



Evolution of ptygmatic folds in migmatites from the type area (S. Finland)

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Abstract

It is proposed that ptygmatic folds in migmatites form during leucosome–melanosome differentiation. Volume loss (by depletion of quartz and feldspar) takes place in the interlimb domains of folds, leaving a residual melanosome. Buckling leucosomes increase in volume due to this process and are protected from substantial thinning. Concurrent with tectonic segregation, albeit at a lower rate, the leucosome expands by replacing the melanosome. This process is induced by fluid activity at the leucosome boundary, as suggested by the occurrence of secondary offshoot veinlets. Segregation and growth causes the most typical aspect of ptygmatic folds: preservation of an overall buckle shape during the stage when the folds become isoclinal and devoid of interlimb matrix. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Ptygmatic structure was defined originally as strong contortion of granite veins or layers in host rock that has an unfolded fabric (Fig. 1; Sederholm, 1913). In later work, this definition was expanded to include isoclinal buckle folds in other rock types (Mittra and Datta, 1978; Ramsay and Huber, 1983, pp. 7–13; Martel and Gibling, 1993; Twiss and Moores, 1992, p. 237; Lescuyer et al., 1994). A high viscosity contrast (ca 1000:1) between a folded layer and its matrix was deduced, based on the similarity between the shape of ptygmatic folds and that of elastic sheets buckled in air (Ramsay and Huber, 1983) This interpretation is supported by the occurrence of isoclinal buckles with (nearly) no matrix left in their interlimb domains. Thus, even when the folds are apparently locked (Price and Cosgrove, 1990, pp. 401–404), they are not affected by overall flattening to attain a similar shape. This is the most distinctive property of ptygmatic folds. Despite this consensus, a number of problems

persist about the formation of ptygmatic folds, specifically in migmatites.

If it is accepted that a high viscosity contrast existed between quartzo-feldspathic veins and their schistose or gneissose matrix, then what was the cause of this rheological contrast? Extrapolations of creep test results do not suggest a large viscosity contrast between granite and schist at relevant geological conditions (Shea and Kronenberg, 1992; Ranalli, 1995). Furthermore, if this fold style depends on intrinsic rheological properties of the rocks, then why are not all folds of granitic veins in schistose matrix ptygmatic?

These problems relate to the central issue of the present paper: what specific process took place *during the stage of fold closure* that caused the preservation of a buckle style of ptygmatic folds.

Many authors have related the occurrence of ptygmatic folds in migmatites to the overall presence and migration of partial melt in the rock, but gave no detailed model of fold development (Wilson, 1952; Bradley, 1957; Ashworth, 1985, p. 20). Furthermore, no explanation is given for the enigma that, as described in this paper, ptygmatic folds are found predominantly in rocks that do not display melt-forming metamorphic reactions.

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Fig. 1. Ptygmatic structure: strongly contorted granitic vein in gneissose matrix that has unfolded fabric. Location: Kemiö. Scale: lens cap = 5 cm.

In this paper, it is proposed that the style of ptygmatic folds is governed largely by differentiation and growth of limbs. These processes may have had a strong effect on the relative viscosities of host rock and veins, but they also had an independent effect on the geometry of the fold structures.

2. Terminology

The terminology used to describe ptygmatic folds in migmatites is illustrated in Fig. 2. Throughout the paper, the following nomenclature is used for the diverse elements in migmatites: migmatites are composite rocks in which three constituents can be distinguished: mesosome or host rock, leucosome or vein, and melanosome (Ashworth, 1985, p. 2–4). Leucosomes are quartz–feldspar-rich ‘granitic’ layers

or veins that are mantled by biotite or hornblende-rich melanosomes (‘selvages’). In the rocks in this study, leucosome and melanosome are separated by a zone in which the quartz–feldspar microstructure is similar to that in the melanosome, but which is devoid of mafic minerals: the term ‘depleted zone’ is proposed for such domains.

3. Material studied

The rocks studied are migmatitic gneisses from the classic gneiss and migmatite belt in S. Finland. This belt is of Svecofennian age (1.9–1.8 Ga) (Front and Nurmi, 1987; Heeremans et al., 1996), and is characterized by a low- P , high- T type of metamorphism (Schreurs and Westra, 1986; Heeremans et al., 1996). Most samples have been derived from the Mustio area (Bleeker and Westra, 1987; Veenhof and Stel, 1991). The rocks in this region were affected by metamorphism that at peak conditions reached 650–680°C at 4.5 kbar (Blom, 1988; Schreurs and Westra, 1986). All the samples are derived from locations well outside the orthopyroxene isograd as mapped by Schreurs and Westra (1986). The main phase of deformation took place after peak metamorphic conditions were reached (Bleeker and Westra, 1987; Heeremans et al., 1996). One sample from Kemiö Island, located within the ‘muscovite + quartz zone in metapelites’, is discussed. The rocks of this area have mineral assemblages that suggest a low partial pressure of water ($P_{\text{H}_2\text{O}} = 0.4P_{\text{total}}$) and $P_{\text{total}} = 3$ kbar (Dietvorst, 1982).

All specimens studied are characterized by the occurrence of isolated quartz–feldspar veins (leuco-

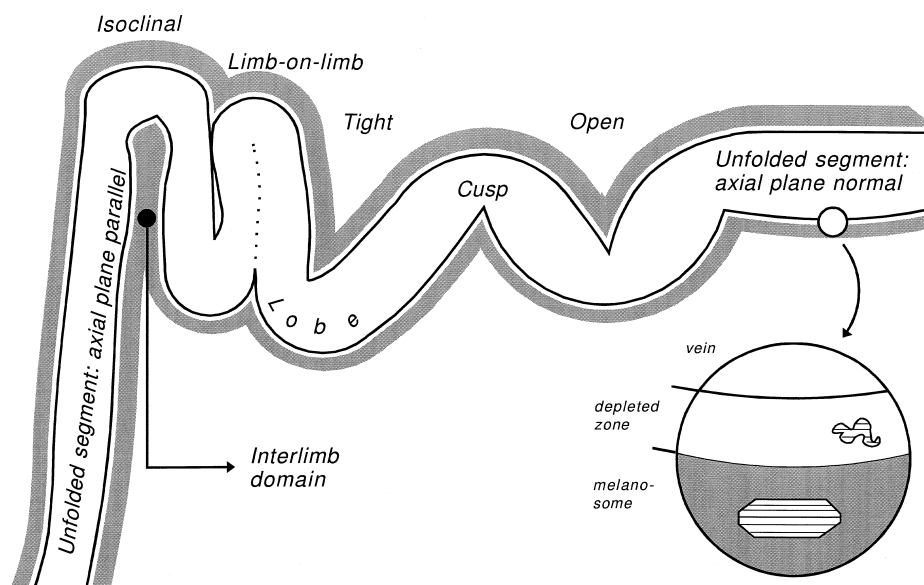


Fig. 2. Terminology used to describe the diverse structural elements of ptygmatic folds in migmatites. See text.

somes) that are oblique to the compositional banding in the host rock. This relation suggests that the leucosomes did not nucleate on primary rock inhomogeneities, but are secondary veins. The relative volume of the leucosomes, averaged on the scale of outcrop, never exceeds 10%. The host rocks to the veins are medium grained (0.2 mm) quartzo-feldspathic gneisses which are biotite- and/or hornblende-bearing. A description of the samples is given in Appendix 1.

4. Fold shape

Open to tight folds display a lobe–cusp structure, characterized by relative thinning of the hinges (with

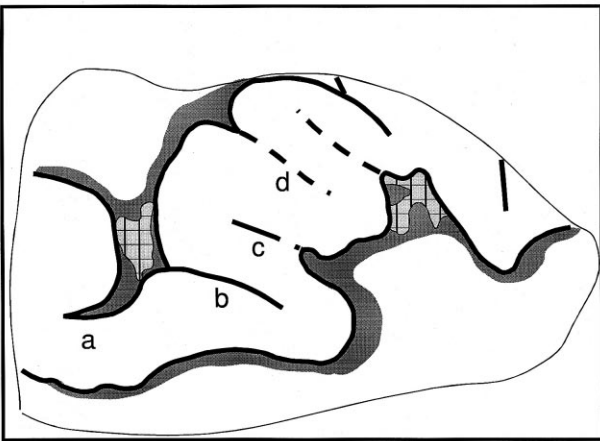
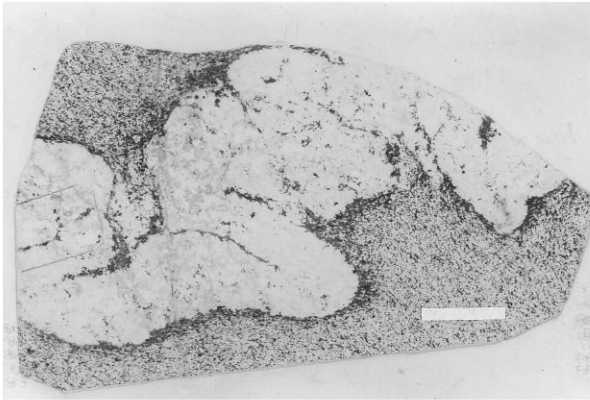


Fig. 3. Photograph and cartoon of thin section (14×10 cm) of ptygmatic fold train showing transition, from left to right, of tight (a) to isoclinal (b) folds. At (c), the interlimb domain is disruptive and appears to be overgrown by the vein. At (d), the interlimb domain largely disappeared and a limb-on-limb fold is found. The outline of the interlimb was reconstructed on the basis of ore- and remnant mica-‘dust’ trails. The folded vein is a coarse grained ($d = 2$ mm) tonalite embedded in a melanosome composed mainly of biotite (black on line-drawing). Cross-hatching domain within the realm of the melanosome are interpreted as zones of biotite depletion due to hydrothermal activity. Specimen HS 174.

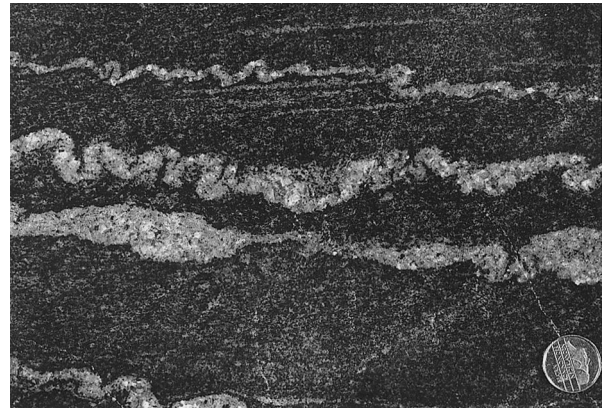


Fig. 4. Photograph of polished section of specimen HS 89-24 showing (partly) folded granitic veins in dark coloured, biotite–hornblende rich gneiss. Note that the veins contain folded as well as unfolded parts, and that folding is strongly disharmonic. The compositional banding in the host rock (running approximately E–W) is unfolded, but it appears to be deflected at the near vicinity of fold hinges. Scale: diameter of coin is ca 1 cm.

respect to the limbs), and absence of a true ‘inner arc’ (Figs. 1 and 2). Isoclinal folds have straight limbs, and the lobe–cusp character is less clear. Many isoclinal folds have no (or only relicts) of host rock present in interlimb domains (Fig. 3); the term ‘limb-on-limb’ is proposed for these structures. A ‘train’ of limb-on-limb folds may thus, at first sight, appear as an unfolded, thickened vein.

The specimens selected for study show relatively simple, cylindrical folds. Fold axes are parallel to the mineral lineation that is defined by long axes of biotite, hornblende or quartz grains. Open to tight folds have no axial plane foliation, micas in interlimb matrix form a funnel-shape pattern congruent with the vein wall. Host rocks of folded veins are foliated, usually displaying gneissic layering that trends at a high angle to the axial planes of the folds (Figs. 1 and 4).

The ratio of the length of a vein (l_0) and the enveloping surface of folds (l_1) in a specimen is variable, and unfolded segments may be found adjacent to folded ones (Fig. 4). Ptygmatic folds are strongly disharmonic with respect to folds in a neighbouring vein (Fig. 4). Apparent shortening values deduced from l_0/l_1 ratios range up to 90%. The ratio of wavelength (L) and thickness (a) of the veins varies in the range $L/a = 5–10$. Many fold-trains display inconsistent L/a values, due to abrupt changes in thickness of veins over a fold hinge.

Folded veins may demonstrate unfolded segments, of which two types can be distinguished on the basis of the orientation relationships to the ‘gross’ axial plane of folds: ‘axial plane-normal’ and ‘axial plane-parallel’ (Fig. 2). The general absence of boudinage of fold limbs and unfolded veins is a distinctive aspect of

ptygmatic structure (with the exception of one case, HS 302).

5. Textural and compositional variation

Veins and host rock differ consistently in grain size and in content of mafic minerals. Most folded veins have mantles that differ in composition from that of the host rock as well as from that of the veins. The development of vein mantles appears to be strongly related to ongoing metasomatic and metamorphic alterations at or near the vein wall.

5.1. Veins and host rock

The host rock as well as the veins are largely composed of quartz and feldspar. The veins are mica-poor (ca. 1 vol.%), the host rock contains >15 vol.% biotite, while the melanosome mantle of a vein may contain >50% biotite. In some cases, near the boundary, trails of anhedral biotite are included in the veins. Without exception, if mica is found in the veins, it occurs as strongly anhedral flakes, displaying haematite and dust-stained rims.

In two specimens (HS 87 and HS 89-24), it was found that axial-plane-normal types of unfolded vein-segments have different composition than folded ones. In both cases, the latter appear to be feldspar-enriched relative to the former.

The grain size of quartz and feldspar in the veins is between 10 and 25 times larger than that in the host rock (0.2 mm in the latter; see Fig. 5). In some cases (HS 89-24), folded segments of veins have a reduced grain size with respect to unfolded ones. In general, hinge domains of folds have a reduced grain size with respect to the limbs.

In the host rock as well as in the veins, quartz and feldspar grains are highly irregularly shaped, displaying amoeba-type outlines and strongly sutured phase boundaries (Fig. 5). Quartz–feldspar boundaries display deep (up to 3 mm) lobes of quartz in feldspar, transecting the twin pattern of the latter, and yielding typical embayment structures. In sections cut perpendicular to the fold axes, no shape preferred orientation of the minerals in the veins is observed.

5.2. Mantles to the veins

Veins are enclosed by either melanosome, depleted or composite mantles. Melanosome mantles are enriched in biotite (\pm quartz) and depleted in feldspar (\pm quartz) with respect to the host rock. Plagioclase in melanosomes has similar Ca-content as in host rock domains. Melanosome mantles enclose tightly to isoclinaly folded veins, but are also found along axial-

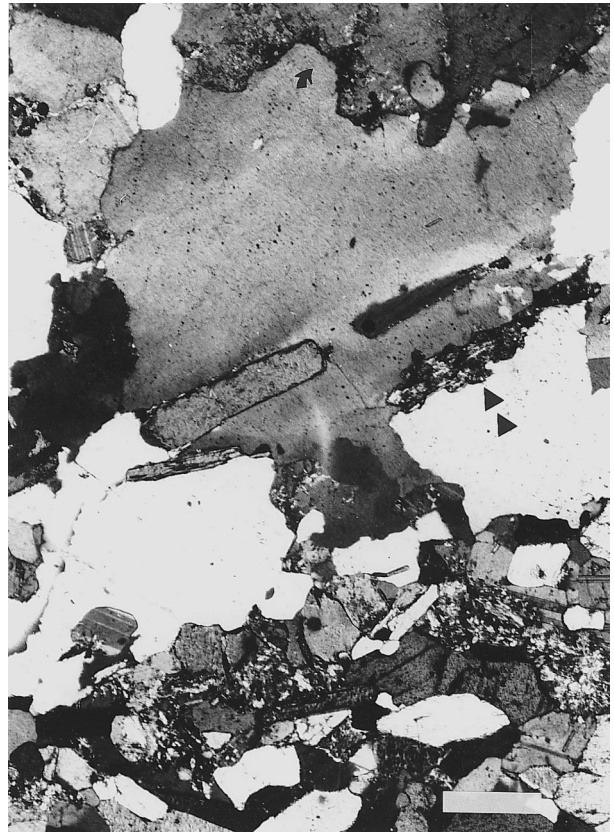


Fig. 5. Micrograph (crossed polarizers) showing the texture in granitic quartz–feldspar vein (top 75%) and finer grained matrix (below). Arrow near the top points to a bulge of quartz into albite. At the boundary of the vein and matrix strongly anhedral biotite occurs (double arrow). Scale bar = 1 mm.

plane-parallel type of unfolded vein segments. In specimens HS40-6 and HS87, only folded vein segments display melanosome mantles.

In melanosomes, biotite occurs in two microstructural settings (Fig. 6). At the vein boundary, strongly anhedral mica flakes are found, usually with frayed boundaries. Grain boundaries of this type of mica are stained by haematite and rutile needles, while magnetite is found locally. Away from the vein boundary, subhedral biotite crystals are found, some of which transect the twin pattern of plagioclase crystals.

Depleted mantles have a similar quartz–feldspar microstructure to the host rock, but are devoid of mafic minerals. They differ from the veins in grain size, and locally in mineral composition. Mantles of this type are found at folded as well as unfolded vein segments in all the specimens. At the mesoscopic scale, depleted mantles were not recognized as such, as they appear as integral parts of the veins. Relicts of biotite and hornblende are found in depleted mantles; these minerals are strongly anhedral, and show deep embayments.

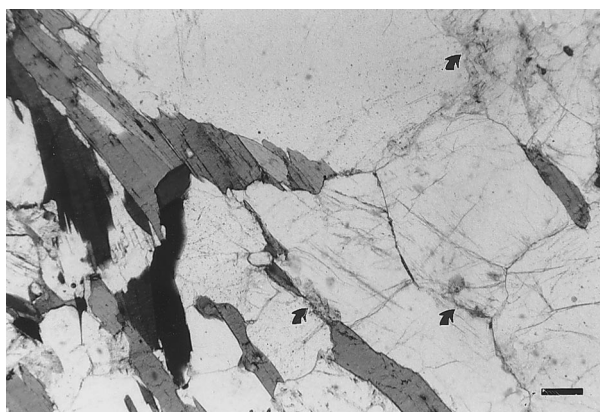


Fig. 6. Micrograph (parallel polarizers) showing the transition of biotite microstructure from a 'depleted zone' (left), to melanosome (right). Biotite in depleted zone is anhedral. Feldspar (white) boundaries in this zone are stained by haematite (light grey) + biotite-dust (black), suggestive of biotite break-down (at arrows). Specimen HS 87. Scale bar = 0.3 mm.

5.3. Limb-on-limb folds

Isoclinal folds with (nearly) no interlimb volume are found in nearly all ptygmatic fold trains. In some cases, a relict-interlimb domain can be delineated by trails of relict-micas or ore. In other cases, limbs appear to be completely 'welded'.

In specimen HS 174 and HS 302, limb-on-limb folds occur in conjunction with isoclinal folds that display very thin (0.5 mm thick), discontinuous interlimb domains. In the latter, biotite-bearing strands (relict interlimb domains) alternate with domains where two fold limbs touch (Fig. 3). Biotite in discontinuous interlimb strands is strongly anhedral, displaying frayed boundaries. These domains are transitional to limb-on-limb structures.

5.4. Offshoot veinlets

Ptygmatically folded veins may display offshoot veinlets (specimen HS87, HS 40-6; HS89-24), that transect folded melanosome mantles and propagate in the host rock (Fig. 7). These veinlets are characterized by depletion of biotite relative to the host. Within the veinlets, the external foliation can locally be traced by relicts of biotite. The rims of veinlets are mica-enriched, with (001) of mica oriented parallel to the trend of the veinlets. When oriented parallel to the enveloping surface of the main veins, the veinlets are buckled.

5.5. Non-ptygmatic folds

One specimen (HS90-7) demonstrating non-ptygmatic folds is described. It differs from the other specimens in a number of respects: the folds are harmonic

and have a similar style. Folded quartz–feldspar veins have no mantles with distinct mineralogical composition, and no offshoot veinlets were found.

6. Deformation mechanisms and metamorphic processes

The formation of a specific fold shape is commonly interpreted in terms of viscosity contrasts and variation in other rheological parameters between a competent layer and its matrix (Price and Cosgrove, 1990; Hudleston and Lan, 1995; Lan and Hudleston, 1996). For such an evaluation, an interpretation is given of the deformation mechanisms involved on the grain scale. It is shown, however, that additional processes have affected the shape of the veins and the folds. Compared to 'normal' folds, the most striking microstructural attribute of ptygmatic folds is the presence of vein mantles that differ in composition from the host rock. In this section, it is proposed that mantle formation involved tectonic segregation as well as fluid-induced replacement growth. Both processes lead to a volume increase of the veins during folding.

6.1. Deformation mechanisms on the grain scale

The microstructure in the veins is typified by strongly sutured phase boundaries, bulge-edge structures and plagioclase embayment. This indicates that extensive phase boundary migration has taken place (Gower and Simpson, 1992). It was proposed that this microstructure is formed by diffusional flow (Gower and Simpson, 1992). These authors noted that during phase boundary migration considerable redistribution of matter takes place in rocks. In turn, if this process takes place in the presence of a differential stress, it

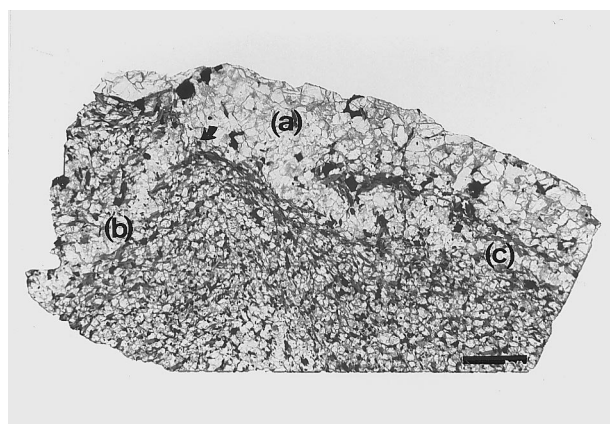


Fig. 7. Photograph of 'thick' section (200 μm) of part of a leucosome (a) and two offshoot veinlets (b) and (c) transecting the melanosome mantle of the main vein. One veinlet (c) shows buckling. The external foliation is traceable in the offshoot veinlets; one site is marked by arrow. Detail of specimen HS 87. Scale bar = 3 mm.

must constitute a deformation mechanism. Alternatively, phase boundary migration may have taken place in response to dislocation creep mechanisms, i.e. to lower dislocation densities. Grain size reduction at sites of relatively high strain (fold hinges) supports such an interpretation (Ranalli, 1995). It is therefore concluded that veins deformed by a combination of dislocation creep, assisted by mass transfer.

No evidence for the presence of a melt phase during deformation has been found. No igneous textures or melt-related deformation structures could be identified (cf. Blumenfeld and Bouchez, 1988; Vernon and Collins, 1988; Shelley, 1993). If such structures have ever been present, they apparently did not survive phase boundary migration processes.

6.2. Differentiation and volume change

It is proposed that, apart from distortion on the grain scale, differentiation accommodated deformation. Microstructural relations found in the vein mantles indicate that evolution of the interlimb matrix during progressive folding was governed by two contrastive processes. Mica-enrichment took place by tectonic segregation (cf. Sawyer and Robin, 1986) in the bulk interlimb domain. In contrast, fluid-induced mica-depletion took place at the vein boundary as well as in offshoot veinlets. This process caused a local replacement of melanosome by leucosome and, consequently, growth of the vein. The term 'replacement' growth is suggested for this process. Whereas the effect of tectonic segregation appears to be dependent on structural position (predominantly in interlimb domains of folds), replacement growth took place irrespective of ongoing deformation.

In part, deformation was accommodated by tectonic segregation. This deduction is based on the compositional variation related to progressive folding. A synfolding origin of melanosome can be deduced from the observation that in some cases (HS40-6, HS87) melanosome is found only in the interlimb domains of tight to isoclinal folds, but is lacking in unfolded (parts of) veins. In other cases (HS89-24), interlimb domains of folds are more mafic than mantles of unfolded segments. Moreover, folded parts of veins (HS87, HS89-24) have an increased feldspar content with respect to axial-plane-normal unfolded segments. This increase in feldspar content balances the local decrease in feldspar component in melanosomic interlimb domain. This compositional variation is consistent with tectonic segregation during fold closure, by which feldspar migrates from interlimb domains (leaving a more mafic melanosome) to the veins. This interpretation supports general models of differentiation in high grade gneisses and migmatites (Robin, 1979; Sawyer and Barnes,

1986; Sawyer and Robin, 1988; Kretz, 1994; Brown et al., 1995).

Microstructures indicate that, near the vein boundaries and in offshoot veinlets, biotite in interlimb melanosomes was unstable. At these sites, mica is invariably anhedral (frayed) and is stained by rutile and haematite. Instability of mica is also apparent in limb-on-limb folds. In these structures, a mafic interlimb appears to have been replaced by coarse grained quartz–feldspar aggregates. The texture of these aggregates is nearly indistinguishable from that of the veins, apart from the presence of mafic relicts and trails of ore. It is proposed that at these sites the depletion of biotite induced grain growth and phase boundary migration of quartz and feldspar (cf. Shelley, 1993). As a result of these processes, replacement growth of the vein at the expense of melanosome took place.

It is proposed that destabilization of biotite near vein boundaries was induced by fluids. The most direct evidence for the relation of fluid activity and mica breakdown is the presence of offshoot veinlets. The veinlets are characterized by depletion of mica, while mica-enrichment took place at the boundaries. The veinlets show transitional relationships with the texture of the host rock, and relicts of the host rock foliation can be traced in these structures. From these microstructures, it is concluded that the veinlets did not generate as open veins, nor as melt-injection structures. On the other hand, the veinlets have all the aspects of replacement structures, formed by fluid escape from the main vein. They are interpreted accordingly.

Mica-depleted mantles (HS89-24) of the veins show identical microstructural relations to the host rock as offshoot veinlets. It is proposed that these were formed in a similar way: by fluid-induced breakdown of mafic minerals. All studied ptlygmatically folded veins show evidence of such focused fluid flow. This accords with the model of Brown et al. (1995) that competent leucosomes are in general the locus of fluid activity and migration (cf. Whitney and Irving, 1994; Holtz et al., 1995).

Whereas the effects of fluid activity are clearly exposed, it is difficult to constrain its nature. It has been envisaged that a mica-destabilizing fluid in the veins may have lowered $f_{\text{H}_2\text{O}}$, f_{H_2} , $f(\text{HF}, \text{HCl})$, and/or increased f_{O_2} , a_{H^+} and $a_{\text{Si}^{4+}}$ (Olsen, 1977, 1984; Munoz, 1992; Dachs, 1994; Smit and van Reenen, 1997). In some of the cases discussed here, the presence of a contrasting fluid in veins and matrix is possibly illustrated by the preferential occurrence of CO_2 in the veins (specimens HS87 and HS89-24). However, it has been envisaged that at high grade conditions, the most active fluid phase in high grade rocks may have been a brine that has escaped trapping due to exceptionally high wetting angles (Smit and van Reenen, 1997).

7. Scenario of ptygmatic folding

In the following model, it is presumed that the ptygmatic folds discussed have originated by folding (buckling) of a more or less planar vein or layer. It is beyond the scope of the paper to discuss the formation of these veins in detail, but as they are oblique to layering in the gneisses, it is probable that they represent metamorphic segregation structures (Ashworth, 1985).

A scenario of ptygmatic folding in migmatites is proposed on the basis of textural variations. It is envisaged that, in all the stages of deformation, breakdown of mafic minerals took place by fluid activity at the vein boundaries (Fig. 8a).

The first stage of folding involved buckling, leading to open folds of granitic veins. Given the strong imprint of mass transfer on the texture, it is proposed that the viscosity contrast between veins and matrix was governed by difference in grain size and mica content (Evans and Kohlstedt, 1995; Rutter, 1983; Schwarz and Stöckhert, 1996).

Tight to isoclinal folds developed during fold closure (Fig. 8b). These structures are characterized by a change in mineral composition of interlimb domains

by loss of feldspar and quartz. In the cases where the quartz–feldspar ratio of veins differs significantly from that of the host rock, a detectable compositional change of the veins also took place. The compositional changes correspond to ongoing differentiation, by which feldspar (\pm quartz) migrated from interlimb domains into the veins. Interlimb domains became mica-enriched (melanosome). At the vein boundaries, ongoing fluid activity caused actual mica-depletion that led to local grain growth and (apparent) growth of the vein.

Isoclinal folds with disruptive interlimb domains developed by further depletion of mica and concurrent grain growth of quartz and feldspar (Fig. 8c). At the sites where mica was depleted, two (or more) fold limbs appear to be in microstructural continuity. By further depletion of mica from interlimb domains, limb-on-limb isoclinal folds developed from folds with disruptive interlimb domains.

This scenario illustrates how during differentiation, the limbs of the folds escaped from thinning and a ptygmatic shape was maintained. First, overall shortening of fold trains was accomplished by volume loss in interlimb domains. This was balanced in part by volume increase of the veins, while the amount of

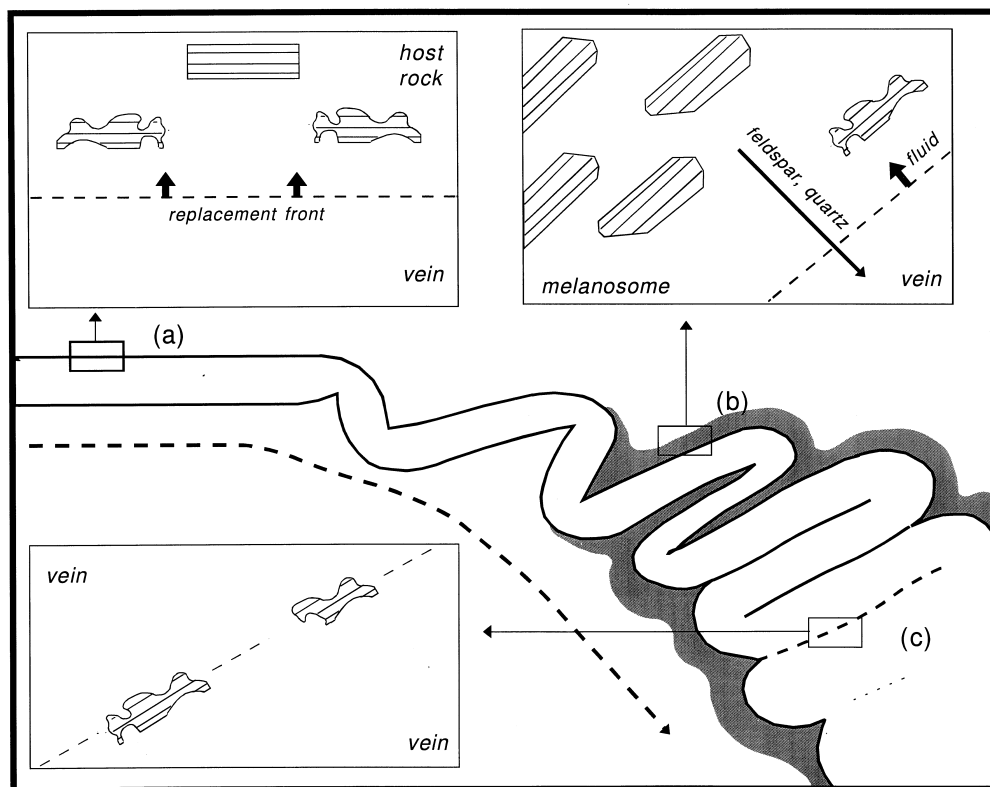


Fig. 8. Scenario of progressive (from left to right, following broken line) ptygmatic folding of a granitic vein in gneissose matrix. Details: at (a) it is illustrated that fluid escape from leucosome causes break-down of biotite at the boundary, while this is compensated by neo-crystallization. At (b) folding of the leucosome is accompanied by mechanical differentiation. At (c) biotite migrates out of interlimb domains and limb-on-limb folds are formed.

thinning of the limbs may have been small (Kretz, 1994). Secondly, thinning of limbs is counteracted by (apparent) growth of the limbs during mica-depletion in the interlimb domain.

8. Ptygmatic folding and partial melting: discussion

Are ptygmatic structures diagnostic for the presence of partial melts during deformation of migmatites? This question has been raised since these structures were defined (Sederholm, 1913). In this section, it is discussed that the presence of a melt phase is not a *conditio sine qua non* ptygmatic structure is formed.

Ptygmatic structures in rocks from Kemiö Island are found within the zone where muscovite + quartz is stable in neighbouring metapelites. This suggests a metamorphic temperature of ca. 560–600°C (Dietvorst, 1982), which is too low for partial melting. It is presumed that these rocks did not undergo a type of retrogradation that has wiped out all the microstructural evidence of a higher grade of metamorphism on a regional scale. Accepting this, the microstructural relations demonstrate that partial melting was no prerequisite for the formation of ptygmatic structure.

In the samples from the Mustio area, ptygmatic folds occur specifically in ‘meta-graywacke’-type of rocks that recorded a metamorphic temperature of ca. 650–680°C. None of the rocks that were studied contain muscovite, and microstructures indicative of known melt-forming reactions with biotite are lacking. Detailed metamorphic studies suggest a low partial water pressure in the rocks ($P_{\text{H}_2\text{O}} < 0.4P_{\text{total}}$), cf. Schreurs and Westra (1986). This combination of factors preclude that there was a significant amount of melt present *in the bulk of the rocks*. The temperature range is too low to generate melt in muscovite-free graywackes by mineral reactions (Stevens et al., 1997), while a low $P_{\text{H}_2\text{O}}$ should have prevented melt formation by interaction of minerals and pore fluid.

Whether a melt phase was present at the leucosome–melanosome boundaries is difficult to evaluate at present. Melt may have been generated during infiltration of fluids (Olsen, 1984), but given the predominance of CO₂-rich fluid inclusions in veins it is uncertain whether $P_{\text{H}_2\text{O}}$ of the ingressing fluid was high enough to induce local partial melting. Experimental results suggest that, at low strain rates, the effects of a small amount of melt on stress-induced mass transfer are similar to that of presence of a fluid phase (Dell’Angelo and Tullis, 1988). Moreover, it is envisaged in this paper that the style of ptygmatic folds is largely governed by segregation processes. The processes may proceed in the presence as well in the absence of a melt phase (Brown et al., 1995), while the resulting microstructural configuration may be similar.

Therefore, it is concluded that ptygmatic structures are not ‘diagnostic’ for presence of a partial melt phase in migmatites.

9. Conclusions

Ptygmatic folding in migmatites takes place while veins and mantles are differentiating. Throughout the entire history of the folds, growth of the leucosome may take place, by which a replacement front migrates away from the vein boundary. At least during fold-closure stages, mechanical differentiation takes place. Related to differentiation, volume loss takes place in the vein mantles, while the limbs of the folds increase in volume. These processes prevent the fold limbs from thinning. These factors are suggested to be the key to explaining ptygmatic structure, as they facilitate the preservation of the buckle shape during fold closure.

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Appendix A

A.1. Microstructure and composition of six samples

Six specimens are described in this section. Given mineral compositions were obtained by conventional point counting. Compositions of individual minerals were acquired by microprobe analyses. The following abbreviations are used (mainly after Kretz, 1983): Qtz = quartz; Kfs = K-feldspar; Pl = plagioclase; An% = percentage anorthite; Ab = albite; Bt = biotite; Amf = amphibole.

Specimen HS87 demonstrates a progressive change in mineral composition of the melanosome with folding. A vein consisting of folded and unfolded segments (Fig. 9a, b) has been analysed. In the former, open, tight, isoclinal and limb-on-limb folds are found (Fig. 9a). Melanosomes are found only in interlimb domains of tight to isoclinal folds. The host rock

shows a largely unfolded compositional banding defined by varying mica content.

An axial-plane-normal type of unfolded vein segment (Fig. 9b) has composition Kfs (50%), Qtz (34%) and Pl (15%). Folded segments of veins are largely composed of Kfs (78%) and Qtz (20%). With respect to the host rock, melanosome in interlimb domains shows a relative increase in Bt (20 vs 40%, respectively), while Kfs is largely depleted (31 vs 4%). In tight-isoclinal segments, the twin structure of plagioclase is transected by subhedral biotite crystals. Microprobe analyses show that restite plagioclase has similar composition to the plagioclase host rock ($An\% = 32$). Offshoot veinlets from the main vein have been found in this specimen, some of which are folded. The veinlets are characterized by depletion of biotite.

In contrast to the host rock, most fluid inclusions in the veins are CO_2 -bearing ($T_m = -56^\circ C$).

Specimen HS 302 has isoclinal and limb-on-limb folds of alkali-feldspar/quartz veins. It is the only specimen found in which boudinage of the veins has been observed (Fig. 9c).

The host rock is feldspar-rich (58% Ab) and relatively mica-poor (16% Bt). The interlimb domains of isoclinal folds are composed of Qtz–Bt aggregates (in the case where the interlimb domain is relatively broad, viz. 5–10 mm), or of (discontinuous) biotite strings of ca. 0.5–1 mm thickness. In the latter, biotite is strongly anhedral.

Unfolded parts of the veins trending parallel to the axial plane of the folds show boudinage. In boudin necks, a deflected biotite foliation can be traced; bio-

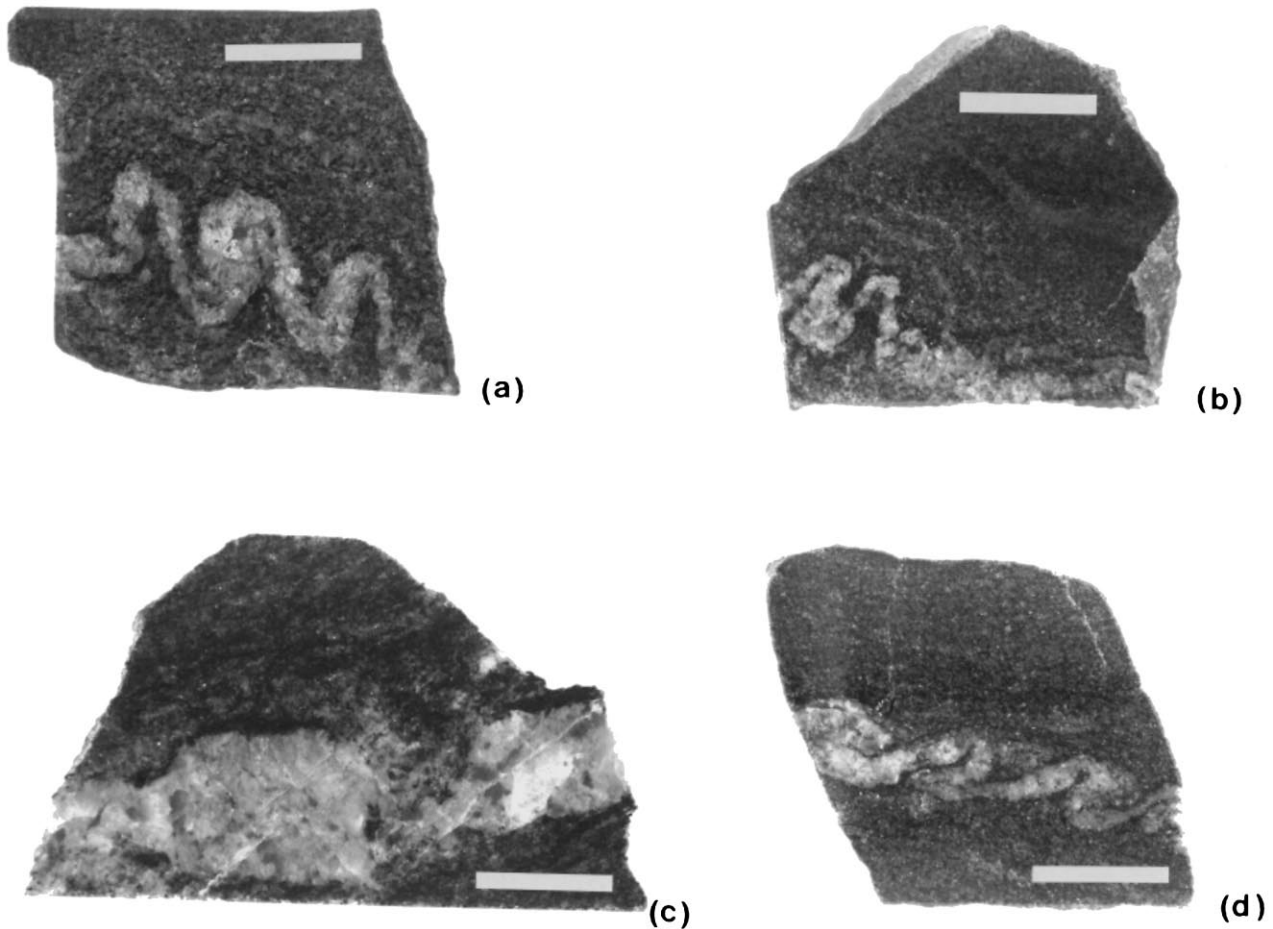


Fig. 9. Composite of polished sections of parts of specimens, which were not demonstrated in the main text. (a) Part of specimen HS 87, showing a fold in granitic vein. Open (extreme left), tight, isoclinal and limb-on-limb folds are shown. Scale bar = 2 cm. (b) Idem, demonstrating transition from an 'axial-plane-normal type' of unfolded vein to folded section. Scale bar = 2.5 cm. (c) From specimen 302; boudin in granitic vein. Boudin necks display texture similar to that of offshoot-veinlets (Fig. 7) and depleted mantles of veins (Figs. 3 and 4), characterized by depletion of biotite relative to the host. Scale bar = 1 cm. (d) Specimen 40-6; tight-isoclinal asymmetric ptygmatic folds. Scale bar = 2 cm.

tite in these domains is strongly anhedral. The boudin necks have considerably lower mica content than host rocks.

Specimen HS 40-6 (Fig. 9d) illustrates that despite a large similarity in composition of host rock and veins, apparently a large viscosity contrast existed. The rock is typified by the occurrence of Ab–Qtz (ratio 4:1) veins in a matrix of Ab–Qtz–Bt. The only *compositional* difference between vein and matrix is the occurrence of 15% Bt in the latter. Melanosome occurs in interlimb domains of folds only. The composition of the host rock is 70% Ab, 15% Qtz and 15% Bt. In tight folds, the mineral composition of melanosome in interlimb domains is Ab (20%), Qtz (40%) and Bt (40%). In isoclinal folds, quartz–biotite and monomineralic biotite domains are found. A relatively broad (5 mm thick), weakly folded offshoot veinlet from the main vein is found in this specimen (not displayed on Fig. 9d).

Specimen HS 174 demonstrates ptygmatic folds of a feldspar–quartz vein (Fig. 3). Some of the folds are isoclinal, and have an interlimb domain consisting of a string of biotite. It appears as if the ‘train’ of isoclinal and limb-on-limb structure constitutes a thickened vein, which itself is mantled by biotite-rich melanosome. Irregularly outlined feldspar-rich domains are found in melanosomic interlimb domains.

Specimen HS89-24 typifies ptygmatically folded veins in a host rock of which the mineral assemblage points to lower amphibolite facies conditions. The sample was collected in the Kemiö domain. It is composed of Pl (An% 23), Qtz, green amphibole and green biotite.

Two types of leucosome occur in this specimen: strongly folded K-feldspar-rich veins, and weakly folded to unfolded plagioclase-rich veins. Even of neighbouring veins, l_0/l_1 ratios are strongly varying (Fig. 4). Despite the apparent difference in l_0/l_1 ratios, the L/a value appears the same for all folded veins. The enveloping surface of the folds are at an angle (10°) to the compositional layering in the host rock (see below); and are parallel to the trend of unfolded veins.

K-feldspar–quartz veins contain unfolded parts with optically undeformed crystals of coarse-grained K-feldspar and quartz. At places where these grade into isoclinally folded segments, a strong reduction in grain size can be observed, and extensive myrmekitization of the boundaries took place. With respect to the host rock, most of the interlimb domains of folds show enrichment of mafic minerals and depletion of Pl and

Qtz. At contrast to unfolded parts of veins, folded segments of K-feldspar-rich veins contain non-myrmekitic plagioclase (up to ca. 15%).

Along their entire length, K-feldspar-rich veins are mantled by depleted zones composed of Pl and Qtz, while amphibole may occur as anhedral relicts. In the veins, some CO₂ inclusions are found.

Specimen HS90-7 contains harmonic type of similar folds i.e. non-ptygmatic. It is described here to illustrate that lack of compositional change in interlimb domains can be correlated with development of folds with non-ptygmatic style. The specimen contains folded veins composed of K-feldspar and quartz, and are found in a fine-grained host rock of quartz, plagioclase and biotite. In contrast to ptygmatic folds, (over-)thickening in the hinge domains took place. The veins have no clear selvage. The interlimb domains of the folds in this specimen show no enrichment of any of the minerals, unlike those in ptygmatic folds.

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