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A method for quantitatively analysing dynamic recrystallization in deformed quartzitic rocks

BRETT FREEMAN

Department of Geology, University of Newcastle upon Tyne, NE1 7RU, U.K.

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Abstract—Quantification of the microstructural changes brought about by dynamic recrystallization is essential for the interpretation of deformation mechanism histories and for the understanding of recrystallization as a syn-kinematic process. A method is presented for analysing the degree of dynamic recrystallization and for reconstructing the original grain-size distribution from that measured in the deformed specimen. This is based on size distribution measurements and comparative volume calculations between subsets of grains which contain rutile inclusions and subsets which do not. Application of the method to some quartzites from the Kilmory Bay Syncline, S.W. Highlands, Scotland, demonstrates that up to 25% of the apparent matrix grains are new grains produced by the dynamic recrystallization of porphyroclasts, and that the new grains alone compose more than 12% of the total rock volume. These figures are 2–3 times larger than estimates made by normal petrographic inspection. It is also shown that grain-size distributions alone convey little information about the microstructural changes and that grain-size vs volume fraction graphs are more meaningful.

INTRODUCTION

DEFORMATION of metasedimentary rocks in the Earth's crust is a complex process which may involve several mechanisms at any one time. The relative contribution of each mechanism will vary spatially with variations in mineralogy and microstructure from bed to bed, and temporally as the microstructure is modified with strain. Dynamic recrystallization of grains deforming by dislocation creep tends to reduce the overall grain-size towards a stress dependent steady-state grain-size (Twiss 1977). This, in turn, produces a shift in the relative contribution of each mechanism in favour of grain-size sensitive mechanisms such as diffusional creep or, if a fluid phase is present, solution mass transfer processes. Attendant with the progressive change in grain-size distribution is a loss of 'memory' of mechanisms operating in the earlier stages of the deformation mechanism history. Consequently the mechanisms which are inferred from routine petrographic studies are only pertinent to the understanding of the final stages of deformation.

In quartz tectonites it is sometimes possible to assess the importance of mechanisms in earlier parts of the history. This entails making reliable estimates of the original microstructures, particularly the grain-size distribution. Attempts to do this are usually based on the observations of grain-size variations from low to high strain zones, with the implication that the low strain grain-size distribution represents an earlier state of that now seen in the high strain zone (e.g. Rathbone & Harris 1979). However, this approach is unsound unless the XY plane of the finite strain ellipsoid in the high strain zone is oblique to the original layering. In this paper a technique is described which enables the pre-deformational grain-size distribution to be determined in rocks which have suffered extensive dynamic recrystallization.

METHOD

General considerations

Any quantitative study of dynamic recrystallization, whether on experimentally or naturally deformed material, depends on our ability to distinguish between the new and old grains which make up the small grain-size fraction. Experimentalists are able to compare pre- and post-deformation states directly, but as the following hypothetical example illustrates, the microstructure we observe in naturally deformed rocks can be ambiguous. Consider two undeformed quartzites of contrasting microstructure. Quartzite 'A' comprises equiaxed grains with a mean diameter d, while 'B' has a bimodal grain structure, the large fraction centred about d and the small grain sizes about $d/10$. We can imagine deformation under conditions where the equivalent steady state grain size is close to $d/10$. Clearly after very large strains the microstructures 'A' and 'B' will be indistinguishable, both reflecting the steady state grain-size. Also, similar microstructures may evolve after large strains in 'A' and relatively small strains in 'B', which could lead to misinterpretation.

The problem is essentially that of being able to locate the original grain boundaries after deformation. Identification of new grains in the mantles of deformed porphyroclasts (White 1976) is often quoted as evidence for dynamic recrystallization, but unfortunately this cannot be quantified (thus resolving the above problem) without having an objective method for distinguishing between old and new grains at distances greater than one grain diameter from the porphyroclast margin.

Use of rutile inclusions to locate original grain boundaries

Detrital quartz grains often contain inclusions of rutile

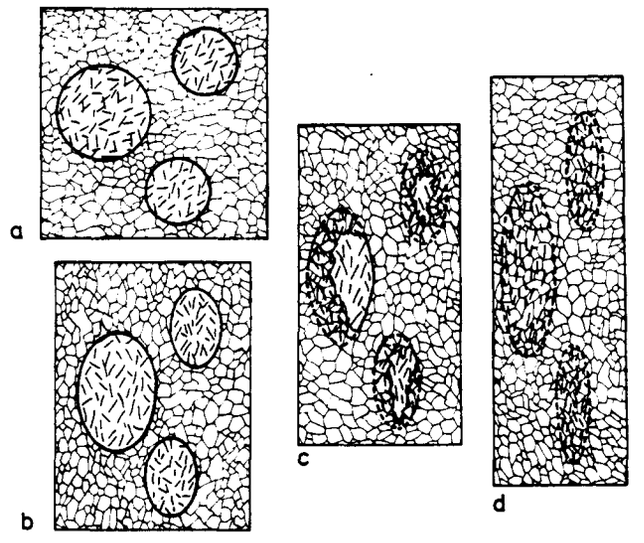

Fig. 1. Schematic representation of the progressive recrystallization of three porphyroclasts containing rutile inclusions. (a) No deformation. (b) Slightly deformed but with no recrystallization. (c) Core and mantle structure developed. Remnant porphyroclast partially surrounded by rutilated new grains (dotted lines indicate the inferred original grain boundary). (d) Total recrystallization but original grain boundary marked by rutiles.

needles which remain present throughout deformation and are apparently unaltered during metamorphism at least up to greenschist facies (see also Mitra 1976). Initially the positions of the rutile needles are controlled by the clastic grain boundaries (Fig. 1a). As deformation proceeds the original grains change shape (Figs. 1b and 2a), and their boundaries may eventually become lost altogether, lying somewhere in the recrystallized grain mantle (Figs. 1c and 2b). During this time the needles themselves are deformed (Mitra 1976) and their angular distributions modified by rotation within the quartz lattice. Their most important property, however, and the one which forms the basis of the quantitative method described here, is that they still mark the original clastic grain boundary even after there has been total dynamic recrystallization (Fig. 1d).

Sample preparation and data collection

The technique requires no expensive equipment other than a standard optical photomicroscope with a facility for dark field illumination (d.f.i.). Rutile needles are most clearly observed in d.f.i., provided that care is taken during thin section preparation; I have found that the most satisfactory image is obtained when the rock slice is polished on both sides, mounted on a polished glass slide and viewed without a cover slip. The measured quantities, which are essentially areal in nature, are then most easily made from photomicrographs. The average areal fraction measured from a section through a volume represents the average volume fraction of the phase under investigation (Underwood 1970, p. 27). In this case we can consider rutilated and non-rutilated grains, porphyroclasts and matrix, etc., as distinct phases, so the areal measurements can be used directly in the volume calculations. For purposes of clarity the recommended procedure, and the symbols adopted to represent each quantity, are summarized in Fig. 3.

Theory

The theory is based on two assumptions. The first is that the mechanical properties of rutilated and non-rutilated grains do not differ appreciably; and the second is that the grain-size and grain-shape distributions of the rutilated grains represent an unbiased sample from the population of all the grains.

Before deformation involving dislocation creep, we can imagine a microstructure comprising two subvolumes, $\bar{p}_o$, the volume fraction of large detrital grains and $\bar{m}_o$, the volume fraction of matrix grains (see Fig. 3). (Subscript o refers to the undeformed state.) After an arbitrary amount of strain, during which time synkinematic recovery takes place by dynamic recrystallization, a third subvolume develops comprising all the dynamically recrystallized grains, $\bar{r}_f$ (subscript f refers to the deformed state). The production of $\bar{r}_f$ results in the reduction in volume of the large detrital grains, $\bar{p}_o$, to the observed volume of porphyroclasts, $\bar{p}_f$. Although on textural grounds it may be possible to demonstrate that large detrital grains have partially recrystallized dynamically, it is only possible to measure directly $\bar{p}_f$ and a quantity representing all the small grain-size fraction $\bar{m}_f$, with no way of factorizing $\bar{m}_f$ into its two components $\bar{r}_f$ and $\bar{m}_o$. However, Fig. 3 indicates two further subvolumes which are distinguished by their rutile inclusions: $\bar{p}_r$, rutilated porphyroclasts and their rutilated mantles and $\bar{r}_r$, rutilated recrystallized grains. There is an additional quantity $\bar{m}_r$, which represents rutilated grains which have always been part of the matrix fraction. By the second of the assumptions made in this section $\bar{r}_r/(\bar{p}_r - \bar{r}_r)$ is equivalent to the ratio of all recrystallized grains to all porphyroclasts, therefore if recrystallization is partial the volume fraction of recrystallized grains is

$$\bar{r}_f = \bar{r}_r \cdot \bar{p}_f/(\bar{p}_r - \bar{r}_r) \quad (1)$$

hence

$$\bar{m}_o = \bar{m}_f - \bar{r}_f \quad (2)$$

and

$$\bar{p}_o = \bar{p}_f + \bar{r}_f. \quad (3)$$

If recrystallization is complete, then by a similar argument, $\bar{r}_r/(\bar{m}_r - \bar{r}_r)$ represents the ratio of the volume fraction of recrystallized grains to the total volume of grains in $\bar{m}_f$ and

$$\bar{r}_f = \bar{r}_r \cdot \bar{m}_f/(\bar{m}_r - \bar{r}_r) \quad (4)$$

hence

$\bar{m}_o$ can be calculated from (2)

and

$$\bar{p}_o = \bar{r}_f. \quad (5)$$

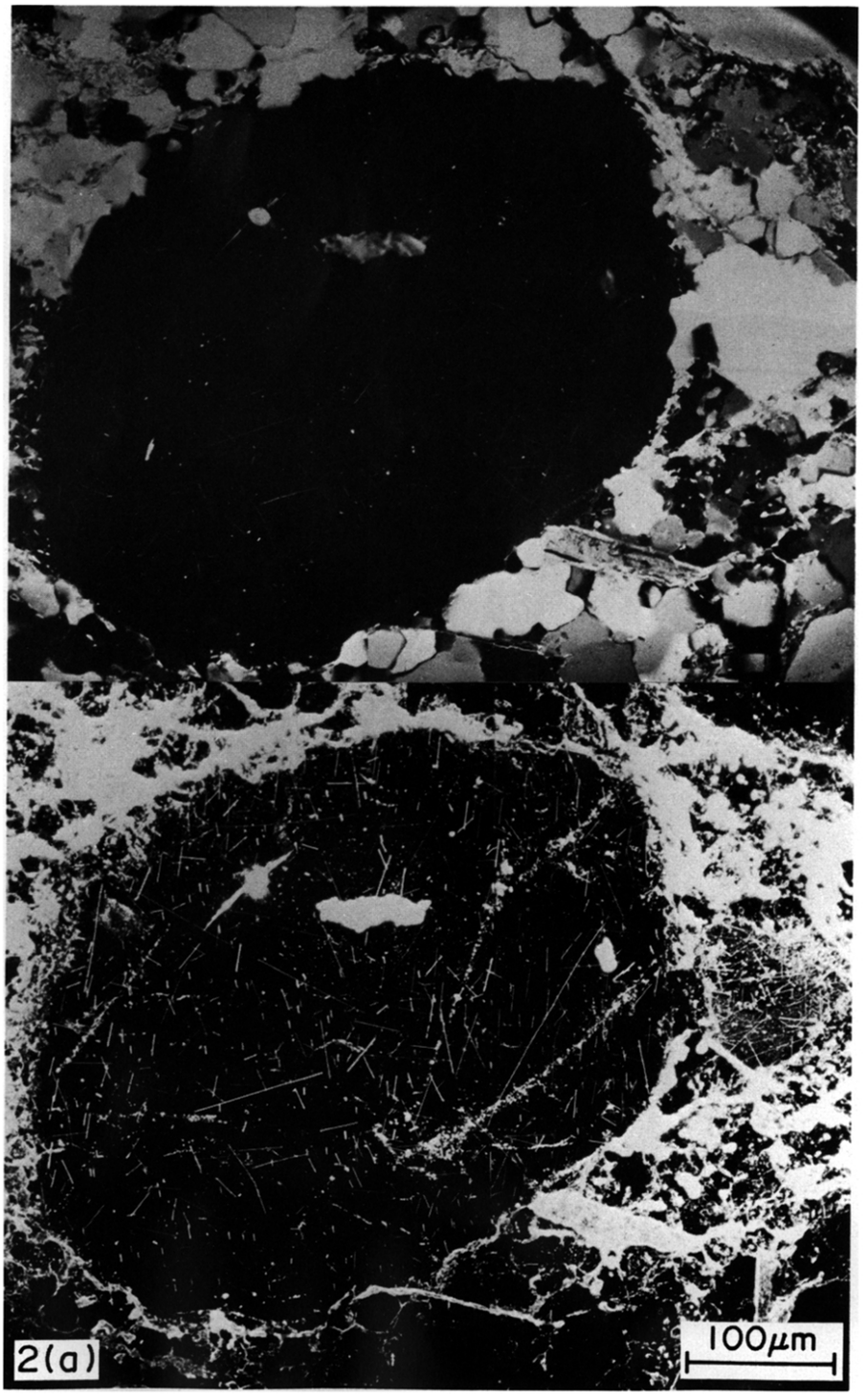

Fig. 2(a) Top, plane polarized light. Slight undulatory extinction, no recrystallization. Bottom, dark field. High density of rutile needles show little evidence of deformation, consistent with optical strain features, cf. 2(b) overleaf.

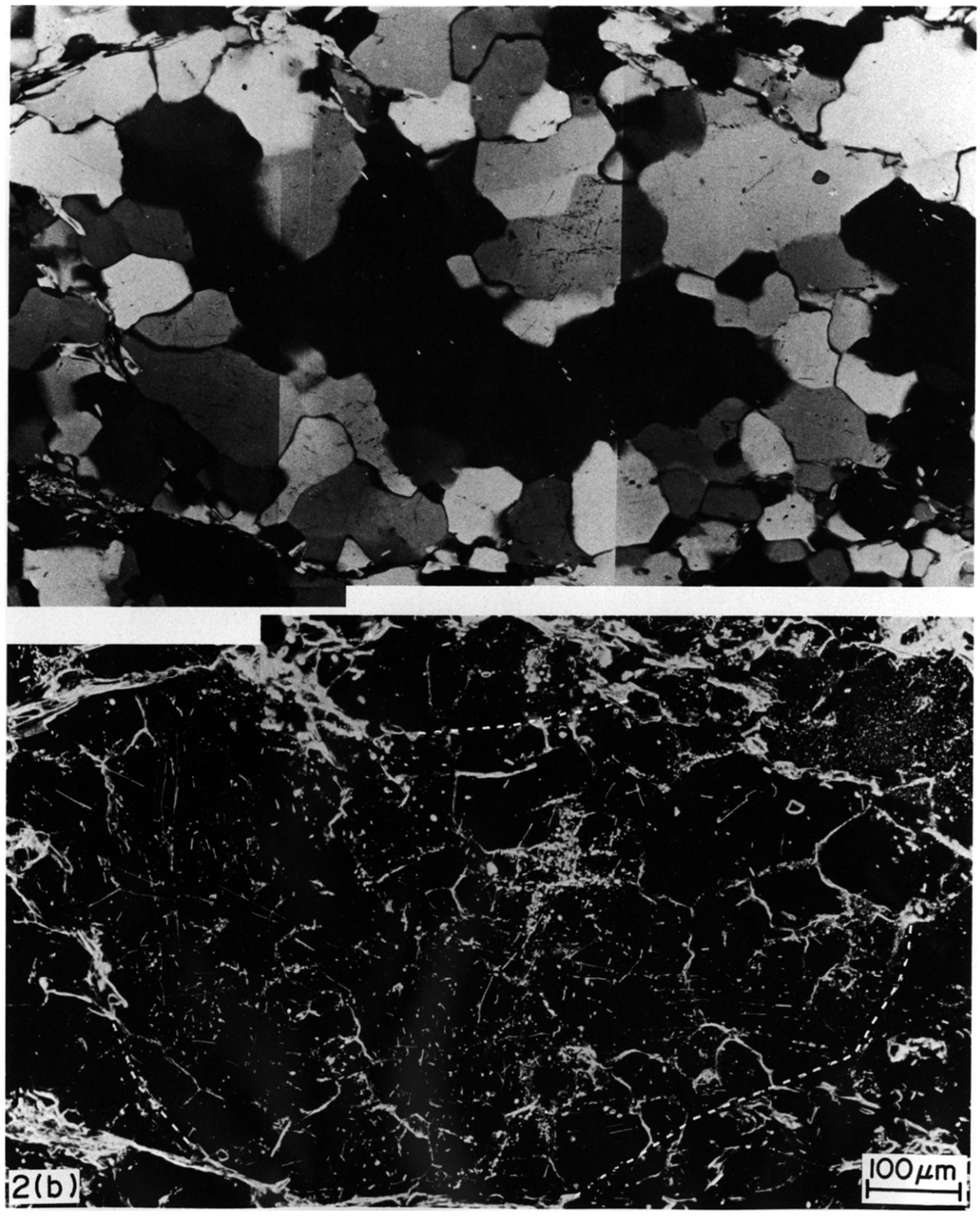

Fig. 2(b) Top, plane polarized light. Remant porphyroclast with mantle of new grains and matrix grains. Bottom, dark field. Rutile inclusions indicate the continuity of the original grain. They are extensively fractured and buckled which is an indication of the amount of deformation of the host grain. White dots mark the inferred clastic grain boundary, that is the limit of the area containing inclusions.

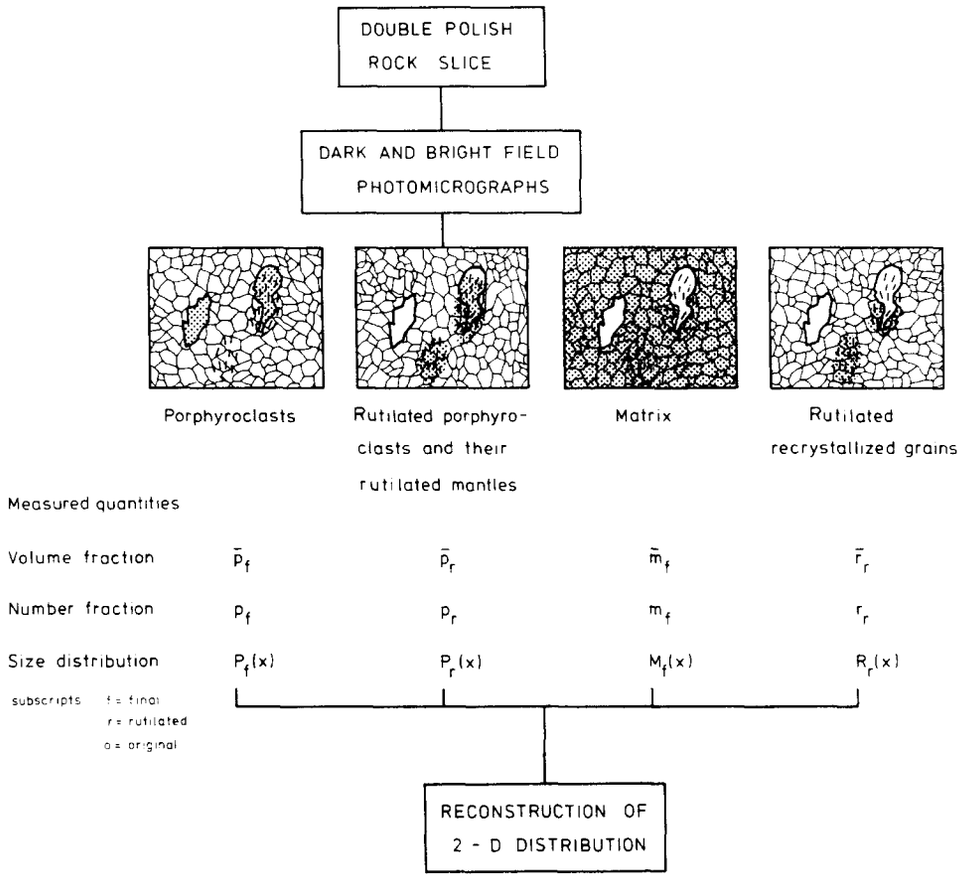

Fig. 3. Flow chart of procedure and symbols used in text. In each of the diagrams the dotted ornament represents the area defined by the symbols beneath them.

Reconstruction of the original grain-size distributions

Figure 3 indicates the measurement of four grain-size distributions expressed as functions of the grain diameter x, $P_f(x)$, $P_r(x)$, $M_f(x)$ and $R_r(x)$, which are constituents of the total grain-size distribution observed in the deformed state. In this section I outline a procedure for combining the constituent distributions in order to reconstruct the pre-deformation distribution $0(x)$.

If the data is in histogram form then each distribution needs to be normalized, that is the sum of the cell areas for each distribution should be made equal to unity. The areas can then be re-adjusted so that each histogram represents a real probability with respect to the observed complete grain-size distribution. This is a simple operation and merely involves multiplying the area of each cell by the ratio of the number of grains in the given subvolume to the number of grains in the whole (representative) volume. The ratios of apparent matrix grains, m_f, porphyroclasts, p_f, and rutilated recrystallized grains, r_r, to the whole can be measured directly but we also require r_r and p_o which are calculated as

$$r_f = \bar{r}_f \cdot r_r / \bar{r}_r \tag{6}$$

and

$$p_o = \bar{p}_o \cdot p_f / \bar{p}_f. \tag{7}$$

If the total grain-size range comprises n cells of midpoint x_i (i = 1 to n) then each cell in the reconstructed distribution is easily evaluated by

$$0(x_i) = m_f M_f(x_i) - r_f R_r(x_i) + p_o P_r(x_i). \tag{8}$$

Experience using this method has shown that it is often difficult to measure enough grains to adequately describe $P_r(x)$ ($=P_o(x)$), and it is then necessary to approximate $P_r(x)$ by $P_f(x)$ so that

$$0(x_i) \simeq m_f M_f(x_i) - r_f R_r(x_i) + p_o P_f(x_i). \tag{9}$$

(It should be noted that this approximation is only valid if r is small). If the distributions are in density function form, the reconstruction is carried out simply by adjusting the areas under the curves, according to the relationships in (8) and (9).

Shifts in dominant mechanism which result from modification of a grain-size distribution are physically more directly related to changes in volume fraction of particular subvolumes than to the numbers of grains comprising those subvolumes. Size by number distributions are, unfortunately, a rather poor representation of these changes since very small variations in the large grain-size tail of the distribution correspond to large changes in volume fraction. Thus it is more appropriate to present the final and (inferred) initial distributions in terms of their volume fractions. We proceed from equations (8) and (9) by finding the total volume of the system expressed in $0(x)$, which is given by $\Sigma_{i=1}^{n}[0(x_i)\cdot x_i^3]$ and the volume represented by each cell, $0(x_i)\cdot x_i^3$. The volume fraction graph, $V(x)$, is then reconstructed by recursively evaluating

$$V(x_i) = 0(x_i)\cdot x_i^3 / \Sigma_{i=1}^{n}[0(x_i)\cdot x_i^3]. \tag{10}$$

EXAMPLE

The analyses used in this example are from Dalradian quartzites of the Kilmory Bay Syncline, S.W. Highlands, Scotland. All data are collected from sections cut parallel to the X–Z plane of the local bulk strain ellipsoid.

Microstructure

Routine petrographic observations indicate that dislocation creep was an important deformation mechanism contributing to the total strain, and was responsible for considerable microstructural changes. New grains in the mantles of porphyroclasts (as evidenced by the presence of rutile needles, see Fig. 2) mimic optical subgrains in the porphyroclast in size and shape. Examination of individual rutilated mantle grains using the back scattered electron orientation contrast technique (Lloyd & Hall 1981) reveals arrays of subgrains (which are too small to be seen optically) which confirm the dynamic nature of the process. Optical subgrain boundaries range from very low angles where a distinction between interference colours is just possible, through to high angles where the 'subgrain' and remnant grain are quite distinct. This suggests that rotation recrystallization (Guillope & Poirier 1979) is the grain refining process. Bulges in the boundaries between new or matrix grains are occasionally observed which suggests that boundary migration occurs as well, but it is thought to contribute little, if at all, to the overall reduction in grain-size recorded.

Volume fraction calculations and grain-size distribution reconstruction

Sampling for the grain-size analyses was performed by census, and the grain diameter of an equivalent circle computed using the centroid method: the centroid of the grain is estimated by eye and the longest diameter, α, measured through it; and a second diameter, β, is measured perpendicular to α and also through the centroid. The diameter of an equivalent circle is then $x = \sqrt{\alpha\beta}$. This is a statistically reliable approach which is easier to perform than graphical planimetry, and more accurate than linear intercept methods. Volumes are then calculated directly from the total grain areas and substituted into (2) and (3) to give the original proportions of matrix and porphyroclasts. A summary of the analyses for three samples is given in Table 1. Without the rutile needle inclusions, which mark the original continuity of the grains, porphyroclasts which are fully recrystallized are easily misidentified as being clusters of matrix grains. Consequently estimates of the amount of dynamic recrystallization made by eye are often 2 to 3 times lower than the values calculated by the method described in this paper.

The original grain-size distribution is inferred from (8); but as Fig. 4(a) shows, the size-by-number distribution gives no impression of the bimodal structure, which is strikingly obvious from thin section. This is easily explained since porphyroclasts are outnumbered by matrix grains by up to 350:1 per unit area. However, the size vs volume fraction graph (Fig. 4b) calculated from (10) gives a clear representation of the initial and final grain-size structure.

Table 1. Summary of volume calculations for three quartzites (see text for discussion)

Sample No.	23460	23463	T15
$\bar{r}_o$	0	0	0
$\bar{r}_f$	0.132	0.162	0.122
$\bar{p}_o$	0.616	0.452	0.332
$\bar{p}_f$	0.481	0.290	0.210
$\bar{m}_o$	0.386	0.548	0.668
$\bar{m}_f + \bar{r}_f$	0.518	0.710	0.790

DISCUSSION

The primary intention of this paper has been to describe a method for quantifying the amount of dynamic recrystallization in deformed quartzitic rocks and to reconstruct the original grain-size distribution. By way of example it has been shown that the method can be applied to naturally deformed rocks, though the study presented is not exhaustive. Future applications could involve use of the theory in the study of grain diminution textures in rocks which have deformed by cataclasis. Its ability to pick out original textures means that grain boundaries delineated by rutile inclusions can be used as strain markers in rocks where R_f/ϕ analyses would otherwise be impracticable due to extensive recrystallization (dynamic or static). Also it is potentially useful to sedimentologists working in terrains where original fabrics have been obliterated by deformation or metamorphism.

The development of the model has been based on the assumption of an initial sedimentary fabric, specifically a bimodal fabric. However this is not a prerequisite, indeed inspection of equations (1) and (4) show that the method should cope with initially uni- or bimodal grain-size distributions; but since the recrystallization is only monitored by the grain-size reduction it produces, the method cannot be used to quantify recrystallization by grain boundary mobility in an already fine-grained matrix. Within the constraints of the model we can examine the factors influencing its reliability. Firstly, consider the volume fraction calculations. Their accuracy is determined by three properties: (a) the abundance of rutilated grains, (b) the density of inclusions within each grain and (c) the increase in grain-size attributable to syntaxial overgrowths which are produced during diagenesis. Unfortunately there is no way of assessing the importance of (c), so we should always expect the calculated $\bar{p}_o$ to underestimate the true $\bar{p}_o$. If the sample of rutilated grains is too small the statistical basis of the theory is undermined, but this can usually be overcome by examination of more thin sections. If the density of inclusions within particular grains is low then the positioning of the inferred clastic boundary becomes

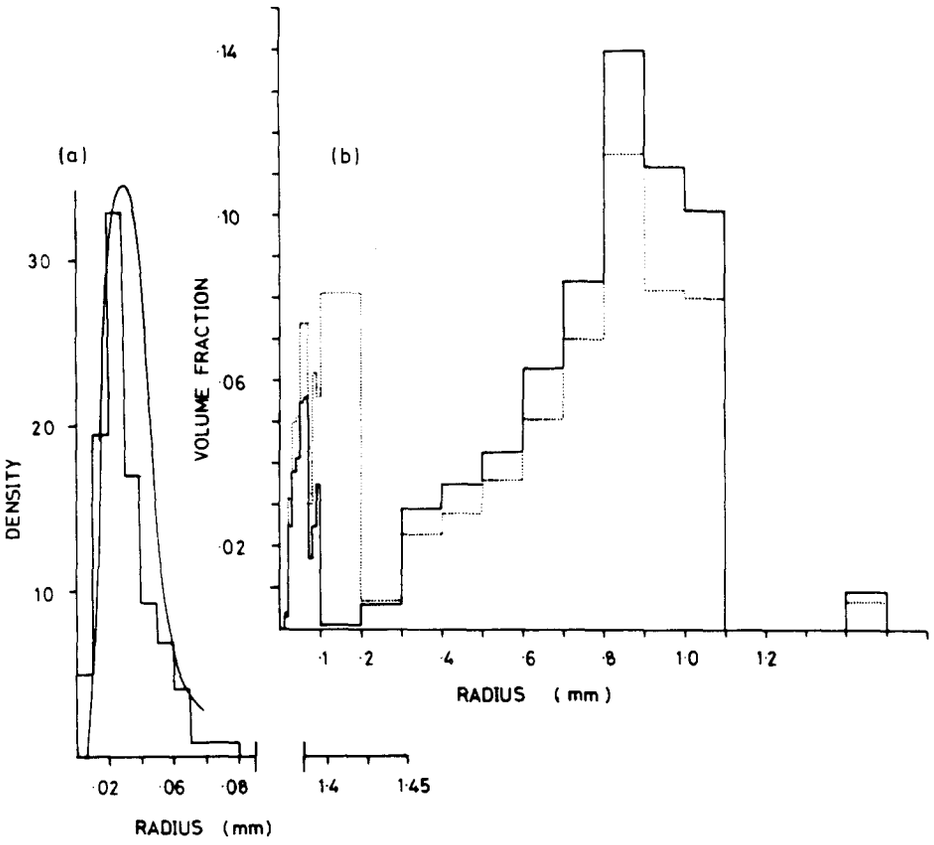

Fig. 4(a) Reconstructed grain-size by number distribution for sample 23460. Smooth curve is the stereologically corrected version. (b) Grain-size vs volume fraction graph for the same sample. See text for discussion.

somewhat arbitrary and the grain, or group of grains, should be included in the non-rutilated subset.

Up to now the assumption has been made that the size of the matrix fraction has remained constant. If the $M_o(x)$ was close to the steady-state grain-size then the assumption is valid. If, on the other hand, there are indications of grain boundary mobility between matrix grains then it is likely that $M_o(x)$ has changed. It is possible to do a crude check by comparing the shapes of $R_f(x)$ and $M_o(x)$. If they differ significantly then $M_f(x)$ is probably a good estimate of $M_o(x)$, otherwise we conclude that either $M_o(x)$ was close to a steady-state grain-size before deformation, or that $M_f(x)$ has been modified to the steady state grain-size.

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REFERENCES

Guillope, M. & Poirier, J. P. 1979. Dynamic recrystallization during creep of single-crystalline halite: an experimental study. *J. geophys. Res.* **84**, 5557–5567.

Lloyd, G. E. & Hall, M. G. 1981. Application of scanning electron microscopy to the study of deformed rocks. *Tectonophysics* **78**, 87–698.

Mitra, S. 1976. A quantitative study of deformation mechanisms and finite strain in quartzites. *Contr. Miner. Petrol.* **59**, 203–226.

Rathbone, P. A. & Harris, A. L. 1976. Basement cover relationships at Lewisian inliers in the Moine rocks. In: *The Caledonides of the British Isles—Reviewed* (edited by Harris, A. L., Holland, C. H. & Leake, B. E.). *Spec. Publs geol. Soc. Lond.* **8**, 101–107.

Twiss, R. J. 1977. Theory and applicability of a recrystallized grain size palaeopiezometer. *Pure appl. Geophys.* **115**, 227–244.

Underwood, E. E. 1970. *Quantitative Stereology*. Addison-Wesley, London, U.K.

White, S. 1976. The effects of strain on the micro-structures, fabrics and deformation mechanisms in quartzites. *Phil. Trans. R. Soc.* **A283**, 69–86.