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State of strain in a quartzite mylonite, Central Australia

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Abstract—The finite strain due to mylonitization of a quartzite has been determined, using measurements of deformed quartz grains and 'ribbons' developed from quartz grains, equant before the deformation. The mylonites are developed in long, narrow, steeply dipping mylonite zones within the Chewings Range Quartzite of Central Australia; this quartzite is very pure (≈98% quartz). The quartzite surrounding the mylonite zones appears unstrained.

The samples examined exhibit severe flattening strains; k values of between 0.01 and 0.12, and r values of between 5 and 30 have been determined. Application of formulae to calculate volume change, assuming the model of an ideal ductile deformation band structure, indicate significant apparent volume losses, with Δ values between −0.69 and −0.95. Such values seem unreasonably high, as no geological evidence for large volume loss is seen. The band structure model is considered inapplicable for these mylonite zones. The observed structural features can best be explained by a deformation history involving severe bulk shortening normal to the zones.

INTRODUCTION

THIS paper reports the determination of an unusual state of finite strain within a quartzite mylonite, using measurements of deformed quartz grains which were approximately equant before the mylonitization. The samples which have been studied are from mylonite zones occurring within the Chewings Range Quartzite. This quartzite outcrops west of Alice Springs, Northern Territory, Australia, and forms the core of the Chewings Range (part of the MacDonnell Ranges); it forms a long, narrow ridge which begins approximately 25 km west of Alice Springs and extends some 80 km further west, abutting and unconformably overlain by the Late Proterozoic Heavitree Quartzite at Ormiston Gorge (Fig. 1). The Chewings Range Quartzite is part of the Arunta Complex of Central Australia, which has not in general been precisely dated, but is of Middle Proterozoic age or

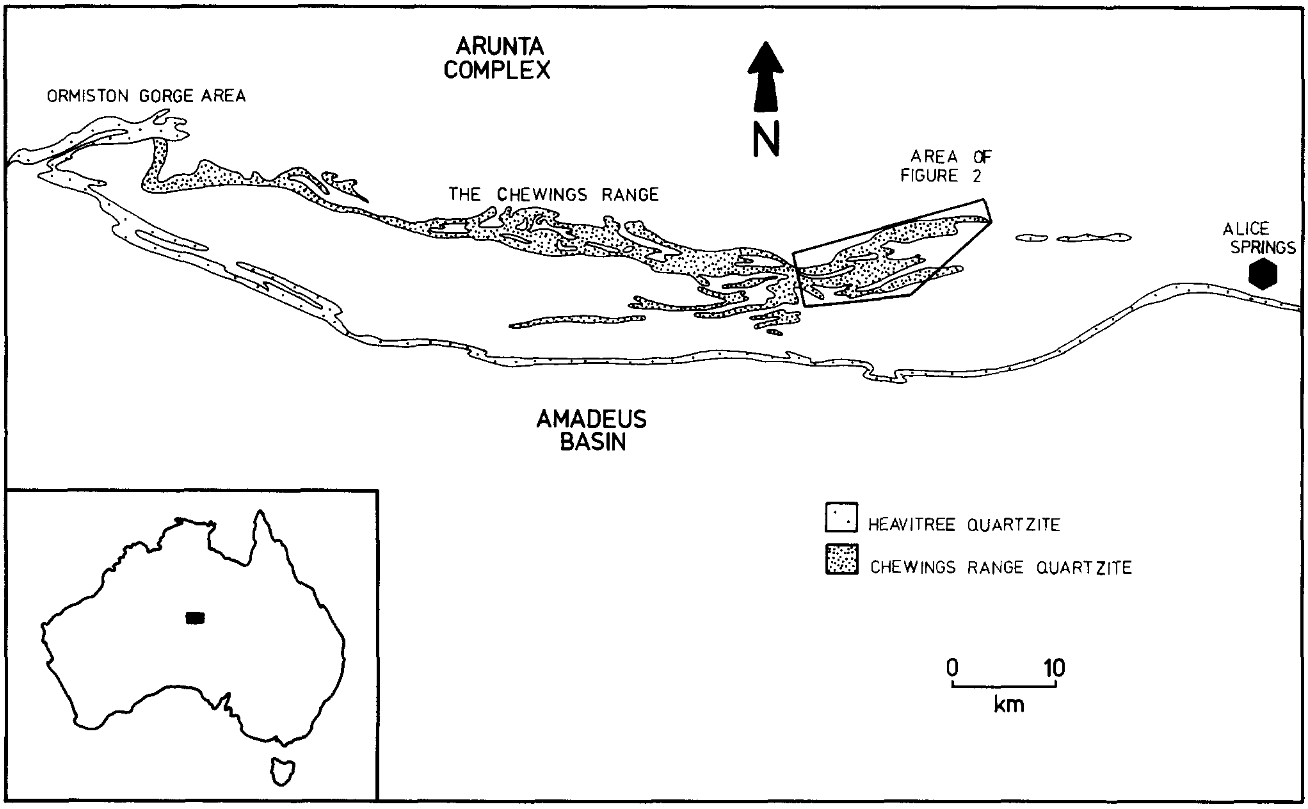

Fig. 1. Geographical location of the area containing the studied mylonite zones. The Heavitree Quartzite is the basal unit of the Amadeus Basin sequence to the south.

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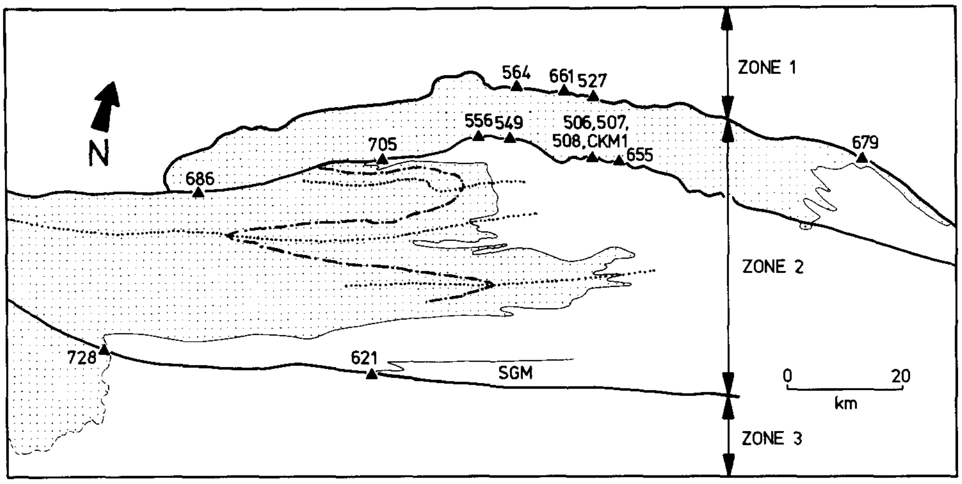

Fig. 2. Simplified geological map of the study area, and sample localities of mylonites collected for strain analysis. The Chewings Range Quartzite is stippled, the surrounding and intercalated schists and gneisses are left blank. SGM is the Simpsons Gap Metasediments. Lithological zones (see text) are shown by the arrows. Heavy solid lines mark the mylonite zones; heavy dot-dash lines are F_2 axial surface trace and fine dotted lines are F_3 axial surface traces.

older, based on structural and stratigraphic grounds. The Arunta Complex in this area is part of a major intracontinental zone of deformation, which trends E–W and extends for more than 500 km across Central Australia (Forman & Shaw 1973).

GENERAL GEOLOGY

The geology of this area has been reported (Mawer 1980, in preparation) and will only be briefly outlined here. The area of study can be conveniently subdivided on a lithological basis into three E–W-trending zones (Fig. 2). These are, from the north, as follows. *Zone 1* is the Burt Bluff Gneiss (Stewart *et al.* 1980), predominantly an augen gneiss which is generally well-foliated and possesses feldspar augen, up to 3 cm in length, in a fine- to medium-grained feldspar–quartz–biotite matrix, and numerous mafic xenoliths. *Zone 2*, a central zone, consists of the Chewings Range Quartzite, intercalated schists of various compositions, and a narrow band of quartz–feldspar–mica schist known as the Simpsons Gap Metasediments (Stewart *et al.* 1980). *Zone 3* , the southernmost zone, is again predominantly well-foliated augen gneiss, the Burt Bluff Gneiss.

Within the study area there are three major mylonite zones (Fig. 2), which are the subject of this paper. All occur at lithological contacts; the northernmost at the contact between the Burt Bluff Gneiss and the Chewings Range Quartzite (Zones 1 and 2), the central at a quartzite–pelitic schist contact, and the southernmost at the contact between the Chewings Range rocks and the Burt Bluff Gneiss (Zones 2 and 3).

The Chewings Range Quartzite in which the mylonite zones are developed is a pure metaquartzite; in fact, at some localities the material is more than 99% quartz. The most important other minerals present are sillimanite and muscovite (totalling only several per cent) in the host quartzite, and muscovite in the mylonitic quartzite. The Chewings Range Quartzite exists as a number of tightly refolded, once-recumbent (nappe-like) large-scale folds which have been partially dismembered by the formation of the mylonite zones.

The mylonite zones

The three major mylonite zones studied transect the map area (Fig. 2). At this scale they are relatively planar, but exhibit very open folding due to minor, late stage deformation. The zones are narrow, ranging in thickness from about one to ten metres; the mylonitic foliation in the zones dips steeply, varying about 15° on either side of the vertical, and the statistical maximum of the mineral lineation is approximately down-dip. The zone boundaries are very narrow (centimetres or less) and parallel to the mylonitic foliation. The foliation in the host rocks over most of the area is approximately parallel to the mylonite zones (except in the hinge areas of major folds) and there is no progressive rotation of this foliation into the zones.

Within the mylonite zones, deformation is markedly inhomogeneous. There is a lack of mesoscopic planarity of the foliation; there are numerous narrower mylonitic layers which enclose essentially undeformed symmetrical lenses of quartzite (identical to the quartzite from outside the mylonite zones), and within these narrower layers deformation is also quite variable. No mesoscopic-scale folding of the mylonitic foliation has been observed.

OPTICAL MICROSTRUCTURES

The deformation microstructures of the quartzite mylonites and the less-deformed Chewings Range Quartzite are unusual and striking, having been preserved due to an almost total lack of either syntectonic or post-tectonic recrystallization. A full description of the microstructures and their development is being undertaken at present (Mawer in preparation); the important features will be summarized here.

The Chewings Range Quartzite from outside the

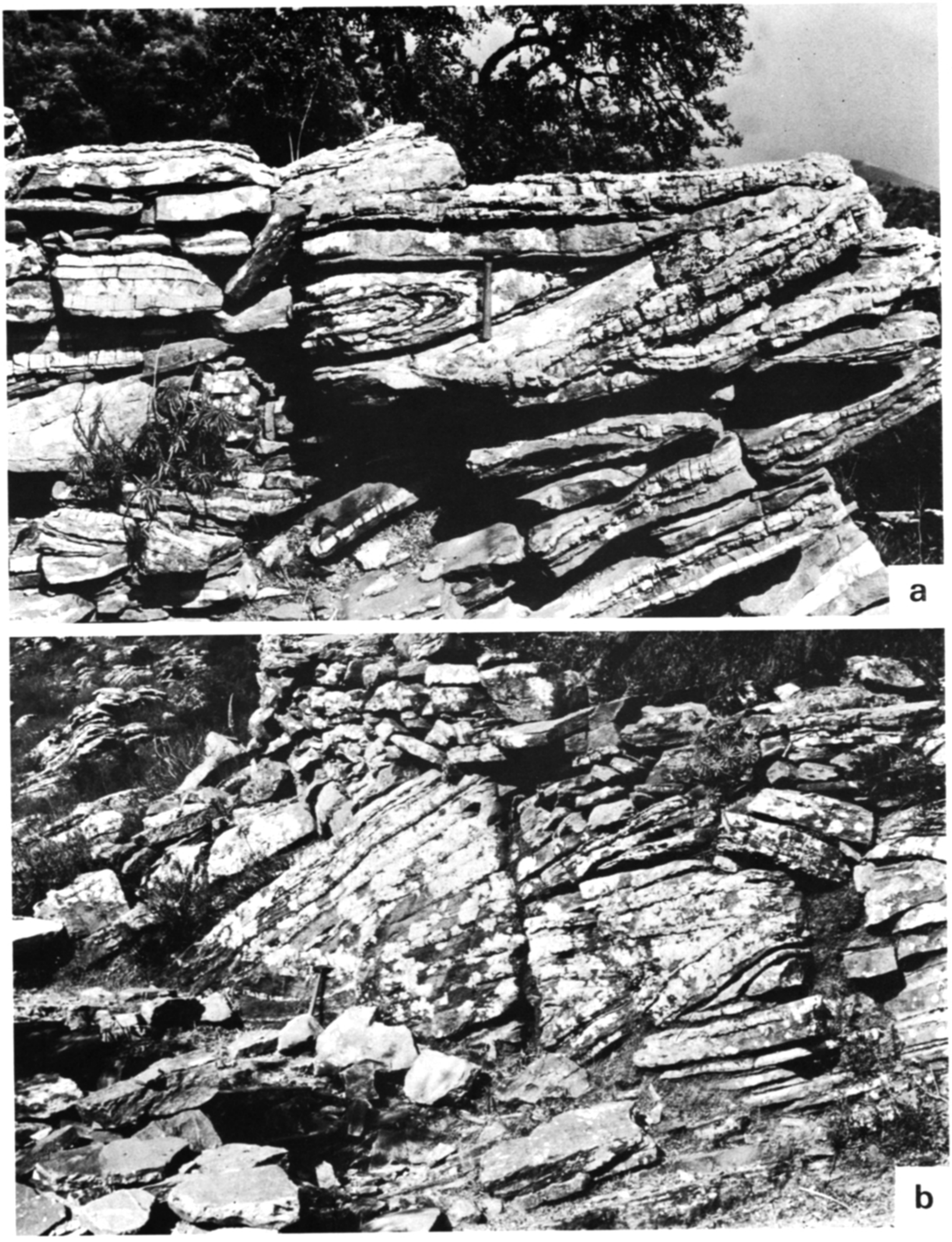

Fig. 3. (a) Photomicrograph of the less-deformed quartzite, perpendicular to the mineral lineation. A weakly developed foliation trends horizontally. Scale bar is 5 mm. (b) Photomicrograph of the quartzite mylonite, sample 506, perpendicular to the stretching lineation. Scale bar is 1 mm.

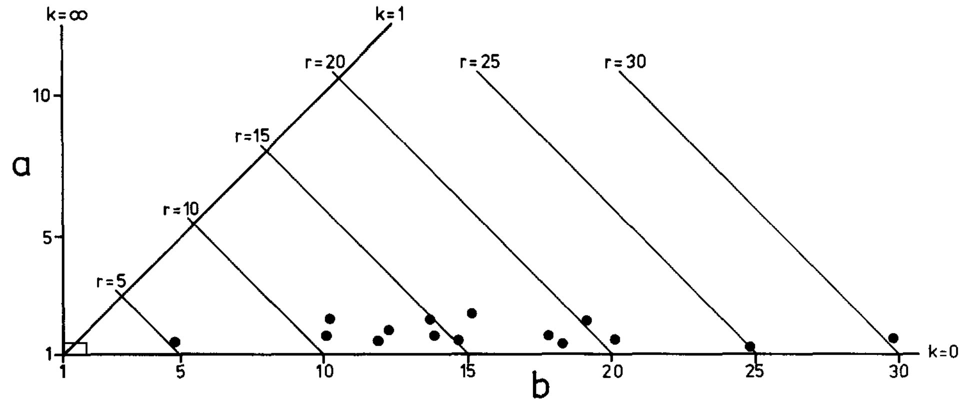

Fig. 4. Flinn diagram with mylonite sample analyses plotted. Contours of *r* refer to strain intensity. The box near origin represents the range of results for five less-deformed quartzite samples.

mylonite zones is, as noted previously, very pure. In thin section, it consists of a coarse, equant, equigranular, interlocking aggregate of quartz grains (Fig. 3a), with a small percentage of radiating fibrous sillimanite spheroids, and very minor amounts of such species as muscovite, tourmaline and opaques. The textures indicate that the quartzite had been considerably grain-size-coarsened prior to the formation of the mylonite zones. There is no crystallographic preferred orientation of the quartz *c* axes.

The quartzite mylonite in thin section exhibits many interesting features. Occasionally single quartz grain 'augen' are observed; these have low length-to-width ratios (usually near 1:1), and investigations with a universal stage show that their *c* axes are approximately perpendicular to the mean foliation plane. These 'augen' are surrounded by highly elongate quartz 'ribbon' grains, which define the mylonitic foliation (Fig. 3b). There is generally a very low degree of recrystallization in these rocks, so these textures are well preserved.

Within the mylonites are developed numerous indicators of shear asymmetry (for example, alignment of grain boundary bulges, folds in old grains, shear band cleavage), which show inconsistent senses on either side of the less-deformed quartzite lenses, and also inconsistent senses across a few centimetres of zone thickness.

The dominant deformation mechanism operative during the formation of the mylonites is considered to have been dislocation creep, in conjunction with slip and kinking on the quartz basal planes. This conclusion is based on the presence of strong crystallographic preferred orientations of quartz *c* axes, dislocation substructures imaged in transmission electron microscopy, and the lack of evidence for the operation of diffusional deformation mechanisms (McLaren & Hobbs 1972, Mawer 1982, in preparation).

STRAIN DETERMINATION

The method

Strain analyses have been performed on five samples of the less-deformed Chewings Range Quartzite adjacent to the mylonite zones, and fifteen samples of quartzite mylonite taken from the three zones (sample localities are shown on Fig. 2). The less-deformed samples all plot at or near to (1, 1) on a Flinn diagram (Fig. 4) and will be considered no further. Length-to-width ratios of deformed quartz grains were determined from measurements made on orthogonal thin sections cut normal and parallel to lineation and foliation; only values from the 'ribbon' grains have been used in the analysis. These ratios were used to calculate parameters *a, b* and *k* (Flinn 1962), and *r* (Watterson 1968), defined in Table 1. The data are presented on a Flinn diagram (Fig. 4) rather than the R_f/ϕ diagram (Dunnet 1969) because of the abrupt transition from less-deformed to mylonitic quartzite, the quite high intensities of the strain, and the minimal fluctuation of the 'ribbon' grain's long axes about the foliation trace (cf. Hutton 1979).

Single quartz grains are seen to be highly elongate in thin section, and are in fact now composed of the elongate 'ribbons' referred to above, which have developed from deformation bands within the original grains (Fig. 3b). In the purest mylonites (from the central zone) it is only rarely possible to identify original grain boundaries, but in the mylonites from the northern and southern zones original grain boundaries are identified readily, as there is usually a slight dispersion of fine white mica (and its weathering products) along them. The strain results below have been derived from measurements of 'ribbons' in mylonites from the central zone, and from measurements of deformed original grains and 'ribbons' in mylonites from the northern and southern zones. Comparison of length-to-width ratios of 'ribbons' and deformed original grains from these latter zones (and in the rare occasions where original grain boundaries could be identified in the central zone mylonites) indicate that the ratios of the 'ribbons' are very similar to the ratios of the whole grains, though obviously they have smaller absolute dimensions.

The results

The results of the strain analysis of the quartzite mylonites are presented in Table 1, and graphically in Fig. 4 (a Flinn diagram; Flinn 1962), Fig. 5 (a logarithmic deformation plot; Wood 1974), and Fig. 6 (a plot of *r* versus *k*).

Table 1. Calculated strain values and parameters for the studied mylonite samples

Sample	a	b	$+\%X$	$+\%Y$	$-\%Z$	k	r	$-\Delta$
(1) Northern zone								
564	1.61	10.03	205	80	82	0.068	10.64	0.839
661	1.47	14.63	215	115	84	0.034	15.10	0.900
527	2.12	10.19	255	67	83	0.122	11.31	0.792
679	1.43	11.86	185	105	83	0.040	12.29	0.879
(2) Central zone								
686	1.78	12.23	240	90	83	0.069	13.01	0.854
705	1.57	17.75	255	120	86	0.034	18.32	0.912
556	2.11	19.01	345	111	89	0.062	20.12	0.889
549	2.20	13.66	300	84	85	0.095	14.86	0.839
506	2.38	15.05	315	82	86	0.098	16.43	0.842
507	1.56	29.76	320	175	91	0.019	30.32	0.948
508	1.14	24.78	215	180	88	0.006	24.92	0.954
CKM1	1.59	13.76	235	103	84	0.046	14.35	0.884
655	1.42	20.04	245	140	87	0.022	20.46	0.929
(3) Southern zone								
728	1.46	4.82	120	48	69	0.120	5.28	0.697
621	1.34	18.22	235	140	87	0.020	18.56	0.926

Notes: (1) Samples listed from west to east, see Fig. 2.

(2) (i) $a = \frac{X}{Y}$, $b = \frac{Y}{Z}$ where X, Y and Z are magnitudes of maximum, intermediate and minimum finite strain ellipsoid axes, respectively (Flinn 1962).

(ii) $k = \frac{a-1}{b-1}$ (Flinn 1962).

(iii) $r = a + b - 1$ (Watterson 1968).

(iv) $\Delta = ABC - 1\ \frac{A}{B}\cdot\frac{C}{B} - 1$ where A, B and C are equivalent to X, Y and Z above (Schwerdtner 1982).

(3) $+\%X$, $+\%Y$, $-\%Z$ from Fig. 6, values approximate.

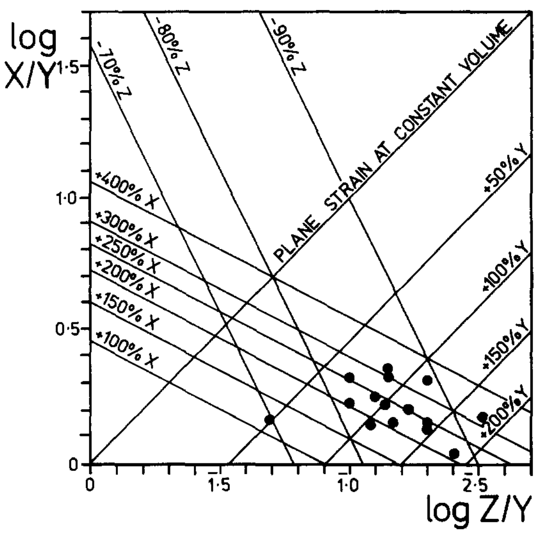

Fig. 5. Logarithmic deformation plot of mylonite sample results.

Perhaps the most striking feature of the results is the low values of, and low range in, the parameter k which describes the shape of the strain ellipsoid. All values so far calculated range between 0.01 and 0.12. The parameter r (Watterson 1968), a measure of the strain intensity, shows variation from ~5 to 30, with most values between 10 and 20. It must be pointed out that these values are averages, and almost certainly are minimum values (see next section). As a visual indication of the meaning of these numbers, Fig. 7 shows unit cubes which have been drawn to indicate the approximate finite strains accumulated for the respective samples as numbered; thin sections cut parallel to the mylonitic foliation exhibited large elliptical quartz grains with wavy undulose extinction and shapes that accorded well with these deformed cubes.

The recorded values indicate extreme flattening-type finite strains. From the logarithmic deformation plot (Fig. 5) the approximate percentage increase or decrease in the X, Y and Z directions may be read off. It is seen that the values cluster around an increase in X of 200–300%, an increase in Y of 100–150% and a decrease in Z of 80–90%. These are surprising values, and to the writer's knowledge (c.f. fig. A1 of Pfiffner & Ramsay 1982) represent some of the most intense flattening strains yet recorded. Figure 6, a plot of r vs k, shows that there is a general trend for the strain ellipsoid to become more oblate as the strain intensity increases, even considering the low values of k and high values of r. Two further points are considered; sources of error in the strain analysis, and the possibility of volume loss from the mylonite zones.

Possible sources of error

The strain analysis of these mylonites was subject to several possible sources of error. The major problem arises from measurement of the 'ribbon' grains, and the calculation of their principal strain ratios. In thin section (Fig. 3b) the thickness of the individual grains (the Z dimension) varies along the length of the grain. However, considering the vast difference between the Z and the X and Y dimensions, this is not a serious problem; an average measurement for Z of each individual grain was derived and used in the analysis. Another source of error

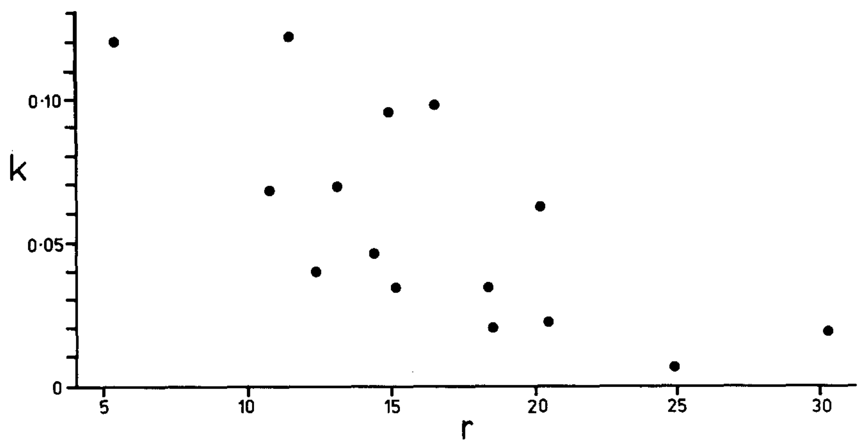

Fig. 6. Plot of k vs r for analysed mylonite samples.

lies in the fact that the tips of the 'ribbon' grains often exhibit severe grain-boundary bulging or some recrystallization, but again considering the extreme difference between the X, Y and Z dimensions this will not cause gross inaccuracy. A more serious problem occurred due to some 'ribbon' grains which were longer than the 75 mm of material available for measurement in one thin section. These grains were thus not included in the analysis; the strain ratios were calculated by averaging approximately 30 pairs of measurements per thin section and so the presence of these occasional very long grains would tend to minimize calculated values, but again considering the disparity in dimensions of grains this feature is probably not critical.

As mentioned previously, only the 'ribbon' grains of quartz have been measured and used in the strain analysis; these were presumably oriented so that slip was fairly easy, and they strained passively or nearly so, whereas the rare 'augen' grains were in 'hard' orientations. A further point to consider is the possibility of any geometric effect on the finite strain, that is, an effect due to the presence of a crystallographic preferred orientation. As stated previously, the quartzites prior to mylonitization possessed no c-axis preferred orientation, so that geometric hardening or softening effects were minimal.

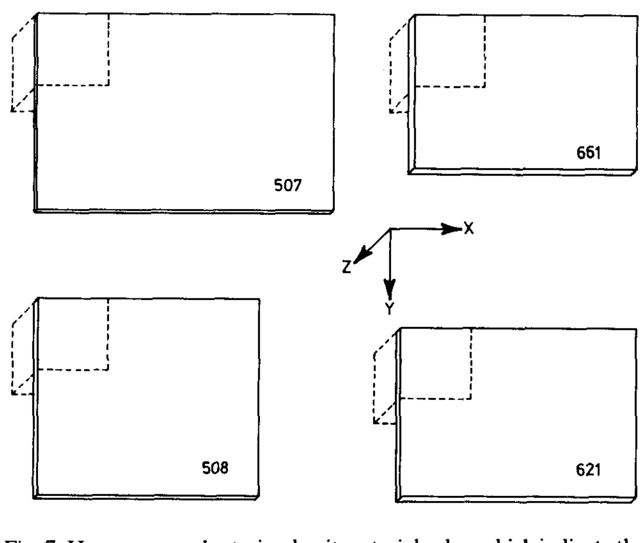

Fig. 7. Homogeneously strained unit material cubes which indicate the finite states of strain for the samples as numbered, looking down on the flattening plane.

In general, the quartzite is very pure. The mylonites of the central zone are developed within the purest quartzite, whereas those of the northern and southern zones are developed in slightly less-pure quartzite; comparison of the various strain parameters (Table 1, Figs. 4–6) shows that any hardening effect due to the presence of mineral species other than quartz was not great, but perhaps it minimized the averages mentioned in the previous section. However, while the intensity of the strain recorded in the northern and southern zones is perhaps slightly less than that in the central zone, the type of strain (flattening close to axially symmetric shortening) is identical.

Volume loss?

One way in which the observed finite strains within the present mylonite zones could have been attained is by significant volume loss during formation (c.f. Ramsay & Wood 1973); such volume loss tends to cause strain values to plot within the flattening field of a Flinn diagram. With this possibility in mind, values of apparent dilation were calculated using the measured strain values and equations derived from the theory of band structures.

A number of geological structures, including shear zones and mylonite zones, have been analysed and modelled as being ideal bands which have undergone ductile deformation different from that occurring in the surrounding material (e.g. Ramsay & Graham 1970, Cobbold 1977, Schwerdtner 1982). This band structure theory is based upon the following premises. The band is of finite width and indefinite length, and the length is much greater than the width (to allow one to consider just the central, approximately parallel-sided segment of the band and escape complications due to its presumably ellipsoidal tip). (2) The band walls are approximately plane and parallel to one another. (3) The surrounding material is undeformed (or has undergone homogeneous deformation, Schwerdtner 1982), whereas the material within the band is subjected to a continuous ductile deformation which was different in type or intensity to that occurring outside the band. As all these premises hold for the mylonite zones studied, certain equations derived from the ideal band structure theory were used to calculate apparent volume changes within the zones. Equations from Schwerdtner (1982) allow calculation of Δ, the cubic dilation (cf. Ramsay & Wood 1973), using magnitudes of principal strain. The values so obtained are shown in Table 1.

It is immediately obvious that the derived apparent volume losses are very large, varying from some 69% in the least deformed mylonite to a value in excess of 95% in the most strongly deformed rock, with most values between 83 and 95% apparent volume loss. Such values are thought to be untenably high, for the following reasons. Firstly, based on measurements of grain principal diameters it is seen that the volumes of quartz grains from the less-deformed quartzite (both immediately surrounding, and enclosed as pods by, the quartzite mylonite) are closely comparable to volumes of grains from within the mylonite. Secondly, there is no evidence seen in thin section of the operation of diffusive deformation mechanisms (no microstructures such as pressure shadows or overgrowths), and finally, no mesoscopic geological evidence is observed for any sort of mass diffusive process (no structures such as differentiated layering or quartz veins). It is, thus, considered that the observed finite strains in these mylonite zones have been accumulated without any volume loss from the zones.

DISCUSSION

It has been shown that the approximately (macroscopically) planar zones of mylonite found within the Chewings Range Quartzite of Central Australia have developed in response to a deformation history involving severe flattening, but no volume loss, on the bulk scale. Within these mylonite zones deformation is extremely inhomogeneous, with the transition from essentially unstrained quartzite to intensely deformed mylonite taking place over centimetres or less. One must consider how these unusual finite strain states and strain variations were developed.

It has long been thought that some mylonite zones formed in response to either a combination of progressive inhomogeneous simple shearing and progressive inhomogeneous bulk flattening to varying degrees (e.g. Hossack 1968, Coward 1976), or in response to progressive inhomogeneous bulk flattening not necessarily related to translational movements (e.g. Johnson 1967, Ross 1973). The first hypothesis may be imagined as a frame hinged at all corners which is extended along one diagonal, the second as a sheet of foam rubber loaded perpendicular to the plane of the sheet. It can be shown that unless there is extension along both principal directions in the plane of maximum flattening (that is, the bulk strain is triaxial and the strain ellipsoid is oblate), there must be volume loss from the mylonite zone, as neither model is volume-conservative for plane strain.

For the present mylonite zones the volume loss indicated is improbably large, and the finite strain is triaxial (flattening). The band structure theory, as presently formulated, thus seems unable to explain these zones. The deformation is considered to be coaxial at the scale of the zone width because symmetrical ellipsoidal lenses of less-deformed quartzite are enclosed by anastomosing mylonitic layers, with microstructures indicating opposite senses of shear asymmetry on either side. Deformation appears to be locally coaxial even at the scale of single thin sections shown by the existence of 'augen' quartz grains with *c*-axes perpendicular to the mean foliation trace and surrounded by anastomosing 'ribbon' quartz grains.

The formation of the present mylonite zones can be explained with reference to the model of Bell (1981), involving what he termed 'progressive, bulk, inhomogeneous shortening'. Bell pointed out several constraints which must obtain if this model is to explain the formation of mylonite zones: (i) the maximum finite elongation must plunge approximately down-dip on the foliation; (ii) the foliation must anastomose if the zone is to remain on average planar at the macroscopic scale (assuming the anastomosing foliation corresponds to local variations of strain) and (iii) the shear asymmetry shown by individual mineral grains is consistent with the proposed strain history (e.g. opposite asymmetries on either side of ellipsoidal pods of less-deformed material).

It has been shown that the mylonite zones studied fulfil these criteria perfectly. However, there still remains the problem of extrusion of material from the zones. This extrusion is required because of the deformation history involving bulk shortening and the triaxial flattening strains recorded in the mylonite zones, necessitating extension in all directions perpendicular to the shortening direction. Laterally, the required extension may possibly be taken up by complex variations of strain, such as a transition to a strain pattern dominated by transcurrent simple shear. Bell stated (1981, pp. 282–283) that for the vertical extension required, provided that the maximum extension was down-dip in the foliation plane, the problem could be resolved by crustal thickening. There are several difficulties involved in applying this concept to the present mylonite zones. If the strain showed a smooth variation with a wide transition zone from unstrained to strained rock, the idea would be feasible (but would the resultant structure be a mylonite zone?). With the present zones however, considering their nominal transition width from less-deformed to mylonitic quartzite, and the extreme strains involved, the problem remains. It does not seem possible that a 'dyke' of mylonite could be intruded into the overlying rock, though this invasion may be negated by diffusive mass transfer at the interface, driven by steep chemical potential gradients between dissimilar rock types and high dislocation densities (high internal elastic strains) in the mylonite.

Three arguments may be considered.

(1) The strain measurements are wrong, and do not reflect flattening. That is, the geometry of the finite state of strain tells nothing about the deformation his-

tory/strain path. This is obviously possible in some situations, but is difficult to imagine in the present case with an essentially homogeneous, initially random-fabric material that shows no evidence of diffusive mass transfer.

(2) The measurements are correct with respect to the type of strain, but (grossly) overestimate its magnitude. Strain in the present case is concentrated in narrow, anastomosing zones; locally the strain is very high whereas the bulk strain may not be. It is hard to see how quartz grains in a matrix of quartz grains all being deformed together could behave so as to consistently overestimate the strain that the volume of material has suffered.

(3) The measurements are a true reflection of the finite strain within the mylonite zones, which leads directly back to the problem of extrusion of material.

As seen from the above, this problem in respect to the present case does not at first appear easily solvable. It will be discussed in detail in a forthcoming paper.

One possible explanation for the development of the large flattening strains is that the mylonites have undergone a two-stage deformation history, a later deformation with a large simple shear component being impressed upon a similar earlier one, having shear directions perpendicular to one another. No geological evidence of such a history is observed; no overprinting relationships between any sorts of structures occur within the mylonites, and there is no indication of any large translations, either vertically or horizontally. A history involving large components of two perpendicularly superimposed simple shears is thus rejected.

CONCLUSIONS

(1) Steeply dipping mylonite zones have been developed within pure, initially unstrained quartzite. These zones are planar at the macroscopic scale, but are seen to be composed of anastomosing mylonitic layers surrounding less-deformed lenses at the mesoscopic scale.

(2) Strain analysis using measurements of deformed quartz grains and 'ribbons' developed from quartz grains (considered equant before mylonitization), shows that the mylonites have accumulated very large flattening strains. All analysed mylonites plot close to the axis $k = 0$ of a Flinn diagram, usually at quite large distances from the origin.

(3) Application of equations derived from the ductile band structure theory to determine volume changes within the mylonite zones indicate apparent volume losses of between 70 and 95%. These values are unreasonable; no geological evidence is seen for such large volume losses, and it is considered that the band structure theory is inadequate to explain these mylonite zones.

(4) The development of these mylonite zones can best be explained in terms of a deformation history involving severe bulk shortening normal to the zones, without volume loss.

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