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Accordion vs. quantum tectonics: insights into continental growth processes from the Paleozoic of eastern Gondwanan

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Keywords
growth, continental, into, insights, tectonics, quantum, gondwanan, vs, eastern, accordion, paleozoic, processes, GeoQUEST

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GR Letter

Accordion vs. quantum tectonics: insights into continental growth processes from the Paleozoic of eastern Gondwana

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Abstract

The Early Paleozoic Lachlan Fold Belt of eastern Australia is widely regarded as an ancient convergent plate margin beneath which paleo-Pacific (Panthalassic) oceanic lithosphere was continuously subducted. It is cited as the type example of a retreating accretionary orogeny. However, sandstone compositions, the sedimentological nature and timing of chert accumulation and overall stratigraphic architecture are not necessarily consistent with this model. We suggest an alternative explanation for growth of Gondwanan continental margin. Oceanic lithosphere outboard of the passive Gondwana continental margin was subducted beneath an extensive intra-oceanic island arc that now crops out as an allochthonous element (Macquarie arc) within the fold belt. Once intervening oceanic lithosphere was eliminated this arc collided with and was emplaced upon the Gondwana margin. Recognition of four such events along this margin through the Phanerozoic suggests it is a significant mechanism for continental growth.

Keywords: continental growth; arc collision; passive margin; Gondwana; Paleozoic

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1. Introduction

Since the advent of plate tectonic theory, eastern Australia has been viewed as an ancient convergent plate margin beneath which paleo-Pacific (Panthalassic) oceanic lithosphere was continuously subducted. Evolution of the Terra Australis orogen (Cawood, 2005) is explained as a consequence of accordion-style back arc extensional events interspersed with transitory periods of compression associated with coupling between subducting and over-riding plates. The Early Paleozoic Lachlan Fold Belt of eastern Australia (Glen, 2005) is regarded as the type example of an "extensional accretionary orogen" (Cawood et al., 2009; Collins, 2002). Such systems are considered to have always faced an ocean (Cawood et al., 2011) and thus not to have formed by orogenesis following Wilson Cycle-style ocean closure culminating in continent-continent collision. Their entire development is regarded to have occurred on the upper (continental) plate of a convergent margin. In the accretionary orogen model, large-scale slab retreat along a continental convergent plate margin generates widespread extension with attendant rifting and back-arc development. Extensional episodes are punctuated by short-lived orogenic contractional events. Closure of an extensive back-arc basin is associated with subduction of buoyant oceanic lithosphere and transitory plate coupling, which results in the emplacement of the arc system back onto the continent from which it originated (Collins, 2002). Such systems are envisaged to grow through the off-scraping and addition of material from the down-going slab into subduction complexes. Abundant modern examples rim the Pacific with the Lachlan Fold Belt being considered a typical representative of the final product of such a system (Cawood et al., 2009; Collins, 2002).

During the Early Paleozoic, extensional episodes followed by contraction associated with plate coupling are inferred to have occurred along eastern Gondwana (Australia) culminating at the end of both the Cambrian and Ordovician. The existing model potentially explains the presence of exotic intra-oceanic features such as the Ordovician Macquarie island arc (Glen et al., 2007a; Glen et al., 1998; Percival and Glen, 2007) amongst rock successions, which otherwise exhibit unambiguously continental characteristics (Figure 1).

Whether this style of "accordion tectonics" affected development of the Lachlan Fold Belt or not is a matter we address in this paper. From literature review and personal field observations, we conclude that numerous aspects of the observed geology appear to be incompatible with the existing model. Geological evidence, such as the overwhelming dominance of super-mature quartz arenites in the detrital sedimentary record both in- and out-board of coeval mafic to intermediate intra-oceanic volcanic arc rocks combined with the absence of any arc-trench polarity across the system, represent marked departures from what is observed on modern accretionary margins (Isozaki et al., 2010). The preponderance of quartzites suggests that throughout the Ordovician *in situ* elements of eastern Gondwana developed as part of a passive continental margin situated in a lower rather than upper plate setting. Discriminations between autochthonous and allochthonous components of the Lachlan Fold Belt are here reinterpreted. Distinctive, coeval yet incompatible, tectonic elements likely developed in isolation from one another. As such, unique explanations are required for the evolution of each element, as well as, a model that deals with the manner of their juxtaposition.

We advance a new hypothesis in which Ordovician geology of eastern Australia is explained by an alternative model. Subduction of oceanic lithosphere, lying outboard of a passive continental margin, beneath a west-facing intra-oceanic island arc eventually resulted in collision of this offshore arc with Gondwana. Late Ordovician collision and continent directed obduction of the Macquarie arc initiated the regional Benambran Orogeny. We also suggest that a series of such collision and subduction-flip events, rather than extension followed by plate-coupling, has played a fundamental role in the stepwise growth of the Gondwana margin. The quantum addition of juvenile, island-arc material to continental margins is the major contributor to the stepwise episodic growth of continental crust along so-called accretionary orogens.

2. Regional geological setting

Autochthonous Ordovician rocks of eastern Australia are characterised by a marine sedimentary succession of highly quartzose turbiditic sandstones succeeded by siltstones with regional intercalations of coeval horizons of ribbon-bedded grey cherts (Percival et al., 2011). Shallow water rocks occur in the far west with an extensive overall seaward-deepening miogeoclinal prism represented by the Ordovician 'mud-pile' (Coney, 1992) across Victoria and New South Wales. The dominance of super-mature sediments and wedge geometry point to interpretation as a passive continental margin (Bradley, 2008). This originally thin but regionally extensive succession has subsequently been structurally thickened by widespread isoclinal folding and imbricate thrust faulting (Fergusson, 2003; Glen et al., 2009).

Arc volcanic rocks of Late Ordovician age crop out extensively between central and eastern zones of the Lachlan Fold Belt and are allochthonous with regards to other lithologies. Geochemistry indicates that these rocks, the Macquarie arc, formed in an intra-oceanic island arc setting (Glen et al., 2007a; Glen et al., 2011; Glen et al., 1998) away from any influence of pre-existing continental crust. They are strikingly different to coeval elements of the fold belt against which their contacts are always faulted. Rocks autochthonous to the Gondwana margin occur both west and east of the Macquarie arc, which we regard as having been emplaced over the *in situ* passive margin succession as a regional-scale nappe. The Gilmore suture (Scheibner, 1985) delineates the western limit of this allochthonous island arc terrane.

Portions of the Lachlan Fold Belt are well exposed along the south coast of New South Wales. They include structural repetitions of a basalt/chert/turbidite sequence (Glen et al., 2004) and are locally associated with zones of mud-matrix mélange (Fergusson and Frikken, 2003; Miller and Gray, 1996). This, combined with their location oceanward of Ordovician island arc-related volcanics, has led some researchers to suggest the succession is reminiscent of an ocean plate stratigraphy (Isozaki et al., 1990). Hence, eastern portions of the fold belt have been interpreted as an accretionary complex, the growth of which was inferred to have been associated with a west-dipping subduction zone beneath the Macquarie arc (Gray and Foster, 2004).

Sections are well-exposed on coastal headlands near the township of Narooma where pillow basalts are overlain by an Ordovician sequence comprising thinly bedded chert succeeded by siltstones that are transitional into quartzose turbidites (Glen et al., 2004). Outwardly similar successions in accretionary orogens worldwide are commonly regarded as representative of an ocean plate stratigraphy (Maruyama et al., 2010). Alternatively, this succession is controversially interpreted to represent an exotic accreted seamount (Fergusson et al., 2005; Glen et al., 2004). In either interpretation, these rocks are interpreted to have originated on an oceanic plate and to have later been transferred to the Gondwana margin.

3. Comparison with well-studied subduction complexes

Although large-scale geological similarities to well-studied subduction complexes (e.g. Isozaki et al., 2010) exist, subtle, yet important, departures from the detail in successions predicted by the accretionary orogen model are readily observed. Whereas accretionary complexes develop exclusively on the trenchward side of modern arc systems above the Wadati-Benioff zone, in notable contrast, the inferred ocean plate succession in the Lachlan Fold Belt occurs either side of the Macquarie arc.

3.1 Overall stratigraphy vs. ocean plate stratigraphy

A fundamental observation from convergent plate margins is that they exhibit a distinctive lithostratigraphic architecture (Coleman, 1975), which is repeated in a series of thrust slices that become younger trenchward. In classic examples such as the Late Mesozoic-Cenozoic of SW Japan (Isozaki et al., 1990), beneath which Pacific ocean crust has been subducted, chert of a hypothetical ocean plate stratigraphy is typically confined to an interval immediately overlying basaltic basement. The chert is, in turn, succeeded by a coarsening and thickening upwards succession of tuffaceous cherts followed by trench-fill turbidites. In individual tectonic slices the internal stratigraphy becomes younger towards the arc but across the accretionary complex there is a progressive trenchward-younging of the ocean plate stratigraphy (Figure 2).

The Lachlan Fold Belt certainly contains numerous thrust slices that repeat a ubiquitous stratigraphic motif. However, rather than exhibiting an overall younging polarity, structural repetitions exhibit remarkable internal consistency with chert restricted to discrete temporal intervals (Glen et al., 2009). Occurrences of chert horizons can be correlated across the fold belt either side of the Macquarie arc (Percival, 2012; Percival et al., 2011). Notably, the cherts are restricted to discrete lower and upper horizons, the ages of which are coeval amongst tectonic slices. This consistent match between litho- and chrono-stratigraphies lies in distinct contrast to the time-transgressive nature of the ocean plate stratigraphy observed worldwide in accretionary complexes. An additional contrast with the idealised ocean plate stratigraphy and the Lachlan Fold Belt succession is that while the former coarsens up-section and culminates in turbidites, this is not the case in the Lachlan Fold Belt where finer-grained sediments such as shales typically succeed quartzose turbidites of the Adaminaby Group (Percival et al., 2011).

3.2 Nature of cherts

Whilst chert is a common lithology in subduction complexes, many varieties exist and by itself chert is not necessarily diagnostic of any particular tectonic setting (Jones and Murchey, 1986). The presence of radiolarian chert simply indicates an interval of pelagic sedimentation in which the accumulation of organisms with siliceous skeletons predominated. Although some cherts in the fold belt overlie pillow basalts, there is no *a priori* reason requiring either an oceanic-island or mid-ocean ridge basalt setting. Intraplate pillow basalts are well known from continental shelves on passive margins (Smith and Lewis, 2007). On closer examination, where fresh, most of the Lachlan cherts are black and/or grey. They are locally bioturbated and contain a fauna that includes radiolarians together with sponge spicules, lingulide and acrotretide brachiopods, fragmentary graptolites, and rare filaments attributed to cyanobacteria (Percival, 2012). As such, they differ markedly from coeval red ribbon-bedded radiolarian-rich varieties of chert typical of subduction complexes such as the Djungati terrane in the New England Fold Belt in northeast NSW (Aitchison and Flood, 1990). Co-occurrences of black organic-rich chert, shales and quartzites are known from miogeoclinal successions documented elsewhere such as the Paleozoic of western North America (Orodvician Valmy Formation of the Roberts Mountain Allochthon in Nevada; Turner et al., 1989). The Lachlan Fold Belt chert, quartzose sandstone, siltstone stratigraphy is also reminiscent of Tethyan passive margin successions such as those seen south of the Indus-Yarlung Tsangpo suture zone in NW India and Tibet. The Karamba Formation in NW India (Robertson and Sharp, 1998) contains quartzites and radiolarian chert horizons as well as local occurrences of alkaline basaltic rocks. It is tightly folded and structurally imbricated in a manner analogous to the Ordovician of the Lachlan Fold Belt. A similar passive continental margin succession extends along the former southern margin of Tethys from the Himalaya to the Mediterranean (De Wever, 1989). Considered in the context of overall Ordovician stratigraphy, these cherts and the stratigraphic context in which they occur exhibit greater similarity to those of a continental margin chert association rather than any ophiolitic, seamount or island arc associations (Jones and Murchey, 1986). Furthermore, restriction of chert to particular stratigraphic intervals (predominantly Chewtonian or Darriwillian; Percival et al., 2011) across a regionally extensive area suggests some sort of paleoenvironmental control on the deposition of this pelagic material (De Wever et al., 2001). Although the ultimate repository of quartzose sands eroding off the Gondwana margin was to be on submarine fans at the base of the continental slope their passage may have been impeded by transgression and relative sea level high (Munnecke et al., 2010) that would have favoured pelagic deposition in areas starved of clastic input.

3.3 Sandstone petrography

Detrital-mode (QFL) compositions of clastic sandstones are widely regarded as diagnostic of tectonic setting (Dickinson and Suczek, 1979; Marsaglia and Ingersoll, 1992). Lower to Middle Ordovician sandstones are highly quartzose and contain minimal lithic detritus (Fergusson and Tye, 1999). Detrital (QFL) modes all plot within the recycled orogen field of Dickinson and Suczek (1979). Lachlan Fold Belt sandstones are thus enigmatic in the context of any subduction model. Where present, any lithic component is dominated by recycled sedimentary or metamorphic clasts, whereas clasts of volcanogenic origin and tuffs are absent. Published data contrast with what might be expected of trench-fill sediments off-scraped into an accretionary complex (Marsaglia and Ingersoll, 1992). Such highly mature sediment compositions typify modern passive plate margins devoid of volcanism where sediment transport pathways are long. This is further supported by the heavy mineral content which is dominated by the ultrastable minerals zircon and tourmaline (Fergusson and Tye, 1999). In comparison, sandstone compositions within convergent plate margin settings including backarc, and forearc basins, as well as, accretionary complexes, are dominated by arc-derived volcanic detritus (Marsaglia and Ingersoll, 1992). The only volcanogenic sandstones of Ordovician age reported are those associated with the allochthonous Macquarie arc (Colquhoun et al., 1999), which are everywhere in structural contact with quartzose Adaminaby Group turbidites (Meffre et al., 2007). Moreover, the accordion tectonic model requires an unlikely situation in which, Gondwana-derived, quartz-rich turbidites, originating from a shelf in the far west of the fold belt, first travelled into a proximal back arc basin, then across the Macquarie Arc edifice, onwards into the trench before finally spilling out onto a subducting ocean plate to be interbedded with basalts and cherts (Figure 3). It is not until the Silurian that arc-derived volcanogenic detritus begins to arrive in abundance across the fold belt (Barron et al., 2007). The quartzose Ordovician 'mud-pile' (Coney, 1992) of the Lachlan Fold Belt thus seems an exceptionally unlikely candidate for trench-fill sediment and interpretation as a passive margin succession is a better fit.

3.4 Mélange

Zones of broken formation and mélange are well developed and particularly well exposed along the New South Wales south coast. Their existence is interpreted to support models that invoke development of these rocks in a convergent plate margin setting as well as to infer subduction polarity (Fergusson, 2003; Fergusson and Frikken, 2003; Miller and Gray, 1996). As mélanges and/or broken formation are also present elsewhere across the fold belt (Watson and Gray, 2001) their occurrence is used as a basis to argue for the existence of multiple subduction zones (Soesoo et al., 1997). Whilst mélange is not uncommon in such settings, it is not necessarily exclusive to them (Festa et al., 2010). In areas such as Taiwan (Huang et al., 2008) and Timor (Barber et al., 1986; Harris et al., 1998; Keep and Haig, 2010) where mud diapirism is prevalent, it is commonly associated with the early stages of arc-continent collision where over-pressured, water-saturated, partially consolidated, sedimentary sequences of passive continental margins have begun descending into a trench associated with the collision of an island arc.

4. An alternative model

For the above stated reasons, we conclude that the Lachlan Fold Belt is unsuitable as a type example of the very orogenic system for which it has been proposed to best serve (Cawood et al., 2009). Thus, we propose an alternative model for its development. This model provides an explanation that is consistent with the allochthonous nature of the Macquarie arc relative to the continental margin while also explaining the highly quartzose compositions of Lachlan Fold Belt turbidites.

During Ordovician times the eastern margin of Gondwana (autochthonous succession) developed as a continental passive margin. As such, it was predisposed to a lower rather than upper plate setting. Mature quartzose sediment was shed eastwards from a deeply weathered continental landmass and deposited as a miogeoclinal wedge. Combinations of eustatic and oceanographic events likely controlled the exact nature of sedimentary lithologies. When sea level was relatively high, coarser quartzose sediments were sequestered along the coast and upwelling of silica-rich cold waters along the continental margin likely facilitated the development of radiolarites. During eustatic low intervals quartz sands were transported across the shelf and redeposited by turbidity currents. Local alkaline basaltic intraplate magmatism provides a smattering of pillow basalts through the succession.

Oceanic lithosphere that lay outboard of a passive margin along the Gondwana continent was subducted eastwards at a site of intra-oceanic plate convergence. In contrast to the scenario envisaged in the extensional accretionary orogen model, the (Macquarie) arc developed in an upper plate setting on a different plate outboard of, and tectonically above, the Gondwanan plate. When oceanic crust between this intra-oceanic arc and continent was entirely consumed by east-dipping subduction the Macquarie arc then collided and was emplaced (obducted) onto the leading edge of the Gondwanan margin that remained in the lower plate. The collision is recorded in the Benambran orogeny (Glen et al., 2007b). Notably, early structures associated with this orogeny are south- to southwest-verging (Collins and Hobbs, 2001) rather than east-verging as might be expected in the accretionary complex model. Areas such as the Wagga-Omeo metamorphic zone (Morand, 1990) and Cooma Complex (Johnson, 1999) SW of main occurrences of Macquarie arc rocks potentially represent different erosional levels in the collision system where complete removal of the over-riding arc has occurred. The restricted occurrences of blueschist-facies metamorphic blocks within zones of mélange (Spaggiari et al., 2002) to the west of the Macquarie arc hint at the former location of a trench.

Following collision of the arc, the polarity of subduction flipped in a manner similar to that observed today in the presently active arc-continent collision system of Taiwan. As a result, the continental margin succession of the Lachlan Fold Belt was thereby transferred to the upper plate complete with the now obducted Macquarie arc. As west-directed subduction of the Paleo-Pacific (Panthalassa) became established under the Gondwana plate margin in the Late Silurian to Middle Devonian, a major magmatic belt that manifests itself today in the I and S-type granites of Australia, developed (Chappell and White, 2001) and a new important phase in the evolution of Gondwana ensued.

In analogous modern systems such as Taiwan (Huang et al., 2008) and ancient analogues along the southern margin of Tethys in Ladakh (Corfield et al., 1999), Oman (Searle et al., 2004) and Cyprus (Robertson, 2004) or on the Kamchatka Peninsula in the NW Pacific (Hourigan et al., 2009), intra-oceanic island arcs are emplaced onto continental margins that have been drawn into intra-oceanic subduction systems by consumption of intervening oceanic crust. Notably in such settings, structural imbrication of the continental margin succession is widespread as is the development of mud-matrix mélange (Huang et al., 2008). Supra-subduction zone rocks in upper plate positions have over-ridden miogeoclines for a considerable distance (100's of km) such that their eroded remnants now lie 'inboard' of former continental passive margins. Relics of the obducted systems, including fragments of arcs commonly accompanied by ophiolites that are rootless and float above thrust-sheets marked by widespread mud-matrix mélange, crop out both inboard and outboard of eroded remnants of the allochthonous sheet. Variations in the angle of incidence for plate convergence induces an oblique component of displacement and some elements of the arc may be further translated and shuffled along the plate margin as they collide (McCaffrey, 1992).

We suggest that iterative growth of eastern Gondwana through arc-continent collisions provides a better explanation for recorded orogenic events. Australia records several such events in Archean through Proterozoic time (Korsch et al., 2011) and at least four such events may have occurred during the Phanerozoic evolution of eastern Australia. They are potentially important in explaining the Cambrian (Delamerian – Tyennan –Ross orogenies of western Victoria, Tasmania and North Victoria Land in Antarctica respectively (Gibson et al., 2011; Greenfield et al., 2011; Meffre et al., 2000), Late Ordovician (Benambran orogeny – Macquarie arc – this paper), Late Devonian (Kanimblan orogeny – Gamilaroi arc in New England region of New South Wales (Aitchison and Flood, 1994)) and Permo-Triassic (Hunter-Bowen orogeny – Gympie – Koh – Brook Street arcs in Queensland, New Caledonia and New Zealand respectively (Meffre et al., 1996)).

Our alternative model envisages arc-continent collision events (quantum tectonics) as a primary means of large-scale continental growth. Although individual events may be short-lived and commonly leave but a cryptic record (Dewey, 2005) their significance in the construction of orogenic systems should not be under-estimated. Tectonic transfer of primitive island arc rocks from one plate to another, whereby they constitute quantum additions to a continental margin (Figure 4), represents a first order contributor to the growth of continental crust globally.

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Figure Captions

Figure 1. Distribution of key elements of Ordovician geology of the Lachlan Fold Belt in New South Wales and Victoria, eastern Australia (after Glen et al., 2009). Note how coeval correlative zones of highly quartzose sedimentary rocks of continental derivation (Adaminaby Group) flank intra-oceanic mafic rocks of the Macquarie island arc. GS = Gilmore suture.

Figure 2. Cartoons to illustrate the nature of the ocean plate stratigraphy, its evolution through time, and the progression within this sequence that might be expected to be preserved in an accretionary wedge (Isozaki et al., 1990). Contrast this with the Lachlan Fold Belt succession in which discrete upper and lower chert horizons occur (Glen et al., 2009) and between which quartzose turbidites are preserved. Unlike an ocean plate stratigraphy the Lachlan Fold Belt succession fines-upward with quartzose turbidites succeeded by shales and mudstones. Note also the differences in detrital sandstone compositions reported from the fold belt compared with those of typical accretionary complexes found globally (Colquhoun et al., 1999; Dickinson and Suczek, 1979; Marsaglia and Ingersoll, 1992)

Figure 3. Geodynamic models proposed to illustrate sequential development of elements of the Lachlan Fold Belt during the Ordovician. On the left side of the diagram the existing accretionary orogen model envisages the Macquarie arc originating on the same plate as quartzose sediments of the Lachlan Fold Belt with the gap between continent and arc closing through plate-coupling possibly associated with accretion of elements of the Narooma terrane. Note how, during the Ordovician, turbidity currents transporting quartzose sediments derived from the continental margin seemingly defy gravity to flow across ridges and trenches. The right hand side of the diagram is our preferred arc-continent collision model in which the Macquarie island arc originates on a plate offshore from eastern Australia. It is transferred to the Gondwanan plate as a result of subduction flip resulting from jamming of the subduction channel after the leading edge of the continental margin (lower plate) enters the trench in the Late Ordovician. The diagrams are not drawn to scale and no vertical/horizontal aspect ratio is implied.

Figure 4. Cartoon illustrating the differences between the existing ‘accordion-style’ model for an accretionary orogen (Cawood et al., 2009; Collins, 2002) and the ‘quantum tectonics’ model for continental growth proposed in this paper.

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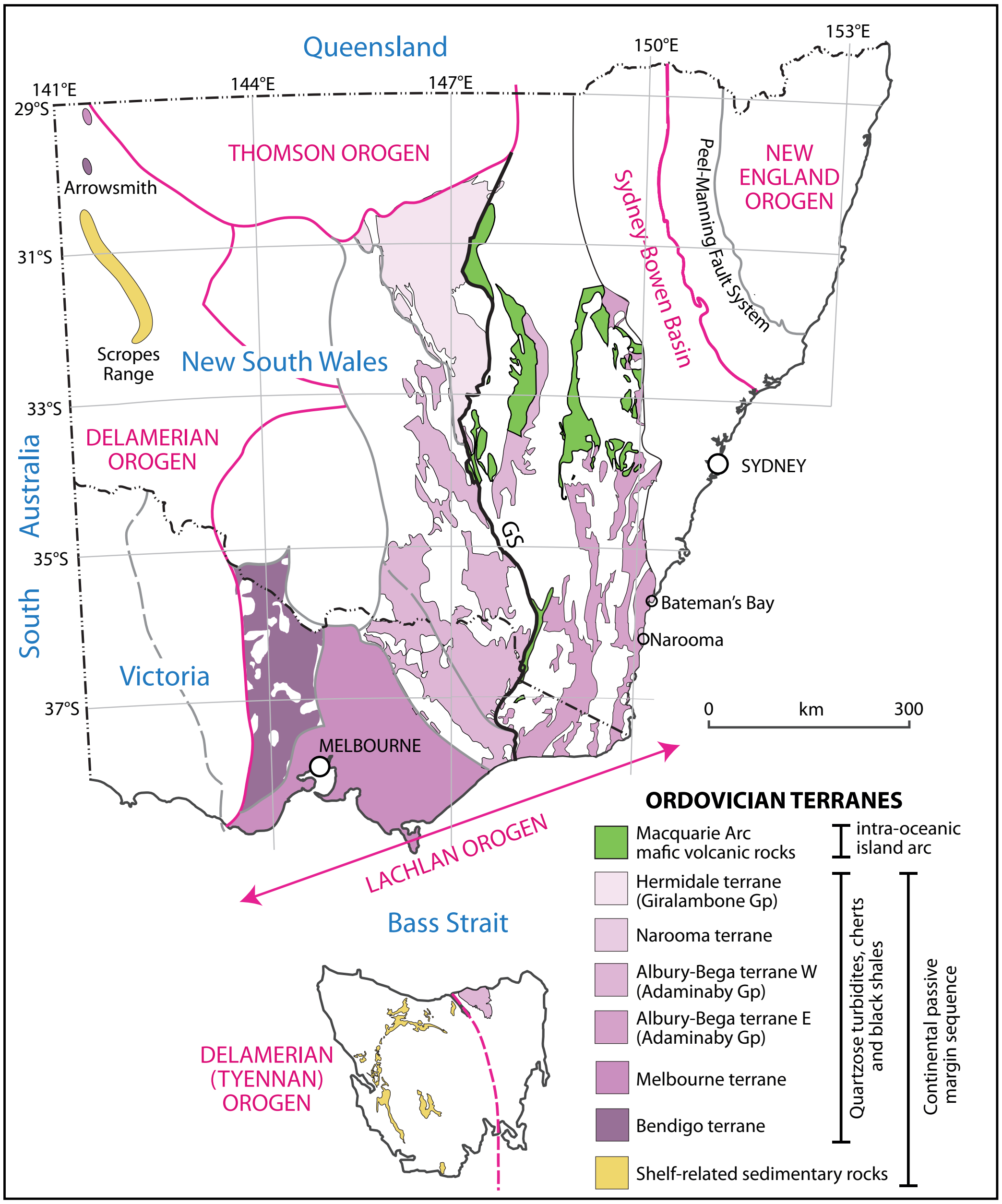
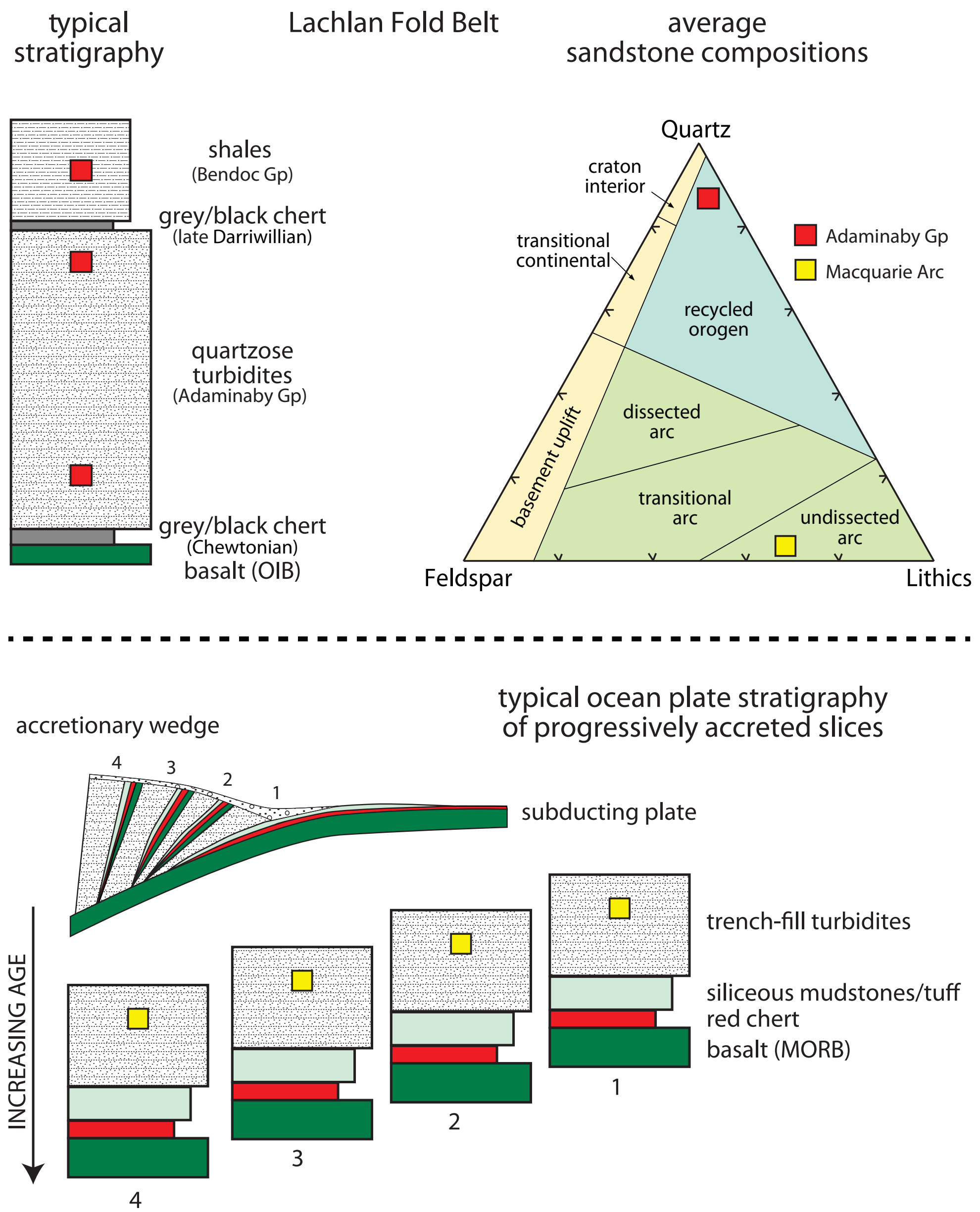
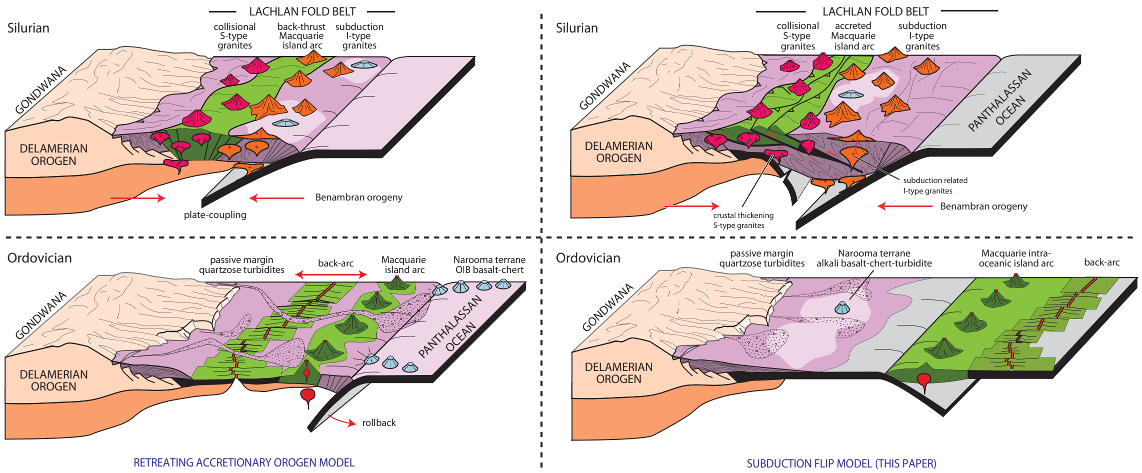


Aitchison and Buckman Figure 1

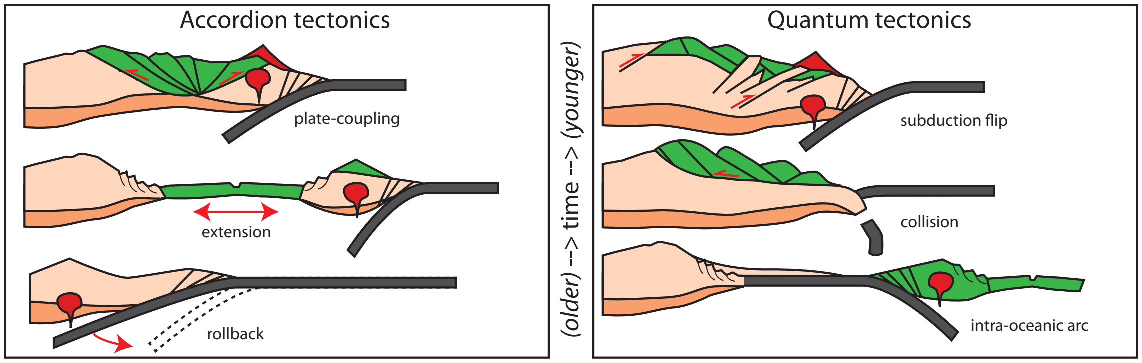


Aitchison and Buckman Figure 2



Aitchison and Buckman Figure 3

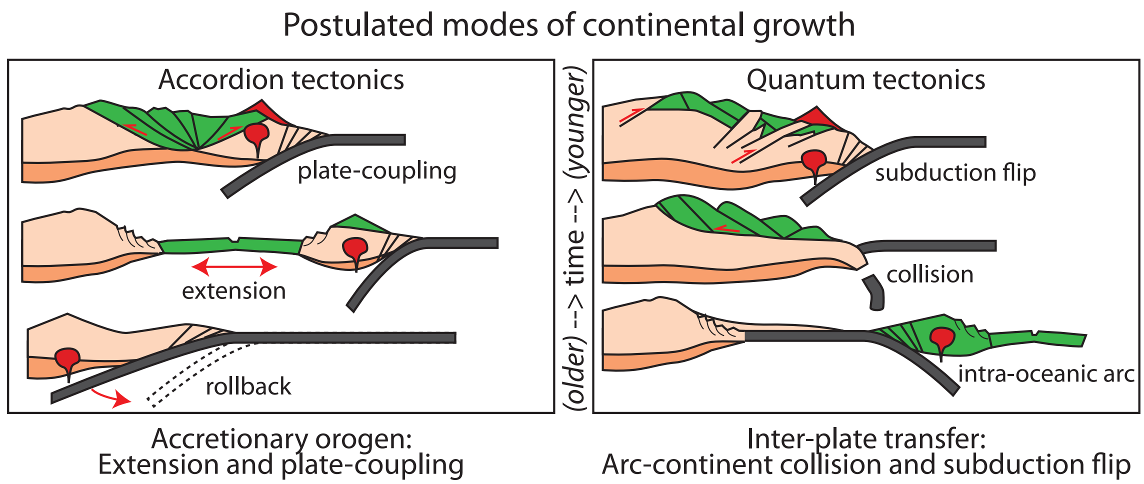
Postulated modes of continental growth



Accretionary orogen:
Extension and plate-coupling

Inter-plate transfer:
Arc-continent collision and subduction flip

Aitchison and Buckman Figure 4



Graphical abstract

Highlights

- Exemplar for accretionary orogen model reinterpreted
- Continental growth is facilitated by collisions of offshore island arcs
- Portions of intra-oceanic arc transferred to continental plate
- Evidence for four such events along eastern Gondwana during Phanerozoic