Strain partitioning and magnetic fabrics in particular flow

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Strongly deformed Archean sandstones and conglomerates in northwestern Ontario show extreme heterogeneity of strain, with pebbles deformed more than feldspar grains, which are more deformed than quartz grains. Despite the heterogeneous changes of shape, particular flow has preserved a strong preferred grain orientation and the magnetic susceptibility ellipsoid usually still tracks the orientations of the principal strain.

Introduction
Sandstones and conglomerates of Archean age are exposed in a wedge-shaped area of rocks between major tear faults along the interface of the Wabigoon greenstone belt and the Quetico metasedimentary belt of northwestern Ontario. The rocks were studied in an area of about 20 km² at 48°45′N., 92°30′W., nearly 200 km west of Thunder Bay, Ontario. The sequence of clastic sediments includes alluvial fan deposits and some fluvial sediments (Wood 1980) in the present area. The disposition of the strata in the area is incompletely known because of the lack of bedding markers and lack of exposures in critical areas. However, the rocks are known to be deformed in the northwestern part of the study area and in the eastern part of the study area, where multicycle folds occur. The folds have wavelengths of up to 2 km and much larger amplitudes. It is sometimes difficult to evaluate the structural position of individual outcrops in the arrangement of major folds.

Data for strain analysis
Over 100 oriented samples of the strongly deformed arkosic arenites and wackes were selected from 45 different outcrops or parts of outcrops. Multiple, large (75 mm × 50 mm) thin sections were made perpendicular to the cleavage and to the fabric plane. The lengths of the longer and shorter dimensions and the orientations of the principal axes were visually identified and recorded for at least 50 sand-size quartz clasts or 50 sand-size feldspar clasts from each suitable thin section. The orientations of the grains were recorded with respect to the penetrative schistosity defined by the preferred orientation of the micaceous minerals. The grain-shape data were analysed separately for quartz and for feldspar from over 100 thin sections. Strain was estimated from the grain shapes and orientations in the following ways.

1) “De-straining” methods. Each assemblage of natural grain shapes and orientations was “de-strained” by successive increments until the assemblage “matched” a hypothetical prestrain uniform or random distribution. The χ² and z²-for-runs statistics were used to optimize the match, and graphs were plotted in all cases to check the success of the match. (For details see Borradaile, in press.) This method, like the R²/X and R²/y methods, assumes passive behaviour of the markers.

2) The “minimum strain” method of Borradaile (1981) was applied. This does not assume that the grains behave passively but rather that they quickly align with the early principal strain orientations and then change shape. In natural conglomerates and sandstones the clasts are not usually passive strain markers. Only part of their change in shape and reorientation is attributable to a passive geometrical transformation. Sediments are not continua and different parts of the fabric plane, and perpendicular to the lineation (XZ fabric plane). The lengths of the preferred extension at that time. Although it may have already undergone some past passive strain all subsequent passive shape change can be determined simply by the minimum method.

These two contrasting philosophies of strain analysis should provide upper and lower limits on the actual strain of the...
The strain ellipse ratios for each compatible pair of XZ and YZ sections were then combined to define the strain ellipsoid axial ratios. These ratios were determined for quartz and feldspar separately by both the "de-straining" and the minimum method. Which of these methods gives more meaningful results?

Comparison of the strain ratios for quartz and feldspar by different methods

An overview of all strain ellipsoid ratio determinations for samples with 50 grains in each of at least two principal planes is given in Fig. 1. Strains determined by the optimization method are larger than those determined by the minimum method. Which of these methods gives more meaningful results?

The "de-straining" methods, like all methods of the R̂ family (Ramsay 1967), assume passive behaviour of the clasts. Since the clasts are not perfect strain markers and were generally less ductile than the matrix they will have rapidly aligned by rigid-body rotation after only a little strain of the rocks. A much larger strain would be required to develop the same preferred orientation in passive markers. Therefore, the "de-straining" methods may overestimate the strain responsible for the orientations of the grains used in the analysis. On the other hand, the minimum method must underestimate the strain of the sedimentary particles for they did not instantaneously align with the embryonic cleavage at the commencement of tectonic strain.

Presumably the true strains experienced by clasts of a given composition lie somewhere between the extremes indicated by the different methods of analysis in Fig. 1. The more interesting question, how the strains of grains relate to the bulk strain (the strain of the whole rock), will be discussed below.

Strain partitioning

Figures 2–4 indicate the X/Y versus Y/Z strain ratios for quartz and feldspar grains. A few results are also presented from strain analysis of field measurements on shapes and orientations of granitoid pebbles. Strain data for quartz and feldspar grains in the same sample are connected by tie lines. Where
strain data for pebbles were available from the same outcrops; their strain ellipsoid shape is also connected by a tie line to the quartz and feldspar data.

The strain data for pebbles are inferior to those for sand grains measured in this section. This is because the natural outcrop surfaces on which pebble shapes were measured are not their principal planes. (Data were only collected where the surfaces were less than 15° from principal fabric planes.) Also, the accuracy of measurement in the field is not as good as in the laboratory. The most reliable results of many such attempts to measure strain from pebbles in outcrops are illustrated.

Data for the principal strain ratios \( a = X/Y, b = Y/Z \) of sand-size classes are shown in Figs. 2 and 3, and those for outcrops where it was possible to estimate crudely the strain of pebbles are shown in Fig. 4.

In all but one sample the clasts and pebbles show a flattening deformation \( (b > a) \). Considering sand-size classes, two categories arise. In some examples, quartz shapes are less strained than those of feldspar (Fig. 2: 13 samples); in others quartz is slightly more strained than feldspar (Fig. 3: 11 samples). The sense of partitioning between quartz and feldspar is not determined by the location of the outcrop within the region, but that cannot be ruled out entirely because the precise position of every outcrop with respect to major folds does not appear to be influenced by the location of the outcrop. Because the orientation of the fabrics on an outcrop scale is consistent, gross heterogeneity of strain between parts of outcrops does not appear to be sufficient to account for the greater strains of the pebbles.

In the context of the original sedimentary rock, the pebbles were certainly more rigid than equal volumes of the interbedded sandstone. However, during the greenschist facies metamorphism it is possible that there was a smaller difference in rheidity between the pebbles and their matrix. Under those conditions the granitoid pebbles could act as polygranular strain markers whose outlines record the sum of the strains of the constituent grains and of the intergranular motion. The intergranular motion would not simply involve grain-boundary sliding but rolling of grains, relative motion of groups of grains in the pebbles, and perhaps some cataclasis. For this reason the umbrella term “particulate flow” is used to describe the intergranular motions (Borradaile 1981; Lister and Williams 1983).

Where this reasoning applies, strain analyses of individual grains cannot represent the strain of the whole rock. The bulk strain of the rock may be more closely approximated by the strains of polygranular strain markers such as pebbles. In pebbles, however, particularly of plutonic igneous rocks as in the present study, the cohesion of grains within pebbles will be greater than between grains in the matrix. Thus strains estimated from pebbles will still underestimate the bulk strains of the conglomerate.

Anisotropy of magnetic susceptibility

Some rock types may show a good correlation between the orientations of principal directions (and even the logarithms of ratios of principal values) of magnetic susceptibility and those of finite strain (Rathore 1979; Kügler et al. 1981; Rathore and Henry 1982) especially at lower and moderate strains. In this study large strains have been shown to be differently accommodated by quartz, feldspar, and polygranular pebbles. If magnetic susceptibility can remotely sense finite strain, how will it correlate with the strained fabric?

In all cases the minimum susceptibility is oriented nearly perpendicular to schistosity, which is shown to be indistinguishable from the XY plane of the strain ellipsoid and the grain-shape lineation, which is oriented north-south (L). (Lower hemisphere, equal-area projection.)
A magnetic susceptibility anisotropy (MSA) is a useful tool for studying the deformation of rocks. In a recent study, Borradaile and Tarlino investigated the relationship between magnetic susceptibility anisotropy and strain in Permian sediments from the Maritime Alps (France). They found that the principal susceptibilities can track the strain directions, and the granitophile magnetite grains are smaller than the quartz and feldspar clasts. This suggests that the magnetite grains may be involved in complex orbital motions within the intergranular spaces of the metasediment during deformation.

However, there is no direct correlation between the magnitudes of principal susceptibilities and the strain values. The persistence of some component of the bedding fabric is one possible explanation for this. In view of the heterogeneous nature of particulate flow, it is remarkable that the principal susceptibilities can track the principal strain directions so well. The magnetic grains are orders of magnitude smaller than the quartz and feldspar clasts, and, being more rigid, they are probably involved in complex orbital motions in the intergranular spaces of the metasediment during deformation. This attests to the value of magnetic susceptibility anisotropy (MSA) studies even in rocks that have undergone such heterogeneous strain and flow.

In present study, strains are high and there have clearly been both active and passive components to the fabric evolution. Of even more importance, the strain is differently distributed between different mineral species in individual samples. It is therefore to be expected that MSA would be less directly related to simple estimators of either bulk or grain strain where the heterogeneous nature of particulate flow dominates (Fig. 6A and B).

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