

GLACIOMARINE EARLY PERMIAN STRATA AT BACCHUS MARSH, CENTRAL VICTORIA – THE FINAL PHASE OF LATE PALAEOZOIC GLACIATION IN SOUTHERN AUSTRALIA

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WEBB, J.A. & SPENCE, E., 2008. Glaciomarine Early Permian Strata at Bacchus Marsh, Central Victoria – The Final Phase of Late Palaeozoic Glaciation in Southern Australia. *Proceedings of the Royal Society of Victoria* 120(1): 373–388. ISSN 0035-9211.

As the Late Palaeozoic continental ice sheet covering most of Victoria retreated in the late Sakmarian, the inland sea along its northern margin expanded southwards into central Victoria to deposit a well-exposed sequence of glaciomarine strata (the upper part of the Bacchus Marsh Formation) at Bald Hill near Bacchus Marsh. The initial transgression formed a thin conglomerate due to limited reworking of a glacially deposited diamictite. A relatively shallow, protected, low energy embayment of the inland sea then accumulated ~180 m of interbedded dolomitic sandstones and siltstones with abundant sedimentary structures, including climbing ripples and, on the bases of sandstone beds, runzelmarks. These sediments were deposited by north-flowing turbidity currents generated annually by the summer influx of sediment in the meltwater streams draining the ice sheet. Following each turbidity flow, the surface of the silt was frequently burrowed by *Planolites* and colonised by microbial mats, which provided cohesion, so the silt surface was wrinkled rather than eroded by the next turbidity flow. Each sandstone/siltstone couplet probably represents one year of deposition, so the sediments accumulated very rapidly (~0.2 m/year) and the entire sequence was deposited in <1000 years; this is typical of glaciomarine environments. The interbedded sandstone/siltstone sequence coarsens upwards, accompanied by a decrease in dolomite content and a change in ichnofauna from *Planolites* to *Muensteria*; this was due to progradation of the delta at the mouth of the meltwater streams, so that the uppermost sediments were deposited in fresh water. The presence of typical marine fauna and dolomite in the sediments indicates that the inland sea had approximately normal salinity and must have been connected to the open ocean, probably the Tethys Ocean to the northwest, but not to the very extensive fresh-brackish inland sea in Antarctica to the south.

Key words: Glaciomarine, Early Permian, turbidites, palaeogeography, Bacchus Marsh.

THE LATE PALAEOZOIC GLACIATION that affected large parts of Gondwana, extending northwards from Antarctica and covering much of southern Australia, deposited glacial sediments throughout substantial areas of Victoria. At its maximum extent in the Early Permian, virtually all of Victoria lay beneath an icesheet that overwhelmed the topography (O'Brien et al. 2003). The glacial origin of the Early Permian strata in Victoria was originally recognised by Selwyn (1861); these sediments have been the subject of continuing interest and have been studied in some detail (e.g. David 1896; Jacobson & Scott 1937; Crowell & Frakes 1971; Roberts 1984; Bowen & Thomas 1988; O'Brien et al. 2003). The age of the sediments, based on leaf fossils, was the subject of controversy between the palaeontologists McCoy, Clarke and Feistmantel who first worked on the fossils (Archbold 1998), but the presence of the typical Gondwanan Permian leaf genus *Gangamopteris* enabled McCoy (1875) to demonstrate the Permian age, which was later confirmed using brachiopods (Garratt 1969; Archbold 1991).

The Victorian glacial strata are predominantly continental except in northern Victoria, where a shallow sea was present along the northern margin of the ice sheet (O'Brien 1986). As the glaciation waned and the glaciers retreated southwards, the sea expanded, as shown by the presence of Early Permian marine fossils, including brachiopods and conulariids, in central Victoria (Archbold 1991; Thomas 1969). The focus of most Victorian Permian studies has been the continental glacial sediments, but the volumetrically minor glaciomarine strata in central Victoria are worthy of attention, because they testify to the history of the waning stages of the glaciation.

The best exposed sequence of the glaciomarine strata lies on the side of Bald Hill, adjacent to Bacchus Marsh in central Victoria. These sediments, which are described in detail in this paper, provide an ideal opportunity to determine the sedimentary environment and palaeogeography of the ice sheet margin during the final stages of the Late Palaeozoic Gondwanan glaciation.

REGIONAL SETTING

Within Victoria Permian sediments occur in several separate areas; the thickest and best exposed are found around Bacchus Marsh (Fig. 1; Singleton 1973). These are mapped as the Bacchus Marsh Formation (Roberts 1984), a name that takes precedence over the Wild Duck Formation proposed by Edwards et al. (1998) for Permian sediments throughout Victoria (O'Brien et al. 2003).

The Permian sediments at Bacchus Marsh unconformably overlie Ordovician sandstones and shales of the Melbourne Zone, which is part of the Lachlan Fold Belt (VandenBerg et al. 2000). The Ordovician sediments were deposited in a deep marine turbiditic environment. In a series of subsequent tectonic events they were folded, faulted and subjected to regional low-grade metamorphism; this is evident in the shales, which generally have a well-developed slaty cleavage. Quartz veining occurred concomitantly with the folding. The Tabberabberan Orogeny in the mid-Devonian completed the cratonisation of the Victorian part of the Lachlan Fold Belt, and was followed by widespread intrusion of granites in the Late Devonian; several of these plutons outcrop in the Bacchus Marsh area, and are surrounded by hornfels contact aureoles.

Glaciation commenced in the latest Carboniferous and terminated in the Early Permian (Sakmarian; Warne et al. 2003). At this time Victoria lay at high southern latitudes adjacent to Antarctica. As the continental icesheet advanced across Victoria from Antarctica, it formed striated and polished pavements that are exposed at a number of localities in central Victoria (Singleton 1973); the striations indicate that the direction of ice movement in this area was broadly from the south and southwest (Bowen & Thomas 1988). The relief of the pre-existing surface was probably relatively subdued (<1000 m); the ice completely covered the landscape, as shown by the lack of coarse angular debris that could have been derived from valley sides (O'Brien et al. 2003). The ice sheet was temperate, i.e. wet-based and not frozen to its bed, except perhaps at the margins (O'Brien et al. 2003). As a result the ice could slide over the underlying sediments and bedrock and produced large volumes of meltwater and sediment, analogous in many ways to the present-day temperate glaciers of Alaska (Molnia 1989).

At the close of glaciation sea level rose and the land rebounded due to isostatic uplift as the glaciers melted. Uplift continued after sea level had stabi-

lised, and central Victoria became dry land. It remained above sea level, subject to weathering and erosion, throughout the Mesozoic. Minor deposits of fluvial Triassic sediments at Bacchus Marsh indicate that the land surface was probably low relief and crossed by south-flowing rivers (Webb & Mitchell 2006).

In the Paleocene-Eocene, eruptions of olivine basalts (Pentland Hills Volcanics) covered much of the Bacchus Marsh area, reaching up to 170 m thickness in places. These lavas are overlain by Tertiary fluvial sands and gravels with coal seams (Werribee Formation). Subsequent uplift and faulting, in particular along the Rowsley Fault during the Pleistocene (Singleton 1973), resulted in incision by creeks and rivers to expose the underlying Permian strata.

BACCHUS MARSH FORMATION AT BALD HILL

The Bacchus Marsh Formation outcrops as six separate blocks bounded by mostly east-west faults (Fig. 1); movement on the faults may have extended back to the Permian (Singleton 1973). Korkuperrimul Creek has cut through two of these blocks. The north-western one has ~1100 m of glacial section exposed, and records a number of glacial advances and retreats; the thickness of the section probably reflects synsedimentary faulting (O'Brien et al. 2003). The southeastern block, at Bald Hill ~1.5 km northwest of Bacchus Marsh, is triangular (Fig. 1); it is faulted to the north and east against Tertiary sediments and volcanics (Roberts 1984). Along the southern side of the Korkuperrimul Creek valley at Bald Hill is excellent outcrop of a continuous section 280 m thick (Fig. 2A); the upper ~180 m are glaciomarine sediments that are the subject of this study.

The Bacchus Marsh Formation at Bald Hill comprises, in stratigraphic order, diamictites interbedded with massive to laminated sandstones that contain large-scale synsedimentary deformation structures, conglomerate (Morton Conglomerate Member; Roberts 1984), and interbedded sandstones and siltstones that are often dolomitised (Fig. 1). The latter unit is distinctively different from the other parts of the Bacchus Marsh Formation, and could be separated as a new formation; however, the outcrop is too limited to warrant this.

The upper two units of the Bacchus Marsh Formation contain, respectively, conulariids and Zone APP2 palynomorphs (the latter in equivalent strata at

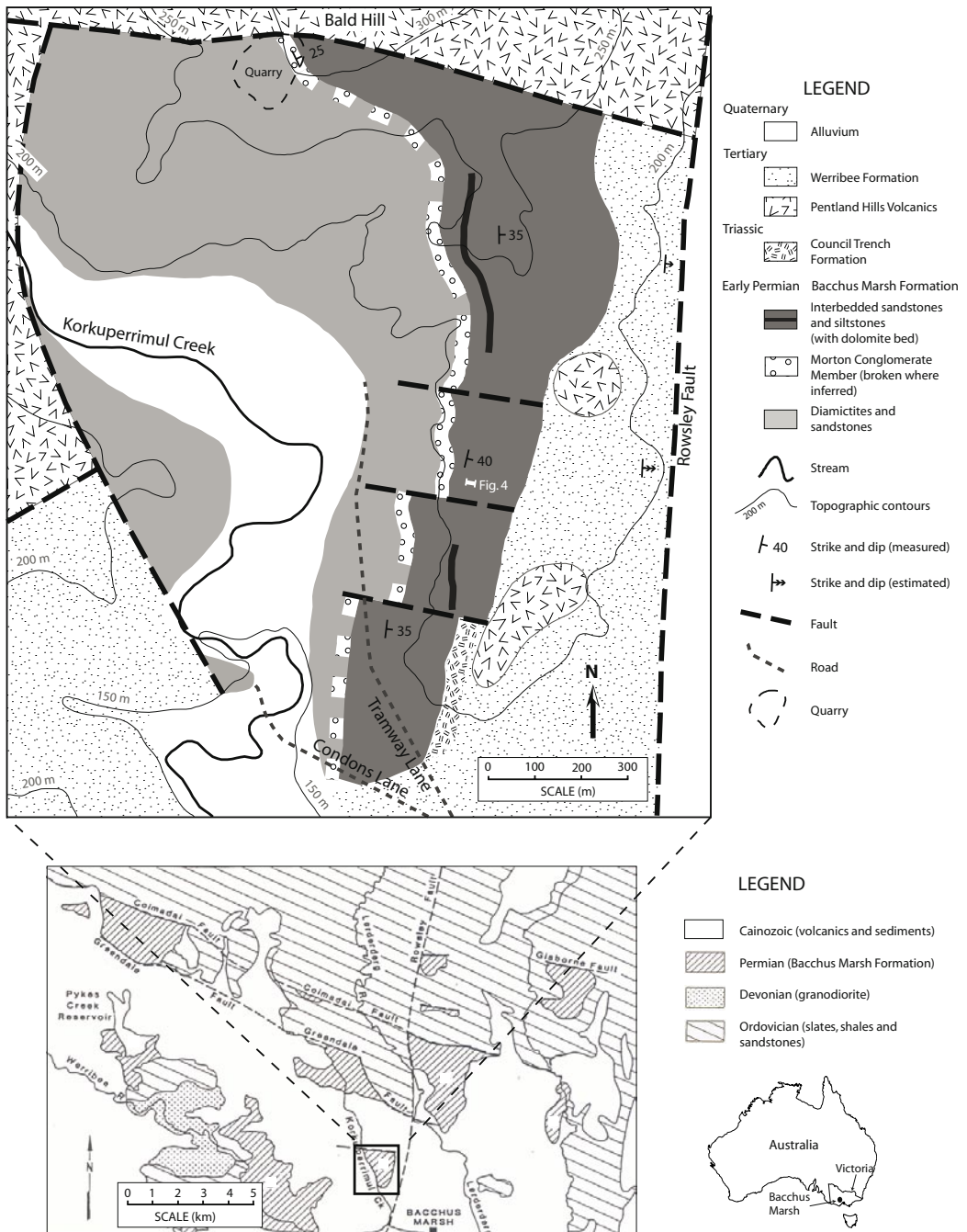


Fig. 1. Detailed map of Bacchus Marsh Formation at Bald Hill, and Permian outcrops around Bacchus Marsh (from Singleton 1973).

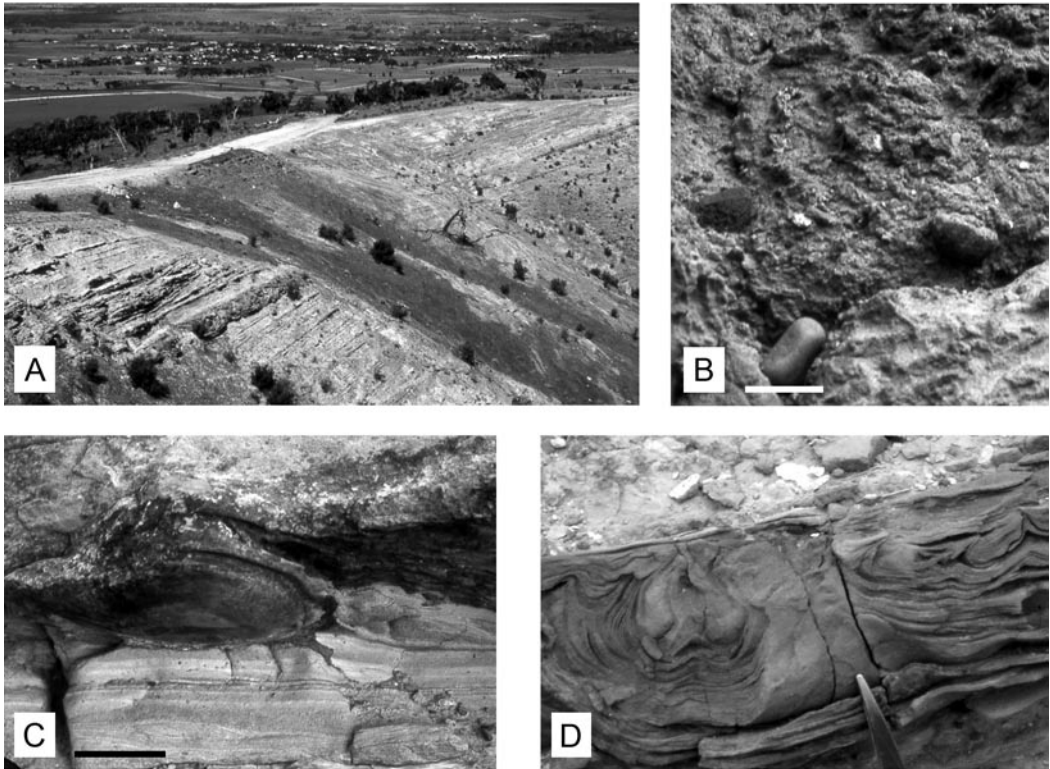


Fig. 2. A, General view of Bacchus Marsh Formation outcrop, looking south from Bald Hill. B, Morton Conglomerate Member; 50 mm scale bar. C, Dolomite concretion; 50 mm scale bar. D, Convolute lamination in sandstone bed; note geological hammer for scale.

Lerderderg Gorge; C. Foster quoted in O'Brien et al. 2003); together these indicate a late Sakmarian (Early Permian) age (Warne et al. 2003).

The glacial and fluvioglacial sediments beneath the conglomerate will be briefly discussed before describing the glaciomarine sequence (conglomerate and interbedded sandstones and siltstones) in detail.

Diamictite

Only a few beds of diamictite outcrop at Bald Hill, as massive red to grey gravelly sandstones, containing scattered mostly rounded clasts up to 75 cm across of locally derived lithologies: Ordovician quartz sandstone (~45%) and slate (~10%), Devonian granite (~35%) and hornfels (~10%). The clast density is 1 to 75 per square meter of outcrop. Vein quartz clasts (~1%) have very similar fluid inclusions to quartz veins within the Ordovician sediments in the Brisbane

Ranges to the southwest. The poorly sorted coarse sandstone matrix of the diamictites comprises generally angular grains of quartz, rock fragments (slate, hornfels and sandstone), weathered plagioclase, K-feldspar and microcline, and muscovite (in order of abundance) in a matrix of quartz silt and clay. A few of the gravel-sized clasts show striated facets due to glacial transport, but the majority are subrounded to well-rounded, probably reflecting an origin as unlithified river gravels picked up by the advancing glaciers. The diamictites were deposited under subglacial to sub-iceshelf conditions (O'Brien 1996).

Massive to laminated sandstones

Interbedded with the diamictites are 1–10 m thick beds of medium to coarse sandstone, very similar in texture and composition to the sandstone matrix of the diamictites. Many of the sandstone beds are massive;

others show plane, trough or ripple cross-lamination. One bed contains *Calamites* stems and leaf impressions of *Gangamopteris* and *Glossopteris* (Douglas 1969; Rigby & Chandra 1990). At the base of some beds are thin mudstone lenses that have frequently been partially eroded off and then overlain by sandstone. Two sandstone beds show large scale soft sediment deformation in the form of asymmetric recumbent folds with amplitudes of up to 15 m and axial planes striking east-west and dipping south; the folds indicate a sense of movement from south to north, and are truncated by overlying beds. Smaller scale folds occur in one bed of plane-laminated sandstone; the folds have the same asymmetry as the larger structures, but are smaller (3–10 cm amplitude).

These sediments were probably deposited on a sandy, high energy delta in a periglacial lake (O'Brien 1996); the smaller scale folding was caused by slumping down the delta front. The large-scale folding formed beneath the glacier due to ice deceleration and compressional strain where the bed conditions changed downflow from melting to frozen (Drewry 1986). The asymmetry of the folding indicates clearly that the glaciers at Bacchus Marsh were moving north. The presence of two beds with large-scale folding records two glacial advances; altogether at least nine major periods of glaciation are recorded in the thicker Bacchus Marsh Formation section at Korkuperrimul Creek northwest of Bald Hill (O'Brien et al. 2003).

MORTON CONGLOMERATE MEMBER

An easily recognised matrix-supported conglomerate, Morton Conglomerate Member (Fig. 2B), can be mapped across the Bald Hill Permian outcrop (Fig. 1); it was first described by Selwyn (1861) and formally named by Roberts (1984). This bed truncates the underlying sandstones and is distinguished by the abundance of clasts. It is 1–5 m thick, and consists of clasts up to 28 cm in diameter of granite, hornfels, sandstone, slate and quartz in much the same proportions as the underlying diamictites. The clasts are all subrounded to rounded. The medium to coarse moderately well sorted sandstone matrix has a similar composition to the underlying sandstones and diamictite matrix, except that it contains patches of dolomite cement, both as fine-grained masses and occasionally as rhombohedral crystals ~0.2 mm across. The dolomite rhombs often have a cloudy core surrounded by a clear rim that may contain a cloudy growth band. Quartz and muscovite grains in

the sandstone matrix may have a thin layer of dolomite surrounding them, and dolomite crystals have frequently grown into the cleavage planes of the muscovite, tearing these grains apart. Dolomite is also present as an intergranular cement within the outer 1–5 mm of many of the granite clasts, indicating that these clasts had undergone some weathering before being deposited in the conglomerate.

The conglomerate represents a diamictite with reduced matrix content, as shown by the similarity of the clast compositions. Rare conulariids (*Notocoenularia*) have been recorded from the Morton Conglomerate Member (Thomas 1969), indicating a marine environment of deposition, also shown by the presence of dolomite cement (dolomite forms predominantly in marine sediments; Tucker & Wright 1990). The conglomerate formed during the initial transgression into the area as the glaciers melted, and formed as the diamictite was reworked by marine processes, probably weak tidal currents in an embayment (see discussion below). The reworking was insufficient to remove the entire matrix and did not form any sedimentary structures.

INTERBEDDED SANDSTONES AND SILTSTONES

Lithology and sedimentary structures

Above the Morton Conglomerate Member is a 180 m thick section of interbedded sandstones and siltstones (Figs 1, 2A). The fine-medium sandstones are moderately well sorted lithic greywackes and litharenites. They have a similar texture and composition to the sandy matrix of the underlying conglomerate; the clay minerals in the matrix are illite and kaolinite (identified using XRD analysis). Organic matter is abundant in both sandstones and siltstones, as disseminated grains and dark brown laminae, some of which contain poorly preserved presumably microbial cells ~0.05 mm across.

Dolomite is widespread and forms both occasional cemented layers and ovoid concretions 2–100 cm in diameter (Fig. 2C); the smaller concretions are more spherical. Dolomite is most common in the finer-grained, thinner beds, and decreases in abundance up section; it is completely absent in the uppermost strata. The dolomitised beds can be traced laterally for several hundred meters (Fig. 1); they are more resistant to weathering and stand out on the hillside exposure, as do the dolomite concretions.

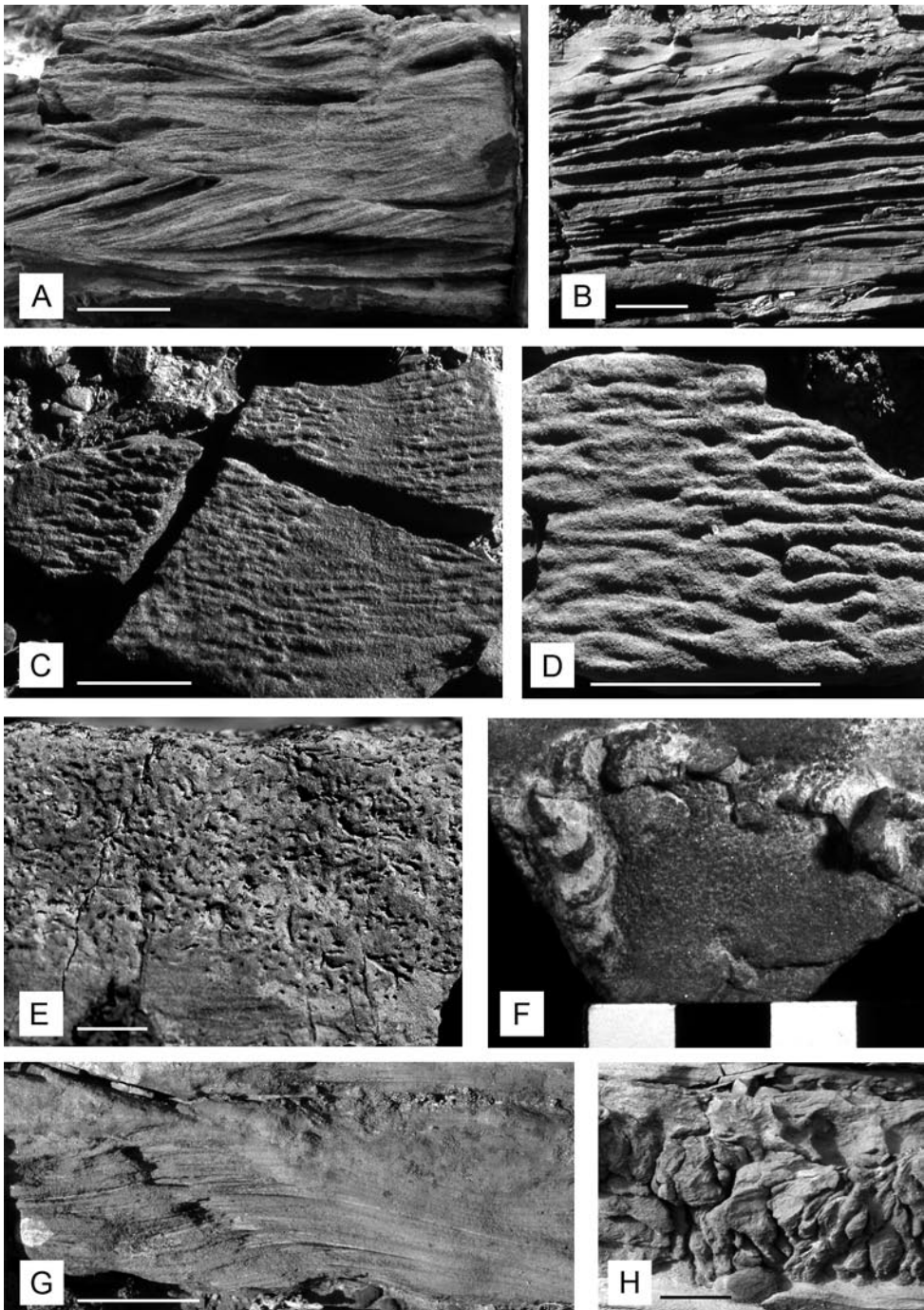


Fig. 3. Structures in interbedded sandstone/siltstone unit. A, Unidirectional ripple cross-lamination in sandstone bed; 50 mm scale bar. B, Plane laminated sandstone bed; 50 mm scale bar. C, D, Runzelmarks on bases of sandstone beds; 50 mm scale bars. E, *Planolites* in dolomitised siltstone; 10 mm scale bar. F, *Muensteria* in sandstone bed near top of section; scale bar in cm increments. G, Climbing ripple in sandstone bed; 50 mm scale bar. H, Convoluted base of sandstone bed; 50 mm scale bar.

Similar to the conglomerate, the dolomite occurs as microcrystalline patches and, less commonly, as rhombohedral crystals; the latter are finer (0.05 mm) and less well formed than in the conglomerate.

Thin conglomerate beds appear at the top of the section; these are <10 cm thick and contain rounded pebbles (up to 8 cm across) of granite, slate and sandstone, together with rip-up clasts of mudstone and grains of angular quartz, feldspar and biotite, representing disintegrated granite pebbles. The sandstone beds associated with the pebble layers at the top of the Bacchus Marsh Formation are generally strongly ferruginised and yellow-brown in colour; some of the thicker beds contain plant stems and occasional leaf fragments of *Gangamopteris*.

The interbedded sandstones and siltstones form an overall upwards-coarsening sequence. Immediately above Morton Conglomerate Member is a massive grey siltstone with rare fine sandstone laminae. This unit has yielded marine arenaceous foraminifera (C. Foster quoted in O'Brien et al. 2003), and grades upwards into thinly interbedded centimeter-thick sandstones and siltstones (Fig. 4). The sandstones become thicker and more common up sequence. Individual sandstone beds have a sheet-like geometry; dolomitised beds can be traced for several hundred meters with no significant change in thickness. The upper boundaries of the sandstones are generally sharp, but commonly grade rapidly into the overlying siltstones. About 20 m above the conglomerate the first ripple cross-laminated beds enter the section. Above this level the sandstones contain abundant sedimentary structures, apart from a few massive beds up to 40 cm thick. Plane-laminated beds are very abundant (Fig. 3B), and unidirectional ripple cross-lamination is common (Fig. 3A). Climbing ripples with an amplitude of several centimeters are occasionally present, and show a low angle of climb (Fig. 3G). Within the thicker sandstone beds there may be more than one cross-laminated set, interbedded with plane laminated intervals, and the common preservation of the upper surfaces of the ripples gives a pinch and swell appearance to the cross-laminated sets. Overall each sandstone bed represents deposition by a unidirectional current during a single event under upper and lower flow regime conditions. The current direction, measured from the dip direction of the cross-lamination, is consistently towards the north (Fig. 5).

Also common in this part of the section are unusual structures present on the bases of sandstone beds overlying siltstones, as well-defined semicontinuous,

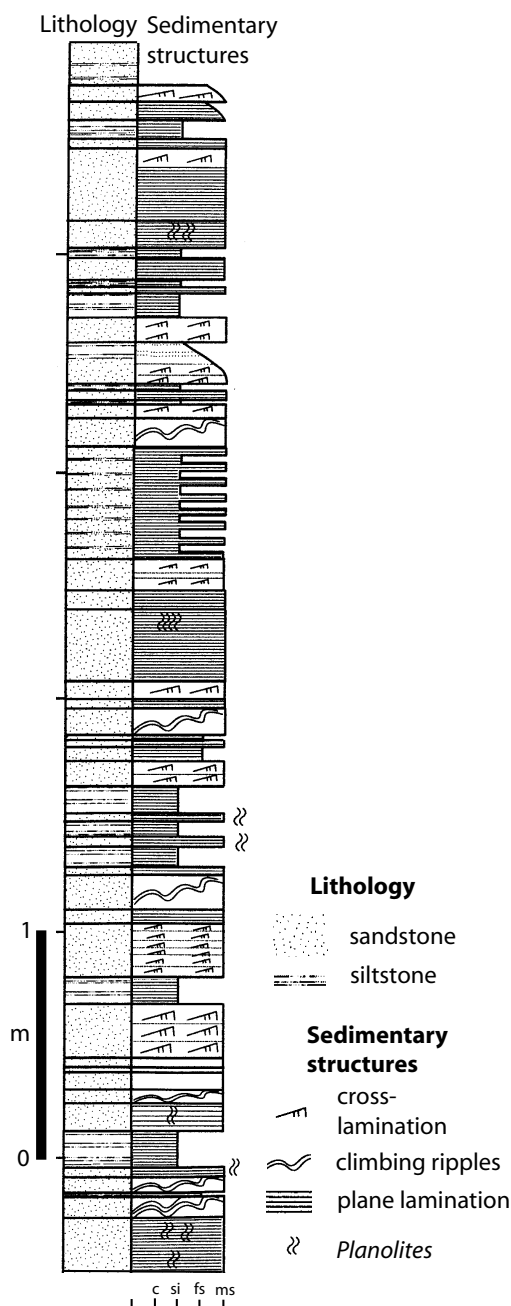


Fig. 4. Representative stratigraphic section of middle part of interbedded sandstone and siltstone unit at Bald Hill; see Fig. 1 for location. c = clay, si = silt, fs = fine sandstone, ms = medium sandstone. Solid horizontal lines in Lithology column represent bedding planes.

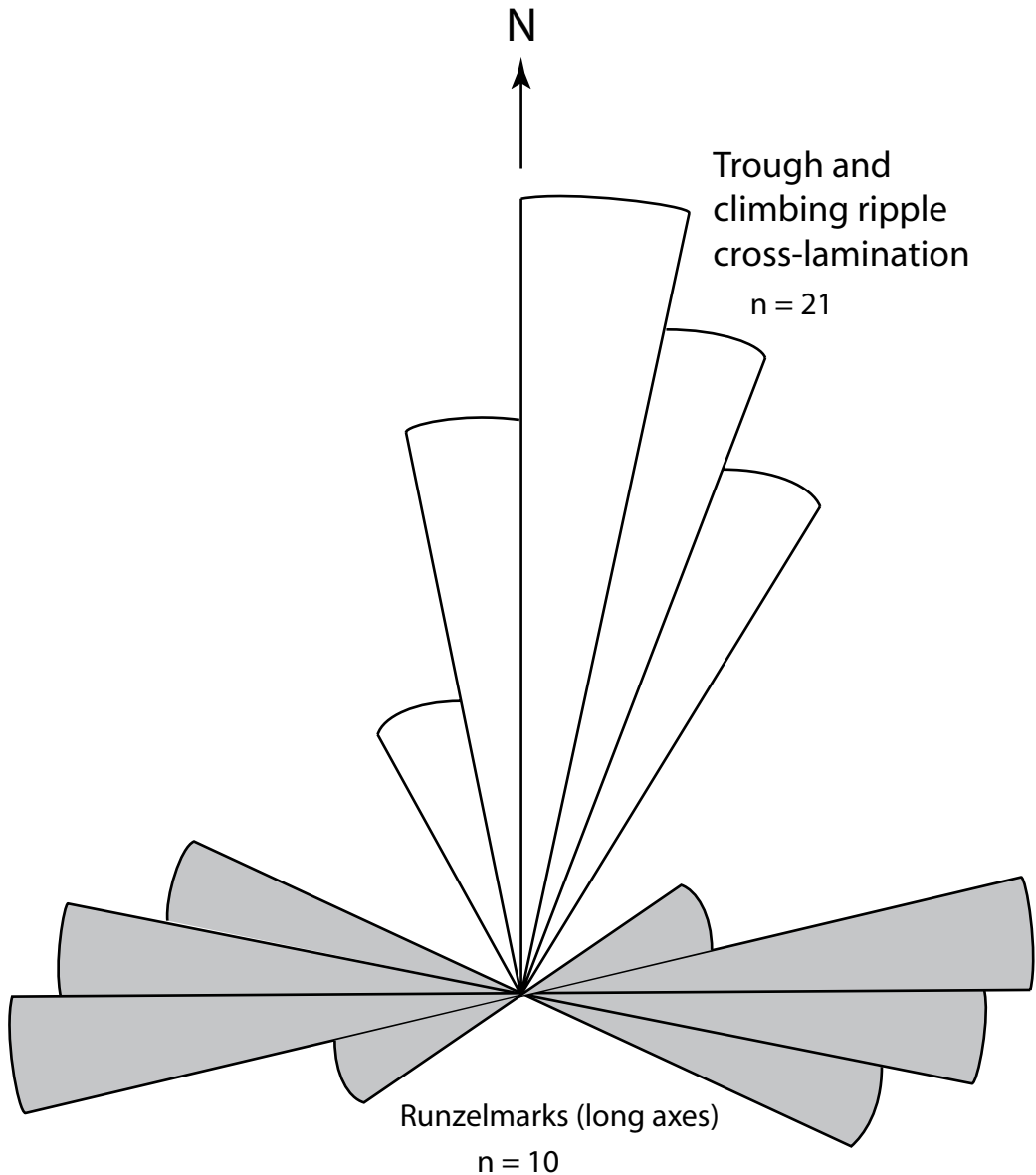


Fig. 5. Palaeocurrent directions from ripple cross lamination and runzelmark orientations; overall dip of the bedding removed using a stereogram.

subparallel ridges that vary gradationally in width from 1–10 mm to several cm; the ridges are a consistent width on any particular bed (Figs 3C, D). The larger ridges are more irregular and have been emphasised by load casting, but they are clearly an original sedimentary structure. The ridges are oriented consistently east-west (Fig. 5), i.e. perpendicular to

the current direction that deposited the sandstones. They are best described as runzelmarks (wrinkle marks), and appear to have formed by wrinkling of the cohesive surface of a siltstone by frictional drag of the unidirectional current that deposited the overlying sandstone; downslope movement of the sediments after deposition may also have been involved

(Maltman 1994). Runzelmarks are generally described from tidal flats, where wind blows shallow water over cohesive muds, causing them to wrinkle (Reineck & Singh 1980); runzelmarks in these environments are generally irregular in shape. The runzelmarks in the Bacchus Marsh Formation have clearly formed subtidally; the cohesiveness of the mud surface may reflect the presence of microbial mats, as the siltstones contain abundant organic laminae with poorly preserved presumably microbial cells.

Convolute lamination occurs in several sandstone beds (Figs 2D, 3H); the original plane lamination of the beds has contorted irregularly into ball and pillow structures. Convolute lamination reflects internal foundering of the heavier sand into the underlying liquefied mud, and was probably triggered by the loading imposed by the sudden deposition of the overlying sand. Alternatively, the penecontemporaneous deformation could have followed earthquake events, as in the glaciomarine Middle Permian sediments of the southern Sydney Basin (Du et al. 2005).

Closely spaced, subhorizontal unlined tubular burrows (*Planolites*), up to 1.5 cm long and 0.2 cm in diameter (Fig. 3E), are common in many of the siltstone beds in the lower two-thirds of the section. *Planolites* is often more abundant towards the top of beds and is most evident in beds that have been dolomitised; the burrow infills are cleaner than the surrounding sediment and have not been cemented by dolomite, so they weather out as fine holes. This ichnofossil was probably formed by worms and is typical of quiet marine environments at all water depths (Ekdale et al. 1984). *Planolites* has been recorded from glacial environments, e.g. outer shelf muds in the glaciomarine Gulf of Alaska (Eyles et al. 1992).

Towards the top of the section there is a change in the ichnofauna; *Planolites* is replaced by occasional *Muensteria* (Fig. 3F), subhorizontal intrastatal burrows within sandstone beds. The burrows are up to 1.5 cm across and 15 cm long, fairly straight or with a moderate curvature, and have well-defined meniscoid backfill. They were possibly formed by small arthropods (? insect larvae) travelling through the sediment at a shallow depth; *Muensteria* is typical of terrestrial environments, and is known from glacial deposits of various ages (Ekdale et al. 1984).

Depositional processes

The sandstone beds in the lower two-thirds of the section formed within a predominantly marine envi-

ronment, as shown by the presence of *Planolites*, arenaceous forams and dolomite; the underlying conglomerate is also marine, as already discussed, and an open marine fauna (brachiopod and fenestellid bryozoan) is present in nearby coeval sediments (Garratt 1969; Archbold 1991).

The Bald Hill sandstone beds were deposited by periodic high-energy currents with a consistent direction, and the sedimentary structures present (plane lamination, cross-lamination, climbing ripples; Figs 3A, 3B, 3G, 4) indicate upper and lower flow regime conditions. The interbedded siltstones were deposited by waning flows (as shown by the sharply gradational tops of many sandstone beds) and then from suspended sediment under quiet water conditions. Taken together, these features are typical of deposition by turbidity flows. However, the sandstones lack the classic Bouma sequence (Bouma 1962; Einsele et al. 1991). The basal interval A (graded sands lacking other sedimentary structures) is absent, because the sediment supply did not encompass a large variation in grain size; the Ordovician slates which provided most of the sediment break down into fine-grained material (O'Brien 1996).

Following a turbidity flow, the surface of the silt was frequently burrowed by *Planolites* and colonised by microbial mats. The mats provided cohesion, so the silt surface was wrinkled rather than eroded by the next turbidity flow.

Turbidity currents generated by episodic slumping occur commonly on glaciomarine shelves, and act to carry bedload and suspended material to the seafloor where interbedded sands and silts are deposited, with the sands characterised by grading and climbing ripple lamination (Drewry 1986, Molnia 1989). Turbidites have been recorded in glaciomarine sediments associated with the waning stage of the Late Palaeozoic glaciation elsewhere in Gondwana. The Early Permian Mackellar Formation was deposited in an extensive inland sea in Antarctica, largely by turbidity flows supplied by meltwater streams flowing across a braided outwash plain formed as the glaciers retreated (Miller & Collinson 1994).

The turbidity flows that deposited the Bald Hill sandstones contained high levels of suspended sediment and could have been underflows formed when sediment-laden meltwater streams entered the ocean, generating a sediment plume that flowed along the seafloor. However, sediment plumes may also flow either at or just beneath the water surface (overflow) or within the body of water (interflow); plume behaviour depends on the relative density of the stream and

seawater. Meltwater streams have high sediment loads and therefore high density, both because of the abundant sediment supply, and because cold water has a greater viscosity than warm water and can carry a higher sediment concentration (Drewry 1986). However, for underflows to be generated in seawater, the inflowing meltwater must contain about 32 g/L suspended solids (Hunter et al. 1996), to overcome the density difference between salt and fresh water. Meltwater streams can contain more than one g/L of suspended sediment, but rarely reach sufficient levels to form underflows in seawater, so overflows are most common where glacial streams enter the ocean (Molnia 1989). Thus the turbidity flows that deposited the interbedded sandstones and siltstones at Bald Hill were probably not formed by underflows; instead they were most likely initiated by slumping on oversteepened slopes of freshly deposited sediment, unstable due to high porewater pressures resulting from rapid deposition (Eyles & Eyles 1992).

Each turbidite in the Bald Hill section was generated by spring/summer melting of the glacier margin to the south, providing a sudden influx of sediment-laden fresh water to the ocean. In glacial streams sediment discharge increases rapidly in spring as melt increases and easily transported sediment is flushed out; often a large proportion of the annual sediment load is discharged during only a few days of very high summer flow (e.g. Metcalf 1979). The periodic spring/summer sediment influx is followed by negligible discharge of almost clear meltwater over winter, allowing the fine suspended sediment in the seawater to settle out under quiet conditions, perhaps assisted by freezing over of the sea. Although sediment inflow from glacial streams varies daily and due to major flood events, most variation is seasonal, so each sandstone and overlying siltstone in the Bald Hill sequence could have been deposited over one year.

To check if the sandstone/siltstone couplets represent annual deposition, a cyclicity analysis was carried out. The lithology (sandstone or siltstone) was recorded every 2 cm for three measured stratigraphic sections totalling 169 m; each lithology was then analysed for each stratigraphic column (6 analyses in all) using a Walsh Transform in a two coded (presence/absence) system (Jell & Brownlaw 2000). The results (Fig. 6) show peaks in cyclicity at 0.14–0.18 and 0.28–0.37 cycles/meter present in four of the six analyses, with another peak at 0.53 cycles/meter present in only two of the analyses. There are on average 50 sandstone/siltstone couplets every 10

m, giving an overall accumulation rate of 0.2 m/year (assuming that the couplets are annual). Using this sedimentation rate, the major cycles have periodicities of 28–35 and 13.5–18 years respectively, with a minor cycle at 9.5 years. Sunspot activity causes short-term climate variation that may be reflected in the sediment record; at present it has a periodicity of ~11 years, with less marked additional cycles at 22 and 5.5 years (Moran & Morgan 1997). However, in the Permian the length of the main sunspot cycle was ~14 years (Ernesto & Pacca 1981), matching one of the main Bald Hill periodicities (13.5–18 years); the other (28–35 years) is twice as long, as might be expected from the ratios of the present sunspot cycles. This suggests that the sandstone/siltstone couplets at Bald Hill are annual cycles.

The total thickness of the interbedded sandstones and siltstones at Bald Hill is approximately 180 m; for an average accumulation rate of 0.2 m/year, this represents <1000 years. This very rapid sedimentation rate reflects the combination of sediment availability, a high-energy transport medium and sufficient accommodation space. Accumulation rates of this magnitude are known from present-day glaciomarine environments, e.g. up to 0.3 m/year on the Alaskan shelf (Molnia 1989).

The disintegrated granite pebbles in the conglomerate layer were transported as weathered clasts frozen into the glacier; they were probably carried in river ice and broke up as they thawed during transport in the meltwater stream. The dolomite cement rind in many of the granite clasts in Morton Conglomerate Member also indicates that these clasts had undergone weathering prior to deposition.

Environment of deposition

Deposition of the glaciomarine strata at Bald Hill occurred on the southern edge of an extensive inland sea (Fig. 7; O'Brien 1986; Struckmeyer & Totterdell 1990). However, there is no evidence of wave or tide reworking of these sediments, as is common on modern glaciomarine shelves, e.g. Alaska, where long-shore currents and waves quickly remove and redeposit sediment supplied by meltwater streams (Molnia 1989). Furthermore, Early Permian glaciomarine sediments in southeastern New South Wales record extensive storm reworking (Eyles et al. 1998). This suggests that the Early Permian glaciomarine sedimentation at Bald Hill occurred in a protected embayment, analogous sedimentologically to a fjord (but in a different

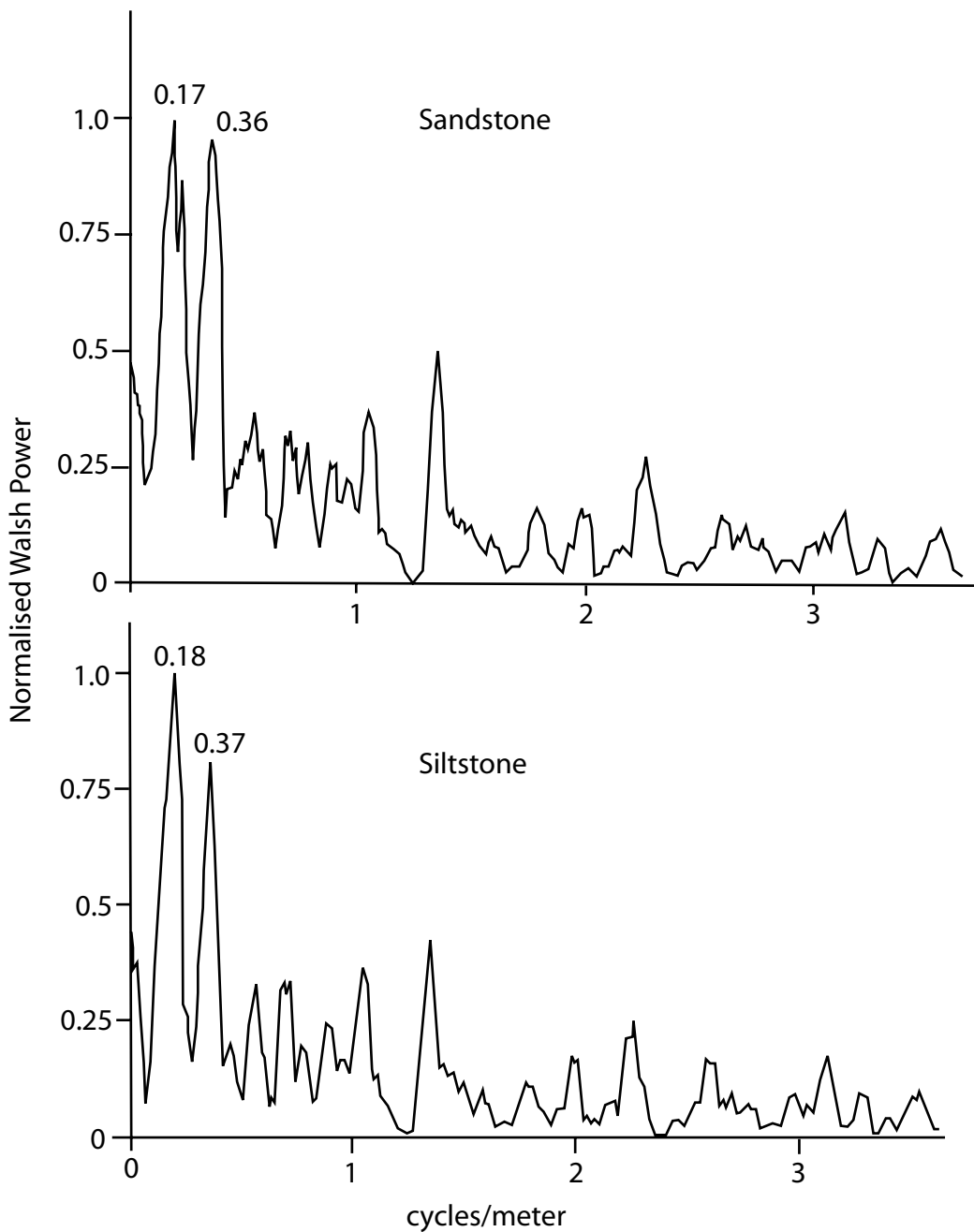


Fig. 6. Representative Walsh transform analyses of the bed cyclicity in the interbedded sandstone/siltstone unit at Bald Hill; part of stratigraphic section analysed is shown in Fig. 4.

topographic setting, lacking confining steep walls). Fjords almost always have a sill at the mouth, so they are semi-enclosed but generally have free connection

to the ocean (Drewry 1986). In fjords beyond the direct influence of glaciers and icebergs, meltwater runoff during summer contributes a high sediment input,

forming prograding deltas at the mouths of meltwater streams; submarine slumping on the steep delta slopes is ubiquitous and generates turbidity currents that deposit moderately well sorted interbedded silts and cross-laminated sands on the fjord floor (Powell 1983; Armentrout 1983; Syvitski et al. 1987). Rates of sedimentation in fjords are very high, particularly near deltas, and reach 0.2 to over 1 m/year (Drewry 1986; Molnia 1989). In winter sediment input virtually ceases; sea ice may cover the fjord and tidal currents, often weak, are the only energy source.

The embayment at Bald Hill was relatively shallow; the total thickness of the section of interbedded sandstones and siltstones (180 m) represents approximately its depth. The barrier separating it from the inland sea was probably moraine left by the retreat of the glacier that truncated and folded the underlying beds. During deposition of the Bald Hill strata meltwater streams entering the embayment formed a delta front sloping consistently towards the north, as shown by the northwards palaeocurrent directions recorded by the turbidity flows moving down the delta slope (Fig. 5). There is no evidence of icebergs (e.g. dropstones, sediment deformation), so the glacier margin had retreated inland. The overall upward coarsening trend within the interbedded sandstone/siltstone section, whereby the sandstones become thicker and more common and thin pebble layers appear, formed as the delta prograded. There is an accompanying up-sequence decrease in abundance of dolomite and change in ichnofauna from *Planolites* to *Muensteria*, along with the appearance of leaves and stems in the sandstones. *Muensteria* is characteristic of non-marine environments (Ekdale et al. 1984), so this reflects a change to freshwater conditions at the mouth of the meltwater stream flowing into the advancing delta.

The fauna within the glaciomarine sediments comprises *Planolites* (? one species), arenaceous foraminifera and rare conulariids (one species of *Notocoularia*); one species of the brachiopod *Trigonotreta* and a fenestellid bryozoan have been described from nearby coeval sediments at Coimadai Creek (Garratt 1969; Archbold 1991). The low diversity of the fauna suggests that conditions in the embayment were hostile; those organisms that could adapt became very abundant (*Planolites*). The limiting factors were the seasonal high turbidity, particularly on the sea floor, and the low nutrient concentrations accompanying the quiet conditions in the embayment; present-day fjords with minimal biomass and diversity have a low level of hydrody-

namic energy that inhibits nutrient input (Drewry 1986). The low temperatures and winter darkness did not limit faunal diversity, because Early Permian sediments in the Sydney Basin to the northeast and Tasmania to the southeast, deposited under open ocean conditions, contain a much more diverse fauna (Herbert & Helby 1980; Clarke 1989). Salinity was probably not an issue. The abundance of dolomite indicates that the salinity of the Permian inland sea in central Australia was approximately normal, as does the presence of open ocean fauna (conulariids, brachiopods and bryozoans). Thus the connection between this sea and the open ocean must have been sufficiently broad and deep to maintain the salinity of the inland sea despite the influx of fresh water from the melting ice sheet; in comparison, the Baltic Sea, which is about half the dimensions of the Permian sea, has substantially lower salinity than ocean water, because of its restricted connection to the open ocean.

PALAEOGEOGRAPHY

In the Early Permian central Victoria lay at about 75–80°S, close to the Palaeo-Pacific Ocean (Fig. 7). During the glaciation an inland sea occupied part of central Australia, extending into northern Victoria. As the continental ice sheet receded, this sea expanded southwards into central Victoria to Bald Hill, as shown by the glaciomarine sediments there. The salinity of this inland sea was close to normal and the connection to the open ocean unrestricted, as previously discussed. Struckmeyer & Totterdell (1990) and Veevers (2000) proposed that this connection was with the Palaeo-Pacific Ocean and lay to the south of Victoria, across present-day Tasmania. However, ice transport directions across southeastern Australia indicate that this area was covered by the continental ice sheet, which was probably centred in North Victoria Land in Antarctica (Fig. 7; O'Brien et al. 2003). The inland sea cannot have connected directly eastwards to the Sydney Basin, because a north-south mountain range separated the two (Herbert & Helby 1980). Instead it is more likely that the inland sea joined the shallow sea that covered north-western Australia in the Early Permian (Fig. 7), and connected with the Tethys Ocean to the northwest rather than the Palaeo-Pacific Ocean to the east.

The palaeobiogeographic affinities of the fauna in the Bacchus Marsh Formation are unclear, due to the very small number of species present. The brachiopod

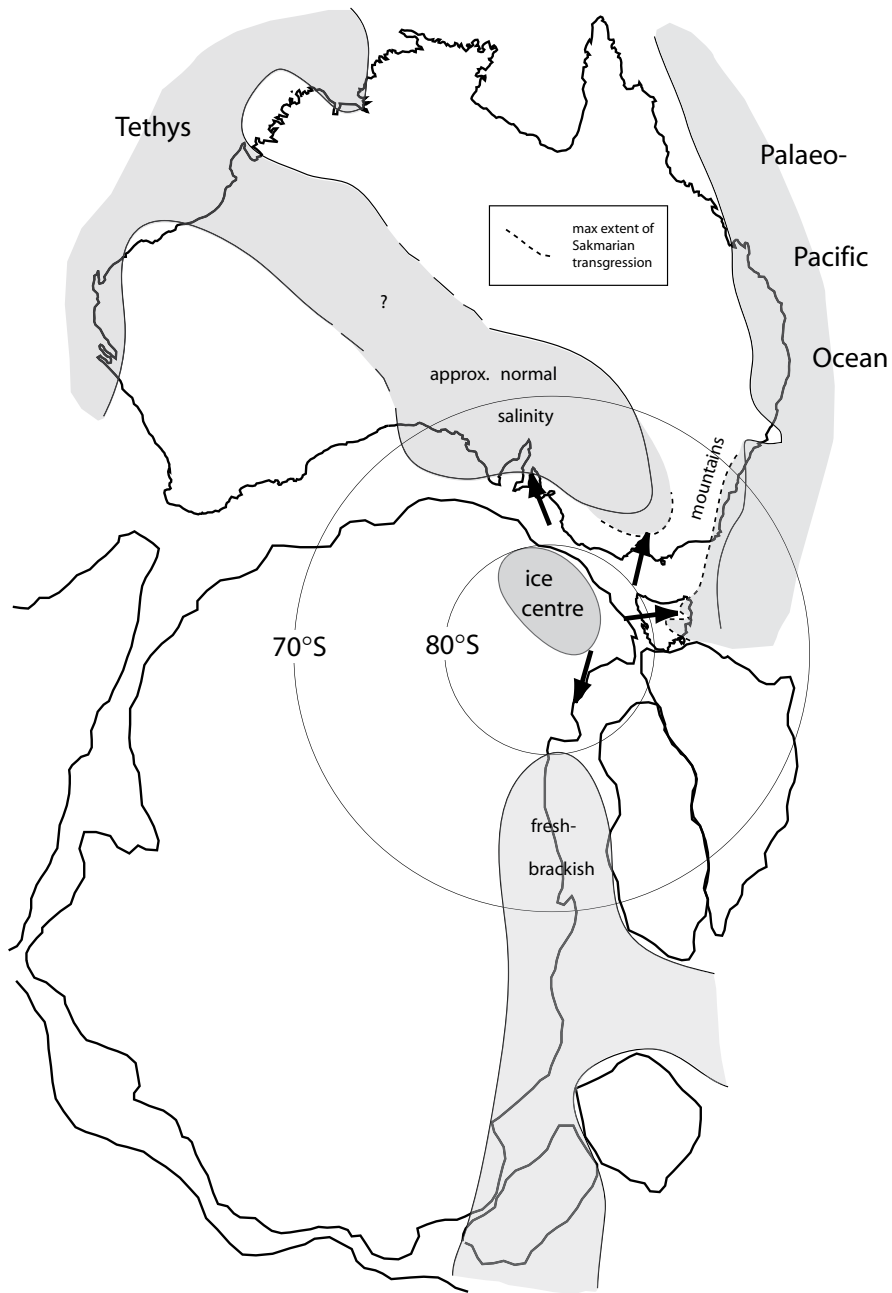


Fig. 7. Palaeogeography of Australia in the Early Permian, showing the coastline at the maximum extent of the continental ice sheet (solid line), and during the waning stages of the glaciation (dotted line). Plate reconstruction and Antarctic coastline from Miller and Collinson (1994); position of ice centre and generalised ice transport directions (shown by arrows) from O'Brien et al. (2003); coastline in Tasmania from Clarke (1989); palaeolatitude from Veevers (2000); coastline in eastern and northwestern Australia from Struckmeyer and Totterdell (1990) and Herbert and Helby (1980). Note that plate reconstructions by Struckmeyer and Totterdell (1990) and Veevers (2000) place the Lord Howe Rise east of southern Australia; Miller and Collinson (1994) place it east of Antarctica, as shown here; both interpretations are consistent with the palaeogeographic arguments presented here.

Trigonotreta is present in both the Westralian and Austrazean Provinces that occupied the western and eastern margins of the Australian portion of Gondwana respectively (Archbold 2000). The conulariid *Notoconularia* is present in only the Austrazean Province, but it is so rare in the Bacchus Marsh Formation that the significance of this is uncertain.

In Antarctica another Early Permian inland sea formed in front of the retreating continental ice (Fig. 7), and was bordered by a braided outwash plain (Miller & Collinson 1994). This sea accumulated 100–200 m of turbidites that resemble the coeval Bald Hill glaciomarine sediments. However, the lack of fossils and absence of dolomite in the Antarctic turbidites indicate that the sea here was fresh to brackish and therefore did not connect to the Australian sea; instead it extended several hundred kilometers towards South Africa (Fig. 7).

CONCLUSIONS

At Bald Hill in central Victoria a well-exposed sequence of glaciomarine strata forms the upper part of the late Sakmarian Bacchus Marsh Formation, and was deposited in an inland sea of normal salinity that extended across central Victoria when the continental ice sheet receded to the south. As the glacier retreated and sea level rose, the initial transgression at Bald Hill deposited a thin conglomerate, formed by limited reworking of a diamictite. A relatively shallow, protected, low energy embayment of the inland sea then accumulated ~180 m of interbedded dolomitic sandstones and siltstones with abundant sedimentary structures, including runzelmarks on the base of sandstone beds. These sediments were deposited by turbidity flows generated annually by the summer influx of sediment in the meltwater streams draining the ice sheet. Following each turbidity flow, the surface of the silt was frequently burrowed by *Planolites* and colonised by microbial mats, which provided cohesion, so the silt surface was wrinkled rather than eroded by the next turbidity flow. The very rapid accumulation rate (~0.2 m/year; the entire sequence was deposited in <1000 years) is typical of glaciomarine environments. Palaeocurrent data from the turbidites show that the seafloor sloped northwards. The very limited fauna in the sediments probably reflects the seasonally turbid bottom waters and low nutrient levels. The interbedded sandstone/siltstone sequence coarsens upwards, accompanied by a decrease in dolomite content and a change in ichno-

fauna from *Planolites* to *Muensteria*; this was due to progradation of the delta at the mouth of the meltwater streams. The approximately normal salinity of the inland sea shows that it was connected to the open ocean, probably the Tethys to the northwest, but not to the very extensive fresh-brackish inland sea in Antarctica to the south.

ACKNOWLEDGEMENTS

This paper is dedicated to Neil Archbold, who introduced JW to the Bacchus Marsh Permian sediments, and who helped with the initial fieldwork. Steve Hearn (University of Queensland) assisted with the Walsh transform analysis. The landowners at Bald Hill are thanked for allowing access to their properties.

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