Jumb Quarry, Kentmere

[NY 449 074]

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Highlights

This is an important site, where volcanic accretionary lapilli have been the source material for significant quantitative analyses of the strain associated with the formation of slaty cleavage. It is the only site in the Lake District where such detailed strain analyses have been made.

Introduction

The quarry exposes part of the Wrengill Formation of the Borrowdale Group (Soper and Numan, 1974) which, here, is composed of water-worked air-fall tuffs of broadly andesitic composition (Figure 3.22)A. Little work has been done on these volcaniclastic sediments (Moore and Peck, 1962; Bell, 1981), but particles within the tuffs have been used as indicators of strain since the work of Sharp (1849).

First estimates of strain using the deformed lapilli were made by Green in 1917, but the major period of quantitative strain analyses was started by Oertel (1970) who sampled at Jumb Quarry and concluded that the originally spherical lapilli had compacted during diagenesis and subsequently been distorted by strain during slaty cleavage formation. Publication of his results sparked off a heated debate in the literature between Oertel (1970, 1971, 1972) and other workers (Helm and Siddans, 1971; Mukhopadhyay, 1972; Ramsay and Wood, 1973; Wood, 1974) who argued that the lapilli shape indicated a period of cleavage-producing strain which had been superimposed on variably shaped, but undistorted lapilli.

At the very heart of this debate was the question of the origin of slaty cleavage; did the cleavage plane represent a principal plane of the total strain ellipsoid or was it the principal plane of some component of the total strain? Further work in other slate belts (Siddans, 1972; Wood,1974) and a more extensive survey and analysis of the Borrowdale Group lapilli (Bell, 1981, 1985) has produced a solution which suggests that the observed particle shape is the product of strain modification, both diagenetic and tectonic, of variably shaped lapilli, but that cleavage formation is related precisely to the shape of the tectonic strain ellipsoid.

Description

Jumb Quarry lies wholly within a tuff unit of the Wrengill Formation of the Borrowdale Group. It is one of a series of roofing-slate quarries in these beds in the Lake District, but here the lapilli horizons were presumably worked for their decorative qualities. The lapilli are contained within a distinctive tuff deposit, which has been traced as a stratigraphical marker horizon across the whole of the Borrowdale outcrop, and which has been invaluable for correlation within the upper part of the volcanic succession (Soper and Numan, 1974; Bell, 1981).

The tuff is composed of a sequence of light to dark green, fine- to coarse-grained, bedded air-fall tuffs, which are interbedded on a scale of several centimetres with structureless poorly-sorted tuffs containing lapilli. The lapilli themselves are distinctive ellipsoidal, or sub-ellipsoidal objects composed of a central core of coarse ash identical to the matrix, which grades systematically to an outer shell of light-green to white, fine ash (Figure 3.21).

Superimposed on the tuff sequence is a pervasive slaty cleavage (late Caledonian, S_1). The cleavage planes themselves are formed by the almost perfect alignment of minerals on the cleavage face. The cleavage planes dip steeply to the north-west (typically 80 degrees) and the mineral lineation is steeply plunging on that plane. Bedding dips variably from 30–70°SE, so the bedding–cleavage intersection lies almost at right-angles to the mineral lineation. The cleavage is not folded, except by infrequent minor kink bands.

Interpretation

Sedimentary structures and the absence of evidence for marine conditions, suggest that the tuffs in this area were deposited into shallow freshwater lakes, lying on the flanks of the major volcanic centres. The nature of the lapilli indicates they are fossil 'hailstones' and were most probably the products of a violent eruption which produced a massive ash- and steam-laden thundercloud above a volcanic crater. They would have oscillated within this cloud until their increasing weight, or the waning of the energy of the eruption, allowed them to fall into the soft, wet, ashy mud.

The ellipsoidal lapilli make excellent strain markers, since their composition, and hence their competency, does not differ from that of their matrix. They are also found in large enough numbers to give statistically valid results. Each lapillus is now roughly ellipsoidal (some exactly so) and at Jumb Quarry the short axis of most lies roughly normal to the cleavage plane, and their long axes lie roughly along the mineral lineation on the cleavage face. They show that there can be no doubt that compression across the cleavage produced the planar fabric and an accompanying extension within the plane of cleavage caused the mineral lineation.

Estimates of 66% shortening, normal to cleavage, were made by Green in 1917, the first documented strain analysis using the accretionary lapilli. Oertel. (1970) calculated a single ellipsoidal shape which was an average of many measured lapilli. He then factorized this into a plane strain (conserving volume and with no change of length along the intermediate axis) oriented in the cleavage frame, that is one ellipsoid axis normal to the cleavage plane, one within the cleavage plane parallel to the mineral lineation and an oblate strain (long and intermediate axes equal) oriented in the pre-cleavage bedding frame. He concluded that the tuffs had compacted by some 50% normal to bedding prior to cleavage formation, and then shortened by about 50% across the cleavage plane. These results were broadly in agreement with Green's estimate.

Helm and Siddans (1971) repeated the analysis using Rf/■ technique (a graphical technique which allows the calculation of the finite strain (RI) from measurements of a population of elliptical strain markers which show a variation of orientation ((■) of their axes) on specimens from the nearby Steel Rigg Quarry and elsewhere. Their results seemed to indicate that elliptical lapilli were randomly oriented prior to cleavage formation. Their cleavage strain was not plane (k = 1), but had a k value of 0.4, and the mean-shape of the lapilli differed from the cleavage frame by less than five degrees.

The lengthy debate that followed these studies, concerned the origin of slaty cleavage and focused on the relationship of the strain ellipsoid to the cleavage plane. It was continued by Bell (1981) who analysed samples from nine localities including Jumb Quarry and Steel Rigg Quarry using both an Rf/■) technique and an average ellipsoid factorization technique similar to that used by Oertel. His results (Figure 3.22)A and B showed that, in localities of intense cleavage and steep bedding like Jumb and Steel Rigg, the lapilli had probably been compacted by 66% in bedding prior to a tectonic strain which caused shortening of some 50–70% across cleavage and which was close to, but not exactly plane (k values from 0.8 to 1.2). Elsewhere along strike, particularly in localities that lay on the gentle north-dipping limb of a major fold, tectonic strains were much lower and the long axis of the average lapillus pitched at a high angle to the cleavage mineral lineation.

Subsequent work by Bell (1985) related the variation of tectonic strain along the outcrop, to the process of cleavage formation, concluding that the lapilli shapes supported a cleavage-forming mechanism that began as layer-parallel shortening, accomplished largely by volume loss, and developed into plane strain with conservation of volume with the onset of lowest-grade metamorphism and full cleavage development.

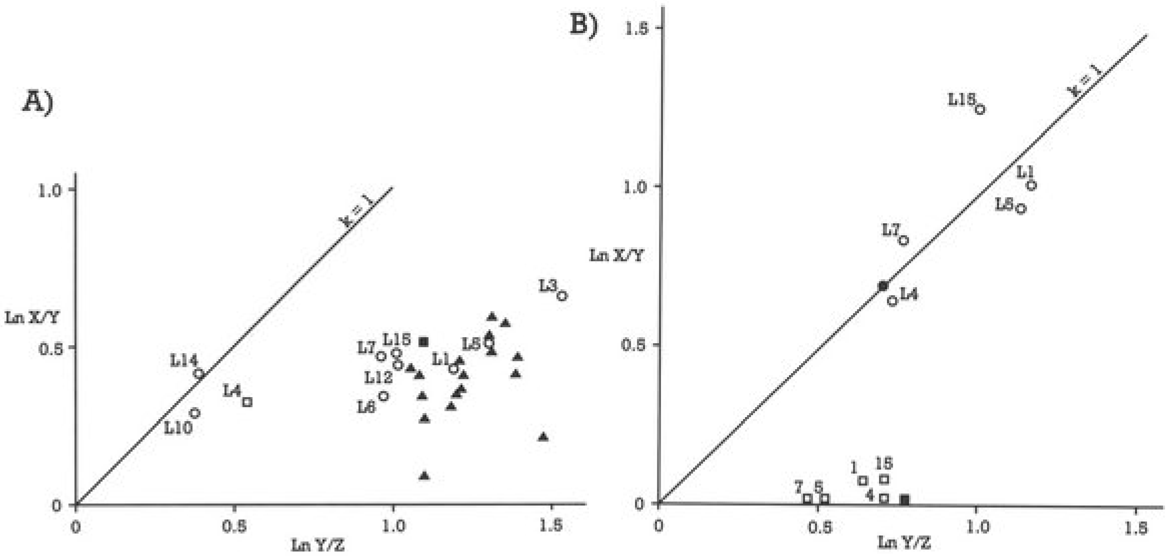
The modern consensus is that the strain which formed the cleavage is probably somewhat oblate ($k < 1$), rather than plane, and almost certainly has the cleavage plane as its principal plane. The lapilli have suffered another distortion as well as cleavage formation and this is most likely to have been compaction during diagenesis. Volume loss normal to the cleavage plane seems to be important in the earliest stages of tectonic deformation, even after diagenetic compaction.

Jumb Quarry provides important exposures of intensely cleaved volcanic accretionary lapilli within the Borrowdale Group, which have been used as strain markers. Opportunities for such accurate studies of strain are extremely rare in deformed rocks. They provide invaluable evidence for the calculation of crustal shortening. Results indicate that the late-Caledonian slaty cleavage (S_1) formed by compression and volume loss normal to the cleavage plane, and subvertical stretching. Strain measurement from this site suggests a 50–70% crustal shortening for this part of the Caledonides.

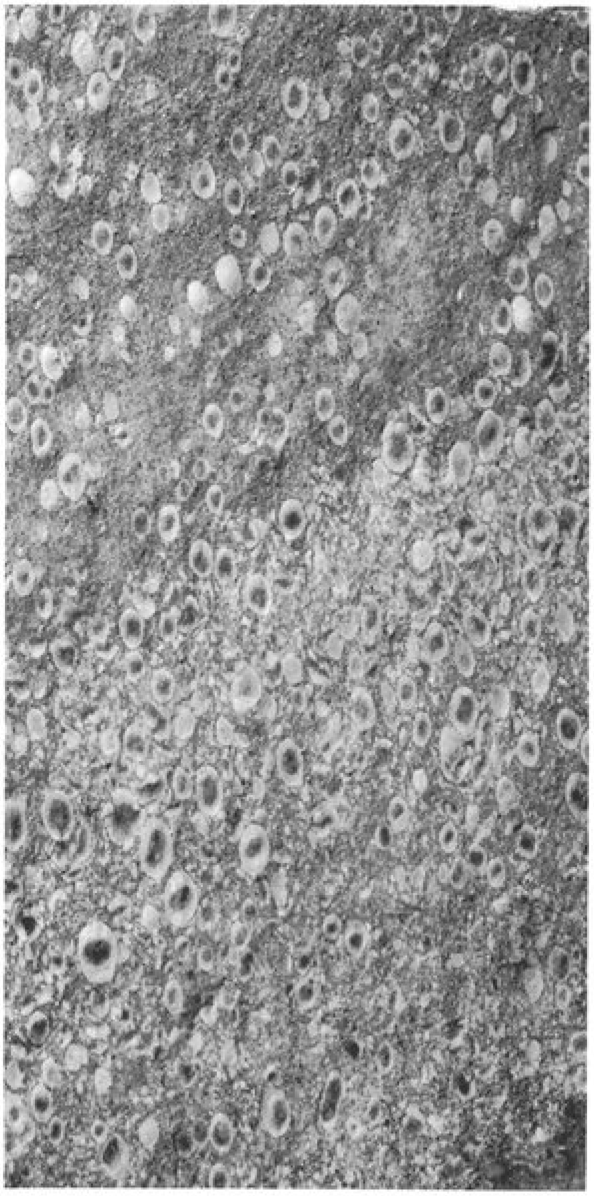
Conclusions

This locality makes it possible to actually measure the amount of compression which the Lake District suffered when continental collision brought about the closure of the Iapetus Ocean around 400 million years before the present. At Jumb Quarry, beds of volcanic ash contain accretions that were once near spherical and which are now near-perfect ellipsoids. In common with other rocks in the volcanic Borrowdale Group, these lapilli were compressed and deformed by this mountain-building event, which geologists call the Caledonian Orogeny. This distortion of the originally spherical lapilli tells us that the rocks in this part of the Lake District were shortened by between 50% and 70% by extreme compressive strain caused by the collision of northern (Scottish–American) and southern (Lake District–European) continents.

References



(Figure 3.22)A and B Flinn plots of average lapilli shapes (A) and actual strain ellipsoids (B) for accretionary lapilli horizons within the Borrowdale Volcanic Group. Ellipsoid long, intermediate, and short axes are denoted by X, Y, and Z respectively. (A) shows the range of overall lapilli shapes throughout the Borrowdale Group (data from Bell (1981 — open circles), Oertel (1971 — open squares), Green (1917 — solid squares) and Helm and Siddans (1972 —solid triangles)). (B) Bell (1981) resolved compaction strains (squares) and tectonic strains (circles). Compaction strains are uniaxial ((X = Y) > Z, k tends to zero) whereas tectonic strains are almost plane (k = 1) (data from Bell, 1981).



(Figure 3.21) Jumb Quarry. The deformed accretionary spheres of volcanic ash have been used to measure the Caledonian strain in these Ordovician rocks. The cleavage plane photographed is 30 cm high and shows the intersection of bedding plunging to the left. (Photo: Dept of Geology, Manchester University.)