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Syn-migmatization way-up criteria

JEAN-PIERRE BURG

CNRS-UP361, Centre Géologique et Géophysique, USTL Place E. Bataillon, 34095 Montpellier Cédex 5, France

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Abstract—Most geopetal (way-up) structures are developed during primary formation or soon after in sedimentary or igneous rocks. In migmatite terrains the possibly anomalous behaviour of rocks in which melt is present has often limited structural synthesis. Geopetal relationships may, however, be recognizable in at least some migmatites. Asymmetries in two structural relationships ('cauliflower structure' and 'vein cluster'), involving neosome veins conformable with the main foliation of layered migmatites, are interpreted as indicating the way-up of these rocks when they were partially molten. Additional examples recognized in the literature suggest that similar structures can be seen in a wide range of geological environments. These prove to be as reliable as sedimentary top and bottom features and suggest that the migmatites containing them were essentially sub-horizontal while being strained and melted.

INTRODUCTION

GEOPETAL (way-up) structures are invaluable aids for deciphering the structural histories of deformed supracrustal terrains of all ages and locations. Most previously recognized way-up structures are developed in sedimentary or igneous rocks during either primary formation or early diagenesis. Common examples are cross- and graded-bedding and dewatering structures in sediments, pillow shapes in lavas, and infills in fossils and vesicles (e.g. Hills 1963).

The variability and complexity of structures in migmatite terrains has been recognized by previous workers in the deep levels of the crust (e.g. Berthelsen 1960, Mehnert 1968, Campbell 1980). This has been attributed to the possibly anomalous behaviour of rocks in which melt is present (e.g. Holland & Lambert 1969, Arzi 1978, McLellan 1984) and has often limited structural synthesis of such terrains.

This paper describes a technique that may be applied to solid-state migmatite terrains to define the layer-facing. Asymmetries in two structural relationships involving neosome veins conformable with the main foliation within layered migmatites are separately analysed, first in terms of a descriptive classification and secondly in terms of geometric implication. Next their ubiquity is investigated through (previously unrecognized?) examples figured from other regions described in literature. Finally the genesis or proposed mechanisms of origin are examined. These structures are interpreted as indicating geopetal relationships (way-up) at the time of melting (migmatization), and suggest that the migmatites containing them were essentially sub-horizontal while being strained and melted. It is concluded that they are simple observations that must be given due consideration in structural analysis of rocks in which melt was present. Further work comparing primary and diagenetic geopetal structures with the syn-tectonic, syn-migmatization way-up structures in the same rocks will be necessary to establish whether these supracrustal sequences were essentially undeformed, or already had a complex deformation history before they melted at depth.

CAULIFLOWER STRUCTURES

Description

'Cauliflower structures' are similar to rounded cusp and pointed lobe structures (mullions or class 3 folds, e.g. Ramsay, 1967; convex forms of Mehnert 1968) on some scales in profile. However, they differ not only in internal structure and in the fact that they cross the foliation, but, more importantly, in that most are preferentially developed on the same side of concordant (i.e. foliation-subparallel) veins whose other surface is distinctly more planar. Foliation of the country rock may either bend around the bud in a pinch-and-swell manner or may be cut by the vein boundary. The structure is best seen in *YZ* planes of rocks (orthogonal to both the lineation and the foliation, equated with the *X* axis and *XY* plane of the finite strain ellipsoid, respectively). In flat-lying migmatitic sequences cauliflower structures have formed on the upper side of veins. The type field example (Fig. 1a) chosen to illustrate this top and bottom feature of a neosome vein is situated in the Rhodope Massif of Bulgaria. Migmatites have suffered a strong shear deformation during amphibolite facies regional metamorphism (Burg *et al.* 1990). Greyish granodioritic gneisses contrast sharply with white pegmatoid in remarkable differentiation veins several metres long and some tens of centimetres wide. Veins of the area are straight, sigmoidal and folded, cross-cutting and parallel to foliation (e.g. Ivanov *et al.* 1985). The wide range in shapes and sizes indicates that the veins were formed as melts or hydraulic intrusions at all increments of deformation. Therefore they are syn-tectonic. The use of cauliflower structures defines overturned limbs of large-scale post-foliation, tight folds (interlimb angles 30–50°) whose location may not be convincingly established due to the poor outcrop of first-order hinge lines and the rarity of parasitic folds (work in progress with Professor Ivanov and his team, from Sofia University).

Reliability

The author has used 'cauliflower structures' in several field areas of varied tectonic framework (Himalayas, Alps, Kabylia, French Variscides, Caledonides) and contends that they are common. Additional examples of cauliflower structures found in the literature are good supporting arguments because they illustrate more objectively than personal observations the wide range of geologic settings in which similar structures exist. The examples drawn after photographs in Fig. 2 were selected because they are published in classical text books and easily accessible publications. They display on scales from centimetres to a few metres veins with one wall consisting of a series of lobate forms in contrast with relative smoothness of the other wall. This is interpreted as a top and bottom feature, the bulbous boundary being taken as the hanging wall of the migmatitic terranes. This interpretation is consistent with the present day up-sequence direction as defined from outcrop features (sky-line, plants, shadows, etc.) on the published photographs. In effect, the author has not seen many published plates that convincingly suggest up-side down veins, even after an extensive bibliographic search. Rocks in Flatvarp in Sweden may be one exceptional example (fig. 11 of Mehnert 1968).

Interpretation

Cauliflower structures seem to result from unequal pressure controlled inflation of syntectonic veins. Shear deformation tends to straighten both wall and roof vein boundaries in XZ sections. As sketched in Fig. 3 upward protrusions are best preserved in YZ sections because comparatively little deformation occurs along the Y axis when deformation approximates plane strain, which might be expected in deep levels of the crust. The basic process thought to produce cauliflower structures in anatectic, partly melted rocks is an instability in the top surface of the neosome vein, which tended to rise on wavelengths of cm to dm (as a melt, hydrous fluid, or by crystallization) along either falling pressure gradients or inverted density gradients enhancing upward mass-transfer on a macroscopic scale during deformation.

To date, most authors agree that concordant neosome veins result from metamorphic differentiation, a process implying that material is dissolved or melted from areas of high pressure or high mean stress, and after transport, deposited in areas of low pressure or low mean stress (e.g. van der Molen 1985a). In other words there is a tendency for low viscosity material to migrate to pressure shadows developed in high viscosity layers (Ramberg 1949, Robin 1979) or to other dilational sites, for example as along secondary shear bands during non-coaxial deformation. Following these arguments, the localization and orientation of the foliation-parallel veins may be determined dynamically by heterogeneous shear deformation. Developing shear zones with a high strain rate compared to that of the surrounding gneiss induces contrasts in viscosity, and possibly in porosity due to some dilatancy, hence creating sites for nucleation and deposition of pegmatitic to granitic material. Once the vein is formed upward migration of fluids leads to budding crystallization at, and inflation of, the boundary between the vein and the hanging-wall, which results in formation of the cauliflower structures. This implies upward melt migration and intrusive behaviour of the anatectic melt on a small scale. It is irrelevant here whether cauliflower structures are primary (intrusion) phenomena or secondary deformation structures. What is important is that they record the general upward direction during migmatization.

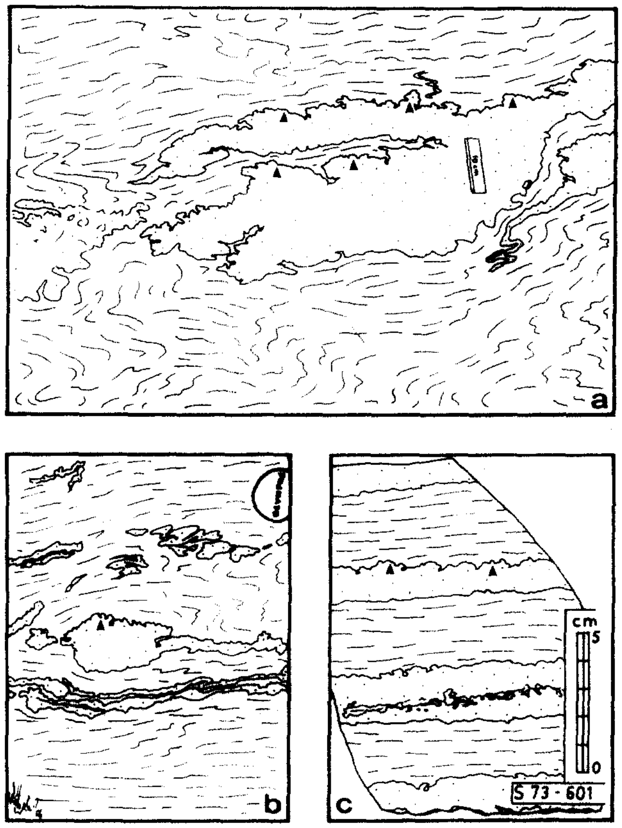

Fig. 2. Examples of cauliflower structures at different scales sketched from photographs. Quartz, plagioclase (and K-feldspar ?) veins = leucosomes (dotted) in gneisses (dashed). Triangles point toward the inferred hanging-wall. (a) "Migmatitic phenomenon" photographed by Mehnert in Granholmen, Sweden, drawn after fig. 1.1 of Ashworth (1985). (b) "Discontinuous segregations that are conspicuously coarser-grained than the moderately well-foliated, dark-coloured hornblende–biotite feldspar schist" drawn from part of fig. 11-9 of Best (1982), unspecified location. Note that the inferred top-side is consistent with growing grass in the lower left corner. (c) "Migmatite hand specimen" from Arvika, Sweden, drawn after fig. 14 of Johannes (1983). While this article was being refereed, a convincing plate with a top-side interpretation has been published by Culshaw & van Breemen (1990, fig. 7c).

Fig. 1. (a) Budding protrusions (arrowed) developed on upper side of a concordant pegmatoid vein whose lower surface is distinctly smoother than the upper one. *YZ* plane of rock (orthogonal to both the lineation and the foliation). Bistritza valley, 15 km east of the Blagoevgrad township, Rhodope Massif; Bulgaria. This 'cauliflower structure' permits definition of the top-side of the sequence at the time the vein formed. (b) Not completely separated boudins of amphibolite underlain by a quartz–feldspar vein (arrowed) several metres long and a few centimetres wide on the long lower surface. Note that there is no veining along the upper amphibolite boundary. This asymmetric vein cluster is seen in the *XZ* plane of rock, Vetcha valley, 6 km north of the Krychtim township, Rhodope Massif of Bulgaria.

ASYMMETRIC VEIN CLUSTER

Description

The term 'asymmetric vein cluster' is coined to describe leucosome veins on one side of competent layers (e.g. mafic sheets). In flat-lying anatectic sequences mafic layers are lined on the lower surface by quartz–feldspar neosome veins commonly several metres long and a few centimetres thick, whereas there is no or little veining along the upper layer boundary. The structure is seen in any plane of finite strain at a high angle to the main foliation (Fig. 3). In the *XZ* example shown in Fig. 1(b), which is also taken from the Rhodope Massif of Bulgaria, an amphibolite layer has started to pull apart and down into partially separated boudins. The granodioritic gneiss between the amphibolite layers has undergone extension by ductile shear. Boudins seem to float and rotate upon a white layer of pegmatoid leucosome that underlines the lower surface. The vein cluster is a bottom-side indicator less common than cauliflower structures because it may be destroyed after breaking of the competent layer during progressive deformation. A more deformed stage includes well-known leucosome segregation infillings between boudins and veining along the upper boundary. The resulting product of progressive deformation leads to the widespread occurrence of fragments floating within remarkably planar pegmatitic layers.

Reliability

Other illustrations of asymmetric vein clusters are relatively uncommon in the literature. One may be identified in fig. 143(A) of Break & Bonds (1982) exhibiting early stages of migmatite evolution in Archean metasediments of Ontario, Canada. The most spectacular one is displayed Fig. 4(a). A pegmatite vein underlying an amphibolite layer has started to rise between two boudins, developing 'cauliflower structures' on top of the pegmatitic swell. Another interesting plate has been published by van der Molen (1985b) and is interpreted in Fig. 4(b). It exemplifies how boudinage may obscure vein clusters once boudins have separated. The top-side interpretation suggested here is consistent with the upper side of the sequences shown by landscape features. Figure 10 of Mehnert (1968) displays boudinage of a dark amphibolite injected by pegmatoid leucosomes resembling an asymmetric vein cluster. This strongly suggests again that rocks in Flatvarp are indeed upside-down.

Interpretation

Asymmetric neosome clusters are interpreted as accumulations of melt trapped beneath impermeable refractory layers as the neosome rose (episodically or progressively) during migmatization. Where such trap layers later boudinaged, the underlying neosome rose between boudins. Additions of later neosome between the boudins demonstrate the syntectonic nature of the migmatization.

The process envisaged to be responsible for asymmetric vein clusters is as follows. A layer, or set of layers, is embedded in a medium of contrasting rheological properties. Local solution (or melting) and gravity driven upward migration of material is essential. Deposition of pegmatoid material is concentrated under the more competent layers, which agrees with the theory of deformation of a multilayer as developed by van der Molen (1985a). This is governed by upward diffusion of the pore fluid through the less competent layers to separation surfaces where differences in mean stress arise from rheological contrasts with competent layers that behave like mechanical obstructions. This process probably favours boudinage by increasing the viscosity difference between the competent layers and their surroundings. In addition, the vein may act like a melt-lubricated shear. Where the competent layer breaks with progressive deformation, there are sites for upward melt flow and new sites for deposition of material

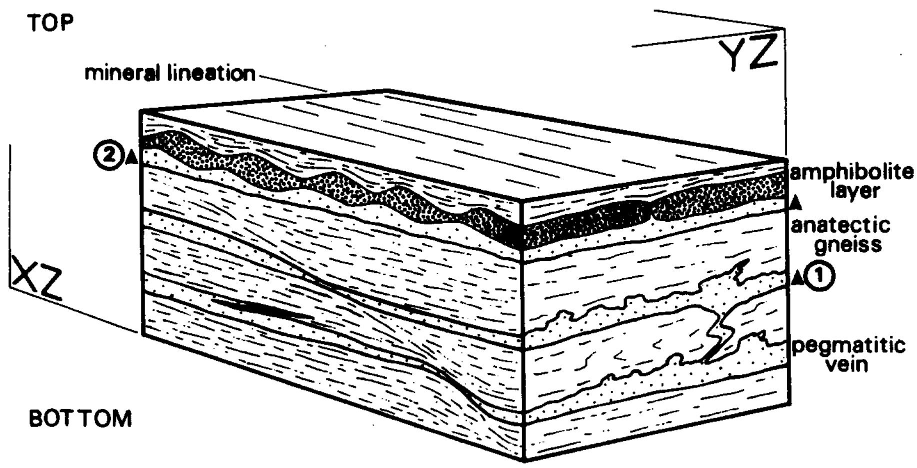

Fig. 3. Schematic block diagram illustrating cauliflower (1) and asymmetric vein cluster (2) structures in an idealized normal sequence of flat-lying anatectic gneisses. Arrows point towards the top of the sequence. Observations in the *YZ* plane of finite strain are essential. Shear deformation as indicated by shear bands in *XZ* sections is top-to-the-right.

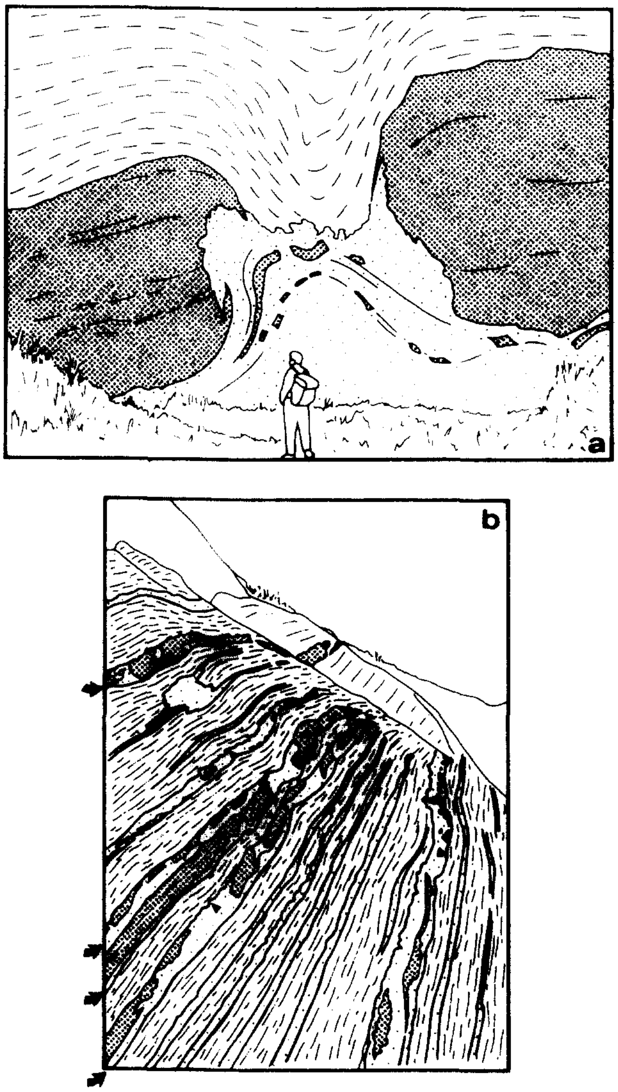

Fig. 4. Examples of asymmetric vein clusters sketched from field photographs. Leucosomes and pegmatitic veins (dotted) in gneiss (dashed) with boudinaged amphibolites (stippled dark). (a) "Spectacular boudinage of a Kangâmiut dyke in the north-east part of Sondre Stromfjord" drawn after fig. 77 of Escher & Watt (1976). Note that the pegmatoid vein lies below the dyke only. Ascent of the pegmatitic vein occurred between boudins (incipient destruction of the vein cluster structure) and developed cauliflower structures eradicating the rock foliation on the top-side. Both cauliflower and asymmetric vein cluster structures consistently indicate the top-side. (b) "Thin boudinaged layers of amphibolite in differentiated gneiss" at Sondre Stromfjord Airport, drawn after fig. 4(a) of van der Molen (1985b). Asymmetric vein clusters (arrowed) were partly destroyed by progressive deformation. This intensely deformed stage includes leucosome segregation in zones between boudins and veining along the upper boundary. The resulting product of progressive deformation leads to the widespread occurrence of fragments floating within remarkably planar pegmatitic layers as described in many field areas. Possible 'cauliflower structures' (triangles) are consistent with the top-side as defined by the sloping sky-line.

between boudins. Eventually, old or new neosome develop topside cauliflower structures in the gaps between boudins and the asymmetry of the vein cluster is partly or totally destroyed, giving rise to layered gneisses as commonly described in migmatitic regions with competent inclusions within conformable neosomes.

CONCLUSION

Cauliflower and asymmetric-vein-cluster structures are macroscopic and syntectonic differentiation products crystallized in mechanically controlled sites. Where found nearby in the same migmatized sequence, cauliflower structures are consistently top-side, and asymmetric vein (neosome) clusters are consistently bottom-side. The central point of their description and interpretation is clear: pegmatoid veins found in migmatitic terrains involve an interplay of ductile-flow and upward mass-transfer and transport. Their growth is considered to be governed by geometric and kinematic constraints: deposition occurs within zones between rocks and rock-domains of contrasting rheologies. Unequal inflation of the upper boundaries and undercoating of impermeable roof-layers develop shapes that permit the definition with some confidence of the top and bottom of the sequence at the time syntectonic veins were formed. As a corollary, and because of the great significance of the horizontal plane in geology, regions where similar structures are identified had a primarily flat-lying attitude of foliations. The geopetal nature of vein-cluster neosomes and those displaying cauliflower structures is further reinforced by appropriate changes in their facing when followed around major post-migmatization folds. These structures are therefore potentially useful tools for the recognition of large-scale folds and inverted migmatitic sequences as their occurrence is found to be relevant to many high-grade gneiss terrains. The structures added here improves the armoury of tools to help unravel the post-migmatization tectonic histories of complex migmatite terrains. More attention to migmatites by structural geologists, and specially to *YZ* planes where gravity driven features are best preserved, appears as a prerequisite to bring out new bases for study of deep-level processes.

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