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Strain paths during slaty cleavage formation—the role of volume loss: Discussion

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Bell (1985) in his study of strain paths seeks to explain the wide range of final shape factors (Fig. 1) shown by accretionary lapilli in slaty tuffs of the Borrowdale Group, English Lake District. Using a carefully developed argument, several tectonic strain paths were evaluated for their effects on a single compaction strain state ($X = Y > Z$; $Y/Z = 1.86$); the different paths were plane strain without volume loss, plane strain with incremental volume loss, pure volume loss, and composite models. The best fit to the recorded data was a history of initial pure volume loss giving way progressively to a final stage of near constant volume plane strain. Such a proposal, if generally applicable, could have considerable implications for deformation processes in low-grade tectonites as it requires that fluid expulsion during tectonism is strongly concentrated in the earliest stages with volume conservation at higher strains. This outcome of the work appears questionable in the light of recent evidence for large fluid to rock ratios during some regional metamorphic events (e.g. Rumble *et al.* 1982) and the probable role of infiltration (Etheridge *et al.* 1984) in mass transfer processes which dominate in the lower grades.

The main limitation of Bell's discussion is that only one compaction state ($Y/Z = 1.86$) is used and, more importantly, that only one possible compaction value is countenanced (Bell 1985, p. 565) to explain all the final lapilli data. In analysing the effects of constant volume plane strain, the chosen compaction strain (1.86) could not account for the 'X_f gentle' data group (Fig. 1) which, for the conditions stated, required a compaction ellipsoid of $Y/Z = 3$ (67% shortening normal to the XY plane). The latter value was rejected because it could not account for the bulk of the final accretionary lapilli shapes implying that only one pre-tectonic compaction strain was responsible for all the final data. Why the analysis was restricted to one compaction value was not stated. Was it influenced by Moore & Peck's (1962) observation that compaction strain increases with sample age (see also Bell 1981, p. 466) suggesting a proportionality between shortening during compaction and amount of overburden? A similar trend was hinted at by Tobisch *et al.* (1977, fig. 5, p. 29).

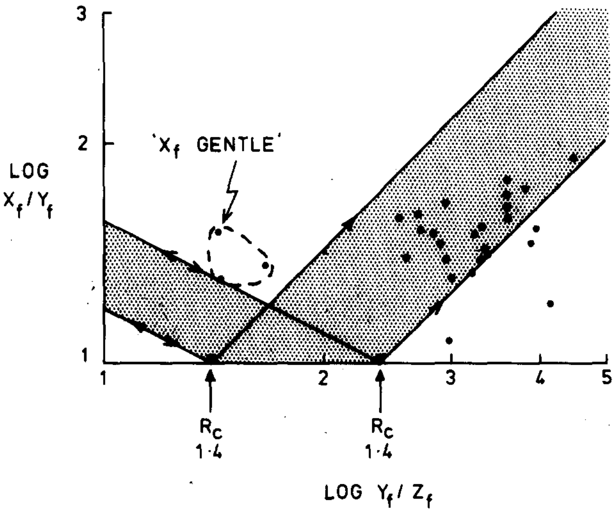

Fig. 1. Logarithmic Flinn plot with average shapes of accretionary lapilli samples from Borrowdale Group (Bell 1985). The shaded area shows the range of final lapilli ellipsoids that can be generated by superimposing plane strain without volume loss on compaction strains ranging from $Y/Z = 1.4$ to $Y/Z = 2.4$. R_c = compaction strain.

Published documentation on accretionary lapilli compaction states, and controlling parameters, is scant. Seymour & Boulter (1979) noted that two specimens from the same locality have compaction strains of $Y/Z = 1.50$ and $Y/Z = 1.95$ representing 33 and 49% shortening perpendicular to the XY plane. Boulter (1983) recorded, from a single formation, compaction strains in accretionary lapilli tuffs varying from $Y/Z = 1.39$ to $Y/Z = 1.83$, and commented that some examples showed virtually zero compaction strain because of early carbonate replacement of the matrix. Also after factorization of the Borrowdale accretionary lapilli shape factors into 'cleavage strain', and pre-tectonic components, Bell (1981) determined a range in the latter from $Y/Z = 1.5$ to $Y/Z = 2.0$, though these results are somewhat dependent on assumptions made during the analysis. Unpublished data on the untectonized Tumbiana Formation of the Fortescue Group, Western Australia, show that within one formation some accretionary lapilli beds have undergone no compaction because of early carbonate cementation whereas the highest compaction strain recorded is $Y/Z = 2.6$. The majority of samples lie in the range $Y/Z = 1.4$ to $Y/Z = 2.4$. Trendall (1965) briefly commented on the wide variation in compaction strains in the Tumbiana Formation accretionary lapilli which, on the basis of limited measurements, were shown to range between $Y/Z \cong 1.08$ and $Y/Z \cong 1.75$. Because overburden would not have varied greatly along strike and nearly the extreme range is seen in single localities (100 m^2), other variables (cementation history, volume concentration, lapilli internal structure and composition, etc.) are responsible for the range of final shapes.

It would seem probable, therefore, that the range of final accretionary lapilli shapes recorded from the Borrowdale Group was generated from a range of compaction strains whatever the strain path. When the extreme values of the Tumbiana data are removed, compaction strains ranging from $Y/Z = 1.4$ to $Y/Z = 2.4$ are not unexpected in thick volcanic piles and a wider range cannot be ruled out. Constant volume plane strain, superimposed on a range of compaction strains from 1.4 to 2.4 (Fig. 1), still does not account for all of the 'X_f gentle' set from the Borrowdale Group but plane strain with 20% incremental volume loss (Fig. 2) does include this part of the data though misses some of the main cluster of data points. Figure 2 is constructed for cleavage at 90° to bedding; variable cleavage/bedding angles or a degree of non-coaxial strain could be invoked to include all data points. Incremental strain studies on the slaty accretionary lapilli tuffs of the Borrowdale Group would be useful to further define likely strain paths. Considering that one probable contributor to the strain history (folding strains) is not taken into account, the fit shown in Fig. 2 is good. Some strain paths during tectonic deformation may also have involved less than 20% volume loss; four Tumbiana accretionary lapilli tuffs that show only moderate to weak calcite cementation have a mean density of 2.6 g cm^{-3} which is not much less than the 2.7 for Lake District cleaved tuffs quoted by Bell (1985).

The observed final lapilli data are consistent with the composite model of Bell but a simpler model that also fits the data is plane strain, associated with moderate incremental volume loss, superimposed on variable compaction strains. Incremental volume loss also better accords with recent observations of a link between deformation mechanisms of a mass transfer type and fluid flow through deforming tectonites.

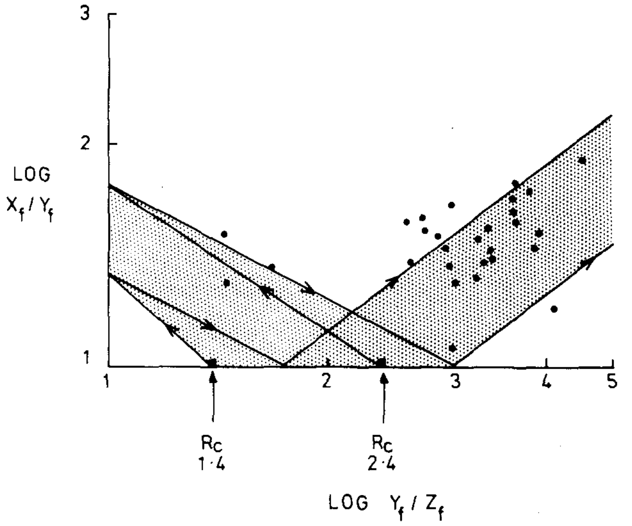

Fig. 2. Log Flinn plot as Fig. 1 but with the shaded area showing the result of superimposing plane strain plus 20% incremental volume loss on the range of compaction strains when cleavage is superimposed on bedding at right angles.

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