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Stratigraphic imprint of the Late Paleozoic Ice Age in eastern Australia: A record of alternating glacial and nonglacial climate regime

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Abstract
Stratigraphic and sedimentological data from New South Wales and Queensland, eastern Australia, indicate that the Late Paleozoic Ice Age comprised at least eight discrete glacial intervals (each 1–8 Ma in duration, here termed "glaciations"), separated by nonglacial intervals of comparable duration. These events spanned an interval from mid-Carboniferous (*c*. 327 Ma) to the early Late Permian (*c*. 260 Ma), and illustrate a pattern of increasing climatic austerity and increasingly widespread glacial ice from initial onset until an acme in the late Early Permian, followed by an opposite trend towards the final demise of glaciation in the Late Permian. The alternating glacial–nonglacial motif suggests that the Late Paleozoic Ice Age was considerably more dynamic than previously thought. These patterns are remarkably consistent with recent interpretations of paleofloral change, eustatic sea-level fluctuations and CO_2–climate–glaciation relationships for this interval of time. The detailed record of alternating glacial and nonglacial climate mode disclosed herein may facilitate more closely resolved evaluations of stratigraphic records elsewhere, notably in far-field, ice-distal, northern hemisphere successions.

Introduction

The Late Paleozoic Ice Age is considered to have had a profound impact on Earth's natural systems (e.g. Frakes *et al*. 1992). Strata deposited during this interval record the only complete transition of a vegetated Earth from an "icehouse" to a "greenhouse" state (Gastaldo *et al*. 1996), and so learning about this crucial time interval contributes to a more complete understanding of global changes that may result from rising levels of CO_2 in the atmosphere. Essential questions concerning the Late Paleozoic Ice Age's initiation, extent, duration, style (i.e. ice sheet, ice cap, alpine glacier, thermal regime), demise, and influence on Earth's physical, chemical and biological systems remain unanswered.

Stratigraphic records of the Late Paleozoic Ice Age are known from virtually all Gondwanan continental remnants, and indeed were pivotal in the original establishment of the concepts of Gondwana and continental drift (Wegener 1915; Du Toit 1937). Despite this, however, there remains no general consensus as to the timing, duration and extent of glaciation in Gondwana (Figure 1, and see review by Isbell *et al*. 2003). Moreover, considerable emphasis in recent research has been placed on far-field (ice-distal) and proxy records of the Ice Age, particularly sedimentological, stratigraphic, and geochemical records contained within cyclical successions or "cyclothems" deposited at low paleolatitudes and preserved in what is now the northern hemisphere (e.g. Heckel 1994; Von Bitter *et al*. 2006). The argument cited to support the fidelity of such records is that they are uncomplicated by near-field isostatic and other geodynamic effects. However, such records cannot be definitively interpreted in terms of glacial cycles until a detailed chronology of near-field events is available from the continental remnants of Gondwana. To date, construction of a highly resolved record of glaciation from Gondwana has proved to be a major challenge to researchers, with few detailed chronologies available.

Most current reconstructions of the Late Paleozoic Ice Age invoke a single, long-lived ice sheet, as large as 150×10^6 km^3, which covered Antarctica and extended northward over southern Gondwana (e.g. Veevers & Powell 1987; Crowley & Baum 1991, 1992; Francis 1994; Ziegler *et al*. 1997; Hyde *et al*. 1999; Scotese *et al*. 1999; Veevers 2000). Although this concept is entrenched in the literature, it has neither been validated nor nullified by detailed evidence from Antarctica or Australia. The hypothesis of Powell & Veevers (1987) and Veevers & Powell (1987) that a continental ice sheet covered much of Australia throughout the Pennsylvanian was based in large part on the assertion of a Pennsylvanian lacuna, or stratigraphic gap, throughout Australia. This statement is somewhat misleading, as thick Pennsylvanian successions are in fact extensively preserved in a number of basins in eastern and central Australia (Figure 2). Furthermore, recent research into the direct, ice-proximal record of glaciation suggests that Gondwanan glaciation was less spatially extensive and occurred in shorter discrete intervals (during the Mississippian, Pennsylvanian, and Early Permian) than was previously believed (Isbell *et al*. 2003). In their recent comprehensive review of the Late Paleozoic Ice Age, however, Isbell *et al*. (2003) declined to portray the distribution of glacial strata in eastern Australia.

We have conducted extensive fieldwork in Queensland and New South Wales, eastern Australia, aimed at characterizing the Carboniferous and Permian succession and identifying the parts of that succession that preserve a record of glacial, proglacial or periglacial depositional environments (collectively

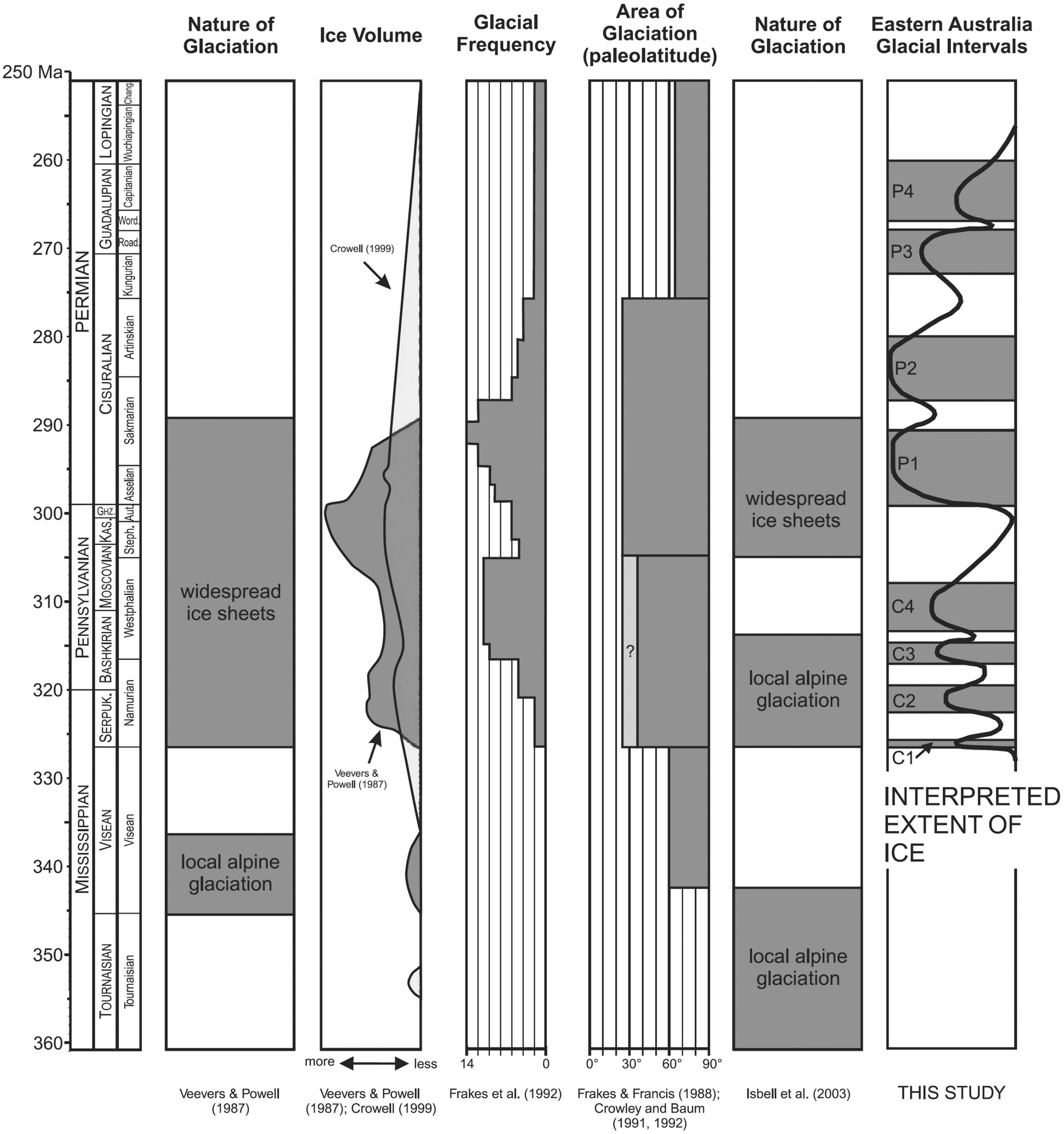

Figure 1. Timing, duration and character of the Late Paleozoic Ice Age according to previous workers (Veevers & Powell 1987; Frakes & Francis 1988; Crowley & Baum 1991, 1992; Frakes *et al.* 1992; Crowell 1999; Isbell *et al.* 2003), with glacial intervals recognized in this study, and our interpretation of glacial ice extent based on the geographical extent and inferred "proximality" of glacial facies found through the Carboniferous and Permian of eastern Australia.

referred to as "glacial" herein). Our investigations have focused on areas where a relatively thick and complete stratigraphic record is preserved. These include the Tamworth Belt, Sydney and Gunnedah Basins of New South Wales, and the Bowen and Galilee Basins and northern New England Fold Belt of Queensland (Fielding *et al.* 2001; Figure 2).

Criteria for recognition of glaciations

Criteria for the recognition of glacial environments (in the broad sense, as defined above) include presence of diamictites (poorly sorted terrigenous clastic sedimentary rocks with a wide range of grain size), sedimentary intrusions, rhythmites (alternating well-sorted laminae or beds of fine- and coarser-grained lithologies, with or without isolated, dispersed gravel), laminated mudrocks with outsized dispersed clasts, glendonites (pseudomorphs after ikaite), and various distinctive clast shapes (Table 1). Classification of units as glacial has been made only where multiple criteria are recognized, or where a single criterion appears to unambiguously indicate glacial influence by virtue of its occurrence out of context with enclosing facies. Complex interbedding of these lithologies, both ver-

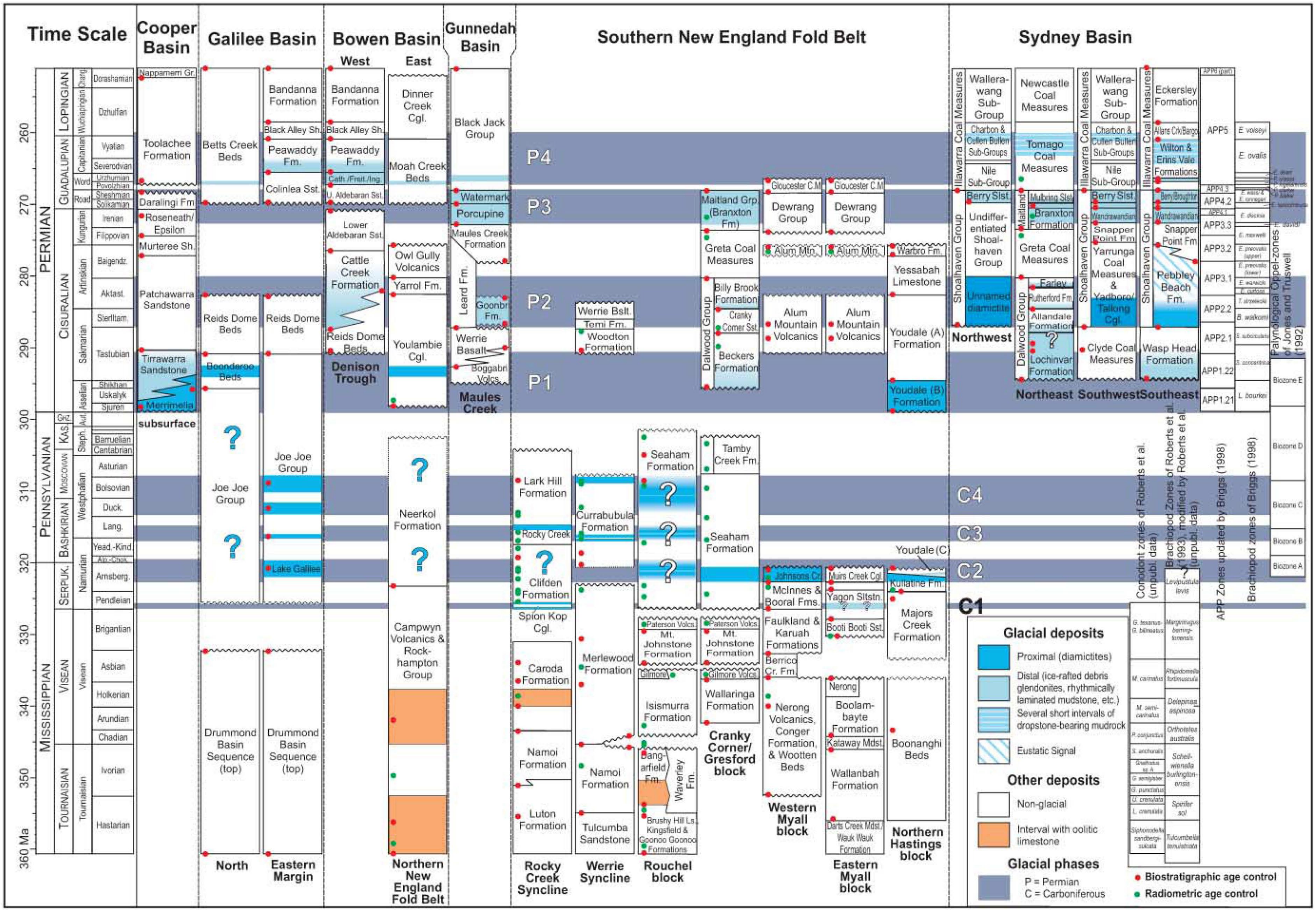

Figure 2. (**a**) Summary time–space framework for the Carboniferous and Permian of eastern Australia (New South Wales and Queensland) highlighting the eight glaciations recognized in this work (C1–C4, P1–P4). Formations containing facies of glacial affinity are colored medium blue (proximal facies), pale blue (distal facies), diagonal cross-hatched blue (thin, isolated intervals of lonestone-bearing mudrocks), or horizontal cross-hatched blue (eustatic signal only). Blue question-marks indicate formations in which it has not been possible to assess whether or not glacial facies are preserved; white question-marks indicate formations within which glacial facies have been recognized but the exact placement of those glacial intervals cannot be constrained. Anchor points provided by biostratigraphic data and absolute ages are indicated by colored spots.

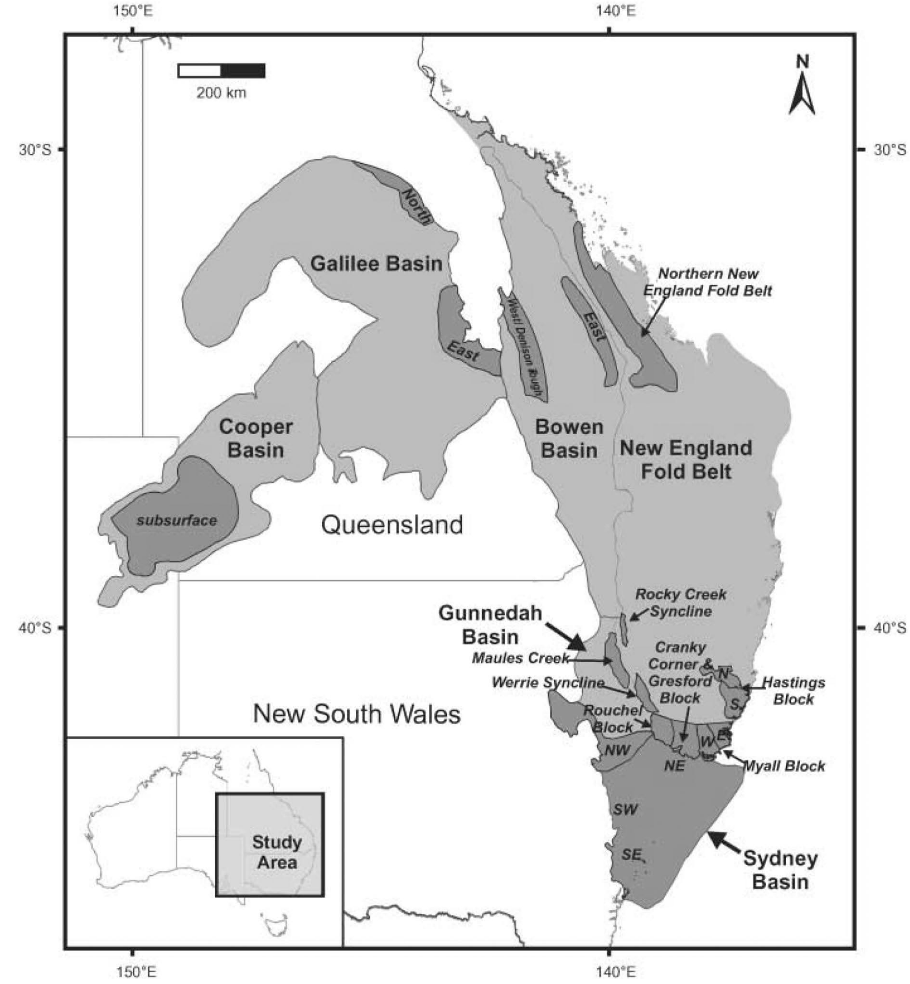

Figure 2. (**b**) Map showing locations of outcrop areas investigated in this study.

tically and laterally, is another distinctive aspect of glacigenic intervals. The only example of an interpreted glacially striated surface from the study area was reported by Osborne & Browne (1921) from the Hunter Valley of New South Wales, but regrettably could not be confirmed during this study.

Virtually all of the studied Pennsylvanian record was formed in non-marine environments, whereas a substantial portion of the Permian record is of coastal to nearshore marine origin. Nonetheless, there is considerable overlap between resulting facies associations in terms of diagnostic criteria (Table 1). Units shown in deep blue in Figure 2a contain evidence of proximity to glaciers (presence of diamictites, chaotic fabrics, abrupt lateral facies changes), those shown in lighter blue indicate more distal glaciomarine or glaciolacustrine settings (such as outsized lonestones in fine-grained facies, rhythmically laminated mudrocks), those with horizontal blue bars indicate only discrete intervals of mudrocks with dispersed clasts, and those with cross-hatched pale blue indicate only indirect glacial influence such as evidence for abrupt, large-scale base-level shifts (particularly, drops of several tens of metres). Care has been taken to separate out stratigraphic signatures of tectonic processes, such as the onset of the Hunter–Bowen Contractional Event in the Late Permian (e.g. Fielding *et al*. 1997, 2001; Glen 2005), from those likely to be of glacial origin.

A thorough review of Carboniferous–Permian stratigraphy, resolving all lithostratigraphic units within the areas of interest to published biostratigraphic zonations (e.g. Briggs 1998) and geochronological anchor points, was used to establish a time framework for each area (Figure 2). Details of the criteria used to constrain formations, and stratigraphic logs showing detailed stratigraphy in the outcrop belts, are available online at http://www.geolsoc.org.uk/SUP18297. Correlations between areas and mismatches (e.g. between formations recognized in more than one area) were resolved in a manner that invokes the least internal inconsistency. The majority of precise and accurate absolute ages germane to this analysis were derived from zircons by the sensitive high-resolution ion microprobe (SHRIMP) U–Pb method (e.g. Claoué-Long *et al*. 1995; Roberts *et al*. 1995*a*, *b*, 2004, 2006; Opdyke *et al*. 2000). Issues pertaining to the veracity of the standards used to obtain these ages have been raised (Black *et al*. 2003). Where possible, ages derived from different reference standards were reconciled to the currently accepted standard (TEMORA), using correction factors published by Black *et al*. (2003). Unfortunately, some ages are internally inconsistent and conflict with other stratigraphic data, making them prime targets for future dating efforts. We have used the latest geochronological time scale for the Permian system (Wardlaw *et al*. 2004), but have used the time scale of Menning *et al*. (2000) for the Carboniferous because it retains the original European stage zonation of the Carboniferous, which was not used by Davydov *et al*. (2004). This is required because the stages derived from Russia adopted by Davydov

Table 1. Summary of facies criteria used in this study to diagnose glacial intervals.

Lithology	Description	Interpretation
Diamictites, and associated clast-rich sandstones and conglomerates–breccias	Mixtures of mud, sand and gravel-grade material (gravel <30%), widely varying texture (mud v. sand matrix, sorting, clast abundance) and fabric (clast distribution, presence or absence of stratification and soft-sediment deformation), clasts to large enclaves of intraformational lithologies, complex interbedding and lateral transitions of units with contrasting texture and fabric, transitions into conglomerates and interbedded facies described below	Mixed lithologies record a variety of settings from (potentially) subglacial, through ice-contact proglacial to glacimarine–glacilacustrine and nonglacial environments, and a variety of processes including lodgement, mass failures, viscous to turbulent flows onland and under water
Interbedded mudrocks and conglomerate–diamictites	Alternating beds of conglomerate and/or diamictite, as above, and laminated to soft-sediment-deformed siltstone, clasts <cobble grade	Seasonal or other periodic influx of mixed sediment from ice melt into lake or sea
Rhythmites	Rhythmically interlaminated or interstratified claystones and siltstones, or claystones, siltstones and sandstones, with or without stratified and/or dispersed gravel, drop structures, deformed bedding, microfaults	Influx of sediment into lakes or shallow seas under strongly seasonal (varved) or other periodic discharge, gravel indicates ice-rafted debris
Mudrocks with dispersed lonestones, aggregates of gravel and sand	Laminated and variably bioturbated mudrocks containing dispersed clasts of basement lithologies (mainly volcanic, granitic, metasedimentary and vein quartz) ranging up to 2 m in *a*-axis dimension, and/or dispersed sand to clusters or aggregates of sand, drop structures, loading and associated soft-sediment deformation	Sea- or lake-floor setting with coarse debris dropped or dumped from floating ice (ice-rafted debris), sand aggregates may record fall of frozen sand masses through water column
Mudrocks and sandy mudrocks with glendonites	Mainly fine-grained lithologies with calcite pseudomorphs after ikaite-bladed, stellate or rosette forms <30 cm long	Cold sea- or lake-floor setting
Clastic sedimentary intrusions (dykes and minor sills)	Sheet-like or anastomosing dykes (or rarely, sills) of mudrock, sandstone, pebbly sandstone or conglomerate, in many cases displaying a physical connection with a source bed, width varies from millimeters to meters, some show layering parallel to outer margins	Injection of sediment under high fluid pressure under glacial ice load or through permafrost in proglacial zone
Well-sorted siltstones to very fine-grained sandstones	Bodies of massive, flat laminated and ripple cross-laminated, well-sorted siltstone to very fine-grained sandstone	Windblown loess, locally reworked by flowing water
Gravel	Wide range of clast size and shape, including minor proportions of faceted, bullet-shaped and striated clasts, some clasts with exfoliating surfaces, some very angular quartzose sandstone clasts	Working of gravel within and below glaciers, long-term exposure to freeze–thaw processes

et al. (2004) cannot be recognized in eastern Australia. Nonetheless, timing and duration of Carboniferous glaciations have been estimated using the Davydov *et al*. (2004) time scale and are given in Table 2.

Units recognized by us as having a glacial signature were placed within the stratigraphic framework, and most were found to be laterally extensive (Figure 2). Recognition of a glacial character for these units was not used as a basis for correlation; rather the framework was established independently of any perceived interpretation. The most important observation to be made from the distribution of glacial strata in the eastern Australian basins is that they are confined to discrete intervals of 1–8 Ma (here termed "glaciations," to distinguish them from the shorter-lived "glacials" that are well documented from the Neogene). Glaciations are separated by intervals of nonglacial facies of comparable duration (Figure 2). Those intervals interpreted as nonglacial contain none of the distinctive facies or other characteristics listed above. Furthermore, in the mainly marine Permian record, formations that contain glacial facies also show vertical facies relationships that indicate relative sea-level fluctuations (notably, abrupt drops) of up to 70 m, whereas the intervening nonglacial intervals show evidence for much more modest relative sea-level shifts (<30 m, typically). These patterns are interpreted to reflect differences in the magnitude and frequency of eustatic sea-level change through the Permian section (Rygel *et al*. 2008*b*). A persuasive argument in favour of a glacial origin for the intervals highlighted in Figure 2 is their inter-regional lateral extent (thousands of kilometers), spanning several sedimentary basins of varying tectonic context (Figure 2).

We recognize eight glaciations, four in the Carboniferous (labelled C1–C4) and four in the Permian (labelled P1–P4), spanning the period from 327 to 260 Ma. Each is described in brief below, together with the nonglacial intervals that separate them. In Figure 2, ages of units are cited as closely as possible, although we acknowledge that the available data do not allow for precise age determinations. We cannot estimate the full extent of glacier coverage in eastern Australia from the available data set, and, furthermore, a lack of recognition of glacial character in a particular area at a particular stratigraphic level does not preclude its being recorded. Nonetheless, the relative

Table 2. Comparison of timing of glacial intervals using Menning *et al.* (2000) time scale v. Davydov *et al.* (2004) time scale.

Horizon	Menning age (Ma)	Davydov age (Ma)	Menning duration (Ma)	Davydov duration (Ma)
C4 top	308.0	309.4	5.0	3.6
C4 base	313.0	313.0		
C3 top	315.0	314.3	2.0	1.3
C3 base	317.0	315.6		
C2 top	319.5	317.4	3.0	4.5
C2 base	322.5	321.9		
C1 top	325.5	325.7	1.0	1.0
C1 base	326.5	326.7		

changes in geographical extent and inferred glacial proximality of facies through the Carboniferous and Permian systems of eastern Australia can be used as a proxy for long-term patterns of climate change (summarized in Figure 1).

Stratigraphy

No record has yet been found in eastern Australia of the Late Devonian to early Mississippian glacial epoch recognized elsewhere (Glacial I of Isbell *et al*. 2003). Indeed, the Mississippian of eastern Australia (until *c*. 337.5 Ma) contains evidence of at least warm temperate climate in the form of regionally extensive oolites (Figure 2). The earliest evidence for glacial conditions identified by us in Queensland and New South Wales (Glaciation C1) is at *c*. 326.5–325.5 Ma (earliest Namurian, Pendleian, latest Mississippian; Figure 2), and is confined to the Spion Kop Conglomerate of the Tamworth Belt and Yagon Siltstone of the eastern Myall Block, New South Wales. This is somewhat later than the suggested early Asbian (mid–late Viséan) commencement of glaciation proposed by Wright & Vanstone (2001), and perhaps suggests that contributions to the eustatic record from ice expansion and contraction in different parts of Gondwana were not synchronized. The uppermost occurrence of oolites in eastern Australia, however, coincides with the onset of the Ice Age as proposed by Wright & Vanstone (2001).

Glaciation C1

Glaciation C1 (Figure 2) is recognized at present in only two discrete areas. The earliest Namurian (Roberts *et al*. 2003) Spion Kop Conglomerate, a thick succession of diamictite and poorly sorted conglomerate with striated and faceted clasts, was interpreted by White (1968) to represent proximal proglacial environments during a series of glacial advances and retreats in a non-marine setting. Our investigation broadly confirms this interpretation, although we see glacial facies (diamictites) only at the base and top of the unit (Birgenheier 2007). The only other rock unit containing a probable record of this event that we have recognized is the earliest Namurian Yagon Siltstone of the eastern Myall Block (Crane & Hunt 1980; Roberts *et al*. 1991*a*). An interval in the middle of this unit contains dispersed gravel and glendonites among strongly soft-sediment-deformed mudrocks interpreted as marine slump deposits. Overall, the limited distribution of the C1 interval is interpreted to record the initial onset of the Late Paleozoic Ice Age, involving glaciers of probably limited extent, perhaps largely confined to paleovalleys.

Strata between Glaciations C1 and C2

The termination of glacial conditions at the end of Glaciation C1 is demonstrated by (1) the upward transition from diamictites at the top of the Spion Kop Conglomerate into fluvial sandstones, conglomerates and commonly carbonaceous mudrocks with plant fossils of the Namurian Clifden Formation (Roberts *et al*. 2003), and (2) a thick unit of undeformed, bedded marine mudrocks and sandstones that overlie the slumped interval in the Namurian Yagon Siltstone (Crane & Hunt 1980; Roberts *et al*. 1991*a*). The same interval is also exposed in the lowermost Seaham Formation of the southern New England Fold Belt, which is composed largely of fluvial conglomerates, particularly in the type section at Seaham (Süssmilch & David 1919; Roberts *et al*. 1991*a*).

Glaciation C2

Glaciation C2 (322.5–319.5 Ma: mid-Namurian, latest Mississippian; Figure 2), is at present recognized in four units exposed in Queensland and New South Wales: the Lake Galilee Sandstone in the Galilee Basin, Johnson's Creek Conglomerate (Myall Block) and Kullatine and Youdale C Formations (northern Hastings Block) in the Tamworth Belt, and tentatively in the Seaham Formation (Rouchel and Gresford Blocks).

The Lake Galilee Sandstone (Gray & Swarbrick 1975) is known only from the subsurface, but contains complexly interbedded diamictites and other characteristic glacial facies in drillcores that define a complete nonglacial–glacial–nonglacial cycle. The Johnson's Creek Conglomerate (Roberts *et al*. 1991*a*) contains a suite of proximal proglacial facies, including diamictites and rhythmically laminated mudrocks interbedded with other facies such as thick fluvial conglomerates in the Stroud Road area. The Kullatine Formation (Voisey 1939; Lindsay 1966; Bourke 1971) contains, indeed seems dominated by, thick intervals of probable marine diamictites with striated and faceted clasts in a series of outcrops NW of Kempsey, and comprises interbedded sandstones, conglomerates and diamictites in the Kunderang Brook area east of Walcha. The marine mudrock-dominated Youdale C Formation (Bourke 1971; Roberts *et al*. 1991*b*) was found to contain an interval of dispersed extraformational gravel in fine-grained mudrocks at exposures in Pinnacle Creek, near Kunderang Brook. Although not well constrained in time, the lower Seaham Formation in the type section at Seaham village (Süssmilch & David 1919; Roberts *et al*. 1991*a*) and at Six Mile quarry near Raymond Terrace contains an interval of outsize clast-bearing, rhythmically laminated mudrocks that could also be representative of C2.

The more widespread distribution of C2 deposits in New South Wales and Queensland relative to those of C1 suggests that glaciers were developing over a larger area during this time.

Strata between Glaciations C2 and C3

Intervals of principally non-marine, fluvial and lacustrine strata can be shown conclusively to separate glacially influenced deposits of Glaciations C2 and C3 in the Galilee Basin of Queensland, constrained palynologically (Jones & Fielding 2004; Jones & Truswell 1992). Alluvial facies and pyroclastic rocks underlie glacial deposits of C3 in both the Currabubula Formation and upper Clifden Formation of the Tamworth Belt, New South Wales, in both cases constrained by radiometric ages (Roberts *et al*. 2006), although Glaciation C2 cannot be recognized in these successions (Figure 2).

Glaciation C3

Glaciation C3 (317–315 Ma: latest Namurian to earliest Westphalian, early Pennsylvanian; Figure 2) is recorded in two discrete intervals of continental proglacial strata in the Currabubula Formation of the Tamworth Belt and adjacent areas (Carey 1937; Whetten 1965; Roberts *et al*. 2006), an interval of proximal proglacial strata in the upper Rocky Creek Conglomerate (McKelvey 1969; Roberts *et al*. 2003) and a similar interval in the Joe Joe Group of central Queensland (Jones & Fielding 2004, 2007). In the lower Currabubula Formation at Currabubula township, an interval of proglacial lake deposits with rhythmic grain-size alternation between clay, silt and sand-grade laminae, and dispersed gravel (Rosedale Member) is interbedded with other mudrocks, sandstones and conglomerates (Whetten 1965; Birgenheier 2007). This interval overlies alluvial conglomerates showing no evidence of glacial influence, and is overlain in turn by interbedded fluvial sandstones and conglomerates, and pyroclastic rocks. At a slightly higher stratigraphic level (constrained by ignimbrite bodies, some of which have been dated: Roberts *et al*. 2004, 2006), a thicker, more complex interval of interbedded proximal proglacial facies is exposed in Cana Gully, NW of Werris Creek. This unnamed member comprises rhythmically laminated proglacial lake mudrocks with abundant outsized gravel, with some massive and soft-sediment-deformed sandstones and thick diamictite bodies with striated and faceted clasts (Birgenheier 2007). Multiple cycles of glacial advance and retreat are implied by this complex stratigraphic succession.

The Rocky Creek Conglomerate at Rocky Creek, which is well constrained by dated ignimbrites (Roberts *et al*. 2003), comprises a thick succession of alluvial conglomerates with rare, thin intervals of rhythmically laminated mudrocks, and a complex interval of interbedded conglomerate, diamictite and rhythmite with outsized gravel (including abundant striated and faceted clasts) at the top of the unit (Birgenheier 2007). This uppermost interval is interpreted as the product of sediment accumulation in a proximal proglacial, mainly lacustrine environment. A similar interval of interpreted proximal proglacial strata is recorded in the lower Joe Joe Group of the southern Galilee Basin, Queensland (Jones & Fielding 2004, 2007). A further, less well-constrained interval of possible C3 glacial strata is preserved in the Seaham Formation in the type section, where, according to Süssmilch & David (1919), it comprises a 60 m interval of diamictites.

A similar geographical range to the preceding C2 interval suggests that glaciers were of comparable extent and character.

Strata between Glaciations C3 and C4

The nonglacial interval between Glaciations C3 and C4 is constrained by alluvial strata and pyroclastic rocks overlying the Rocky Creek Conglomerate (Roberts *et al*. 2003), within the upper Currabubula Formation, within the Joe Joe Group (Jones & Fielding 2004, 2007), and possibly within the upper Seaham Formation (Figure 2).

Glaciation C4

The youngest glacial interval of the Carboniferous (C4, 313–308 Ma: mid-Westphalian, mid-Pennsylvanian; Figure 2) is recorded by one complex interval of continental proglacial strata in the uppermost Currabubula Formation, two such intervals in the Joe Joe Group, and possibly a further such interval in the upper Seaham Formation (Figure 2). The uppermost Currabubula Formation at The Gap, west of Werris Creek, preserves a substantial interval of laminated mudrocks with outsized clasts (<1.25 m in diameter), diamictites of varying texture and fabric, and intraformational siltstone clast breccias, interbedded with less extensive stratified siltstones, sandstones and conglomerates (Birgenheier 2007). This section is interpreted as proximal to more distal proglacial deposits in a continental, lacustrine to fluvial environment. In the Joe Joe area of central Queensland, two distinct intervals of interpreted proglacial strata are preserved. The lower interval contains complexly interbedded diamictites, soft-sediment-deformed conglomerates and sandstones, and laminated mudrocks with outsized gravel, whereas the upper interval is characterized by mainly rhythmically laminated mudrocks with some outsized gravel (Jones & Fielding 2007). At Seaham, the uppermost Seaham Formation contains a 30 m interval of rhythmically laminated mudrocks overlain by a similar interval of diamictites (Süssmilch & David 1919).

Overall, the Carboniferous record seems to indicate initial establishment of glaciers of probably limited extent (C1), which expanded to cover a larger geographical range (C2) but then during subsequent glaciations did not expand any further into the sedimentary basins of eastern New South Wales and Queensland (C3–C4; Figure 1).

Strata between Glaciations C4 and P1

A substantial time interval (*c*. 9 Ma) separates glaciation C4 from the first glaciation of the Permian, P1. This interval spans the late Westphalian and the Stephanian–Autunian, or late Moscovian to Ghzelian, to approximately the Carboniferous–Permian boundary, and corresponds to an interval interpreted from proxy climate data to be one of more temperate, even greenhouse climate by Montañez *et al*. (2007). In eastern Australia, this interval is represented by a variety of units, some of which directly overlie glacial facies of C4 (Figure 2). Among these, the best constrained is the upper Joe Joe Group, which comprises a thick succession of fluvial and lacustrine facies and some pyroclastic deposits with no evidence of glacial influence, and the similar, uppermost Seaham Formation and overlying Tamby Creek Formation.

Glaciation P1

The onset of Glaciation P1 defines a major change in the character and distribution of glacial facies in eastern Australia. P1 (299–291 Ma: Asselian to early Sakmarian) is recorded in predominantly glaciomarine deposits in the Bowen–Gunnedah–Sydney Basins of eastern New South Wales and Queensland (Fielding *et al*. 2001), in a large number of geographically widespread areas (Figure 2). Among the formations preserving a direct or indirect record of glaciation are the Wasp Head Formation of the southern Sydney Basin (Gostin & Herbert 1973; Rygel *et al*. 2008*a*), Lochinvar Formation of the Hunter Valley (Süssmilch & David 1919; Booker 1961) and Youlambie Conglomerate of the northern New England Fold Belt (Jones 2003).

Whereas the basal Wasp Head Formation of the southern Sydney Basin contains only an indirect record of the waning stage of this event (Rygel *et al*. 2008*a*), the most complete records are preserved in the faceted and striated clast-bearing marine mudrock and diamictite successions of the Youdale B Formation in the Kunderang Brook area (Bourke 1971; Roberts *et al*. 1991*b*) and in a thick succession of interbedded diamictites, deformed sandstones and conglomerates, rhythmically laminated mudrocks with outsized gravel and other facies within the Youlambie Conglomerate of the Cania area in SE Queensland (Dear *et al*. 1971; Jones 2003). Continental proglacial and possibly subglacial facies are also preserved in thick successions in the continental interior Galilee and Cooper Basins to the west (Boonderoo Beds, Jones 2003; Tirrawarra–Merimelia Formations, Chaney *et al*. 1997). To some extent, this broad distribution of glacial facies probably reflects the greater area covered by subsiding sedimentary basins in the Permian (relative to the Pennsylvanian), but it is also consistent with more extensive ice cover in eastern Australia as has been asserted by previous workers (e.g. Dickins 1996; Lindsay 1997).

Strata between Glaciations P1 and P2

The interval between Glaciations P1 and P2 is well preserved in successions of shallow marine to coastal facies that display no evidence of glacial influence (Figure 2), including the Youdale A Formation (Bourke 1971; Roberts *et al*. 1991*b*) and Wasp Head Formation (Gostin & Herbert 1973; Rygel *et al*. 2008*a*), and by continental, coal-bearing successions of the Reids Dome Beds in Queensland (Draper & McClung 1983) and Clyde Coal Measures in southern New South Wales (Tye *et al*. 1996). In addition to the lack of tangible glacial indicators, this and the other nonglacial intervals of the Permian are recorded in the marine successions by evidence for only modest shifts in paleobathymetry (<30 m) as demonstrated by facies juxtapositions. This is in contrast to the glacial periods, in which abrupt facies juxtapositions recording interpreted shifts of up to 70 m in paleobathymetry are common. The P1–P2 nonglacial interval is epitomized by the Wasp Head Formation of the southernmost Sydney Basin, in which evidence of progressive deepening in a nearshore, open marine setting, with short shallowing-upwards parasequences, is interpreted as recording a progressive eustatic sea-level rise gradually overpowering the isostatic rebound at the end of P1. Facies juxtapositions indicate relative sea-level shifts of <30 m in this unit. This pattern is abruptly truncated by the onset of Glacial P2 at the base of the Pebbley Beach Formation (Rygel *et al*. 2008*a*).

Glaciation P2

Glaciation P2 (287–280 Ma: late Sakmarian to mid-Artinskian; Figure 2) is also recorded in predominantly glaciomarine facies in geographically dispersed areas, including the lower Pebbley Beach Formation of the southern Sydney Basin (Gostin & Herbert 1973), diamictites of the Megalong Conglomerate and equivalents in the western Gunnedah Basin (Dulhunty & Packham 1962), and Cattle Creek Formation of the Bowen Basin (Draper 1983). An aspect in which P2 and possibly the succeeding P3 differ from earlier glaciations is in the direct evidence for isostatic loading on the shallow marine environment. For P2, this effect is most prominently displayed in the basal Pebbley Beach Formation in the southern Sydney Basin, where the onset of glacimarine conditions (recorded by an abrupt and massive increase in the abundance and size of outsized basement clasts, and of diamictites) coincides with a major flooding surface and not an erosion surface or sequence boundary. The evidence for isostatic loading during P2 and P3 implies that ice sheets may have both been larger than during the preceding glacial intervals and more proximal to the Bowen–Gunnedah–Sydney Basin system. The lower Pebbley Beach Formation consists of 22 short cyclical repetitions of diamictites and laminated dark grey marine mudrocks, with a hiatal surface between the two facies in each case indicated by a palimpsest trace fossil assemblage. Each of these "cyclothems" is interpreted to record a glacial advance–retreat cycle of unknown duration (?Milankovitch band), with the hiatal surface recording the glacial advance and maximum, the diamictite recording the glacial retreat, and the laminated mudrocks recording the interglacial sea-level maximum.

Strata between Glaciations P2 and P3

The waning phase of Glacial P2 is recorded by an upward transition in the Pebbley Beach Formation from the glacial–interglacial cyclothems noted above, through outsize clast-bearing mudrocks and sandstones, to shallow marine strata incised at several levels by estuarine channel fills (Fielding *et al*. 2006), recording repeated fluctuations in paleobathymetry of up to 70 m. Although these facies juxtapositions indicate large-scale relative sea-level changes, they are not associated with any direct facies evidence for glaciation (e.g. outsized gravel is essentially absent), and so it is suggested that these perhaps glacioeustatic changes may record glaciation elsewhere in Gondwana. The upper Pebbley Beach Formation is truncated by a major marine transgression at the base of the overlying Snapper Point Formation, which is sandstone dominated, contains little outsized gravel debris, and preserves evidence of only modest shifts in paleobathymetry (Bann *et al*. 2007). Similar coastal to nearshore marine facies are preserved in the upper Cattle Creek Formation and overlying Lower Aldebaran Sandstone in Queensland, and in paralic coal-bearing deposits of the Greta Coal Measures in the northern Sydney Basin (Boyd & Leckie 2000). Within the Snapper Point Formation, however, one isolated but spectacular example of an iceberg keel turbate is preserved (Eyles *et al*. 1997), suggesting that even during nonglacial intervals icebergs were active, much as they are today in the cold temperate realm. This is the only such feature yet convincingly documented from the Carboniferous and Permian of eastern Australia.

Glaciation P3

Glaciation P3 (273–268 Ma: late Kungurian to latest Roadian) is similar in most respects to the preceding P2, although its timing coincides with a major disconformity and depositional hiatus in Queensland (Figure 2). Facies, however, are dominantly glaciomarine deposits in the Wandrawandian Siltstone to Broughton Formation of the southern Sydney Basin (Thomas *et al*. 2007), equivalent Branxton Formation to Mulbring Siltstone of the Hunter Valley (McKellar 1969), and the Porcupine and Watermark Formations of the Gunnedah Basin (Tadros 1993). In all of the above formations, the onset of the glacial, as defined by a massive increase in the abundance and size of extraformational gravel dispersed in marine deposits, is demarcated by a regionally extensive flooding surface rather than by an erosional sequence boundary. This again suggests that the western Gunnedah and Sydney Basins were sufficiently close to ice centres at this time to be affected by isostatic loading. Complicating this pattern, however, is the onset of the Hunter–Bowen Contractional Event, which in the Sydney Basin is marked by an abrupt change in sediment provenance from basement quartz and lithic-dominated to first cycle volcanic-dominated at the base of the Berry Siltstone, also a major flooding surface (Tye *et al*. 1996).

Strata between P3 and P4

The separation of the Middle Permian glacial record into two discrete intervals is moot, as the interval separating P3 and P4 is only *c*. 1 Ma, but the formations containing evidence of glacial influence are nonetheless separated by formations containing no such evidence. Accordingly, separation into two intervals is the preferred solution. Specifically, the basal Illawarra Coal Measures (Pheasants Nest Formation) in the southern Sydney Basin, Tomago Coal Measures in the northern Sydney Basin, Black Jack Group in the Gunnedah Basin, and Upper Aldebaran Sandstone and equivalents in Queensland show no dispersed gravel or other glacial indicators as listed in Table 1.

Glaciation P4

P4 (267–260 Ma: late Wordian to late Capitanian; Figure 2), is regionally extensive throughout New South Wales and Queensland, and is recorded only by occurrences of distal glaciomarine facies (outsized basement clasts in mudrocks, glendonites) in certain formations of the Illawarra Coal Measures (Bembrick 1983; Bamberry *et al*. 1995) and correlatives (e.g. Diessel 1992) in New South Wales, and in the Freitag, Ingelara and Peawaddy Formations of Queensland (Fielding *et al*. 2007). As before, the onset of P4 coincides with a major flooding surface at least in Queensland (base of the Freitag Formation, which could again indicate an isostatic loading effect on the western margin of the Bowen Basin). The Freitag Formation is indeed similar to the earlier Pebbley Beach Formation in being a relatively thin unit composed of a series of short, condensed and top-truncated, unconformity-bounded sequences accumulated under conditions of limited, and time-variable, sediment supply (Fielding *et al*. 2007). Evidence from both Queensland and New South Wales, particularly the latter, indicates a series of relatively short-lived (<1 Ma) glacial intervals within P4, the inter-regional correlation of which is not currently possible with any degree of rigour.

The onset of the Hunter–Bowen Contractional Event in Queensland occurs within Glaciation P4. It is marked in the western Bowen Basin by an abrupt change in sand composition from quartz dominated to first cycle volcanic dominated at the base of the Peawaddy Formation (Baker *et al*. 1993), and in the east by the disruption of the shallow marine depositional setting by submarine debris flows and magmatic activity (Fielding *et al*. 1997). These effects can be separated from facies patterns resulting from ice-rafting and other glacial influences.

The stratigraphically highest evidence of glacial conditions in the Permian of eastern Australia lies in the Newnes Formation of the Illawarra Coal Measures and Shortland Formation of the Tomago Coal Measures in New South Wales (Diessel 1992). These patterns (Figure 1) suggest that the Late Permian was characterized both by westward retreat of glaciers into the elevated hinterland of the Lachlan and Thomson Orogens and ultimately by southward contraction of glaciers towards the paleo-South Pole.

Discussion

The foregoing establishes that in eastern Australia, the Late Paleozoic Ice Age was recorded as a series of discrete glaciations, separated in time by intervals of nonglacial conditions. Issues of timing can only be addressed in general terms with current geochronological constraints, and new age data are necessary before any further progress in correlation can be made. Nonetheless, we submit that the cyclical patterns evident from our time–space stratigraphic analysis are real, and not artefacts. These patterns are independent of the changing nature of depositional environments and of underlying tectonic forcing.

The Late Paleozoic Ice Age lasted for *c*. 67 Ma in eastern Australia, and as such was the longest-lived icehouse interval in the Phanerozoic. The nature and distribution of glacial and nonglacial intervals through the Carboniferous and Permian indicate that the Late Paleozoic Ice Age initially grew from a short-lived and areally restricted phenomenon to a more widespread and longer-lived regime in the Pennsylvanian. The fact that the earliest evidence for glacial conditions in eastern Australia does not coincide with the interpreted onset of the Ice Age from presumed glacioeustatic fluctuations in the northern hemisphere (e.g. Wright & Vanstone 2001) perhaps suggests that eustatic signals were a composite of contributions from disparate glacial events at different times on the various parts of Gondwana.

The acme of the Late Paleozoic Ice Age in terms of areal extent, ice volume and longevity was during the Early Permian. The glacial regime then deteriorated through the Middle Permian, and had collapsed by the Late Permian (Figs 1 and 3). These patterns are consistent with some previous reconstructions of the Late Paleozoic Ice Age in Australia (e.g. Dickins 1996; Lindsay 1997) and with more generalized reconstructions from earlier work (e.g. Veevers & Powell 1987; Frakes *et al*. 1992; Isbell *et al*. 2003). Our results are, however, inconsistent with the proposition by Veevers & Powell (1987) and Gonzalez-Bonorino & Eyles (1995) that the acme of the Late Paleozoic Ice Age was in the Pennsylvanian, when Australia was covered by a continental-scale ice sheet. Although most reviews suggest that the Late Paleozoic Ice Age collapsed during the late Early Permian (after our P1), the eastern Australian record shows persistence of glacial conditions for a further 20–30 Ma. Similar indications of later Permian glaciations are also known from southern Africa (Isbell *et al*. 2003) and Siberia (Chumakov 1994).

We furthermore note the striking coincidence in timing and duration between the glaciations documented here and intervals of interpreted low atmospheric pCO_2 and surface temperature defined by stable isotopic proxy records (Montañez *et al*. 2007) and paleofloral community reorganizations noted in Euramerica by Gastaldo *et al*. (1996), DiMichele *et al*. (2001) and Cleal & Thomas (2005). We note considerable unanimity, but also some disparities, between the interpreted timing of glaciations in eastern Australia and those recognized elsewhere in Gondwana.

Complex stratigraphy within the record of individual glaciations suggests multiple cycles of glacial advance and retreat, but beyond crude estimates based on overall duration, interval thickness and assumptions of linear accumulation rates, it is not possible to determine the time scales of cyclicity. Strong indications of Milankovitch band cyclicity are nonetheless preserved in several formations (e.g. the Artinskian upper Pebbley Beach Formation of the southern Sydney Basin: Fielding *et al*. 2006).

Conclusions

The view that emerges from this work is one of pulsed Late Paleozoic glaciation in eastern Australia, rather than a single, protracted glacial event. We conclude that over a series of alternating glacial–nonglacial intervals, each 1–8 Ma in duration, glaciers gradually expanded in volume and geographical extent in eastern Australia through the Pennsylvanian into the Early Permian, reached an acme in the late Early Permian and then contracted through the Middle Permian. These patterns indicate that the Late Paleozoic Ice Age was considerably more dynamic than previously thought. The eight glaciations can be correlated over a large area of eastern Australia. Future work will establish whether or not this pattern can be correlated to other regions of Gondwana, but will require the acquisition of new, precise and accurate geochronological data. Nonetheless, our data provide a detailed framework with which to compare stratigraphic patterns in far-field regions. It is hoped that this may contribute to a fuller understanding of late Paleozoic stratigraphy and environmental change.

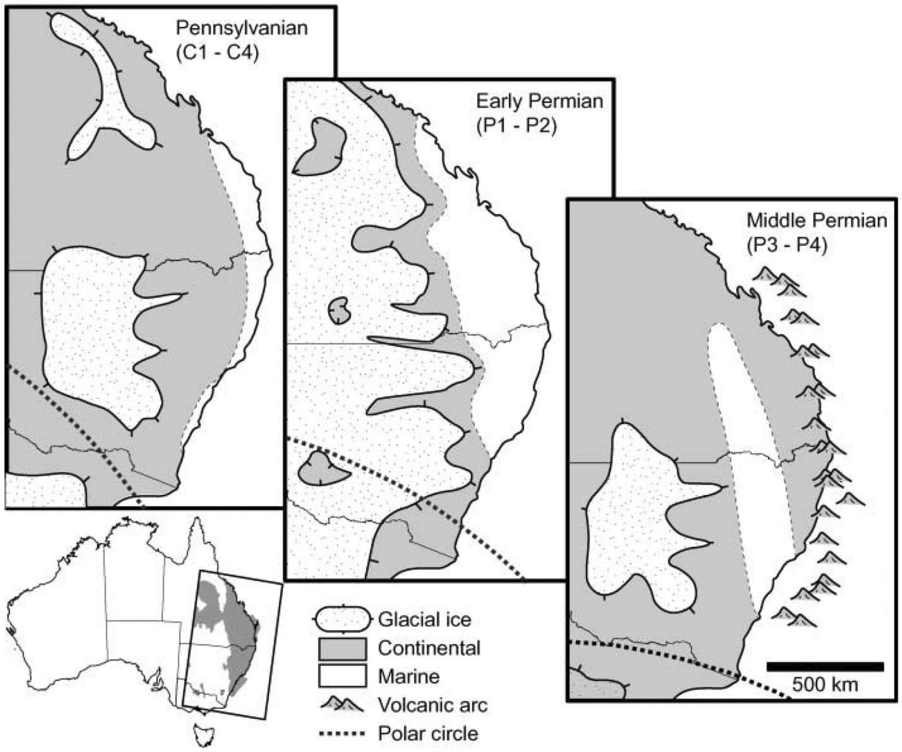

Figure 3. Paleogeographical maps of eastern Australia to show the interpreted extent of glacial ice in (**a**) the Pennsylvanian, (**b**) the Early Permian, and (**c**) the Middle Permian. Location of field areas is also shown in an inset map.

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