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Coaxial progressive deformation textures in extrusive and shallow intrusive rocks, southwest Japan

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Abstract—Fine-grained rocks from an andesite dyke, a dacite dome and a basalt flow contain microshear zones overprinting an aligned microlitic groundmass. In each case, the shear zones comprise conjugate sets bisected by the plane of crystal alignment. This texture indicates coaxial (or pure shear) flow in contrast to simple shear which is generally considered to be the dominant kinematic flow type in extrusive and shallow intrusive rocks. This is interpreted as resulting from a change from non-coaxial to coaxial flow, coinciding with increasing viscosity during emplacement. This suggests that deformation of extrusive and shallow intrusive rocks in the near-solid state during the latter stages of emplacement may be more important in the development of aligned rock textures than fluid-state flow of the magma as is commonly envisaged.

INTRODUCTION

Studies of extrusive and shallow intrusive rocks commonly make the simplifying assumption that flow has occurred by simple shear and/or that the flow type has remained constant throughout emplacement. Textures with aligned crystals are commonly interpreted in terms of theoretical models of the behaviour of rigid particles in highly non-coaxial flows (e.g. Fernandez & Laporte 1991). However, other flow types are possible and the simplest of these can be characterized by vorticity numbers ranging from $W_k = 1$ (simple shear) to $W_k = 0$ (pure shear) (Passchier 1988). In contrast to metamorphic rocks where structures and textures have been used to determine the degree of non-coaxiality during deformation (e.g. Wallis 1992), studies of the textures of extrusive and shallow intrusive rocks are poorly represented in the structural geology literature. This may be due to a perception that the fluid-state flow commonly experienced by such rocks makes them less amenable to the techniques of structural analysis. For batholithic rocks, structural studies have been successful since, although strain may be high, significant evidence of strain is commonly preserved in the near-solid mass during progressive cooling and multiple injection (e.g. Ramsay 1989, Melka *et al.* 1992). In dykes (Shelley 1985, Greenough *et al.* 1988, Wada 1992), domes and flows (Bonnischsen & Kauffman 1987, Fink & Manley 1987) crystal alignment foliations have been thought to reflect viscosity gradients during fluid-state flow. However, unlike studies of batholithic rocks, little consideration has been given to the influence of near-solid state flow of progressively solidifying extrusive rock on the development of textures. Recently, Smith *et al.* (1993) demonstrated that at least 15% coaxial progressive deformation was imposed on a dyke rock as it solidified. They suggested that coaxial progressive deformation may have been the dominant process in forming the strong crystal alignment in the rock. In this paper we present further evidence of the importance of syn-emplacement coaxial progressive deformation of igneous rocks with a range of compositions and modes of emplacement. We also discuss how structural studies of extrusive and shallow intrusive igneous rocks can potentially make a contribution to solving general problems such as the nature of the transition from distributed to localized progressive deformation.

COAXIAL PROGRESSIVE DEFORMATION TEXTURES

The prevalence of the opinion that textures in extrusive and shallow intrusive igneous rocks are dominated by the effects of fluid flow ignores the fact that such rocks must become increasingly viscous before solidification. During that time strain rate decreases and groundmass crystals are likely to be forming. Therefore, the nature of the flow in this late stage is very important in the development of rock textures. We present textures from three different fine-grained igneous rocks to illustrate this point.

Andesite dyke

Smith *et al.* (1993) reported a vertical vitrophyric andesite dyke trending NNW near the village of Sezaki on the Shimane Peninsula on the Japan Sea coast of

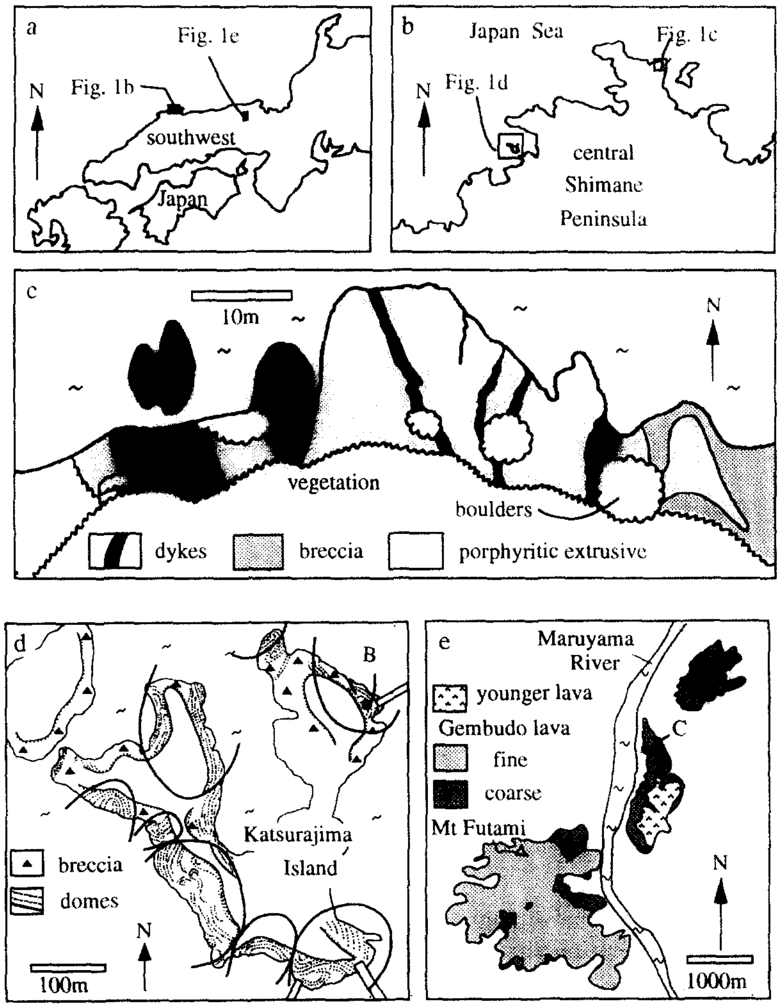

Fig. 1. (a) Location diagram, southwest Japan. (b) Location diagram, Shimane Peninsula. (c) Andesite dykes near Sezaki on the Shimane Peninsula. Detailed description is made of samples from dyke A. (d) Domes on Katsurajima Island off the Shimane Peninsula. Detailed description is made of a dacite dome at B. (e) The Gembudo basalt lava flow. Detailed description is made of a sample from C.

southwest Japan (Figs. 1b & c). The 10 m wide dyke has a strong banding about 5 mm thick except in a 2 m wide zone near the centre. The unbanded zone has horizontal columnar joints whereas the banded part has more irregular jointing. We interpret the banding as being a result of multiple injections of magma and the unbanded zone as the last part of the dyke to solidify or the last of the series of multiple injections. Investigations of thin sections in three orthogonal orientations, the horizontal plane, parallel to the dyke margins and perpendicular to the dyke margins (Fig. 2a), showed that the dyke has a fabric in which the plane of alignment of plagioclase (and augite) phenocrysts is parallel to dyke margins. In addition to alignment of phenocrysts, plagioclase microlites are also strongly aligned but the fabric is disrupted at regular intervals by conjugate microshear zones (Figs. 3a & b). The axes of extensional (ε_1), intermediate (ε_2) and shortening (ε_3) finite strain were determined from these conjugate microshear zones ($\varepsilon_{1,2,3}$ in Fig. 2a). Both the banded and unbanded parts of the dyke contain microshear zones but they are more closely spaced in the banded part. Using the centre line of a microshear zone (Fig. 3a) as a reference line, we have measured the orientations of microlites up to 150 μm from the zone centre (Fig. 4a). The microlites in the zone are sub-parallel to the zone. More than 45 μm from the centre line there are few crystals parallel to the zone and the orientations of crystals with respect to the shear zone increases with distance. Beyond 65 μm most crystals are oriented between 30° and 60° to the microshear zone. In the groundmass these features appear as a curvature of microlite trends through the microshear zone.

Shelley (1985) interpreted intergrowth of crystals from inside and outside microshear zones as indicating crystal growth concurrent with shearing. He interpreted the textures to be the result of 'Riedel-type' shear zones within margin-parallel simple shear flow in the dyke. Smith *et al.* (1993) confirmed the formation of shear zones concurrently with microlite growth but interpreted the textures as indicative of coaxial progressive deformation of the solidifying dyke rock caused by the magma pressure of unsolidified parts of the dyke or multiple injections. Evidence for coaxial progressive deformation comes from the consistent orientation of the bisector of conjugate shear zones (Fig. 5a) perpendicular to the plane of crystal alignment and thus, in this case, the dyke margins. Smith *et al.* (1993) made an estimate of 15% shortening based on orientation, spacing and displacement on microshear zones. The displacement across shear zones was estimated, conservatively, to be 50 μm from the apparent displacement of other shear zones and the general curvature of the foliation through the zones. However, a more accurate determination of flattening is possible by measuring the displacement of the boundaries between bands by the microshear zones (Fig. 5b). This displacement is seen to be greater than previously estimated requiring a re-evaluation of the amount of strain.

The component of shear zone displacement in the shortening direction produced by an individual shear zone is:

$$x_d = d \sin \theta, \quad (1a)$$

where d is the displacement along the shear zone and θ is orientation of the shear zone measured from the normal to the shortening direction (Fig. 6). In order to determine the shortening of the rock overall, equation (1a) must be modified to account for the spacing of shear zones. The average spacing of shear zones along the bisector of two conjugate orientations is given by:

$$x_s = 0.5\, s \sec \theta, \quad (1b)$$

where s is the average spacing between shear zones measured normal to the shear zones (Fig. 6). The spacing is halved to account for the conjugate shear zones. Therefore, the shortening is given by:

$$e = 2d \sin \theta / s \sec \theta \quad (1c)$$

which can be simplified to:

$$e = (d/s) \sin 2\theta. \quad (1d)$$

Figure 5(b) shows that the displacement across an individual shear zone can be as high as 500 μm, however, we will use a value of 250 μm to account for other shear zones with less displacement. A representative spacing of shear zones of 500 μm will be used and the orientation of shears will be taken as 45°. By equation (1d), these values give a shortening of 50% (that is, a finite strain ratio of $R_f = 4$). This is a minimum value as there may have been distributed shortening preceding that achieved by displacement on shear zones.

Dacite dome

Katsurajima Island lies in a bay of the Shimane Peninsula of southwest Japan. The island comprises a complex of silicic Miocene domes and breccias (Figs. 1b & d). On the eastern side of the island (B in Fig. 1d) there is a dacite dome (SiO_2 = 66%) in which the textures are remarkably similar to those described above for the Sezaki andesite dyke. The rocks are vitrophyric with phenocrysts of olivine and plagioclase and have a strongly aligned microlite foliation. This foliation is disrupted by closely spaced microshear zones (Fig. 3c). Investigation of thin sections oriented parallel to three cooling column faces showed that microshear zones formed a conjugate pair (Fig. 2b). Finite strain axes were determined from these conjugate microshear zones ($\varepsilon_{1,2,3}$ in Fig. 2b).

Measurements of microlite orientations, with respect to the centre line of the microshear zones, show that within the zone there is strong alignment of microlites sub-parallel to the zone. Further from the zone centre line crystal orientations become more oblique to the zone levelling off at about 45° to the zone (Fig. 4b).

The microshear zones form conjugate sets which are bisected by the foliation (Fig. 4c) indicating that the shear zones, and possibly also the foliation, formed by coaxial progressive deformation. There are no markers to accurately determine the displacement on individual shear zones but the spacing of shear zones suggests flattening equivalent to that in the andesite dyke. The shortening direction indicated by the conjugate zones is approximately parallel to the axis of cooling columns. We interpret this coaxial progressive deformation as being caused by the magma pressure of the dome stretching the stiff carapace of the dome as it solidified.

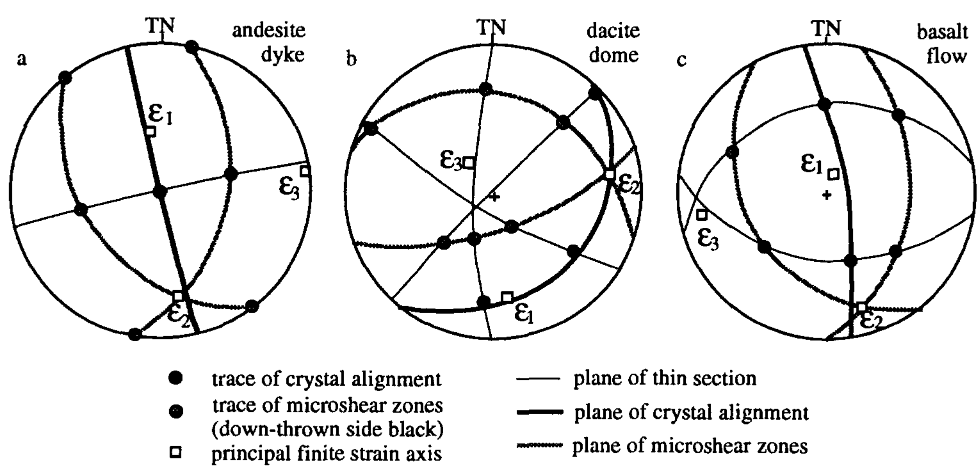

Fig. 2. Lower-hemisphere equal-angle stereograms of three-dimensional fabrics in representative samples from each of the three localities in Fig. 1. (a) Andesite dyke, (b) dacite dome and (c) basalt flow. Cooling column axis in (b) and (c) is parallel to the intersection of thin section planes.

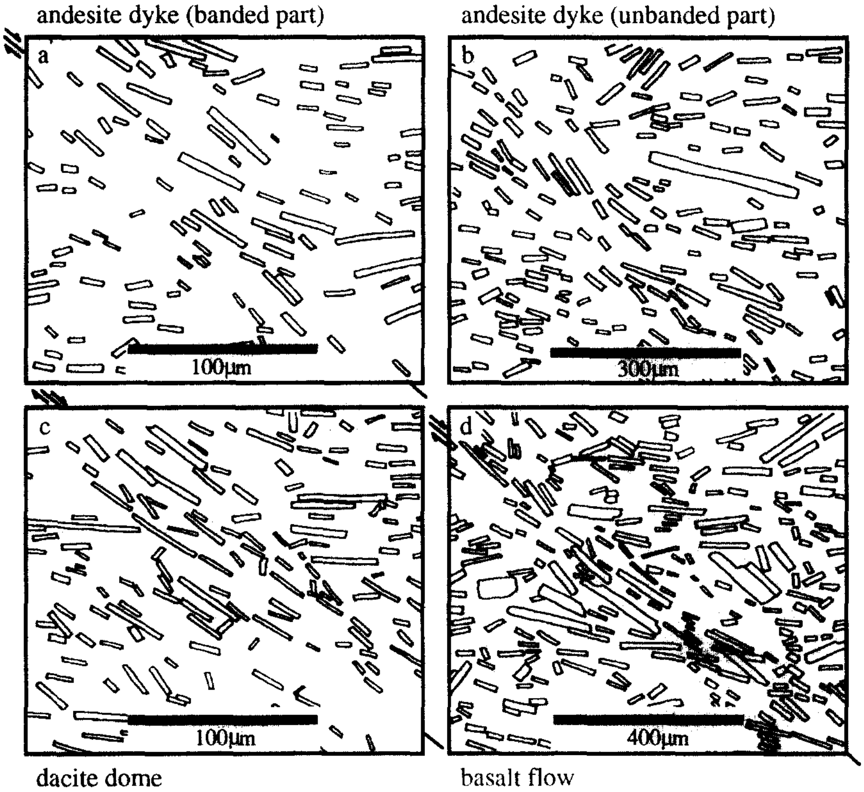

Fig. 3. (a) Micrograph of a microshear zone (top left to bottom right) from the banded part of an andesite dyke rock from near Sezaki on the Shimane Peninsula (A_1 in Fig. 1c). (b) Micrograph of a microshear zone (top left to bottom right) from the unbanded part of an andesite dyke rock from near Sezaki on the Shimane Peninsula (A_2 in Fig. 1c). (c) Micrograph of a microshear zone (top left to bottom right) in dacite dome rock from Katsurajima Island off the Shimane Peninsula (B in Fig. 1d). (d) Micrograph of a microshear zone (top left to bottom right) in basalt flow rock from the Gembudo lava (C in Fig. 1e). The crystal alignment foliation is parallel to the length of the bar scale in (a–d) and sections are cut approximately perpendicular to the intersection of the conjugate shear zones.

Basalt flow

The Gembudo lava is a Quaternary alkali olivine basalt (SiO_2 = 51%) in southwest Japan (C in Fig. 1e). The flow has a total thickness of about 100 m. The lower portions are coarse grained and grade upward into finer grained lava, particularly near the supposed vent at Mt Futami (Furuyama *et al.* 1991). The sample described here (C in Fig. 1e) is from the coarser phase of the lava about 50 m above the lava base and about 2000 m from the vent. The Gembudo lava is famous for its complex cooling joint patterns indicating that the lava formed as a complex system of lobes and tubes. Where the sample was collected the columnar joints are near-horizontal and trend E–W suggesting that it was near the side of such a lobe or tube.

The rock is nearly holocrystalline with a groundmass consisting of plagioclase lathes, olivine, clinopyroxene, opaque minerals and a small amount of glass. Within the groundmass, shear zones deflect the alignment of microlites but these zones are much more widely spaced than in the two previous examples. The rock is more coarse-

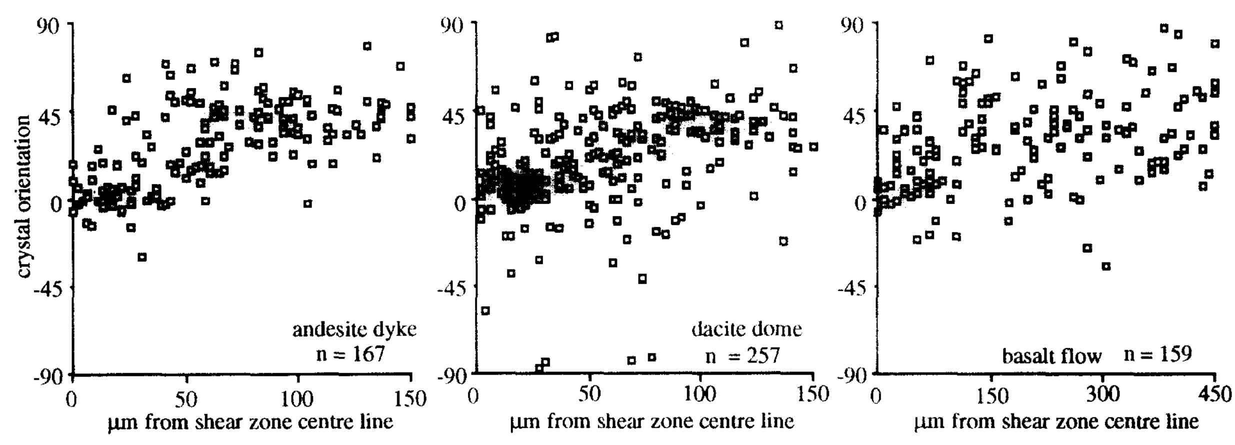

Fig. 4. Scatter diagrams of crystal alignment, measured in degrees from the centre line (edge ticks in Fig. 3) of microshear zones (anticlockwise positive). (a) Andesite dyke (Fig. 3a), (b) dacite dome (Fig. 3c) and (c) basalt flow (Fig. 3d). Note: horizontal scale is the same for (a) and (b) but is compressed by one-third in (c). Measurements extend to beyond fields of view in Fig. 3.

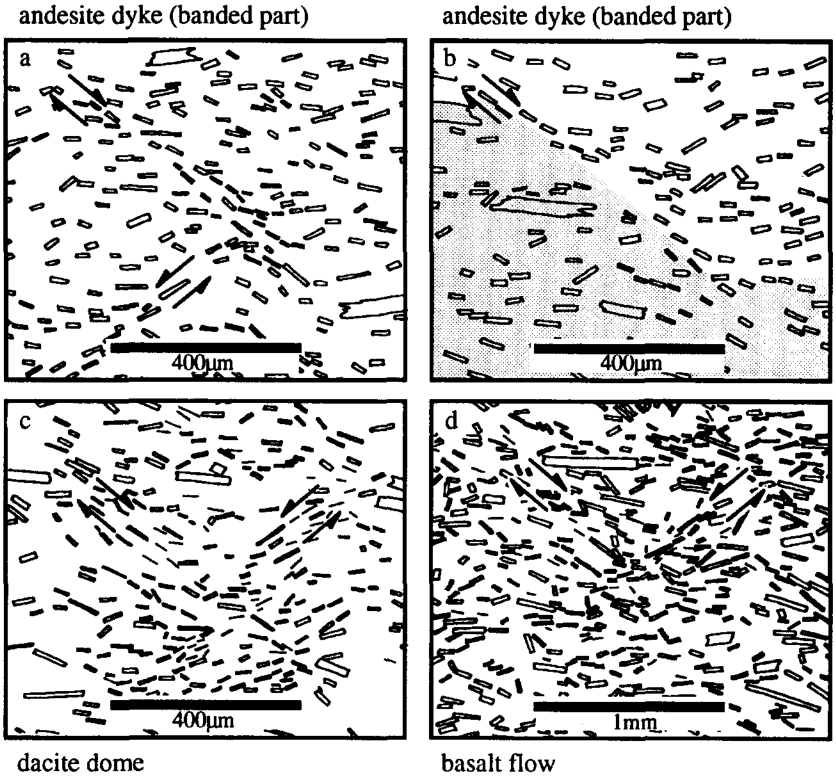

Fig. 5. (a) Micrograph of conjugate microshear zones (both diagonals) from the banded part of an andesite dyke rock from near Sezaki on the Shimane Peninsula (A_1 in Fig. 1c). (b) Micrograph of a microshear zone (top left to bottom right) from the banded part of an andesite dyke rock from near Sezaki on the Shimane Peninsula (A_1 in Fig. 1c). The displacement on the shear zone is indicated by the offset of a band (shaded). (c) Micrograph of conjugate microshear zones (both diagonals) in dacite dome rock from Katsurajima Island off the Shimane Peninsula (B in Fig. 1d). (d) Micrograph of conjugate microshear zone (both diagonals) in basalt flow rock from the Gembudo lava (C in Fig. 1e). The crystal alignment foliation is parallel to the length of the bar scale in (a to d) and sections are cut approximately perpendicular to the intersections of the conjugate shear zones.

grained than the dyke and dome described above, and the shear zones are also wider than in the other examples (Fig. 3d). Investigation of thin sections oriented parallel to two cooling column faces showed that the microshear zones comprise a conjugate pair (Fig. 2c).

Microlite orientations measured up to 100 μm from the zone centre show alignment oblique to the zone. At 100–450 μm from the zone there is diffuse alignment of crystals between 0° and 90° (anticlockwise, Fig. 4c). These microshear zones also form conjugate orientations (Fig. 5d) with the shortening direction being approximately parallel to the axis of cooling columns.

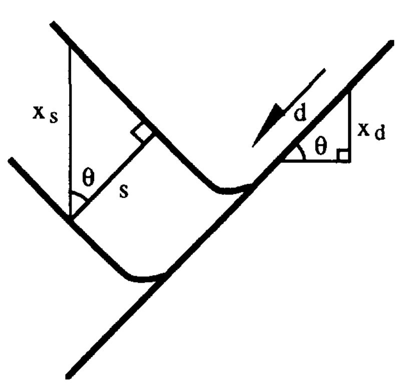

Fig. 6. Schematic diagram of the relationship of elements measured to determine the shortening indicated by microshear zones (equations 1a–1d). Variables are defined in the text.

We interpret these features to indicate coaxial progressive deformation of the rock, perpendicular to the flow margins, as it solidified.

In summary, these three rock types all contain similar textural–structural elements. That is, a plane of crystal alignment comprising phenocrysts and groundmass microlites bisecting conjugate microshear zones. The shortening directions are at a high angle to cooling surfaces as represented by the dyke margins (Fig. 2a) and the plane normal to column axes (Figs. 2b & c). This texture indicates coaxial progressive deformation of the rock during the final stages of solidification.

DISCUSSION

In volcanic and sub-volcanic processes large volumes of material are transported for long distances. Coaxial flow, however, is not an effective mode for transporting material. Therefore, the evidence presented here of coaxial flow in the final stages of solidification must be explained in the context of non-coaxial flow in the earlier stages. Non-coaxial flow arises primarily from velocity gradients perpendicular to the flow direction which are kinematically equivalent to simple shear deformation. However, there would almost certainly also be velocity gradients parallel to the flow direction. Such gradients would be kinematically equivalent to a pure shear component. Therefore, unsteady non-coaxial flow is to be expected as these gradients change in response to physical factors such as the width of conduits. During this flow it is probable that reasonably stable crystal alignment orientations could be established (Passchier 1988). However, these alignments would then be modified by the nature of the deformation path, in particular the late-stage kinematics.

Deformation path

The progressive deformation history of a rock is commonly represented by a path leading from some undeformed state through higher values of strain to the final configuration of the rock. This approach requires that some undeformed state can be determined, for example, in analysis of veins which can be assumed to have been originally straight (e.g. Wallis 1992). This approach cannot be taken for most studies of igneous rock textures as it is not generally possible to determine an undeformed configuration. Consequently, we will take the approach that the only configuration of which we can be sure is the present (final) one of the rock. We can then work back from the final configuration to find earlier parts of the history.

The microshear zones described above represent the most recent deformation imposed on the rock. Using the strain ratio measured from the andesite dyke there could have been a finite strain of up to $R_f = 4$ resulting from the coaxial flow during the later stages of emplacement. This is in marked contrast to the conventional view that volcanic and sub-volcanic flow is dominantly by simple shear which remains steady until complete solidification (Cas & Wright 1987, p. 29). Clearly, such a model cannot be applied to the rocks described here as it does not account for the coaxial flow before solidification.

The model could be adapted by suggesting simple shear kinematics until the formation of microshear zones. However, there is no evidence or theoretical justification for localization of deformation to be accompanied by an abrupt change in kinematics. In fact, such a situation is extremely unlikely because before initiation of microshear zones the deformation is evenly distributed and nucleating microshear zones must be compatible with the existing deformation. This means that the flow just prior to the initiation of microshear zones was probably coaxial as well but distributed more evenly. As there is evidence that the microlites were growing as the shear zones formed then it is reasonable that microlites were also growing during the distributed coaxial flow. Phenocrysts would also have been rotated into parallelism and so the distributed coaxial flow stage played an important role in textural development. It is not possible to determine how much strain accumulated in this stage. We suggest conservatively that the distributed flattening could have been of an equivalent magnitude to the localized flattening. Prior to both the localized and distributed coaxial flow stages non-coaxial flow is required to achieve transportation of the magma/lava.

In summary, we recognize two main stages of the

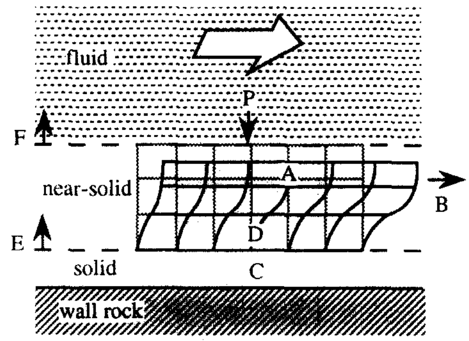

Fig. 7. A theoretical model of coaxial flow in a dyke. Near-solid material lies in a zone between the fluid magma and solidified magma adjacent to the wall rock margin. Hydrostatic pressure of the magma (P) is applied normal to the interface. The grid shows a hypothetical undeformed and deformed state of the near-solid magma. The near-solid magma undergoes coaxial progressive deformation (A) causing extrusion (B) parallel to the flow direction of the magma (open arrow). To maintain compatibility with the rigid wall rock and/or solidified dyke rock (C), there must be a zone of simple shear (D). The solid to near-solid interface (E) and the fluid to near-solid interface (F) both migrate into the dyke during cooling or move step-wise into the dyke in the case of multiple injection.

formation of volcanic and sub-volcanic rocks. In the early fluid stage the magnitude of strain is very large whereas in the late near-solid stage the strain is more moderate. This change reflects the increasing viscosity of extrusive and shallow intrusive rocks prior to solidification. The fluid stage is probably dominated by non-coaxial kinematics whereas, in the examples described here but not necessarily generally, the near-solid stage is characterized by coaxial progressive deformation. As the solidification process proceeds progressively through the material, the movement of the fluid magma could cause deformation of the solidifying magma at the margins. This is the process which has been described for forming block lavas and breccia carapaces on domes (Fink & Manley 1987). This idea can be extended to say that the flow of the fluid part (and its magma pressure in general) could cause stretching of the outer part of a body during its solidification (Fink & Manley 1987). This process could be the one which caused the coaxial progressive deformation textures in the rocks described in this paper. This model is in principal similar to that for some batholithic emplacements described as 'balloon' tectonics (e.g. Ramsay 1989).

The model is problematic where the margins are constrained by contact with rigid wall rock. Strain compatibility requires that parallel longitudinal strains should be equal across a coherent boundary (Ramsay & Huber 1983, p. 34). The wall rock contacts of the dyke described in this paper showed no evidence of faulting indicating that the coaxial flow in the dyke (A in Fig. 7) must be compatible with the rigid wall rocks and/or solidified dyke rock (C in Fig. 7). This constraint requires that the longitudinal strain rate parallel to the dyke margin reduces to zero at the contact and also that there is simple shear (D in Fig. 7) adjacent to the contact to accommodate extrusion (B in Fig. 7). We did not observe zones of simple shear possibly because the coaxial domains occupy the majority of the rock, as there is no kinematic restriction on the relative widths of the coaxial and simple shear domains. The situation is further complicated by the migration of the solid to near-solid interface (E) and the fluid to near-solid interface (F) into the dyke during cooling. Also multiple injection of magma would result in repetitions of the strain pattern of Fig. 7. Thus, the model does not represent a complete explanation of the strain pattern in the dyke but it does demonstrate the theoretical possibility of maintaining compatibility between a rigid wall and a zone of coaxial flow.

Deformation localization

The microshear zone textures described here are an example of deformation localization. These shear zones initiated after microlites began to grow and formed synchronously with the microlites (Shelley 1985). Presumably the shear zones stopped when the rock became completely solidified.

Ramsay (1989) showed that in a granite batholith deformation also becomes localized in shear zones towards the end of solidification. He showed that these zones formed in response to stretching of solidifying rock caused by emplacement of more magma. This transition has long been the focus of study in metamorphic rocks where it has significance for determining the conditions of the brittle–ductile transition of rock during deep burial. The fact that the transition occurs in some, but not all, igneous rocks makes study of the controlling conditions relevant to solving wider structural problems. The primary controls on localization are presumably the viscosity of the material and strain rate of the deformation.

General applicability

Stretched vesicles (Coward 1980) and crystals (Shelley 1985) oblique to dyke margins have been used to infer simple shear. However, further investigation of these textures may reveal evidence of other flow types. For example, Shelley (1985) interpreted the obliquity between groundmass feldspar laths and dyke margins as the result of simple shear kinematics. He also described groundmass shears which he related to the 'Riedel shears' described in wrench fault systems. However, the groundmass shears were at a much higher angle to the margin than 'Riedel shears' indicating a significant component of shortening normal to the dyke margins. Such an oblique fabric associated with shortening may indicate a non-coaxial kinematic pattern intermediate between simple and pure shear. This is difficult to resolve and would require evidence of asymmetric development of structures (Fernandez & Laporte 1991).

The final point of our discussion is that in extrusive and shallow intrusive igneous rocks there is an opportunity to chemically determine the viscosity–temperature relationship of the melt (Bottinga & Weill 1972). Hence, aspects of the model we have proposed may in the future be tested quantitatively in a way that is not, as yet, possible for sedimentary and metamorphic rocks. Consequently, the study of foliations in extrusive and shallow intrusive igneous rocks provides a unique opportunity for understanding the relationship between flow types and deformation textures in general.

CONCLUSIONS

Structural analysis of the textures of rocks from an andesite dyke, a dacite dome and a basalt flow indicates that, in the final stages of emplacement, the rocks deformed by coaxial flow (or pure shear). If highly non-coaxial kinematics are assumed during the fluid flow of magma, these observations indicate a decrease in vorticity during emplacement. Such a decrease in vorticity may be a general occurrence during the cooling of igneous rocks. Therefore, structural analysis of textures of extrusive and shallow intrusive rocks must consider the following points.

(1) The influence of flow types other than simple shear.

(2) Possible changes in flow type during emplacement.

(3) The timing of textural development within the context of the deformation path.

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