Influence of the concentration of rigid markers in a viscous medium on the production of preferred orientations. An experimental contribution, 1. Non-coaxial strain

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The finite strain state of rocks can be related to the preferred orientation of rigid markers and to their axial ratio. Very little is known about the relations between the concentration of rigid markers and the fabric they develope. This is tested experimentally for a simple shear flow. It is obsereved that interactions between markers slow down their rotation. For any given finite strain in the matrix, the preferred orientation is weaker with an increase of the concentration of markers. This can lead to noticeable underestimations of the finite strain magnitude. On the other hand, interacting markers keep their metastable orientation (near to the shear direction) longer than isolated markers. This ameliorates the ability of such fabrics to record the finite stretching direction.

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Introduction

The literature contains many theoretical and experimental works about the development of shape fabrics. Assuming the pseudoviscous behavior of rocks (Ferguson, 1979), these works constitute an important basis for structural analysis. However, shape fabrics, especially many stretching lineations in metamorphic rocks, are often supported by quite concentrated populations of markers. None of the various finite orientation analysis methods currently available (Ramsay & Huber, 1983) take account of the possible effects of mechanical interactions between markers. We have performed a series of experimental tests of the influence of the rigid markers concentration on the development of preferred orientations in a simple shear flow.

Theoretical background

Equations giving the time-behavior of rigid markers in both coaxial and strictly non-coaxial flows have been derived by Jeffery (1922) and experimentally verified by many authors. Practical forms of these equations for the case of progressive simple shear may be found for instance in Gay (1968), Ghosh & Ramberg (1976), or Fernandez et al. (1983). In the latter, a fabric of rigid particles with identical shapes evolves periodically, with a rigid-body rotation period depending on the aspect ratio of the markers (Fernandez et al., 1983). The fabric passes through a maximum of "intensity" when its longest axis (i.e. the longest axis of the fabric ellipse) coincide with the shear direction, for a critical shear strain γc given by:

$$\gamma c = \pi / \sqrt{1-K^2}$$

with $K = (n^2-1) / (n^2+1)$, n = axial ratio of the axisymetric markers, K = shape factor. When n > 1, a rigid particle, and consequently a rigid particle fabric, has a metastable orientation when subparallel to the shear direction, and the shear strain range corresponding to this metastability increases with an increasing n.

Figure 1 shows the evolution of γc as a function of K. For axial ratios > 5, the shape factor varies only slightly and the fabric evolution will not differ significantly for likely geological strains (Pfiffner & Ramsay, 1982). In other words, the evolution of

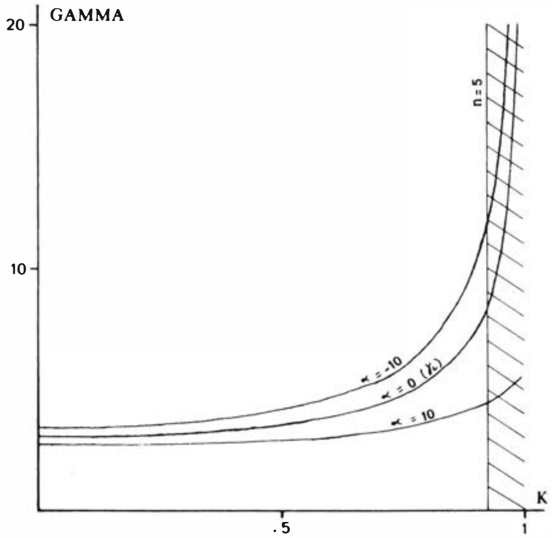

Fig. 1 – α = -10, 0, and 10 curves in a gamma/K diagram (α is the angle between the fabric best axis and the shear direction). The ruled area represents markers with behavior approximating that of a passive line-marker (n>5). The α = -10 and α = 10 curves are plotted in order to illustrate the increase of fabric metastability with an increasing n.

fabrics of rigid markers with n > 5 approximates those of passive-line markers fabrics although, for very high shear strains, this approximation breaks down.

We have found little in the literature about the effect of interactions between markers. Mason & Manley (1957) have shown that, in three dimensions, interacting particles rotate in orbits which differ from those predicted by the Jeffery's model without interaction. In his experiments, Tullis (1976) noted that the effect of interference between grains was to reduce the preferrence in orientation. We attempted to test these interaction effects on the experimental development of rigid particles fabrics in a simple shear flow.

Experimental procedure

The shear box used here is that described by Fernandez *et al.* (1983), and was inspired by those of Taylor (1934) and Willis (1977). It is composed of a continuous rubber belt driven around two vertical drums 7 cm high and 5 cm in diameter, placed in a long perspex box. The distance between the drums is 50 cm. When a viscous material is placed within the box, the slow rotation of the drums, powered by a direct current motor, generates a homogeneous simple shear between the two sides of the belt. A mixture of clear honey with titanium oxide was used here as the viscous matrix; it had a viscosity of about 50 to 70 Pa.s. The rigid markers were cut from a thin PVC sheet or from a toothbrush. A layer of mercury at the bottom of the box ensured the homogeneity of the stain by avoiding friction between the matrix and the box. Markers were disposed with a homogeneous distribution on the upper surface of the matrix. The theoretically linear behavior of their rotation relative to the applied strain tensor (Jeffery, 1922) was respected because of the very high viscosity contrast between markers and matrix, and because of the slow applied strain rate (2×10^{-3} to 5×10^{-4} s^{-1}, depending on the experiments).

Experimental results

Experiments have been performed with populations of markers with identical shapes (n = 2.5, 5 or 30), for various concentrations which have been estimated from the surface ratio markers/markers +

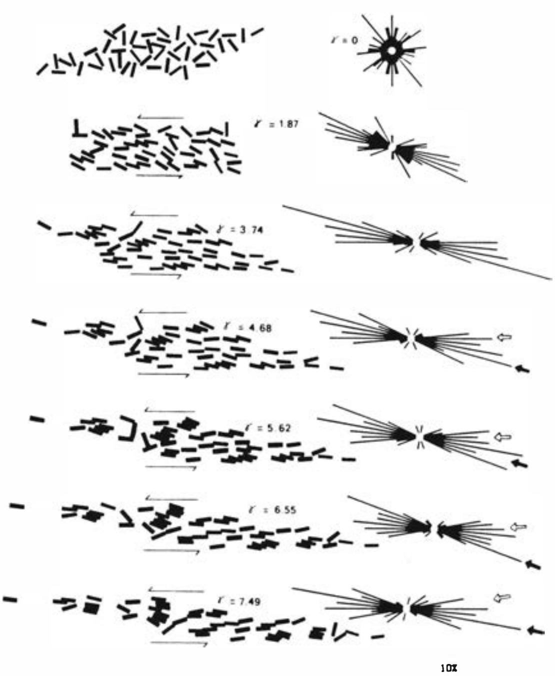

Fig. 2 – Steps of MS17 experiment, with n = 5 and concentration 25 %. The black arrow represents the effect of interacting markers on the frequency distributions, the white arrow represents "free" markers. The frequency roses are constructed with five degrees interval (boundaries 2.5, 7.5, 12.5, etc. . .).

matrix (which is a function of the number and the size of the markers). Two markers interact when the distance between them is lower than their length.

Figure 2 shows increments of one experiment, with n = 5. At shear strains about 4–5, two directions of preferred orientation are distinguishable. These correspond to regimes in which the markers interact or not (i.e. some are "free"). The interacting markers rotate more slowly toward the shear direction. This clearly demonstrates that the rotation of rigid particles is disturbed and slowed by interactions such as collisions (Mason & Manley, 1957) and especially the tile effect (Fernandez et al., 1983).

The experimental data have been treated by means of the normalized orientation Tensor method (Harvey & Laxton, 1980). This tensor is defined as:

$$T = \frac{n}{N} \begin{bmatrix} Xi & XiYi \\ YiXi & Yi \end{bmatrix}$$

with N = number of markers, Xi & Yi = direction cosines relative to the OX (shear direction) and OY axes of the reference frame. The ratio of the eigenvalues of T is the ratio Rf of the fabric ellipse. The orientation of the first eigenvector is the orientation of the fabric ellipse's longer axis with respect to the shear direction. This treatment has been applied on successive steps for every experiment. The results are plotted in Figures 3, 4 and 5, respectively for axial ratios 2.5, 5 and 30.

In order to facilitate their description, these curves may be distributed into three groups.

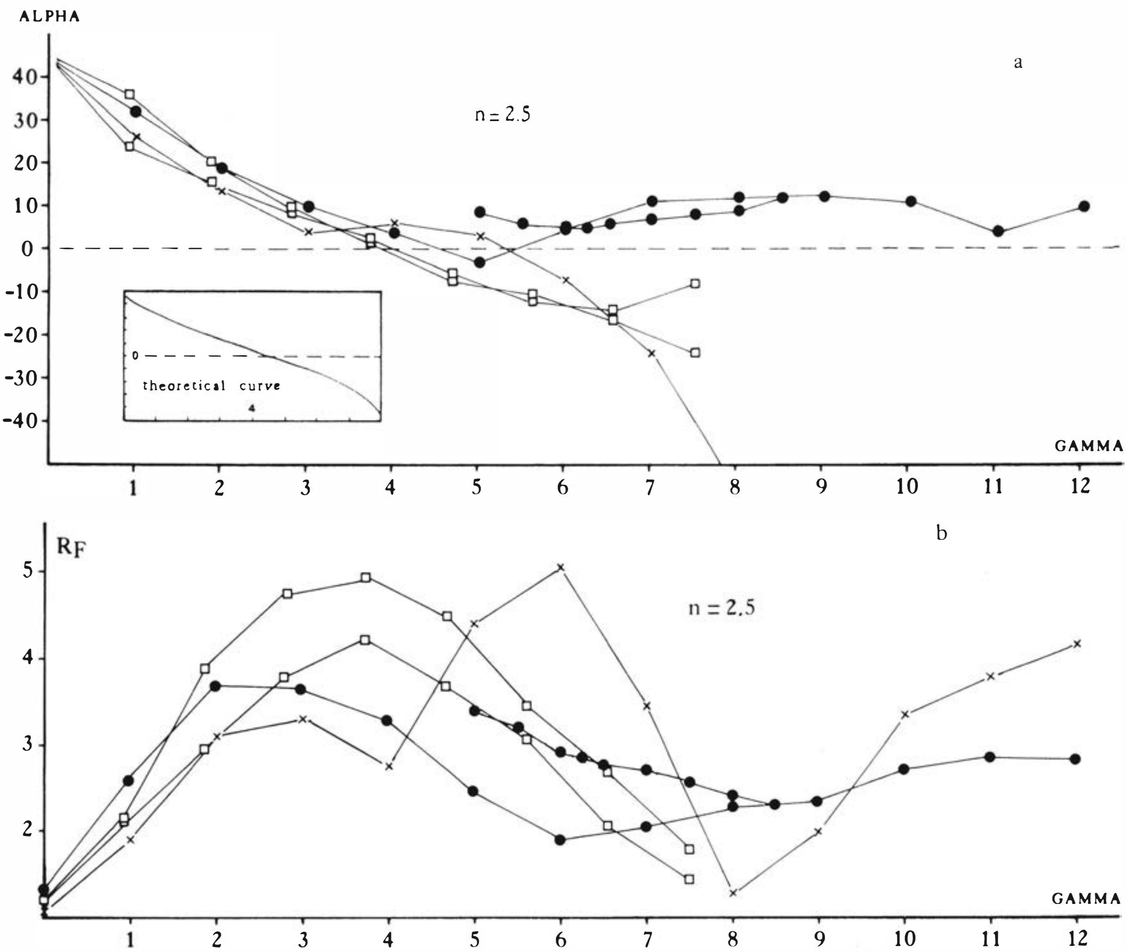

Fig. 3 – Data treatment for n = 2.5 (see text for further discussion).
a – Diagram α/γ.γc is about 4–5 (theoretical one is 4.55).
b – diagram Rf/γ.

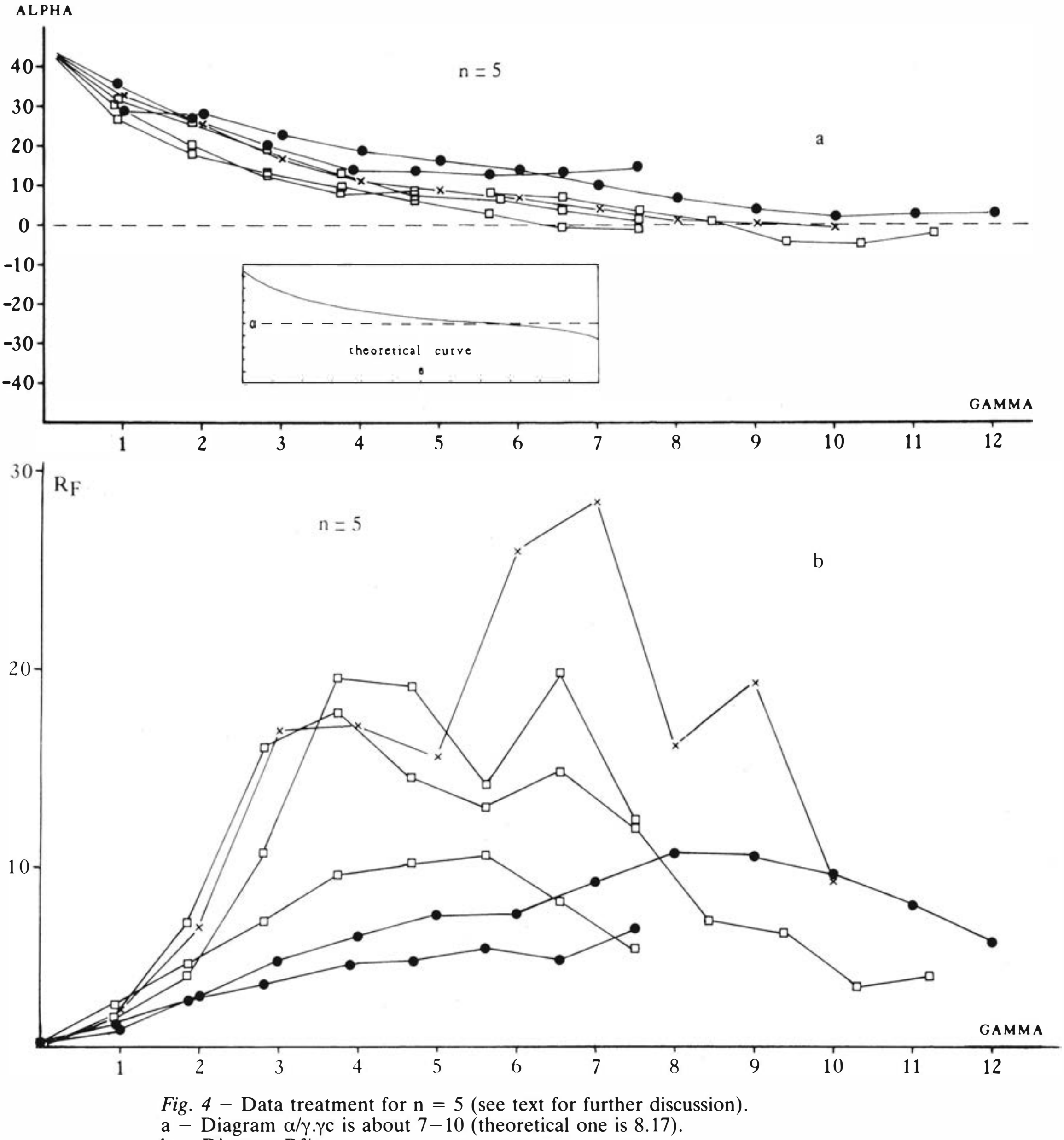

Fig. 4 – Data treatment for n = 5 (see text for further discussion).
a – Diagram α/γ.γc is about 7–10 (theoretical one is 8.17).
b – Diagram Rf/γ.

i – Low-concentration populations (crosses)

The low-concentration tests showed little or no interactions between markers.

The orientation curves (Fig. 3a, 4a, 5a) are very close to theoretical curves obtained from the Jeffery's equation (Fernandez, 1984). Small deviations are probably of the same order of magnitude as possible errors inherent in the experimental model (slight variations of n, measurement errors, low number of markers in the low-concentrated experiments, and uncontrolled local heterogeneities in the matrix).

For each n, the Rf curves (fig. 3b, 4b, 5b) give a satisfying image of the time-evolution of the intensity of ideal fabrics (without any interactions).

ii – Concentrated populations (white squares)

For this second group of experiments, initial markers concentrations were such that only some markers interacted. The other markers were free or underwent negligible disturbance.

As in the first group, the orientation curves (a) are not significantly different from theoretical ones, except for the last step (γ=8) in one curve of fig. 3a.

On the other hand, the Rf curves (b) are significantly modified. The maxima of Rf decrease with increasing concentrations; furthermore, the corresponding values of γ become lower than γc. This is related to the distinct evolution of interacting and free markers. The fabric intensity decreases when its longest axis rotates beyond or through the shear direction (see also Fig. 2).

iii – Higly-concentrated populations (black dots)

In this third group, most of the markers interacted, and this had a significant effect upon the fabric orientation (a). The angle α diminishes a little more slowly with an increasing shear strain (i.e. K is slightly higher for a given γ) when n=5, and essentially, the fabric keeps its metastable orientation a longer time. For n= 2.5, the rotation of the fabric axis reverses. This "reverse effect" is assumed to be due to the interactions, and it corresponds approximatively to a return to increasing Rf.

The Rf magnitudes (b) are still lower, but in the n=5 experiments, the shear strain value corresponding to the maximum is again close to that ($\simeq \gamma c$) for which α becomes almost 0.

Rf varies most when n = 5. For lower axial ratios, the variations decrease proportionally with the maxima for low-concentration populations. On the other hand, when n increase, the Rf variations become weaker again (fig. 5b). In fact, the markers then tend to rotate rapidly toward the orientation of passive line markers for which there is no rigid body rotation, and thus no mechanical interaction. So, the interaction effects are most sensitive with "intermediate" axial ratios (about 5).

One test was made using a highly concentrated population of markers with mixed n = 2.5 and 5. The orientation trends of both the subfabrics are plotted in Figure 6. As in the previous experiments, both fabrics kept their metastable orientation for longer times, because of their high concentration of markers.

The two curves cross at γ=8 (Fig. 6) because of the reverse effect on the n = 2.5 subfabric. Fernandez et al. (1983) pointed out that populations with mixed axial ratios constitute good indicators of the sense of shear for shear strains < 2 γc (for the

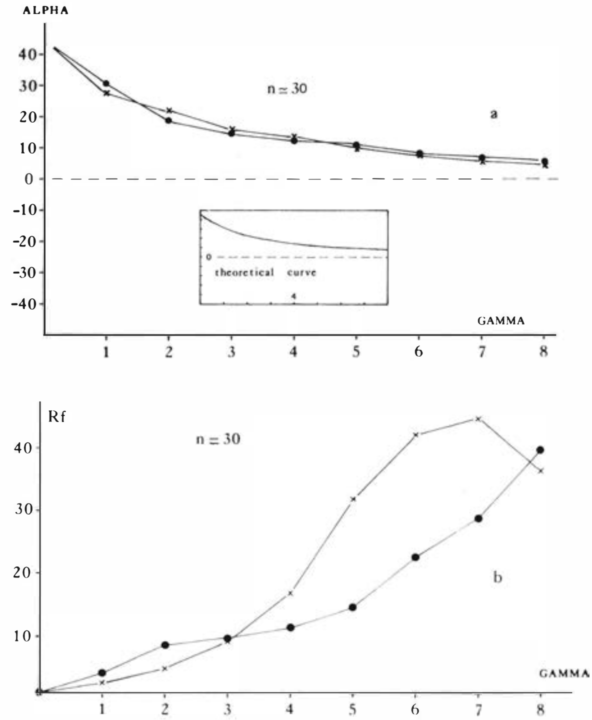

Fig. 5 – Data treatment for n ~ 30 (see text for further discussion).
a – Diagram α/γ. (Theoretical γc is 47.18).
b – Diagram Rf/γ.

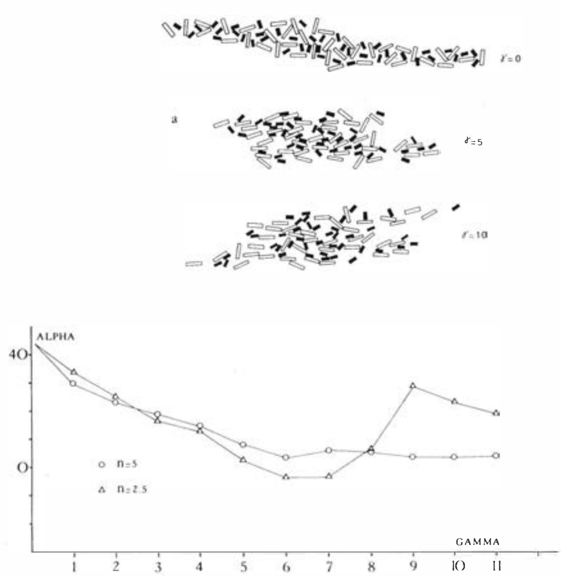

Fig. 6 – Mixed population treatment.
a – Steps γ = 0, 5 and 20 of the fabric evolution (n = 2.5 for black markers, n = 5 for white markers, concentration 38 %).
b – Diagram α/γ. See text for further discussion.

lower n). Figure 6 shows that this criterion is no longer valid for highly concentrated populations of rigid markers.

Implications of finite orientation and magnitude related to strain

This work has demonstrated that variations in the concentration of rigid markers can affect both the fabric orientation and the apparent magnitude of strain of the rock complex.

For realistic geological average shear strain values, it has been demonstrated that rigid markers fabrics with axial ratios greater than 5 (see Fig. 1) give a reasonable approximation of the finite strain state in the matrix. Nevertheless, the interaction effect reduces Rf for a given shear strain. Thus, finite strain analyses using concentrated populations of rigid markers are expected to significantly underestimate the finite strain magnitudes of the rock complex. In the case of markers with low axial ratios, the relations between Rf and Rs (finite strain ellipse ratio) in simple shear flows are complicated by the periodicity of the fabric evolution. Interactions reduce this period.

On the other hand, highly concentrated populations have been shown to increase the metastability of the fabric around the shear direction. This means that, the more concentrated are the markers in the matrix during simple shearing, the better is the approximation of the finite stretching direction indicated by the longest axis of the fabric.

Tests have still not been performed for pure shear, but it seems likely that interactions between rigid particles will also tend to prevent or slow down their rotation in that case. Thus, the longest axes of the markers in highly concentrated populations will probably rotate more slowly toward the principal stretching direction than in populations with low concentrations. The use of such populations to estimate finite strain magnitudes is therefore also likely to lead to underestimations of the bulk strain.

Conclusion

The experiments reported here have shown that interactions between rigid markers slow their rotation during homogeneous simple shear of their matrix. The effects of these interactions on the development of the fabrics decrease their intensity at a given shear strain and increase (in time) the metastability of their longest axis around the shear direction.

The consequences on finite strain significance of rigid marker fabrics are the following:

– Finite strain magnitudes are expected to be underestimated with orientation analytical methods. This underestimation increases with the marker concentration, and is maximum for axial ratio 5 in the experiments described here.

– Highly concentrated populations are better markers of the finite stretching direction than populations with low concentrations.

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