Journal of Structural Geology, Vol. 13, No. 6, pp. 625 to 634, 1991
Printed in Great Britain

0191-8141/91 $03.00+0.00

Linear dilatation structures and syn-magmatic folding in granitoids

HARM STEL

Institute of Earth Sciences, Vrije Universiteit, de Boelelaan 1085, 1081 HV Amsterdam, The Netherlands

(*Received* 7 *May* 1990; *accepted in revised form* 31 *December* 1990)

Abstract—Folding of the magmatic foliation of the composite Orijärvi batholith (SW Finland) took place at sites where viscosity contrasts existed: at gabbro–tonalite interfaces and at the rim of the intrusion. Chilled margins at these interfaces are both folded and boudinaged. Folds are highly disharmonic and die out in internal parts of the batholith. Folded tonalites display a lineation defined by quartz rods which are morphologically similar to ribbons in mylonites. The host rock however is non-mylonitic and shows primary magmatic structures. Crystallographic fabrics in rods are near random, and unstrained rutile inclusions suggest that quartz in this texture is undeformed. The rods are accompanied by a conjugate extensional foliation of biotite schlieren. By comparison with rods in quartz–feldspar veins, the quartz ribbons in tonalite are interpreted as linear dilatation structures at the intersection lines of conjugate shear bands, the shear directions of which were perpendicular to the axes of the rods. Folded chilled margins and rodded tonalite are enclosed by undeformed gabbro and tonalite, suggesting that folding took place while the bulk of the batholith was still liquid. It is proposed that folds were formed by magma flow along a largely solidified gabbro–tonalite boundary zone, whereby interfaces were folded and simultaneously stretched.

INTRODUCTION

DISCRIMINATION between magmatic and tectonic deformational structures is one of the main problems in the geometrical analysis of granitoids (Hutton 1988, Paterson *et al.* 1989, Ramsay 1989). This paper deals with such a problem: rocks are described that demonstrate primary magmatic textures on the one hand and tectonic structures on the other.

The structures occur in the Orijärvi batholith (Svecofennian belt, SW Finland), which is a composite intrusion of tonalite and gabbro (Eskola 1914, Tuominen 1957) (Fig. 1). Folds of the magmatic foliation are found at the rim of the batholith and internally at gabbro–tonalite interfaces. They do not persist in the country rock. On the scale of a hand specimen, rocks appear undeformed in sections perpendicular to the fold axes. Moreover, primary structures appear unstrained, and feldspars show magmatic growth textures. These observations have led Eskola (1914) to suggest that folding took place at a magmatic stage. However, apparently undeformed granitoids display a strong quartz lineation in sections parallel to fold axes. The origin of this lineation is not *a priori* clear. Morphologically, the rods can be classified as 'type 3' ribbons in the terminology of Boullier & Bouchez (1978). Such ribbons have been interpreted as resulting from recrystallization and grain growth of strongly deformed quartz-rich domains in mylonites (Culshaw & Fyson 1984). However, the lineated granitoids are not mylonitic, as they demon-

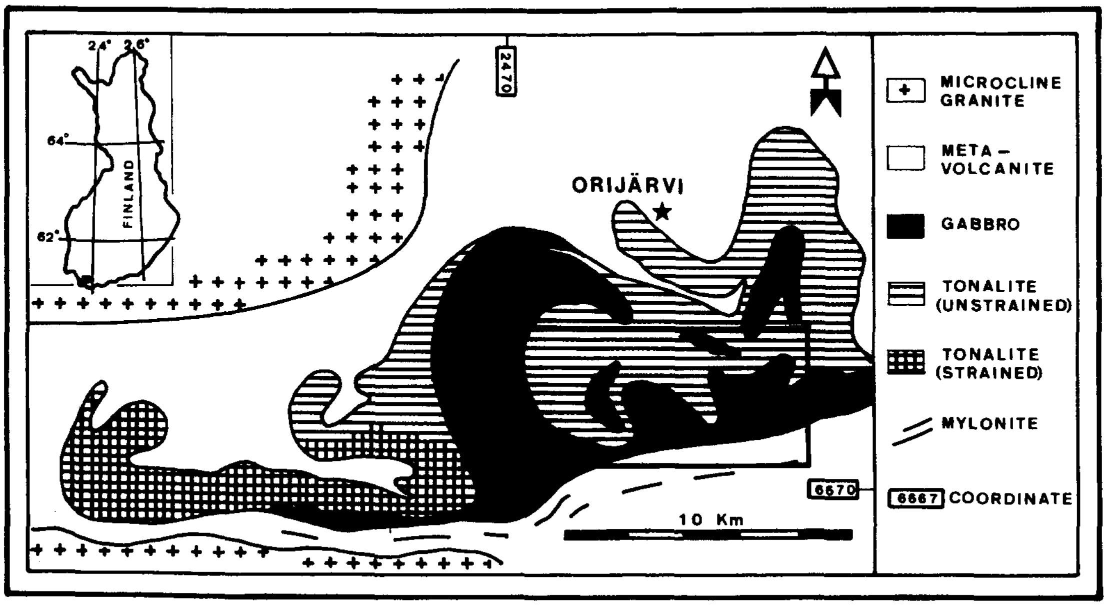

Fig. 1. Geological map of the Orijärvi batholith, SW Finland. The area included in Fig. 2 is indicated by a rectangle.

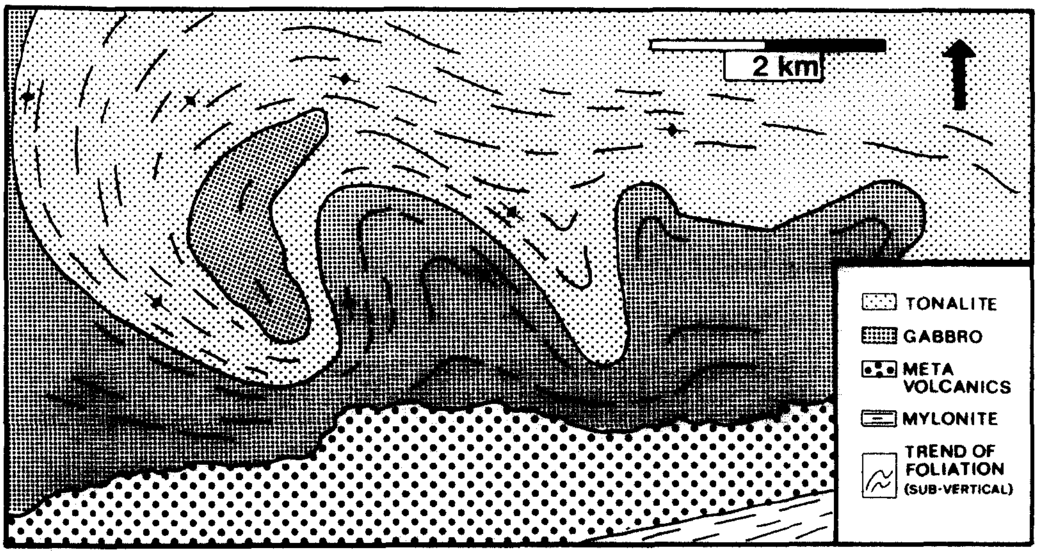

Fig. 2. Form-surface map of the trace of the compositional banding in gabbro and tonalite of part of the Orijärvi batholith. All foliations are sub-vertical, as are lineations defined by quartz rods.

strate primary magmatic structures. The quartz rods are interpreted as representing dilatation structures, formed at intersections of microscopic shear bands. The connection between ribbons and conjugate shears has been noted before (Sander 1946, pp. 165–199, Lister & Dornsiepen 1982), but the new aspect of the present interpretation is that ribbons are dilatational structures. It is proposed that folding and dilatation were simultaneous with stretching of the largely crystallized gabbro–tonalite boundary zone, while the bulk of the batholith was still in a liquid state.

GEOLOGICAL SETTING AND COMPOSITION OF THE ORIJÄRVI BATHOLITH

The Orijärvi batholith, with an age of 1.85–1.9 Ga (Nurmi & Haapala 1986), is one of the early orogenic intrusives in the Svecofennian belt of SW Finland. The rocks crystallized from a composite magma, with gabbroic and tonalitic components that did not mix (Hartel 1988). Intrusive rocks are locally transitional to metavolcanic country rock, suggesting that magma intruded its own extrusive products.

The composition of the tonalitic rocks varies, mainly due to differences in quartz content, while the ratio of feldspar to dark mineral content is stable. All variations between quartz diorite and quartz-rich tonalite occur;. Tonalites contain 65% plagioclase (20–40% An), 20% biotite and hornblende and 10% quartz. Quartz-rich tonalites, which are found near contacts with gabbro, contain 60% quartz, 30% plagioclase, and 5–10% biotite and hornblende. Tonalites become gradually richer in quartz near the boundary with gabbro; at the interfaces nearly pure quartz bands are found.

Regional deformation affected the Orijärvi batholith mainly at its margin, and locally late-orogenic shear zones are found (Ploegsma 1989). Internally, the batholith appears unstrained.

MESOSCOPIC AND MACROSCOPIC STRUCTURE

Three types of structure were observed in tonalitic rocks from the Orijärvi batholith: magmatic layering; folds; and a quartz ribbon lineation parallel to the fold axes.

The magmatic foliation, S_m, is a compositional layering defined by bands that differ in dark mineral content. Locally, flow textures such as imbricate feldspars are found, especially near gabbro–tonalite interfaces. Feldspar crystals are aligned conformably to S_m or imbricate (Hartel 1988); mica and hornblende are oriented parallel to crystal faces of feldspar.

Folds on macroscopic (wavelength 1–2 km) and mesoscopic (wavelength 0.5–10 m) scales are found at boundaries of the tonalite and inliers of gabbro (Fig. 2). These die out away from the boundary. Locally, a chilled margin of gabbroic composition, occurring at the gabbro–tonalite interface, is boudinaged while the magmatic banding in the gabbro is folded (Fig. 3). At other places, a tonalitic boundary layer is folded, while the chilled margin of the gabbro is both boudinaged and

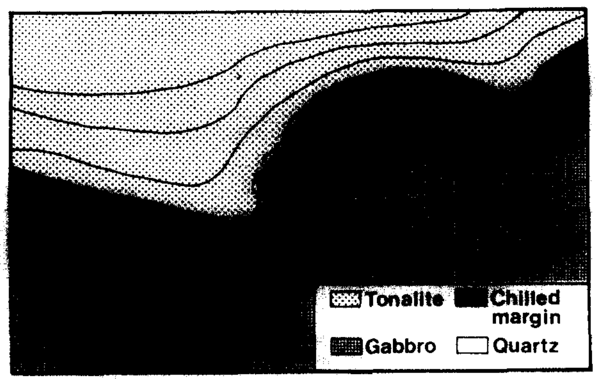

Fig. 3. Tracing of a photograph of an outcrop showing boudinage of the chilled margin at the gabbro–tonalite interface. Boudinage is accompanied by quartz veining. Note that the magmatic banding in the gabbro and tonalite is folded. Scale bar: 10 cm.

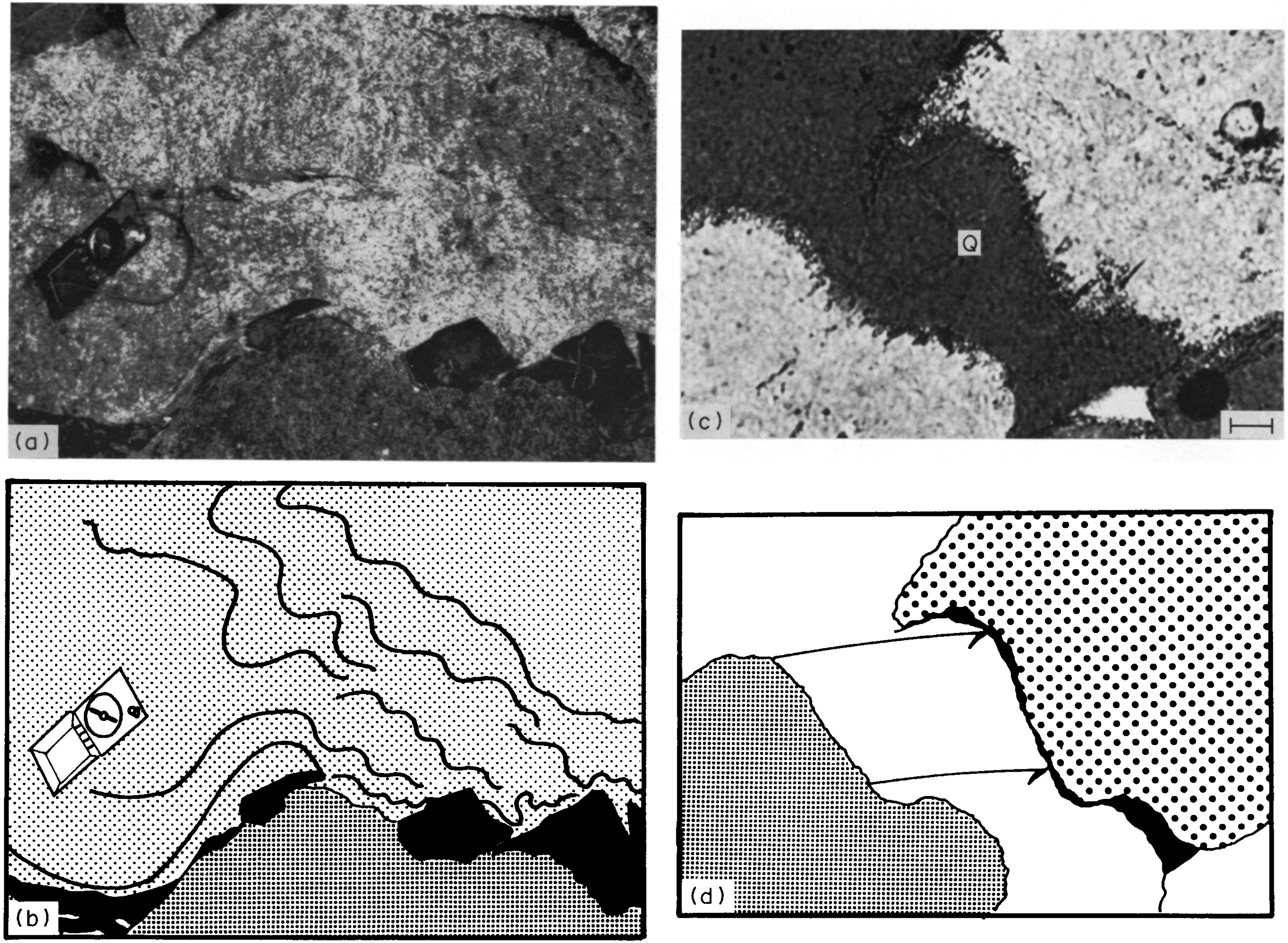

Fig. 4. (a) Photograph of the interface between gabbro (grey) and tonalite (dark). Note that the interface is folded, while the chilled margin (black) is both folded and boudinaged. Gabbro at the interface is undeformed. (b) Line drawing of (a), showing the trace of the folded magmatic foliation in the tonalite. The legend is as in Fig. 3. (c) Photomicrograph of matching opposite boundaries of quartz (Q) in between two feldspar crystals. Scale bar: 0.1 mm. (d) Tracing of (c), showing the degree of fit if the two feldspars (ornamented) are united by a translation and a small amount of rotation according to the arrows. The misfit is

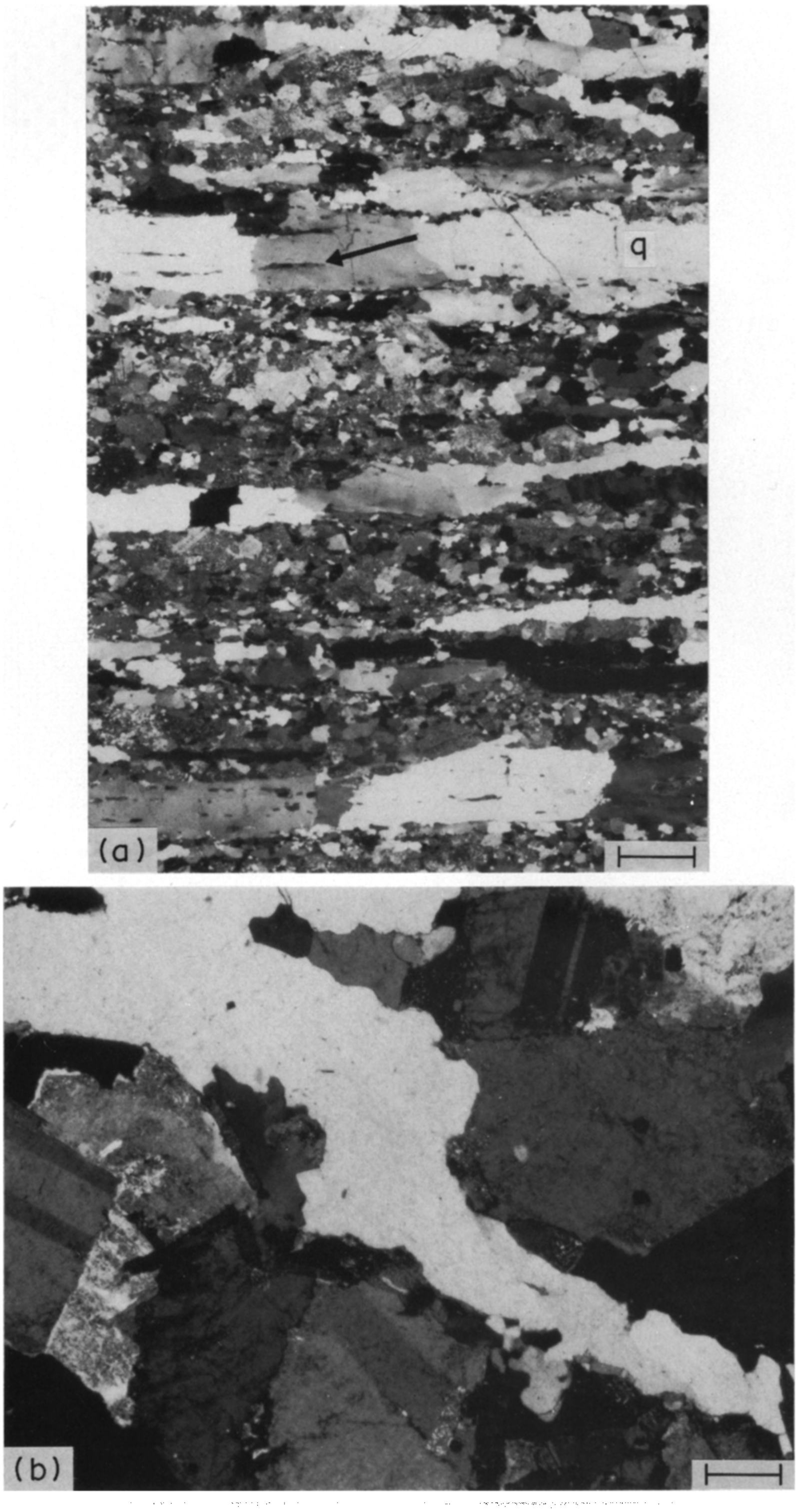

Fig. 5. (a) Photomicrograph of longitudinal section of quartz ribbon (q) with inclusion trails of plagioclase and biotite (one trail is indicated by the arrow). Scale bar: 1 mm. (b) Cross-sectional shape of a quartz rod (light material), showing a near-fitting relationship of opposite boundaries over a distance of >3 cm. Scale bar: 0.5 cm.

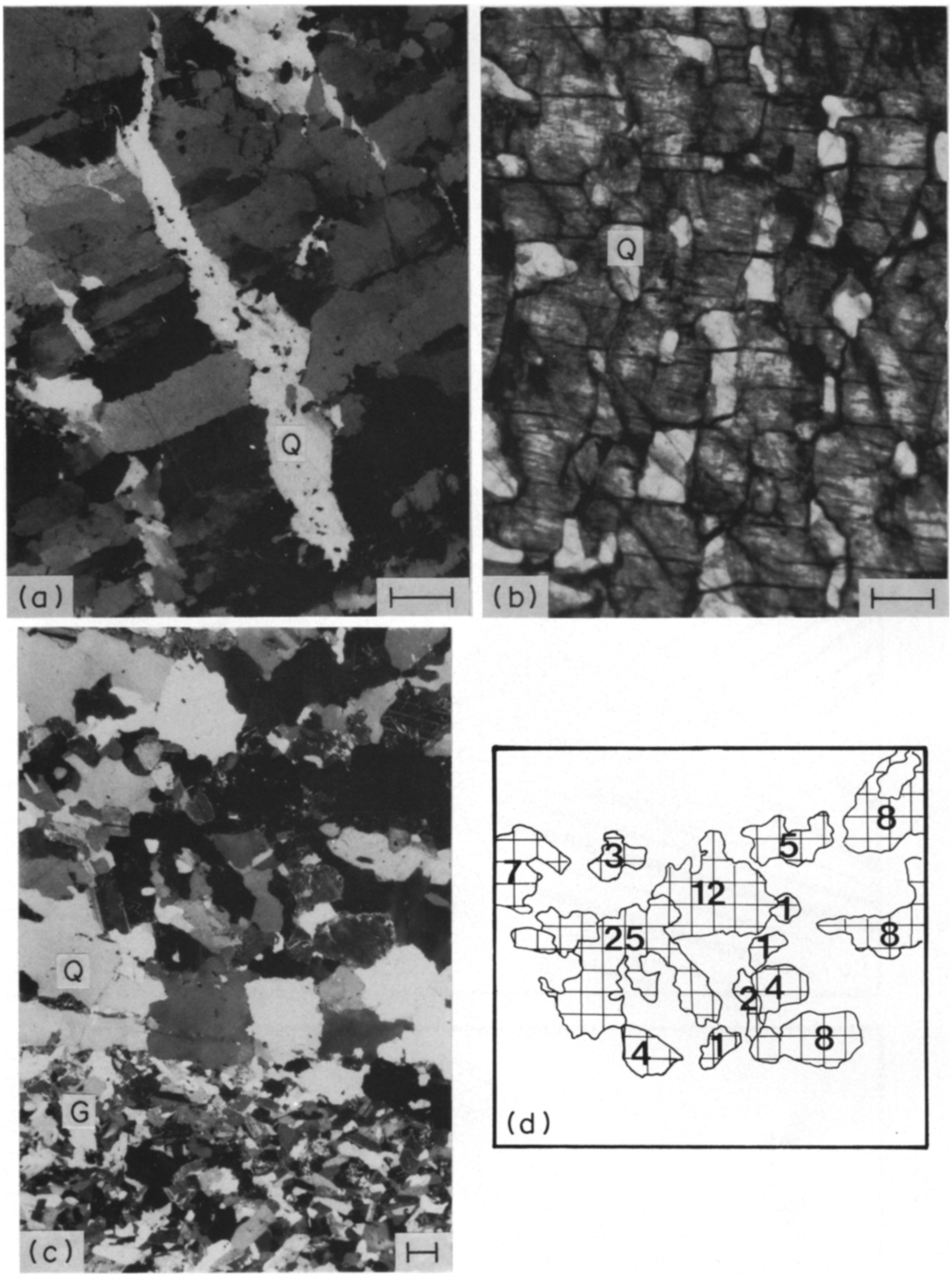

Fig. 6. (a) Longitudinal section of linear quartz ribbons (Q) in K-feldspar host. Note the fitting opposite boundaries of quartz K-feldspar interfaces. Feldspar inclusions in quartz are similar in crystallographic orientation to the host. Scale bar: 1 mm. (b) Cross-section of linear quartz ribbon in K-feldspar host. Two sets of faults (N–S and E–W) are an integral part of the quartz–feldspar interfaces. Scale bar: 1 mm. (c) Photomicrograph of tonalite–gabbro (G) interface. Note that a nearly pure quartz rim (Q) occurs at the interface, and note also the inclusion trail in this rim. Scale bar: 1 mm. (d) Tracing of the upper part of (c), in which the non-quartz constituents (mainly feldspar aggregates) are cross-hatched. One square represents 0.25% of the area shown. The number of full squares per domain is represented (the total amount is 90). Note the area which is occupied by quartz amounts to >75% in this particular case.

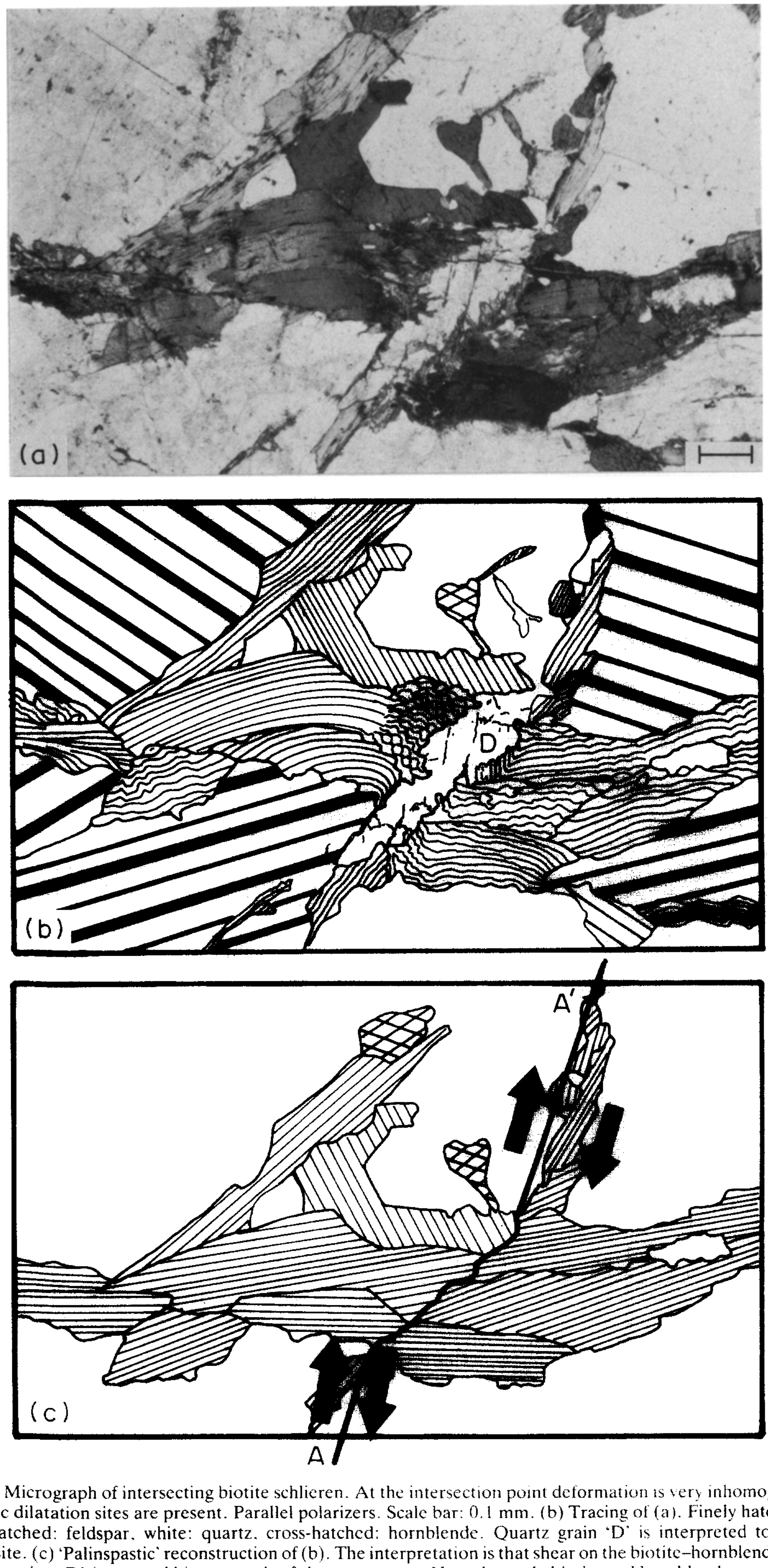

Fig. 7. (a) Micrograph of intersecting biotite schlieren. At the intersection point deformation is very inhomogeneous, and microscopic dilatation sites are present. Parallel polarizers. Scale bar: 0.1 mm. (b) Tracing of (a). Finely hatched: biotite, coarsely hatched: feldspar, white: quartz, cross-hatched: hornblende. Quartz grain 'D' is interpreted to represent a dilatation site. (c) 'Palinspastic' reconstruction of (b). The interpretation is that shear on the biotite–hornblende trail A–A', caused dilatation 'D' (see a and b) as a result of shear step-over. Note that only biotite and hornblende are ornamented.

folded (Figs. 4a & b). Gabbroic rocks adjacent to the chilled margin are undeformed.

A distinct type of discontinuity is defined by quartz rods in the tonalites. The longest axes of rods are aligned and define a prominent lineation parallel to the fold axes. This lineation is the only mesoscopic structural element that can be related to folding. No axial-plane foliation was found associated with the folds. In fact, with the unaided eye, no penetrative fold-related anisotropies were observed in sections perpendicular to the fold axis. On a decimeter scale, the texture of the folded tonalite is characterized by coarse felsic domains that occur as irregularly outlined pockets with no preferred orientation.

TEXTURE AND MICROSTRUCTURES

Quartz rods constitute the only mesoscopic structure that is spatially related to folding. This section focuses on their microstructure and microstructural relation to the host rock. The microstructure of rodded tonalities is compared to that of K-feldspar veins that contain linear quartz veins. The latter show a relatively simple microstructure, for which a general mechanism of linear vein formation can be deduced.

Quartz-rich tonalite

The microstructure of quartz-rich tonalite is dominated by quartz rods which occur in a matrix of feldspar, hornblende, biotite and fine-grained quartz (Fig. 5a). Aspect ratios X:Y:Z (longest, to intermediate, to shortest axis, respectively) of the rods vary between 100:4:1 and 5:2:1. The rods are up to *ca* 20 cm in length and *ca* 2 mm in cross-sectional diameter. The X axes of the rods are aligned, whereas Y and Z axes have no fixed orientation. The rods are evenly spaced on a distance of 1 cm. They are composed of three or four coarse quartz crystals which are strain free or demonstrate weak undulose extinction. The quartz includes rutile needles which are randomly oriented. No micro-folding or boudinage of these needles has been observed. Crystallographic orientation patterns of quartz rods are near-random (Stel & Breedveld 1990) (Fig. 8).

Most rods contain feldspar inclusion trails that are aligned parallel to the boundaries (Fig. 5a). In cross-section, a systematic relationship between opposite boundaries of some rods was observed. Parts of feldspar–quartz boundaries appear to match, such that two or three feldspar or mica crystals can be united by translating opposite boundaries (Figs. 4c & d). On the scale of several centimeters, some composite boundaries of quartz megacrystals, involving several feldspar and biotite grains, demonstrate a near-fitting relationship (Fig. 5b).

Near the contact with the gabbro, the tonalitic rocks become gradually more quartz rich, and at the boundary a 0.1–0.5 cm wide rim of pure quartz is found (Fig. 6c). This quartz rim contains inclusion trails parallel to the interface. Microstructurally, quartz in the rim appears similar to quartz in the rods.

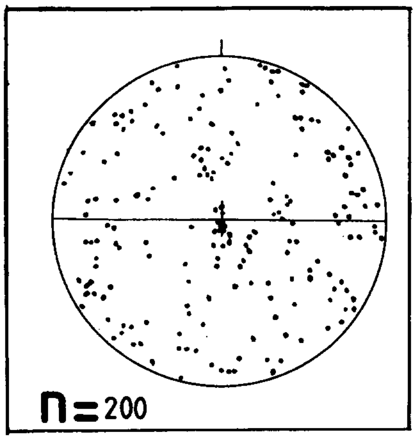

Fig. 8. Fabric diagram of quartz *c*-axes in ribbon-bearing tonalite. Equal-area lower-hemisphere projection. Orientation is similar to that in Fig. 5(a).

In contrast to feldspar and quartz, biotite demonstrates intra-crystalline deformation structures such as kink bands and micro-shears. While on a cm–dm scale biotite and hornblende define a planar layering, on a mm scale they appear to consist of two sets of 'schlieren' that intersect in a line parallel to the X axes of the rods. Locally, asymmetric tails of mica and asymmetric micro-boudinage structures allow establishment of shear movement associated with mica schlieren (cf. Simpson & Schmid 1983). At intersection sites, schlieren appear to be offset, and micro-faults in mica and hornblende crystals occur. Quartz is found in dilatation structures at the intersection line (Fig. 7).

Potassium–feldspar veins

Numerous K-feldspar veins occur at the rim of the batholith, specifically in regions where country-rock is brecciated. Locally, these veins contain quartz rods which are (sub)parallel to rods in adjacent tonalite. Longitudinal sections of rods show inclusions of feldspar fragments with crystallographic orientation similar to that of the host at the adjacent vein wall (Fig. 6a). Opposite boundaries of quartz ribbons have a one-to-one fit with each other. In cross-sections, linear quartz ribbons show a relatively simple geometry, with rectangular and square forms (Fig. 6b). Quartz crystals are strain-free, and are distributed regularly within a deformed (fractured) feldspar host. The occurrence of quartz appears to be restricted to intersection lines of two sets of regularly spaced micro-faults and microscopic shear zones coinciding with (010) and (001) crystal cleavages. Most micro-faults do not cross-cut the quartz, instead they are an integral part of the quartz–feldspar interfaces.

INTERPRETATION

Longitudinal sections of quartz ribbons in K-feldspar show two diagnostic microstructures: the fitting of opposite boundaries of the ribbons, and the inclusion of host fragments in the ribbon. The fitting of opposite boundaries is diagnostic for dilatation veins (Ramsay & Huber 1983, p. 239): the linear veins are interpreted accordingly. Inclusion trails of feldspar fragments of similar crystallographic orientation to the feldspar at the vein wall suggest diverse stages of isolation of host fragments by a crack–seal process (Ramsay 1980). In cross-section, quartz veins demonstrate a close association with step-overs of faults, and it is concluded that they were formed in such locations. A model for the formation of linear quartz veins in feldspar is presented in Fig. 9. It involves the creation of step-overs by dislocation of one set of faults by another, perpendicular set. It is inferred that only those parts of feldspar veins which were favourably oriented with respect to the local stress system were dilated by this mechanism.

In a number of respects, the microstructural setting of linear quartz ribbons in tonalites is similar to that of linear quartz ribbons in K-feldspar veins.

— Quartz ribbons in both cases occur in an environment that contains two perpendicular anisotropies intersecting in the ribbon axes. Cleavage in feldspar is thought to play an analogous role to the composite biotite foliation in ribbon gneiss. The foliation was possibly induced by shear along pre-existing primary discontinuities, that is along biotite aligned with crystal faces of brick-like stacked feldspar megacrystals in a cumulate (Best 1982, p. 177). Demonstrably, shear took place along these surfaces, along which largely undeformed parts of the rock were shifted. On a small scale, there is a clear relationship among mutual displacement of shear bands, dilatation and the presence of quartz. In cross-section, opposite boundaries of quartz rods are found to match, some perfectly. These microstructures prove the dilatational origin of at least part of the quartz rods. Another indication of the relationship between dilatation and quartz rods is the transitional relationship to quartz-rich veins in the brecciated chilled margins of gabbro.

— The inclusion patterns of quartz rods in the tonalites and in the feldspar veins are comparable, and are characterized by trails of mineral fragments which run parallel to the boundary.

— Quartz rods in the feldspar veins occur as optically strain-free crystals in a deformed feldspar host. Most quartz rods in the tonalites are also optically strain free; they display near random crystallographic orientation patterns, and contain randomly oriented, non-strained rutile needles. This strongly suggest that quartz in rods in the tonalites is non-strained (Mitra 1978). Thus as in the K-feldspar veins, non-strained linear quartz domains occur in an environment containing two sets of shear bands.

Based on the strong resemblance of microstructures, it is proposed that the origin of linear quartz ribbons in tonalite is similar to that of linear quartz ribbons in K-feldspar. In summary, linear quartz ribbons are interpreted as dilatational structures created by slip on two sets of shear bands in a direction perpendicular to the longest axis of the ribbons. This interpretation is fundamentally different from the classic interpretation of quartz ribbons in mylonites (Boullier & Bouchez 1978), in which the longest axis of the ribbons is thought to

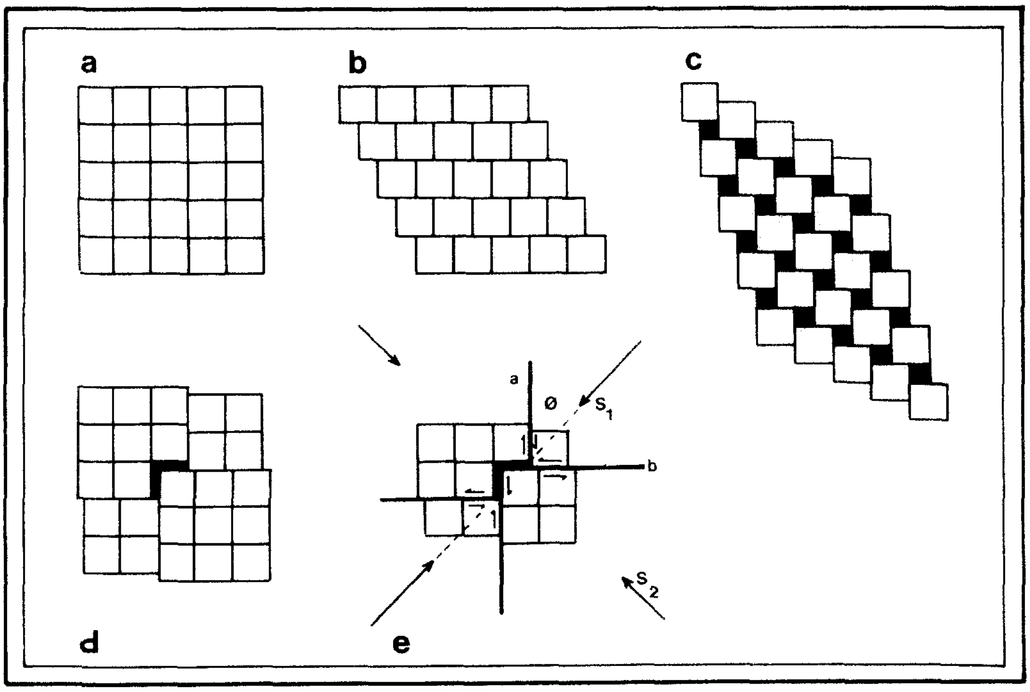

Fig. 9. Two-dimensional model of formation of dilatational sites (black) by slip on faults that contain step-overs due to slip on a perpendicular set of shear faults. (a)–(c) show a sequential development by overprinting of one set by the other. (d) shows creation of a dilatational site by simultaneous slip on the two sets. (e) shows the orientation of stresses during this process. S_1 and S_2 represent possible directions of principal stresses in two-dimensional space ($S_1 > S_2$). See text for discussion.

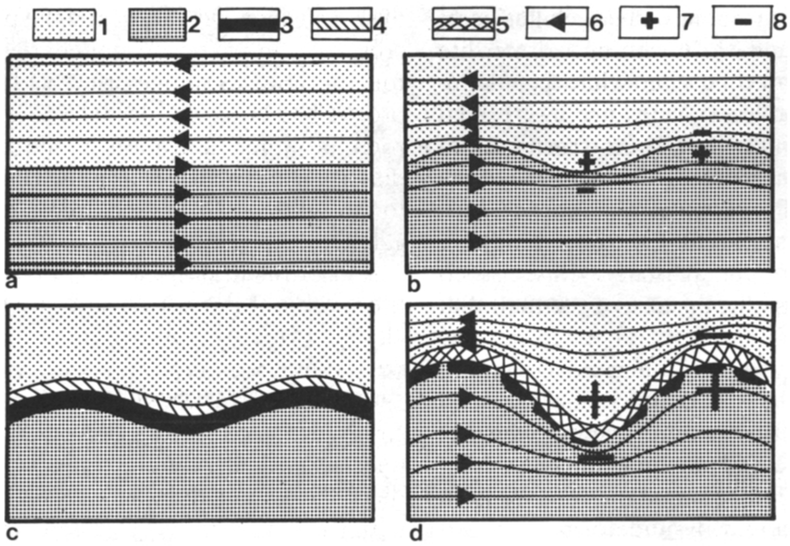

Fig. 10. Schematic representation of fold model due to magma flow at the gabbro–tonalite interface. Symbols: (1) gabbroic magma; (2) tonalitic magma; (3) chilled margin; (4) feldspar cumulate; (5) dilated feldspar cumulate; (6) stream line; (7) & (8) locations of areas in which pressure increases (+) due to decreasing flow velocity at divergent stream lines at wave troughs; and areas in which pressure decreases (−) due to increased flow velocity at convergence of stream lines at wave crests. (a) Laminar flow of unmixed gabbroic and tonalitic magmas. Flow lines and relative flow directions are indicated. (b) Formation of waves at the interface: note that the length of the interface has increased with respect to the length in (a). (c) Frozen-in waves by formation of chilled margin and feldspar cumulus. (d) Amplification of waves by a new magma pulse, whereby a spaced variation in fluid pressure is created, and the boundary extended. Consequently, the earlier formed chilled margin is boudinaged, while feldspar cumulate is dilated and expanded laterally.

coincide with the X-axis of the strain ellipsoid. At present, it is difficult to evaluate whether the mechanism proposed here for ribbon formation can also be applied to specific types of ribbons in mylonites. However, the association of ribbons and conjugate foliations has been reported earlier (Sander 1946, pp. 156–199, Lister & Dornsiepen 1982), and a re-evaluation of this microstructure, with the present dilatation model in mind, could be worthwhile.

The variation in composition of quartz diorites and ribbon-bearing quartz–tonalites is such that the ratio of feldspar to biotite is stable while quartz content varies. Moreover, ribbon-bearing rocks are built-up of domains which have a quartz dioritic composition and those which are composed of nearly pure quartz. Tonalitic rocks occurring within 0.5 m of the interface with the gabbro consist of >65% quartz, and the texture can be characterized as 'isolated feldspar domains, floating in coarse grained quartz aggregates' (Fig. 6d). The compositional and textural variation of the tonalites is adequately explained by secondary introduction of quartz in response to dilatation of a more feldspar-rich rock, by which individual feldspar domains were 'drifted apart'.

FOLD MODEL

Linear quartz ribbons are parallel to the fold axes, suggesting that they are genetically related to the folds. If the interpretation of quartz rods proposed above is correct, it follows that the tonalite–gabbro boundary zone underwent a volume increase, largely by lateral expansion, analogous to the model in Fig. 9. So, it appears that folding and stretching of the boundary zone took place simultaneously. There is independent evidence for this, as chilled margins are both boudinaged and folded, and it is suggested that dilatation of the tonalites in the boundary zone took place simultaneously with the stretching of the chilled margin.

To explain the simultaneous folding and stretching, the following considerations are taken into account. Folds are restricted to the gabbro–tonalite boundary zone, and they are enclosed by non-deformed gabbro and tonalite. This suggests that folding took place while the bulk of the batholith was still liquid. There is evidence (i.e. imbricate feldspar crystals) that magmatic flow took place at the interface (see Best 1982, p. 180, Hartel 1988). Flow in unmixed Newtonian fluids with different viscosities results in the folding of the interface (Rouse 1978, p. 171). Such folds are restricted to the boundary zone (wave base), and it follows that the actual interface must be stretched (Ottino 1989, pp. 1–14).

It is proposed that the presently described folds have been formed by such a process. It is envisaged that folding may have taken place by a scenario such as that represented in Fig. 10. At the first stage of the process, flow of unmixed gabbro against tonalite melt took place (Fig. 10a). This caused folding of the interface (Fig. 10b). The temperature difference between the gabbroic and tonalitic melts caused the formation of a chilled margin, at which the first stage of feldspar crystallization of tonalitic melt was initiated (Fig. 10c). Subsequent pulses of magma flow caused fold amplification due to underpressures at the crests, and overpressures at the troughs (Fig. 10d). Pressure variations are caused by local variations in liquid velocities (cf. Bernouilli's law, see Rouse 1978 p. 171). As a result of fold amplification, incipient solidified material was stretched, chilled margins were boudinaged, and early crystallized tonalite was dilated (Fig. 10d). Flow proceeded while the boundary layer was largely crystallized (cf. Morse 1985). At a given stage, viscous flow may have been transitional to plastic deformation; and new pulses of magma may have deformed earlier crystallized material (Sparks *et al.* 1985, Hutton, 1988, Ramsay 1989). Probably, dilatation of the solidified interface was assisted by increase in liquid pressure of the crystallizing core of the batholith (cf. Best 1982, p. 227).

The dynamics of large volumes of magma and cumulates are still poorly understood, and it is difficult to evaluate the model from that point of view. Nevertheless, it explains all the observed phenomena, and specifically it offers an explanation of simultaneous extension and folding of rocks enclosed by undeformed gabbro and tonalite.

CONCLUSIONS

Linear quartz ribbons in tonalitic rocks from the Orijärvi batholith are dilatation structures that were formed by interference of shear faults along discontinuities. Dilatation occurred largely by lateral extension, and was accompanied by quartz growth. Folds of gabbro–tonalite interfaces, with fold axes parallel to the rods, are related to the increase in volume. Folding and dilatation of the boundary layers were caused by flow of unmixed magmas.

Acknowledgements—Dr Hudleston, Dr van der Pluijm, and an anonymous reviewer are thanked for their comments and suggestions for improvement of the paper.

REFERENCES

Best, M. G. 1982. *Igneous and Metamorphic Petrology*. Freeman and Co., New York.

Boullier, A. M. & Bouchez, J.-L. 1978. Le quartz en rubans dans les mylonites. *Bull. Soc. géol. Fr.* **22**, 253–262.

Culshaw, N. G. & Fyson, W. K. 1984. Quartz ribbons in high grade granite gneiss: modifications of dynamically formed *c*-axis preferred orientation by oriented grain growth. *J. Struct. Geol.* **6**, 663–668.

Eskola, P. 1914. On the petrology of the Orijärvi region in southwestern Finland. *Bull. Comm. géol. Finl.* **40**.

Hartel, T. 1988. Structural analysis of the Simijarvi batholith. Unpublished thesis, University of Amsterdam.

Hutton, D. H. W. 1988. Granite emplacement mechanisms and tectonic controls; inferences from deformational studies. *Trans. R. Soc. Edinb.* **79**, 245–256.

Lister, G. S. & Dornsiepen, U. F. 1982. Fabric transitions in the Saxony granulite terrain. *J. Struct. Geol.* **4**, 81–92.

Mitra, S. 1978. Microscopic deformation mechanisms and flow laws in quartzites within the South Mountain anticline. *J. Geol.* **86**, 129–152.

Morse, S. A. 1985. Thermal structure of crystallizing magma with two-phase convection. *Geol. Mag.* **123**, 205–214.

Nurmi, P. A. & Haapala, I. 1986. The Proterozoic granitoids of Finland: granite types, metallogeny and relation to crustal evolution. *Bull. geol. Surv. Finl.* **58**, 203–233.

Ottino, J. M. 1989. *The Kinematics of Mixing: Stretching, Chaos and Transport*. Cambridge University Press, Cambridge.

Paterson, S. R., Vernon, R. H. & Tobisch, O. T. 1989. A review of criteria for the identification of magmatic and tectonic foliations in granitoids. *J. Struct. Geol.* **11**, 349–365.

Ploegsma, M. 1989. Shear zones in the West Uusima Area, SW Finland. Unpublished Ph.D. thesis, Vrije Universiteit, Amsterdam.

Ramsay, J. G. 1980. The crack–seal mechanism of rock deformation. *Nature*. **284**, 135–139.

Ramsay, J. G. & Huber, M. I. 1983. *The Techniques of Modern Structural Geology, Volume 1: Strain Analysis*. Academic Press, London.

Ramsay, J. G. 1989. Emplacement kinematics of a granite diapir: the Chindamora batholith, Zimbabwe. *J. Struct. Geol.* **11**, 191–210.

Rouse, H. 1978. *Elementary Mechanics of Fluids*. Dover Publications, New York.

Sander, B. 1946. *Einführung in die Gefügekunde der Geologischen Körper*. Springer, Vienna.

Simpson, C. & Schmid, S. M. 1983. An evaluation of criteria to deduce the sense of movement of sheared rocks. *Bull. geol. Soc. Am.* **94**, 1281–1288.

Sparks, R. S. J., Huppert, H. E., Kerr, R. C., McKenzie, D. P. & Tait, S. R. 1985. Postcumulus processes in layered intrusions. *Geol. Mag.* **122**, 555–568.

Stel, H. & Breedveld, M. 1990. Crystallographic orientation patterns of myrmekitic quartz: a fabric memory in quartz ribbon-bearing gneisses. *J. Struct. Geol.* **12**, 19–28.

Tuominen, H. V. 1957. The structure of an Archean area, Orijärvi, Finland. *Bull. Comm. géol. Finl.* **177**.