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Rb/Sr dating of differentiated cleavage from the upper Adelaidean metasediments at Hallett Cove, southern Adelaide fold belt: Discussion

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INTRODUCTION

In a thought-provoking paper Turner *et al.* (1994) provide interesting Rb/Sr data from low-grade sandy and silty metasediments of the Brachina Formation at Hallett Cove, South Australia. They review the geology of the area and the regional setting of the Mount Lofty Ranges, and point out the importance of dating the deformation of these rocks in order to clarify the orogenic history of the region. The potential significance of accurate dating of the differentiated cleavage is accepted. However, the new Rb/Sr data need much more critical examination than was supplied in the paper to determine whether they actually provide new precision on the timing of deformation. Moreover, the paper does not clarify which phases of deformation and metamorphism are being compared in drawing the admittedly tentative conclusions that deformation commenced near the foreland during the Early Cambrian and propagated eastward toward the hinterland, and that the Kanmantoo Group was deposited in a foreland basin.

The purpose of this discussion is to: (i) provide more background on the stratigraphic and structural constraints relevant to the timing of deformation in Adelaidean and Cambrian rocks in the Mount Lofty Ranges, (ii) critically review the geochronological data, and (iii) examine whether the conclusions are justified.

The view that the Adelaidean rocks of the Mount Lofty Ranges underwent deformation prior to deposition of the Kanmantoo Group recalls the interpretation by Thomson (1969) of the 'Duttonian' folding, based on some discordant relationships between Adelaidean strata and both Normanville Group and Kanmantoo Group in parts of the Mount Lofty Ranges. However, these discordances cannot be interpreted as unconformities. As such they would involve unrealistic angles of onlap of the younger beds while, in some cases, the discordant contacts actually truncate folds in the younger beds. They are tectonic contacts (e.g. Daily & Milnes 1973) which truncate bedding above, or below, or both. Many are likely to be Delamerian thrusts or steep faults, but some may be early Cambrian listric extensional faults, or thrust reactivation of such extensional faults.

Had a major fold event occurred in the western part of the Delamerian fold belt during the Early Cambrian, true angular unconformities and truncated folds and cleavage in the older beds would be expected. In the rare cases where sedimentary contacts between Adelaidean rocks, the Normanville Group and Kanmantoo Group are preserved and exposed, they can be demonstrated to be disconformities, as indeed occur also within the Adelaidean succession. There are no *angular* unconformities. Moreover, since the transport direction was toward the northwest, early deformation within the foreland cannot be invoked to depress the crust further outboard to the east, where the greatest thickness of Kanmantoo Group accumulated. Had the Kanmantoo Group been deposited in a foreland basin, the required thrust stacking would have occurred even further to the east. The deformation of Adelaidean rocks at Hallett Cove is therefore immaterial to the depositional tectonic setting of the Kanmantoo Group.

STRUCTURAL RELATIONSHIPS

The folds and cleavage observed at Hallett Cove should not be viewed in isolation but as part of a system of early structures throughout the Mount Lofty Ranges (Fig. 1). These folds are situated near the western limit of exposure of Delamerian deformation at a relatively high stratigraphic level in the Adelaidean to Cambrian succession, and also represent a relatively high structural level. At deeper levels exposed further east, especially in the Burra Group, the folds are more strongly asymmetrical and the axial plane cleavage becomes shallow-dipping and more penetrative. These changes are gradual, however, and there is no evidence to suggest a different age of deformation. The Burra Group is displaced by some major and innumerable minor thrusts, most of which are blind and pass up into asymmetric folds such as those seen at Hallett Cove at higher structural levels. East of the basement inliers, the cleavage is commonly close to bedding-parallel in an E-dipping succession, which is metamorphosed to upper greenschist facies. Further east, across the major Meadows–Williamstown Fault, metamorphic grade increases to amphibolite facies in the Burra Group, where

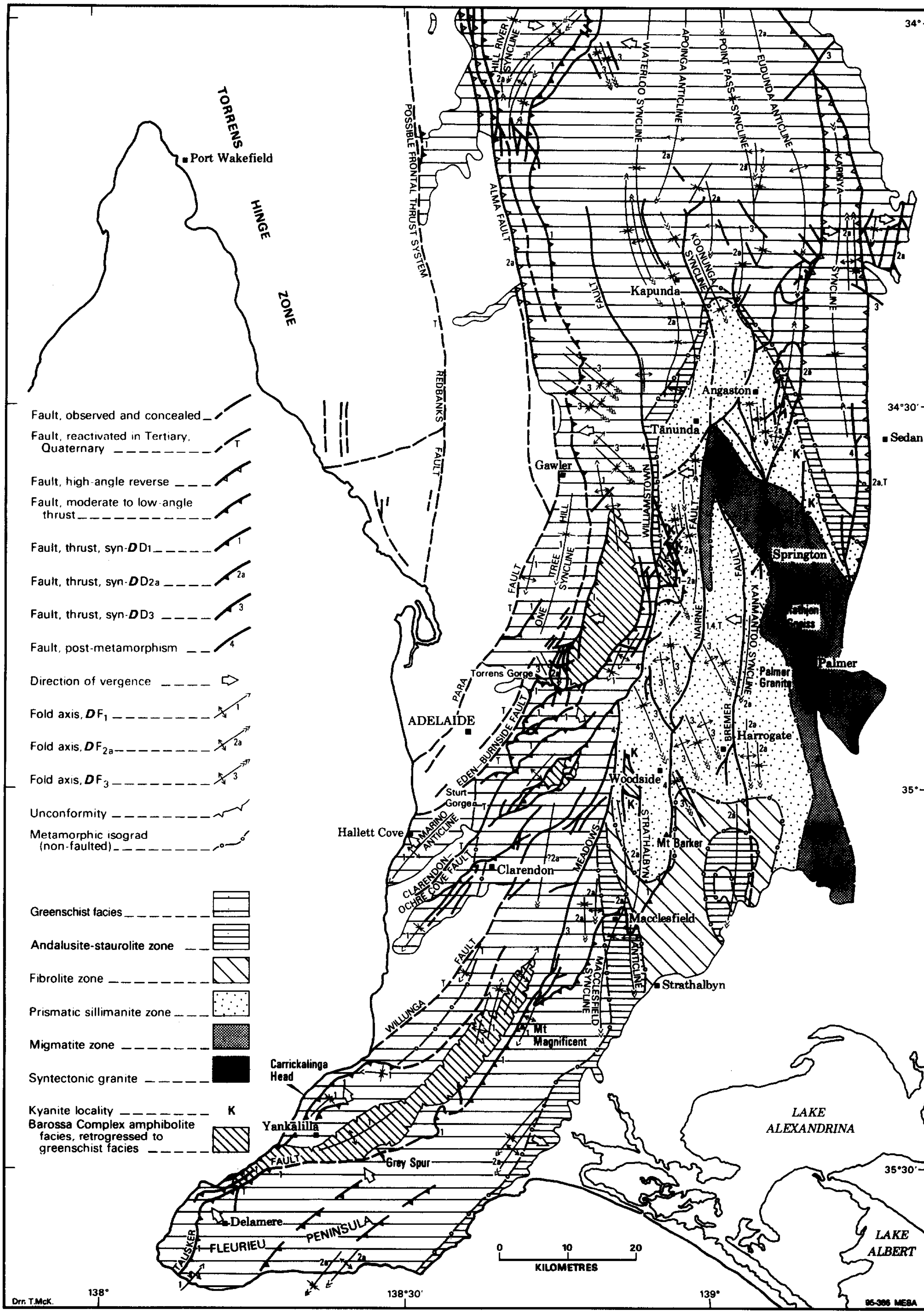

Fig. 1. Structural and metamorphic map of the Mount Lofty Ranges (slightly modified from Preiss (in press)).

the bedding-parallel cleavage becomes a well-developed schistosity. The next significant fault in the eastern Mount Lofty Ranges is the Nairne Fault (Toteff 1990), which separates Adelaidean rocks from the Kanmantoo Group. The same bedding-parallel schistosity is observed in the Kanmantoo Group, though early (F_1) folds associated with this schistosity are rarely seen (Offler & Fleming 1968).

In the western Mount Lofty Ranges, folds and thrusts assigned to D_1 and slaty cleavage, S_1, are dominant, but these are refolded on approximately N–S axes at a few localities. Such F_2 folds are generally open, meso- to macro-scale warps, although locally they are of greater intensity (e.g. Talbot 1964). It should be noted that the differentiated cleavage in the Torrens Gorge (Talbot & Hobbs 1968), quoted by Turner *et al.* (1994), is unrelated to that at Hallett Cove: the Torrens Gorge structure is a differentiated crenulation cleavage resulting from intense deformation of S_1 during D_2. The axial planes of F_2 folds are generally steeply east-dipping in this part of the ranges.

In the eastern Mount Lofty Ranges, F_2 folds are more prominent (Fig. 1). Unlike D_1 structures, their axial planes are steeply-dipping, either east or west, but tending to be mostly W-dipping near the eastern margin of the ranges. These F_2 folds refold bedding and S_1 cleavage equally in Adelaidean and Kanmantoo Group rocks.

The structural styles of the first and second deformation are quite different. As stated by Turner *et al.* (1994), D_1 involved dominantly NW-directed tectonic transport; folds have a strong vergence to the west or northwest and cleavage dips to the east or southeast, except where refolded. D_2 folds, on the other hand, have no consistent vergence but are, on average, upright with N–S axes, and are best developed in the eastern Mounty Lofty Ranges. A third phase of folding along NW–NNW-trending axes affected the high-grade areas of the eastern Mount Lofty Ranges, but does not directly affect the present discussion.

The simplest explanation of the structural evidence is that the Adelaidean, Normanville Group and Kanmantoo Group rocks were all deformed together by D_1 and D_2. D_1 produced NW-directed thrusts and folds in the west, and bedding-parallel schistosity in the east. D_2 produced upright, N–S folds, local and subordinate in the west, but dominant, macroscopic structures in the east.

DATING OF THE DELAMERIAN OROGENY

If all the Neoproterozoic and Cambrian rocks of the Mount Lofty Ranges were deformed together in the Late Cambrian to Early Ordovician, what is the significance of the new geochronological data in relation to dated granitoids? These will be considered in turn:

(1) *Rathjen Gneiss*. This is the oldest of the granitoids, with a U–Pb zircon age of 516 ± 4 Ma (quoted in Turner *et al.* 1994). The body is sill-like, largely concordant with bedding in the Backstairs Passage Formation of the Kanmantoo Group which it intrudes, and shares the layer-parallel foliation of the metasediments. The gneiss has also been tightly folded by F_2, and more openly folded by NNW-trending F_3 folds; it has therefore undergone all of the Delamerian deformation phases, and may, in fact, be entirely pre-tectonic. It could be speculated that the precursor of the gneiss was a subvolcanic felsic sill, which might have had extrusive equivalents that contributed to the great thickness of overburden (?5–10 km) required by the metamorphic conditions of the Kanmantoo Group but entirely removed by post-Early Ordovician erosion. The age of D_1 and all later deformations is most likely less than ~516 Ma.

(2) *Syn-tectonic granitoids* were intruded mainly at about the time of D_2. There has been considerable debate on the precise timing relationships (e.g. Milnes *et al.* 1977, Mancktelow 1990), but close association with D_2 is likely since many of the intrusive bodies are aligned parallel to F_2 fold axes and some display an internal S_2 fabric, and since peak metamorphic conditions are associated with D_2. A wide variety of ages has been reported for the syn-tectonic granitoids, as summarized and referenced by Preiss (in press), including the Encounter Bay Granites (504 ± 8: Rb–Sr), a pegmatite (511 ± 3: Rb–Sr) on Kangaroo Island, and the Palmer Granite (479 ± 15: Rb–Sr on total rocks and minerals; 503 ± 33: Rb–Sr on total rocks only). The age of D_1 is therefore most likely older than ~505 Ma.

(3) *Post-tectonic granitoids* truncate the earlier tectonic fabrics, and reported ages include 481 ± 9 (Rb–Sr) for the Mannum Granite, 471 ± 12 (Rb–Sr) for the Murray Bridge Granite and 488 ± 6 (U–Pb) for a rhyolite dyke on Kangaroo Island. The ages of D_2 and D_3 are therefore likely to be between ~505 and ~490 Ma.

How does the reported age of 536 ± 7 for S_1 cleavage compare with a likely age of ~510 ± 5 Ma for D_1 based on granitoids? Firstly, the age quoted is not a perfectly fitted isochron, and application of a model 1 calculation is inappropriate for such a wide scatter. The model 2 calculation is more applicable, and the resulting error of ±32 Ma is more realistic. An age estimate for D_1 at around 510 Ma falls within this range. Secondly, interpretation of the isochron as a precise measure of the age of the cleavage is based on some unrealistic assumptions. While it is true that the Brachina Formation is a monotonous, thick succession of more or less uniform composition, it does not follow that the initial $^{87}Sr/^{86}Sr$ ratios were precisely identical in samples of detrital sedimentary rock metres apart. This was a common assumption in early attempts at shale dating as a means of determining age of sedimentation. Shale dates based on whole rock samples were of ambiguous reliability, reflecting the effects of source age, diagenesis and low-grade metamorphism, and only rarely dated precisely the time of deposition. Only when it was realized that dating of newly crystallized diagenetic clay minerals was necessary, while eliminating as far as possible any detrital elements, was it possible to obtain reliable shale dates (Clauer 1973), but even these do not have the very narrow error limits of the model 1 isochron quoted by Turner *et al.* (1994). Paradoxically, the latter authors correctly described the line as an errorchron, but then proceeded to draw important conclusions from it. By combining data from widely-separated samples to produce an apparent, very poorly fitted isochron, they are perpetuating the earlier method of shale dating with its shortcomings.

However, the use of Rb/Sr data from separated quartz-rich and phyllosilicate-rich domains of single samples to obtain isochrons is valid, but it can produce only a series of two-point isochrons, each with a slightly different initial ratio. Since two-point isochrons do not allow any internal checks on subsequent redistribution of isotopes, they cannot be demonstrated to record faithfully either the time of formation of the differentiated cleavage or the initial ratios of the samples.

CONCLUSIONS

The data presented by Turner *et al.* (1994) do not provide the precision of age determination for the differentiated cleavage that they claim. At best, a model 2 isochron with an error of ±32 Ma should be applied, in which case it provides no support at all for the concept of an earlier deformation affecting the Adelaidean rocks prior to or during deposition of the Kanmantoo Group. When structural and stratigraphic evidence are considered together with geochronological data, the following sequence of events may be interpreted:

(1) Deposition of the Adelaidean to Early Cambrian succession in a rift and sag-phase basin complex, interrupted by some major disconformities but no compressive deformation.

(2) Renewed active rifting in the later Early Cambrian (~526 Ma) initiating basic volcanism of the Truro Volcanics and listric faulting to produce the Kanmantoo Trough. These faults caused the Kanmantoo Group to be downfaulted adjacent to Adelaidean rocks to the west, and allowed extremely thick clastic deposits to accumulate very rapidly.

(3) It may be speculated that plate convergence further east generated a volcanic arc above the Kanmantoo Group at ~516 Ma, as represented only by a subvolcanic granitic sill (now the Rathjen Gneiss).

(4) When plate convergence impinged on the region of the present Mount Lofty Ranges, it imposed NW-directed structures on all Neoproterozoic and Cambrian rocks during D_1, around 510 Ma. Such deformation would have most probably propagated from the southeast toward the northwest. But the formation of cleavage in the Adelaidean rocks at Hallett Cove near the craton cannot be invoked to represent early convergence in a more outboard setting as would be required if the Kanmantoo Trough were a foreland basin.

(5) Being a D_1 structure, the differentiated cleavage at Hallett Cove certainly does predate peak metamorphism in the Kanmantoo Group, which is associated with syntectonic granite intrusion and D_2 folding at around 505–490 Ma. These structures reflect separate phases of Delamerian deformation, with different structural styles, and not an outboard propagation of a single deformation front.

(6) The present author has looked for but not found evidence for the persistence of D_1 structures to the north in the Flinders Ranges, where most of the folding can be attributed to D_2. In this case it is quite possible that the youngest Cambrian beds of the central Flinders Ranges (Lake Frome Group) were deposited after initiation of compressive deformation in the south.

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