THE PERMO-TRIASSIC GONDWANIAN FOLD BELT

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Summary

The Permo-Triassic Gondwanian fold belt of South America, South Africa, and Antarctica forms one of the most significant geological lineaments in the Southern Hemisphere. Prior to supercontinent break-up, the various segments of the Gondwanian fold belt formed a continuous orogenic belt composed of low grade, folded and thrusted Palaeozoic sedimentary rocks, lying inboard of the SW margin of Gondwana.

Geodynamic models for the Gondwanian orogeny vary from collisional to Andean margin in style. The current consensus of opinion suggests that the Gondwanian fold belt represents compressional back-arc deformation related to an Andean type magmatic arc that developed along the southern margin of Gondwana. The extreme width of the orogen (locally up to 1000 km from the margin), and the presence of dextral transpressive deformation in Antarctica and South America was probably the result of oblique, flat slab subduction.

Formation of the Gondwanian orogen was closely followed by the initiation of Gondwana break-up in the Early Jurassic, with initial fragmentation centred in the proto-South Atlantic region. This lead to the generation, rotation and displacement of allochthonous crustal blocks (Falkland Islands and Ellsworth Mountains) by a yet to be established mechanism. It is possible that the evolution of the Gondwanian orogen and the break-up of Gondwana maybe tectonically linked. Available data appear to support a recently proposed plume-modified orogenic model for the Gondwanian fold belt, accounting for many of its significant geological features, and close temporal relationship of orogenesis and Gondwana break-up.

Introduction

Five fragments of the Gondwanian fold belt, dispersed during Gondwana break-up, are recognised: two reside in Antarctica (Ellsworth and Pensacola mountains), a further two in southern South America (Sierras Australes and Falkland/Malvinas Islands), while the final and best known example, the Cape fold belt, is in South Africa. The Gondwanian fold belt has had important historical and recent roles in the development of Gondwana reconstruction and break-up models. Indeed, the close temporal and spatial relationship between the termination of Gondwanide deformation and the onset of Gondwana break-up suggests that the two events may have been linked by a singular tectonic mechanism. In the light of recent models for plume-modified orogenesis (Dalziel *et al.,* 1999) we review its applicability as a model for the formation and ultimate destruction of the Gondwanian orogen.

Fold belt fragments:

The dispersed fragments of the Gondwanian fold belt once formed part of an extensive system of Palaeozoic age, siliciclastic basins flanking the southwestern margin of Gondwana. As a result, the lithostratigraphy of the individual fold belt segments is similar, being dominated by Ordovician to Carboniferous quartzite and sandstone followed by Permo-Carboniferous glaciogenic deposits. In all fragments, the stratigraphic successions have been intensely deformed at low metamorphic grades during Permo-Triassic times.

The Ellsworth Mountains of West Antarctica form part of the allochthonous Ellswoth-Whitmore mountains crustal block (EWM), which was tectonically rotated ~90° during the break-up of Gondwana. The mountains expose a 13km thick stratigraphic succession spanning Early(?) Cambrian to Permian times (Webers *et al.*, 1992). The stratigraphic succession experienced low-grade burial metamorphism, prior to intense deformation during the Permo-Triassic by two phases of Gondwanian deformation, the latter and most intense event being of a dextral transpressive nature (Curtis, 1998). Provenance studies of the Permian age Polarstar Formation indicate a dissected arc source. Small, scattered nunataks provide limited evidence for the existence of similar Palaeozoic age, deformed, siliciclastic sediments across the EWM crustal block, which exhibit a structural grain predominantly parallel to that in the Ellsworth Mountains.

In the Pensacola Mountains of East Antarctica, Cambrian age sedimentary and volcanic rocks, deformed during the Cambro-Ordovician Ross orogeny, are unconformably overlain by a post orogenic Palaeozoic siliciclastic succession capped by a Permo-Carboniferous glaciogenic sequence (Storey *et al.*, 1996). The subsequent deformation associated with the Gondwanian orogeny produced large-scale, open to close folds possessing a strong cleavage.

The Falkland / Malvinas Islands (FI), like the EWM, form part of a small, rotated (~180°) crustal block. The Islands expose an Ordovician (?) to Permian age sedimentary succession that lies unconformably upon a 1.1Ga crystalline basement. Gondwanian deformation of the cover sequence produced an E-W trending, southerly verging, fold and thrust belt, displaying a distinct deformation front which bounds a weakly deformed Permian sedimentary basin to the south (Curtis & Hyam, 1998). Gondwanian deformation coincides with an inversion of palaeocurrent directions from southerly derived Palaeozoic sediments with a continental source (M.A. Hunter pers. comm. 2000) to northerly derived Permian sandstones sourced by contemporaneous andesitic volcanics (D.I.M. Macdonald, pers. comm. 1999).

A second period of deformation produced a large-scale fold, sub-orthogonal to the E-W trending Gondwanian structures, due to the reactivation of an inferred basement fault, causing uplift of West Falkland relative to East Falkland, prior to intrusion of a suite of 190 Ma dolerite dykes (Curtis & Hyam, 1998). This D_2 event is related to early Gondwana break-up tectonics.

The Cape belt belt (CFB) shares a strong similarity both stratigraphically and structurally to the FI. The majority of the fold belt strikes approximately E-W, with the low to unmetamorphosed Palaeozoic sedimentary succession folded and thrust toward the north and the adjacent Permian Karoo (foreland) basin. Radiometric ages between 294 and 239 Ma are interpreted as episodic pulses of fold belt deformation, although only a single penetrative regional cleavage is observed (Trouw & De Wit, 1999). The presence of a magmatic arc to the south of the CFB has been inferred from the general calc-alkaline geochemistry of intercalated tuffs and sandstone provenance studies (Johnson, 1991). Like the FI, the change from a continental sediment source to a magmatic arc source was coincident with an inversion of palaeocurrent directions from a northerly to southerly derivation.

The Cape syntaxis defines an almost 90° change in the structural grain of the CFB from the southern to western domain. Despite a recent oroclinal-bending model for the formation of the syntaxis (Johnston, *in press*), palaeomagnetic and structural evidence (Bachtadse *et al.*, 1987; De Beer, 1990) indicates that the western domain has not been rotated. A consensual mechanism for the development of the Cape syntaxis remains elusive, although the influence of basement structure may be important.

Northeastern Argentina provides scattered exposure of the Gondwanian orogen. Permian age Gondwanian deformation extends over a wide (~700km) belt, extending from the northeasterly Sierras Septentrionales, through the better known Sierras Australes fold and thrust belt, to the northern margin of the North Patagonian Massif (Rossello *et al.*, 1997). Throughout this belt a NW-SE to NNW-SSE structural grain is dominant, manifest as folded and thrust Palaeozoic siliciclastic succession that verges toward the NW. Across the entire 700 km Gondwanian belt deformation becomes more intense toward the SW (Rossello *et al.* 1997). K-Ar cleavage ages of 260-282 Ma and growth folds in the Tunas Formation (foreland basin fill), suggest contractional deformation occurred throughout the Permian Period. The presence of a dextral component of shear was noted across the entire Gondwanian belt and has been interpreted to be the result of dextral transpressive deformation (Rossello *et al.*, 1997).

Evidence for Permian magmatism is widespread. Syntectonic intrusion of the Sierra Grande Granite (261±5Ma) in the Northern Patagonian Massif, bentonite horizons in the syntectonic Tunas Formation, and magmatic-arc related rocks of the Choiyoi Group, are exposed while magmatic arc rocks inferred to the south of the Gondwanian deformation zone (López-Gamundí *et al.*, 1994).

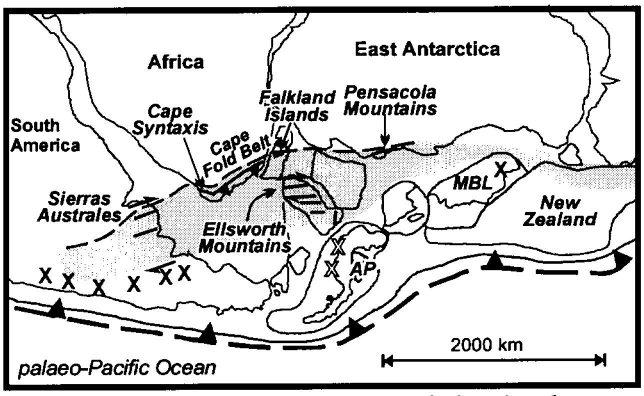

Figure 1: *Permian reconstruction of the Gondwanian orogen. AP-Antarctic Peninsular, MBL-Marie Byrd Land; Magmatic arc rocks: filled crosses – 275-250 Ma, open crosses – 220-200 Ma.*

Fold belt reconstructions

Reconstructions of the allochthonous FI and EWM crustal blocks have commonly been based on a simple realignment of the fold belt segments to form a linear orogenic belt. However, palaeogeographic evidence from the Early Palaeozoic (Curtis *et al.*, 1999) suggests that the EWM block was situated in an outboard position close to southern Africa (Figure 1). This reconstruction highlights the width of the known Gondwanian orogen.

Tectonic models

Both collisional and Andean-style tectonic models have been suggested to account for presence of the Gondwanian orogen. However, in a recent review Trouw & De Witt (1999) highlighted the absence of medium to high-grade metamorphic rocks and collision related igneous rocks, and no evidence for significant crustal thickening. Instead they favoured an Andean-type orogen.

In contrast, evidence for the presence of a Permian magmatic arc is relatively abundant. Arc related igneous rocks are present in South America (López-Gamundí *et al.*, 1994) and Antarctica (Pankhurst *et al.*, 1998; Wever *et al.*, 1994), whilst provenance studies of Permian foreland basin deposits together with intercalated tuff horizons, suggest an arc provenance to the south. As shown in figure 1, the Gondwanian orogen would have occupied a compressional back-arc position (e.g. Trouw & De Witt, 1999) with the extreme width of the deformation belt the likely result of flat slab subduction. The presence of dextral transpressive deformation in the fold belt segments of South America and Antarctica suggest that subduction was probably oblique, with the CFB representing a megascale left-stepping restraining bend (Johnson, 1999) in a back-arc region experiencing distributed dextral transpressive deformation.

Recently, Dalziel *et al.* (1999) suggested that the Gondwanian orogeny and subsequent break-up of Gondwana were tectonically related. In their model Dalziel *et al.* (1999) proposed that the trajectory of the subducting slab shallowed due to the buoyancy of a rising mantle plume beneath the subduction zone. Such a plume modified orogenic model (Murphy *et al.*, 1998) predicts important geological and temporal relationships:

1. A lack of syndeformation magmatism.
2. Wide zone of back-arc deformation migrating inboard.
3. Uplift, erosion, and plume related volcanic rocks

1. Magmatic arc rocks appear to form two temporal groups; Early Permian (275-250 ma) apparently punctuated by 30 Myr gap until Late Triassic (220-200 Ma).

2. The belt of back-arc deformation varies between 700 and as much as 1200 km, potentially narrowing east along the margin. If the Dalziel *et al.* (1999) model is correct, figure 1 predicts that deformation in the Ellsworth Mountains should pre-date that of the more external segments (e.g., CFB and FI). In the absence of widespread radiometric deformation ages an inboard migration of deformation is difficult to prove. However, in the EWM the Permian arc derived succession is intensely folded and cleaved, whereas, equivalent successions in CFB and FI represent a contemporaneous foreland basin succession, suggesting that deformation may have migrated through the Early Permian EWM retro-arc foreland basin.

3. Where geochronological data exists the termination of Gondwanian deformation appears to have occurred at the end of the Middle Triassic (~230 Ma). Recent stratigraphic analysis indicates that the Upper Karoo succession (post-230 Ma) was deposited in a basin controlled by regional continental extension, as opposed to the foreland basin setting of the Lower Karoo succession (Turner, 1999). This change in basin tectonics was accompanied by the

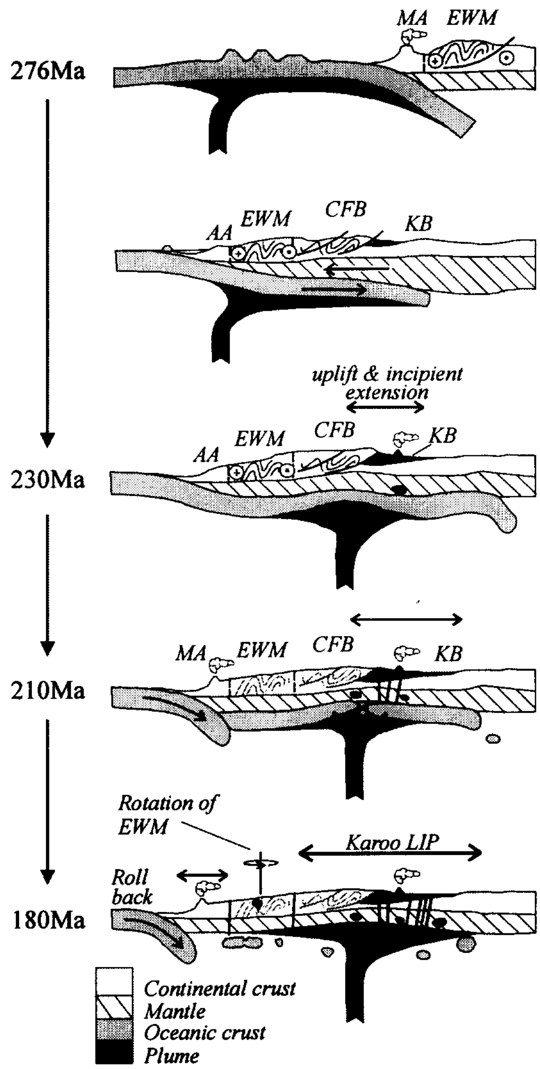

***Figure 2:** Schematic tectonic model for the SW margin of Gondwana. MA – magmatic arc; AA – amagmatic arc.*

deposition of volcanic detritus and later (~210 Ma) eruption of mafic lavas geochemically similar to the younger Karoo basalts. Furthermore provenance studies indicate the contemporaneous uplift of a new sediment source to the southeast of the Karoo basin. Turner (1999) has related this early Karoo-like volcanism, uplift, and extension to a plume. Uplift associated with this putative plume was aligned NE-SW parallel to the present day southeast coast of South Africa. Evidence for pre-190 Ma uplift along a NE-SW axis has also been documented in the FI, although the kinematic style does not immediately correlate with Turner's model.

In our view the available geological data provides credible support for a unified plume modified orogenic / break-up model. Figure 2 shows such a model for the SW margin of Gondwana. At 276 Ma subduction of ocean crust was ongoing at a normal slab angle, either in the absence of a plume or with the continental plate approaching a stationary plume. Between 270 and 230 Ma the plume is either overridden by the SW margin of Gondwana, or a mantle plume rises up beneath the subduction zone. The net result of either scenarios is that the slab angle flattens, thus inducing inboard migration of deformation in a compressional back-arc setting, resulting in a wide (700-1200 km) belt of deformation, and a shut off of arc magmatism. At 230 Ma uplift and extension associated with the thermal effects of the plume initiate extension and minor magmatism in the Karoo basin. Partial assimilation of the subducted slab closely follows (~210 Ma) resulting in the early mafic volcanism, and subduction is re-established at a normal slab dip. The latter causes renewed arc magmatism (e.g. Antarctic Peninsular). Slab assimilation completed, the plume head impacts causing major extension and rifting prior to initiation of break-up and voluminous eruption of the Karoo basalts.

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