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The relationship between foliation and strain: an experimental investigation: reply

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Abstract—Contrary to the criticisms of our ideas by Treagus, we still believe that our experiments show that a secondary preferred orientation of micas or of small kink-like folds, closely resembling similar features in some cleaved rocks, can form at large angles to the $\lambda_1\lambda_2$ plane of strain, where the strain referred to is the strain coeval with development of these features.

WE WISH to thank Dr. Treagus for her comments on our paper and for the opportunity to enlarge on some points inadequately discussed there, and perhaps in the literature in general. Treagus criticizes our paper on three grounds. (1) The grain size in our experiments is coarser than the grain size in slates, while our strain marker elements are finer than typical strain marker objects in slates. This is said to preclude any relevance of our results to slates. (2) We have erroneously assumed homogeneity of the strain field within our strain marker elements. (3) We have calculated tectonic strains only, instead of total strains including a compactional component. This is thought to invalidate the experimental basis for our suggestion that some foliations in rocks form oblique to the $\lambda_1\lambda_2$ principal plane of strain.

(1) Treagus quotes a few grain sizes for slates and schists and compares them with grain sizes for our material pointing out that our materials are coarser than slates and finer than schists. However, we question the relevance of this point. Mica-rich foliated rocks do not come 'in two sizes only'; they form a continuous size series and the same microstructures, as described in our paper, can be found in representatives of all grain sizes. There are commonly differences between the fine-grained and coarse-grained rocks, but they appear to be related to grain-growth processes that are more active at the higher temperatures generally associated with the coarser rocks. These processes modify the microstructure but the processes primarily responsible for the development of the foliation remain the same (this point was discussed more fully in our earlier paper, Williams *et al.* 1977).

Our strain marker elements were chosen as small as possible without however making them so small that the calculated strains fluctuated wildly from one element to the next (see Hobbs *et al.* 1982, fig. 4). This is clearly the best way to bring out the properties of the bulk strain field. We then averaged directions over the 6 to 13 individual elements within each of areas A, B, C, D in order to plot the λ_1 directions shown in figs. 8 and 10 of Hobbs *et al.* (1982). This averaging over many elements should have been made clear in our text. We believe that the resulting λ_1 directions shown in the previously cited figs. 8 and 10 are entirely comparable with λ_1 directions obtained from marker objects in slates. In fact our strain measurements may be better than those obtained from some slates because our markers are defined by an essentially passive array of marker points and we know its original configuration quite exactly.

(2) With regard to Treagus's second criticism as listed above, it is true that the strain is heterogeneous within the triangles. We are simply determining the bulk strain at that scale and since the deformation is undoubtedly heterogeneous right down to the lattice scale the point will apply to any practicable strain marker element. However, in the limb areas where the foliation traces are not parallel to λ_1, the strain does not vary greatly from element to element so that even if we take a large number of elements, so as to reduce the significance of local perturbations, the answer remains essentially the same. The point is that if we consider strain on any reasonable scale, we find areas in which there is a marked difference in orientation between the trace of the 'foliation' and λ_1. In fact there is no reasonable way of analysing the strain that makes the trace of the kinks, and especially that of the mica fabric, everywhere parallel, or even nearly parallel, to λ_1. This is not surprising since both fabrics comprise discontinuities and are there-

fore incapable of tracking a principal plane, in a fold limb, where the strain path has been demonstrably non-coaxial.

(3) Treagus's second criticism concerning strain is to do with the portion of the strain history that our measurements represent. She is of course correct in saying that we are measuring the 'tectonic strain' and not the total strain. She objects to our use of 'finite strain' but we maintain that the tectonic strain in our experiments is a finite strain. We do not use finite strain synonymously with total strain or necessarily with tectonic strain.

More seriously, according to Treagus, we should have considered the total strain and not just the 'tectonic strain'. We do not agree on several counts. First, it is necessary to consider what questions we are trying to answer. There is a significant difference, from the point of view of explaining observed microstructures, between foliations that have precisely tracked the $\lambda_1\lambda_2$ plane throughout their history and ones that have not, but which nevertheless may finish up approximately parallel. We have pointed out in the past that foliations that have not tracked $\lambda_1\lambda_2$ may finish up almost parallel at finite strains (Williams 1976, Hobbs *et al.* 1976, Williams *et al.* 1977). We still believe this to be true of many rocks but in the paper under discussion made the point that we should not always expect it to be true. Despite our earlier statement large discrepancies now seem to us to be possible. However, the point is that we are ultimately interestested in the development of microstructure and the interaction of strain and microstructure. In our opinion an important step in such understanding is to move away from the over-simplified assumption that all foliations track the $\lambda_1\lambda_2$ plane of strain.

With our ultimate goals in mind we will now justify our approach.

(a) Because we are interested in the history of microstructural development we feel free to consider any portion of the history and not bound to consider the total history. In this case we are concerned with the results of the total tectonic history, that is, with that part of the history that converts the sedimentary microstructure to the tectonic microstructure. In passing it is interesting to note that, according to our model, if we consider the total history, then, in the early stages of 'tectonic' deformation, the incipient foliation will be parallel to the $\lambda_1\lambda_3$ plane of total strain, since the material line coincident with λ_3 during compaction is coincident with the incremental λ_1, and finally the finite λ_1, during the tectonic deformation.

(b) Our starting material is designed to simulate a sedimentary rock (it is also relevant to a metamorphic rock with a pre-existing foliation). We would not suggest that the process whereby we develop the microstructure, however, is a good simulation of the natural process. Our sedimentation takes place in air and produces a very porous aggregate which probably has a much poorer preferred orientation than most sediments other than flocculated clay. We then achieve our 'sedimentary' microstructure purely by compaction without any introduction of cement. There is no reason to suggest that the initial compacting strain is the same in magnitude as that occurring in rocks.

(c) Strain analyses in rocks are commonly based on such markers as ooids, fossils and reduction spots. In general these markers are unstrained in tectonically undeformed rocks. Therefore the history determined by strain analysis in many cases is also the 'tectonic' strain.

In conclusion, contrary to Treagus, we still believe that our experiments show that a secondary preferred orientation of micas or of small kink-like folds, closely resembling similar features in some cleaved rocks, can form at large angles to the $\lambda_1\lambda_2$ plane of strain, where the strain referred to is the strain coeval with development of these features.

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