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

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In his discussion of our recent paper on dating of differentiated cleavage from Hallett Cove (Turner *et al.* 1994), Preiss argues that our interpretation of the Rb/Sr data from differentiated cleavages is inconsistent with regional structural correlations in the southern Adelaide fold belt. He also reviews the age data of late- to post-kinematic granitoids; this is less pertinent to our arguments which concerns the early stages of deformation. In particular, Preiss argues that fabrics from the foreland region in the west, where the low grade rocks of Hallett Cove are exposed, can be correlated with fabrics in the more internal parts of the belt, some 50 km further east where higher grade rocks are exposed. As we pointed out in our discussion, and Preiss reiterates, independent isotopic data from intrusive granites constrain the ages of structures in the internal parts of the belt (516–485 Ma), but no such data exist in the external parts of the belt. We welcome the opportunity to discuss these issues further and will comment first on Preiss's structural arguments, and secondly on his discussion of the geochronology.

STRUCTURAL RELATIONSHIPS

In the absence of precise age determination, the traditional approach to structural correlation has been on the basis of 'style', as proposed by Preiss. In essence this approach entails using the *geometry* of structures to constrain their relative temporal relationships. Moreover, Preiss suggests that the southern Adelaide fold belt contains a definable set of kinematically consistent structures and fabric elements that include the Hallett Cove fabrics in the external part of the belt (the subject of our study), and a layer parallel foliation in the higher grade, internal parts of the belt. Kinematic and geometric consistency of structures is a *minimal* requirement for temporal correlation. However, for a variety of reasons which we briefly return to below, kinematic consistency is not a sufficient condition for such correlation. More importantly, our own work, and that of others, has demonstrated that the southern Adelaide fold belt is kinematically far more complex than the simple view advanced by Preiss. The recognition of a more complex evolution necessitates the abandonment of the simplistic correlations proposed by Preiss, and demands far greater emphasis on the precise dating of individual structures and associated fabrics across the fold belt.

We present two sets of observations pertinent to our claim that the structural evolution of the southern Adelaide fold belt is more complex than proposed by Preiss, and which demonstrates that his proposed correlation involves kinematically distinct sets of structures and is therefore inconsistent. We remind the reader that the structures at Hallett Cove are NNE-trending asymmetric folds, presumably developed above blind thrusts, due to the westnorthwest advance of the southern Adelaide fold belt onto the Gawler craton, with displacement essentially orthogonal to the boundary of the orogen.

S_1 *fabrics in the Rathjen Gneiss*

The oldest recognized structural elements in the internal part of the fold belt are the layer parallel fabrics in the Rathjen Gneiss and surrounds (e.g. Sandiford *et al.* 1992, 1995, Oliver & Zakowski in press). The Rathjen Gneiss is an intrusive body which contains primary magmatic zircons dated at 516 Ma (Foden unpublished data), and therefore provides an important constraint on the maximum age of the S_1 fabric. Oliver & Zakowski (in press) describe this fabric in detail. They suggest it is essentially a composite fabric which formed mainly during a N–S sub-horizontal stretching event parallel to the trend of the developing orogen, as evidenced by a locally prominent N–S-trending mineral elongation lineation. Importantly, the deformation recorded within the Rathjen Gneiss occurred under amphibolite facies conditions and involves partial melts. We have independently corroborated these observations, and while we do not necessarily accept the interpretation of bulk crustal extension proposed for this phase of deformation by Oliver & Zakowski (in press), the N–S-stretching lineation associated with early layer parallel foliations do not support Preiss's contention that this fabric is of the same style as the fabrics at Hallett Cove.

Normal and reverse sense displacement in the foreland

As demonstrated by Jenkins (1990) and subsequently Jenkins & Sandiford (1992) and Flöttmann *et al.* (1994), the structures in the foreland parts of the belt are dominated (at the latitude of Hallett Cove) by WNW–verging structures. A kinematically-simple evolution is suggested by the lack of overprinting fabrics in the foreland, and by uniform trends of stretching lineations implying displacement was essentially orogen-normal. However, shear-sense criteria show a more complex kinematic history, with our own work in the Myponga Inlier south of Normanville (in the vicinity of the Garnet Kelly Reserve) showing that both normal and reverse sense shear zones, with greenschist facies mineral assemblages, formed during the formation of the foreland structures. While the detailed significance of these normal sense shear zones remains to be elucidated, it clearly points to a complex history in the foreland, which is not consistent with the simple model proposed by Preiss. The structures at Hallett Cove represent only one displacement increment which cannot necessarily be correlated geometrically with other, more complex structures elsewhere in the fold belt, such as the Rathjen Gneiss. Consequently, a temporal correlation based on geometric considerations remains tentative.

In his discussion, Preiss has articulated the view that in the absence of detailed isotopic constraints the best way structures can be correlated is on the basis of their style (or more strictly kinematics). Unfortunately, in the absence of isotopic constraints, 'style' is also the only basis on which structures can be correlated. However, it is now widely argued that both laterally and vertically, deformation in orogenic belts can be partitioned between orogen normal and orogen parallel displacements. Evidence for this occurs in the form of active seismicity, neotectonic studies, reconstruction of ancient fold belts and on the basis of theoretical arguments (e.g. Lamb 1987, Molnar 1993). If this is the case then the gross geometric constraints of an orogenic belt, e.g. the shape of an adjacent rigid margin, must fundamentally limit the number of kinematically-distinct sets of structures that can form. The problem here is that the evolution of the orogenic belts is kinematically-consistent but temporally-distinct, that is the overall deformation occurs in increments and consequently sets of structures may repeatedly form during each deformation increment.

It therefore appears not *a priori* justified simply to correlate the first deformational episode encountered at each single outcrop as having occurred during the same temporal increment. Considering that the outcrops represent contrasting crustal levels makes a geometric, as well as a kinematic correlation, and any temporal correlation, even more tentative. On the basis of these considerations we see no conclusive evidence that the Hallett Cove and Rathjen Gneiss structures, which formed at different crustal levels and reflect contrasting kinematic imprints, can be temporally correlated. Even in seemingly simple orogens an understanding of orogenic processes is intimately related to knowledge about the timing of different orogenic and kinematic increments.

GEOCHRONOLOGY

Having reinforced the need for isotopic constraints on the timing of deformation events, we turn to our determination for cleavage formation at Hallett Cove and the evidence that this age is indeed that of cleavage formation.

The samples are composed of fine-grained quartz and illite clay minerals, and no detrital micas or feldspars, which might retain a memory of their provenance age, have been recognized (a laser ^{40}Ar–^{39}Ar investigation is in progress to further verify this point). It is the very large fractionation of Rb/Sr during cleavage formation which was of primary interest in our original paper and which facilitates isotopic age determination. Preiss's comparison with shale dating is therefore misleading since we are dating a deformation-related chemical fractionation event, not sediment deposition.

As Preiss observes, two-point isochrons do not allow for any internal checks. Moreover, the calculated errors on such isochrons only reflect analytical error and do not allow for geological error. For these reasons we combined the Hallett Cove data on a single isochron with the following justifications. Firstly, the fine grain-size and distal nature of these sediments argue that the sedimentary beds should have been close to isotopically-homogeneous prior to deformation. Secondly, the initial ratio obtained from the isochron is within error of bulk analyses of these sediments. The fact that the sediments are essentially unmetamorphosed, and that no process, other than cleavage formation, that could result in trace element fractionation has been recognized, provides strong support for the age being that of cleavage formation (and since the effects of alteration or subsequent metamorphism would be to reset the isotopic system, the age is likely to be a *minimum* age).

There seems little doubt that the trace element data record cleavage formation and can be used to constrain the age of this process. The problem then is the precision of this age. Preiss suggests that we claim a precision of 536 $\pm$ 7 Ma for the age of cleavage formation. This is mistaken. As clearly stated in our paper, the isochron is not perfect, and in order to be cautious the model 2 age of 531 $\pm$ 32 Ma was adopted throughout our discussion. The seven two-point isochrons give a mean age of 512 Ma, younger but still within the 95% confidence limits of the errochron. At present this is the only age determination from the external part of the fold belt and given the precision, it is fair to say that more geochronological data are required before the suggestion that this predates deformation in the interior parts of the fold belt can be properly confirmed or refuted (a weighted mean of the ages quoted by Preiss for the syn-tectonic granitoids is 500 Ma). Preiss concurs with us that the high MSWD on the Hallett Cove model 1 isochron probably results from minor inhomogeneities within the sediment layers at the scale of sampling. Having said this, we stress that our study was largely reconnaissance in nature and with hindsight the reduced precision caused by this heterogeneity could be greatly reduced by analysing a number of serial sections cut parallel to, and across an individual *P–Q* fabric. Isotopic determinations on such material would be analytically straight-forward, even though only small (~100 mg) samples would be recovered. Therefore, unlike Preiss, we would like our pilot investigation to encourage further studies which might be able to achieve better precision.

CONCLUSION

In conclusion, we do not find Preiss's structural arguments convincing and the best estimate of the age of cleavage formation remains unchanged at 531 ± 32 Ma. The interpretations of this age are clearly open to discussion, as we emphasized in our original paper. We also emphasized that the data allow, *but do not demand*, that the Kanmantoo Group was deposited in a foreland basin. The best test of the foreland basis and deformation front propagation hypotheses will be further age constraints of the sort we advanced in our original paper, and which we hope will encourage further investigation.

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