A NEW PALAEOGEOGRAPHIC SYNTHESIS OF THE BOWEN BASIN OF CENTRAL QUEENSLAND

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INTRODUCTION

At the previous two Bowen Basin Symposia, we have presented compilations of palaeogeographic maps (Fielding et al., 1990a, 1995). These articles, and the maps therein, summarised the Permian-Triassic evolution of the Bowen Basin, based on the understanding of the time. Significant progress has been made in this area in the past five years, and in this paper we present a time-space relationship diagram (Fig. 1) together with an expanded series of newly modified palaeogeographic maps (Fig. 2) for the Bowen Basin and terrains to the east and west. In addition to further defining the original extent of the Bowen Basin, this analysis provides new insights into the relationships between Permian-Triassic tectonic events and basin stratigraphy.

In addition to the literature cited in our previous Bowen Basin Symposia papers, the results on which the new maps are based (including extensive compilations of palaeocurrent data) have been published in a series of articles over the past five years, notably Fielding et al. (1996, 1997a, b), Pattison et al. (1996), Faraj et al. (1996), Kassan & Fielding (1996a, b), Holcombe et al. (1997a, b) and Allen et al. (1998).

As per our discussion in Fielding et al. (1995), we shall restrict the term Bowen Basin to the named structural feature, and use the term "basin" in reference to the original depositional entity, which we believe is considerably more extensive. The reader is referred to discussions of basin definition and stratigraphic relationships in Fielding et al. (1995, 1997a) for further information.

Recognition of major stratigraphic sequences

Previous research (including Ziolkowski & Taylor, 1985; Murray, 1990) has established three major phases of basin-forming activity in the Bowen Basin: 1) an Early Permian phase of limited crustal extension, which led to the formation of a series of areally restricted, north-south elongate grabens and half-grabens, 2) a late Early to early Late Permian period of mainly passive, thermal subsidence during which a ragged blanket of sediments accumulated across a wide area, and 3) a Late Permian to Middle Triassic interval dominated by foreland thrust loading. Fielding et al. (1990b) provided a review of earlier research, and interpreted the Permo-Triassic stratigraphy of the Bowen Basin in terms of these three periods of basin development. Each major interval is recognisable in terms of a distinct cross-sectional geometry, as well as in terms of distinct facies assemblages, sediment composition and palaeocurrent distributions. The boundaries between Phase 1 and 2, and between Phase 2 and 3, are clearly diachronous, however.

In all previous interpretations of Bowen Basin stratigraphy, the early extensional phase has been assumed to be coeval with volcanic activity associated with the Camboon Volcanic Arc. Our research has shown that this is not the case, but rather that along either side of the Connors-Auburn Arch Late Carboniferous to earliest Permian volcanic rocks of broadly extensional affinity are overlain (locally unconformably) by a mainly sedimentary suite related to later Early Permian extension. No arc-related volcanism can be recognised from the Late Carboniferous or Early Permian.

The two suites of rocks are clearly separable in most areas, as the older extensional unit comprises predominantly subaerial volcanic and volcaniclastic rocks of varied composition with minor, mainly coarse-grained volcanic sediments, whereas the younger, extensional suite consists mainly of sedimentary rocks of widely varying calibre with minor (but locally important) subaqueous basaltic volcanics and felsic ignimbrites, and intrusive rocks of both silicic and mafic composition. In places, however, the igneous rocks of the older unit pass laterally into predominantly sedimentary successions that from their geometry appear to have formed in extensional basins many of which then continued to subside during the Early Permian extension (Phase 1). These sedimentary suites include the Joe Joe Group of the Galilee Basin, equivalent strata in the Cooper Basin, and the basal part of the Youlambie Conglomerate in the Cania area, which preserve a record of the Late Palaeozoic Gondwanan continental glaciation straddling the Carboniferous-Permian boundary. Furthermore, despite the distinction between an older predominantly igneous and a younger predominantly sedimentary assemblage being clear in most parts, a plethora of recently published radiometric ages for these rocks indicate that the two events overlapped in time. While the older suite (the Connors, Bulgonnuna and lower Camboon Volcanics, the lower part of the Lizzie Creek Volcanics and of the Carmila Beds, and possibly part of the Berserker Beds) has yielded radiometric ages of 320-300 Ma, ignimbrites and some igneous rocks from the younger sedimentary suite (upper Camboon and Lizzie Creek Volcanics, upper Carmila Beds, Reids Dome Beds, Youlambie Conglomerate) have provided ages of 305-280 Ma (Fig. 1). Given this it is debatable whether the inception of the Bowen Basin occurred in the Late Carboniferous or in the Early Permian, although it is clear that the initial development of the Bowen Basin was as part of a patchwork of extensional sub-basins that extended over a large part of eastern Queensland.

Geometry of the Bowen Basin

The present geometry of the Bowen Basin is north-south elongate in the southern half, becoming more NNW-trending in the north. Structural analysis indicates that the north-eastern margin was influenced by WSW-directed thrusting in Late Permian to early Late Triassic times, and that the Connors Arch, Gogango Overfolded Zone, Marlborough Block and other elements of the northern New England Fold Belt may have been translated westward by 50 km or more from their original positions. This interpretation also suggests that the present northern apex of the basin near Collinsville is an artefact of the Hunter-Bowen thrusting and of erosion. Isolated, structurally deformed remnants of Permian and Triassic sedimentary rocks preserved in north Queensland (eg. Mount Mulligan) may once have been contiguous with the basin.

The present western margin of the basin is relatively unaffected by the Hunter-Bowen contraction, although some inversion of earlier extensional structures has been noted (Brown et al., 1983; Ziolkowski & Taylor, 1985; Korsch et al., 1992). The north-south orientation of the western margin is considered to reflect accurately the original (extensional) trend. Basin-marginal deposits have in places been removed by erosion, or preserved fortuitously in faulted inliers such as the Moorlands Basin (Sorby & Scott, 1988).

REVISED PALAEOGEOGRAPHIC MAPS

A series of eleven palaeogeographic maps is presented as Figure 2. All show the limits of the structurally defined Bowen Basin, but attempt to include original elements of the basin now incorporated into the northern New England Fold Belt. A recurrent problem in this respect is the incomplete preservation of the Permo-Triassic record in the New England Fold Belt. No attempt has been made to restore the original Permo-Triassic structural configuration. All maps are schematic, but an attempt has been made to infer the actual distribution of depositional systems as far as is possible, and interpreted sediment dispersal directions are based on sets of measured palaeocurrent data.

Figure 2a – Late Carboniferous to Early Permian extension (two discrete phases of extensional subsidence and magmatic activity)

Figure 2a illustrates the early extensional phase of the basin (Phase 1 and its Late Carboniferous to earliest Permian precursor). The first period of extensional activity (latest Carboniferous to earliest Permian) was notable for widespread explosive (mainly silicic) magmatism which formed the Bulgonunna and Connors Volcanics, the lower part of the Lizzie Creek Volcanics, Camboon Volcanics and the lower part of the Carmila Beds and Berserker Beds. Through a combination of this magmatic activity (which likely produced high-profile volcanic edifices) and tectonic forces associated with extension, a basin-and-range topography was formed at this time. In some of the consequent infra-basins thick sedimentary successions were accumulated in mainly non-marine, fluvial and lacustrine settings, although local marine fossil occurrences (Fauna 1 of Dickins: found at Clermont and Cania, among other localities) attest to the occasional inundation of even the most westerly areas by the sea. These deposits collectively formed the Joe Joe Group in the west and the basal part of the Youlambie Conglomerate in the east (Cania area). In both these areas, and in the Galilee Basin further to the west and north, the late Palaeozoic Gondwanan glaciation is recorded in the preservation of ice-contact proglacial, fluvial and lacustrine sedimentary facies within a discrete interval (Mollan et al., 1969; Cummings, 1998; Jones & Fielding, 1999). Joe Joe Group sediment dispersal into the Springsure Shelf area was towards the southeast, perhaps feeding into the larger Galilee Basin to the west. This pattern also suggests that the later extensional basins of the central Denison Trough had not formed at that time, as that area formed the source terrain for the Joe Joe Group. In the northeast, sheets of alluvial fan gravels were shed eastward from the volcanically active highlands that now form the Urannah Complex (Fielding et al., 1997a, Fig. 5a).

A further period of extensional subsidence led to the development of a mosaic of mainly north-south elongate, partly fault-bounded sub-basins, some of which were over the sites of the earlier subsidence but others possibly new basins. These extensional infra-basins were filled centripetally by continental, alluvial and lacustrine deposits (Draper & Beeston, 1985), with some associated volcanic activity (bimodal, comprising subaqueously erupted basalts and associated intrusions, and felsic ignimbrites). Fluvial facies seem to have been formed in areas dominated by axial sediment dispersal (to the north, and/or south), whereas permanent and perhaps deep lake facies characterise other areas where adjacent topography did not allow significant drainage networks to develop. Significant coal resources are preserved in parts of the Reids Dome Beds of the Denison Trough. Evidence of tectonic instability is well-preserved in lacustrine facies in the form of debris flow bodies, slide and slump masses. The Reids Dome Beds occupy the well-defined sub-basins in the southwest (Denison Trough and Springsure Shelf), the Youlambie Conglomerate those in the southeast, the Berserker Beds the eastern coastal area, and the upper Lizzie Creek Volcanics and upper Carmila Beds those in the northeast. All are considered broadly time-equivalent. The transition into overlying marine strata is, however, strongly diachronous, as exemplified by the interfingering contact between the Reids Dome Beds and overlying Cattle Creek Formation in the Denison Trough (Draper et al., 1990).

Figure 2b – late Early Permian infilling of residual extensional topography and marine transgression

Figure 2b depicts the palaeogeography envisaged during the slowing of extensional subsidence in late Early Permian times. Much of the original extensional topography had been filled and a marine transgression was slowly flooding the basin. Remnant basement highs remained exposed both in the central west (Comet Ridge) and along the Urannah/Connors and Coastal Blocks to the east. The distribution of marine sediments through the Broadsound area in the central east suggests an opening to the palaeo-Pacific Ocean to the east, also indicated by extensive evidence for tidal activity in sedimentary facies of the Cattle Creek Formation and equivalents. The lack of coarse clastic facies adjacent to basement blocks, and the presence of thin limestone units (such as the Buffel Formation in the southeast: Draper, 1988) adjacent to some such blocks, suggests that they were not significant sources of sediment into the Bowen Basin at this time. The preservation within the limestones of bioclastic debris from a variety of carbonate-secreting organisms (Draper, 1988) indicates that climate had ameliorated by this time, although the presence of glendonites in marine mudrocks of the Cattle Creek Formation suggests that marine waters were cold. Furthermore, the coarse-grained and angular nature of gravel preserved in marine mudrocks in the Cattle Creek Formation suggests transport into the basin via floating ice (Draper, 1983).

Much of the marine Bowen Basin was starved of sediment at this time, leading to thin accumulation of Cattle Creek Formation and equivalents in most areas, although these units are much thicker in loci of earlier subsidence such as the Denison Trough. The major direction of siliciclastic sediment dispersal into the basin was from the elevated basement terrains to the west (Anakie Inlier, Drummond Basin and more southerly elements of the Thomson Orogen). One major locus of coarse sediment introduction to the basin was at about the latitude of Springsure, fed by a major palaeovalley system across the eastern Springsure Shelf, which may have focused sediment from the ranges to the north and south. Further north, an extensive sheet of coarse-grained alluvium is preserved along the north-western fringe of the basin (where it hosts several gold accumulations in the Clermont and Miclere areas): palaeocurrent data again indicate eastward sediment dispersal. Downdip of these coarse-grained facies, and overlying them, are coastal plain facies of the lower Collinsville Coal Measures and equivalents. Further south, large deltas built eastward into the central Denison Trough at this time, to form the Riverstone Sandstone and Staircase Sandstone Members of the Cattle Creek Formation (Fielding & Lang, 1988; Fielding, 1989). Still further south, coastal plain facies accumulated in the southern Denison Trough to form a complex interfingering between the Reids Dome Beds and Cattle Creek Formation (the so-called “Paralic Reids Dome Beds). All of these formations were fed by sediment derived from the west. Evidence of recycling of earlier sediments (Joe Joe Group) is provided in the widespread gravel dispersed particularly in marine mudrocks of the Cattle Creek Formation.

Because there was still some isolation between sub-basins, and because of the still-active extensional tectonic environment, some areas preserve unusual facies in this interval. Along the northwestern limb of the basin, thick coals accumulated in certain localised sub-basins. Examples of this phenomenon are the No.3 Seam and enclosing strata at Blair Athol (Smith & Miller, 1995), the Wolfang Seam near Clermont (Wilton, 1995), the coal seams of the Calen Coal Measures north of Mackay (Bloomer, 1994; Fielding et al., 1997a) and the lower seams at Collinsville (Williams, 1995). At broadly the same time, along the southeastern margin of the basin, extensive subaqueously-erupted basalts and associated intrusives were formed in the Rockhampton (Rookwood Volcanics: O’Connell, 1995; Stephens et al., 1996; Fielding et al., 1997) and Yarrol (Owl Gully Volcanics: Dear et al., 1971; Cummings, 1998) regions, and similar volcanic activity probably continued in the “Berserker Graben” (Crouch, 1999). Shallow marine limestone formed in some areas.

Figure 2c – regional slowing of extensional subsidence

Figure 2c shows the quiescence of the late extensional volcanic provinces in latest Early Permian times, an extensive area of shallow (and sediment-starved) marine conditions across much of the basin, a fringe of coarse clastic sediments along the western margin, and an extensive area of no sediment preservation over much of the eastern half of the basin. A lack of coarse-grained facies at this time on the eastern side of the basin suggests nonetheless that the basement areas were subdued, perhaps even shallowly submerged, and the continued existence of a gateway to the ocean to the east is also suggested by evidence of tidal activity in coarse clastic sediments in the west. Sediment accumulation continued unabated in the western part of the basin with major deltaic complexes (Lower Aldebaran Sandstone, Blair Athol Coal Measures, lower Collinsville Coal Measures) sourced from the craton to the west. An unconformity (in places more than one) has been noted by hydrocarbon explorationists in the Denison Trough, separating the Lower from the overlying Upper Aldebaran Sandstone. This unconformity, which is locally associated with truncation of strata and minor folding, can be traced through much of the basin (Fielding et al., 1997a), although its cause is not clear. At this time, any Early Permian sediment, which might have accumulated on the Springsure Shelf was removed by erosion.

Figure 2d – onset of regional, passive, thermal subsidence and expansion of the basin eastward

Figure 2d illustrates the onset of basin-wide, uniform subsidence during middle Permian times, which we believe represents a short-lived thermal subsidence phase. During this time, marine conditions covered much of the basin, carbonates accumulated over some slowly subsiding remnant basement highs, and deltaic and coastal coarse clastic sediments continued to accumulate in the west. The tectonic forces associated with the mid-Aldebaran Sandstone unconformity were evidently responsible for increasing the relief of the source area to the west of the basin, reflected in a massive increase in the volume of coarse sediment delivered into the western half of the basin. Major delta complexes in the Upper Aldebaran Sandstone formed at the eastern end of the Springsure Shelf, and also south of Collinsville, fed by coarse-grained alluvial systems that drained the basement terrain to the west. Furthermore, coarse-grained alluvial facies of Upper Aldebaran Sandstone age are preserved across the Springsure Shelf as the lower part of the Colinlea Sandstone (Fielding et al., 1996). Over some remnant basement highs in the east, carbonate bioclastic debris accumulated to form limestones such as the Oxtrack Formation of the Cracow area (Draper, 1988). Quartzose sandstones of high-energy alluvial origin are preserved in the uppermost part of the Calen Coal Measures in the Mackay-Proserpine area (Bloomer, 1994), providing evidence of the position of the eastern basin margin at this time. These rocks are overlain by heterolithic sediments containing bioturbation, and are interpreted to record a marine transgression.

In the west, a thin but distinctive clastic unit of broadly coastal plain affinity, the Freitag Formation, overlies the Upper Aldebaran Sandstone (Fielding & McLoughlin, 1992). This unit becomes thicker, coarser-grained and contains coal seams in the Emerald area, where it describes another delta system that prograded eastward into the central western basin.

Figure 2e – regional, passive thermal subsidence, marine acme

Figure 2e shows the maximum known extent of marine conditions over the basin in the early Late Permian. At this time, former basement highs within the basin were entirely submerged, and the eastern depositional margin of the basin is not preserved landward of the modern coast. The major and now long-lived sediment dispersal system that fed coarse clastic sediment into the western part of the basin continued to be active, forming a major delta complex north of the Emerald area (the German Creek Formation: Falkner & Fielding, 1993a). During the time represented by Figure 2e, the lower German Creek Formation, which is largely devoid of coal was accumulated as a series of deltaic lobes issuing eastward into the basin. Further south, the Catherine Sandstone (John, 1992; John & Fielding, 1993) forms another, smaller deltaic wedge at the eastern end of the Springsure Shelf, which continued to supply sediment to the Denison Trough area. Elsewhere, mainly fine-grained, offshore marine sediments were deposited to form the Ingelara and Maria Formations in the west, and the Barfield Formation, lower Moah Creek Beds, Rannes Beds, Boomer Formation and undifferentiated Back Creek Group strata in the east

(Fielding et al., 1997a). Glendonites are preserved extensively in these mudrocks, suggesting that marine bottom conditions remained cold. Periodically during this time, unstable marine slope conditions were being established at least locally in the eastern part of the basin with associated volcanic activity, leading to the formation of slumps and sediment gravity flow deposits dispersed westward (Fielding et al., 1997a, b). This instability may have heralded the initiation of thrust loading from the east, the first effects of the coming Hunter-Bowen Event (Holcombe et al., 1997a).

Figure 2f – beginning of Hunter-Bowen uplift in the east, major coal measure development in the north (onset of foreland basin conditions)

Figure 2f shows the palaeogeographic situation that prevailed later in the time of accumulation of the German Creek Formation. This scene illustrates the upper, coal-bearing part of the German Creek Formation, which formed as a series of eastward-prograding deltas (Falkner & Fielding, 1993a, b; Hamilton & Fielding, 1998). To the north, however, the German Creek Coal Measures interfinger with the lower part of the Moranbah Coal Measures, which show evidence of dominantly southerly sediment dispersal (still with a minor contribution from the west: Falkner & Fielding, 1993a, b; Esterle et al., 2000). The volcanic lithic composition of the Moranbah Coal Measures also indicates a source that is distinct from the quartz-dominated cratonic provenance of the German Creek Formation, and this together with palaeocurrent data suggest derivation from a rejuvenated hinterland to the north and east of the basin (Baker et al., 1993). Recent studies of the northern New England Fold Belt suggest that massive uplift was occurring at this time in the northeast, which might have stimulated the major reorganisation in sediment dispersal. A major volcanic fallout deposit (the “P Tuff”) is preserved near the top of the German Creek Coal Measures and at an equivalent level in the Moranbah Coal Measures, recording a major, explosive volcanic eruption that showered much of the Bowen Basin with tephra (Michaelsen & Henderson, 2000). Above this horizon, volcanic fallout beds (primary and reworked tuffs) become regionally abundant in the succession.

To the south of the German Creek delta system, the Catherine Sandstone continued to form as a largely delta-margin coastal sand system with minor fluvial supply from the Springsure Shelf, where accumulation of the Colinlea Sandstone was concluded. Concurrently in the central south, marine mudrocks accumulated away from sources of coarse clastic sediment. In the east, more products of submarine slope instability are preserved in the upper Barfield Formation and equivalents (Fielding et al., 1997a, b), and in the overlying, coarser-grained Flat Top Formation of the Cracow area (Edgar, 1987). Sediment dispersal in these units was westward.

Figure 2g – isolation of the basin from the east, progradation of major axial sediment dispersal system, major explosive volcanic activity

Ultimately, the axial, southward-prograding dispersal system filled much of the basin, and this scenario is illustrated in Figure 2g, which shows the palaeogeography envisaged for the upper part of the Moranbah Coal Measures and the overlying Fort Cooper Coal Measures in the north, and the Peawaddy Formation in the south. By this time, a tectonically and volcanically active hinterland to the east (and particularly the NE) of the basin was supplying large volumes of coarse, volcanic lithic detritus westward into the basin, leading to the establishment of a major southerly-prograding delta complex The first phase of progradation followed a widespread marine transgression which is recorded in fine-grained marine facies of the McMillan Formation in the north, and the lower Peawaddy Formation in the south. Progradation and establishment of delta plain conditions formed the upper Moranbah Coal Measures, which become less coal-rich to the south and southeast (Falkner & Fielding, 1993b; BHPAC, 1995). The regional flooding event at the base of the Peawaddy and McMillan Formations may have been caused by sea-level fluctuations or, more likely, an initial pulse of flexural subsidence related to uplift of the eastern hinterland and the consequent crustal loading.

The upper Moranbah Coal Measures and Fort Cooper Coal Measures pass southward into the Peawaddy Formation, which describes a series of elongate delta lobes that project southward into the southern part of the basin, and which ultimately led sediment to spill over westward across the Springsure Shelf towards the Galilee Basin. Thus for the first time in its history, the Bowen Basin approached an overfilled condition in which more sediment was supplied than could be accumulated in the basin.

At least three periods of delta progradation are recognised in the northern Denison Trough (Belcher, 1990) where some coal is preserved in the upper parts of coarsening-upward cycles, and two well-defined (but entirely subaqueously deposited) progradational cycles in the southern Denison Trough (Neville, 1989). The more elongate (as opposed to arcuate) planform of deltas at this time, indicating outflow dominance, reflects the closure of connection to the ocean, and hence the termination of tidal circulation in the basin: none of these formations show any evidence of tidal influence. All of these strata contain abundant evidence of contemporaneous volcanic activity in the form of primary and reworked airfall tephra beds. During this period, the eastern margin of the basin was undergoing considerable tectonic upheaval, and thick gravel deposits are preserved in places (eg. the Dinner Creek Conglomerate of the Fitzroy region: Fielding et al., 1997a). It is tentatively suggested that the source of the volcanic activity, and of much of the voluminous sediment supplied to the basin, lay in the establishment of a continent-margin volcanic arc situated somewhere immediately seaward of the present coastline.

Figure 2h – latest Permian overfilling of the basin by volcanic sediment shed from the east and north, thin-skinned thrust deformation to form the Gogango Overfolded Zone, and Marlborough Block

Figure 2h illustrates the palaeogeographic situation interpreted for the latest Permian, in which the southward prograding, axial dispersal system had completely overwhelmed other sediment supply to the basin and had filled (even overfilled) the basin. This interval commenced with a flooding event that is evident only in the southern half of the basin. This event, which gave rise to the fetid black mudrocks and tuffs of the Black Alley Shale in the south, is different from previous such events in that no evidence of marine conditions is preserved, rather the basin was an enclosed inland water body. The youngest marine fossils in the Bowen Basin are preserved in the top of the underlying Peawaddy Formation, in places forming thick accumulations of shells termed the “Mantuan Productus Beds”: this horizon effectively marks the end-Permian extinction event in the basin, here some time before the Permian-Triassic boundary and controlled by environmental factors, but globally constituting the most severe biotic crisis in Earth history.

The toxic lacustrine deposits of the Black Alley Shale pass northward into tuff-rich shallow lacustrine facies of the Burngrove Formation, and further north into fluvial facies of the lower Rangal Coal Measures. The southward axial dispersal system established earlier ultimately infilled the Black Alley lake, coarse-grained sediment spilled westward across the Springsure Shelf into the Galilee Basin, and the entire Bowen Basin became an immense alluvial/coastal plain environment. The thick and extensive coal seams of the Rangal Coal Measures formed in this environment, perhaps influenced by climatic fluctuations that caused cyclical variation in sediment supply into the basin (Fielding et al., 1993). Significant volcanic activity occurred during accumulation of the Black Alley Shale and equivalents, but waned later during accumulation of the upper Rangal Coal Measures.

In the southeast, the flooding event recorded by the Black Alley Shale is preserved in the base of the Gyranda Formation, which then coarsens upward into a tuffaceous, sandstone and conglomerate-dominated interval which was dispersed westward and southward (Miller, 1992).

The Gyranda Formation passes upward into the Baralaba Coal Measures, the lowermost part of which contains abundant primary and reworked volcanic tephra (Kaloola Member: Edgar. 1987; Miller, 1992). Towards the eastern basin edge, the coals of the Baralaba Coal Measures thin, and the inter-seam strata become rich in conglomerates derived from the rising hinterland to the east.

Because of the lack of evidence of marine influence on the Black Alley Shale, it is tempting to speculate on a tectonic cause for this flooding event. Recent studies of the adjacent northern New England Fold Belt have suggested that the extensive thin-skinned thrust deformation of the Gogango Overfolded Zone occurred at this time (Holcombe et al., 1997a, Harbort & Holcombe, unpublished data), and was followed by thrust emplacement of the Marlborough Block. Shortening of tens of kilometres is indicated by structural analyses (Fergusson, 1991; Holcombe et al., 1997a), suggesting that a significant crustal load may have been imposed on the eastern margin of the basin at this time. Accordingly, the Black Alley Shale flooding event is interpreted as a consequence of flexural subsidence induced by the loading of the crust in the Gogango Overfolded Zone and environs immediately to the east of the basin.

Figure 2i – latest Permian to Early Triassic basin-wide establishment of well-drained alluvial conditions, further volcanic activity

Figure 2i illustrates the palaeogeography that succeeded that of the coal-bearing Rangal Coal Measures and equivalents, in which the waterlogged environment that allowed extensive coal formation was progressively replaced by a well-drained alluvial surface. On this surface, mainly fine-grained alluvial systems similar to those of the underlying coal measures crossed the plain, but lower water tables caused extensive oxidation to impart strong colouration to alluvial facies (reds, browns, greens). The dominantly well-drained landscapes of the Rewan Group did not allow preservation of coal.

The onset of this well-drained alluvial landscape was diachronous in the central parts of the basin, where the basal part of the Rewan Group is of Permian age, but elsewhere a disconformity separates Permian coal measures from overlying Triassic reddened facies. During this time, continued transverse drainage from both west and east converged into major south-draining axial fluvial systems, similar to the situation interpreted for the Rangal Coal Measures. Volcanic activity associated with the interpreted continent-margin arc continued to provide the principal supply of sediment to the basin, which was initially underfilled but later became overfilled allowing sediment to spill westward into the Galilee Basin (Kassan, 1993; Kassan & Fielding, 1996a, b). Primary volcanic rocks of equivalent age and predominantly intermediate composition are preserved in parts of the New England Fold Belt adjacent to the southeast margin of the basin (Muncon Volcanics, Neara Volcanics: Dear et al., 1971; Campbell et al., 1999), and a large suite of coincident radiometric ages has been derived from granites and other intrusive rocks throughout the northern New England Fold Belt (Holcombe et al., 1997a; Allen et al., 1998; Hutton et al., 1999). Large closed lakes may have existed in the southern part of the basin at times, and may owe their origin to further pulses of rapid flexural subsidence.

Figure 2j – late Early Triassic temporary cessation of orogen-derived sediment supply, pulse of quartzose sand from the craton (Clematis Group), subsequent lacustrine flooding in the south to form the Snake Creek Mudstone

In Figure 2j, the mud-rich alluvial landscape of the Rewan Group has been succeeded by a more sand-dominated alluvial setting, fed by quartzose sediment from the west (probably for the most part from the Anakie Inlier). The Clematis Group is dominated by transverse drainage from the craton to the west, focusing into a major, southward draining axial fluvial system. Sandy alluvial systems and associated floodplains seem to have characterised the entire basin at this time (Kassan, 1993; Kassan & Fielding, 1996a, b). The cause of this reversal in sediment dispersal direction is not clear, but it may be related to a recently-discovered phase of thrust deformation and uplift in the Drummond Basin to the west of the Anakie Inlier.

Accumulation of the Clematis Group in the south was terminated by a further, widespread lacustrine flooding event, which gave rise to the Snake Creek Mudstone, the basal Member of the Moolayember Formation in the southern Bowen Basin. This event may once again have been driven by rapid flexural (foreland) subsidence associated with tectonic forces in the orogen to the east.

Figure 2k – re-establishment of orogen-derived and southward axial fluvial drainage systems, ultimate encroachment of westward-propagating, thin-skinned thrust systems

Figure 2k illustrates a return to the fluvial drainage pattern of earlier Triassic units in the Middle Triassic Moolayember Formation, which is the youngest preserved formation in the basin (Kassan, 1993; Kassan & Fielding, 1996a, b). As with some previous units, drainage at least periodically spilled westward across the Springsure Shelf towards the Galilee Basin. In the far southeast, alluvial fan gravels shed westward from the tectonically active, rising hinterland (Fielding et al., 1996). Following (perhaps, to some extent, during) accumulation of the Moolayember Formation, thin-skinned thrust systems propagated westward across much of the basin associated with the climax of the Hunter-Bowen Event (Holcombe et al., 1997a). During this terminal deformation, in addition to the development and propagation of new thrust systems, older thrusts were reactivated and Early Permian extensional faults were reactivated to form prominent inversion anticlines in the Denison Trough (Paten et al., 1979). The timing of the terminal thrust deformation of the Hunter-Bowen Event is tightly constrained to the late Middle Triassic by the age of the youngest preserved strata in the Bowen Basin and the Carnian (Late Triassic) age of overlying, undeformed coal measures at Callide (Biggs et al., 1995; Jorgensen & Fielding, 1996).

PALAEOGEOGRAPHIC AND TECTONIC CONTEXT OF COAL RESOURCES WITHIN THE BOWEN BASIN

Huge coal resources are preserved within Permian rocks of all three basin-forming phases of the Bowen Basin. It is not possible to isolate any single, geological factor responsible for generating this resource wealth, but rather different combinations of factors have conspired at different times to provide the conditions necessary for the accumulation of economic coal resources.

Early Permian extensional basin deposits

Significant coal deposits are hosted in Early Permian extensional infra-basin fills, particularly in the west (Denison Trough). Here, the coals of the Reids Dome Beds and equivalents are often thick (<10 m or more) and low in sulphur but high in ash, and have complex splitting patterns related to their accumulation in wetlands associated with active alluvial and shallow lacustrine sedimentation, and under conditions of rapid, tectonic subsidence.

Late Early Permian, late extension deposits

Late in the history of the extensional basins, there are instances where rapid tectonic subsidence provided the accommodation for thick coal deposits to form in isolation from coarse clastic sediment supply. This situation, analogous to that in the Late Triassic extensional basins of southeast Queensland (Ipswich, Tarong, Callide, etc.: Jorgensen & Fielding, 1999), provided optimal conditions for the formation of localised, thick (<40 m), low sulphur and low ash coals. In places, where marine incursion followed accumulation of peats, some elevated sulphur levels are encountered. Thick coals formed in this tectonically controlled environment are preserved at Blair Athol, Wolfang, Calen, Collinsville and elsewhere.

Late Early to early Late Permian passive thermal subsidence deposits

On the extensive coastal plains developed along the western edge of the Bowen Basin during mid-Permian times, substantial coal bodies were able to form. Several of these reach economic thickness and quality, such as those in the Aldebaran Sandstone at Valeria (Smith, 1995) and at Collinsville (Williams, 1995), and most notably the laterally extensive coal seams of the German Creek Formation (Falkner & Fielding, 1993a; Hamilton & Fielding, 1998). The coastal plain environments that formed at this time doubtless encouraged the formation of coal bodies, but the great lateral extent, lack of splitting and cyclic development of the moderately thick (<8 m) coals within the German Creek Coal Measures require additional explanation. Hamilton & Fielding (1998) have suggested that the German Creek Formation accumulated under strong orbital controls, in which cyclical climatic variations (and hence sea-level variations) occurred on a scale of tens of thousands to hundreds of thousands of years, related to the Milankovitch periodicities. Such cyclicity may help to explain the widespread development of the peat-forming environment during this time.

Late Permian foreland basin deposits

Major coal development occurred both early in the development of the Late Permian foreland basin (Moranbah Coal Measures) and later, following complete infilling of the residual marine basin (Rangal Coal Measures and equivalents). In both of these cases, coals reach significant thicknesses (<10 m), are generally low in sulphur and tolerably low in ash content, but show significant variations in geometry with multiple splitting patterns. The greater degree of seam splitting in the Moranbah and Rangal Coal Measures relative to that in the underlying German Creek Coal Measures can be attributed to the greater rates of sediment supply to the mainly axial drainage systems that hosted these deposits. The large volume of coal formed at this time may have been encouraged by prolific plant biomass production, fed by the significant influxes of mineral nutrients supplied to the basin by volcanic eruptions.

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Figure 1. Time-space diagram for the Bowen Basin.

Figure 2. Palaeogeographic maps for the Bowen Basin.