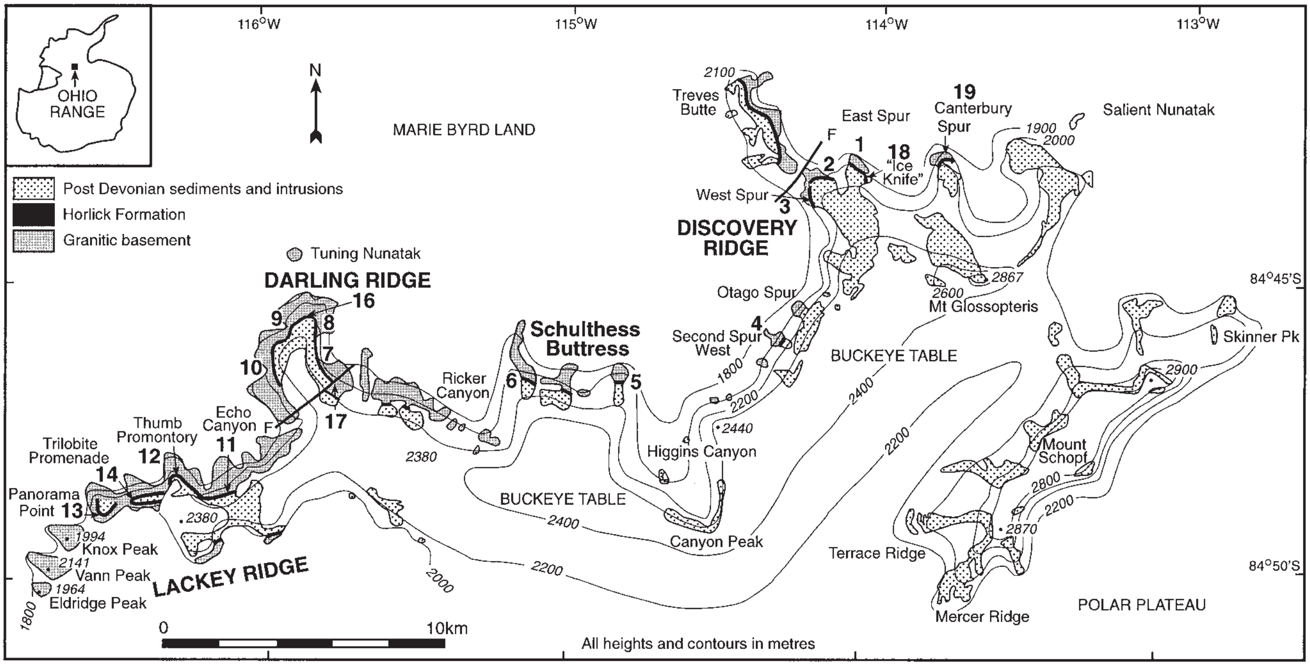


Fig.1. Outcrop of the Horlick Formation (black) along the north-facing Ohio escarpment with the location of measured sections indicated.

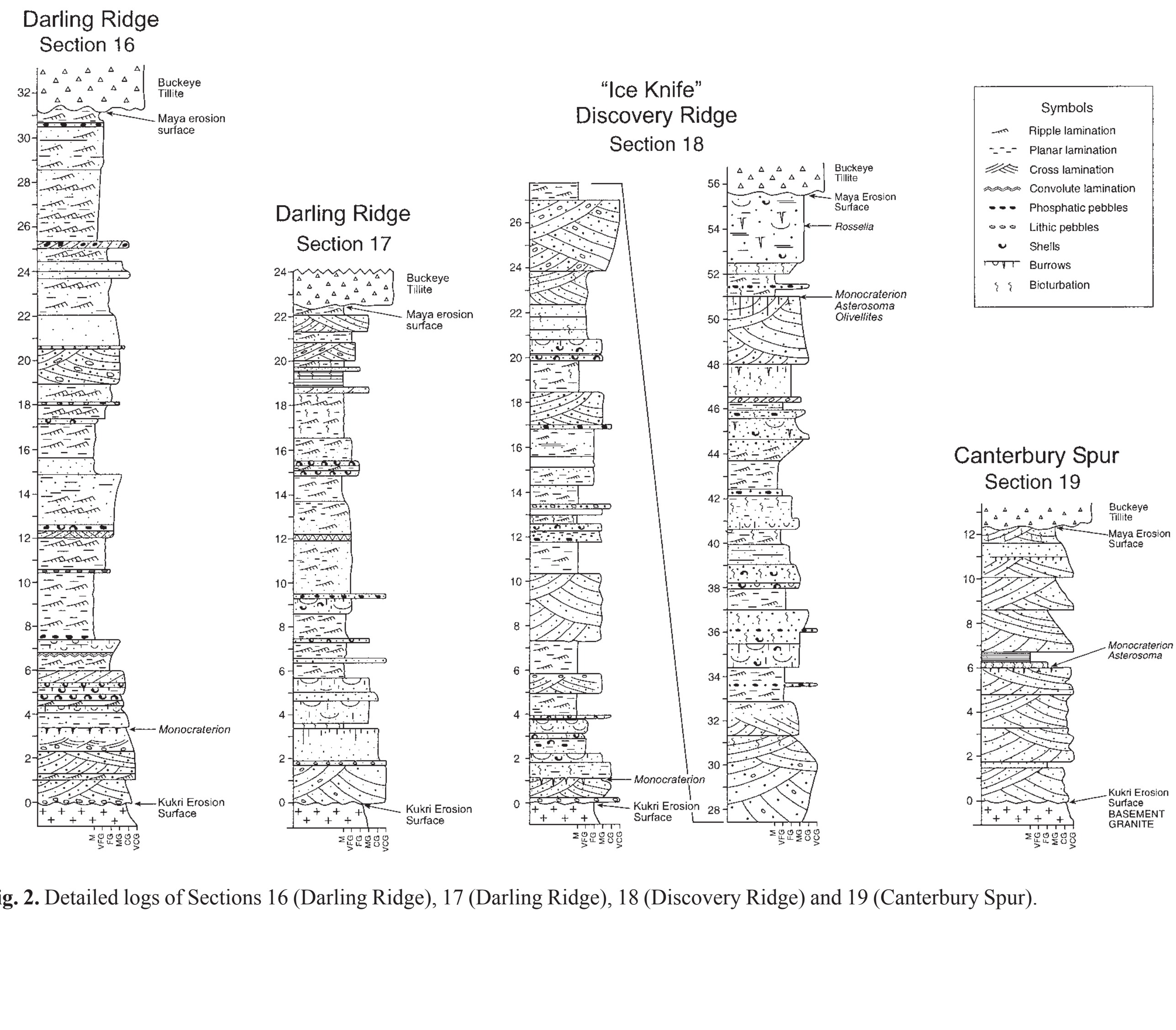


Fig. 2. Detailed logs of Sections 16 (Darling Ridge), 17 (Darling Ridge), 18 (Discovery Ridge) and 19 (Canterbury Spur).

Table I. Summary of lithological characters, depositional environments and faunal content of the nine lithofacies present in the Horlick Formation. Based on McCartan & Bradshaw (1987), Bradshaw & McCartan (1991), and trace fossils this paper.

Lithofacies	Characteristics	Environment	Max. thickness	Occurrence	Body fossils	Trace fossils
Cross-bedded Sand sheet Lithofacies (Lithofacies 1)	Coarse to very coarse-grained cross-bedded sandstones; thin siltstones; thin basal conglomerate.	Marine; tidal to upper shoreface, follows marine transgression;unbarred coastline.	10.5 m	Basal sandsheet; thin interbeds associated with Lithofacies 2 & 3	Rare *Pleurothyrella*, *Orbiculoidea*, finely comminuted fish bone; psilophyte plants.	*Monocraterion* Ichnocoenosis
Pleurothyrella Lithofacies (Lithofacies 2)	Medium to coarse-grained sandstones; burrowing moderate to intense.	Middle shoreface; side of subtidal sand bars.	5 m	Forms second sandsheet; interbedded with Lithofacies 3 & 7.	*Pleurothyrella, Orbiculoidea*, *Lingula, Tanerhynchia*; rare *Modiomorpha, Palaeosolen*, *Nuculites*; bryozoa.	*Catenarichnus* Ichnocoenosis
Laminated Mudstone Lithofacies (Lithofacies 3)	Interbedded mudstone & very fine-grained sandstone; lenticular & wavy-bedded; interbedded storm deposits.	Marine; tidal influence; flanks of sand-tongues & hollows between them.	2.5 m	Follows second sandsheet; repeated several times higher in sequence.	*Pleurothyrella* (broken in storm deposits); rare *Nuculites*, *Orbiculoidea*, trilobite fragments, psilophyte plants.	*Arenicolites* Ichnocoenosis. Discreet, short vertical & horizontal burrows
Feldspathic Lithofacies (Lithofacies 4)	Micaceous fine-grained feldspathic sandstones; ripple lamination, small-scale hummocky cross stratification & parallel lamination; well sorted.	Marine; top of sand-tongues; above wave-base.	2.5 m	Intimately associated with Lithofacies 3; repeated several times higher in sequence.	Rare *Pleurothyrella, Orbiculoidea, Obrimia* & *Ancryocrinus*?	*Cruziana-Rusophycus* Ichnocoenosis; *Arenicolites* Ichnocoenosis
Poorly-sorted Lithofacies (Lithofacies 5)	Coarse to very coarse-grained sandstones; poorly-sorted; trough cross-bedded; shale clasts.	Marine; deposited in long-shore channels or tidal delta channels near river mouths.	7.5 m	Also interbedded with Lithofacies 3 & 4.	Rare *Orbiculoidea, Obrimia, Machaeracanthus, Burmeisteria*.	*Spirophyton* Ichnocoenosis
Phosphatic Lithofacies (Lithofacies 6)	Fine to medium-grained feldspathic sandstones; poorly sorted; phosphatic clasts common.	Marine; lag deposits on seaward flanks of outer shoreface sand-tongues.	0.20 m	Usually very thin; repeated several times	*Orbiculoidea, Lingula, Pleurothyrella; Burmeisteria* fragments, fish plates & bone; rare *Nuculites* & *Obrimia*.	None
Shell-bed Lithofacies (Lithofacies 7)	Medium to coarse-grained feldspathic sandstones; poorly sorted; carbonate cement.	Marine; outer shoreface to open shelf.	0.25 m	Usually associated with Lithofacies 2 & 3.	Numerous molluscs, trilobites, brachiopods, etc. (see Bradshaw & McCartan 1991).	None
Spirifer Lithofacies (Lithofacies 8)	Fine to coarse-grained, muddy, feldspathic sandstones; poorly sorted; parallel bedded; burrowing common.	Marine; steeper parts of subtidal sandbars.	3.5 m	Only at top of sequence on Discovery Ridge.	*Australospirifer, Plectonotus, Prothyris, Obrimia*, crinoid remains, bryozoa.	*Rosselia* Ichnocoenosis
Schulthess Lithofacies (Lithofacies 9)	Medium to very coarse-grained, highly feldspathic sandstones to granule conglomerate; mudstone clasts; channelling & festoon bedding.	Fluvial channel	10 m	Only on Schulthess Ridge.	None	None

Fig. 3. Folded vein within a very large basic inclusion in basement quartz monzonite truncated by the pre-Horlick erosion surface. The erosion surface is overlain by a coarse, poorly-sorted basal breccio-conglomerate of angular vein-quartz, feldspar and lithic clasts. The black fragments above the erosion surface are phosphatic. The top part of the basal bed and the bed following show opposite sediment transport (herrirngbone structure) suggestive of tidal conditions. Arrow indicates hammer handle for scale.

McCartan 1991). Fossils are usually confined to thin bands representing death assemblages that were probably concentrated by storms. Interbedded quartzose and feldspathic sandstones contain few shells but have a significant ichnofauna (Bradshaw *et al.* 1984, Bradshaw & McCartan 1991). This ichnofauna will be described fully in a later paper (Bradshaw unpublished data), and is only summarized here.

This paper provides new information on the sedimentology of the Horlick Formation and its relationship to basement rocks, a review of its ichnofauna, a discussion of the palaeoenvironmental setting of the Ohio Range during the deposition of the Devonian, and a brief overview of the palaeogeography of the Transantarctic Mountains during the Devonian.

Relationship of Horlick Formation to basement

Like Devonian sediments elsewhere in the Transantarctic Mountains, the Horlick Formation overlies basement rocks with pronounced unconformity in the Ohio Range. On

Fig. 4. Lower part of Section 8 on Darling Ridge. The Kukri Erosion Surface below the first sand sheet (1–2 m thick) is clearly visible and truncates a weathered zone of variable thickness in the basement granitoid

Discovery Ridge and Treves Butte, the Kukri Erosion Surface truncates very large, altered basic inclusions in the basement granitoids (Fig. 3), but at most other localities the basement is homogenous quartz monzonite. Weathering of basement below the erosion surface is striking in some sections (e.g. Section 8, Darling Ridge), but the depth of weathered rock (0–10 m) varies greatly with location and appears to be a result of pre-Horlick trimming of an older, undulating weathered land surface (Fig. 4). The level nature of the trimmed surface, as well as an *Orbiculoidea* shell lying on the erosion surface at Echo Canyon, Lackey Ridge (Section 11), suggests that in the Ohio Range at least, the Kukri Erosion Surface achieved its final form as part of a wave-cut platform during the initial transgression of an Early Devonian sea (Bradshaw 1991). An extensively exhumed erosion surface is present on the north side of West Spur Discovery Ridge (base Section 2), and a smaller

Fig. 5. Wide channel, cut in basement quartz monzonite, infilled with sands of the Cross-bedded Sand sheet Lithofacies at the base of Section 16, Darling Ridge. At this locality the basal sand sheet is 3.5 m thick. Arrows points to basal contact.

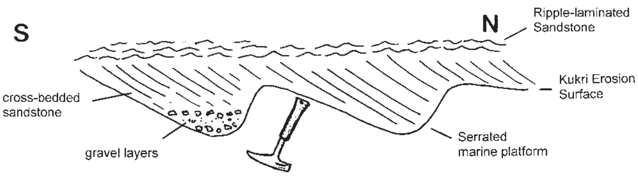


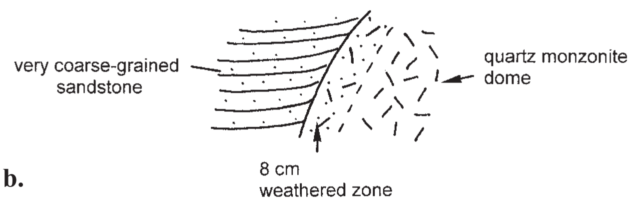
Fig. 6. Field drawing of serrated marine platform buried by sandstones of the Cross-bedded Sand sheet Lithofacies at the bottom of Section 18, east of the "Ice knife" on East Spur Discovery Ridge.

exposure occurs near Echo Canyon (Lackey Ridge, base Section 11).

Although the Kukri surface is level on a large scale, it sometimes shows a local relief of up to 2 m. Nowhere was the 20 m of relief seen that was reported by Long (1965). Post-Beacon Supergroup faulting occurs in the range, and Long's relief may be simply a disparity of heights of the erosion surface at localities separated by hidden faults.

The basal beds of the Horlick Formation are coarse, laterally discontinuous sandstones that infill depressions between low rounded domes (East Spur Discovery Ridge,

a.



b.

Fig. 7a. Rounded domes of quartz monzonite buried by sandstones of the Cross-bedded Sand sheet Lithofacies at the base of the Horlick Formation on Lackey Ridge between Sections 11 and 12. View looking south, uphill. Hammer for scale circled. Arrow x points to very coarse-grained, poorly-sorted feldspathic sandstone in between the domes. Arrow y indicates westward dipping cross-sets of sandwave burying the domes. The sediment here is well-sorted quartzarenite. **b.** Detailed field drawing of contact of Horlick Formation sediment (left) against quartz monzonite dome (right).

Fig. 8. Typical outcrop of the Horlick Formation showing the alternation of sandstone and mudstone lithologies. Sandstones of the Cross-bedded Sand sheet Lithofacies overlie basement quartz monzonite at the bottom of the photograph (black arrow). White arrow points to figure for scale. Type section for the Horlick Formation (Section 1) on East Spur Discovery Ridge.

Section 1), with the overlying continuous sand sheet often having a thin basal lag of angular quartz fragments. At other localities, very coarse, cross-bedded sandstones infill large channels down-cut into the basement (Darling Ridge, Section 16) and are followed by the main sand sheet (Fig. 5). At the base of Section 18 on the East Spur of Discovery Ridge, the Horlick Formation was deposited on a serrated marine platform, where coarse gravel accumulated in eroded troughs before the relief was buried by shoreward dipping tabular cross-beds (Fig. 6).

On Lackey Ridge between Echo Canyon (Section 11) and Thumb Promontory (Section 12) two very large granitic, dome-like bodies (horizontal diameter 7 m and 5 m) are buried by the lowest Horlick sediments (Fig. 7). Whether the domes are attached to, or simply rest on, basement is not clear in outcrop, but they appear to be residual giant domes of quartz-monzonite identical to the underlying basement. The domes show an 8 cm weathering rind, and the sediment infilling the space between them is very coarse-grained and poorly-sorted sandstone rich in plagioclase feldspar. The domes are likely to represent the harder remnants of terrestrially exfoliated granitoid masses that were denuded by wave-action during an Early Devonian transgression, and were eventually buried by the first sand sheet. Similar

Fig. 9. Coarse sandstones of the Cross-bedded Sand sheet Lithofacies in the basal sand sheet of Section 11 on Lackey Ridge. Bracket at right indicates possible tidal bundle. Arrow points to hummock-like drape. Scale in cm.

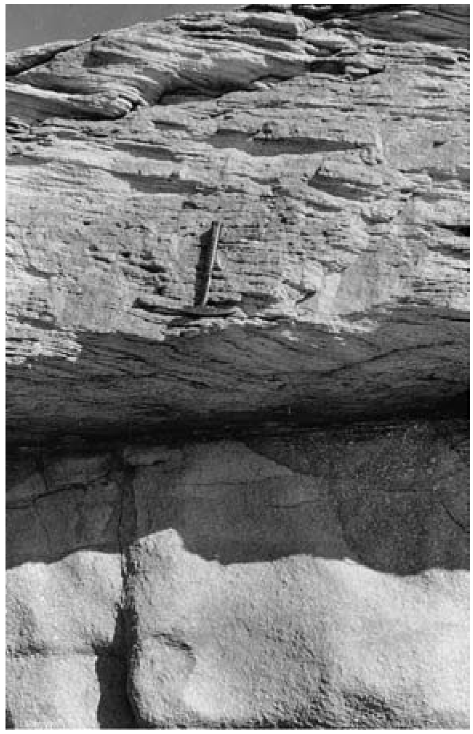


Fig. 10. Tabular sandstone cross-set (Cross-bedded Sand sheet Lithofacies), with fining up laminae and rippled bottomsets, burying a thin lag of phosphatic pebbles (not visible) that rests directly on phosphatized basement granite. Base Section 11, Echo Canyon, Lackey Ridge. Hammer for scale.

domes may be the source of very large, rounded granitic boulders that occur in the overlying glacigenic Buckeye Formation not far above its base. The boulders were probably recycled from areas where the Horlick Formation was being actively removed during the Late Carboniferous–Permian glaciation.

Horlick Formation: sediments, trace fossils, interpretation

The Horlick Formation comprises an alternating sequence of medium to coarse-grained sandstones and laminated mudstones, siltstones and fine sandstones (Fig. 8). The sequence was subdivided into nine numbered lithofacies (Bradshaw & McCartan 1983), which have been changed to names in this paper and summarized in Table I.

Body fossils are common at certain horizons (see Bradshaw & McCartan 1983), but lithologies in which they are scarce or absent, principally the sandstones, possess an abundance of trace fossils. Six ichnocoenoses can be recognized and are described below with the lithofacies in which they most commonly occur.

Cross-bedded Sand sheet Lithofacies

This lithofacies (Lithofacies 1 of McCartan & Bradshaw 1987) comprises coarse to very coarse-grained, cross-bedded quartzose or feldspathic sandstones in a sand sheet that is found at the base of most sections, and is repeated higher in the sequence only as very thin interbeds associated with sediments of the *Pleurothyrella* and Laminated Mudstone lithofacies.

In places, a thin basal conglomerate (up to 25 cm thick) is present, consisting largely of fine to medium pebble-size, angular vein-quartz clasts, but locally including lithic, phosphatic and feldspar clasts (Fig. 3). In some sections, however, the basal conglomerate is absent, and very coarse-grained quartzose sandstone rests directly on basement (e.g. Trilobite Promenade, Lackey Ridge, Section 14). At other localities, such as Section 16 (end Darling Ridge), the initial deposits are very coarse-grained to granule feldspathic sandstones, and quartzose sandstones tend to be finer-grained and confined to very thin interbeds.

The lower beds are generally cross-bedded, sometimes showing tidal bundles (Fig. 9, bracket), with thin siltstone horizons. Some cross-sets possess hummock-like sandstone drapes (Fig. 9, arrow). Near the base of Section 11 (Echo Canyon, Lackey Ridge), an extensive 1.70 m thick tabular cross-set with fining-up laminae and rippled bottom-sets buries a channel lag of phosphatic pebbles that rest directly on phosphatized basement granite (Fig. 10). Ripples indicate a south-west flowing current. The cross-set laterally truncates very coarse-grained sandstones interbedded with lenticular bedded silty shales that pass southwards into wavy and flaser bedded sediments. The outcrop pattern suggests a storm-wave dominated area passing laterally into a large sandwave that was migrating south-westwards along a channel bottom.

This lithofacies is sparsely fossiliferous (see Table I), and trace fossils are also scarce, largely consisting of the vertical burrows *Monocraterion* and *Skolithos* of the *Monocraterion*

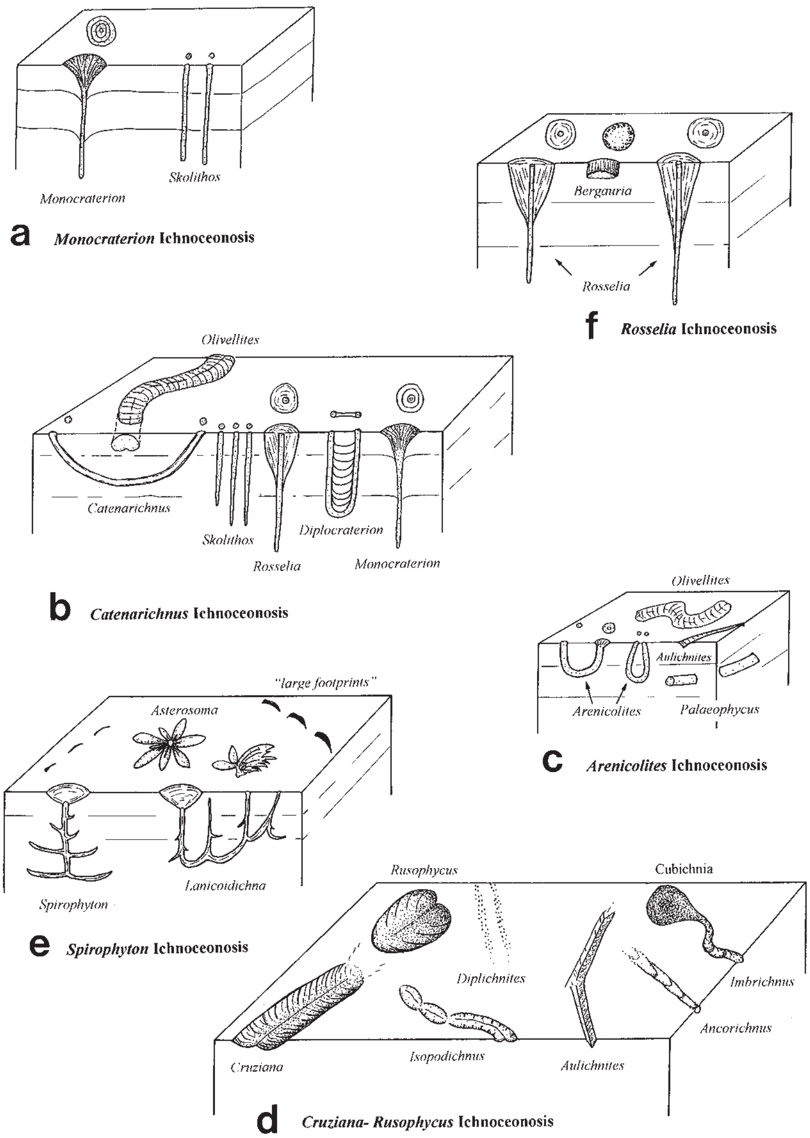


Fig. 11. Diagram to show component trace fossils of the six ichnocoenoses in the Horlick Formation (not drawn to scale).

Ichnocoenosis (Fig. 11a). The ichnocoenosis is best developed in horizontal and ripple-laminated fine to medium-grained sandstones at the top of the basal sand sheet where *Monocraterion* is common. Normally this is between 1–1.7 m above base (Sections 2, 11, 18), but where the basal sand sheet thickens, it occurs at 3.5 m (Section 16), or at 6 m and 10 m above base where the sand sheet is anomalously thick (Section 19). The bounding surfaces of beds containing this ichnocoenosis frequently possess numerous *Monocraterion* burrow openings (Fig. 12). Density of burrowing varies from relatively concentrated with 51 openings per m^2 (Section 1, 12 m above base) to relatively sparse with 18 openings per m^2 (Section 2, 1.5 m above base). The same bounding surfaces may contain scattered shells of *Orbiculoidea*, a shallow water inarticulate brachiopod.

The appearance of abundant *Monocraterion* could be used as a marker horizon in the lower sand sheet, indicating

Fig. 12. Bedding plane at the top of the lower sand sheet (Cross-bedded Sand sheet Lithofacies) showing numerous burrow apertures of *Monocraterion*; Section 16, Darling Ridge. Hammer for scale arrowed.

Fig. 13. Two *Pleurothyrella* Lithofacies horizons part way up the sequence in Section 11, Echo Canyon, Lackey Ridge. Two episodes of burrowing are visible. *Catenarichnus* (c), ?*Skolithos* (s) and *Diplocraterion* (d) are recognisable. Scale in cm.

a change of bottom conditions as the transgression continued landwards. This period of *Monocraterion* formation is usually followed closely by the *Pleurothyrella* Lithofacies.

Longitudinal sections of *Monocraterian* indicate prolonged colonization of the sandstones with upward adjustment of the funnel-shaped openings to keep pace with sedimentation, so producing a series of stacked funnels. Changes in grain size within the different laminae of the burrow suggest that the animal producing *Monocraterion* was able to cope with sand grains of very different sizes.

Skolithos, on the other hand, is sparser and largely limited to the basal beds of the sand sheet, consistent with its reputation of preferring high energy environments and shifting sands.

The Cross-bedded Sand sheet Lithofacies is interpreted as a wave-dominated, tidally influenced sequence of sand deposits, with local short-lived areas of mud deposition in which plant material settled out. A sparse fauna of trilobites and brachiopod shells in both sandstones and mudstones suggests that all sediment was marine, and that the mudstones were not paralic as suggested by Long (1965). The near-shore region was crossed by deeper flow-dominated channels. Ripple laminated finer sandstones containing trace fossils suggest deeper water sedimentation and the establishment of *Monocraterion* colonies, with burrows keeping pace with sedimentation.

Arnot (1991) obtained unusually high C/S ratios for four samples from very thin psilophyte-bearing shales in this lithofacies that suggest a freshwater environment, despite being enclosed by beds containing marine fossils and phosphatic material. The plant sample in the same bed as a trilobite provided the highest C/S ratio for the Horlick Formation (840 C:1 S, cf. Normal marine = 4 C:1 S), while two other samples from a single thin psilophyte-bearing shale provided markedly dissimilar C/S ratios (470 C:1 S and 20 C/1 S respectively). As Woolfe (1993) has used this data to suggest nonmarine conditions for unfossiliferous Devonian sediment in southern Victoria Land, these suggestions have to be viewed with suspicion. The anomalous C/S ratios for the Ohio Range beds may be the result of mobilization and removal of sulphur.

Pleurothyrella Lithofacies

(Lithofacies 2 of McCartan & Bradshaw 1987). Bioturbated, medium to coarse-grained sandstones containing *Pleurothyrella,* best developed in the second sand sheet. At a single locality on Darling Ridge (Section 9), *Pleurothyrella* Lithofacies sandstones rest directly on basement.

The initial *Pleurothyrella* sand sheet is usually made up of four distinct sand units, each about 50 cm thick, separated by thin (*c*. 10 cm) laminated shales. In outcrop, these beds weather as four discreet, step-like exposures. The *Pleurothyrella* Lithofacies is repeated several times higher in the sequence.

The sandstones are usually quartzose, sometimes poorly-sorted, and often highly bioturbated. The structure of each unit varies considerably from locality to locality. Where bioturbation is intense, internal lamination is lost and the bed has a hackly, yellow weathering appearance with pockmarked bedding planes. However, less bioturbated beds indicate amalgamation of sandstones with alternating cycles of burrowing and sedimentation, the latter sometimes preceded by erosion (Fig. 13).

An anomalous, rounded, bryozoan-encrusted quartz pebble, 4 cm in length, was found at the top of one *Pleurothyrella* bed on Darling Ridge (Section 10) and suggests a prolonged break in sedimentation. A similar period of non-deposition is shown by the top of a bed on Lackey Ridge (Trilobite Promenade) near the base of Section 14 which is current smoothed and studded with small phosphatic pebbles, fish bone and shells similar to the Phosphatic Lithofacies (see below). Sediment banked behind these clasts suggests transport from north-west to south-east, a similar current direction to that indicated by parting lineation in sandstone interbeds in the overlying Laminated Mudstone Lithofacies beds. To the south, the smoothed surface is overlain by 90 cm of very coarse-grained cross-stratified *Orbiculoidea*-bearing sandstone that wedges out eastwards. This is interpreted as interfingering of the Cross-bedded Sand sheet Lithofacies with belts of *Pleurothyrella* and Laminated Mudstone lithofacies further offshore.

Shells are usually absent or rare in the strongly bioturbated units, suggesting diagenetic solution, but are more common where burrowing is less intense (see Table I). Thick bryozoan encrustations were observed on some *Pleurothyrella* shells (Bradshaw & McCartan 1991 fig. 6).

The *Pleurothyrella* Lithofacies contains the

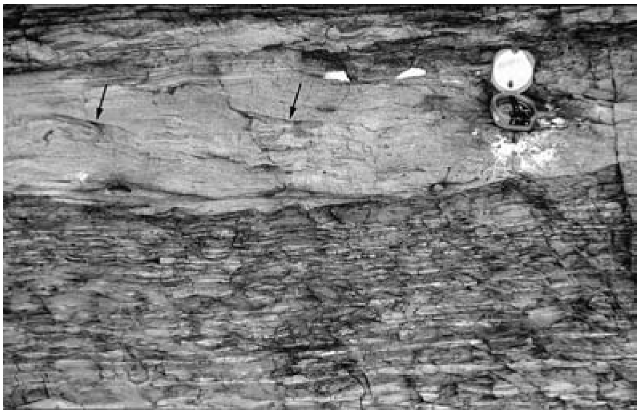


Fig. 14. Cross-bedded sandstone unit of the Poorly-sorted Lithofacies, with shale (arrows) and fish bone clasts visible on the forsets, interbedded within the Laminated Mudstone Lithofacies. Section 1, East Spur Discovery Ridge. Brunton Compass for scale.

Catenarichnus Ichnocoenosis (Fig. 11b), which is repeated several times above the second sand sheet in the same lithofacies. *Rosselia socialis*, produced by a mud-filtering or deposit feeding organism, is particularly common, with funnels terminating at several different levels, indicating an animal that was unable to adjust its burrow to repeated alternations of sedimentation and non-deposition.

Large arc-shaped *Catenarichnus antarcticus* (Bradshaw 2002) is most obvious in the top of less bioturbated beds (Fig. 13), and the largest burrow observed was 37 cm between arc arms, and 11 cm deep. It is common to find these burrows partially or largely removed by erosion before further deposition, and in some cases bedding planes contain only the lowest portion of the burrow. Occasionally, a deep and well preserved *Catenarichnus* burrow faithfully mirrors a shallower partially collapsed one, suggesting attempts by the animal to burrow more deeply as erosion occurred (c in Fig. 13).

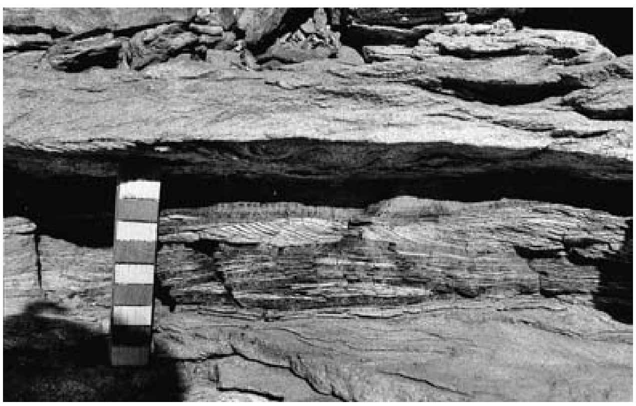


Fig. 15. Thin interbed of Laminated Mudstone Lithofacies within Feldspathic Lithofacies sandstones, showing mud-draped asymmetrical ripples with associated reactivation surfaces and stoss side sedimentation that suggest tidal influence. Section 11, Echo Canyon, Lackey Ridge. Scale in cm.

Narrow, poorly preserved, vertical to oblique burrows, tentatively identified as *Skolithos* (s in Fig. 13), postdate *Catenarichnus*. A vertical burrow 2 cm wide and 13 cm deep in the top part of one bed may have been formed by the burrowing bivalve *Palaeosolen*, external moulds of which have been recorded from the top of other beds (Bradshaw & McCartan 1991).

The U-shaped burrow *Diplocraterion parallelum*, which has parallel arms and a meniscate structure, is also occasionally preserved (d in Fig. 13), especially in less bioturbated beds. At least one example showed retrusive (upward) behaviour, followed by protrusive (downward) behaviour, indicating fluctuating sedimentation rates. The vertical burrows *Monocraterion, Cylindricum,* and the horizontal, back-filled burrow *Olivellites,* also occur.

The lithology and trace fossil content of the *Pleurothyrella* Lithofacies suggest that these beds were probably slowly deposited, with significant periods of non-deposition and erosion. The environment is likely to have been below wave base but subject to moderate current activity at times. The four layer construction of the second sand sheet, with its very thin mudstone “spacers”, may reflect short-lived transgressions onto the land area during which time only mud accumulated on the sea floor beyond the surf zone. The transgressions were followed by longer regressive periods of sand sedimentation below wave base and the establishment of a prolific infauna. Rapid changes in bottom current activity created alternating periods of sedimentation and erosion, which is reflected in the burrowing behaviour of the infauna. Higher in the sequence this lithofacies probably developed on the sides of subtidal sandbars.

Fig. 16. Sediments of the Laminated Mudstone Lithofacies grading up into ripple-laminated sandstones and parallel-laminated flaggy sandstones of the Feldspathic Lithofacies. A small channel has been eroded into the Laminated Mudstone/Feldspathic Lithofacies couplet and is infilled with coarse sandstones of the Poorly-sorted Lithofacies. Section 3, West Spur Discovery Ridge. The depth of the channel is 30 cm.

Laminated Mudstone Lithofacies

In this lithofacies (Lithofacies 3 of McCartan & Bradshaw 1987) lenticular and wavy-bedded mudstones are interbedded with thinly laminated, very fine sandstones (Fig. 14). Mud-draped asymmetrical ripples with associated reactivation surfaces and stoss side sedimentation at Echo Canyon, Lackey Ridge (Section 11) suggest tidal influence (Fig. 15). The Laminated Mudstones are often interbedded with thin horizons (e.g. 11 cm) of poorly sorted, very coarse, storm deposited sandstones containing fragmented *Pleurothyrella* shells. Thicker interbeds with erosive bases are of cross-laminated sandstones of the Poorly-sorted Lithofacies and have shale and bone clasts along foresets (Fig. 14, arrow).

A unit of Laminated Mudstone Lithofacies, 2–2.5 m thick, always follows the second sand sheet near the base of the succession, but the lithofacies is repeated several times higher in the sequence.

Body fossils are rare (see Table I) and trace fossils are generally not common, although more bioturbation was observed at the eastern end of the range in this lithofacies (e.g. East Spur Discovery Ridge, Section 18), than at its western end. The ichnofauna is discreet, part of the *Arenicolites* Ichnocoenosis (Fig. 11c) which comprises *Arenicolites*, *Aulichnites*, *Palaeophycus* and *Olivellites*. Many of the short, irregular vertical and horizontal burrows infilled with fine sandstone or siltstone are difficult to identify. Rare horizontal burrows with horizontal meniscus have been identified as *Teichichnus*.

The establishment of this lithofacies following the deposition of the second sand sheet suggests that the sea continued to deepen as the Early Devonian transgression progressed. The depositional area became affected by storms which produced a bar-and-trough bottom topography, with the laminated mudstones accumulating in the troughs. The troughs experienced tidal currents as shown by the nature of the ripples. Major storms swept coarser material out from the shore, and produced the thin, poorly sorted sandstones with broken shell material that are interbedded with the mudstones.

The Feldspathic Lithofacies

This lithofacies (Lithofacies 4 of McCartan & Bradshaw 1987) comprises fine-grained, well-sorted, commonly micaceous, feldspathic sandstones. Interference ripples are common, often with mud drapes. Thin, parallel laminated sandstones that show good parting lineation, and into which the ripple laminated sandstones frequently grade (Fig. 16), are included in this lithofacies. Convoluted horizons up to 15 cm thick are occasionally present and ripple sets sometimes show deformation. The ripple-laminated sandstones contain the highest proportion of plagioclase to potassium feldspar in the Horlick Formation ((McCartan & Bradshaw 1987).

This lithofacies is intimately associated with the Laminated Mudstone Lithofacies and the two may alternate within a single unit. The Feldspathic Lithofacies is also interbedded with erosive based sandstones of the Poorly-sorted Lithofacies, and was observed grading up into cross-bedded sandstones with shale clasts of the same lithofacies (Darling Ridge, Section 16).

Body fossils are rare (see Table I), but trace fossils are common, and two ichnocoenoses are present; the *Cruziana-Rusophycus* Ichnocoenosis and the *Arenicolites* Ichnocoenosis. The *Cruziana–Rusophycus* Ichnocoenosis (Fig. 11d) is confined to the more thickly bedded horizons, such as 13 m above base at Trilobite Promenade, Lackey Ridge (Section 14), although some of its elements are found in thinner sandstones in other sections. The ichnocoenosis comprises *Cruziana rhenana, Rusophycus*, *Imbrichnus*, *Diplichnites gouldi, Diplichnites*, *Isopodichnus*, *Ancorichnus* cf. *capronus* and *Aulichnites*.

Cruziana, *Rusophycus* and *Diplichnites* are all consistent with surface trails produced by trilobite-like animals, although no skeletal material is known from these beds. However, disarticulated fragments of *Burmeisteria (Digonus) antarcticus* are particularly common in the Shell-bed Lithofacies, indicating that trilobites were present in the depositional basin. Some of these trilobites grew to a large size (width of the largest observed head shield was 18 cm), and although this size is consistent with the width of some of the Horlick Formation *Diplichnites* trackways, it is too large to have made the *Cruziana* and *Rusophycus* traces, except as juveniles.

Isopodichnus, a different trail, also occurs in this lithofacies. The simplicity of appendage scratch marks suggests that, although its producer was probably a small arthropod, it was not a trilobite.

The horizontal, back-packed burrow *Ancorichnus* cf. *capronus* is confined to fine-grained, rippled sandstones at Trilobite Promenade and in several other sections. It is likely to have been made by an opportunistic animal following storm intervals. Opinion is divided as to whether these animals were polychaetes or small arthropods.

Imbrichnus, intimately associated with larger indeterminate Cubichnia, also has doubtful origins and could have been created by either a mollusc (?gastropod; these are common in some beds) or arthropod (?crustacean). The poorly defined backfill of this prominent burrow, together with possible leg scratch marks and smooth, rounded marks at one end of resting depressions along the burrow, favour a crustacean animal. This animal was burrowing either immediately below the sediment/water interface or produced a surface trench in poorly consolidated sediment as it methodically searched the sediment for food, pushing material behind it as it went.

A single example of *Aulichnites*, possibly made by a small crawling spired gastropod (e.g. *Holopea*), occurs alongside *Rusophycus* at Trilobite Promenade.

The *Arenicolites* Ichnocoenosis is confined to horizontal and rippled laminated beds in this lithofacies and predominantly comprises the U-shaped, spreitenless burrow *Arenicolites.* These particular examples have deeper, more closely spaced, downward-diverging arms compared to the *Arenicolites* in other lithofacies, and the exhalent aperture lacks a sand collar. The U-shaped burrows indicate the presence of worm-shaped animals, such as small holothurians, that were either suspension feeders, deposit feeders, or a combination of both.

Both ichnofaunas suggest the passage of transient animals across the sediment surface and short-lived opportunistic shallow burrows after sedimentation. Deposition was probably rapid.

The Feldspathic Lithofacies represents well-sorted sand tongues that migrated across mud infilled hollows containing Laminated Mudstone Lithofacies sediment (McCartan & Bradshaw 1987). While the lower part of the sand tongues and adjacent troughs experienced tidal influences, the top of the sand tongue was at, or above, wave base. Sedimentation at wave base produced interference ripples, whereas sediments above this level were deposited as low angle, thinly bedded, planar cross-bedded laminae (Fig. 16). Parting lineation on the thin foresets indicate a high flow regime, probably caused by strong onshore wave action and shoreward movement of sediment, predominantly from the south-south-east to north-north-west. The sand bars were colonized by burrowing animals, but many of these may have had to relocate due to wave action.

The high proportion of feldspar suggests that more fresh material was accumulating in this lithofacies than elsewhere in the succession. It implies rapid transport and accumulation of material from a rugged granitic landscape that was suffering little chemical weathering, possibly due to low temperatures. In other lithofacies, the feldspar was either mechanically worn down, or diagenetically reduced to clay in beds that were relatively slowly deposited, full of organic material and highly burrowed, such as the *Pleurothyrella* Lithofacies. Convoluted horizons and deformed ripples in the Feldspathic Lithofacies also suggest rapid deposition.

The Poorly-sorted Lithofacies

This lithofacies (Lithofacies 5 of McCartan & Bradshaw 1987) includes trough cross-bedded, coarse to very coarse-grained, poorly-sorted sandstones with occasional shale clasts. Black phosphatic pebbles may be present above the erosional base of some sandstones.

This lithofacies can occur in units up to 7.5 m thick, or be interbedded with horizons of Laminated Mudstone or Feldspathic lithofacies (see Fig. 14). Sandstone beds were observed grading up into ripple laminated sediments of the Feldspathic Lithofacies, and also downcutting into Laminated Mudstone/Feldspathic lithofacies couplets (as in Fig. 16). Current action was strong for the coarser beds and sedimentation was probably rapid.

Body fossils are rare (see Table I) and usually confined to the better sorted, medium-grained sandstones, especially where these are interbedded with Laminated Mudstone and Feldspathic lithofacies sediments. Trace fossils are also rare and form the *Spirophyton* Ichnocoenosis (Fig. 11e), which comprises the burrows *Spirophyton, Asterosoma, Lanicoidichna*, and "large footprints". The assemblage is best seen in a thin coarse-grained sandstone 23 m above base on East Spur Discovery Ridge (Section 1).

The ichnocoenosis is characterized by large *Spirophyton* burrows infilled by mud from the overlying mudstone. The radiating burrow system *Asterosoma* in the same bed occasionally exhibit *Spirophyton*-like spreite ridges at the base of some of the blind radiating tunnels, suggesting a common creator. *Lanicoidichna*, a ramifying burrow system made up of both horizontal and vertical elements, is also common at this horizon and there are many instances where parts of this burrow system appear very like incomplete *Spirophyton.*

It is possible that the three types of burrow reflect different behaviour by the same animal, with the complicated *Spirophyton* burrow produced when food was plentiful, dwelling burrows (*Asterosoma*) produced at other times, while exploratory tunnels excavated in search of food (*Lanicoidichna*) were created when food was short.

The "large footprints" found in a short single line on the top of a poorly-sorted sandstone on Lackey Ridge, represent part of one side of a double row of superficial footprints. A large arthropod animal (not a trilobite) is thought to have produced these prints, which have a completely different pattern to those produced by trilobites.

The paucity of both trace fossils and body fossils in this lithofacies, suggests that the environment was not amenable to life, probably because rapid sedimentation discouraged bottom faunas. Only in the more slowly deposited beds, or along the top of a deposited unit, do trace fossils become common.

The erosional contact of this lithofacies with the Feldspathic Lithofacies, and the occasional gradation between the two, suggests that the migrating feldspathic sandstone bars were bisected by active longshore marine or tidal delta channels near river mouths, in which the Poorly-sorted Lithofacies sediment accumulated.

Phosphatic Lithofacies

The Phosphatic Lithofacies (Lithofacies 6 of McCartan & Bradshaw 1987) comprises thin (1–20 cm), fine to medium-grained, poorly-sorted feldspathic sandstones in which phosphatic clasts are common (phophatized mud pebbles, fish bone and plates, trilobites and inarticulate

Fig. 17. Heavily burrowed, parallel-bedded, poorly-sorted sandstones of the *Spirifer* Lithofacies at the top of Section 1, East Spur Discovery Ridge. Hammer for scale.

brachiopods). This lithofacies is present in most sections and though repeated several times, comprises only a small proportion of the total succession.

Body fossils are common (see Table I), but no trace fossils have been observed.

Most of the phosphate in the Horlick Formation is concentrated into these beds. Phosphatization of sediment just below the sediment-water interface can occur in epicontinental seas, seaways, and coastal embayments during prolonged pauses in sedimentation, often in shallow water (Cook 1984). Renewed wave action, sometimes associated with marine transgression onto the land surface, led to ripping up of the phosphatic sediment (and fossils) and distribution of the debris, sediment and shell fragments, as thin units. The phosphate rich beds are therefore thought to represent short, renewed marine transgressions across the basin.

Shell-bed Lithofacies

The Shell-bed Lithofacies (Lithofacies 7 of McCartan & Bradshaw 1987) comprises thin (25 cm or less), medium to coarse-grained, feldspathic, and calcareous sandstones in which fossils are abundant (see Bradshaw & McCartan 1991 for details). The lithofacies is present in most sections, often repeated several times, but overall is relatively rare. The tops of some beds are crowded with current-oriented tentaculitids.

Body fossils occur in dense accumulations and include mainly molluscs (bivalves and bellerophontids) brachiopods and trilobites. No trace fossils were observed.

These beds are typical tempestites produced during major storms. Offshore shelly bottom faunas were probably exhumed by storm waves and their shells concentrated by winnowing, with the lighter tentaculitid shell fraction being deposited last at the top of the bed as storm-energy waned.

Spirifer *Lithofacies*

The *Spirifer* Lithofacies (Lithofacies 8 of McCartan & Bradshaw 1987) is present only on Discovery Ridge having been probably removed elsewhere by Late Carboniferous–Permian glacial erosion. The lithofacies comprises parallel-bedded, poorly-sorted, muddy, fine to coarse-grained sandstones, with layers of subrounded quartz granules, or shell debris, and occasional cobbles of phosphatized sediment with bryozoan fossils (Fig. 17).

Body fossils are common (see Table I) and include *Australospirifer* for the first time in the Horlick sequence. Crinoid holdfasts also occur, and some thick-shelled molluscs have encrusting bryozoan colonies, which in some cases have become detached and buried separately (see Bradshaw & McCartan 1991, fig. 5). The fine-grained sediment infill of articulated shells found in coarse sandstone (Bradshaw & McCartan 1991, fig. 4) suggest exhumation by storm waves from a siltstone host and reburial in a coarser grained, higher energy environment.

Burrowing is abundant in this lithofacies with local destruction of primary lamination. Trace fossils comprise the *Rosselia* Ichnocoenosis (Fig. 11f), which is dominated by long, well developed *Rosselia socialis*. Burrows extend downwards from many different horizons, suggesting pauses in sedimentation, while erosion of the funnel entrance of some burrows, to leave only the sand infilled lower tube, indicates a period of erosion after burrowing and before renewed deposition.

The base of some sandstones contain large *Bergauria* cf. *Langi*. These are short vertical depressions that were excavated in the top of underlying mudstones later becoming infilled with coarse granular sandstone. The *Arenicolites* Ichnocoenosis is present in thin horizons where *Rosselia* is absent.

The *Rosselia* Ichnocoenosis is believed to have developed in a fully marine, probably middle shoreface environment, supported by the presence of spiriferid brachiopods and crinoidal remains. *Rosselia* is likely to have been made by a deposit or filter feeding worm-like animal that preferred stable conditions. *Bergauria* may have had a sea anemone origin.

Arnot (1991) obtained high C/S ratios from a muddy interbed within the *Spirifer* Lithofacies which, in his view, indicated a brackish water environment of half normal salinity. This is difficult to accept when interbedded faunal evidence such as crinoid debris and spiriferid brachiopods indicate fully marine offshore conditions. As mentioned in the Cross-bedded Sand sheet Lithofacies, anomalous C/S ratios may be the result of leaching of sulphur and its concentration elsewhere.

Schulthess Lithofacies

The Schulthess Lithofacies (Lithofacies 9 of McCartan &

Bradshaw 1987) comprises thick, cross-bedded, medium to very coarse-grained, highly feldspathic sandstone to granule and pebble breccio-conglomerate, containing deformed mudstone clasts. Channel and festoon bedding are common. This lithofacies is found only on west Schulthess Buttress (Section 6) and sedimentary structures suggest that it was probably deposited in a fluvial channel setting (McCartan & Bradshaw 1987). No body or trace fossils have been observed in this lithofacies.

Sedimentation summary

There is a recognisable sequential pattern to lithofacies in the lower part of most sections. Throughout the Ohio Range the basal erosion surface is overlain by an almost continuous sand sheet composed largely of the marine Cross-bedded Sand sheet Lithofacies, but which at one locality (Section 6) merges laterally into by the coarser fluvial sandstones and breccio-conglomerates of the Schulthess Lithofacies (west Schulthess Buttress). In Section 9 on Darling Ridge the basal sand sheet is absent and at the extreme end of Lackey Ridge, north of Section 13 (Panorama Point), it is very thin (80 cm). As well as at west Schulthess Buttress (10 m), the sand sheet increases in thickness at other points, such as on Canterbury Spur (Section 19) where it is 10.5 m thick, and on Treves Butte. Although Treves Butte could not be climbed because of sheer cliffs and steep snow slopes, an American party, based in the Wisconsin Range, visited the site by helicopter in January 1965 and recorded 11 m of "barren" (unfossiliferous) sandstone in the basal sand sheet below *Pleurothyrella*-rich sandstones at the bottom of a 21 m section (G.A. Doumani, personal communication 1981). Channel orientation in the basal sand sheet is predominantly north-east–south-west with movement of sediment towards the south-west.

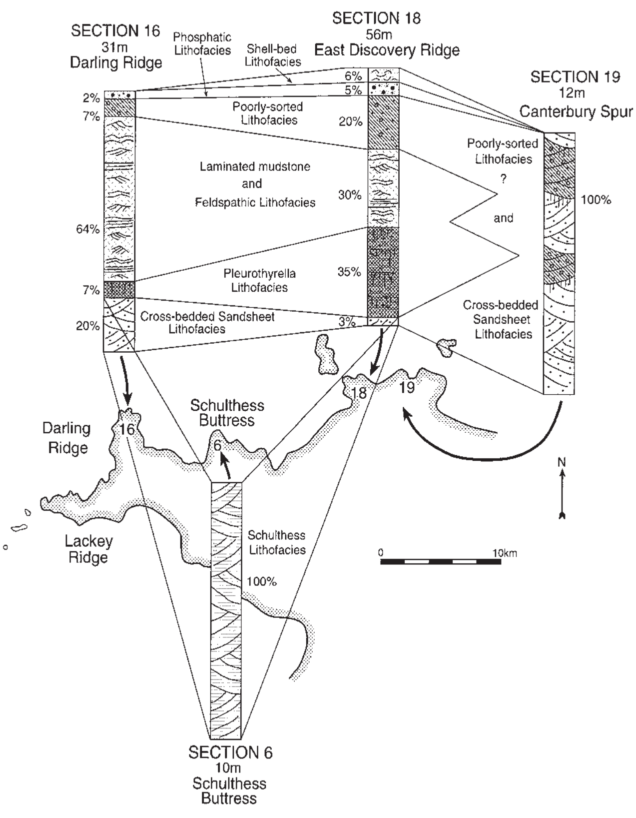


Fig. 18. Aggregate percentages of different lithofacies in four sections along the Ohio Range escarpment. For detailed logs of sections 16–19 see Fig. 2. For all other sections see McCartan & Bradshaw (1987).

In all sections but Section 9 (Darling Ridge), the basal sand sheet is followed by a second sand sheet between 1 m and 2 m thick composed of burrowed *Pleurothyrella* Lithofacies sandstones. In Section 9 the *Pleurothyrella* Lithofacies rests directly on basement granite and suggests onlap onto a local basement rise of several metres height.

The second sand sheet is always followed by the Laminated mudstone Lithofacies, which is closely associated (both laterally and vertically) with moderately well-sorted, fine sandstones of the Feldspathic Lithofacies. In each section the lowest unit of the Laminated Mudstone Lithofacies is relatively thick (e.g. 2.5 m, Section 17), but higher in the sequence it occurs as thinner interbedded units.

The upper part of the Horlick Formation tends to be more variable. Coarse-grained sandstones of the Poorly-sorted Lithofacies are found interbedded with repetitions of the Laminated Mudstone and Feldspathic lithofacies, while thin units of Phosphatic and Shell Bed lithofacies are found scattered throughout all but the top of the sequence. An attempt was made to correlate the shell-bed horizons, and four main beds appear to be present; one 6–7 m above base, a second at 10–13 m, a third at 15–19 m and a fourth at 36–38 m above base. However, correlation was difficult because the thickness of many sections has been reduced by pre-Permian erosion, and at only five sections (1, 2, 3, 10 and 18) does the succession exceed 30 m. It was noted that the thin phosphatic pebble horizons, possibly marking transgressive events, occur at roughly similar heights above base as do the shell-bed horizons (e.g. 5–6 m above base, 9–11 m, 12–15 m, 17–18 m), suggesting that the shell beds may have developed not long after significant transgressive events. The *Spirifer* Lithofacies is confined to the top of the thickest sequence (East Spur Discovery Ridge sections 1, 2 & 18). Channel orientation and sediment movement seem more variable in the higher sandstones than in the initial sand sheet. Parting lineation, found principally in low angle planar-bedded sandstones of the Feldspathic Lithofacies, has a predominant north-west-south-east direction, with a secondary north-east-south-west lineation, and a less common north-south lineation.

The proportion of different lithofacies varies throughout the range, and lateral changes are rapid. However, there seem to be broad differences in the percentages of lithofacies present between the western end of the Ohio escarpment (Darling Ridge, Section 16) and the eastern end ("Ice knife" on East Spur Discovery Ridge, Section 18) (Fig. 18). For example, at the western end 64% of the total section is composed of the finer elements of the formation, represented by a combination of the Laminated Mudstone and Feldspathic lithofacies, compared with only 30% at the eastern end. It was noted that burrowing is more obvious in the Laminated Mudstone Lithofacies at the eastern end of the range compared with the west. The Cross-bedded Sandstone Lithofacies is better represented in the west (20% W cf. 3% E), but the *Pleurothyrella* Lithofacies (7% W cf. 35% E), Poorly-sorted Lithofacies (7% W cf. 20% E), Phosphatic Lithofacies (2% W cf. 5% E) and the Shell-bed Lithofacies (0% W of the sequence cf. 7% E) are reduced.

Between Darling and Discovery ridges, on Schulthess Buttress W (Section 6), the entire 10 m sequence is comprised of uniform sandstones of the Schulthess Lithofacies, probably deposited in the lower reaches of a river mouth. More typical Horlick lithologies lie 4 km to the east (Section 5) and 7 km to the west (Section 17) into which the Schulthess Lithofacies must merge laterally over these distances. The most easterly measured section in the range (Canterbury Spur, Section 19, see Fig. 2) is 10.5 m thick and is also composed entirely of sandstone, in this case comparable to the Cross-bedded Sand sheet and Poorly-sorted lithofacies. Although the section contains no body fossils, marine trace fossils (e.g. *Monocraterion, Asterosoma*) are present at several horizons. This section may also have been deposited close to a river mouth delta that was interfingering west with the coarse sandbars and finer troughs represented by Section 18 on the east side of Discovery Ridge 3 km away (Fig. 2), and north-west with the "barren" sandstone unit on Treves Butte. The unusually thick sandstone units in Section 18 between 7 & 10 m and 24 & 31 m tend to support this.

A high proportion of basal sand sheet sandstone is quartz-rich due to removal of feldspar in the basement regolith by weathering. McCartan & Bradshaw (1987) record less than 5% feldspar in some sections.

Thickening of the basal sand sheet, infilling of channel structures and an increase in the proportion of feldspar proximal to the Schulthess Lithofacies at Schulthess Buttress is consistent with accumulation close to a large river mouth that was discharging freshly eroded material into the area, where it was rapidly deposited. Elsewhere, the basal sandstones were probably accumulating in more shallow water, closer inshore, where less feldspar survived. Longshore drift was westward and another river mouth to the east must have supplied sediment to the sections between Schulthess Buttress and Discovery Ridge (McCartan & Bradshaw 1987). The thick basal sandstones on Canterbury Spur and Treves Butte may mark the position of this second river mouth.

Palaeoenvironmental summary

The lowest sand sheet was produced by active sedimentation associated with a marine transgression. It was followed by the second sand sheet representing periodic but relatively uniform deposition over a broad area in an epeiric sea, with each phase followed by profuse bioturbation, and exhumation and disarticulation of shallow water brachiopods (Figs 13). The lower two sand sheets preceded the development of a bar-and-trough bottom topography represented by the Laminated Mudstone and Feldspathic lithofacies, where gradations between the two lithofacies are common.

The occasional gradation of the Feldspathic Lithofacies into the Poorly-sorted sandstone Lithofacies, without the more usual interdigitation, or an erosional contact, suggests that the migrating bars were bisected by active longshore marine channels, or tidal delta channels near river mouths.

The thin beds of the Phosphatic Lithofacies are likely to represent short, renewed marine transgression onto the adjacent land area, the effects of which were felt across the entire basin.

The Shell-bed Lithofacies represents typical tempestites, with the shells of bottom faunas becoming concentrated by wave action. The shell beds represent major storm events that were widespread across the depositional basin.

The Schulthess Lithofacies is recognized by its coarseness and lack of body and trace fossils. It occurs clearly at only one locality, but may be present to a lesser degree at the base of the sequence on Canterbury Spur, and possibly also on Treves Butte.

Antarctic Devonian palaeogeography

Two facts prevent a comprehensive overall reconstruction of Antarctic sedimentary basins during the Devonian.

Firstly, most localities do not show a conformable passage upwards from the highest preserved Devonian beds into Carboniferous or younger beds. In most cases the Devonian is truncated by the Maya Unconformity below the Late Carboniferous–Permian glacial sequence, and an unknown amount of Devonian sediment may have been removed throughout the Transantarctic Mountains. The exception is the Ellsworth Mountains where the Wyatt Earp Formation is considered to be Devonian in age, with a maximum thickness of 300 m in the Sentinel Range. In the Heritage Range, where the only Devonian fossils in the formation are found, the top of the sequence contains interbedded conglomerate similar to the overlying Late Carboniferous–Permian Whiteout Conglomerate Formation (Spörli 1992). In the adjacent Sentinel Range, the upper part of the Wyatt Earp Formation contains isolated pebbles that are thought to have been ice rafted. A continuous section into Carboniferous rocks appears to be present in both ranges, although the Devonian–Carboniferous boundary cannot be identified. In places there is deformation of sediment below the conglomerate and local erosional contacts (Spörli 1992), but this could be intra-Carboniferous.

Secondly, where the lower part of the Taylor Group (Beacon Supergroup) rests unconformably on older rocks, the beds are difficult to date at most localities because no body fossils are present. The exceptions are the Ohio Range, where a shelly fauna (no graptolites, conodonts or ammonoids) suggests an Emsian (lower Devonian) age, and the McMurdo Dry Valley region, where poorly preserved palynomorphs suggest an age little older than Emsian. Middle to Late Devonian fish fossils in southern Victoria Land provide a reliable age for the upper part of the Taylor Group below the glacial Maya Unconformity, but these beds (Aztec Formation) exist only between the Mackay and Darwin glaciers.

The Devonian of the Ellsworth Mountains (Wyatt Earp Formation) occurs at the top of a very thick, apparently conformable, Palaeozoic clastic sequence (Crashsite Group), which ranges from Late Cambrian (Shergold & Webers 1992) to Devonian in age (Webers *et al.* 1992). A limited Devonian fauna was collected from a 128 m thick section of Wyatt Earp Formation near Planck Point, Heritage Range (Webers *et al.* 1992), and provided the first definite age. The fossils, which occur in concretions in sandstone, are identical to those found in the Ohio Range (personal observation) and a similar Emsian age is likely. Deposition occurred under shallow marine conditions. Spörli (1992) also noted trace fossils and “shredded plant material”.

The association of the Ohio Range fauna with that of the highest formation of the Crashsite Group in the Ellsworth Mountains is interesting because the Ohio Range basement is a Ross Orogeny granitoid (?Cambrian) and the Ellsworth basin had Cambrian sedimentation in a probable rift environment (Curtis 2001). The two areas became connected only when erosion had unroofed the Cambro–Ordovician Ross granitoids, and the sea transgressed onto the roots of the Ross mountain chain to deposit the Horlick formation in the Ohio Range, and the Wyatt Earp Formation in the Ellsworth basin.

In the Devonian, the Pensacola Mountains would have lain between the Ohio Range and the Ellsworth Mountains before the Ellsworth-Whitmore block rotated from a position adjacent to South Africa (Grunow *et al.* 1991) during late Permian earth movements. How much of the Pensacola Mountains succession is Devonian is not clear. *Haplostigma* from an isolated outcrop of sandstones and shales has been used to suggest that the highest formation below the glacial Gale Mudstone (Dover Sandstone) could be Middle Devonian in age (see Bradshaw & Webers 1988 for review), although the range for this plant genus is broad. The Dover Sandstone is 1200 m thick, and has a thin basal conglomerate of rounded quartz and phosphate pebbles. It is tempting to correlate the surface below this conglomerate with the Kukri Erosion Surface. Storey *et al.* (1996), while agreeing that the Dover Sandstone could be correlated with part of the Beacon Supergroup, considered that the underlying 3000 m thick Neptune Group was older, and likely to have been deposited while the Ross Orogeny was taking place. They interpret most of the Neptune Group as a syntectonic alluvial fan complex, but saw the highest formation, the Heiser Sandstone, as marine. As there is no fossil control for the Neptune Group, the age of this marine transgression, and how it might relate to the Ohio Range, is unknown.

Although there can be no question that the Ohio Range and Ellsworth Mountains sedimentary basins were linked during the early Devonian due to the similarity of their faunas, it is unlikely that the Ellsworth-Ohio basin communicated with the central Transantarctic Mountains basin. Isbell (1999) has listed evidence which suggests that rather than the glacial dissection of a continuous sheet of Taylor Group sediments from the Ohio Range to Victoria Land, as previously thought, it is more likely that Taylor Group sedimentation occurred in separate intermontane or “successor” basins, separated by basement highs. This is supported by the onlap of Late Carboniferous–Permian sediments onto a high between the Amundsen and Ramsey glaciers along the margins of the central Transantarctic Mountains basin (Queen Maud High of Collinson 1990), and by the fact that the glacial sequence tends to be thick where the Taylor Group is thick, and thin where the latter is absent. Isbell considers that the Taylor Group filled depressions on the eroded Ross orogenic belt. This is borne out in the Central Transantarctic Mountains basin where, near the Starshot Glacier, a 5 m basal conglomerate is followed by 123 thick shale unit Castle Crags Formation) below the more characteristic Beacon quartzarenites (Alexander Formation). Isbell suggests deposition in a depression on the Kukri erosion surface, possibly in a lacustrine environment. In the Churchill Mountains south of the Byrd Glacier, sandstones and local conglomerates bury a paleokarst topography developed on deformed Cambrian marble, with a relief of up to 700 m (Anderson 1979).

The Devonian sequence of the southern Victoria Land and Darwin Glacier region is generally accepted as forming in another intracratonic basin north-west of a ‘Ross’ basement high that lay south of the Byrd Glacier (Barrett 1981, 1991, Collinson *et al.* 1994, Woolfe & Barrett 1995). Up to 1500 m of predominantly arenaceous sediments accumulated in this basin, and there is evidence of onlap of the lower Taylor Group formations onto another basement high to the north (Balham Valley High, Bradshaw 1981), with sediment transport from the Ross Sea side of the basin as well as from the East Antarctic Craton. More is known about the Devonian sedimentation of this region than for the Central Transantarctic basin, and there is unresolved controversy over whether the lower part of the Taylor Group is coastal marine or fluvial. Trace fossils and sedimentary structures locally suggest a marine influence (Bradshaw 1981, Bradshaw & Webers 1988), but elsewhere other features suggest a fluvial influence (Woolfe 1993), pointing to an intimate mixing of the two environments in a coastal belt. The proliferation of trace fossils, including ichnogenera normally associated with marine environments, and present in the contemporaneous marine Horlick Formation (*Diplichnites, Skolithos, Arenicolites, Cruziana, Rusophycus, Aulichnites*, "large footprints"), suggest that the possibility of periodic marine incursions should be taken seriously. Ichnofaunas in the Darwin and Cook Mountains, and their comparison with those of the Dry Valley region, will clarify this story (M.A. Bradshaw, unpublished data). There is no dispute about the alluvial origin of the Middle to Late Devonian Aztec Siltstone Formation at the top of the Taylor Group (dated on fish fossils, Young 1988), which contains typical alluvial plain sediments, palaeosols and root horizons (McPherson 1979). The Aztec Siltstone Formation overlies the Beacon Heights Orthoquartzite, which occasionally contains *Haplostigma,* suggesting a middle Devonian age. There is southward thinning of both formations in the Cook Mountains south of the Mulock Glacier (M.A. Bradshaw, unpublished data).

The southern Victoria Land basin may have extended well to the east below the Ross Sea. Multichannel seismic profiles indicate 6–7 km of stratified sediments, likely to be Beacon Supergroup and older Palaeozoic rocks, below Cenozoic rocks in the Victoria Land basin (Cooper & Davey 1985). The combined thickness of the Beacon Supergroup (Taylor and Victoria Groups) exposed on land is 2.5 km. In late 1999, the Cape Roberts Sea Floor Drilling Programme on the western side of the Victoria basin terminated in middle Taylor Group sediments (?Arena Sandstone) after passing through nearly 940 m of Cenozoic sediments (M.G. Laird, personal communication 2001).This suggests that the whole of the Victoria Group (Permian–Triassic) and the top part of the Taylor Group was removed before Cenozoic sedimentation commenced.

Woolfe & Barrett (1995) inferred that the marine palaeopacific margin in the Devonian lay at least 1000 km east of the southern Victoria Land Taylor Group basin, based on the extent of the pre-Ross Swanson Group, and allowing for *c*. 33% extension during the Cenozoic. However, the existence of Swanson Group in Marie Byrd Land does not indicate the position of the Early Devonian coastline. In New Zealand (at Reefton) Greenland Group rocks, the probable equivalent of the Swanson Group, are unconformably overlain by thick Lower Devonian nearshore sandstones, and shelf limestones and mudstones. It is possible that these marginal Gondwana seas extended much further west and communicated with epicontinental seas further inland to provide the marine influence shown by the sediments of southern Victoria Land and their ichnofauna (Bradshaw 1999).

Summary and conclusions

The Horlick Formation accumulated adjacent to a tide and storm dominated coastline. A thin initial sand sheet was deposited on a wave-trimmed platform, in places burying wave-cleaned domes of exfoliated granite, and merging into thick fluvial sediments near river mouths. A thin second sand sheet deposited beyond the wave zone became intensely bioturbated during episodic deposition, after which tidally influenced migratory sand shoals and muddy hollows developed. Lithologies are repeated higher in the succession, with short, powerful storms carrying a shelly benthic fauna shoreward, and minor transgressive phases producing thin, phosphate-rich horizons.

The sandstones in particular were home to a variety of organisms, many of them arthropods. Freshwater and brackish type C/S ratios obtained from horizons that contain occasional marine fossils suggest that this technique should be used with caution and does not accurately identify marine conditions in the Horlick Formation.

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