PERGAMON

Journal of Structural Geology 22 (2000) 523–528

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

Character and kinematics of faults within the turbidite-dominated Lachlan Orogen: implications for tectonic evolution of eastern Australia: Discussion

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Received 6 April 1999; accepted 4 November 1999

1. Introduction

Having spent many years working in the western Lachlan, we explore some of the issues related to the tectonic evolution of this region. Gray and Foster (1998) argue that the geology of the western Lachlan suggests a subduction–accretion setting and present a tectonic model involving multiple subduction zones to illustrate the concept. They cite structural style and intermediate pressure metamorphism, including rare relics of transitional blueschist facies, as evidence of a subduction setting. All these features, however, are also consistent with the simpler interpretation of intraplate collapse of a marginal sea driven by outboard convergence.

We believe that it is premature to consider that the western Lachlan is a subduction–accretion complex without explaining why the rock record lacks the features typically associated with those processes. The nature of the western boundary 'backstop' of the accreted western Lachlan needs to be further clarified. Also their latest modified interpretation of their geochronological data, with episodic rather than continuous deformation (Foster et al., 1999), has important implications for their discussion of the tectonic evolution.

2. Subduction–accretion complex analogies

Gray and Foster (1998, p. 1692) argue that the western Lachlan is analogous to the Shimanto Complex of Japan and the Kodiak Complex of Alaska because of similarity of structural style and lithological association. We feel that the western Lachlan differs significantly from these accretionary complexes in that it lacks the features *diagnostic* of subduction–accretion. The vast expanse of monotonous, quartz-rich turbidites in the western Lachlan are more typical of a passive rather than a convergent margin (VandenBerg and Stewart, 1992). Also, there are no widespread zones of broken formation, disrupted units or melange that may involve sea-floor volcanics, limestone and chert to suggest the processes of offscraping or underplating as seen in the Shimanto and Kodiak complexes (Fisher and Byrne, 1987; Sample and Moore, 1987; Isozaki et al., 1990; Taira et al., 1992).

It is not surprising that the faults in the Lachlan turbidite pile have propagated differently from those in classic North American foreland fold-and-thrust belts (Gray and Foster, 1998, p. 1692) because favourable sites for detachments do not exist in the grossly homogeneous Lachlan stratigraphy (Gray and Willman, 1991). We note that the Taiwan slate belt, a foreland fold and thrust belt thrusting the passive margin sequences of China back towards that craton due to collision with the Luzon arc, has similar lithologies and structures to that of the western Lachlan (Davis et al., 1983; Tillman and Byrne, 1995).

In the subduction–accretion hypothesis, about 400 km of oceanic slab needs to be subducted westward as the engine driving the deformation of the Stawell and Bendigo zones (Gray and Foster, 1998, fig. 18). However, there is not a single magmatic product of the appropriate age (450–420 Ma) to account for the fate of the subducted slab. For the slab not to

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PII: S0191-8141(99)00171-6

have reached the depths from which melts are normally generated (~70–120 km) it must have been dipping at an anomalously low angle for the entire 30 my period of convergent deformation (only about 10–17°). Such anomalously shallow dips generally only occur when the transient ingestion of oceanic plateaus or ridges embedded in the subducting slab cause a localised (in time and space) gap to develop in the magmatic arc (McGeary et al., 1985). In the western Lachlan however, there is simply no arc for a gap to have developed within, therefore what mechanism are Gray and Foster (1998) invoking to explain the complete absence of a magmatic arc?

3. Backstop to the deforming wedge

We request further clarification of their concluding figure (Gray and Foster, 1998, fig. 18), which shows their proposed structural evolution of a deforming sedimentary wedge and its application to the Lachlan. In the initial stage the wedge appears to be developing in an intra-oceanic setting (fig. 18a). Sediments to the west of the subduction zone—which appear to be those in the vicinity of the 'Stawell–Ararat Fault Zone'—lie and continue to lie upon undeformed oceanic crust outside of the accretionary prism but then become structurally thickened and verge towards the subduction zone for unexplained reasons (fig. 18b–e). What is driving the east-vergent deformation of this upper crust shown west of the subduction zone?

Even if accepting subduction beneath the western Lachlan, then a backstop is necessary to initiate deformation of the sedimentary wedge—as discussed in the references on wedge tectonics they quote (Gray and Foster, 1998, p. 1717). Presumably this backstop is the continental craton of the Delamerian Fold Belt that was deformed into a mountain belt to the west of the Lachlan at 515–500 Ma to become the sediment source for the Lachlan wedge. Both sand-box (e.g. Wang and Davis, 1996) and numerical models (e.g. Willet et al., 1993) predict that convergence towards a backstop initially causes a doubly-vergent pop-up structure to develop (Fig. 1a), with a backstop directed retroshear (the Moyston Fault) developing *at the same time* as the seaward directed proshears in the wedge (e.g. the 'Stawell–Ararat Fault Zone').

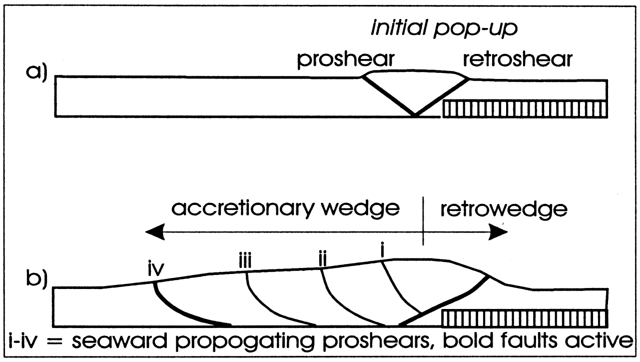

Fig. 1. Fault development in accretionary wedge models with (a) initial development of a doubly-vergent pop-up, (b) followed by development of seaward-propagating prosheats, which often become transported through the retrowedge (figure adapted from fig. 3 of Wang and Davis, 1996).

This is especially the case for the commonplace type-1 backstops (see Byrne et al., 1993), which is the geometry documented by deep seismic profiling across the Moyston Fault (Korsch et al., 1999) with the Delamerian Fold Belt 'backstop' seen wedging eastwards beneath the Lachlan Fold Belt 'accretionary prism'. As convergence continues with time, proshears within the accretionary wedge may be transported through the retrowedge. When this occurs, the proshears and their related fabrics will be truncated by those of the retroshear in its relatively stable position against the backstop (Fig. 1b).

This is the relationship we document for the craton-directed Moyston Fault and its highly strained hanging wall at the western margin of the Lachlan (Cayley and Taylor, 1998, p. 30). This is the geometry imaged by the deep seismic (Korsch et al., 1999) which matches that theoretically predicted for this tectonic setting by Beaumont et al. (1994, p. 129): "The retro step-up shear is a spatially concentrated zone of high deformation and may be associated with a strong, dipping reflectivity fabric. The more weakly deformed prowedge forms an oppositely dipping fabric and this fabric is progressively translated in the hanging wall of the retro step-up shear. This process creates an apparent truncation between the two fabrics. Both fabrics are, however, forming independently during the same tectonic process so this apparent truncation should not be interpreted as evidence of two independent processes, one of which overprints the other".

In the final stages of the tectonic evolution (fig. 18f) the Moyston Fault is finally shown as a late-stage contact between the backstop and the wedge, but in their interpretation what existed here before the Moyston Fault—can a diagram be drawn to illustrate this?

4. The Moyston Fault

The Moyston Fault is the present-day contact between the Delamerian and Lachlan fold belts and thus the name and nature of this important structure needs to be clarified. Foster and Gleadow (1992) have full credit for the insightful recognition that the fold belt boundary lay in the approximate position of the Moyston Fault on the basis of differential uplift history during later Mesozoic reactivation. However, the actual fault contact between the two fold belts, the Moyston Fault, was not recognised and defined until later (Cayley, 1995; Cayley and Taylor, 1996). Foster and Gleadow (1992) therefore correlated the boundary to the Woorndoo Fault, which was the only named fault shown on the available maps.

The Woorndoo Fault is an inferred structure, invoked to explain nearby steeply inclined and indurated Grampians Group similar to that seen further north adjacent to the Golton Fault—a late structure of limited displacement within the Delamerian Fold Belt (Spencer-Jones, 1965, p. 21). Whether the Woorndoo Fault is actually the along-strike continuation of the Golton Fault or an effect of the Moyston Fault somewhere just to the east, is unclear (Fig. 2). Given this uncertainty, we prefer to call the bounding fault between the Lachlan and Delamerian fold belts the Moyston Fault, which is well exposed, rather than hybridise that name with an inferred structure whose origins are unclear and which could well be unrelated to the fold belt boundary.

When describing major faults in the Lachlan, Gray and Foster (1998; figs. 2 and 5) showed the Moyston Fault as disconnected from the 'Stawell–Ararat Fault Zone' by a zone of simply chevron folded 'schist and volcanogenic rocks' (see their figs. 2 and 5). The 'Stawell–Ararat Fault Zone' was described as a 'major zone of intense deformation', however, the 'schist and volcanogenic rocks' in the immediate hanging wall of the 'Stawell–Ararat Fault Zone' are actually even more highly strained and of higher metamorphic grade than the rocks 'within' the fault zone (for example, the Mount Ararat Fault; Wilson et al., 1992). Continuing westward from the 'Stawell–Ararat Fault Zone', progressively deeper stratigraphic levels, more highly strained and higher grade metamorphic rocks are encountered across numerous faults until a sharp cut-out across the Moyston Fault.

Clearly the 'Stawell–Ararat Fault Zone' is but the easternmost part of a large high strain zone, which we interpret to be related to the Moyston Fault (Cayley and Taylor, 1996, 1998). This east-dipping fault juxtaposes amphibolite grade polydeformed schist in its

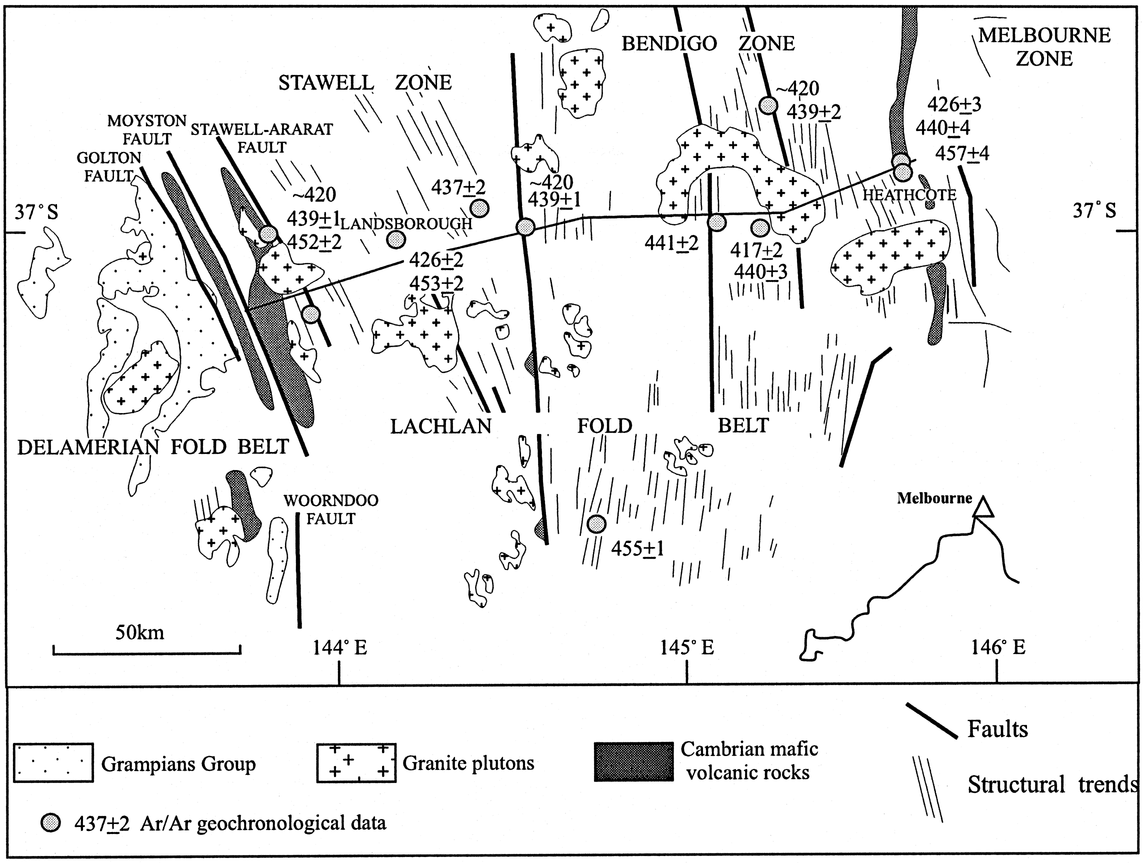

Fig. 2. Regional geological setting of the western Lachlan, showing convergence of the Golton and Moyston Faults towards the Woorndoo Fault and locations of all the Ar/Ar data with the apparent ages of deformation in millions of years (ages compiled from all the recent Gray and Foster publications including Foster et al., 1999).

hanging wall against essentially uncleaved prehnite–pumpeyllite grade sandstone in its footwall and therefore has the largest vertical displacement of any fault in the western Lachlan (Cayley and Taylor, 1996, 1998). The concomitant increase of strain intensity and metamorphic grade towards the Moyston Fault suggests a linked development, and therefore a protracted movement history for the Moyston Fault (Cayley and Taylor, 1998).

The large craton-directed Moyston Fault is one element reminiscent of those associated with the classic orogenic systems of North America, involving thrust-imbrication of passive margin sequences towards a cratonic interior. Such faults were previously unrecognised in the Lachlan Fold Belt—this was one of the reasons why the Lachlan had been regarded as an anomalous orogen and a major factor in preventing the original suggestions of an intraplate convergent setting from being concluded with certainty (e.g. Fergusson and Coney, 1992).

5. Tectonic synthesis

Gray and Foster (1998, p. 1716) argue that the geometry, complex transport directions and timing of deformation in the Lachlan are unlike the foreland fold and thrust belts of North America and thus prefer a subduction–accretion setting to explain the tectonic evolution. However, there is no evidence *diagnostic* of such processes and all the data equally support intraplate collapse of a marginal sea. This is reinforced by their recent re-interpretation of the geochronology that now supports episodic rather than continuous deformation (Foster et al., 1999).

In the geochronological companion paper, their original view of 'a diachronous, transgressive deformation extending over ~50 million years' (Gray et al., 1997) has been modified to one of 'two major orogenic events in the western Lachlan': 'one at ~440–420 Ma (in the Stawell and Bendigo zones) and one at ~390–380 Ma (in the Melbourne Zone), rather than a continuum' (Foster et al., 1999). This latest interpretation numerically confirms what has long been inferred from field relationships—major deformation of the Stawell and Bendigo zones by an event approximately equivalent in time and effect to the major Benambran Deformation of eastern Victoria, followed by major deformation of the Melbourne Zone in the later and separate Tabberabberan Deformation (e.g. VandenBerg, 1978, pp. 274–277; Cayley and McDonald, 1995, pp. 80–82; Willman, 1995, p. 12; Taylor et al., 1996, p. 13).

These orogenic events are separate in time but clearly overprinting in space—especially in the central and eastern Lachlan. The comparable timing of the superimposed deformation events in the western Lachlan with those of the central and eastern Lachlan means that deformation could easily have been driven by outboard convergence. Thus the reappraisal of geochronology appears to negate their earlier interpretation that required redefinition of 'the time interval from what was previously defined as Benambran to Tabberabberan as one orogenic event' (Gray et al., 1997, p. 7). The acceptance of two widespread and discrete deformation episodes means that their previously complex scenario (e.g. Gray et al., 1997, pp. 7–9) of multiple subduction zones to explain the ongoing progressive deformation in different parts of the Lachlan at the same time is no longer necessary.

Given the change in interpretation, we suggest that the linked deformation timing between the western and central–eastern Lachlan supports the interpretation of deformation driven by outboard process. Rather than being related to underlying subduction, the east-vergent parts of the Stawell and Bendigo zones may have formed because of underthrusting of rigid crust during the convergent deformation—as proposed in one of the original thin-skinned interpretations of this region (Fergusson et al., 1986). This interpretation, taking into account: the improved resolution of the Benambran and Tabberabberan events in the western Lachlan; the recent mapping of the Stawell and Bendigo zones; and the possible existence of older rigid crust beneath the Melbourne Zone, appears to us to be the simplest explanation that accounts for the tectonic evolution of the western Lachlan (Cayley and Taylor, 1999). Closure of a marginal sea by outboard convergence has already been suggested specifically for the western Lachlan (see Fergusson and Coney, 1992 for a review) and in general terms for other world examples (Boyer and Elliott, 1982, p. 1221)

Gray and Foster (1998) cite the presence of transitional blueschists as tangible evidence that subduction locally accompanied the deformation, but such assemblages are consistent with intraplate deformation scenarios in which the whole lithosphere is thickened (see Sandiford and Dymoke, 1991) so that subduction is not required. Even if future work demands a subduction origin for the transitional blueschists, such assemblages could have been formed during the Middle to Late-Cambrian Delamerian/Tyennan Deformation of eastern Australia and Tasmania. Similar blueschist metamorphism occurred at that time (Turner and Bottrill, 1993; Turner et al., 1998) when volcanics equivalent to those in Victoria were incorporated into the Tasmanian crust (Berry and Crawford, 1988). Therefore the blueschists in Victoria may have been generated during the Tyennan/Delamerian event and thus have no implications for the younger Lachlan orogenesis.

6. Conclusions

We are in broad agreement with Gray and Foster (1998) that the deep marine turbidite pile of the western Lachlan was accreted to the eastern margin of the older Delamerian Fold Belt during strongly convergent and protracted deformation.

The deformation in western Victoria is resolved into three discrete events: (1) the Late Cambrian Delamerian Deformation (515–500 Ma) in the west, with sediment derived from this uplifted source shed eastward into the proto-Lachlan basin during the Late Cambrian to Ordovician (500–450 Ma) in a period of tectonic quiescence—a passive or transcurrent margin?; (2) a younger episode of protracted deformation (450–420 Ma) affecting the deep marine rocks of the Stawell and Bendigo zones that is separate in time from both the older Delamerian; and (3) the younger Tabberabberan deformation (390–380 Ma) of the conformable Ordovician to Devonian sequences of the Melbourne Zone to the east, which were derived from the earlier deformed rocks to the west.

We argue that there is nothing diagnostic in the rock-record for subduction–accretion processes in the western Lachlan. All proposals for deconstructing the Lachlan in order to better understand the mechanisms driving the deformation remain weakened until complexities such as: large craton-directed thrusts; the possibility of underlying continental fragments; and the possibility of large-scale duplication by strike-slip faults are finally resolved. Until convergent intraplate deformation models are fully explored in the light of recent mapping then the subduction–accretion interpretation remains highly speculative and the region should not be used as an example of an accretionary wedge (e.g. Soesoo et al., 1997; Gray and Foster, 1998).

Acknowledgements

Fons VandenBerg and Vince Morand gave helpful advice on many issues raised in this discussion. Chris Osborne is thanked for figure draughting and this discussion is published with the permission of the General Manager of the Geological Survey.

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