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Experimental investigation of the effects of fluid heterogeneity upon the motion of rigid ellipsoidal inclusions during bulk inhomogeneous shortening

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Abstract—An experimental study of the motions of rigid ellipsoidal inclusions within deforming homogeneous and heterogeneous fluid systems indicated that the time behaviour of such objects, measured relative to the experimental apparatus, can vary significantly between the two system types during inhomogeneous time-dependent flow. Initially aligned ellipsoidal inclusions within a deforming homogeneous fluid were rotated in the same sense as an adjacent passive strain marker. Introduction of heterogeneity, by partially enclosing the ellipsoidal inclusions with a less viscous fluid, resulted in three different rigid-body behaviours during deformation. The behaviours observed for initially aligned ellipsoids in the system containing fluid heterogeneities were: (1) opposite-sense rotation to that of the strain marker; (2) negligible rotation of the objects; and (3) same sense of rotation as that of the strain marker.

A computerized, time-based, analysis of the deformation, possible through the incorporation of marker particles into each of the two different deforming systems, revealed similar deformation kinematics for the two experimental types at both the system and sub-system scale. Results of the experiments indicate that significant differences can occur in rigid-body behaviour between apparently similarly deforming homogeneous and heterogeneous systems. The results suggest that fluid flow theory, as derived for rigid-body behaviour in homogeneous fluids, may be unsuitable for the purpose of qualitatively predicting rigid-object behaviour within deforming rock systems that are highly anisotropic at the porphyroblast/porphyroclast scale. This notion is supported by an examination of the assumptions and simplifications upon which the theory relating to rigid-body behaviour in homogeneous fluids was originally based. © 1997 Elsevier Science Ltd.

INTRODUCTION

The motion of rigid objects, such as porphyroblasts and porphyroclasts, within some deforming rock systems are important for the determination of shear sense and deformation history (e.g. Elliot, 1972; Ghosh and Ramberg, 1976; Simpson and Schmid, 1983; Bell, 1985; Passchier and Simpson, 1986; Passchier, 1988; Bell and Johnson, 1992). Inclusion trails preserved within porphyroblasts may provide valuable information regarding the deformation history of the rock mass within which they are contained (Zwart, 1960; Johnson, 1963; Simpson and Schmid, 1983; Cobbold and Gapais, 1987; Bell and Johnson, 1989; Bell and Hayward, 1991; Davis, 1995). However, the interpretation of inclusion trails is model dependent (Johnson, 1993).

There are two principal approaches that have been considered with regard to predicting the possible motion of rigid objects (e.g. porphyroblasts and porphyroclasts) during rock deformation and these give contrasting results (Johnson, 1990; Vernon *et al.*, 1993). One approach considers that such objects may behave in a like manner to rigid objects contained within similarly deforming homogeneous fluids, the rotation of the objects within the rock mass being dependent on the level of vorticity and object shape (Rosenfeld, 1970; Ghosh and Ramberg, 1976; Lister and Williams, 1983; Freeman, 1984; Passchier, 1987a,b, 1988; Passchier *et al.*, 1992). In addition, several authors have provided arguments for the rotation of rigid objects in geological examples (Spry, 1963; Schoneveld, 1977; Powell and Vernon, 1978; Busa and Gray, 1992). The other approach proposes that heterogeneities within the rock, at the porphyroblast/porphyroclast scale, can result in deformation partitioning and little or no rotation of the rigid objects (Bell, 1985, 1986; Bell *et al.*, 1986, 1989; Johnson, 1990; Hayward, 1992). Several authors provide arguments for non-rotation of rigid objects in geological examples (Fyson, 1980; Steinhardt, 1989; Johnson, 1990, 1992; Bell *et al.*, 1992; Hayward, 1992; Davis, 1993).

The motion of rigid objects in deforming homogeneous fluids

Initial theoretical studies of the motion of rigid bodies within a homogeneous fluid undergoing simple shear flow were conducted by Jeffery (1922). Later studies (e.g. Saffman, 1956; Bretherton, 1962) resulted in analytical solutions of the linearized governing equations being obtained for systems where the inclusions were described as ellipsoids of revolution. These investigations described rotation of inclusions in the direction of the sense of the applied simple shear; some bodies eventually adopted preferred orientations. (Some recent studies have been conducted into the fabrics developed by different shaped markers (e.g. Fernandez *et al.*, 1983) and also the affects of mechanical interactions between particles (Ildefonse *et al.*, 1992) in simple shear flows.)

Reed and Tryggvason (1974) conducted a theoretical study of the preferred orientations of ellipsoidal objects in a viscous matrix deformed by pure and simple shear. Ghosh and Ramberg (1976) examined the effect of combinations of pure and simple shear on the behaviour of ellipsoidal inclusions during deformation. Ghosh and Ramberg (1976) found three different types of behaviour were possible for ellipsoidal inclusions. These were rotation in the same or opposite sense as the simple shear, and non-rotational behaviour. The type of behaviour displayed is dependent upon the ratio of simple and pure shear rates, the initial orientation of the inclusion and its axial ratio. Passchier (1987a) expanded the work of Ghosh and Ramberg (1976) so as to examine the orientation of the asymptotes for rotation both of symmetric objects and of those that deviated slightly from axial symmetry. Passchier (1987a) applied the theory to a rock sample, determining a potential vorticity number of the flow by examining the orientations of feldspar porphyroclasts within a quartzite mylonite.

Passchier (1987a) also defined requirements that should be met before applying the theory to a deforming rock system. Some of these requirements are: (1) the fabric and general setting of the samples should be indicative that deformation was reasonably homogeneous on the scale of the sample; (2) grain size in the matrix should be significantly smaller than the size of the objects in order to make the assumption of homogeneous flow; and (3) object shape should be regular and should closely approach orthorhombic symmetry.

The possible motion of rigid objects in heterogeneous systems

Bell (1981, 1985) described a process by which rigid objects within a deforming rock system may not rotate because of partitioning of the deformation around them. This model of deformation partitioning takes account of grains of differing composition reacting differently to applied stresses within the matrix. Bell (1981) stated that the crystallographically dominant (001) basal cleavage plane in micas is an ideal recipient for any shear components to a deformation. Deformation partitioning of this type may occur on a variety of scales within a deforming rock system as a result of primary or secondary heterogeneity within the rock (Bell, 1981, 1985; Gapais *et al.*, 1987; Bell and Hayward, 1991; Davis, 1995). During deformation partitioning different rock types, minerals and portions of the rock take up: (1) no strain; (2) dominantly progressive shortening strain; (3) progressive shortening plus shearing strain; or (4) progressive shearing strain (Bell, 1981, 1985). Under these conditions, Bell argued that a porphyroblast will not generally rotate (relative to geographic co-ordinates) providing that it does not internally deform (Bell, 1985, fig. 1a).

Objectives of this study

This study compared the time behaviour of rigid, ellipsoidal inclusions within a deforming homogeneous fluid with their behaviour when partially enclosed by a less viscous, fluid heterogeneity. The incorporated heterogeneity consisted of a vertical column of a less viscous fluid enclosed by the more viscous fluid. This less viscous fluid column partially enclosed the ellipsoidal inclusions that were located with their long axes vertical within the column (Fig. 1a). Having a relatively low viscosity fluid close to the surface of the inclusions was intended to provide a thin slip domain, capable of accommodating shear components, which may be crudely analogous to that provided by the basal cleavage plane of micas partially enclosing porphyroblasts. The viscous gel was intended to represent the presence of competent minerals in the system.

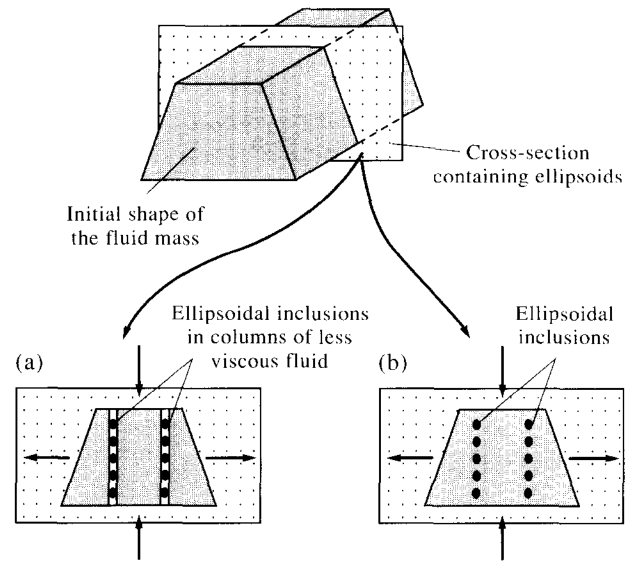

Fig. 1. Diagrammatic representation of the initial shape of the fluid mass combined with a cross-section showing the plane and distribution of the inclusions at the commencement of an experiment for (a) experiments incorporating fluid heterogeneity and (b) a homogeneous fluid system. Arrows (bold) indicate primary directions of extension and shortening of the fluid mass during the deformation process.

Coaxial bulk inhomogeneous shortening, which is equivalent to Ramsay's (Ramsay, 1963) inhomogeneous form of pure shear (Bell, 1981) was chosen as the type of deformation to be simulated because most geological deformations are inhomogeneous (Hobbs *et al.*, 1976) and potentially involve a component of shortening (Bell, 1981). Also, to aid description and discussion, the word 'inhomogeneous' will be used in relation to the deformation distribution and 'heterogeneous' will be used in relation to the nature of the fluid system.

EXPERIMENTAL APPARATUS

Stewart (1996) used an apparatus capable of deforming a homogeneous fluid mass by coaxial bulk inhomogeneous shortening. Stewart (1996) employed this apparatus to examine some of the possible relationships that may form between spherical porphyroblasts and passive foliations in this particular type of inhomoge-

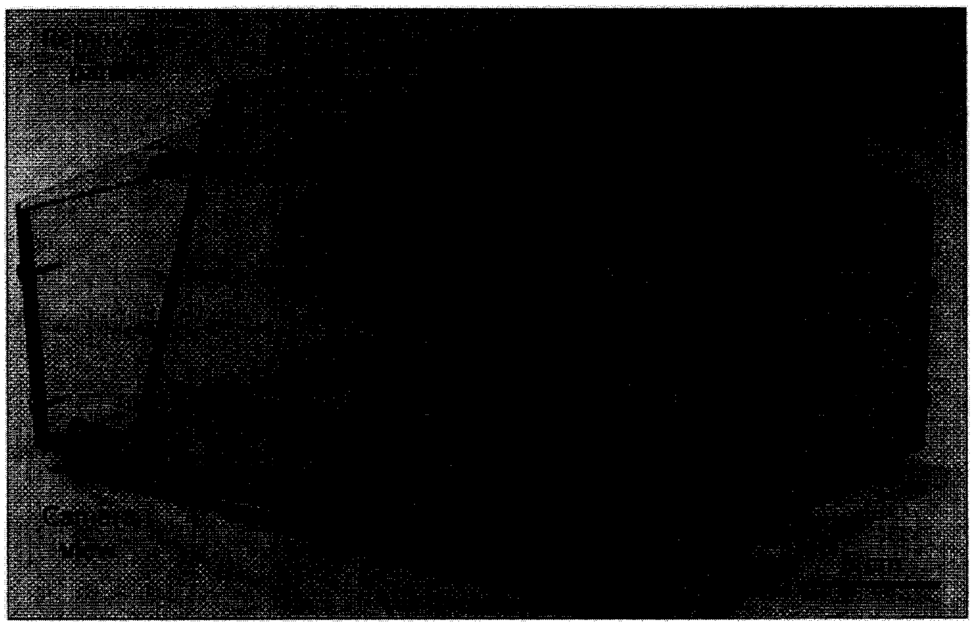

Fig. 2. Photograph of the experimental apparatus (less the viscous fluid). The container was constructed from clear polycarbonate materials allowing an undistorted view of the motion of the inclusions during the experimental deformations. Removal of the indicated panels allowed deformation to commence.

neous time-dependent flow. The apparatus consisted of a fluid container that allowed the initial support and release of the fluid mass while permitting the motion of the inclusions to be viewed during deformation (see Fig. 2). The fluid reservoir, consisting of two removable panels, the sides and base, defined the initial shape of the fluid mass to be deformed (Fig. 1).

The clear viscous fluid used in these experiments was a borate cross-linked polyvinyl alcohol gel (Casassa *et al.*, 1986). The fluid had a viscosity of the order of 2.5×10^3 Pa s at a strain rate of 3×10^{-2} s^{-1} and behaved as a Newtonian fluid over the range of strain rates generated by the experimental deformations (Stewart, 1996).

The column of less viscous fluid, used as a heterogeneity within the main body of polyvinyl alcohol gel, was water coloured with red ink. The water was coloured so as to differentiate the column from the more viscous fluid. Water has a viscosity of approximately 1×10^{-3} Pa s (25°C) giving a viscosity ratio between the two fluids of the order of 10^6. This ratio is quite large. However, no data are available relating to what may be a representative ratio within the scope of the deformation partitioning model. Carey (1962) suggests that the range of viscosities for deforming sediments (shales, sandstones, limestones and conglomerates) may be up to 10^6. In view of this, an experimental viscosity contrast of the order of 10^6 may be geologically sound as deformation partitioning occurs at all scales of deformation.

The acrylic ellipsoidal inclusions are approximately 8 mm in length as measured along the long axis. They had approximately circular cross-sections (4 mm diameter) perpendicular to the long axis, with diameters of 4 mm. A hole approximately 0.5 mm in diameter ran through the ellipsoid along the long axis. This hole was necessary to allow the emplacement of the ellipsoids in a near vertical orientation. Ellipsoidal inclusions were used as their orientation could be easily determined from their profile. The spherical inclusions utilized by Stewart (1996) were not used as the line that separated the two hemispheres, and provided orientation data, for each inclusion could not be reliably observed in experiments that incorporated the coloured heterogeneity.

Within the experiments incorporating the fluid heterogeneity the columns of less viscous fluid that partially enclosed the inclusions also served as strain markers. During deformation the orientations of inclusions and strain markers were recorded over time using a 35 mm camera oriented perpendicular to the main direction of extension and focal plane parallel to the container side (Fig. 2).

EXPERIMENTAL PROCEDURE

Fluid was placed into the reservoir to a depth of 12 cm and the inclusions emplaced within the fluid mass. The general distribution of inclusions within the fluid mass is shown in Fig. 1(a & b). By simultaneously removing the supporting panels (Fig. 2), the fluid mass was allowed to collapse under the effect of gravity, resulting in an inhomogeneous time-dependent flow (Stewart, 1996). Photographs of the deformation were taken at 2-s intervals for the duration of the experiment. In all experiments the behaviour of the inclusions and passive markers was analysed until the flowing fluid contacted the walls of the container that were perpendicular to the direction of fluid propagation.

The viscosity of the fluid varied slightly between experiments due to dehydration of the gel in use and storage. Experiments lasted an average of 43.6 s with a standard deviation (σ) of 7.6 s. The differing experimental duration between experiments did not result in any marked change of behaviour for the inclusions within an experiment type. The inclusions, on average, sank in the gel with a maximum sink rate of 8 mm per day, which is insignificant over the average experimental duration.

Homogeneous fluid experiments

Three experiments were performed whereby the inclusions and strain markers were placed within a reservoir of homogeneous polyvinyl alcohol gel that was then deformed by bulk inhomogeneous shortening. These experiments served as the control against which the inclusion and strain marker behaviours observed in the experiments with fluid heterogeneities could be contrasted. In these experiments five ellipsoidal inclusions were uniformly distributed in each of two vertical columns within the reservoir of gel (Fig. 1b). In two of the experiments the inclusions were emplaced such that their long axes were as close to vertical as possible, perpendicular to the direction of extension of the fluid during collapse. The remaining experiment was performed with each inclusion's long axis initially oriented at an angle to the vertical, within the plane of the section containing them. This was done so as to examine the sensitivity of the rigid-body motion to the initial orientation of the inclusion. Small particles of graphite were also distributed throughout the section of fluid containing the inclusions in order to allow computerized analysis of the flow. Within all three experiments thin vertical dye lines (passive strain markers) were placed within 5 mm of the vertical columns of inclusions.

Experiments incorporating heterogeneity

Four experiments were performed with the inclusions uniformly distributed in vertical columns of the coloured, less viscous fluid (Fig. 3). The less viscous columns of fluid containing the inclusions were placed in the same locations as the columns of inclusions in the control experiments. These fluid columns also served as the strain markers for the experiment. The columns of fluid widened (in the plane of extension) with shortening as the deformation progressed. Therefore, an interpolated line down the approximate centre of these markers was used to determine strain marker orientation. As in the control experiment the inclusions were positioned with their long axes as close to vertical as possible. After insertion, the width of the column of less viscous fluid varied slightly allowing the inclusions to be held in location by their partial contact with the viscous gel (see Fig. 3).

Two experiments used the same number of inclusions as the control experiment. The other two experiments involved the use of four inclusions uniformly distributed within each column of less viscous fluid. In one experiment small graphite particles were distributed within the fluid cross-section containing the vertical columns and used to perform a quantitative analysis of the flow.

The columns of fluid containing the inclusions were inserted into the main body of gel by first freezing a tube containing the fluid and rigid objects. This assembly was then pushed into the main body of gel. The tube was then withdrawn leaving the frozen column of fluid to thaw. Once thawed, the result was a column of less viscous fluid containing the inclusions within the main body of gel. In one experiment an attempt was made to create an initial state whereby a localized unit of less viscous fluid would partially enclose each ellipsoid. This was attempted by inserting small plugs of gel, into the tube mentioned above, to separate each inclusion and its associated unit of less viscous fluid from the next. After insertion of this divided column into the gel it was noticed that the less viscous fluid of the column thawed more quickly than the small plugs of gel. At the start of the experiment the plugs still had not thawed completely and behaved as separate objects within the column during the deformation. Some inclusions interacted with these plugs through physical contact during the deformation. Within the experiments, inclusions that interacted with the plugs of gel or other inclusions were excluded from the analyses of inclusion behaviour.

RESULTS

System deformation characteristics

Both the homogeneous and heterogeneous systems deformed in a manner that was two-dimensionally (horizontally and vertically) inhomogeneous on the scale of the experiment. Computer analysis of the fluid-system deformation was possible for the experiments that had small marker particles incorporated into the cross-section of the fluid containing the inclusions (Stewart, 1996). Deformation analysis was undertaken using the software package 'Marker Analysis' (Bons *et al.*, 1993) that allows the analysis and visualization of deformation in see-through experiments that incorporate marker particles. This software allowed production of undeformed and deformed grids and strain ellipses for both experimental types (Fig. 4). Grid sizes differ for the two analyses shown, as each grid represents the largest usable set of marker particles for each experiment.

There were two principal directions of fluid movement: (1) downward, due to the collapse of the fluid mass (shortening); and (2) laterally toward the box ends (extension—see Fig. 5). Inhomogeneity of the flow in the extensional direction is indicated by the curve in the

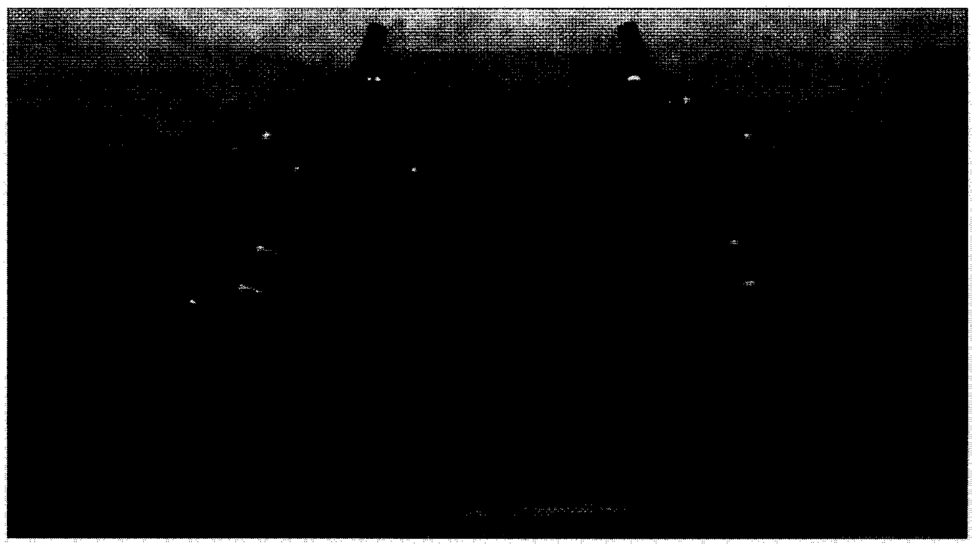

Fig. 3. Photograph of the apparatus before the commencement of an experiment involving fluid heterogeneity. The main body of gel fills the region between the two inclined panels. The less viscous column of fluid is the darker shade material with ellipsoidal inclusions uniformly distributed throughout its length. This column also serves as the strain marker for the extensional flow. Inspection of the columns shows both fluids were in contact with each inclusion.

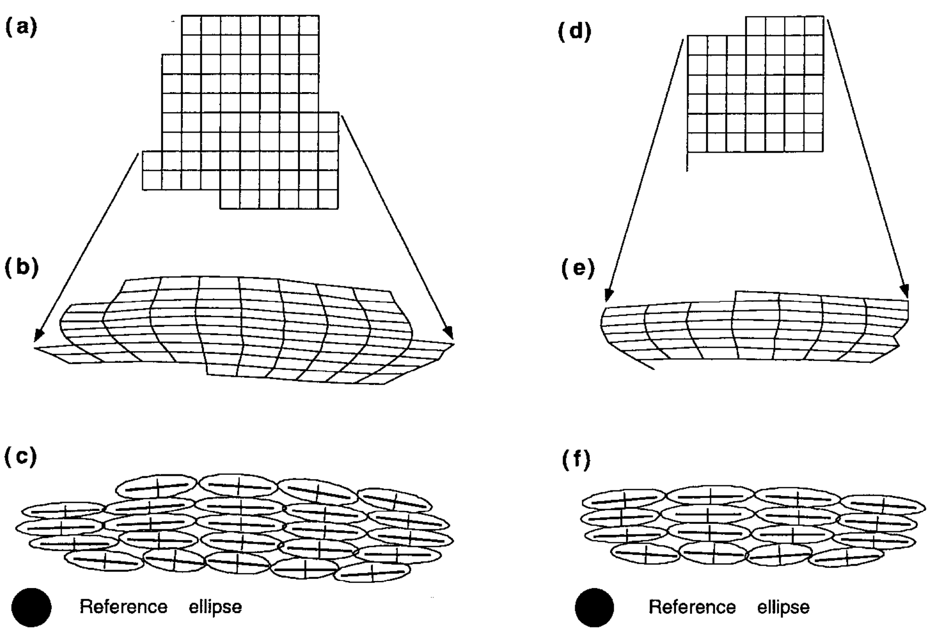

Fig. 4. (a) Undeformed grid and (b) deformed grid for an experiment involving inclusions located in homogeneous fluid. (c) Strain ellipses relating to the deformation of the homogeneous fluid. (d–f) represent undeformed and deformed grids and strain ellipses, respectively, for an experiment incorporating the fluid heterogeneity. Both the strain ellipses and deformed grids were produced using the Marker Analysis software (Bons *et al.*, 1993).

strain markers (Fig. 6) for both the homogeneous and heterogeneous fluid systems. By examining Figs 4–6 it can be seen that the deformation characteristics at the system scale were quite similar for the two experimental types.

For the experiments incorporating marker particles the kinematics of deformation were also examined in four different sub-systems that contained inclusions and strain markers. Sub-system boundaries were distributed (Fig. 7a & b) (based on the work of Stewart, 1996) to reflect areas of fluid displaying differing kinematic characteristics (e.g. in sub-systems 1 and 4 a dextral sense of shear parallel to the direction of extension was indicated by the strain marker while a sinistral sense of shear was indicated in sub-systems 2 & 3—see Fig. 6).

Examination of Fig. 7(a & b) shows that each of the sub-systems had marker particles dispersed throughout its domain. Bons *et al.* (1993) stated that the Marker Analysis software can be employed to calculate the mean kinematics of deformation for a group of marker

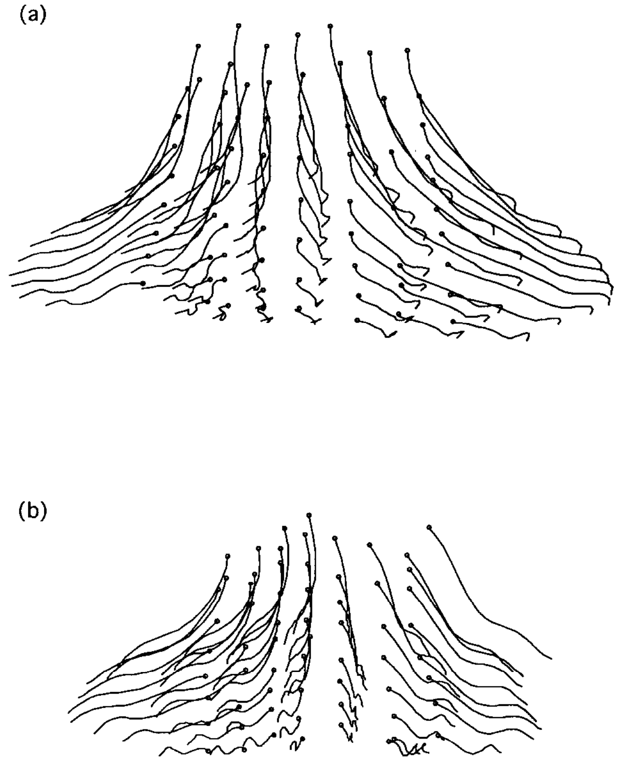

Fig. 5. Interpolated marker particle paths produced using the 'Marker Analysis' deformation analysis program (Bons *et al.*, 1993): (a) for the homogeneous system and (b) for the system that incorporated the fluid heterogeneity. Small dots represent the initial locations of the marker particles.

particles over time. The software was used as such to calculate the bulk kinematics of deformation for each group of marker particles representing a sub-system. Shown in Fig. 7(a & b) are plots of the bulk values of the finite rotation of the principal stretching directions (PSD), which are the long and short axes of the strain ellipse (Bons *et al.*, 1993), and the orientation of the instantaneous stretching axes (ISA) for each sub-system. All orientations were measured as deviation in degrees from the vertical. A clockwise deviation was given a negative value; an anti-clockwise deviation was given a positive value.

Principal stretching direction rotation sense in sub-systems 1 and 3 reverses during deformation indicating a reversal in the sense of the simple shear (Stewart, 1996) in these sub-systems for both experiment types (Fig. 7a & b). The PSD rotation within sub-systems 2 and 4 (Fig. 7a & b) suggests a consistent shear sense within these sub-systems (Stewart, 1996) for both experiment types during the deformation. Overall comparison of plots of PSD rotation and ISA orientation for sub-systems 1–4 between homogeneous (Fig. 7a) and heterogeneous systems (Fig. 7b) shows that the deformation kinematics for these sub-systems were similar for both experimental types at that scale.

The orientation of each inclusion and a portion of strain marker, either adjacent to (homogeneous experiments) or partially enclosing (heterogeneous experiments) it, was determined for sub-systems 1–4. These data were plotted against total duration for each experiment (Figs 8 & 9). Measured orientations of strain marker and inclusion represent orientation with time from the initial positions of these lines and objects, respectively.

Homogeneous fluid experiments—inclusion behaviour

Figure 8 shows the results of the three experiments performed using the homogeneous fluid for the four sub-systems. Motion of inclusions and adjacent strain marker may be compared for each sub-system. Inspection of the left-hand column of graphs (Fig. 8) shows that strain marker behaviour was consistent within each sub-system and across experiments. Examination of the right-hand column of graphs (Fig. 8) shows that, with the exception of inclusion (a) in sub-system 3, the behaviour of the inclusions was consistent within each sub-system and across experiments. Comparison of left and right columns of Fig. 8 shows agreement between the sense of rotation of the inclusions (excluding a) and the sense of rotation of the portions of immediately adjacent strain marker for each sub-system. Several inclusions were initially oriented at varying degrees to the vertical so as to assess the sensitivity of inclusion rotation sense to initial orientation. The results suggest the rotation sense of the inclusions (i.e. in the same sense as the marker line) was, in general, robust with respect to initial orientation within the range of orientations tested. The exception was inclusion (a) in Fig. 8 which initially did not display a significant change in orientation. The behaviour of this inclusion suggested that it may have initially been close to a stable position at -16° in sub-system 4. However, because of the time-varying nature of the deformation kinematics it was unlikely that a single stable position could have existed for an inclusion over the duration of the experiment. Significantly, the inclusion began to rotate at about the same point in time that the PSD rotation sense reversed within the deforming sub-system. Inclusions initially oriented near -16° in sub-system 7 for the experiments incorporating the fluid heterogeneity did not display similar behaviour and rotated throughout the deformation.

Experiments incorporating heterogeneity—inclusion behaviour

Strain marker motion within the four sub-systems was similar to the motion observed in the control experiments (compare the left-hand columns of Figs 8 & 9) and consistent within each sub-system (inspect the left-hand column of Fig. 9). Comparison of the behaviour of inclusions in similar locations between the control and contrast experiments shows that the introduction of fluid heterogeneity produced significantly different behaviour in 50% of the inclusions involved (compare the right-hand columns of Figs 8 & 9).

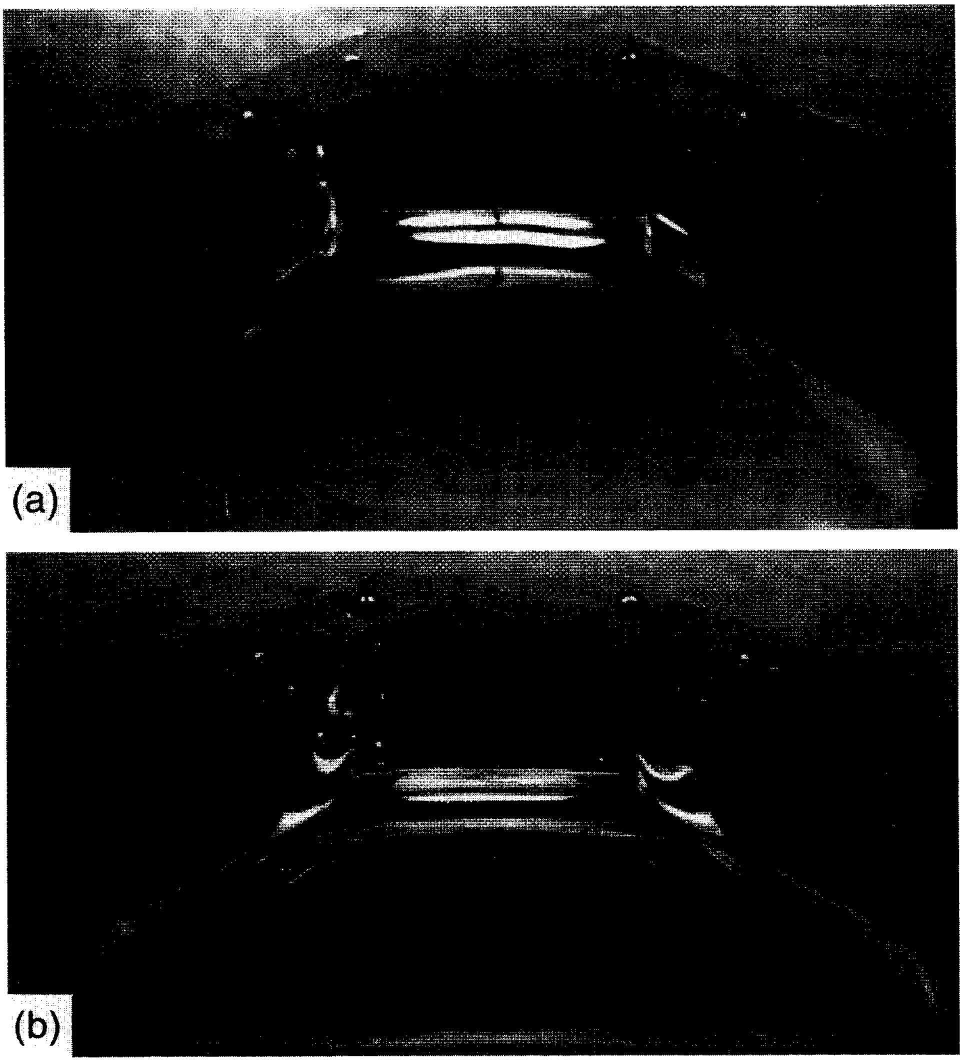

Fig. 6. Photographs displaying the curve in strain markers, at the completion of an experiment, and thus inhomogeneity of flow in the extensional direction for both (a) a homogeneous fluid experiment and (b) an experiment incorporating the less viscous fluid heterogeneities.

While one basic type of motion was identified in the control experiment for the inclusions located in sub-systems 1–4 (rotation in the same sense as strain marker), three types of motion were exhibited by the inclusions in the contrast experiments. These were: (1) rotation in the opposite sense to the strain marker and control objects despite similar initial orientations of the inclusions (27%); (2) no significant rotation of the inclusions despite being in a sub-system where the strain marker and the control objects rotated (19%); and (3) rotation in the same sense as the strain marker and inclusions in the control experiment (50%). The remaining 4% of objects exhibited behaviour that was a combination of type 1 and type 3.

Type 1 behaviour seems to be the result of increased sensitivity to the initial orientation of the inclusion due to adhesion between the gel and inclusion, combined with the ability of the less viscous fluid to accommodate the back-rotation of the ellipsoid. Photographs taken during the experiment show that the initial orientation of the inclusion was such that the ellipsoid contacted the viscous gel on both sides of the fluid column but on different portions of the ellipsoid. For example, the upper portion of the ellipsoid contacted the gel on one side of the column and the lower portion contacted the gel on other side (Fig. 10a). As deformation progressed the column widened and rotated due to progressive shortening. The rotation of the column would have also produced a flexural-flow (Hobbs *et al.*, 1976) effect across the column. The relative movement of the opposite sides of the column, combined with the inclusion's contact with the gel across the widening column, rotated it in the opposite direction to the strain marker (Fig. 10b). The resistance of the less viscous fluid to the motion of the ellipsoid was not great enough to break the gel–ellipsoid contact across the column. This notion is supported by photographic and graphical data for an inclusion in sub-system 3 (a in Fig. 9) during an experiment incorporating fluid heterogeneity. As can be seen this inclusion rotated in a clockwise and then an

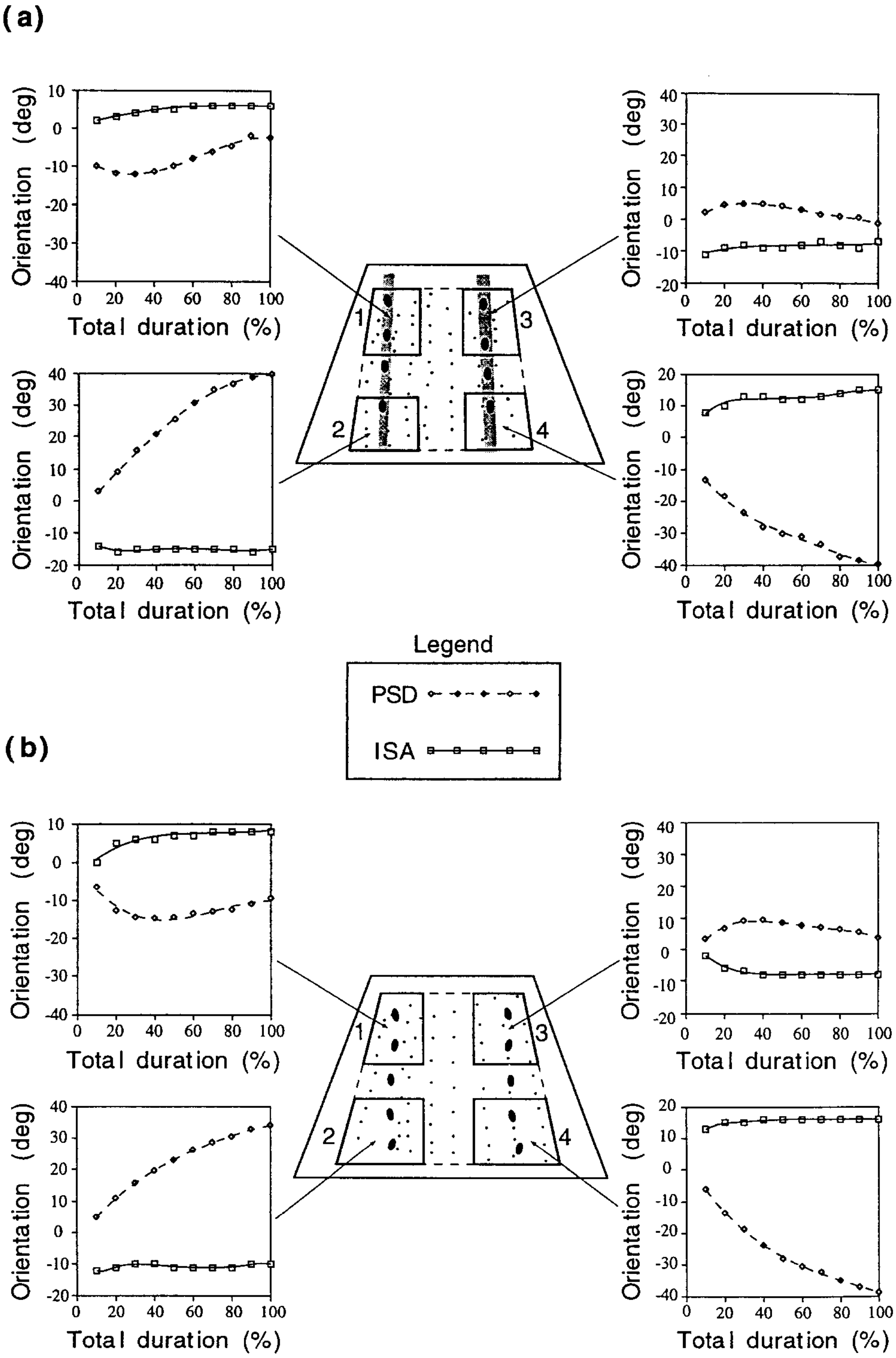

Fig. 7. Diagram showing the cross-section of the fluid mass, approximate locations of inclusions (solid ellipses) and passive particle distribution (dots) for experiments involving (a) fluid heterogeneity and (b) homogeneous fluid. Also shown are sub-systems for which kinematic analysis was performed (numbered 1–4) and plots representing finite PSD (principal stretching direction) rotation and ISA (instantaneous stretching axes) orientation for those areas.

anti-clockwise sense. The commencement of the period of anti-clockwise rotation corresponded with a visible break in the contact between the inclusion and gel on one side of the column. Once the contact across the column was broken the inclusion was free to rotate with the side of the column with which it remained in contact. Thus, it began to rotate with the strain marker boundary.

Type 2 behaviour, in which inclusions did not rotate significantly but strain markers did, seems to be the result of two different processes. One process resulting in this

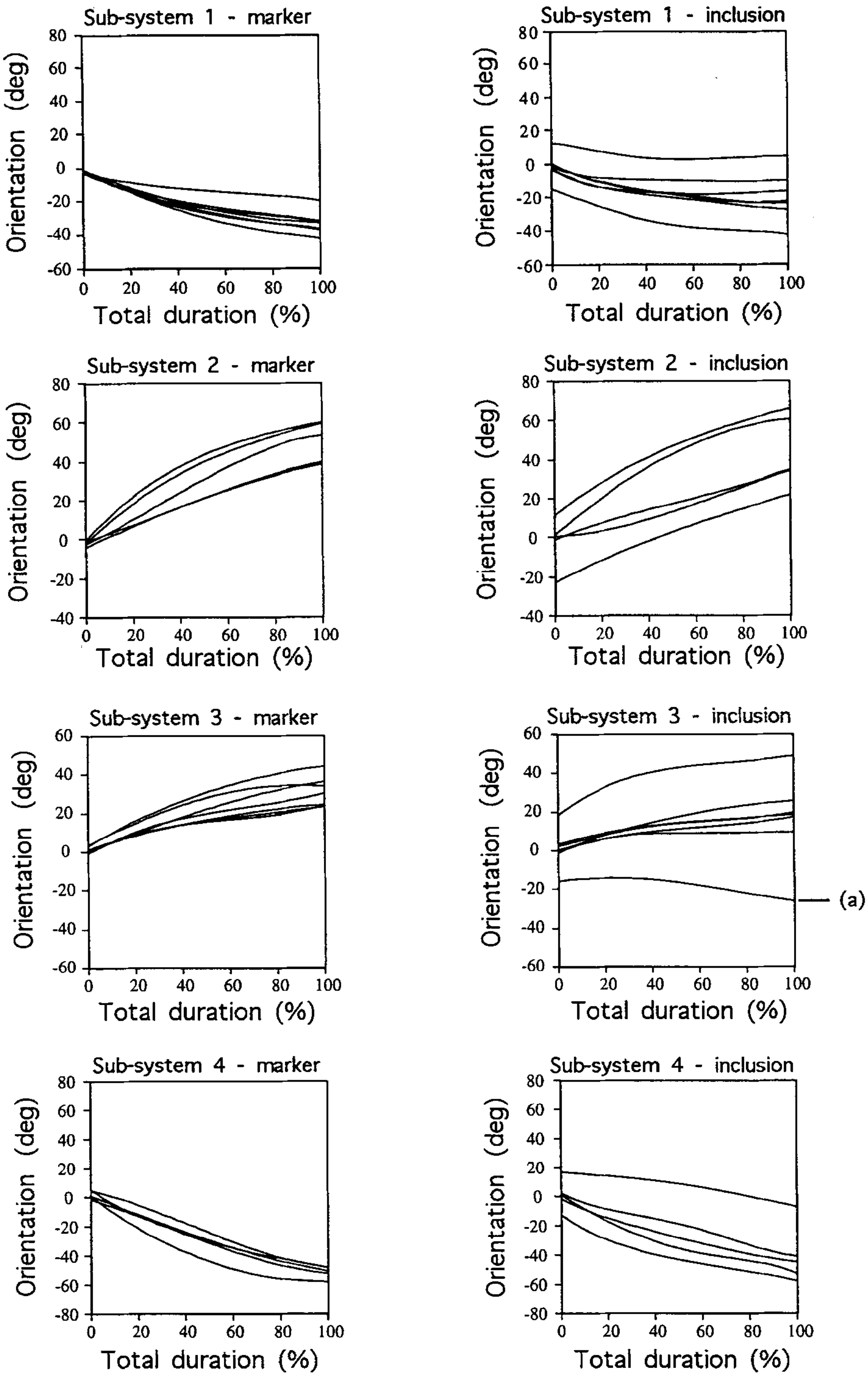

Fig. 8. Paired graphs displaying strain marker orientation and inclusion orientation, respectively, against percentage of total experimental duration, for all homogeneous fluid experiments, for sub-systems 1–4.

behaviour seems to be the amount of rotation of the column being matched by the level of (type 1) back-rotation of the inclusion. In the other process the less viscous fluid, which probably also facilitated a slip (low friction) domain between inclusion and gel, allowed accommodation of the shear induced by the deformation without significantly rotating the inclusion (see Fig. 11).

Inclusions exhibiting this behaviour rotated less than 10° from their initial orientations, whereas the control objects in similar locations rotated significantly. Compare the behaviour of inclusions (b)–(e) in Fig. 9 with that of inclusions in the same sub-systems for the control experiments (Fig. 8).

Type 3 behaviour was similar to that observed in the control experiment. In the heterogeneous experiments 54% of the inclusions that displayed type 3 behaviour

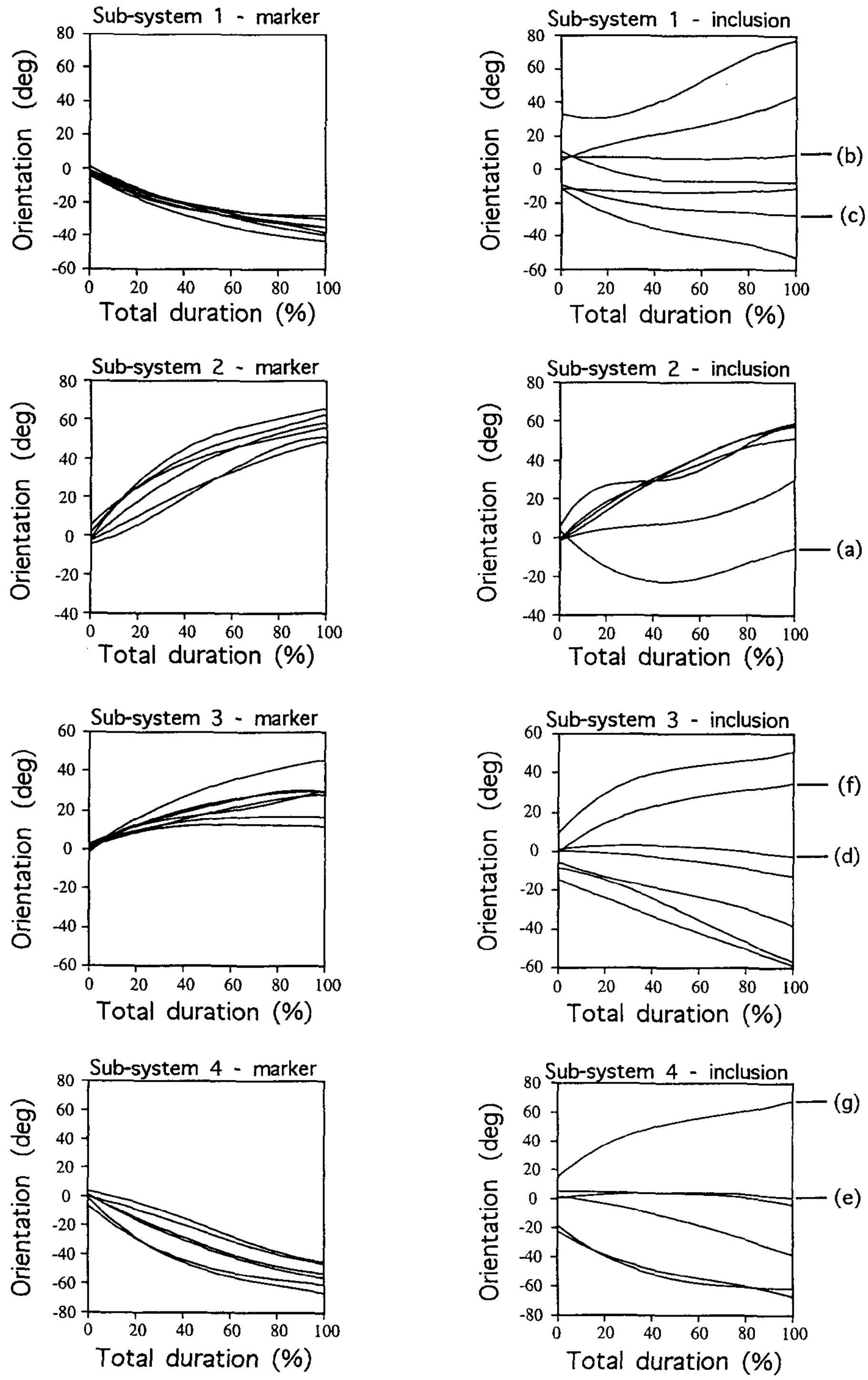

Fig. 9. Paired graphs displaying strain marker orientation and inclusion orientation, respectively, against percentage of total experimental duration, for all experiments performed with a fluid heterogeneity incorporated into the homogeneous fluid, for sub-systems 1–4. Several different behaviours are evident: (a) forward- and back-rotation of an inclusion; (b–e) no significant rotation of an inclusion; (f) rotation of an inclusion in the same sense as the strain marker; and (g) rotation of an inclusion in the opposite sense to the strain marker.

were the lowermost in their columns. The greater overall fluid pressure near the base of the experimental rig caused some of the less viscous fluid to be moved upward. Consequently, they were primarily enclosed by the more viscous fluid. The motion of the inclusions contained in these 'less' heterogeneous fluid environments (27% of the total number of inclusions) was similar to the control objects (Fig. 9) and seemed to result from similar processes.

Inclusions that were not lowermost in the column but displayed this behaviour had a portion of their surface adhering to the gel on one side of the less viscous column.

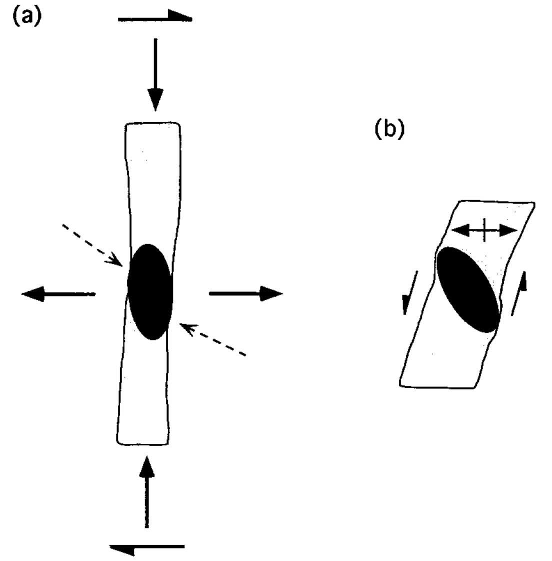

Fig. 10. Diagrammatic representation of type 1 behaviour whereby inclusions rotated in the opposite direction to sub-system strain marker. (a) Shaded area represents the less viscous column located within the gel. Bold arrows represent principal directions of compression and extension. Bold half-arrows represent sense of strain marker rotation. Dashed arrows indicate principal areas of contact of gel with the inclusion surface. (b) Widening of the column combined with relative movement of the column walls due to a flexural-flow type effect resulted in opposite sense rotation of the ellipsoid.

This allowed the inclusion to rotate with the column wall during deformation.

DISCUSSION

Experimental results

Although the system and sub-system scale deformation characteristics were similar across the two experiment types, the introduction of fluid heterogeneities made a significant difference to the rotational behaviour, and the process of rotation, of the ellipsoidal inclusions. The three principal behaviours displayed by inclusions in the heterogeneous system are descriptively the same as the full range of behaviours possible for ellipsoidal rigid objects embedded within a viscous medium undergoing combinations of pure and simple shear (Ghosh and Ramberg, 1976). However, as described earlier, the behaviours observed within these experiments are, in general, produced by different processes. The exceptions are the inclusions that had a relatively low level of representation by the less viscous fluid heterogeneity in their local fluid environments. Therefore, it appears that an important factor that influences object behaviour is the level of heterogeneity present at the scale of interest. The experiments also suggest that different levels of friction adhesion between differing mineral types during deformation may also affect the behaviour of rigid bodies during deformation.

Within the heterogeneous fluid experiments it is likely that the axial ratio (Ghosh and Ramberg, 1976) of the objects would influence their rotational behaviour. This

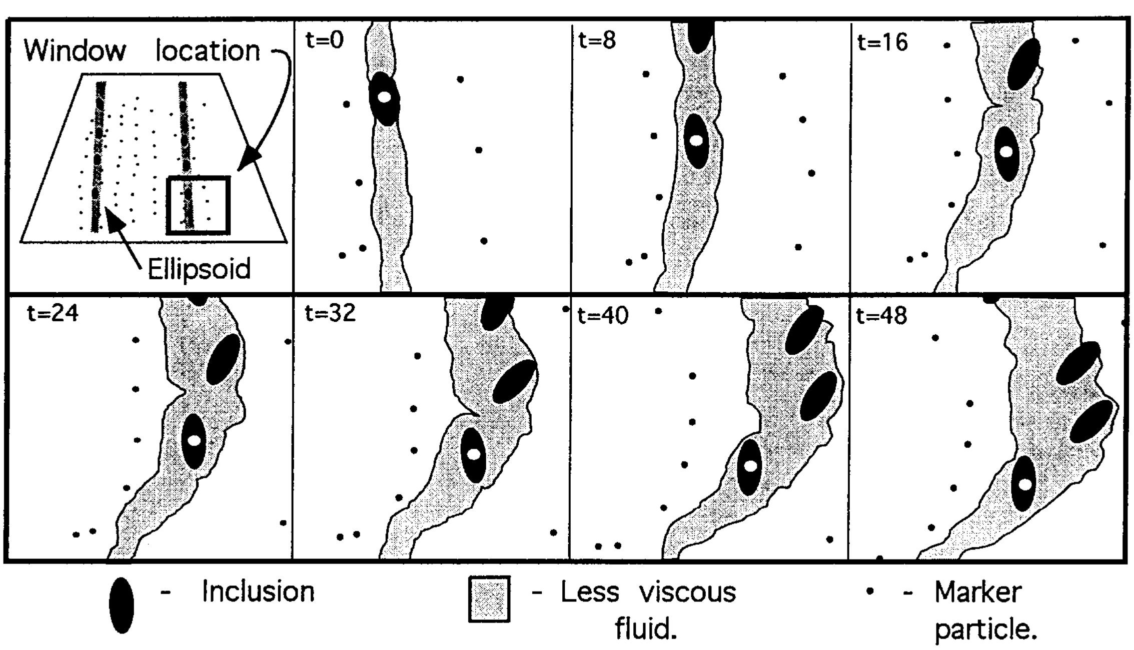

Fig. 11. A sequence of line drawings, produced from photographs, that show the deformation of the fluid system as viewed through a fixed window. The top-left frame shows the window location in relation to the initial-state system cross-section. Remaining frames show deformation at various times, *t* (in s). The inclusion denoted with a white spot displays type 2 behaviour. As the photographs give a two-dimensional image of a three-dimensional relationship between the two fluids and the inclusion, some inclusions can occasionally appear to be totally enclosed by the less viscous fluid; this is not so. In the experiments incorporating fluid heterogeneity the inclusions will have always had some contact with both fluids during deformation.

would certainly be the case for the type 1 and the sub-set of type 2 behaviours where the inclusions were observed to rotate in the opposite direction to the strain marker, due to the inclusions contacting and adhering to the viscous gel on either side of the widening less viscous column. In such cases the amount of rotation would probably depend on the axial ratio, the lengths of the major and minor axes of the inclusion, and the amount of widening of the less viscous column. Axial ratio would have certainly played a role in determining the rotational behaviour of the sub-set of inclusions, displaying type 3 behaviour, that had local fluid environments with relatively low levels of heterogeneity. Such inclusions appeared to have been rotated in a manner consistent with the homogeneous system.

These results suggest that the behaviours of porphyroblasts/porphyroclasts partly or wholly enclosed by micaceous minerals within a more competent matrix may, if the viscosity contrast and level of heterogeneity is similarly large, be different to that of rigid objects in homogeneous fluids. Also, in deforming fluid systems that are suitably heterogeneous at the scale of rigid inclusions, it seems that a less viscous fluid partially enclosing an inclusion can, in some cases, facilitate a lack of rotation of that object.

Homogeneous fluid flow theory

Consider a porphyroblastic rock that contains a strong planar anisotropy in the matrix, such as a pervasive cleavage, and that the porphyroblasts contain curved inclusion trails. It could be assumed that the curved inclusion trails resulted from rotation of the porphyroblasts in accordance with the rock mass having deformed similarly to a homogeneous fluid. However, before such an assumption is made it should first be verified that the rock system satisfies the relevant requirements for application of homogeneous fluid flow theory, as described by Passchier (1987a) and outlined earlier.

In addition to these requirements the rock system should also satisfy a further requisite: that it behaved as an isotropic fluid during deformation. This requirement arises because original work by Jeffery (1922), upon which later theoretical studies were based (e.g. Reed and Tryggvason, 1974), involved obtaining solutions to the linearized Navier–Stokes equations. The formulation of the Navier–Stokes equations is based on the premises for a Newton–Stokes fluid (Streeter, 1961), one of which is that the fluid is mechanically isotropic (it has no preferred directions).

Lister and Williams (1983) commented that in the deformation of a material with a strong planar anisotropy, full advantage would be taken of the planes of weakness within the material. The presence of pervasive phyllosilicate layers with a preferred crystallographic orientation in the 'fluid' would cause it to shear at different rates when sheared parallel, perpendicular or oblique to the layering. Consequently, the basic premise of homogeneous fluid flow is not valid for the rock system described and some doubt must remain in relation to the process that brings about the formation of the inclusion trails.

Homogeneous fluid flow theory should only be assumed to model an anisotropic system, such as that described, when a suitable justification exists for considering the effects of the anisotropy to be insignificant at the scale of interest. It is possible that such anisotropy could produce significant differences in rigid-body behaviour from those inferred by homogeneous fluid flow theory. Indeed, these experiments showed that the time behaviour of rigid ellipsoidal inclusions in a fluid system incorporating heterogeneities can be different to their motion within a homogeneous fluid.

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