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TECTONIC CYCLES OF THE NEW ENGLAND OROGEN, EASTERN AUSTRALIA: A REVIEW

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Running title: Geochronology and Tectonic Cycles of the New England Orogen

ABSTRACT

The New England Orogen (NEO), the youngest of the orogens of the Tasmanides of eastern Australia, is defined by two main cycles of compression–extension. The compression component involves thrust tectonics and advance of the arc towards the continental plate, while extension is characterised by rifting, basin formation, thermal relaxation and retreat of the arc towards the oceanic plate. A compilation of 623 records of

U-Pb zircon geochronology rock ages from Geoscience Australia; the Geological Surveys of Queensland (Qld) and New South Wales (NSW); and other published research throughout the Orogen, has helped to clarify its complex tectonic history.

This contribution focuses on the entire NEO and is aimed at those who are unfamiliar with the details of the orogen and who could benefit from a summary of current knowledge. It aims to fill a gap in recent literature between broad-scale overviews of the orogen incorporated as part of wider research on the Tasmanides (e.g. Champion, 2016; Glen, 2013; Rosenbaum, 2018), and detailed studies usually specific to either the northern or southern parts of the orogen.

The geochronology database and maps of the orogen (GIS files available from the authors) are provided as supplementary material. Within the two main cycles of compression−extension, six accepted and distinct tectonic phases are defined and reviewed. Overviews of these tectonic phases form the basis for this contribution. Descriptions and maps of geological processes active during each phase are included, together with a summary of zircon data and a brief discussion of the broader tectonic framework. The maps reveal the centres of activity during each tectonic phase, and the range in U-Pb zircon ages highlights the degree of diachronicity along the length of the NEO. In addition, remnants of the early Permian offshore arc formed during extensive slab rollback, are identified by the available geochronology. Estimates of the beginning of the Hunter-Bowen phase of compression, generally thought to commence around 265Ma are complicated by the presence of extensional-type magmatism in eastern Qld that occurred between 270 and 260Ma.

KEY WORDS: Tectonic cycles; zircon U–Pb geochronology; New England Orogen; slab rollback; extension; GIS maps

INTRODUCTION

The New England Orogen (NEO) is the easternmost of the Tasmanides, a series of geological regions of eastern Australia formed by repeated extensional and compressional events that commenced in the early Cambrian (Champion, 2016). (The term 'orogen' is used here as discussed in Champion (2016), to designate an orogenic province or region, historically referred to as a fold belt, as opposed to an 'orogeny' or 'orogenic event'.) Until Australia split with Gondwana, beginning with minor rifting around 160Ma, and formation of oceanic crust by around 100Ma (Matthews et al. 2016), the Tasmanides, that comprise the Delamerian, Lachlan, Thomson, Mossman and New England Orogens, formed the north-eastern portion of the Gondwanides of eastern Gondwana.

The NEO extends along the eastern coast of Australia from near Townsville in Qld to Newcastle in NSW, and is bounded to the west for almost its entire length by the Sydney-Gunnedah-Bowen Basin System (Figure 1). The contiguous basins separate the NEO from the Thomson and Lachlan Orogens to the northwest and southwest respectively. Division of the NEO at approximately the NSW−Qld border by overlying Cretaceous sedimentary rocks of the Clarence-Moreton Basin (Figure 1) has led to much research being focused either on the northern or southern sections of the orogen.

The NEO, as now preserved on the Australian mainland, was shaped from the Upper Devonian to Triassic and is the youngest of the Gondwanide/Tasmanide provinces which formed during long-lived subduction that continues today along the Tonga-Kermadec system (Glen 2005, 2013).

The earliest stage of formation of the orogen is thought to involve westward obduction of a Silurian-Devonian intra-oceanic arc (or arcs) and associated sedimentary sequences onto the Gondwana margin (Blake, 2013; Donchak, 2013; Flood & Aitchison, 1992; Glen, 2013; Offler & Murray, 2011). Following obduction, and until the latest Carboniferous, a continental volcanic arc was active over a westward dipping subduction zone along the eastern Gondwanan margin (Champion, 2016; Champion, Kositcin, Huston, Mathews, Brown, 2009; Glen, 2013). This arc, its forearc basin and accretionary complex, are the major foundations of the Orogen with subsequent tectonic activity focused within these early-formed terranes.

A period of extensive rifting followed cessation of the Carboniferous arc. The Sydney-Gunnedah-Bowen Basin System was initiated at this time and structure and sedimentation patterns in the basins reveal the regional tectonics (Korsch, Totterdell, Cathro, & Nicoll, 2009b). Mechanical (backarc) extension followed by progressive transfer to thermal subsidence, then foreland loading related to the next cycle of compression (the Hunter-Bowen Orogeny) is documented in the sedimentary sequence (Fielding, Sliwa, Holcombe & Jones 2001; Korsch & Totterdell, 2009; Korsch, Totterdell, Fomin

& Nicoll, 2009c). The Hunter-Bowen Orogeny was followed by a second period of extension during the Triassic (Babaahmadi, Rosenbaum, & Esterle, 2015; Champion, 2016).

Thus two major cycles of compression−extension are recognised in the NEO. The term 'cycle' is used here simply to describe major changes in the coupling of the Gondwanan/Australian plate with the subducting oceanic plate to the east. It does not account for (i) variations in rates and/or angle of slab subduction or slab failure, (ii) imply uniformity over long distances, (iii) put constraints on timing of slab movements, or (iv) infer mechanisms for crustal accretion (Hildebrand, Whalen & Bowring, 2018).

These major cycles are divided into six phases based on periods of arc activity and the tectonics reflected by depositional patterns in the major basins. The evolution of the New England Orogen may thus be divided as follows:

Transition from Lachlan/Thomson Orogens to New England Orogen

1. Calliope-Gamilaroi Arc - >375Ma, Silurian−Devonian (supra-subduction zone 4 of the Tasmanides (ssz4) of Glen, 2013)

Compression - Cycle I

2. Currabubula-Connors Arc - ~375 − ~305Ma, Upper Devonian−Carboniferous (ssz5 of Glen, 2013)

Extension & Relaxation - Cycle I

3. East Australian Rift - ~305 − ~280Ma, Upper Carboniferous−Mid Permian (ssz6 - Glen (2013))
4. Thermal relaxation - ~280 − ~265Ma, Mid−Upper Permian (ssz6 of Glen, 2013)

Compression - Cycle II

5. Hunter Bowen Orogeny - ~265 − ~230Ma, Upper Permian−Mid Triassic (ssz7 of Glen, 2013)

Extension - Cycle II

6. Triassic Extension - ~230 − ~200Ma, Mid Triassic−Lowest Jurassic (ssz8 of Glen (2013))

The timing of compressive or extensional events is often diachronous within an orogen (e.g. Champion, 2016; Hoy & Rosenbaum, 2017) and there can be overlap between the end of one cycle and the beginning of another, especially with regard to the extremities of the orogen. With this in mind, the above age cut-offs are best estimates based on current data.

METHODOLOGY AND LIMITATIONS

This paper is based on a review of a considerable, but not exhaustive, body of literature on the NEO and is divided into the six orogenic phases outlined above. For each phase, a map is provided illustrating the exposures of rocks associated with that period. The maps are produced from a compilation of zircon U-Pb isotopic ages of volcanic and plutonic rocks obtained from the 'Geochron Delivery System' of Geoscience Australia (Geoscience Australia, 2017), the 'Geochronology Database' of the Geological Survey of NSW (GSNSW, 2017), and supplemented from various other sources as referenced in the text. Figure 2 shows the locations of all samples included in this compilation, comprising zircon data from 306 plutonic, 308 volcanic, and 9 metamorphic rocks. An Excel file of the database is included with supplementary data. Data from zircon provenance studies in sedimentary and metasedimentary rocks have not been incorporated as these require study in their own right.

The descriptions of the geological units outlined by the figures vary in detail, according to their relative importance in defining the tectonic regime for each phase. Generally, the location and timing of igneous activity is taken in this work to be the most definitive criteria and thus it is given more emphasis while sedimentation in basins is often dealt with cursorily.

Additionally, the U-Pb age data has been analysed and presented in various tables and graphs covering each tectonic phase of the orogen. Peaks in igneous activity have been calculated using Isoplot (Ludwig, 2003) frequency distribution in bins of five million years. The results of this analysis are subject to the rock sampling biases of researchers, together with the inherent bias of available outcrop, but broadly indicate the main periods of plutonism and volcanism.

A cursory assessment of zircon inheritance in igneous rocks is also included. The data is a mix of single point analyses and grouped ages where a statistically significant population could be calculated. It does not distinguish between xenocrysts, which lack zircon rims grown in the host rock, from inherited cores that have cogenetic rims. These zircon components are also subject to sampling bias, depending on whether a given study selected a representative range of zircon grains to date, or focused solely on determining an emplacement or eruption age. Therefore, conclusions regarding inheritance should be considered with this in mind. Zircon inheritance in magmas that outcrop outside the boundaries of the NEO has not been included.

Some of the early U-Pb isotopic zircon dating used the SL13 standard that was later found to be inhomogenous, nevertheless its accuracy was determined to be within 2% (Black et al., 2003; Orihashi, Nakai & Hirata, 2008). Use of this standard is noted where applicable and a correction of 1% has been applied. This has been chosen as a median between dates that may be correct and those that err by a full 2%.

Where U-Pb isotopic dates are not available, the ages of volcanic and plutonic rocks are drawn from both printed maps and GIS data from the Geological Surveys. These ages are usually based on studies of other radiogenic isotopes (e.g. K/Ar, Rb/Sr, Ar/Ar). For the northern NEO (NNEO), maps of volcanic and plutonic rocks developed by Purdy (2013b) have been an invaluable resource.

Available zircon hafnium isotopes covering the orogen have also been compiled.

Cross-sections of the orogen for each tectonic phase have been adapted from the work of other authors and provided. Time-space diagrams are not included as excellent compilations are available in Champion (2016, Figures 2.16 and 2.17).

Metamorphism in the NEO is the subject of a further study and is not presented in this review.

The global tectonic context relevant to different phases of the NEO has been appraised by reference to GPlates models developed by Domeier and Torsvik (2014) and Matthews et al. (2016) (hereafter referred to as the Domeier-Matthews GPlates model), which simulate plate movements from 410Ma to the present. The model records the formation of Pangea by the amalgamation of Gondwana in the south, with Laurussia and Siberia in the north, at around 320Ma. Pangea split into a modified Gondwana and Laurasia around 240Ma. Many references refer to the southern continent as Gondwana even during its period as part of Pangea and this has been repeated in this contribution.

PHASE 1 - TRANSITION FROM LACHLAN/THOMSON OROGENS: CALLIOPE-GAMILAROI OCEANIC ARC (>375MA, OBDUCTED SILURIAN−DEVONIAN OCEANIC ARC)

Background

There has been significant debate about the nature of the Calliope-Gamilaroi arc (Blake, 2013). Early authors proposed that it was continental-margin style (e.g. Henderson et al. 1993), but extensive geochemical work by Murray &

Blake (2005), Offler & Gamble (2002) and Offler & Murray (2011), suggests it is an intraoceanic island arc.

Accretion was by obduction and the timing is constrained by an unconformity near Mt Morgan (Figure 3) in Qld (Blake, 2013) and the possible presence of clasts of Lachlan Orogen quartz-arenite in the Keepit Conglomerate of the Tamworth Belt (Figure 1) in NSW (Flood & Aitchison, 1992). Korsch, Cawood & Nemchin (2010) found an abrupt increase in zircon abundance in the Keepit Conglomerate and overlying units of the Tamworth Belt . Zircon grains are absent or rare within older units that are considered to be sourced from mafic volcanism of the Calliope-Gamilaroi oceanic arc. Zircon grains from the Keepit Conglomerate produced an age peak at ~366Ma with no older grains recorded (Korsch et al., 2010).

Fragments of the obducted Silurian−late Devonian arc crop out in the Calliope Province in the NNEO and the Silverwood Group and Gamilaroi Terrane in the south (Figure 3). It is possible that more than one arc is represented in the sequences (Blake, 2013; Buckman et al., 2014; Manton, Buckman, Nutman & Bennett, 2017). However, other authors favour a single arc, e.g. van Noord (1999), Offler & Gamble (2002).

A mix of rock types is found in the various arc outcrops (Aitchison & Flood, 1994; Morand, 1993; Stratford & Aitchison, 1997) and include felsic volcanic rocks and tuff, volcaniclastic sandstone and conglomerate, limestone, mudstone and, in the upper sequences, pillow basalt and dolerite.

Figure 3, inset A, graphs all U-Pb ages older than 375Ma that have been determined for NEO rocks. It includes Calliope-Gamilaroi Terrane rocks as well as other older rocks exposed along the Peel Fault (see 'Extensional exhumation of deep crustal rocks').

Tectonics: Compression & Accretion of Oceanic Arc

The Domeier-Matthews GPlates model plots Gondwana during the early to mid Devonian, centred on the South Pole. Eastern Australia, at its northern extremity, was aligned along latitude 30℃S (Figure 3, inset B). Australia rotated and moved obliquely northwards, perpendicular to eastwards movement on the adjacent Phoenix plate, which together with the spreading, Izangi and Farallon plates, made up the proto-Pacific or Panthalassa Ocean. Accretion of the Calliope-Gamilaroi Arc is accommodated by inclusion of a small, unnamed plate between Gondwana and the Phoenix plate that was consumed at around 380Ma. Motion between the Gondwanan and Phoenix plate then changed to oblique, both plates rotating in a similar direction, and Australia moved to the south-east. According to the model, a collision between Laurussia and the Patagonian coast of Gondwana at about 390Ma was followed by an extended period of transform movement between the two plates, progressively closing the Rheic Ocean (Figure 4, Inset B).

Offler & Murray (2011) proposed that two subduction zones existed along eastern Gondwana during the late Devonian: one dipping west beneath the Lachlan Orogen and one dipping east beneath an island arc (Figure 12a). Debate about the tectonic setting for the arc and its relationship with the Gondwanan continent is summarised in table 1 in Offler & Murray (2011). The presence of an eastwards dipping subduction zone was reasoned to facilitate obduction, rather than subduction of the arc against the continent (Aitchison & Flood, 1994; Offler & Murray, 2011).

Recent studies of dolerite dykes in Devonian sequences of the Tamworth belt/Gamilaroi Terrane (Figure 1) by Offler & Huang (2018) indicate these rocks formed in a nascent back-arc setting during the Middle Devonian (383-385Ma). They propose a rift environment produced by rollback of a westerly dipping slab with the arc (Calliope-Gamilaroi Arc?) and associated subduction zone located offshore to the east. This model necessitates a single subduction zone rather than two as previously suggested (Offler & Huang, 2018; Offer & Murray, 2011).

Major compressional events affecting the Lachlan Orogen include the Lower to Middle Devonian Tabberabberan Orogeny (~399.5−385Ma) and the Lower to Middle Carboniferous Kanimblan Orogeny (~360−340Ma) (Gray, Foster & Butcher, 1997; Gray et al., 2003; Offler & Huang, 2018). Sedimentary rocks covering Tabberabberan structures provide evidence for Middle Devonian rifting in the Lachlan Orogen also (Champion, 2016; Offler & Huang, 2018; Willman, VandenBerg & Morand, 2002).

The exact nature and timing of obduction of the Callipe-Gamilaroi Arc(s) remains unclear. It must have followed the Mid-Devonian extensional event; however, it is constrained by establishment of a new continental Carboniferous Arc (see next section) that became active around 360Ma, coinciding with the Kanimblan Orogeny. Compressional structures related to the Kanimblan Orogeny have not been identified in the New England Orogen (Champion, 2016).

A contractional event in the Hill End Trough (Lachlan Orogen) has been dated at 373 Ma by 40Ar/39Ar dating of white mica in a mylonite zone (Glen & Watkins, 1999; Offler & Huang, 2018) and informed the proposal by Offler & Murray (2011) that the Gamilaroi Terrane was obducted by 375Ma.

Establishment of the continental Currabubula-Connors Arc, followed the arc-continent collision. Obduction of the Calliope-Gamilaroi arc marks the end of the Lachlan and Thomson Orogens and commencement of accretion of the New England Orogen along the eastern Gondwana margin (Champion, 2016; Scheibner, 1998).

PHASE 2 - COMPRESSION CYCLE I: CURRABUBULA-CONNORS ARC (~375−305Ma, UPPER DEVONIAN−UPPER CARBONIFEROUS LONG-LIVED CONTINENTAL ARC)

Background

All elements of a Carboniferous continental margin arc, namely: arc, forearc basin, backarc basin and accretionary complex, are preserved in the NEO (Figure 4). Zircon U-Pb age data has clarified the relationships between various units in each terrane and facilitated understanding of the tectonics.

Arc and Forearc Basin: Continental margin marine to terrestrial environment

A continental volcanic arc was active along the length of the NEO for most of the Carboniferous, e.g. Korsch et al. (2010), Skilbeck & Cawood (1994).

McPhie (1987) likened the arc to the modern Andean system of South America. This interpretation was informed by Whetten (1965), who described voluminous glacial till in the Currabubula Formation of the forearc basin (Tamworth Belt), and reasoned it was derived from alpine glaciers. Similarly, White (1968) concluded that a tillite from the Spion Kop Conglomerate of the forearc basin north-west of Tamworth (Figure 4), was also typical of alpine glaciation. In contrast, Jenkins, Landenberger & Collins (2002) suggested that given the proximity of marine sedimentary rocks, the arc was more akin to the current Indonesian Arc.

In Qld, the arc is preserved in the Connors-Auburn Province, but in NSW its presence is largely inferred from ignimbrites and tuffs in the associated forearc basin. It has been described under various names: Currabubula Arc (Jeon, Williams & Chappell, 2012; McPhie, 1983; Roberts, Offler & Fanning, 2006; Scheibner & Veevers, 2000), Baldwin-Currabubula Arc (Glen, 2013), Keepit-Connors Arc (Cawood, Leitch, Merle & Nemchin, 2011), and Kuttung Arc (Buck, 1989; Harrington & Korsch, 1985a). Here it is referred to as the Currabubula-Connors Arc, acknowledging its original name and its relationship to the NNEO.

The forearc basin comprises the Yarrol Province in Qld and the Tamworth Belt in NSW (including the Hastings Block) (Figure 4). Both provinces are faulted against the accretionary complex, via the Yarrol Fault in Qld and the Peel-Manning Fault system in NSW. The Peel Fault has been traced under the Clarence-Moreton basin where it follows the strong curvature of the forearc units and appears to connect with the Yarrol system (Brooke-Barnett and Rosenbaum, 2015).

U-Pb zircon dating over the past decade has resolved the controversy over the age of volcanic rocks in the Connors-Auburn Province (Holcombe et al., 1997b). Volcanic rocks belonging to the Currabubula-Connors Arc are grouped as the Connors Volcanic Group in the Connors Subprovince and the equivalent Torsdale Volcanics in the Auburn Subprovince.

They comprise predominantly rhyolitic to dacitic ignimbrites with minor lava flows. Rare andesitic and basaltic lavas and volcaniclastic rocks outcrop in localised areas (Withnall, 2013; Withnall, Hutton, Bultitude, von Gnielinski & Rienks, 2009). The Campwyn Sub-province of the forearc basin in the NNEO contains extensive arc-proximal rocks comprising basaltic lavas and silicic tuffs and ignimbrites of the Campwyn and Tanderra Volcanics (Blake & Withnall, 2013).

In the southern NEO (SNEO), volcanic rocks (predominantly ignimbrites) sourced from the arc are preserved at many localities along the forearc basin, e.g. Currabubula and Willuri Formations near Tamworth, (Roberts & James, 2010), Isismurra Formation between Muswellbrook and Scone, and the Newtown and Chichester Formations at Paterson (Buck, 1989). Carboniferous ignimbrites are also exposed through overlying sediments of the Sydney Basin, SE of Singleton (Figure 4) (Brakel, 1972; Willey, 2010). The rhyodacitic ignimbrites of the Nerong Volcanics at Port Stephens (Buck, 1989; Glen, 2013; Scheibner, 1998) are the only exposure of proximal-source arc volcanics in NSW.

Volcanic centres of the arc in NSW are inferred to have been located approximately 100km west of, and with a trend sub-parallel to, the Peel Fault system (Buck, 1989; Jenkins et al., 2002; McPhie, 1984). Thrusting is proposed to have either buried the arc beneath the forearc basin and the Sydney-Gunnedah basins, directly to the west, or offset to the south (Glen & Roberts, 2012; Klootwijk, 2013; Korsch, Johnstone & Wake-Dyster, 1997).

The forearc basin was largely marine in the Early Carboniferous but became progressively continental as the arc developed until, from about 315Ma, it was entirely continental (e.g. Roberts, Offler & Fanning, 2006). Facies in the Tamworth Belt of the SNEO range from marginal continental in the west to shallow and deeper marine to the east (Champion, 2016). McPhie (1987) documented continental conglomerate layers inter-bedded with silicic ignimbrite layers along the western margin of the belt. To the east, limestone, and shallow marine sedimentary rocks and tuffs derived from the arc occur. Similar shallow marine to continental facies are recorded in the forearc basin rocks of the Yarrol Province in the NNEO, with oolitic limestones commonly found in the Lower to Mid Carboniferous Rockhampton Group and terrestrial conditions prevailing during Late Carboniferous deposition of the Youlambie Conglomerate (Blake & Withnall, 2013).

Carboniferous granitoids that represent the roots of the Currabubula-Connors Arc, crop out in both the Connors and Auburn subprovinces of the NNEO (Figure 4). Of note is a belt of Carboniferous granitoids in NSW located approximately 100km west of the inferred edge of the NEO, in the Lachlan Orogen. The Bathurst Batholith and a several plutons to its north and south, have similar geochemistry to ignimbrite and volcaniclastic rocks in the forearc basin (Jenkins et al., 2002; Shaw & Flood, 1993). These denote a volcanic province active from 345Ma − 310Ma. Scheibner (1998) noted the distinct aeromagnetic and radiometric signature of these plutons and proposed that aeromagnetic anomalies to the north indicate the continuation of the belt under Mesozoic cover (Figure 4).

At the far southern end of the Sydney Basin, three Carboniferous granitoids have been exposed through thinned sedimentary cover. Recognition of the age of these plutons led Bodorkos et al. (2010) to consider the possibility that yet more may be present beneath the Sydney Basin.

Extensive Carboniferous and Permian volcanism and plutonism occur throughout the eastern half of northern Qld and are grouped as the Kennedy Igneous Association (Black, 1994; Champion & Bultitude, 2013; Oversby, MacKenzie, McPhie, Law & Wyborn, 1994). Volcanism and intrusive activity concurrent with the Currabubula-Connors Arc is concentrated in an area immediately north to northwest of the NEO, between Townsville and Cairns (Blevin, Allen & Chappell, 1999). U-Pb zircon ages ranging from 357Ma − 306Ma are found in rocks of the Kennedy Igneous Association.

Backarc Basin: Localised or widespread?

A backarc basin has not been identified for the Currabubula-Connors Arc in the SNEO, however isolated outcrops of Carboniferous sedimentary units found within a radius of ~40km of Wangaratta in central-eastern Victoria, are in a back-arc position (Fergusson pers. comm.). In the NNEO however, rifts and deposition patterns revealed in seismic data for the largely buried Drummond Basin (Figure 4) have led to its interpretation as a backarc basin that formed in the Late Devonian (Henderson & Blake, 2013). Three small intracratonic, extensional basins just north of the Drummond Basin have similar ages and comparable depositional histories (Bryan, 2004) and are considered to be part of the same system.

Three cycles of deposition are recognised in the Drummond Basin. Cycle 1 (~370−345Ma) reflects initial rifting with input of predominantly silicic ignimbrites and lavas, but also basaltic and andesitic lavas and sills, and volcaniclastic rocks. This was followed by west-derived cratonic sedimentation of Cycle 2 (~345−335Ma), and finally a return to input of volcaniclastics during Cycle 3 (~335−320Ma) (Henderson, Davis & Fanning, 1998).

An 250m-long gravity ridge (Beresford Gravity Ridge), that follows the axis of the basin, has been attributed to a dense body deep in the crust. Specifically, it has been interpreted as mafic rocks formed during extension and rifting in a back-arc environment (Henderson & Blake, 2003; Murray, Schiebner & Walker, 1989).

Volcanic related sedimentation in the Drummond Basin is particularly extensive (Henderson & Davis, 1993) and this could reflect input from a broad zone of volcanism, perhaps indicative of shallow subduction.

Accretionary Complex: Turbidites, chert and basalt, mudstone and minor limestone

The Wandilla Province is the accretionary complex of the Currabubula-Connors Arc in Qld. The accretionary succession in NSW has several names: Texas-Coffs Harbour Slope and Basin (Scheibner, 1998), Anaiwan Terrane (Flood & Aitchison, 1988), Woolomin Slope and Basin (Buck, 1989), Woolomin Province (Champion, Kositcin, Huston, Mathews & Brown, 2009) and Tablelands Complex (Cawood, Leitch, Merle & Nemchin, 2011a; Korsch, 1977; Rosenbaum, Li, & Rubatto, 2012; Runnegar, 1974).

Deep-sea trench-fill turbidites and minor limestone, juxtaposed against oceanic basalt, chert and mudstone that have been scraped off the down-going plate, typify the accretionary complex throughout the orogen. Radiolarian studies of the chert layers indicate the oceanic sedimentary rocks are predominantly Silurian to Late Devonian in age and formed far from continental influence (Aitchison, 1990; Aitchison, Flood, Stratford & Davis, 1990; Kachovich, 2013). In the SNEO, a cohesive sequence of Silurian−Devonian basalt and chert has been variously referred to as the Woolomin Group (Spry, 1953, 1955) or the Djungati Terrane (Buckman et al., 2014; Flood & Aitchison, 1988). These appear to form the earliest part of the accretionary complex, dominated by ocean floor sedimentary rocks before significant build-up of Carboniferous turbidites in the trench.

The turbidites are predominantly volcaniclastic, and provenance studies of zircons (Craven & Daczko, 2017; Korsch et al., 2009a) indicate they were sourced predominantly from the Currabubula-Connors Arc. Exceptions are the outboard Shoalwater Formation of the Coastal Subprovince and parts of the Neranleigh-Fernvale Beds of the Beenleigh Block in Qld. A greater range of zircon ages was detected in these quartz-rich turbidites. It has been suggested that streams draining the continental interior breached the arc and quartz-rich sediment accumulated from longitudinal transport along the trench (Korsch et al., 2009a; Leitch, Fergusson & Henderson, 2003).

Summary of U-Pb zircon dating of igneous rocks

Table 1 summarises the U-Pb zircon dating that has been carried out on volcanic and plutonic rocks of the Currabubula-Connors phase. Figure 4 - Inset A, is a graphical representation of the data grouped into bins of five million years.

In the SNEO, the earliest activity recorded from the Currabubula-Connors Arc is from zircons in the Keepit Conglomerate (unimodal peak ~366Ma) (Korsch et al., 2010). Maximum ages of igneous rocks are ~355Ma. In the NNEO, ignimbrites from the base of the forearc basin have yielded U-Pb zircon ages of 373−350Ma. Early volcanism (U-Pb ~360Ma) is also recorded at the base of the Drummond Basin. Waning of the arc is recorded in the south by zircon ages of ignimbritic units from the top of the forearc basin (U-Pb zircon ages of 308−305Ma), while in the far north, magmatism of the Kennedy Igneous Association is continuous up to 306Ma.

Zircon provenance studies in the forearc basin and accretionary wedge (Craven & Daczko, 2017; Hoy, Rosenbaum, Wormald & Shaanan, 2014; Korsch et al., 2009a), indicate that although volcanism was continuous over this period, there were peaks of igneous activity in the arc at ~ 350−340Ma and 325−320Ma in the north and ~ 355−350Ma and 327−320Ma in the south.

These peaks appear in Table 1 data, but younger peaks are also evident. There is some sampling bias resulting from research to establish the Carboniferous−Permian boundary in Australia, e.g. Roberts, Claoue-Long & Jones (1991).

Zircon inheritance

A general summary of zircon inheritance in Currabubula-Connors plutonic and volcanic rocks is presented in Figure 10a.

The presence of a range of inherited zircons is characteristic of S-type magmas and may hint at the presence of continental rocks in the deep crust. However, as indicated under 'Methodology and Limitations' the nature of this compilation of inherited ages is most useful for highlighting areas that may warrant further research.

The available data for inherited zircon grains from both volcanic and plutonic rocks of the Currabubula-Connors arc reveal that primarily the zircons are the product of recycling or contamination from magmas formed during earlier stages of the arc. However,e much older zircons are present.

Nearly all the Currabubula-Connors volcanic rocks that have been sampled are ignimbrites, and some very old zircons are found in these rocks. Bryan et al. (2004) noted a range of zircon inheritance in ignimbrites of the Campwyn Volcanics and contrasted this with a lack of significant inheritance in Permo-

Carboniferous rocks. They attributed this to anatectic melting and reworking of continental crust. Similar patterns of inheritance are seen in ignimbrites from the SNEO.

The earliest zircon ages in plutonic rocks of the NEO come from the 325Ma Mount Gibraltar Microsyenite that is exposed through the thinned edges of the Sydney Basin west of Wollongong and the 323Ma Tommy Roundback Granodiorite that outcrops just south of Bowen. The latter is described as a muscovite-biotite monzogranite containing ovoid mafic inclusions (Cross et al., 2015) but has not been categorised into A, S or I-type. This description is similar to that for S-type granites from the succeeding phase of extension (see Phase 3 - plutonism).

Tectonic Framework: West facing subduction

Relative to the Gondwana margin, the Currabubula-Connors Arc reflects an almost static, west-facing subduction system that was active for almost the entire Carboniferous period, from ~366−305Ma. Jenkins et al. (2002) and Glen (2013) proposed that a dual volcanic chain formed over continental crust. The dual volcanic belts exemplified by the Carboniferous plutonic rocks in the Lachlan and Thompson Orogens, and the Currabubula-Connors arc adjacent to the forearc basin are indicative of gently dipping Benioff zones. The longevity of the Currabubula-Connors Arc was attributed to moderate rates of convergence, and a low-density subducting slab (Jenkins et al., 2002). Offler, Roberts, Lennox, & Gibson (1997) concluded from a study of metamorphism in the forearc and accretionary prism of the SNEO, that relatively cold lithosphere, far from a spreading ridge, was being subducted at the time of forearc basin formation.

During decline of the arc and its coincident erosion, significant detritus from the interior continent reached the forearc basin as evidenced by the ancient zircon content of the upper Tamby Creek Formation beneath the Permian Cranky Corner Basin in NSW (Claoué-Long & Korsch, 2003).

In the Domeier-Matthews GPlates Model, the Gondwanan and Phoenix plates rotate about similar poles throughout the period of the Currabubula-Connors Arc (Figure 4, Inset B). Convergence is steady and generally at low, oblique angles. However, for most of this time convergence at the other end of the Gondwanan plate, with Laurussia, varies between high angles to direct compression, resulting in the assembly of Pangea by 320Ma. Also, around 320Ma, the model shows a dramatic change in movement of the plates of the Panthallassan Ocean. Instead of the Izangi and Farallon plates rotating away from both each other and the Phoenix plate, the rotation directions of the Izangi and Phoenix plates become similar but oblique, and a similar relationship exists between the Phoenix and Farallon plates.

A modelled shift in the Euler pole for Gondwana rotation occurs at ~310Ma, from a distant position to one centred in present-day New Guinea. A reduction in the velocity of movement of eastern Gondwana in relation to the Phoenix plate is indicated, although both continue to rotate in a similar direction. Thus following assembly of Pangea, there were major reorganisations of the plates globally.

Craven & Daczko (2017) noted a drop-off in zircon production in accretionary complex metasedimentary rocks from ~320Ma (the final assembly of Pangea). This was interpreted to be a signal of waning volcanism and a switch from the prevailing tectonic setting of moderate compression to one involving extension. The zircon record of the Currabubula-Connors Arc indicates it became extinct at ~305Ma.

PHASE 3 - EXTENSION CYCLE I: EAST AUSTRALIAN RIFT (~305-280Ma, UPPERMOST CARBONIFEROUS - LOWER/MIDDLE PERMIAN)

Background

During the Uppermost Carboniferous – Lowest Permian, coupling of the Gondwanan and Phoenix plates changed, with subsequent retreat of the subduction zone eastwards. Extensive rift basins formed along the entire orogen and as far as the northern tip of Qld. A change to bimodal magmatism reflected activity in a backarc environment, and a new oceanic arc formed offshore.

Permian Basins

By approximately 305Ma, Carboniferous arc volcanism had virtually ceased, and the East Australian Rift System of Korsch, Harrington, Wake-Dyster, O’Brien & Finlayson (1988) and Korsch et al. (2009b), was developing in a backarc environment (Donchak, 2013; Holcombe et al. 1997b; Jenkins et al., 2002; Shaanan, Rosenbaum & Wormald, 2015; Shaanan & Rosenbaum, 2018; Veevers, 2006). Several graben systems opened, from far north Qld to at least as far as the south coast of NSW (Figure 5), the most extensive being the Sydney-Gunnedah-Bowen Basin System.

The incipient Sydney-Gunnedah-Bowen rift formed along the still hot and rheologically weak Carboniferous arc (Figure 4). Carboniferous plutons are found both west and east of the basin system, and the apex of the rift is defined by the preponderance of rift-phase volcanic rocks exposed in the Connors Subprovince in Qld (Figure 5). Several smaller rift and trans-tensional basins, including the Manning and Nambucca basins in NSW, formed within the Carboniferous forearc basin and accretionary wedge sedimentary rocks (Aitchison & Flood, 1992; Cranfield, Donchak, Randall & Crosby, 2001; Glen 2013). Leitch (1988) proposed that a large, all-encompassing Permian basin, that he named the Barnard Basin, existed to the east of the Sydney-Gunnedah-Bowen rift system, separated by a belt of basaltic to rhyolitic volcanism. The numerous smaller basins covering the Carboniferous forearc basin and accretionary complex are thus preserved remnants of the once larger system. Similarly, the Bowen Basin is thought to have extended much further east than its present outcrop and has been fragmented by subsequent folding and uplift (Allen, Williams, Stephens & Fielding, 1998; Holcombe et al., 1997b). Small basins also formed within the Lachlan and Mossman Orogens (Korsch et al., 2009b).

MORB-like volcanic rocks were extruded in the rift basins as subduction migrated to the east (Champion, 2016; Glen, 2013; Jenkins et al., 2002; Rosenbaum, 2012). Early rifting created continental-fluvial depositional conditions in the basins. However, by ~285−280Ma a marine transgression transformed the environment to a coastal setting, and instigated marine shelf sedimentation in the basins (Fielding, Sliwa, Holcombe & Jones, 2001).

Igneous Activity - Volcanism

Upper Carboniferous−Lower Permian volcanism is bimodal, a feature that distinguishes it from the Carboniferous arc volcanism and prompted early recognition of the change to extension in the New England Orogen (Leitch & Asthana, 1985; Scheibner 1998). Jenkins et al. (2002) underscored the fundamental differences in the geochemistry of magmatism in the two phases.

In Qld, rift volcanic rocks outcrop extensively around the northern and eastern margins of the Bowen Basin as the Bulgonunna, Leura, Lizzie Creek and Camboon volcanics (Draper, 2013).

In NSW, limited outcrops of the Boggabri Volcanics and Werrie Basalt occur on the eastern edge of the Sydney-Gunnedah Basin, and Rylstone Volcanics on the west (Brownlow, 1997, 1999; Brownlow and Arculus, 1993, 1999; Pemberton et al., 1994; Roberts, Offler & Fanning, 2004, 2006). A study of borehole data in the Gunnedah Basin (Leitch, 1993) revealed aerially extensive ignimbrites and flows of the Boggabri Volcanics and Werrie Basalt overlying Lachlan Orogen metasedimentary rocks on the floor of the Basin.

Rift volcanic rocks also floor the smaller rift basins to the east of the Sydney-Gunnedah-Bowen Basin System. These include the Abercorn Trough, Cressbrook Basin, Nambucca Block and Manning Basin (Figure 5) (Draper, 2013; Jenkins et al., 2002; Korsch et al. 2009b; Leitch, 1988; Moody et al., 1993). The similarity of depositional phases in the Cressbrook basin and the Bowen basin led Campbell (2005) to support the premise of a much larger 'proto-Bowen' Basin.

Although outcrops of rift volcanic rocks are limited in NSW, there is a strong indication that the bulk of them are buried. A large gravity anomaly that corresponds with the deepest parts of the Sydney-Gunnedah-Bowen basins, the Meandarra Gravity Ridge (Murray, Scheibner & Walker, 1989), extends from the southern extremity of the Sydney Basin northwards to just west of the Auburn Subprovince in Qld (Figure 5). Modelling of the gravity data by Krassay, Korsch & Drummond, (2009), together with interpretation of seismic data has provided indications for the gravity ridge to represent a thick sequence of mafic rocks that intruded and/or extruded at the core of the rift system.

Detailed analysis of geochemistry from a range of rift-phase mafic volcanic rocks in the Sydney Basin by Jenkins et al. (2002) revealed a transition with time from light rare earth enriched to flat N-MORB normalised multi-element and chondrite normalised REE patterns, characteristic of magmas from a back-arc setting. The authors concluded that this indicated ongoing slab retreat and upper plate lithospheric thinning over the period 290−270Ma.

Igneous Activity - Plutonism

There was a moderate amount of Upper Carboniferous−Lower Permian plutonism in the southern and central NEO but it was prolific in the north. However, it was not confined to the orogen, volcanic and intrusive activity extended to the northern tip of Qld through strata of the Thomson and Mossman Orogens (Champion & Bultitude 2013; Holcombe et al., 1997b).

Major outcrops of rift-phase granitoids within the NEO occur in the Connors Subprovince (Figures 1 & 5) and comprise most plutons of the Urannah Suite (Allen, Williams, Stephens & Fielding, 1998; Black 1994; Cross, Bultitude & Purdy, 2012). The adjacent Bulgonunna Volcanics and Bulgonunna plutons that intrude strata of the Drummond Basin also formed contemporaneously with rifting, and similarities between the Urannah and Bulgonunna suites have been noted (Allen et al. 1998).

The Urannah Suite granitoids are predominantly I-type, although small S-type phases are present in the Mount Shields Granodiorite and Tally Ho igneous complex (Figure 5) (Withnall, Hutton, Bultitude, von Gnielinski & Rienks, 2009). Compositions of the suite (Allen, 2000; Bultitude, 2013) indicate derivation from a young lithosphere with little crustal input and have been interpreted as resulting from a significant thermal event associated with extension (Allen et al. 1998).

Less extensive rift-phase plutons intrude the Auburn Subprovince and Wandilla Province (Figures 1 & 5). Three peraluminous plutons in the Auburn Subprovince that group geochemically have dates consistent with the rift-phase and may be S-type. The S-type Wratten Suite of granitoids and the Chahpingah Meta-Igneous Complex intrude the Yarraman and North D'Aguilar Subprovinces of the Wandilla Province.

In the SNEO, the Bundarra and Hillgrove Supersuites as well as other ungrouped plutons (Figure 5) including the Kaloe Granodiorite in NSW, and the Bullangang, Mt You You, Jibbinbar, and Ballandean plutons in Qld are geosynchronous with rifting (Rosenbaum et al. 2012). All intrude the accretionary wedge and the majority are S-type. The exceptions are I-type ungrouped plutons and a number of small mafic plutonic rocks (e.g. Bakers Creek Suite).

Shaw and Flood (1977) reasoned that the S-type Bundarra and Hillgrove suites had formed from partial melting of the deepest parts of the accretionary complex as a result of influx of metasomatically altered upper mantle wedge material. Geochemical signatures from the Bakers Creek Suite led Jenkins et al. (2002) and McKibben et al. (2016) to conclude these magmas formed in a back-arc setting.

Gympie Arc - part of the Rift phase arc

Consensus is emerging that the Gympie Province in south-east Qld (Figure 5) represents a portion of the new arc that succeeded the Currabubula-Connors Arc (Champion, 2016; Donchak, 2013; Hoy & Rosenbaum, 2017; Li, Rosenbaum, Yang & Hoy 2015; Little et al., 1992).

The sequence in the province is unique within the NEO and its significance has been hotly debated. Sivell and Waterhouse (1988) and Sivell and McCulloch (1997, 2001) completed a detailed geochemical and petrological study of more than 13km of drill core through the Gympie Group, which led to a revision of the geology as well as a reinterpretation of the tectonic setting. The basal Highbury Volcanics is now recognised as a sequence of basalt and associated sedimentary rocks that represent early submarine volcanism in an island arc with no geochemical evidence for involvement of continental crust. Depositional horizons record a gradual change from deep marine muds to shallow water pyroclastic deposits. Although no age data is available for the Highbury Volcanics, it has been proposed they are contemporaneous with rift volcanism in the NEO (Li et al., 2015).

An increasing input from continental crust and a change to andesitic and minor dacitic volcanism marks the overlying Rammutt Formation. Calculated geochemistry for the crustal input matched that of the Carboniferous accretionary prism of the NEO (Sivell and McCulloch. 2001).

A study of detrital zircons from the Rammutt and overlying formations of the Gympie Group (Li et al., 2015), indicated a NEO provenance for these units. It was estimated the Rammutt Formation was deposited between 295Ma and 265Ma, thus spanning the active rift to thermal relaxation phases of the NEO.

Summary of U-Pb zircon dating of igneous rocks

Table 2 and Figure 5 - Inset A, summarise the U-Pb zircon dating for rift-phase volcanic and plutonic rocks.

It is worth mentioning the methodology used to calculate U-Pb zircon ages for igneous rocks that span the Currabubula-Connors Arc/ Rift Phase boundary. Late peaks in continental arc activity (310 − 315Ma and 305 − 310Ma respectively - see Table 1) have been estimated for plutonic rocks from the Connors-Auburn Province in Qld and the Kennedy Igneous Association to the north of the NEO. Similarly, plutons attributed to the rift phase have ages 305 − 300Ma (Table 2). Bryan et al. (2004) pointed out the significant problems of determining inherited components versus crystallisation ages and eruption ages, particularly when a variety of statistically valid results can be derived. Cawood et al. (2011a) decided to treat all zircons older than 300Ma as inherited for their age calculations (c.f. Craven & Daczko, 2018). Reprocessing their data by including all dated zircon grains and using Isoplot to obtain the first valid weighted mean, with MSWD close to or less than 1, and probability greater than 0.05, (after sequentially eliminating data points with the highest weighted residual values), in some cases did not significantly change the previously determined age. However, in a few cases it did, e.g. NE13/15 Dundurrabin Granodiorite from 290.3±5.5Ma to 295.2±6.9Ma, NE77/07 Tia Granodiorite from 295.7±2.8Ma to 300.1±2Ma. The dilemma of how to identify inherited zircons that are probably close to a real crystallisation age for a magma continues to be a problem. Jeon, Williams and Chappell (2012) had success in the Bundarra Suite using $\delta^{18}O$ in zircons. However, this approach may not always work.

Age peaks in the available zircon data vary between the Kennedy Igneous Association, and the NNEO and SNEO.

Zircon Inheritance

The majority of zircon inheritance in rift phase igneous rocks is from the Currabubula-Connors Arc (Figure 10b). Older zircons in granitoids are associated almost exclusively with S-type plutons, while those from volcanic rocks are found in tuffs and ignimbrite layers within sedimentary units.

Claoué-Long & Korsch (2003) recorded a large increase in inherited zircons in a tuff horizon dated at 300Ma, at the top of the Tamby Creek Formation in the Cranky Corner Basin north of Newcastle in NSW. Inheritance ranged from the Carboniferous to Archaean. Overlying horizons did not contain any zircons older than the Currabubula-Connors Arc. Incorporation of similar, zircon abundant, sedimentary horizons into the S-type granites may contribute to the abundance of ancient zircons in these plutons.

Extensional exhumation of deep crustal rocks

Rift phase extension exposed a range of deep crustal metamorphic, mafic and ultramafic rocks. They are spread along the length of the orogen with a concentration along the Yarrol-Peel fault systems. The largest outcrops occur in the Marlborough Block (Bruce & Niu, 2000; Bruce, Niu, Harbort & Holcombe, 2000; Holcombe et al. 1997b; Murray 1969, 2007), and North D'Aguilar Sub-province of the NNEO (Holcombe, Little, Sliwa & Fielding, 1993; Little, Holcombe & Sliwa, 1993; Sliwa, 1994). Murray (2007) interpreted the Princhester Serpentinite of the Marlborough Block to be a remnant of partially melted upper mantle peridotite from on oceanic spreading centre that later interacted with magmas in a Devonian island arc setting. Holcombe and Little (1994) concluded the greenstones of the North D'Aguilar area to be fragmented parts of a seamount associated with an oceanic fracture zone.

Glen (2013) has proposed that the Peel-Yarrol system is a long-lived crustal structure that reflects a subduction zone dating back to the Neoproterozoic. His model invokes a slither of Gondwana broken off during rifting of Laurentia and later forming the locus for oceanic arcs that end up as the Calliope-

Gamilaroi Arc. Exhumed blocks include ophiolite, eclogite, serpentinite matrix mélange, norite, gabbro, pyroxenite, dolerite, basalt, plagiogranite and chert, and ages range from 562Ma to 436Ma (Aitchison & Ireland, 1995; Fanning, Leitch & Watanabe, 2002; Fukui, Watanabe, Itaya & Leitch, 1995; Offler 1999; Offler and Shaw 2006; Sano, Offler, Hyodo & Watanabe, 2004; Watanabe, Leitch, Fukui, 1993; Watanabe, Fanning, Leitch & Morita 1999).

Outcrops in NSW in the Manning-Port Macquarie area are interpreted to be remnants of a Cambrian supra-subduction system (Och, Leitch & Caprarelli, 2007; Phillips G., Offler, Rubatto & Phillips, D., 2015; Sano et al., 2004), and later Ordovician arc magmatism (Champion, 2016; Offler & Shaw, 2006).

Figures 12c and 12d show how deep crust and upper mantle can be exposed during extensive rifting.

Tectonics

Klootwijk (2009) attributed the beginning of subduction roll-back to a change in the rotation of Gondwana from counter-clockwise to clockwise. The Domeier-Matthews GPlates model incorporates such a change at ~300Ma by a shift of the Euler pole from New Guinea to Antarctica (Figure 4, Inset B and Figure 5, Inset B). Kroner, Roscher & Romer (2016) propose a plate reorganisation at this time that resulted in opening of the Neo-Tethys Ocean.

Upper Carboniferous − Lower Permian extension was first noted by Leitch (1988) in the Manning region of NSW, and conclusively demonstrated by Little et al. (1992), Holcombe and Little (1993), Holcombe and Little (1994), and Little et al. (1995) as a result of their detailed work on the North D'Aguilar core complex in Qld. Claoué-Long and Korsch (2003) found clasts of basalts in conglomerates of the Cranky Corner Basin that were reliably dated as late Carboniferous and indicated extension earlier than previously recognised in NSW. Subsequent U-Pb zircon dating (Table 2) has confirmed the early onset of rift volcanism following cessation of activity in the Currabubula-Connors Arc.

Structural and sedimentological analysis of the Sydney-Gunnedah-Bowen Basin System (Korsch et al. 2009c) indicated that rifting commenced with the Denison Event about 305−300Ma producing an eastern series of half-grabens that are bounded predominantly on their western sides by east-dipping faults and contain volcanic-dominated deposits. A second phase of rifting further to the west was estimated to occur around 285Ma producing half-grabens without associated volcanism. Around 280Ma, mechanical extension appeared to cease and give way to foreland loading.

There has been some argument for a short period of compression around 305 to 300Ma (Cawood et al. 2011a; Glen, 2013; Phillips, Robinson, Glen & Roberts, 2016; Roberts, Offler & Fanning, 2006; Veevers, 2013). Unconformable deposition of Permian sedimentary rocks over the preceding Carboniferous sequence is recorded in several areas in NSW (Claoué-Long & Korsch 2003; Olgers & Flood 1970). Early Permian movement on faults in the Tamworth Belt (Roberts et al., 2006) and interpretation of shear zones at the Wongwibinda and Tia Metamorphic Complexes as compressional features (Craven, Daczko & Halpin, 2012; 2013; Dirks, Hand, Collins & Offler, 1992;

Dirks, Offler & Collins, 1993; Farrell, 1988; 1992) are also used as the basis for this contention.

Researchers in Qld have found no need for a compressional phase to explain similar unconformities in the NNEO. Murray et al (2012) noted that extensional tectonics resulted in tilting and erosion of Carboniferous rocks that produced disconformities or angular unconformities along contacts with overlying extensional packages and concluded that "the variation in relationships at this basal contact can be attributed to different degrees of tilting of basement blocks during extension."

Modelling by King and Ellis (1990) and Weissel and Karner (1989) shows how uplift can occur during extension.

The position of the arc following extension has been debated, (e.g. Murray, 1988; Scheibner, 1998). There is emerging agreement that it was offshore relative to the accretionary complex, but not necessarily far offshore, and the Gympie Province represents part of the Permian supra-subduction zone sequence (e.g. Glen (2013), Hoy & Rosenbaum (2017), Li et al. (2015)).

PHASE 4 - EXTENSION CYCLE I CONTINUED: THERMAL RELAXATION (~280−265Ma, MID TO UPPER PERMIAN GRAVITATIONAL SAGGING AND LOCAL EXTENSION)

Background

Although sedimentation in the Sydney-Gunnedah-Bowen Basin System indicates a period of thermal relaxation and sagging starting around 280Ma, Korsch et al. (2009c), and Korsch and Totterdell (2009) indicate this was not synchronous across the basin and some local extension may have been ongoing until around 270Ma. Fielding, Sliwa, Holcombe and Jones (2001) describe increasing marine inundation from ~285Ma until ~265Ma, then starting in the north, the basins gradually returned to fluvial systems as thermal relaxation changed to foreland loading.

Oroclines

Oroclinal bending forms major structures in the NEO (Figure 6) that are particularly evident in geophysical maps covering the orogen. They are described under this phase as there is some agreement among researchers that they were forming over this period, however it is likely that they were initiated earlier.

During thermal relaxation, subduction rollback continued in at least the SNEO, producing the oroclinal bending that affected both the Carboniferous forearc basin and accretionary wedge, as well as the belt of Rift phase granites (Rosenbaum et al. 2012). There is general acceptance that the Texas and Coffs Harbour megafolds near the NSW-Qld border are oroclinal bends (Flood & Fergusson, 1982; Li, Rosenbaum & Donchak, 2012). However the presence of a mirror double orocline in the Manning-Hastings area is more controversial (Cawood et al., 2011a, b; Fielding, Shaanan & Rosenbaum, 2016; Lennox, Offler & Yan, 2013; Offler, Lennox, Phillips & Yan, 2014; Rosenbaum, 2012; Rosenbaum et al., 2012; White, Rosenbaum, Allen, & Shaanan, 2016), and the curved trace of exhumed serpentinites has been explained as the result of oroclinal bending during extension, later deformation during compression, or the combination of the two. Most recently, Phillips, Robinson, Glen & Roberts (2016) have concluded there was an original curvature in the Tamworth Belt that was exaggerated by later compressional faulting. There is also some argument regarding the exact timing of orocline formation. Offler and Foster (2008) suggest the period 273−260Ma, Cawood et al. (2011a) propose 270−265Ma, Li et al. (2014) nominate an extended period from 290−266Ma, and Donchak (2007) and (Fergusson, 2017) argue for a start around 305Ma concurrent with initiation of rifting. Shaanan, Rosenbaum, Pisarevsky & Speranza (2015) also indicate initiation of the oroclines concurrent with the earliest rifting and propose oroclinal movement ceased before 272 Ma.

Fergusson (2017) attributes subduction of a seamount chain to the onset of subduction roll-back and orocline development, while Klootwijk (2013) and Veevers (2013) relate rollback and formation of the oroclines to a clockwise rotation of Gondwana that produced contemporaneous oroclines in Europe (Cantabrian-Asturian Arc; 310—295 and Central Iberian Arc 315−305Ma).

Igneous Activity

Cawood et al. (2011a) described a 'magmatic gap' in the NEO between 280−265Ma, and certainly, known igneous activity during this period is relatively sparse. However, there are still many volcanic and plutonic rocks that have either not been dated, or have been dated by systems easily reset during subsequent tectonic activity. It is possible that future zircon dating may reveal more magmatism attributable to this phase than has been identified to date.

The Gympie Arc continued to be active during this period as revealed by zircon provenance studies of various units of the Gympie Group. An age peak of 265Ma was obtained for the andesitic-dacitic Calton Clastics of the Rammutt Formation within the Gympie Group (Li et al., 2015). In an earlier study, Korsch et al, (2009a) obtained a peak at 276Ma for zircons in a sandstone layer within a volcaniclastic granule conglomerate of the Rammutt Formation.

At the same time, volcanism and plutonism is recorded in a wide belt, approximately 350 km long, extending northwards from the top of the Gympie Group to the Stanage Peninsula in the NNEO (Figure 6). Lavas and pyroclastics of the Owl Gully Volcanics, Rookwood Volcanics, Berserker Group, Double Mountain Volcanics and Peninsula Range Volcanics are considered to be coeval (Murray et al, 2012). Of these, the Double Mountain Volcanics and Berserker Group have been U-Pb zircon dated. The Double Mountain Volcanics have an age of 270Ma, while lavas and volcanic breccias in the Berserker Group record ages of 268, 276 and 277Ma.

Plutons with similar relax-phase ages cluster at the top and bottom of this belt. On the Stanage Peninsula, the Mailmans Gap Granodiorite has been U-Pb dated at 269Ma and other plutonic rocks in the area are assumed to be the same age. The bimodal Kyle Mohr Igneous Complex, that outcrops at the southern end of the Rookwood Volcanics and is considered by Murray et al. (2012) to be coeval with them, has a U-Pb age of 270Ma.

Further south, in a belt extending southwards from Gladstone to midway between Monto and Bundaberg (Figure 7 - Inset B), the Castletower Granite, Many Peaks Granite, Hazeldene Quartz Diorite, New Moonta Diorite and an unnamed Quartz Diorite, all have U-Pb ages of 268 or 269Ma. Magmatism in this region overlaps the proposed start of the following Hunter-Bowen contraction (Hoy and Rosenbaum, 2017). The youngest dates are ~260Ma. However these significantly pre-date the bulk of Hunter-Bowen igneous activity. The occurrence of bimodal magmatism in this area led Carson, von Gnielinski & Bultitude (2006) to surmise this may be indicative of an episode of crustal extension (~270−260Ma), eastwards of, and postdating the earlier events between 300−280Ma.

In the SNEO, the Greymare Granodiorite that crops out ~50km NNW of Stanthorpe near the NSW-Qld border, and the Drake Volcanics, ~50km SE of Stanthorpe in northern NSW (Figure 6), have dates of 279Ma and 265Ma respectively. Further south, a group of plutons at Barrington Tops, ~100km NNW of Newcastle, has produced U-Pb ages between 277 and 266Ma, lavas and sills in the nearby Stroud-Gloucester and Myall Synclines have U-Pb ages from 276 to 269Ma and tuffaceous units in the northern Sydney Basin have dates ranging from 272 to 266Ma (Figure 6 - Inset B), indicating regionally active igneous activity (Table 3).

At the far southern edge of the Sydney Basin, the Gerringong Volcanics and associated group of plutons, originally thought to be ~ 240−258Ma based on K-Ar dating (Carr, 1998), but later estimated to be ~265Ma in age (Campbell & Conaghan, 2001), have been confirmed at (265−263Ma) by U-Pb zircon dating (Belica et al. 2017; Metcalfe, Crowley, Nicoll & Schmitz, 2015).

Outside the New England Orogen, volcanic rocks and a significant group of plutons that intrude the Mossman Orogen (Figure 6), have Relax phase U-Pb zircon ages. The plutons extend from north of Cooktown to south of Cairns in northern Qld and most plutons are S-type, which differentiates them from all the other plutonic rocks in the region (Blevin, Allen & Chappell, 1999). The most recent dating reveals ages between 268−275Ma (Murgulov et al. 2013).

A significant feature of igneous activity during the Relax phase is the relative size and abundance of mafic plutonic rocks. Mafic magmatism rivals the more felsic varieties during this period and is present from the Stanage Peninsular in Qld to Kialoa (south of Wollongong) in southern NSW (Figure 6).

Summary of U-Pb zircon dating of igneous rocks

Table 3 (see also Figure 6 - Inset A) lists 'Thermal Relaxation' volcanic and plutonic rocks that have been dated using U-Pb isotopes in zircon. The same sampling bias and methods of estimation of peak activity apply as for previous tables.

The retreat of magmatism from north Qld is reflected in the data for the Kennedy Igneous Association, with the peak for the period at 280—275Ma. In both the NNEO and SNEO, the data indicate a low level of activity ramping up between 270—265Ma.

Zircon Inheritance

There are fewer dated zircons from Relax phase magmas and this partly reflects the reduced volume of volcanics and intrusives of this period preserved on the Australian mainland.

Unlike zircon inheritance in previous phases, ancient zircon grains prevail over those inherited from the Currabubula-Connors Arc (Figure 10c), particularly in the granitoids of the belt from the Stanage Peninsula to Monto-Bundaberg. This degree of inheritance is unusual in plutons that are categorised as I-type.

In the SNEO, zircons older than the Currabubula-Connors Arc are restricted to the Barrington Tops plutons but are not plentiful.

Tectonics

Although conditions in the Sydney-Gunnedah-Bowen Basin System indicate a period of relative quiescence, the orogen was still tectonically active with most of the igneous activity offshore in relation to the current coastline of Australia.

Crouch (1999) concluded from a study of sediments in the Berserker Group in Qld that they were deposited in a back-arc basin close to an active arc to the east. There was limited subsidence in the basin and it was originally more extensive than its present faulted margins, and perhaps continuous with the Bowen Basin. The presence of Kuroko-style massive sulphide mineralisation in the sequence argues further for a back-arc environment. An abundance of silica-rich pyroclastic rocks led Crouch (1999) to favour a continental arc over an oceanic arc.

The bi-modal (basaltic-rhyolitic) Rookwood Volcanics exhibit a typical oceanic back-arc geochemical signature (Murray et al., 2012; Withnall, Hutton, Bultitude, von Gnielinski & Rienks, 2009), that also suggests a very thin subcontinental lithosphere (Withnall et al., 2009).

Murray et al. (2012) nominated the andesitic Owl Gully Volcanics as possible remnants of the arc. They have a strong subduction signature that Murray considered to be consistent with a continental margin arc or a mature island arc.

Although the Highbury Volcanics, the earliest member of the Gympie Group, formed over oceanic crust, Sivell and McCulloch (2001) calculated that the isotopic signature of andesites from the Rammutt Formation resulted from mixing of magma from a depleted mantle source with sedimentary rocks typical of the Carboniferous accretionary complex. They also recognised plant fossils and conglomerates in the Rammutt Formation that indicated some continental affinity.

It would thus appear that in the NNEO, the active arc was on the edge of southern Pangea (Gondwana) during the period 277−265Ma and rollback of the subduction zone was not as extensive as further south.

In the far south of the orogen, tuff layers (266−272Ma) in the Greta Coal Measures and overlying Maitland Group and Tomago Coal Measures of the Sydney Basin are thought to have been sourced from an active arc to the east and northeast (Campbell and Conaghan, 2001; Carr, 1998; Grevenitz, Carr & Hutton, 2003; Herbert, 1997; Scheibner, 1998; Veevers et al., 1994), referred to as the Currarong Orogen. The potassic trachyandesites of the Gerringong Volcanics and mafic plutonic rocks of the Milton, Termeil and subsurface Coonemia Complexes (~ 140 km apart) have been attributed to the Currarong Arc, which has been traced using magnetics, ~200 km offshore to the NNE from Wollongong (Bradley, 1993a, b; Carr, 1998).

It was originally proposed that volcanism of the Currarong 'Orogen' was an extension of the New England 'Orogen' ('orogen' inferred here as active arc), based on dating at the time (Veevers et al., 1994). However, the younger (Hunter-Bowen) volcanism results from a subsequent compressional phase, generally thought to commence ~265Ma at the earliest.

While extensional back-arc, and arc magmatism was active in the NNEO and southernmost NEO, oroclines were forming in the area in between. The Greymare Granodiorite (279Ma) and the Drake Volcanics (265Ma) that crop out in the middle of the oroclinal structures, appear to bookend the 'Thermal Relaxation' phase, and have formed from magmas that are distinct from others in the same area.

The Greymare Granodiorite is depleted in potassium, thorium and uranium and stands out as a dark area on radiometric images of the area (Donchak, Bultitude, Purdy & Denaro, 2007). The rhyolitic to dacitic Drake Volcanics formed in a shallow, shelf environment and unlike the terrestrial volcanic rocks of the Hunter-Bowen phase (and like the Berserker Group), are mineralised (Perkins, 1988).

Based on palaeontological work by Briggs (1998), Cawood et al. (2011a) concluded that sedimentation ceased in the Barnard (Nambucca, Texas, Manning) Basin around 280 to 275Ma. Recent studies of detrital zircons from Permian sediments in the Nambucca block and sedimentary outliers in the Texas block reveal that deposition in the Barnard basin continued, at least locally, until at least 280Ma (Campbell, Rosenbaum, Shaanan, Fielding & Allen, 2015; Shaanan, Rosenbaum & Wormald, 2015).

Figure 12d shows extreme crustal thinning by the end of the extensional phase as is currently seen in basins such as the East China Sea. Mantle-derived volcanics have extruded in pull-apart basins (e.g. Cheju Basin and Sydney-Gunnedah-Bowen Basin System).

The Currabubula-Connors arc is split by the Sydney-Gunnedah-Bowen Basin System and the Peel-Yarrol fault edges a major extensional basin. S-type granites have formed in the Carboniferous accretionary complex and mixed I- and S-type granitoids on the edge of the remnant Carboniferous arc. The Gympie-Currarong Arc is active some distance from the exposed continent.

The Domeier-Matthews GPlates model shows a shift in the Euler pole for Pangea at ~280Ma to somewhere northwest of New Guinea (Figure 6, Inset C). At around 275Ma the Cimmerian terrane broke from southern Pangea and moved northwards (Figure 7, Inset C). According to the model, the next significant event in the region is the formation of a new plate to the north-east of Australia and relocation of the Pangean Euler pole to central Australia at around 260Ma (Figure 7, Inset C). This inferred increased compression between the Phoenix and Gondwanan plates and heralded the next phase of the NEO.

PHASE 5 - HUNTER-BOWEN OROGENY & ARC (~265−230Ma, LATE PERMIAN−MID TRIASSIC COMPRESSIVE CONTINENTAL ARC)

Background

Advance of the subduction zone resulted in extensive overthrusting and strong deformation of Carboniferous and Permian sequences. This period of strong compression defines the Hunter-Bowen phase.

Widespread granitoids and volcanic rocks, concentrated in the SNEO, mark the roots of the contemporary continental arc, here named the Hunter-Bowen Arc.

Igneous Activity (U-Pb dates Table 4)

Hunter-Bowen phase magmatism is widespread throughout the orogen, although it is limited north of the Stanage Peninsula in Qld with just a small pocket near Bowen and a small group of plutons of the Kennedy Igneous Association, between Port Douglas and Cooktown (Figure 7). It is prolific in the SNEO, but does not extend south of Tamworth, although the Sydney-Gunnedah-Bowen Basin System contains numerous tuffaceous horizons sourced from this arc.

Igneous activity that commenced during the Relaxation phase in the Gladstone-Monto-Bundaberg belt ceased around 260Ma (Figure 7 - Inset B). After that time, plutonism in the NNEO shifted at least 100km westwards and sparse U-Pb dates reveal ages between 256Ma and 251Ma. No volcanic rocks of this period have been confirmed in the NNEO. However, the undated Airlie Volcanics that outcrop adjacent to the Gloucester Granite (U-Pb 243Ma) near Bowen, are possibly of a similar age.

In the SNEO, magmatism of the Gerringong Volcanics spans the period 265−263Ma and then apparently ceases. Nearby tuffs within the Sydney Basin have ages around 250Ma.

By far the most prolific igneous activity occurred in the New England highlands of NSW, previously the zone of orocline development during the extensional and relaxation phases. Extensive U-Pb dating of tuffs in sedimentary units, as well as volcanic and plutonic rocks, indicates volcanic activity reached a peak between 260—250Ma with peak plutonism between 255—250Ma (Table 4). This period marked the apex of activity in the Hunter-Bowen Arc. Plutons are almost exclusively I-type of intermediate composition. Coeval volcanics are a mix of rhyolitic, rhyodacitic and andesitic tuffs and ignimbrites (Barnes, Brown, Brownlow & Stroud, 1991).

A third weaker pulse of activity marked a shift to the east and occurred between ~237−235Ma. This created a line of scattered plutons on the eastern edge of the earlier magmatism, particularly along the Demon Fault and into the Nambucca Basin in NSW. It was a precursor to the next phase of tectonic activity (Li et al. 2012). Volcanic horizons are present within the Toogoolwah

Group of the Esk Basin that Purdy (2013) has assigned to the Early to Middle Triassic (~250−235Ma). However, no U-Pb dating is available (Cross, Purdy & Bultitude, 2012).

Rare S-type intrusions, such as the Mingo granite and Tenningering Granodiorite are part of the Gladstone-Monto-Bundaberg belt of magmatism discussed previously (Figure 7 - Inset B). Parts of the nearby Wigton Granite are also S-type (Cranfield, Donchak, Randall, Crosby & Osborne, 1998; Purdy, 2013).

Summary of U-Pb zircon dating

Table 4 and Figure 7 - Inset A, summarise U-Pb dating information for volcanic and plutonic rocks of the Hunter-Bowen phase. There is significant sampling bias in this data. As well as attempts to define the Permo-Triassic boundary in Australia, e.g. Laurie et al. (2016), economic imperatives for detailed understanding of the stratigraphy of the Sydney-Gunnedah-Bowen basins have driven dating of tuff horizons for correlation across the system. As a result there is a plethora of data from the basins compared with sampling of other bodies.

Nevertheless, the data show a similar peak for the period 255−250Ma in both the NNEO and SNEO (Table 4). There is limited dating of plutonic rocks attributed to this period in the NNEO, but data from the tuffs indicates that volcanism was widespread throughout the orogen. In contrast to extensive outcrop of volcanic rocks of this age in NSW, there are few in Qld. Tuffs in the Bowen Basin may have been sourced, in part, from volcanic activity in the southern portion of the orogen.

The 235−230Ma peak in activity is most obvious in data from the NNEO.

Zircon Inheritance

Zircon inheritance in Hunter-Bowen igneous rocks corresponds primarily to previous phases of the orogen with older zircon grains found mostly in S-type granitoids, dyke swarms, and tuffs within sedimentary units (Figure 10d).

Tectonics

The change in tectonics from extension to compression is marked in the Sydney-Gunnedah-Bowen Basin System by the beginning of rapid subsidence related to foreland loading around 265Ma (Korsch & Totterdell, 2009; Fielding, Silwa, Holcombe & Kassan, 2000). It is also represented by return to fluvial conditions in the basins. A retroforeland thrust belt evolved progressively from east to west with the locus of crustal loading varying with time (Korsch et al. 2009b). Hoy and Rosenbaum (2017) identified three pulses of Hunter-Bowen deformation, but only the youngest affected the rocks of the Gympie terrane.

Seismic data reveals a much greater development of the west-directed thrust belt the NNEO than in the SNEO (Korsch, 2004). Woodward (1995) calculated that thrusting in the SNEO at this time caused the orogen to be transported 75−80 km westward onto the Gondwanan continent. The NNEO compression was four times that of the south (Donchak, 2013) and contraction in the Gogango Overfolded zone is estimated to exceed 50% (Henderson et al., 1993).

Sedimentation in the Sydney-Gunnedah-Bowen Basin System, Esk Basin and probably the Abercorn Trough in Qld ceased around 232Ma (Holcombe et al., 1997a) and the eastern edge of the Bowen Basin was concertinaed in the Gogango Overfolded zone (Fielding, Stephens & Holdcombe, 1997). In the south of the orogen, remnants of the Currabubula-Connors Arc are interpreted to have been overthrust by the Tamworth Belt foreland basin along the Hunter-Mooki Fault at the eastern edge of the Gunnedah Basin (Korsch, Johnstone, Wake-Dyster, 1997).

Hunter-Bowen compression resulted in accretion of at least part of the Gympie-Currarong Arc and upthrusting along the Yarrol and Peel Fault systems of lower crustal mafic and ultramafic rocks, exposed during the Rift Phase (Sano et al., 2004).

The new continental Hunter-Bowen Arc was established just east of the original trace of the Carboniferous Currabubula-Connors Arc and alignment of arc volcanic rocks cuts across the curvature of the oroclines (Rosenbaum et al., 2012).

Collision of Gondwana with the Gympie-Currarong Arc as a trigger for the Hunter-Bowen compression has been alluded to for many years, (e.g. Buckman et al., 2014; Glen, 2005; Harrington & Korsch, 1985b; Nutman et al 2013; Scheibner 1998). However, with increasing acceptance that the Gympie Arc lay close to the continental margin (Cawood et al., 2011a; Cranfield, Shorten, Scott & Barker, 1997; Crouch, 1999; Li et al., 2015; Sivell &

McCulloch, 2001), and evidence that the Gympie Terrane was only affected by the final stage of Hunter-Bowen compression (Hoy & Rosenbaum, 2017), this appears to be an unlikely option. Jenkins et al. (2002) suggested that subduction of an oceanic plateau could be a cause, but according to Cawood et al. (2011a) there is no evidence to support this theory. A review of Hunter-Bowen deformation structures in the NEO by Campbell, Shaanan & Verdel (2017) and Hoy & Rosenbaum (2017) concluded that the switch to compression was not focussed on the Gympie area, and thus triggered by global plate realignments.

The Domeier-Matthews GPlates model, relocates the Pangean Euler pole to central Australia at around 260Ma, indicating little movement on this part of the plate, although it continued to rotate in the same direction as the adjacent Phoenix plate (Figure 7, Inset C). At the same time, movement on the Euler pole for the Phoenix plate created almost perpendicular compression against eastern Australia. Stresses were somewhat relieved around 250Ma with another shift in the Euler pole to a distant location inferring similar, but oblique rotation between the Phoenix and Pangean plates. However, motion of the Phoenix plate is modelled to be faster than that of the north-eastern corner of the Pangean plate, maintaining a state of compression. A break between the northern and southern parts of Pangea, to form Laurasia and a modified Gondwana, occurred about 240Ma although the model records similar movement on the two plates until around 160Ma. At about 230Ma, the Euler pole shifted again and motion of north-east Gondwana became perpendicular to that of the Phoenix plate (Figure 8, Inset B).

PHASE 6 - LATTER TRIASSIC (~230−200Ma, MID TRIASSIC TO LOWEST JURASSIC EXTENSION)

Background

Late Triassic elements of the NEO indicate another period of extension following the end of the Hunter-Bowen Orogeny (Babaahmadi et al., 2015; Holcombe et al., 1997a; Jenkins et al., 2002; Li et al., 2012; Veevers, 2006). The Ipswich Basin, a large basin that extends under cover from offshore Brisbane in Qld to just north of Coffs Harbour in NSW (Figure 8), formed around 230Ma (Purdy & Cranfield 2013). It, together with various smaller extensional basins and the style of coeval volcanism (Stephens, Schon & Ewart,1993), imply a repetition of slab rollback.

Igneous Activity (U-Pb zircon ages Table 5)

Triassic magmatism is concentrated in the NNEO between Brisbane and Gladstone (Figure 8). In NSW, several plutonic rocks extend the line of late Hunter-Bowen plutons southwards along the Demon Fault, and a group of smaller granitoids occurs along the coast between Taree and Coffs Harbour. A few islands off the coast between Bowen and Mackay in the far north of the orogen in Qld are also composed of Triassic granite.

The measured U-Pb zircon ages of volcanic and plutonic rocks of this phase cluster between ~230—225Ma with a few dates extending to 212Ma. Most of the plutonism is I-type. However, several A-type granitoids are included. Part of the Chaelundi Complex, near the Demon Fault, is A-type (Landenberger &

Collins, 1996). A group of A-type plutons dated at 212Ma form high-level intrusions within the Lorne Basin in NSW, and the Smokey Cape Monzonite at Smokey Cape on the coast ~90 km further north (Figure 8) is also A-type (Bryant, 2017; Bryant, Chappell & Blevin, 2003; Cross & Blevin, 2013). In the NNEO, several large plutons west of Bundaberg (Figure 8) are A-type (Purdy, 2013b).

Holcombe et al. (1997a) observed how the change in magmatism from andesitic during the Hunter-Bowen phase to predominantly silicic during the late Triassic marked a new tectonic regime. Rhyolitic ignimbrites are typical of the volcanic rocks of the period and are unconformable on the earlier magmatic rocks.

The Mount Marcella Volcanics at the northern end of the Esk Basin formed either late in the Hunter-Bowen phase or early in this extensional phase. They are described as dacitic to andesitic and two samples provided zircon U-Pb ages of ~230Ma.

Stephens et al. (1993) identified discrete cauldron-forming volcanism, which together with the presence of bimodal, but silicic dominated volcanic rocks and the high silica composition of plutonic rocks, led to his conclusion that these were the products of intra-cratonic rifting.

The composition of many of the magmas indicates derivation from crustal melting of the recently arc-impregnated crust (Holcombe et al. 1997a).

The sub-circular Lorne Basin on the NSW coast north of Taree (Figure 8) records a sedimentation history dominated by coarse conglomerates intruded by caldera forming volcanics. The lowermost horizon in the basin, the Jolly Nose Conglomerate has cobble-sized clasts and is possibly early Triassic (Hunter-Bowen) in age (Pratt, 2010). Richardson (2013) extracted zircons from each of a sandstone and volcanic clast in this unit. The sandstone contained a population of zircons with an age peak of 300Ma, while a limited sample of nine zircons from the volcanic clast had populations peaking at 300Ma and 220Ma which possibly indicates a formation age consistent with latter Triassic extension. The circular nature of the basin and circular internal structures led Tonkin (1998) to propose a possible impact origin. Recent work (Richardson, 2013; Richardson, Buckman & Nutman, 2014) concludes the basin formed behind an active arc located east of the present Australian coastline.

Summary U-Pb zircon dating

Table 5 and Figure 8 - Inset, summarise available U-Pb zircon data for Triassic volcanic and plutonic rocks. The limited data (29 locations, Table 5), indicate a peak in activity between 230—225Ma followed by a waning of magmatism (or migration offshore of the current Australian coastline). Assessment of zircon inheritance was not feasible.

Tectonics

The development of extensional basins and the coeval magmatism immediately following the final pulses of Hunter-Bowen compression marked back-stepping (retreat) of the subduction zone beyond mainland Australia (Donchak, 2013).

The few late Triassic basins including the Ipswich, Tarong, Callide, Nambour and others under younger cover, formed under extension as the slab retreated (Donchak, 2013). The Tarong Basin has a half-graben structure and studies by Holcombe et al. (1997a) concluded this basin structure was common to all. Thin basaltic units mark the base of the basins before magmatism evolved to felsic compositions and coal-bearing strata were mixed with volcanogenic sedimentary rocks.

In the SNEO, there is an eastwards movement of magmatism away from the Hunter-Bowen Arc. In the NNEO, late Triassic magmatism occurs predominantly east of the bulk of the Hunter-Bowen arc but also overprints it.

According to Veevers (2006), extension on the eastern edge of Gondwana from ~230Ma resulted in a change from shallow to steep subduction. The Domeier-Matthews GPlates model indicates that the perpendicular relationship of motion between the Gondwanan and Phoenix plates continued until around 200Ma (Figure 8, Inset B).

During this period, the break with Laurasia continued and a second split in the plates occurred around 200Ma (Matthews et al., 2016). These movements marked the beginning of the break-up of Gondwana.

THE NEW ENGLAND OROGEN - >175 MY OF CYCLIC COMPRESSION AND EXTENSION

Summary of current status of knowledge

U-Pb zircon dating has solved controversies about the Currabubula-Connors Arc and it is now accepted that it was semi-continuous along the length of the orogen, or at least along the part preserved in Australia. It was a continental arc, possibly Andean (Whetten, 1965; White, 1968), or analogous to the Indonesian arc (Jenkins et al., 2002).

With the advent of subduction rollback and rifting in the late Carboniferous to early Permian, the arc migrated eastwards and this appears to have occurred relatively quickly. Overlap in zircon ages from volcanism at the end of the Currabubula Arc, and S-type granites that formed in the new back-arc region, attests to rapid, less than 15 million years, reworking of accretionary complex sedimentary rocks, a fact emphasised by Jeon et al. (2012). This speed of burial resulted in fertile, hydrous sedimentary rocks being subjected to rapidly increasing temperatures, and thus primed for metamorphism and partial melting, initiating S-type granite petrogenesis.

With recent dating information, the Gympie Terrane is now generally accepted to be part of the new arc and it formed initially in an oceanic environment clear of continental influence. However continental sedimentation is seen in the younger strata of the terrane.

The Gympie Terrane was previously considered to be allochthonous to the NEO. However, the volcanic rocks and volcaniclastics of the Berserker Group have been accepted as part of the province. Yet they are attributed to a near-arc, back-arc environment and zircon dates indicate they formed at the same time (275 - 270Ma) as much of the Gympie Group. It is not improbable that these strata are part of an extension to the arc north of the Gympie Group.

At the other end of the orogen, the Currarong Arc is known from dating to have been active around 270 - 265Ma. The arc is thought to extend for at least 200km offshore giving it a strike length of more than 340km in this area. It is proposed here that the Gympie and Currarong Arcs are part of the same system, the Gympie-Currarong Arc.

In between these remnants of the Rift-Relax phase arc, oroclinal bending took place in the SNEO. Where volcanism was focused (if anywhere) in this zone is not known. A closer study of the Drake Volcanics and Barrington Tops plutons which have dates corresponding to this period may be fruitful.

The main focus of rifting also appears to have moved progressively eastwards during the Rift-Relax phase, starting in the core of the Carboniferous arc to create the originally extensive Sydney-Gunnedah-Bowen Basin backarc system at ~ 300Ma, a final pulse around 270Ma is indicated in the immediate back-arc to the Gympie-Currarong Arc, as evidenced by bimodal magmatic activity north-east of the Esk Trough, in the Gladstone-Monto-Bundaberg belt (Figure 7, inset B) (Carson et al., 2006) and a corresponding parallel band of high-temperature—low-pressure metamorphism thought to be related to extension (Jessop, 2017).

With compression associated with the Hunter-Bowen Orogeny the arc again migrated westwards, to a belt well east of the older Currabubula-Connors Arc in the SNEO but overlapping it in the north (Figures 5 & 7).

Triassic extension saw the arc again migrate off the present coastline. Triassic plutonic rocks and volcanic rocks that outcrop within the NEO are all considered to be of back-arc affinity and are all older than 210Ma. Only one Jurassic date has been obtained in the NEO and that is from a trachyte east of Rockhampton. This date has puzzled researchers as no other magmatism of this age is known (Murray et al., 2012). Cretaceous volcanism (137—109Ma) has been recorded west of Rockhampton and Cretaceous plutons (142—117Ma) outcrop between Bowen and the Stanage Peninsula with a small group just north of Gympie. These are the only remnants of subsequent tectonic cycles recorded on the mainland and again reinforce the expansion-contraction differences between the NNEO and SNEO.

There is significant overprinting of orogenic phases in the NNEO that is not seen in the south. These differences in the pattern of extension are echoed in the location and timing of metamorphism within the orogen (Jessop, 2017).

Significant differences between the NNEO and SNEO are also found in the metallogenesis of the province. Blevin (2010) has noted a distinctive Sn-W-Mo dominated granite metallogeny in the SNEO and Cu-Mo-Au dominated metallogeny in the NNEO.

Zircon Data

Figure 9 is a compilation of all U-Pb zircon data for the New England Orogen and Kennedy Igneous Association grouped by 5 million year bins. Subject to sampling bias mentioned previously (Permo-Carboniferous boundary, Permo-Triassic boundary etc.), peaks in zircon ages generally reflect the fluctuating magmatism in the orogen.

With possible differences in crustal composition between the NNEO and SNEO, it is interesting to consider the patterns of zircon inheritance in igneous rocks of the orogen. Again, keeping in mind possible sampling bias, Figures 10E and 10F show all current volcanic and plutonic sourced zircon inheritance data for the NEO (the Kennedy Igneous Association is excluded). Zircons of Proterozoic age appear to be more prolific in igneous rocks from the NNEO, but not significantly so. Plutons and volcanic rocks in the SNEO have also tapped a source of Neo- to Meso- Proterozoic zircons.

The dominating role of the Currabubula-Connors Arc in providing the foundation for the NEO is reflected in the predominance of inherited zircons from this period.

Cycles of compression and extension

Similar to previous cycles within the Tasmanides (Collins, 2002a; 2002b; Glen, 2013; Rosenbaum, 2018), subduction on the eastern margin of Gondwana continued to fluctuate between advance and rollback in the New England Orogen. The Currabubula-Connors Arc was a time of stable moderate compression that lasted for at least 65my (~375-~305Ma). The following East Australian Rift phase of major extension and thermal relaxation lasted for approximately 40my (~305-~265Ma). Cycles shortened with the strong compression of the Hunter-Bowen Orogeny and Arc, ~35my (~265-230Ma) and the subsequent Late Triassic extension, ~30my (~230-~200Ma?).

Figure 11 is a compilation of all available Hafnium isotope data from zircons sourced from within the New England Orogen, or from sedimentary basins containing tuffs sourced from NEO volcanism. The cyclic patterns of compression and extension in the orogen are reflected by cycles of increasing and decreasing εHf in zircons. During the Currabubula-Connors arc phase, magmatism was increasingly contaminated with, or sourced from, crustal material, with time, while the reverse is evident during the Rift and Thermal Relaxation phases. With extension and crustal thinning, magmas contained increasingly juvenile material. Crustal input is also indicated during the Hunter-Bowen Arc. However, the relatively short-lived nature of this arc precluded the level of recycling of crustal rocks evident during the Carboniferous Arc phase. Not enough data is available to clearly show the effects of the Triassic extension, highlighting the need for more research on these rocks, although, younger zircons from the Eromanga Basin (Tucker et al., 2016) hint at this change.

Deformation differences in timing and style: North and South

Differences in the tectonics of the NNEO and SNEO have been obvious since the early days of geological mapping of the region. Superficially, compression and extension in the NNEO are relatively balanced and zones of igneous activity have moved only marginally east-west, often overlapping each other.

In contrast, in the SNEO extension has exceeded compression and magmatic zones have only marginal overlap and usually form distinct belts (Figures 3 to 8).

The present crustal architecture revealed by seismic lines (Korsch et al. 1997) differs from north to south along the orogen. Korsch describes the far northern end of the orogen as dominated by east dipping structures with the NEO thrust over the Thomson Orogen. In the NSW-Qld border area, gently west dipping structures dominate in the lower crust with east-dipping thrusts in the upper crust. The SNEO is characterised by both east and west dipping structures. In the latter two areas, the Carboniferous accretionary wedge is thrust beneath the Lachlan Orogen, but the forearc basin is obducted over the Lachlan, resulting in part in a doubly vergent structure.

Recent interpretation of ambient noise data from the WOMBAT portable seismic array, deployed over the south-eastern corner of Australia, indicates an easterly trending finger of high velocity crust, protruding into the NEO at the same latitude as the oroclines. It has been interpreted as Proterozoic basement and possibly an indenter block (Rawlinson, Pilia, Young, Salmon & Yang, 2016). This is at the northern limit of the array and it is possible that further high velocity material will be revealed as the array is deployed further north.

THE END OF THE NEO VERSUS THE END OF THE TASMANIDES?

Gondwana continued to break apart after the phase of Triassic extension discussed here. Australia and New Zealand broke with Antarctica at around 160Ma and Australia and New Zealand separated plates at ~125Ma. This was followed at ~80Ma by the start of rifting that created the Tasman Sea (Matthews et al. 2016).

The Tasmanides, as part of the Gondwanides of eastern Gondwana, thus ceased around 160Ma, but subduction along the eastern margin of the Australian plate continued. Tucker et al. (2016) found evidence from a study of detrital zircons in the Eromanga Basin that volcanism persisted offshore of the present coast of Qld until opening of the Tasman Sea commenced. It would thus appear that further cycles of compression and extension continued until this time.

As well as creating the Tasman Sea, Cretaceous rifting split the New England Orogen and transported possibly some Carboniferous, some Permo-Triassic, and all post-Triassic elements of the province offshore. Remnants are believed to be distributed throughout the Tasman Sea, including to the north, the offshore Queensland Plateau to Papua New Guinea (Glen, 2013; Mortimer et al., 2008; Shaanan, Rosenbaum, Hoy, & Mortimer, 2018). To the south, the Dampier Ridge, Lord Howe Rise, New Caledonia and New Zealand are considered to contain rifted fragments of the orogen (Harrington, 1983, 2008; Korsch et al., 2009b; Mortimer, 2004; Waterhouse & Sivell, 1987) (Figure 1 - Inset A).

The Tasmanides of eastern Australia ended with opening of the Tasman Sea and theoretically, since the NEO is described as the youngest of the Tasmanides, it also should end at the same time. However, it is generally accepted, that the New England Orogen ended with the Triassic extension (e.g. Adams, Campbell, & Griffin, 2009) and post Triassic elements are considered to be part of another Tasmanide orogen that includes the Rakaia, Waipapa, Maitai, Caples and Murihiku terranes of New Zealand and parts of New Caledonia. This orogen is yet to be formally defined and named. When it is, it will relegate the NEO to the second youngest orogen of the Tasmanides.

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