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Stratigraphic signature of the late Palaeozoic Ice Age in the Parmeener Supergroup of Tasmania, SE Australia, and inter-regional comparisons

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Abstract

Recent research in eastern Australia has established that rather than being a single, long-lived epoch, the late Palaeozoic Ice Age comprised a series of glacial intervals each 1–8 million years in duration, separated by non-glacial intervals of comparable duration. In order to test whether the glacial events recognized in New South Wales and Queensland have broader extent, we conducted a reappraisal of the Parmeener Supergroup of Tasmania, southeast Australia. A facies analysis of the Pennsylvanian to Permian section was carried out, allowing rationalization of the succession into four recurrent facies associations: a) glacial facies association, restricted to the basal Pennsylvanian/earliest Permian Wynyard Formation and correlatives, b) glacially/cold climate-influenced to open marine shelf facies association, which accounts for large parts of the Permian succession, c) deltaic facies association, which specifically describes the Lower Permian “Lower Freshwater Sequence” interval, and d) fluvial to estuarine facies association, which specifically addresses the Upper Permian Cygnet Coal Measures and correlatives. Indicators of sediment accumulation under glacial influence and cold climate are restricted to four discrete stratigraphic intervals, all of which indicate that glaciation was temperate in nature. The lowermost of these, incorporating the basal Wynyard Formation and its correlatives, and overlying Woody Island Formation, shows evidence of proximal glacial influence (subglacial, grounding-line fan and fjordal facies), and is likely a composite of one or more Pennsylvanian glacial event(s) and an earliest Permian (Asselian) glacial. The second, of late Sakmarian to early Artinskian age, comprises an initial more proximal ice-influenced section and an overlying more distal ice-influenced interval. The third (Kungurian to Roadian) and fourth (Capitanian) intervals are both distal glacial records. The four intervals are of comparable age to glacials P1–P4, respectively, recognized in New South Wales and Queensland (notwithstanding apparent discrepancies of < 2 million years in age), and display similar facies characteristics and vertical contrasts to those intervals. Accordingly, it is concluded that the late Palaeozoic stratigraphy of Tasmania preserves a glacial/cold climate record correlatable to that of mainland eastern Australia, lending support to the hypothesis that these events were widespread across this portion of Gondwana.

Keywords: Late Palaeozoic, ice age, glaciation, Tasmania

1. Introduction

Until recently, the late Palaeozoic Ice Age was thought to have been a single, protracted Icehouse interval some 60–70 million years in duration, with some waxing and waning of ice centers across Gondwana (Veevers & Powell, 1987; Crowell, 1999). Increasingly, however, this view is being supplanted by the concept of a multi-phase Ice Age characterized by several, shorter (1–10 m.y.) glacial intervals separated by non-glacial intervals of comparable duration (Isbell et al., 2003; Fielding et al., 2008a, 2008b, 2008c). Eight such, discrete glacial intervals have been recognized by Fielding et al. (2008a) from the stratigraphic record in eastern Australia (New South Wales and Queensland).

Each of these intervals contains sedimentological and other evidence for glacial ice presence either in the depositional basin or in the immediate hinterland to the basin, and each can be correlated in time, within the limitations imposed by current geochronological resolution, over wide areas. The intervening intervals display no evidence whatsoever of glacial conditions, and are thus regarded not as “interglacials” but as longer intervals of time during which climate was more temperate, similar perhaps to the mid-Miocene Climatic Optimum of the Neogene (Holbourn et al., 2004; Zachos et al., 2008).

The issue of whether glacial events or intervals recognized in any particular part of the world were global in extent, or rather more restricted in influence, remains to be satisfactorily resolved

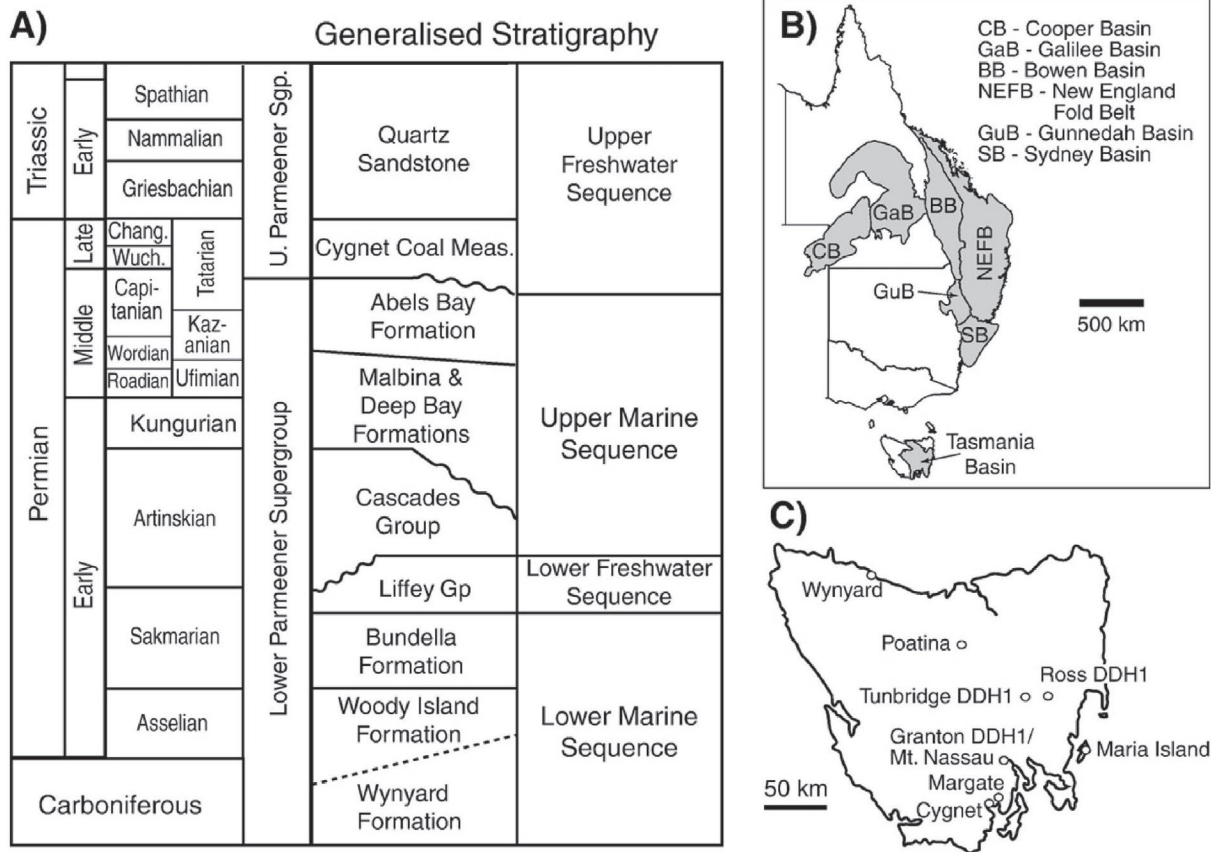


Figure 1. Generalized stratigraphic column and nomenclature for the Carboniferous to Triassic Parmeener Supergroup of Tasmania (from Reid et al., in press), and map showing the context of the Tasmania Basin in eastern Australia.

(Fielding et al., 2008c). Intuitively, and by analogy with the better-known and more highly-resolved Neogene Icehouse, it seems unlikely that all late Palaeozoic glaciations were synchronous globally. Rather, the stratigraphic record, particularly in far-field regions where the main consequence of glaciations was a product of glacioeustatic sea-level fluctuations, is likely to have been a mosaic of effects from asynchronous events at different times in different areas. As more highly resolved stratigraphic records from Gondwana become available, it may become possible to assess whether or which glacial events were indeed synchronous.

As an initial test of the hypothesis that Permian glacial events in eastern Australia are of broader extent, a study of the Carboniferous to Permian Parmeener Supergroup of the Tasmania Basin was undertaken (Figure 1). In the present paper, we report the results of that investigation. The Carboniferous to Permian stratigraphy was examined at a number of surface outcrops and in selected drillcores held at the Tasmania Department of Mineral Resources facility in Mornington, Hobart. Sections were described and interpreted in terms of depositional environment. Evidence for glacial influence, ice rafting and cold climate was carefully noted, and discrete intervals with glacial/cold climate indicators (Table 1 of Fielding et al., 2008a) were recognized. Correlations were then drawn between this record and the stratigraphic framework of Fielding et al. (2008a) from New South Wales and Queensland.

Age control is derived entirely from biostratigraphic data. The most widely used scheme for determining relative age is the marine macroinvertebrate zonation of Clarke and Farmer (1976), which has been correlated in detail to similar schemes for the eastern Australian mainland and to the Australian late Palaeozoic palynostratigraphic zonation (Reid et al., in press Figure 5). At this time, no absolute ages are available for the Parmeener Supergroup, rendering relative age determinations somewhat tentative.

2. Geological setting

During the Pennsylvanian and Early Permian, Tasmania lay within the southern polar circle, according to published palaeomagnetic data and their interpretation (e.g., Li and Powell, 2001; Figure 2). Portions of the Parmeener Supergroup have been interpreted for many years as having been laid down under the influence of glacial ice (Banks, 1980; Clarke, 1989; Reid et al., in press). While the evidence for glaciation is not substantially disputed, the timing and character of glaciation have never been fully established, and so detailed comparisons with events on the southeastern Australian mainland cannot be made.

The Parmeener Supergroup was accumulated in the Tasmania Basin, an intracratonic basin that was active during the Pennsylvanian to Late Triassic, and one of a number of sedimentary basins developed along the Panthalassan margin of Gondwanaland (Veevers et al., 1994). The confinement of Pennsylvanian to end-Sakmarian glacial formations to deep structural lows, and abrupt lateral facies and thickness changes onto marginal structural highs, suggests that these units formed under a period of extensional subsidence in a series of grabens or half-grabens separated by uplifted, block-faulted horsts (Figures 9 and 10 of Reid et al., in press). Some of these structural lows may have been further deepened by glacial scouring associated with mountain or outlet glacier activity, while the highs may have served as glacial centers (Banks & Clarke, 1987; Hand, 1993). The upper half of the Permian section appears unconfined by previous structural topography, and displays a more sheet-like geometry in cross-section. The mainly Triassic Upper Parmeener Supergroup appears to lie unconformably over the Permian section. The uppermost part of the Supergroup comprises coal-bearing strata of Late Triassic (Carnian–Norian) age that may also be in unconformable contact with earlier Triassic sediments.

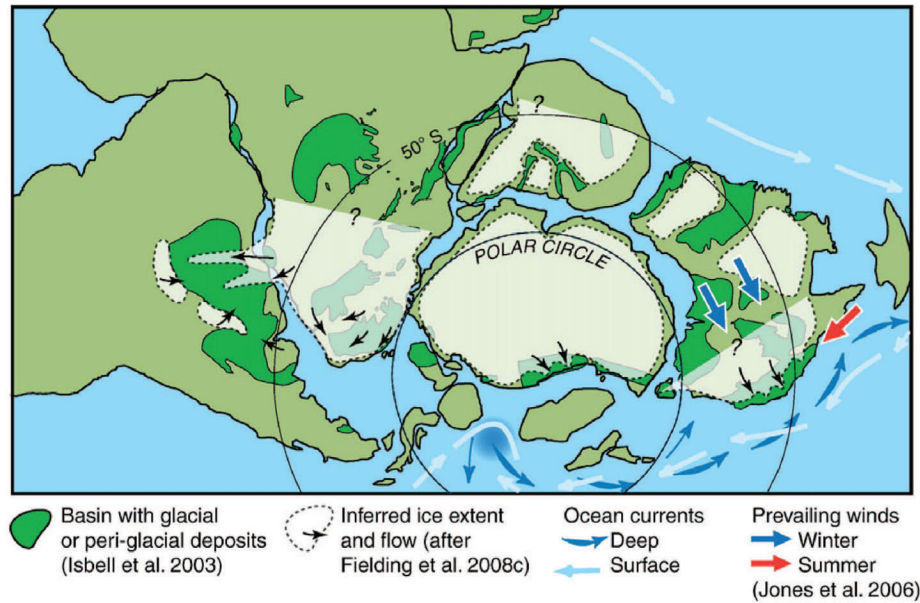


Figure 2. Palaeogeographic reconstruction of Gondwana during the Early Permian, showing generalized interpreted extent of glacial ice, and interpreted wind and ocean current systems (modified from Fielding et al., 2008c). Palaeogeography after Li and Powell (2001), wind/currents after Jones et al. (2006).

The Tasmania Basin is somewhat offset westward from the meridional, north–south strike trend of the Bowen–Gunnedah–Sydney Basin system (BGSBS) located 700–900 km to the north, and lies structurally along trend from Permian outliers in Victoria, and central New South Wales and Queensland (Figure 1). As with these outliers, however, the late Palaeozoic stratigraphy can be closely compared with that of the BGSBS, and interpreted in terms of basin-forming events by analogy.

A tectonostratigraphic comparison between the Parmeener Supergroup of the Tasmania Basin and the BGSBS is presented as Figure 3. The lowermost, structurally confined units are in-

terpreted to have formed during a period of modest but widespread crustal extension across eastern Australia that gave rise to a large number of discrete infra-basins, some of which later coalesced to form the BGSBS (Fielding et al., 2001; Korsch et al., 2009). The more sheet-like upper part of the Permian stratigraphy in the Tasmania Basin can be interpreted as recording the succeeding, late rift and post-rift thermal subsidence phase that is extensively preserved in the BGSBS. In the BGSBS, the Upper Permian succession is extremely thick (thickening eastward), rich in first-cycle volcanic debris, and is coal-rich. It is interpreted to have formed during the initial development of a retroarc fore-

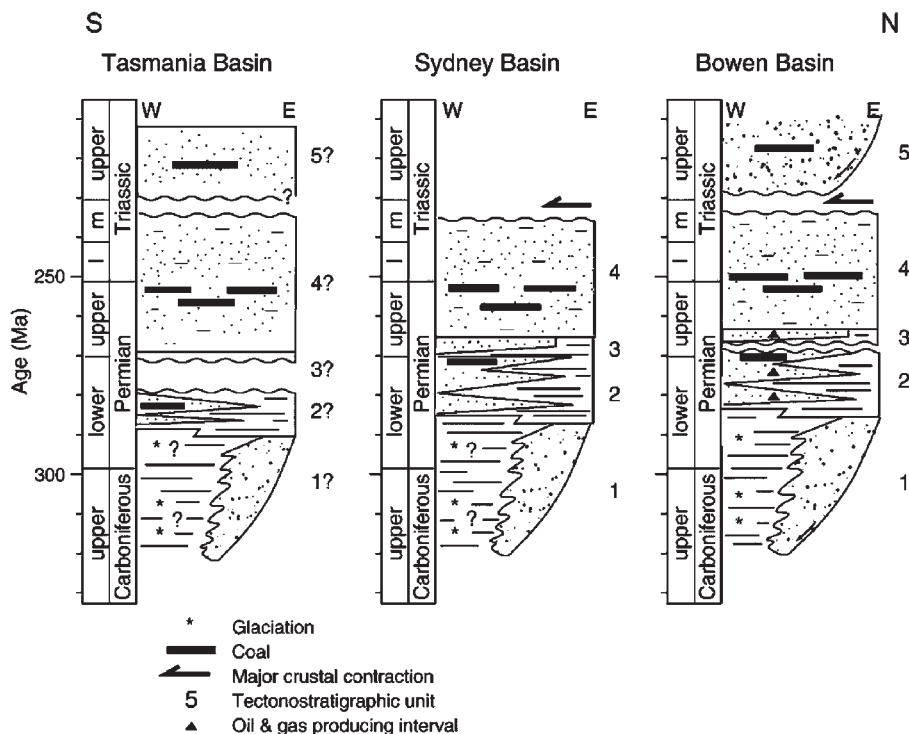


Figure 3. Tectonostratigraphic framework for the Tasmania Basin in the context of the Bowen–Gunnedah–Sydney Basin System to the north. Key to tectonostratigraphic units: 1 – early extension, 2 – late extension, 3 – passive thermal subsidence, 4 – foreland basin, 5 – extension.

land basin during the onset of the Hunter–Bowen contractional orogeny (Holcombe et al., 1997; Glen, 2005). While the BGSBS preserves the direct stratigraphic record of contractional tectonics, the cratonic basins to the west (Figure 1) also preserve a thinner, but clearly correlatable Upper Permian section that is also rich in first-cycle volcanic lithic detritus and airfall tuff beds (e.g., Allen and Fielding, 2007). Accordingly, the Upper Permian, volcanic lithic and tuff-rich coal-bearing section of the Tasmania Basin is interpreted as a cratonic overspill equivalent of the foreland basin succession, similar to the contemporaneous section in the Galilee Basin of Queensland (Allen and Fielding, 2007).

The Triassic non-marine succession of the Upper Parmeener Supergroup is interpreted as a continuation of the Hunter–Bowen foreland basin succession, again by analogy with similar successions in New South Wales and Queensland, both in the foreland and contiguous cratonic basins (Figure 3). The Upper Triassic, coal-bearing succession that forms the uppermost Parmeener Supergroup, however, is interpreted as the record of a separate basin or basins, again by analogy with better-known successions on the mainland. Across eastern Australia, from Leigh Creek in northern South Australia to various locations in New South Wales and particularly Queensland (e.g., Tarong, Ipswich and Callide), discrete, partly fault-bounded basins formed during the Late Triassic as part of a widespread but ultimately failed rifting episode. These basins are well-known for their extremely thick (< 20 m), minable coal bodies of alluvial plain origin. The lithological assemblage, interpreted depositional environment, abundant coal resources, and mineralogy of the Upper Triassic uppermost Parmeener Supergroup are all consistent with their having formed in one or more such extensional basins.

Given the close similarities between the stratigraphies of the Tasmania Basin and the other Carboniferous–Triassic basins of eastern Australia, detailed comparisons of environmental change through the late Palaeozoic of these basins should be achievable.

3. Previous sedimentological research

The stratigraphy of the Parmeener Supergroup has been the subject of numerous investigations, and a plethora of local stratigraphic nomenclature has resulted. Recently, Reid et al. (in press) have attempted to synthesize all of this work into a unified stratigraphic framework, and their scheme is adopted herein. The Parmeener Supergroup is divided into Lower and Upper divisions on lithostratigraphic grounds, but the boundary does not correspond to the Permian–Triassic boundary, which is in many places difficult to locate. A more useful, four-part subdivision of the Parmeener Supergroup was proposed by Clarke and Banks (1975) on the basis of facies assemblages and their sedimentological interpretation. In this scheme, the stratigraphy is divided into (in ascending order) a Lower Marine Sequence (Carboniferous to Sakmarian), a Lower Freshwater Sequence (upper Sakmarian to lower Artinskian), an Upper Marine Sequence (Artinskian to Capitanian) and an Upper Freshwater Sequence (Wuchiapingian to Changhsinian; Figure 2). The boundaries between these four units appear to correspond to fundamental sedimentological changes in the Permian stratigraphy and are here considered to be useful divisions of the stratigraphy.

Several sedimentological investigations have been carried out, most of which were confined to particular formations or to particular outcrop areas. Pertinent results from all previous studies, particularly those carried out by officers of the Tasmania Department of Natural Resources and its predecessors, are summarized by Reid et al. (in press).

Early work on basal Parmeener Supergroup strata was summarized by Banks (1980). These rocks were regarded as glacial deposits to the extent that the word “Tillite” is incorporated into the stratigraphic name of some equivalent units at the base of the Parmeener Supergroup (Reid et al., in press), and was used as a de-

scriptive term in Banks (1980). The broad glacial interpretation of these rocks has not been substantially disputed. Subsequently, further work on the basal strata has developed depositional models for these rocks, arguing for their accumulation in subglacial settings, grounding-line fans, fjords and glacial marine settings (Banks & Clarke, 1987; Powell, 1990; Domack et al., 1993; Hand, 1993).

The sedimentology of the thick mudrock section that overlies the basal “tillites” has also been the subject of some interest, particularly the Tasmanites Oil Shale facies that is widely regarded as a potential oil source rock (Domack et al., 1993; Revill et al., 1994; Domack, 1995). Domack et al. (1993) demonstrated that the Tasmanites Oil Shale is a recurring facies, rather than a single bed as was previously thought, and advocated an offshore marine, oxygenated environment of deposition. A transition from polar to more temperate climate was also recognized upward through the lower part of the Woody Island Siltstone and equivalents by Domack et al. (1993). Glendonites in the basal Permian marine mudrocks (calcite pseudomorphs after the hexahydrate mineral ikaite, which is considered a good indicator of cold sea-floor conditions), were studied by Domack et al. (1993) and Sell-eck et al. (2007). These workers, and Frank et al. (2008), however, caution against using stable isotopic data from glendonites uncritically as an index of paleo-sea floor temperature, because of the complex diagenetic history recorded in the pseudomorphs.

Aspects of the Lower Parmeener Supergroup carbonate lithologies were documented by Runnegar (1979) and Rao (1981, 1983, 1988), and more recently by Rogala et al. (2007) who proposed a unified facies scheme for these rocks. A middle shelf, sea-level highstand context for the high-paleo-latitude, bioclastic (heterozoan) limestones was argued for by Rogala et al. (2007). Martini and Banks (1989) characterized the Lower Freshwater Sequence (Liffey Group and equivalents) as a succession accumulated in shallow marine, deltaic and coastal plain environments under the periodic and mainly indirect influence of glacial ice. The principal glacial influence on the unit was via iceberg rafting of coarse-grained sediment.

4. Facies analysis of the Carboniferous to Permian section

Rather than establish disparate facies schemes for each formation of the Carboniferous/Permian Lower and lower Upper Parmeener Supergroup, in this work we present a unified facies analysis in which the entire section is rationalized into four major facies associations (Tables 1–4). This allows the various formations to be directly compared with each other, and an assessment of the degree of glacial/cold climate influence on their accumulation, if any. The four facies associations respectively represent sediment accumulation in 1. glacial, 2. glacially/cold climate-influenced to open marine shelf, 3. deltaic, and 4. fluvio-estuarine environments.

4.1. Glacial facies association

The glacial facies association comprises an array of facies collectively deposited under the direct and proximal influence of glacial ice in both terrestrial and glacial marine settings (Figure 4). Interpreted environments of deposition include possible subglacial settings, proglacial, grounding-line, proximal glacial marine, subaerial to subaqueous fans, deltas and subaqueous lobes, transgressive reworking of these ice-contact facies in standing water following ice retreat, and relatively quiet water subaqueous environments such as fjords and lakes. This array of seven facies occurs consistently together and is largely restricted to the basal Carboniferous/Lower Permian formations at the base of the Parmeener Supergroup (Wynyard, Truro and Stocker’s Tillite, and equivalents). A characteristic of all facies in this association is a complete absence of bioturbation, despite extensive evidence for sediment accumulation in marine, fjordal or lacustrine water bodies.

Table 1. Characteristics of Facies Association A (glacigenic).

Facies	Lithology	Sedimentary structures	Biota	Interpretation	Stratigraphic unit
1	Laminated, medium to dark grey, fine-grained siltstone and claystone, minor inter-bedded v. fine-grained sandstone, dispersed gravel.	Flat stratification in mudrocks, flat lamination, ripple cross-lamination, ripple form sets, soft-sediment deformation, load casting	None evident	Quiet water setting: marine, fjordal or lacustrine, probable sea-ice cover	Wynyard Fm and equivalents
2	As above but with thin beds of diamictite, thin-bedded	As above	None evident	As above, with periods of open water allowing iceberg movement	Wynyard Fm and equivalents
3	Chaotically mixed and interbedded siltstone, v. fine - fine sandstone, diamictite, and minor conglomerate	As above but pervasively soft-sediment deformed, short clinoform sets locally	None evident	Grounding-line fan affected by mass-wasting processes	Wynyard Fm and equivalents
4	Discrete sandstone beds, generally separated by diamictites	Flat lamination, cross-bedding, probable antidunal bedding, soft-sediment deformation, shear planes	None evident	Jet outflow from subglacial stream into standing water	Wynyard Fm and equivalents
5	Diamictite, mainly stratified but locally massive	Flat stratification, soft-sediment deformation, rare surfaces with aligned gravel	None evident	Proximal glacimarine/glacilacustrine/glacifjordal, to grounding line fan, to locally subglacial	Wynyard Fm and equivalents
6	Conglomerate (thin beds associated with diamictites)	Crude flat stratification	None evident	Reworking of glacial debris in open water during ice retreat	Wynyard Fm and equivalents
7	Conglomerate, thick composite intervals with minor interbedded sandstone	Crude flat and low-angle stratification, imbrication, local cross-bedding, sandstones contain cross-bedding, load casts, ripple cross-laminated	None evident	Probably subaerial outwash fans to locally subaqueous fans	Wynyard Fm and equivalents

In Table 1, A1 to A7 are listed in order of interpreted proximity to glacial ice, from most distal (A1) to most proximal (A5–A7). Facies A1 consists of thinly interbedded and interlaminated claystone, siltstone and very fine- to fine-grained sandstone, with dispersed granule- and pebble-sized limestones (Figure 4A). A variety of ripple-scale structures and soft-sediment deformation structures including dewatering structures and sand volcanoes are present, with rhythmic flat interlamination between finer- and coarser-grained lamination a distinctive feature of this facies. Gravel-sized limestones locally occur concentrated on specific laminae, and some clasts penetrate and deform underlying lamination. A quiet, standing water interpretation is favoured for Facies A1, on open marine shelves, in fjords or in lakes. Seasonal sea-ice is suggested by the presence of delicate lamination and the lack of high-energy wave- and combined flow-generated structures, together indicating dampening of wave activity in the depositional basin (cf. Dowdeswell et al., 2000). The occurrence of sills due to bedrock highs and morainal banks also tends to dampen wave motion within fjords (Boulton, 1990). Low-energy currents and possible sediment gravity flows are indicated by the

presence of ripples and massive, dewatered beds, respectively. Presence of mobile ice is also suggested by the abundance of dispersed limestones with interpreted dropstone fabrics. Abundance of soft-sediment deformation suggests that the depositional surface was frequently fluidal.

Facies A2 is similar to A1 with the addition of enclaves and thin beds of diamictite (Figure 4B). A broader range of clast size is evident in this facies, up to cobble grade. A similar environment of deposition to that for Facies A1 is envisaged, with the addition of periodic berg activity to deliver the range of debris that forms the diamictite beds. Facies A3 comprises chaotically mixed and interbedded mudrock, sandstone and diamictite with minor conglomerate (Figure 4C). Discrete intervals of this facies locally contain short (1–3 m thick) clinoform sets. Large-scale soft-sediment deformation, particularly convolute bedding, is a defining characteristic of this facies (Figure 4C). Facies A3 is interpreted to record the proximal portions of grounding-line fans and associated subaqueous depositional systems. Sediment was issued from point-source tunnel mouths to form jet effluents (Powell, 1990), and the coarser sediment fraction was

Table 2. Characteristics of Facies Association B (glacially/cold climate-influenced to open marine shelf).

Facies	Lithology	Sedimentary structures	Biota	Interpretation	Stratigraphic unit
1	<i>Eurydesma</i> -spiriferid coquina; common pebbles and outsized clasts	Imbricated shells, bivalves disarticulated and often convex-side up	Eurydesmids, brachiopods (mainly spiriferids), deltopectens; various bryozoans; common acrothoracid barnacle borings in shells	Intertidal to subtidal; elongate "barrier" ridges of shell debris	Bundella Fm (Darlington LS)
2	Medium grey, calcareous bryozoan siltstone and sandy siltstone; common pebbles and outsized clasts	Flat lamination, sandy linsen	Fenestrate and large, robust trepostome bryozoans; eurydesmids and deltopectens	Low energy shallow subtidal zone, likely between ridges of Facies 1	Bundella Fm (Darlington LS)
3	Fine-coarse grained sandstone to boulder conglomerate (clasts mainly quartzite and granite), interbedded with interlaminated, bioturbated siltstone-sandstone; associated with Facies 1 and 2	Structureless; in association with Facies 1 and 2; clasts are rounded to well-rounded	Trepostome and stenoporid bryozoans, eurydesmids, some deltopectens, fine-grained beds contain <i>Planolites</i> , palimpsest <i>Thalassinoides</i>	Debris rafted by ice into intertidal-shallow subtidal zone, alternating with ice-free conditions	Bundella Fm ("Erratic Zones")
4	Well-bedded crinoid grainstone to rudstone; sparse dispersed pebbles and cobbles, cobble and shell lags; patchy silicification and chert nodules	Abundant planar to low-angle lamination, pinch and swell bedding; common small to medium scale trough cross-bedding; hummocky bedding and possibly hummocky cross-stratification	Abundant crinoids, conspicuous brachiopods, <i>Eurydesma</i> , deltopectens	Shoreface/subtidal shoals	Cascades Gp (Counsel Creek Fm)
5	Coarse- to very coarse-grained sandstone; common pebbles	Common trough and planar to low-angle cross bedding; large-scale internal erosion surfaces	None	Upper Shoreface	Risdon Ss
6	Poorly fossiliferous fine- to medium-grained sandstone and admixed fine sandstone and siltstone (bioturbated); scattered pebbles	Structureless to well stratified; small-scale trough cross-bedding	BI 2-3: <i>Teichichnus</i> , <i>Rosselia</i> , <i>Zoophycos</i> , <i>Planolites</i> , <i>Phycosiphon</i> , <i>Asterosoma</i> , <i>Paleophycos</i>	Lower shoreface	Minnie Point Fm, Rayer Sandstone
7	Fossiliferous, calcareous fine-grained muddy sandstone and laminated siltstone, sparse granules and cobbles	Flat lamination, regular bedding	Abundant bryozoans (mainly stenoporids), brachiopods BI 3-4: <i>Rosselia</i> , <i>Asterosoma</i> , <i>Planolites</i> , some <i>Phycosiphon</i>	Lower shoreface-offshore transition	Bundella Fm, Malbina Fm, Deep Bay Fm
8	Poorly fossiliferous, fine-very fine sandstone and siltstone; interbedded or admixed (bioturbated); dispersed pebbles and cobbles	Crude stratification, regular bedding Structureless or laminated	Rare bryozoans and brachiopods BI 3-5: <i>Zoophycos</i> , <i>Asterosoma</i> , <i>Planolites</i> , <i>Chondrites</i> , <i>Thalassinoides</i> , <i>Phycosiphon</i> , <i>Paleophycos</i> .	Offshore transition-off-shore	Abels Bay Fm, Woody Island Fm
9	Medium to dark grey, organic matter-rich siltstone, dispersed pyrite, common large glendonites and/or calcareous concretions, rare small gravel		Sparse fenestrate bryozoans and small bivalves BI < 3: <i>Phycosiphon</i>	Offshore or deep, quiet, poorly oxygenated fjordal setting.	Woody Island Fm and equivalents

deposited proximally and reworked by mass flows and failures of oversteepened surfaces. Short clinof orm sets may record the prograding frontal slopes of such subaqueous fans or be the result of truncation and duplication of beds due to ice shove. Facies A4 comprises discrete sandstone beds associated intimately with Facies A5: these sandstone beds are internally dominated by flat lamination, cross-bedding, probable antidunal bedding, soft-sediment deformation and internal shear planes. The shear planes bound thrust-faulted packages of sediment and encompass multiple facies. The thrust packages are often repeated laterally on bedding plane surfaces producing ridges now exposed on intertidal platforms near the town of Wynyard. Facies A4 is interpreted as arising from jet outflows that at times delivered volumes of sand to proglacial and grounding-line fans (cf. Powell, 1990; Russell & Arnott, 2003). The shear planes bounding thrust faulted packages are interpreted to be the result of subaqueous ice shove with multiple ridges possibly representing push structures formed during seasonal advance similar to that of modern De Geer Moraines (Benn and Evans, 1998).

Facies A5 consists of diamictites, with a broad variety of textures and fabrics (Figure 4D). Most diamictites are stratified, but massive varieties also occur. Clast content ranges from 2% to 30% (Moncrieff, 1989), and matrix is typically a mixture of sand and mud. Stratified variants preserve crude planar stratification and soft-sediment deformation structures. Stratified diamictites also include laterally continuous (over tens of m) stacked beds (cm to dm thick) of diamictite. Packets of deformed diamictites bounded by shear planes and thrust over underlying deposits like those

in Facies A3 and A4 also occur. Localities at Wynyard preserve surfaces armoured with oriented and striated coarse clasts (Powell, 1990). Faceted, striated and bullet-shaped clasts are common. There is often little within any given diamictite that allows a precise diagnosis of environment of deposition. Accordingly, the diamictites described here are attributed to a range of settings, from possibly subglacial (armoured and striated clast-rich surfaces), through grounding-line fans to proximal glacialmarine/glacialacustrine/fjordal settings. Stratified diamictites may represent settling from meltwater plumes in association with ice-rafted debris and emplacement as debris flows. Massive diamictites likely result from a combination of proximal settling from meltwater plumes, deposition from debris flows and destruction of internal stratification due to high rates of rainout from floating ice (Cowan & Powell, 1990; Dowdeswell et al., 1994; Smith & Andrews, 2000). Thrust-faulted diamictites are interpreted as subaqueous ice shove structures (Benn and Evans, 1998).

Two conglomerate facies are recognized. Facies A6 consists of thin conglomerate beds associated with diamictites of Facies A5, generally at the top of depositional units. These beds are interpreted to record reworking of diamictite and other facies during ice retreat. Facies A7 comprises thicker, composite units of pebble to boulder conglomerate with minor interbedded sandstone (Figure 4E, F). A range of current-laid sedimentary structures is preserved (Table 1). Facies A7 is interpreted as the deposits of subaerial to possibly subaqueous outwash systems, ranging from coastal alluvial plains (sandar) to possibly subaqueous fan deltas and grounding-line fans in some cases.

Table 3. Characteristics of Facies Association C (deltaic).

Facies	Lithology	Sedimentary structures	Biota	Interpretation	Stratigraphic unit
1	Laminated, medium to dark grey, fine siltstone with minor v. fine-grained sandy streaks, dispersed fine pyrite	Flat stratification in siltstone, sandy streak lamination (linsen), rare gravel, dispersed	None	Prodelta	Liffey Group
2	Interlaminated and thinly interbedded siltstone and v. fine-grained sandstone, variable proportions	Current and combined-flow ripple cross lamination, flat and low-angle lamination, fragmented plant debris, load casts, syneresis cracks	Rare shell fossils BI mainly 0-1, locally < 4: <i>Planolites</i> , <i>Palaeophycus</i> , <i>Phycosiphon</i> , <i>Rhizocorallium</i> , <i>Teichichmus</i>	Distal delta front	Liffey Group
3	Interlaminated and thinly interbedded siltstone and fine- v. fine-grained sandstone (sandstone-dominated), forming short coarsening-upward units	As above	Rare shell fossils BI mainly 0-1 locally < 3: <i>Planolites</i> , <i>Thalassinoides</i>	Medial delta front	Liffey Group
4	Sharply based fine-medium-grained sandstone bodies ≤ 7 m thick	Current and climbing ripple cross-lamination, hummocky cross-stratification, flat and low-angle lamination, cross-bedding	BI mainly 0, locally 0-3: <i>Planolites</i>	Proximal delta front (wave – fluvial dominated)	Liffey Group Liffey Group
5	Muddy v. fine-fine-grained sandstone, dispersed small gravel (locally in layers)	Homogenized by bioturbation	BI is 3-5: <i>Planolites</i> , <i>Palaeophycus</i> , <i>Rhizocorallium</i> , <i>Teichichmus</i> , small <i>Rosselia</i> , <i>Asterosoma</i>	Transgressive ravinement and abandonment	

4.2. Glacially/cold climate-influenced to open marine shelf facies association

This association comprises nine lithofacies which together represent open marine shelf environments of deposition that experienced generally distal or indirect influence from glacial or sea-ice activity, mainly in the form of sediment delivery from floating ice (icebergs and/or sea-ice: Table 2, Figure 5). In Table 2, these facies are arranged from the shallowest to the deepest interpreted depositional settings. The first four facies are bioclastic limestone lithologies that are best-developed in the Darlington Limestone of Maria Island and the Cascades Group (Figure 1). The other facies of Association B are found in a variety of formations throughout the Permian succession of Tasmania.

Facies B1, which is best exposed at the Fossil Cliffs on Maria Island (Reid, 2004), comprises concentrations of marine invertebrate shells (coquinas), principally the bivalve *Eurydesma* and spiriferid brachiopods, with a sandy matrix and dispersed limestones (Figure 5A). Shells are typically disarticulated and commonly lie convex-upward. Based on the apparently reworked nature of the shells, and the interpreted palaeoecology of *Eurydesma* (Runnegar, 1979), Facies B1 is interpreted to have accumulated slowly in intertidal to subtidal shell banks or shoals associated with relatively low sediment-supply coastlines. Facies B2 is similar, but contains somewhat lower concentrations of shells with a greater relative proportion of bryozoans among the biota, and has a muddy matrix (Figure 5B). At its base, Facies B2 contains channel-shaped bodies of calcarenite. Upward, rare channel-shaped bodies are filled with bioclastic debris in beds of calcarenite and calcirudite. Both Facies B1 and B2 contain rare boulders up to 0.5 m in diameter, but pebbles, cobbles and boulders are more common in Facies B2 than in B1. Facies B2 is interpreted to record intertidal to subtidal water depths within similar settings to those recorded by Facies B1, but closer to sources of clastic sediment supply. Channel-form bodies represent rip channels that transported bioclastic debris into deeper water off the sides of shell banks. Rare boulders and dispersed gravel suggest introduction by ice rafting. Gradational boundaries and interbedding between Facies B1 and B2 suggest that the two environments were interchangeable in time and space. The purer carbonate, fossil-rich lithology of Facies B1 suggests that it was formed in deeper water, isolated from clastic sediment supply.

Facies B3 comprises the well-known "Erratic Zones" of the Basal Beds on Maria Island (Reid, 2004) and is also present in

other formations. At the Fossil Cliffs, the lithology of Facies B3 varies abruptly over short distances laterally and vertically, from fine- to coarse-grained sandstone to pebble to boulder conglomerate (Figure 5C). Beds of muddy, clast-rich sandstone to conglomerate alternate with beds of interbedded siltstone and fine-grained sandstone some of which are bioturbated by a restricted suite of trace fossils (*Planolites*, and *Thalassinoides* subtending from the base of coarse-grained beds). Individual clasts are not striated, are up to 2 m in diameter, are angular to rounded, and occur in the conglomerates and within adjacent siltstones. The clasts are predominantly quartzite and granite similar to basement rock lithologies exposed several km south of the Fossil Cliffs. However, rare mica schist, black slate, and limestone also occur (Clarke and Baillie, 1984). Some large clasts appear to be encrusted by bryozoans. Bryozoans and occasional bivalves (*Eurydesma* and *Myonia*) also occur in growth position within the conglomerates, with the thickest conglomerates containing multiple levels of *in situ* encrusting bryozoans. Facies B3 is intimately interbedded with Facies B1 and B2 in the Darlington Limestone of Maria Island. A similar fauna to that of Facies B2 is found within this facies.

Facies B3 is interpreted to record shallow subtidal marine environments (shoreface water depths) that received limited clastic sediment supply from the coast but considerable supply from ice-rafting. Many of the clasts in this facies show clear evidence of having been dropped through the water column. Many of the clast-rich beds show a sandy matrix, implying some wave and current reworking of material over a protracted period, and these beds are interpreted as condensed intervals formed during periods of minimal sediment supply. Alternating coarse debris-rich beds and finer-grained, bioturbated beds with no coarse clasts suggest episodicity to sediment supply, particularly episodicity in the supply of ice-rafted debris. In a low sediment-supply setting, such alternations could potentially represent glacial-interglacial cycles. Similar cyclicity was noted by Fielding et al. (2008b) from the Lower Permian lower Pebble Beach Formation of the southern Sydney Basin. Facies B1 to B3 also bear some similarity to Pleistocene glacial-marine deposits of the Yakataga Formation in southern Alaska (James et al., 2009a), and to boulder barricades and coarse-grained material transported by sea ice (Rosen, 1979; McCann et al., 1981; Gilbert, 1990).

Facies B4 comprises an array of bioclastic limestones containing a variety of invertebrate biota and physical sedimentary structures (Figure 5D). Lag accumulations of shells with

Table 4. Characteristics of Facies Association D (fluvio-estuarine).

Facies	Lithology	Sedimentary structures	Biota	Interpretation	Stratigraphic unit
1	Medium- to very coarse-grained sandstone, minor small gravel at unit bases	Basal and internal erosion surfaces, trough cross-bedding, flat lamination, ripple cross-lamination	Coaly plant casts	Coastal plain fluvial channels	Cygnnet Coal Measures
2	Interlaminated and thinly interbedded siltstone and v. fine – fine-grained sandstone, variable proportions	Linsen bedding, lenticular bedding, wavy bedding, flaser bedding, ripple cross-lamination, small-scale cross-bedding showing bimodal palaeocurrent distributions, symmetrical rippled tops to some beds, small-scale soft-sediment deformation, syneresis cracks	Plant debris, <i>in situ</i> roots (<i>Vertebraria</i>), local bioturbation (B.I. 0–3, <i>Planolites</i>)	Transgressive estuarine channels and basins	Cygnnet Coal Measures
3	Coal and coaly shale	None	Plant material	Coastal plain mires	Cygnnet Coal Measures

dispersed limestones are common as are patches of silicification within the limestone. This facies characterizes large portions of the Cascades Group across parts of Tasmania. Dunham textures range from grainstone to rudstone. Facies B4 is interpreted as shallow marine bioclastic carbonate accumulations in relatively clear water and with minor influence from ice-rafted debris (see also Rogala et al., 2007). The bioclastic limestones are found preferentially occupying zones that overlie or flank basement highs, suggesting that they formed in shallow water environments that were not depocentres and that therefore received relatively little terrigenous clastic sediment supply. A similar environmental setting for Permian cold-water, bioclastic limestones in Queensland was recently proposed by James et al. (2009b).

Facies B5 to B9 represent a spectrum of increasingly finer-grained, terrigenous clastic deposits. Facies B5 comprises coarse- to very coarse-grained sandstone with abundant cross-bedding and no biota (Figure 5E), and is interpreted as the deposits of upper shoreface environments. Facies B6 is muddy fine-grained sandstone with scattered, mainly small gravel, uncommon invertebrate fossils and abundant bioturbation (Table 2). Local stratification is preserved, but is more widely disrupted or destroyed by bioturbation. The lithology, sedimentary structure and trace fossil suite (which is interpreted to be a distal expression of the *Cruziana* ichnofacies) all suggest deposition in lower shoreface environments. Facies B7 is somewhat finer-grained, interbedded with siltstone, more fossil-rich, more heavily bioturbated, and interpreted on this basis as recording deposition in lower shoreface to offshore-transition water depths (Figure 5F). Facies B8 comprises heavily bioturbated, admixed fine-grained sandstone and siltstone with a trace assemblage that is interpreted as an expression of the *Zoophycos* Ichnofacies (Figure 5G). It is interpreted to represent deposition in offshore transition to offshore water depths (at or about storm wave base). Finally, Facies B9 comprises sparsely fossiliferous, bioturbated grey mudrocks with common glendonites (Selleck et al., 2007; Frank et al., 2008) and carbonate concretions (Figure 5H). This facies is interpreted to have formed in relatively deep, quiet offshore marine or fjordal settings.

4.3. Deltaic facies association

The deltaic facies association comprises five facies (Table 3), all of which recur in association with each other, almost entirely within the Liffey Group and equivalents (or Lower Freshwater Series: Martini and Banks, 1989; Figure 1; Figure 6). This inter-

val forms a distinctive unit within the Lower Parmeener Supergroup, hence its definition as “Lower Freshwater Sequence” by Clarke and Banks (1975). Facies C1 to C5 (Table 3) form a continuous facies spectrum, interpreted to record progressively shallower-water, deltaic depositional settings. These facies are characterized by a general absence of marine body fossils and restricted, low-diversity trace fossil suites, characteristic of deltaic deposits (Bann & Fielding, 2004; MacEachern & Bann, 2008). These facies contain dispersed limestones throughout.

Facies C1 comprises laminated grey siltstone with minor interlaminated very fine- to fine-grained sandstone, and is interpreted as the deposits of the distal deltaic fringe, or prodelta. Facies C2 is interlaminated and thinly interbedded siltstone and sandstone in variable proportions with rare shelly fossils, a variety of small-scale current and combined-flow-generated sedimentary structures, abundant plant debris and a restricted trace fossil assemblage (Figure 6B). It is interpreted to record deposition on the lower part of delta fronts. Facies C3 is a more sandstone-dominated, typically coarsening-upward variant of the previous facies, and is interpreted to record deposition higher on the delta front (Figure 6C). Facies C4 forms sharp-based, fine- to medium-grained sandstone bodies < 7 m thick internally dominated by current- and combined flow-generated sedimentary structures (Figure 6A, D, E). These bodies are interpreted as the deposits of the proximal parts of the delta front, including mouth bars (although the nature of outcrop precludes the mapping of such features). Finally, Facies C5 comprises intensely bioturbated, muddy, very fine- to fine-grained sandstone. It is similar to Facies B8 in some respects, but differs from it in its occurrence only within Facies Association C, its lack of marine body fossils, and its somewhat more restricted trace fossil assemblage. Facies C5 is interpreted as the record of transgressive ravinement and abandonment of delta lobes within the Lower Freshwater Sequence.

4.4. Fluvio-estuarine facies association

The fluvio-estuarine facies association occurs only in the Upper Permian Cygnnet Coal Measures and equivalents (part of the “Upper Freshwater Sequence”; Figure 1; Figure 7), and comprises three facies (Table 4). No evidence of glacial influence, either direct or indirect, was noted in this facies association.

Facies D1 consists of thick, erosionally-based, commonly multi-storey bodies of medium- to very coarse-grained (locally pebbly) sandstone (Figure 7A). Sandstone units are internally

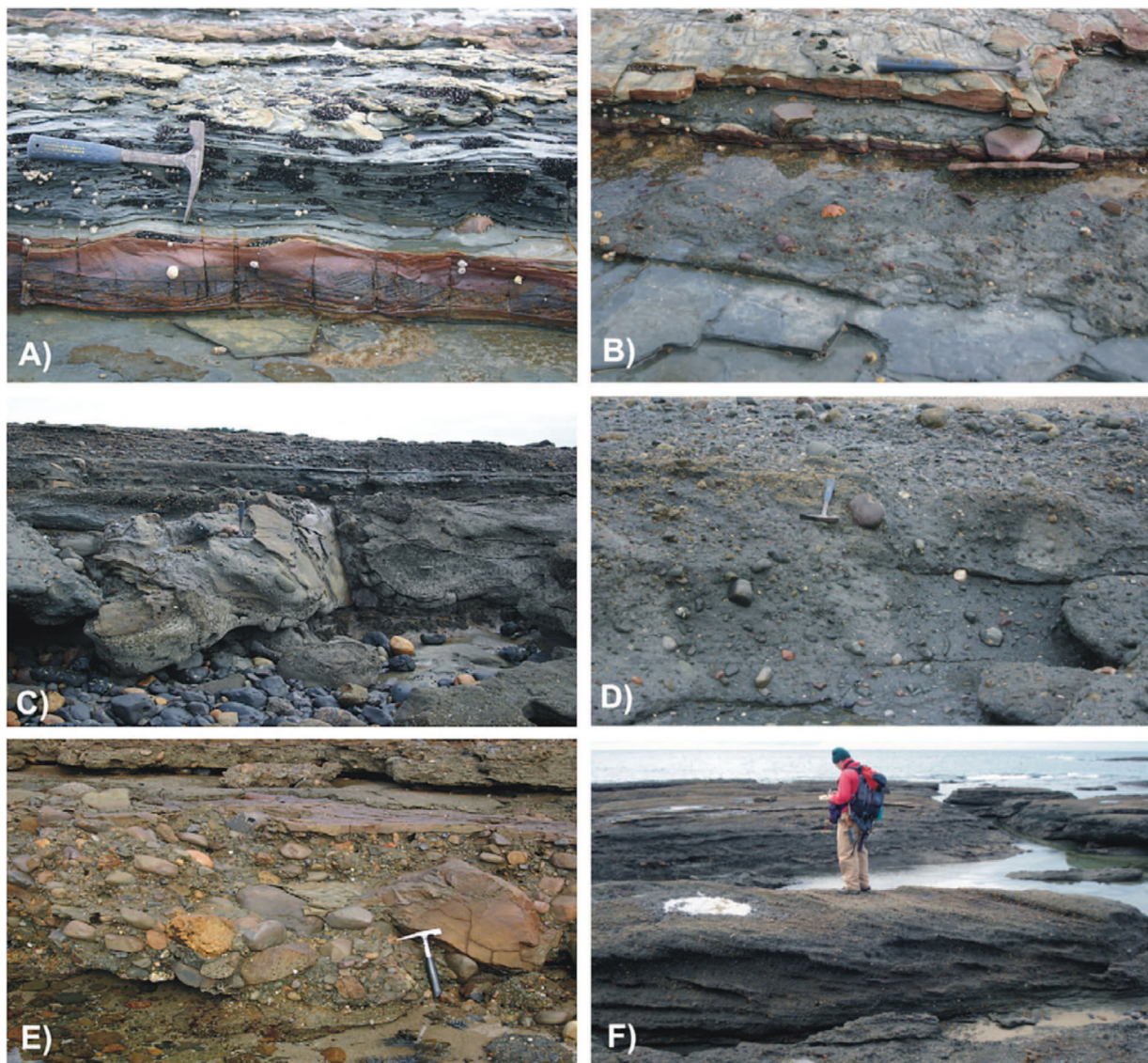


Figure 4. Photographs showing representative views of Facies Association A exposed on the shore platform at Wynyard (hammer for scale is 0.25 m long). **A)** Facies A1, showing interbedded ripple cross-laminated and soft-sediment-deformed sandstone and laminated siltstone with dispersed limestones. **B)** Facies A2, showing similar lithology to Facies A1 with the addition of thin beds of diamictite. **C)** Facies A3, showing chaotically bedded siltstone, sandstone and diamictite. The vertical face of diamictite in the centre of the view is part of a large soft-sediment-deformation structure. **D)** Facies A5, showing clast-rich, unstratified sandy diamictite. **E)** Facies A7 at Wynyard, showing poorly to moderately sorted boulder conglomerate with clast imbrication (flow direction to left). **F)** Sandstone-rich expression of Facies A7, showing cross-bedding.

dominated by cross-bedding, and palaeocurrent distributions from individual localities are strongly unimodal. Coalified plant debris is abundant and bioturbation is absent. Facies D1 is interpreted as the deposits of fluvial channels. Facies D2 comprises variably interbedded and interlaminated fine-grained sandstone and dark grey, organic-rich claystone to siltstone with finely divided plant debris, and typically gradationally overlies Facies D1 (Figure 7B, C). A variety of interlamination structures (linsen lamination, lenticular bedding, wavy bedding, and flaser bedding) is spectacularly preserved, as is small-scale soft-sedi-

ment deformation, including abundant synaeresis cracks. Small-scale cross-bedding is locally common. Palaeocurrent data gathered from this facies show bimodal distributions. *In situ* roots of Permian plants (*Vertebraria*) were found locally within this facies, as was simple *Planolites* bioturbation. Facies D2 is interpreted as estuarine channel and basin environments that formed during transgression of the coastal fluvial channels. A general lack of animal bioturbation suggests that the estuarine environment was mostly toxic to animal life, similar to estuarine channel facies of the Lower Permian Pebble Beach Formation of

Figure 5. Photographs showing representative views of Facies Association B. **A)** Facies B1 at the Fossil Cliffs on Maria Island, bioclastic limestone dominated by shells of the bivalve *Eurydesma*. Scale card is 0.15 m long. **B)** Lower cliff face at the Fossil Cliffs showing interbedding between Facies 1 (uppermost part of cliff), Facies 2 (middle part of cliff) and Facies 3 (lower part of cliff). Backpack is 0.50 m high. **C)** Facies B3 near the Fossil Cliffs, showing beds of clast-rich muddy sandstone and conglomerate interbedded with bioturbated, interlaminated siltstone-fine-grained sandstone (recessive intervals). Hammer is 0.25 m long. **D)** Facies B4, bioclastic grainstone to rudstone of the Berriedale Limestone at Granton, showing tabular bedding structure. **E)** Facies B5, coarse-grained, cross-bedded sandstone of the Risdon Sandstone exposed near Minnie Point south of Cygnet (person for scale in right background). **F)** Facies B7, interbedded bioturbated fine-grained sandstone and siltstone exposed at Flowerpot Point south of Hobart. **G)** Facies B8, admixed, intensely bioturbated fine-grained sandstone and siltstone exposed near Minnie Point. Scale bar is 0.15 m long. **H)** Facies B9, fine-grained laminated siltstone from drillcore Tunbridge Tier DDH2, showing a compound glendonite. Core is 0.05 m in diameter.



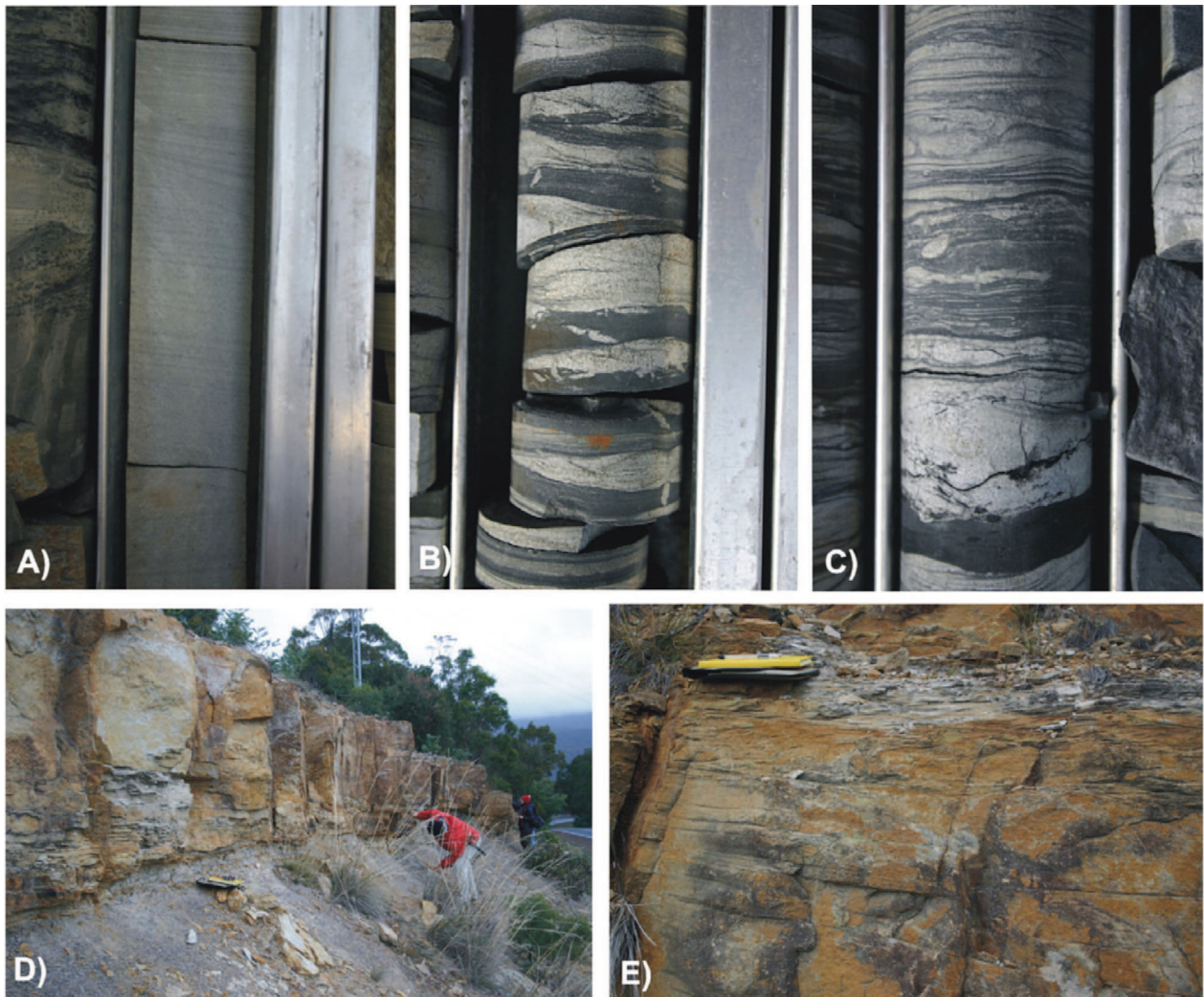


Figure 6. Photographs showing representative views of Facies Association C. A) Slabbed core view of Facies C4 from Tunbridge Tier DDH2, showing flat and low-angle lamination interpreted as hummocky cross-stratification. B) Core expression of Facies C2 in Granton DDH1, showing interlaminated and thinly interbedded siltstone and fine-grained sandstone with minimal bioturbation, lenticular and wavy bedding, and synaeresis cracks. C) Core expression of Facies C3 in Granton DDH1, showing erosion-based sandstone beds containing coalified plant debris, soft-sediment deformation structures and minor *Planolites* bioturbation. D) Outcrop example of Facies C4 sandstone body overlying Facies C1 and C2 at Poatina. E) Detail of internal sedimentary structure (flat and low-angle lamination, overlain by ripple cross-lamination) in Facies C4 sandstone body at Poatina. Notebook is 0.22 m long.

southern New South Wales (Fielding et al., 2006). Modest wave reworking of current-laid deposits is indicated by the symmetrical rippled tops to some sandstone beds. Facies D3 comprises thin and generally shaly coal seams (Figure 7D), locally < 1 m thick (historically mined in the Cygnet coalfield: Figure 1), and is interpreted as the product of coastal mire peat accumulation.

5. Stratigraphic distribution of glacial/cold climate indicators

As can be seen from the graphic log of DDH Tunbridge Tier-2 (Figure 8), the distribution of sedimentological features that can be linked with presence of glacial ice in the basin or immediate hinterland, or of cold sea floor conditions, is episodic rather than continuous. In this section, we document that distribution, and from it we derive an interpretation of glacial intervals within the late Palaeozoic section of Tasmania.

The basal unit of the Parmeener Supergroup is preferentially preserved in structural lows that are herein interpreted as extensional sub-basins perhaps excavated additionally by glacial activity. This unit, variously named Truro, Stocker's and Wynyard Tillite (Reid et al., in press), is overwhelmingly dominated by diamictites and associated lithologies of Facies Association

A (glacigenic). These facies are interpreted as mainly proglacial deposits, formed in a variety of ice-proximal and glacial-marine environments (outwash plains, proglacial lakes and fjords, grounding-line fans) with some possible subglacial deposits or proglacial facies later over-ridden by glacial ice also recorded (diamictites showing rotational shear structures around clasts, boxwork fracturing and other features). Evidence of possible glacial advance-retreat cyclicity is preserved locally where fine-grained mudrocks and rhythmically laminated mudrock-sandstone facies separate longer intervals of diamictite (e.g., 880–900 m in Figure 8), but such organization in vertical stacking patterns is unusual. The absence of conclusively marine body fossils in any of these rocks might be interpreted to reflect a dominance of non-marine environments of deposition, but more likely represents shallow glacial-marine settings where elevated sediment concentration and turbidity, consequent low light levels, variable dissolved oxygen, soupy substrates and variable salinity due to glacial effluent combined to produce a high-stress environment not conducive to many forms of life. The combination of evidence strongly suggests that these facies are the deposits of temperate glaciation. Sparse biostratigraphic data constrain these units loosely to the Pennsylvanian to Asselian. They

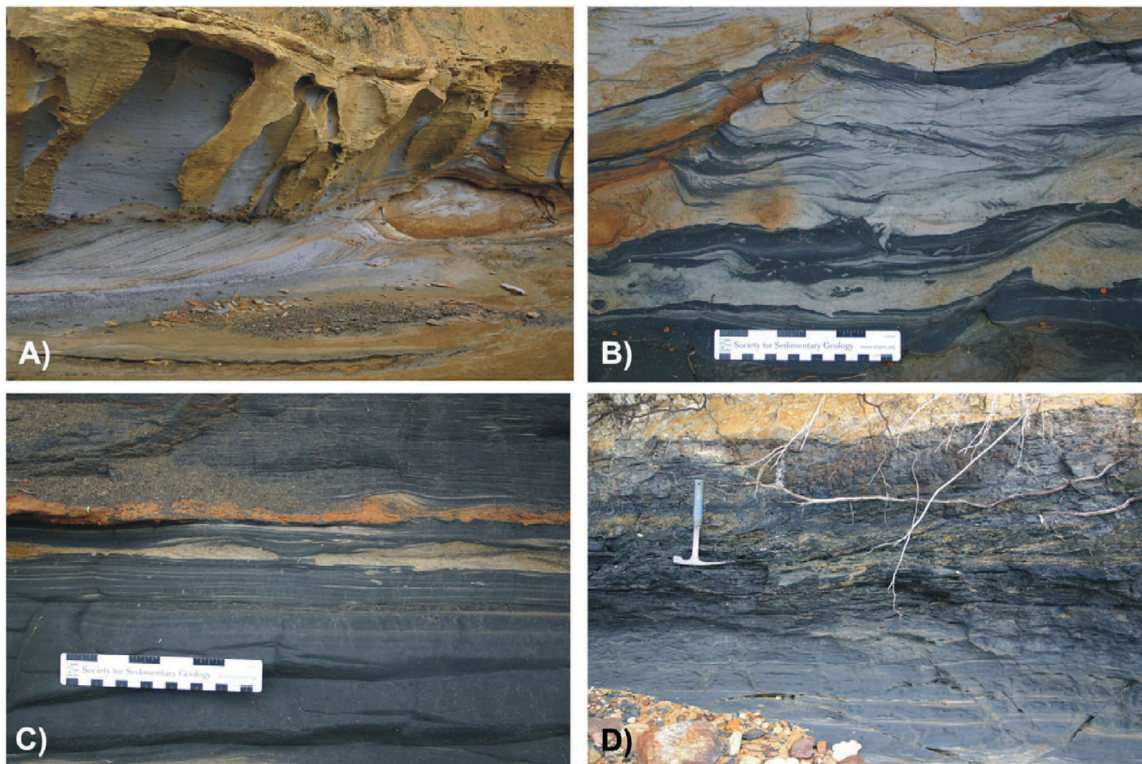


Figure 7. Photographs showing representative views of Facies Association D. **A)** Cross-bedded sandstone of Facies D1 south of Cygnet. 1.5 m of vertical section is seen. **B)** Interbedded fine-grained sandstone and siltstone of Facies D2 at Middleton showing ripple and soft-sediment deformation structures (including syneresis cracks), and simple bioturbation referable to *Planolites* (above scale bar which is 0.15 m long). **C)** Fine-grained variant of Facies D2 at Middleton, showing pinstripe and lenticular bedding of fine-grained sandstone in a dominant lithology of dark grey, unbioturbated siltstone. Scale bar is 0.15 m long. **D)** Fine-grained Facies D2 passing upward into carbonaceous shale and coal of Facies D3 at Middleton. Hammer is 0.25 m long.

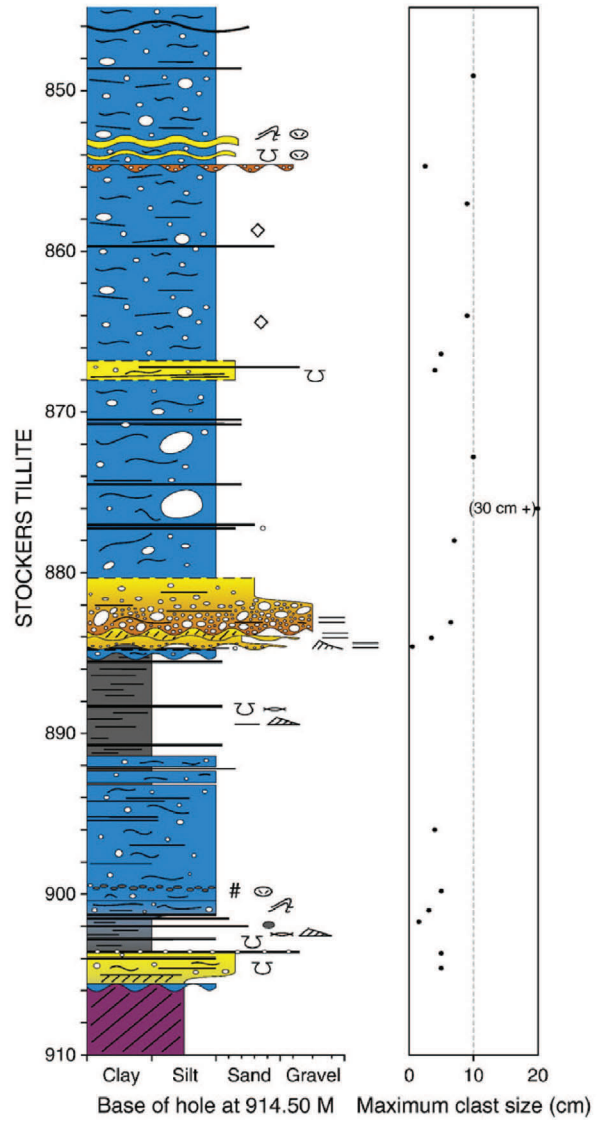
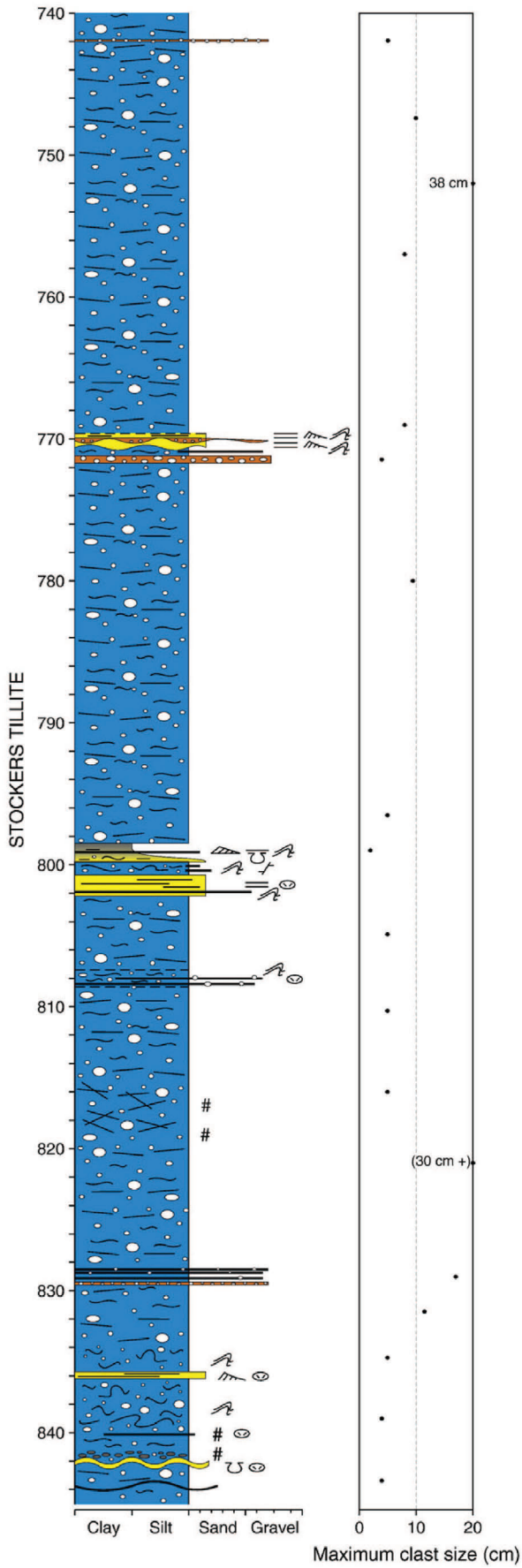
are by far the most proximal record of glacial activity in the Parmeener Supergroup.

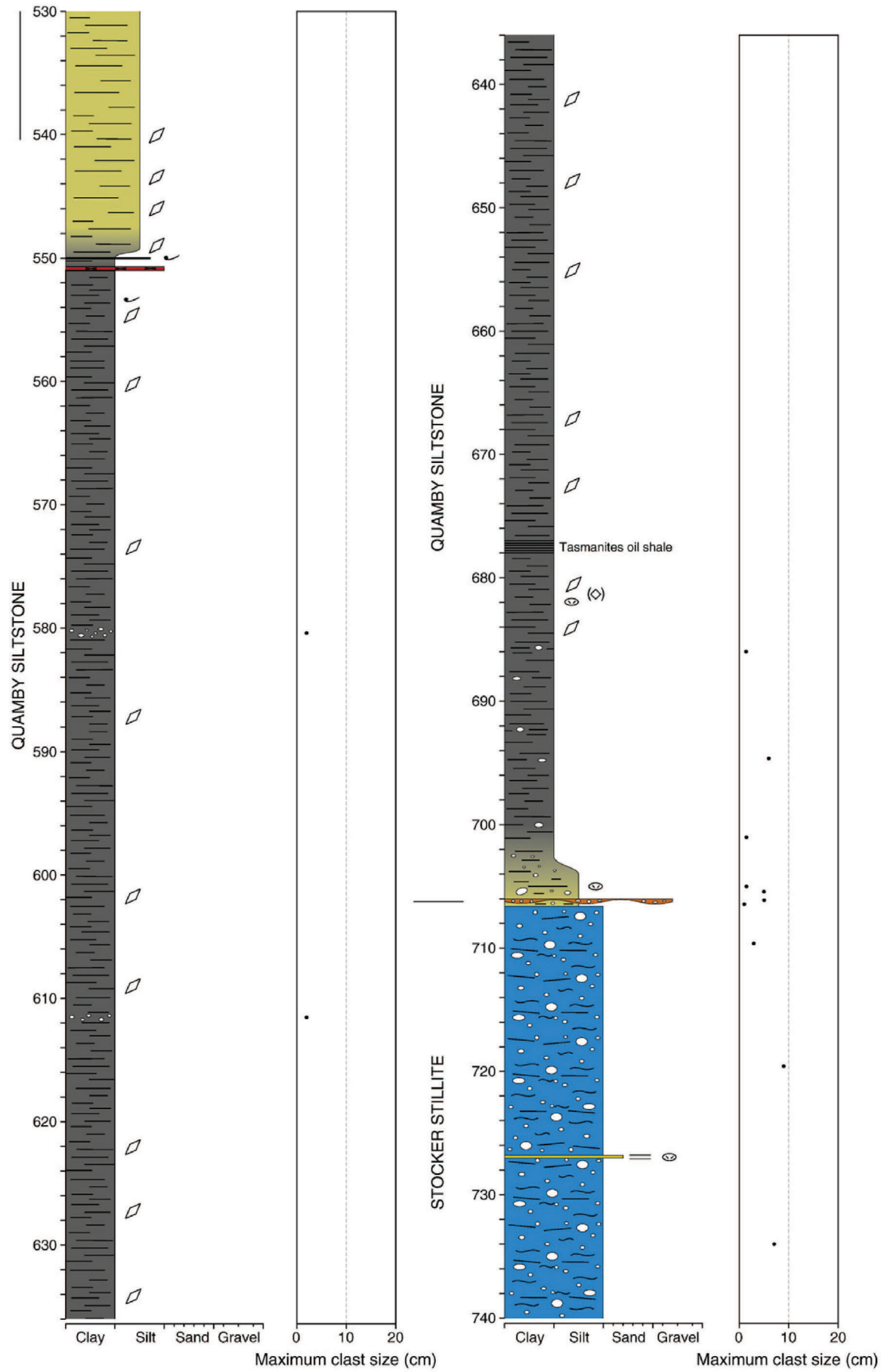
The basal diamictite-dominated units are abruptly overlain by a thick mudrock succession, named Quamby Siltstone and Woody Island Formation (Reid et al., in press). These units are again thickest in the earlier extensional depocentres, where they essentially fill remaining topography (Figure 3). The lower half of this unit is typically fine-grained, laminated, unbioturbated siltstones and claystones, with abundant glendonites and sparse, small lonestones (Facies B9: Table 2). This interval is interpreted to record postglacial flooding of the extensional, glacial valleys to form fjords, and their passive filling with mud from fine-grained sediment plumes discharged into these fjords. The basal facies transition from diamictite to siltstone is typically quite abrupt (Figure 8), suggesting rapid transgression and/or retreat of glaciers out of fjords and on to land at the end of a glacial epoch (cf. Corner, 2006), and both the lack of marine body and trace fossils and the abundance of preserved organic matter in the overlying mudrocks are consistent with data from other such transitions in this time interval (e.g., Buatois et al., 2006), where it has been attributed to release of large volumes of fresh water into partially enclosed basins. Among the distinctive facies of this interval is the “Tasmanites Oil Shale” (Domack et al., 1993; Revill et al., 1994), thin intervals of algal lamosites that yield liquid hydrocarbons on thermal maturation.

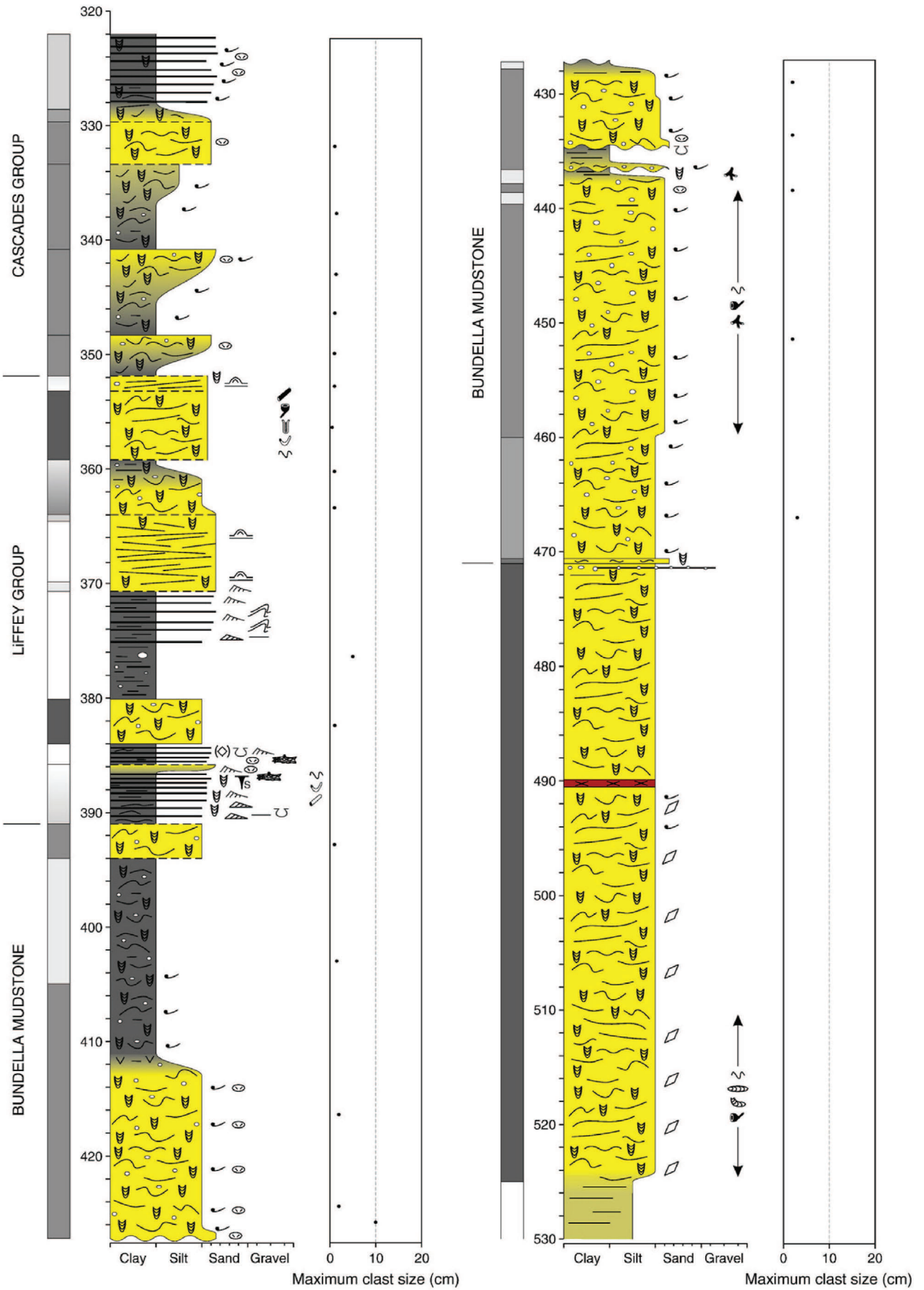
The laminated, fine-grained mudrock passes upward gradually into coarser-grained, admixed siltstone/very fine-grained sandstone with scattered shelly fossils, and becomes progressively more bioturbated upward (Facies B8: Table 2). Dispersed lonestones are again rare but glendonites persist throughout the interval. This is interpreted to record a return to more normal marine salinities in the fjords and encroachment of coarse clastic, coastal depositional systems into the basin. Cold climate is, however, inferred to have persisted from the contin-

ued abundance of dispersed gravel and glendonites.

An arbitrary contact with the overlying lower Bundella Formation and equivalents (Reid et al., in press) is typically taken where the lithology coarsens further to muddy, very fine- and fine-grained, heavily bioturbated sandstone (Facies B7: Table 2, Figure 8). The Bundella Formation forms the upper fill of early extensional topography in the Tasmania Basin. The lithology preserves abundant marine invertebrate body and trace fossils, and an increased lonestone content in the lower part, including horizons rich in large, exotic clasts. In basin-centre locations such as at Poatina, gravel is concentrated in thin beds of clast-rich sandstone to conglomerate that punctuate thick, finer-grained intervals (Facies B3: Table 2). In basin-marginal settings, however, such as on Maria Island, the laterally equivalent Lower Erratic Zone of the Basal Beds comprise a thick section of coarse gravel-bearing sandstones/conglomerates with interbedded finer-grained facies (Facies B3: Table 2, Figure 9). The coarser-grained nature of the Bundella Formation and equivalents relative to underlying units is interpreted to record further encroachment of basin-marginal coarse clastic systems into the marine basin. The greater abundance and caliber of lonestones in these units is interpreted to record an increased presence of floating ice in the basin, associated with a return to more glacially-influenced and/or colder conditions associated with the formation of sea-ice. However, the absence of any Association A facies in this unit suggests that rather than being nearby, glaciated landscapes of this time may have been more distant, such that associated effects were indirect (principally ice-rafting of coarse debris). A characteristic of this interval (and indeed, of the laterally correlative Wasp Head Formation of the southern Sydney Basin: Rygel et al., 2008a) is the abundance of discrete, sand-matrix boulder beds composed of apparently ice-rafted debris. These beds, most prominent in the Lower and Upper Erratic Zones of Maria Island (Reid, 2004; Rogala et al., 2007), may







KEY TO SYMBOLS USED IN GRAPHIC LOGS

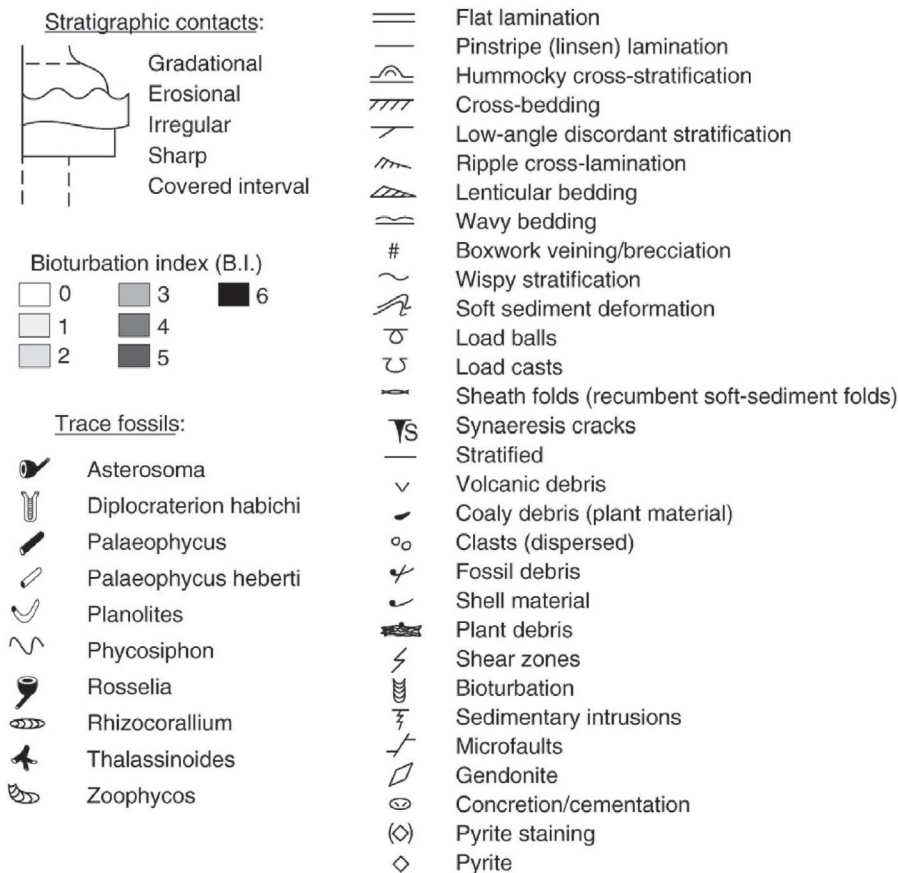


Figure 8. Graphic sedimentological log of the lower Parmeener Supergroup in fully cored stratigraphic borehole Tunbridge DDH-2, showing the distribution of lithologies and facies through the Lower Permian succession, and key to symbols used in graphic logs. Also shown are the intensity of bioturbation (Bioturbation Index – BI – after Bann and Fielding, 2004, where 0 corresponds to no bioturbation and 6 to complete destratification) and maximum size of dispersed gravel at different horizons. Blue – diamictites, grey – mudrocks, yellow – sandstones, orange – conglomerates, purple – basement metamorphic rocks, red – igneous intrusives.

record condensed intervals of gravel accumulated under minimal finer-grained sediment supply and reworked by waves and tides. Each bed could record a single glacial cycle, or perhaps more likely the large-scale release of icebergs during the deglacial phase of such cycles (cf. Eyles et al., 1997; Fielding et al., 2008b; Rygel et al., 2008), or the result of sea ice rafting of debris away from a high relief shoreline such as that associated with paleo-Maria Island during the Permian (e.g., Rosen, 1979; Dionne, 1981; McCann et al., 1981; Banks & Clarke, 1987).

The Darlington Limestone, which overlies the Lower Erratic Zone of the Basal Beds on Maria Island, records an abrupt decrease in the volume of limestones in the succession, and a deepening trend. This bioclastic limestone succession is interpreted to have formed slowly during a time period characterized by minimal glacial influence. The low abundance of limestones that persist through the Darlington Limestone probably reflect occasional berg or sea-ice activity over a long time interval generally characterized by more benign climatic conditions. This is consistent with the interpretation of other Permian limestones in eastern Australia by James et al. (2009b) as recording the intervals following and between major glacial epochs.

The upper part of the Bundella Formation and equivalent Upper Erratic Zone of the Basal Beds on Maria Island record a major increase in the abundance and calibre of coarse debris (Figures 8 & 9). On Maria Island, the top of the Darlington Limestone is marked by the first of several coarse-grained beds containing disorganized clasts < 2 m in long axis dimen-

sion. Facies are similar to those of the Lower Erratic Zone. The upper Bundella Formation and equivalents is overlain by the distinctive Liffey Group and equivalents (“Lower Freshwater Sequence” of Clarke & Banks, 1975; Martini & Banks, 1989; Reid et al., in press). This is the lowermost component formation of the Parmeener Supergroup that overlaps remnant basement highs to form a persistent blanket across the Tasmania Basin (Figure 3). It is also lithologically distinct from the units below and above it (Facies Association C: Table 3), in that it preserves comparatively few marine body or trace fossils, and an abundance of detrital plant material and, locally, coal. Dispersed, generally small gravel is common throughout the Liffey Group. The base of the unit is an abrupt fining in grain-size, from bioturbated muddy sandstones of the Bundella Formation upward into laminated dark grey mudrocks of the basal Liffey Group. The remainder of the unit comprises a series of crudely coarsening-upward units each < 20 m thick. The succession is interpreted to be of broadly deltaic origin, comprising a series of progradational cycles into a shallow marine basin (cf. Bann and Fielding, 2004). The presence of dispersed gravel is taken to indicate persistence of an ice-rafted sediment contribution into the basin, from bergs, sea-ice, or anchor ice. The basal fining-upward trend is interpreted as a flooding surface. Interestingly, this surface may correlate to a flooding surface of apparently similar age that forms the boundary between the Wasp Head Formation and the overlying Pebbly Beach Formation of the southern Sydney Basin.

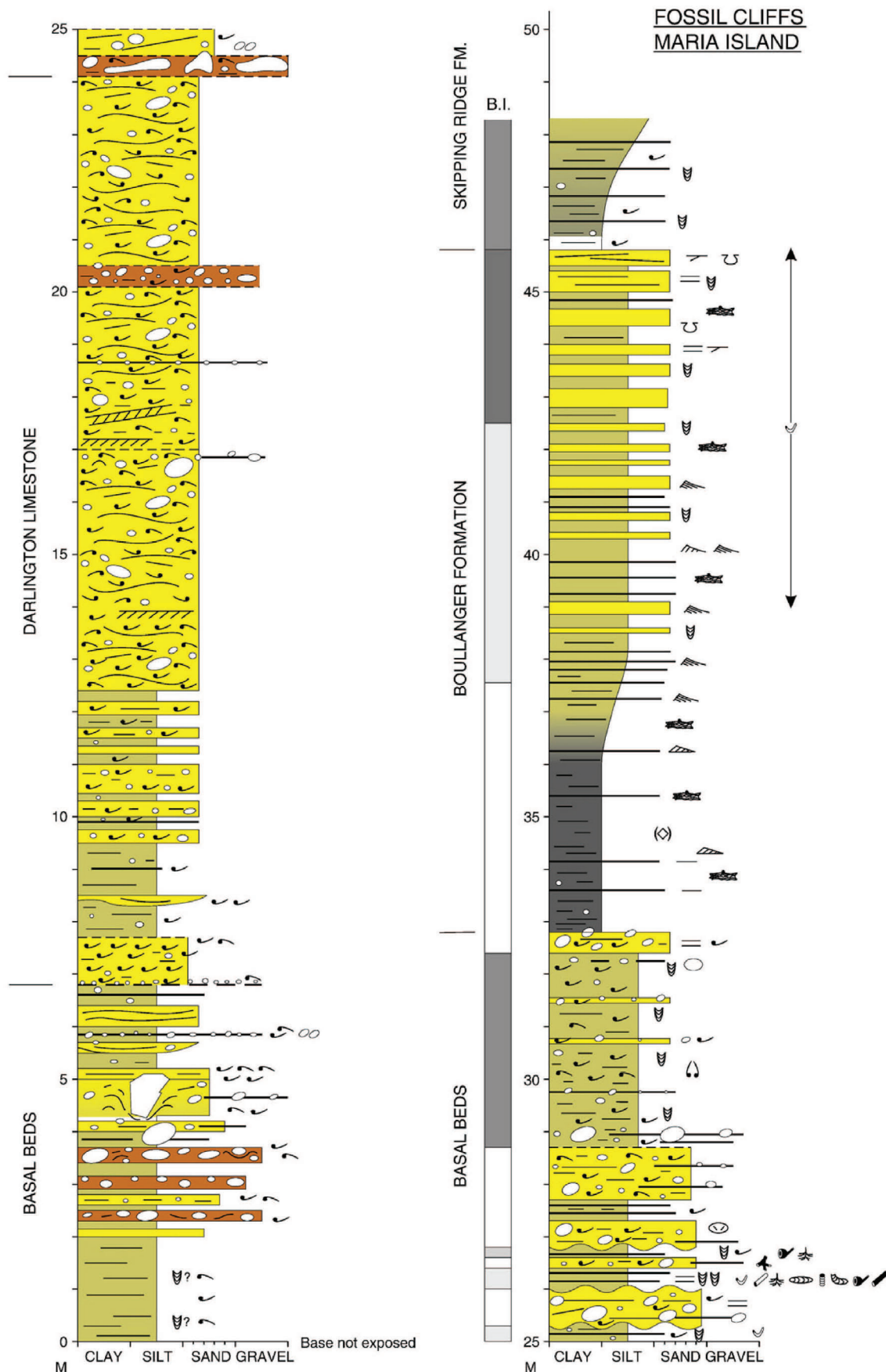


Figure 9. Graphic sedimentological log of surface exposures east of Darlington on Maria Island (the “Fossil Cliffs”: Reid, 2004), showing the Lower Permian section. Details as for Figure 8.

	Mainland	Maria Island
U. Parmeener Sgp.	Quartz Sandstone	Quartz arenite
	Cygnets Coal Measures	
Lower Parmeener Supergroup	Abels Bay Fm	Toarra Formation
	Malbina and Deep Bay Formations	Marra Formation
	Cascades Group	Counsel Creek Fm ----- Skipping Ridge Fm
	Liffey Gp	Boullanger Formation
	Bundella Fm	Basal Beds
	Woody Island Fm	?
	Wynyard Fm	

Figure 10. Stratigraphic column showing the stratigraphic range and interpreted ice-proximal or -distal nature of glacial indicators in the lower Parmeener Supergroup of Tasmania.

The overlying Cascades Group comprises marine fossil-bearing, coarsening-upward clastic units with locally significant bioclastic limestones in the upper part (Facies Association B: Table 2, e.g., Berriedale Limestone of the Hobart area, Counsel Creek Formation of Maria Island). Dispersed gravel is common in the lower part (Nassau Siltstone, and equivalents: Reid et al., in press), and persistent in lower abundances throughout the rest of the interval. This interval is interpreted to have accumulated under conditions of reduced clastic sediment supply, initially associated with distant glacial activity, and later during the waning phase of that activity. In general, Permian bioclastic limestones of eastern Australia are interpreted to have formed most extensively in the immediate aftermath of major glacial episodes (James et al., 2009b), consistent with the inferred relationship observed here. The interval of reduced clastic sediment supply also appears to have been correlative to the upper part of the Pebley Beach Formation of the southern Sydney Basin (Fielding et al., 2006), which preserves similar characteristics.

The Deep Bay/Minnie's Point Formations and equivalents comprise one or more, large-scale, coarsening-upward units rich in marine body and trace fossils, and containing dispersed and locally concentrated limestones. An abrupt fining-upward trend is observed at the base of this interval. This interval is in turn overlain by a similar, crudely coarsening-upward cycle, the Malbina Formation, which is capped by an erosionally-based sandstone body typically a few metres thick, the Risdon Sandstone (Reid et al., in press). Both coarsening-upward cycles are composed of Facies B5–B9 (Table 2) in varying proportions. The contact between the Risdon Sandstone and the overlying Abel's Bay

Formation is another abrupt fining-upward surface. These units are interpreted as the product of sediment accumulation on prograding, shallow marine surfaces, under the varying influence of berg ice, sea-ice, and/or anchor ice. As with previous intervals, this influence is interpreted to have been relatively distal, from the mainly distributed and relatively fine-grained nature of the gravel (mainly granules and pebbles). The Risdon Sandstone is interpreted to overlie a regionally extensive erosion surface (sequence boundary) that records a major drawdown of relative sea-level, and to have been deposited during the subsequent transgression in coastal barrier and tidal channel environments. This interpretation is supported by the clean, cross-bedded nature of the sandstone and the westward (onshore) mode to palaeocurrent distributions. A comparable, erosionally-based sandstone/conglomerate body, the Marangaroo Conglomerate, lies over an erosion surface at a similar stratigraphic level in the southern Sydney Basin (Bambery et al., 1995).

The Abel's Bay Formation comprises a further crudely coarsening-upward interval of siltstone to sandstone with marine body and trace fossils and dispersed, mainly small gravel. Again, Facies B5–B9 (Table 2) dominate this interval. The Abel's Bay Formation is interpreted as the deposits of further marine progradational cycles similar to those below, deposited once again under the distal influence of glacial ice in the form of limited ice-rafted debris. This represents the stratigraphically highest occurrence of ice-rafting indicators in the Permian succession of Tasmania.

The uppermost unit of the Permian succession in Tasmania, the Cygnets Coal Measures and equivalents, overlies the Abel's Bay Formation with typically abrupt to erosional contact. There is also a major facies discontinuity between the two units, with the Cygnets Coal Measures exclusively comprising facies of Association D (Table 4). No marine body fossils were found in these rocks, and only sparse, low-diversity trace fossil assemblages. No dispersed gravel or other glacial indicators were found in the Cygnets Coal Measures. This unit is interpreted to record sediment accumulation in fluvial and fluvio-estuarine settings that were typically not conducive to invertebrate animal life. Sediment accumulation during this time was evidently slow, and the boundary with the overlying Triassic system is difficult to identify.

6. Interpretation and correlation of glacial intervals

From the stratigraphic distribution of glacial indicators summarized above, an interpretation of the major glacial intervals recorded in the late Palaeozoic succession of Tasmania can be made (Figure 10). These intervals can then be compared to those documented from mainland eastern Australia (Fielding et al., 2008a) to determine whether there was synchronicity of glacial epochs across a palaeo-polar to temperate transect.

Because the stratigraphic range of the Pennsylvanian–Permian Wynyard Formation and equivalents cannot be precisely constrained, there is no way of determining whether the unit is a composite of more than one interval of glaciation. Without better age control its relation to Pennsylvanian glaciations in New South Wales and Queensland is unknown. The uppermost part of the diamictites is considered to be Asselian in age, as is the overlying Woody Island Formation (Figure 1). The overlying Bundella Formation and equivalents are considered to be Sakmarian in age (Figure 1). Since there is no discrete interval between the top of the “tillites” and the base of cold climate indicators in overlying mudrock formations, the basal glacial interval is here continued through the Woody Island Formation and up to the lower Bundella Formation (Figure 10). It is nonetheless noted that even the Permian portion of this first glacial interval is composite, with a major deglaciation at the top of the “tillites” overlain by evidence for a subsequent cold epoch represented by more distal, possibly glacially- or sea-ice-influenced facies. This latter phase is best exemplified by the thick succession of oversized clast-bearing facies underlying the Dar-

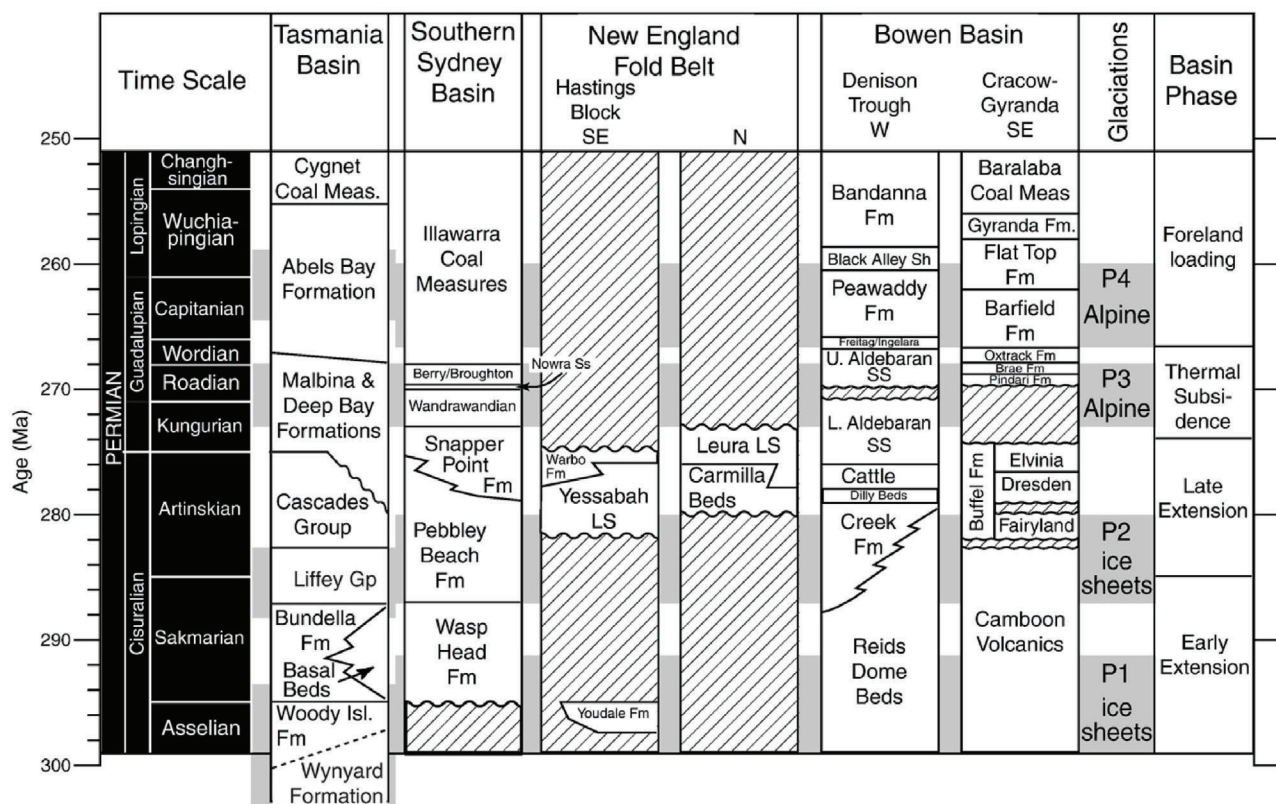


Figure 11. A time-space stratigraphic framework diagram showing the stratigraphic range of glacial indicators in the lower Permian Super-group of Tasmania, and their correlation to glacial intervals recognized in the Bowen-Gunnedah-Sydney Basin System of mainland eastern Australia. Glacial interval nomenclature and interpretation is based on studies in New South Wales and Queensland, mainland eastern Australia (Fielding et al., 2008a).

lington Limestone on Maria Island (Figure 9). Collectively, this first Permian glacial epoch broadly correlates to interval P1 from mainland eastern Australia (Fielding et al., 2008a). A similar (glacial to deglacial) succession is preserved in the ?Pennsylvanian to Lower Permian stratigraphy of the Bacchus Marsh area, Victoria (Pierson, 2008; Webb & Spence, 2008).

The bioclastic Darlington Limestone and equivalents are interpreted as a non-glacial interval, as is consistent with our understanding of the context of Permian limestones elsewhere in eastern Australia (James et al., 2009b). Above the Darlington Limestone lies the "Upper Erratic Zone" and equivalent parts of the uppermost Bundella Formation. These rocks preserve a moderately proximal record of ice-rafting, with clasts up to 2 m+ in diameter. This is interpreted to record a glacial/cold interval that postdated formation of the Darlington Limestone, and which can be correlated with the early stages of glacial P2 of eastern Australia. The Liffey Group and the overlying Nassau Siltstone and equivalents preserve modest volumes and sizes of ice-rafted debris, which progressively decline through the succeeding Berriedale Limestone and equivalents. Accordingly, the lower and middle Cascades Group are nominated as a continuation of the second glacial interval, affected only indirectly by distant glacial ice (Figure 10). This interval coincides with the latter stages of glacial P2 of Fielding et al. (2008a) (Figure 11).

The overlying, regionally extensive flooding surface appears to coincide with a flooding surface at the base of the Snapper Point Formation in the southern Sydney Basin (Bann et al., 2008; Fielding et al., 2008b) and is interpreted to record or post-date the end of the P2 glacial interval (Figure 10; Figure 11). A diffuse interval of abundant ice-rafted debris in marine facies is recorded within the Deep Bay/Malbina Formation interval, and is here defined as a third glacial/cold interval, again only indirectly affected by distal glacial ice or sea-ice rafting. This interval

correlates in time to the equally distal P3 glacial interval of eastern Australia (Figures 10 & 11). Finally, following a further interval containing no glacial indicators, a fourth interval preserving ice-rafted debris is recognized within the lower Abel's Bay Formation. This final, ice-distal record can be correlated in time with the distal P4 glacial interval of eastern Australia (Figures 10 & 11).

At a broad level, the glacial/cold intervals recognized herein from the late Palaeozoic succession of Tasmania correlate well with those recognized previously from mainland eastern Australia, suggesting that on a millions of years timeframe, glacial/cold events were indeed synchronous across the polar to temperate transect represented by the distance between Tasmania and central Queensland. Not only is the overall number of glacial epochs the same, but the nature of the stratigraphic record in each of the four glacials is consistent between Tasmania and NSW/Queensland (Figure 11). Specifically, the most complex and the most proximal record of glaciation is contained within P1 and its Tasmanian equivalent, with an initially moderately proximal record followed by a longer, more distal record in P2 and a distal record in P3 and P4. An overall temporal progression from most proximal to least proximal from P1 to P4 is also preserved. Accordingly, it can be concluded that the record of Permian glacial/cold events can be correlated in detail and confidently between mainland eastern Australia and Tasmania. However, there are discrepancies of < 2 million years between the interpreted age ranges of glacial intervals in Tasmania and those recognized in New South Wales and Queensland (Figure 11), based on applying the published ranges of the different formations in those two regions. This either reflects a degree of diachroneity in the timing of glacial intervals from north to south, or inadequacies in the correlation of the somewhat endemic Tasmanian macroinvertebrate faunas (Clarke and Banks, 1975) to the global Permian stage system.

7. Conclusions

A reappraisal of the late Palaeozoic Parmeener Supergroup of Tasmania has been undertaken in order to ascertain the stratigraphic distribution of indicators of glacial influence and cold climate on sediment accumulation. As in mainland eastern Australia (New South Wales and Queensland), it was found that such indicators were strongly partitioned into discrete intervals, and four such intervals were recognized.

The earliest of these incorporates the basal diamictites of the Wynyard Formation and equivalents, and the overlying marine mudrocks of the Woody Island Siltstone and correlatives. The former show evidence of direct and proximal glacial influence, comprising the deposits of subglacial, ice-contact proglacial/glacimarine and fjordal environments. A major (Asselian) post-glacial transgression/glacial retreat is recorded at the abrupt contact between the basal diamictites and the overlying Woody Island Formation, but evidence of cold climate persists in the form of glendonites and ice-rafted debris. Accordingly, the first Permian glacial interval is believed to have persisted until deposition of the lowermost Bundella Formation.

The second glacial interval, from the upper Bundella Formation and equivalents (Upper Erratic Zone of Maria Island) to the Nassau Siltstone and equivalents, comprises a lower section of proximal glacimarine facies, overlain by a longer interval of more distal glacimarine deposits. It is of late Sakmarian to early Artinskian age. The third and fourth intervals, respectively of Kungurian to Raodian (Malbina Formation) and Capitanian (Abel's Bay Formation) age, are both distal ice-rafting records.

The four glacial intervals correlate well in terms of their inferred age range with glacials P1 to P4, respectively, of Fielding et al. (2008a) defined in New South Wales and Queensland. Not only is the number of Permian glacial intervals identical, but the nature of facies in each interval, and their upward changes in proximity from one interval to the next, are entirely consistent with the mainland eastern Australian record. Accordingly, we conclude from this investigation that the Permian glacials P1 to P4 have widespread extent over the entire length of eastern Australia, despite a degree of inconsistency in interpreted age ranges. Future research should be aimed towards addressing whether a coherent record can be found in the northern Victoria Land region of Antarctica.

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