# Abstract

## A Paleo-Polar to Mid-Latitudinal Transect Preserved in the Permian Succession of Eastern Australia: Trends in Facies, Stratal Stacking Patterns and Petroleum System Elements Through a Prolonged Icehouse Interval

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The late Paleozoic succession of eastern Australia preserves a 2000 km paleo-polar to paleo-mid latitude transect, allowing the evaluation of latitudinal controls on depositional processes, facies, and stratal stacking patterns. This time period was characterized by a profound icehouse climate regime, and in eastern Australia several alternations between glacial and nonglacial states are recorded from the latest Visean to end-Middle Permian section. Thus, the stratigraphic succession in eastern Australia allows the examination both of paleo-latitudinal effects at a given time, and a comparison of temporal changes in each of a series of paleo-latitudinal sites.

In this paper, we focus on Lower-Middle Permian strata preserved in the Tasmania, Sydney, and Bowen Basins of Australia. During Permian time, these basins lay along the southeast Panthalassan margin of Gondwana. Recent plate reconstructions indicate that Australia rotated in a clockwise direction and moved slowly poleward through the Permian, such that the Tasmania Basin remained south of the polar circle, the Sydney Basin migrated from 55°S to within the polar circle, and the Bowen Basin migrated from c. 45°S in the Early Permian to 55°S by Late Permian time. This high-latitude margin was influenced by a shallow poleward-flowing, western boundary current underlain by a deeper countercurrent that originated at polar latitudes. Prevailing wind systems, comprising winter zonal westerlies and summer longshore northerlies, supported year-round upwelling of cold, polar-derived deep water.

The Lower-Middle Permian stratigraphy of this margin is dominated by coastal plain to shallow marine deposits, which formed during a period of modest but regionally extensive crustal extension and subsequent thermal relaxation. Upper Permian strata, rich in coal and first-cycle volcanic debris, formed during the initial development of a retroarc foreland basin at the onset of the Hunter-Bowen orogeny. Whereas the Bowen and Sydney Basins preserve a direct stratigraphic record of orogenesis, deposits in Tasmania are interpreted to preserve a cratonic overspill equivalent of the foreland basin stratigraphy. These Permian strata record four discrete, glacial epochs (P1-P4), each several million years in length, which can be traced throughout the eastern Australian basins. Glacial facies include diamictites, interbedded conglomerates and sandstones, various types of rhythmites, iceberg keel structures, laminated mudrocks with dispersed outsized clasts, glendonites, clastic intrusions, and faceted, striated, and bullet-shaped clasts. The timing and duration of the glacial epochs were estimated using available radiogenic isotope age and biostratigraphic constraints as follows: P1, Asselian – early Sakmarian; P2, latest Sakmarian – early Artinskian; P3, late Kungurian – Roadian; and P4, mid Wordian – Capitanian. Glacials P1 and P2 were the most intense and coincide with evidence for the development of widespread ice sheets across many areas of Gondwana, whereas epochs P3 and P4 were less intense and likely of alpine scale.

Glacial epochs were separated by warmer intervals of similar duration, during which estuarine to variably fossiliferous shallow marine facies (including limestones) that lack evidence of glacial influence accumulated.

In the earliest Permian P1 glacial interval, facies represent proximal proglacial to locally glacial environments in Tasmania (TAS), and an array of mainly marine proglacial to glacimarine environments in New South Wales (NSW) and Queensland (QLD). A trend of more ice-proximal to less ice-proximal facies assemblages is evident from south to north. The end of P1 is represented both by abrupt flooding trends in some areas and by thicker intervals of more gradually fining-upward facies recording progressive deepening elsewhere. The onset of the Sakmarian to Artinskian P2 glacial interval is best-exposed in southern NSW, where an abrupt change to marine proglacial facies is accompanied by evidence for deepening, suggesting isostatic loading of the sedimentary surface. P2 glacial facies are more proximal in NSW than in QLD. Both P1 and P2 intervals preserve complex internal stratigraphy, in many cases recording multiple glacial-interglacial cycles. The close of P2 is again recorded in a variety of ways, with many sections showing a gradual fining-upward and decrease in indicators of glacial conditions. The Kungurian to Capitanian P3 and P4 glacial intervals are in general represented by less proximal facies than their predecessors, typically intervals of outsize clast-bearing mudrocks and sandstones. These in many areas show diffuse boundaries with the nonglacial facies that enclose them. Furthermore, no significant paleolatitudinal changes in the P3 and P4 facies assemblages are evident from TAS to QLD. The documented patterns support the view that the P1 glacial represents the acme of the LPIA, the P2 a less severe, yet regionally widespread, series of glacial events, and P3 and P4 only localized, perhaps Alpine glaciations.

Spatio-temporal trends in meltwater input and temperature along this margin are assessed using Mg/Ca ratios and oxygen isotope compositions of well-preserved brachiopods and calcitic bivalves. These proxy data are considered within the context of the shallow marine deposits (described above), which contain the analyzed fossils. Results are consistent with sedimentological interpretations. It is evident that the meridional temperature gradient along the margin decreased as glacial conditions became less severe, from c. 0.6°C/°latitude to c. 0.4°C/°latitude. These gradients are not diagnostic of global gradients, but rather highlight the amplified effects of global warming at high latitudes. Oxygen isotope records show considerable variability, not only between glacial and nonglacial epochs, but also along the length of the paleolatitudinal transect. When integrated with Mg/Ca-derived paleotemperatures, it is evident that glaciers contributed substantial amounts of $^{18}$O-depleted meltwater to coastal shelves. Meltwater inputs were relatively high and variable during the early part of the record (P1-P2 time), especially in the southern portion of the transect, and gradually decreased as glacial influence waned. This $\delta^{18}$O variability reveals the importance of considering local effects—in this case meltwater input—in the interpretation of oxygen isotopic data from ancient fossil materials.

The Permian succession of eastern Australia has been considered prospective for oil and gas for many years. The greatest success has been in Queensland, at the northern (most temperate paleo-latitude) end of the transect. Thick nonmarine and marine mudrock successions are present, and have been found to have fair to excellent source potential for both oil and gas. Significant volumes of coal are also preserved, which are predominantly gas-prone. Regional topseals are also formed by mudrock units, which are present throughout the transect. The principal limitation to exploration success has been reservoir quality, which is often poor owing to an abundance of labile framework grain types and extensive pore-occluding diagenetic phases. Certain quartz-rich sandstones, principally of incised coastal fluvial origin, have proved to be effective conventional reservoirs for oil and gas. Stacking patterns within these successions reflect the overall limited accommodation regime along the flanks of basins, where the sandstone-prone formations are mainly developed. Accommodation was strongly influenced by the high frequency and large magnitude of eustatically-driven sea-level changes Many of these formations are characterized by a distinctive stratigraphic "motif" in which several thin (<10 – 50 m), condensed, incomplete, and strongly top-truncated sequences, each sheet-like in geometry, are stacked vertically. Formations can be tracked across and even between adjacent basins of differing tectonic context, suggesting that the over-riding control on stratal architecture at this time was the pacing of glacial events and their attendant eustatic sea-level shifts.