Journal of Structural Geology, Vol. 15, No. 11, pp. 1293 to 1301, 1993
Printed in Great Britain

0191-8141/93 $06.00+0.00

Structures and way-up criteria in migmatites, with application to the Velay dome (French Massif Central)

JEAN-PIERRE BURG and OLIVIER VANDERHAEGHE

CNRS UP361, Centre Géologique et Géophysique, Université de Montpellier II, Place E. Bataillon,
34095 Montpellier Cédex 5, France

(*Received* 27 *April* 1992; *accepted in revised form* 9 *November* 1992)

Abstract—A detailed structural analysis has been applied to the migmatite sequence of the southern limb of the Velay dome, France, in an attempt to study the structural implications of the occurrence of metatexites and diatexites. Metatexites have a plastic behaviour presumably dominated by the solid skeleton which largely takes up the deformation. In contrast, diatexites have a predominantly viscous behaviour because the solid framework has been disrupted and they are dominated by the granitic melt rather than the solid component. Therefore, the metatexite to diatexite transition has a major rheological and tectonic importance because it separates regions that record plastic (stable) deformation from regions that record viscous (unstable) deformation where gravitational instabilities may develop.

Mesoscopic, syn-migmatitic way-up criteria, which assume that melt migration is partly driven by gravity, give evidence for a southward overturning of the Velay dome. This overturning is supported by sedimentary and plutonic way-up criteria seen in schists and granitic plutons, respectively. The N–S asymmetry of the Velay dome is related to late-Variscan, asymmetric extension on a regional scale. Consistency of data provides further evidence that syn-migmatization way-up criteria are regionally reliable structural tools applicable to other migmatitic terrains.

INTRODUCTION

THE aim of this work is to pursue the definition of structures that display an asymmetry with respect to the bulk migmatite layering and interpreted as syn-migmatization way-up criteria. Following Burg (1991), we assume that they represent melts trapped under mechanical barriers while migrating upward because of density and viscosity contrasts with the host rock. Migmatite structures are interpreted in the light of theoretical and experimental information on the geometrical and rheological evolution of a rock during partial melting and crystallization. This type of structural analysis and particularly the way-up criteria are applied to the southern part of the Velay dome (French Massif Central). This field application shows that syn-migmatitic way-up criteria give evidence for a large overturned limb facing south. This allows the Velay dome to be interpreted as a late-Variscan structure formed during the collapse of the Variscan platform.

METHOD

Terminology

'Migmatites' have formed when a gneiss has separated into distinct regular and irregular, leucocratic and mesocratic layers, veins and patches, which are commonly referred to as 'leucosome' and 'mesosome', respectively (e.g. Henkes & Johannes 1981). Untwinned, euhedral phenocrysts of K-feldspar, subidioblastic biotite crystals and aggregates, myrmekitic intergrowth of quartz and plagioclase suggest that leucosomes are crystallized melts. Even if leucosomes are not entirely liquid during their formation, these textural features are consistent with a dense suspension behaving predominantly as a highly-viscous fluid (Van der Molen & Paterson 1979, Wickham 1987, Cooper *et al.* 1989). Accordingly, and as a first approximation, we assume that leucosome bodies represent the melt fraction segregated during partial melting, in contrast with the mesosome that constitutes the essentially solid fraction that may contain some unsegregated melt. Hence, following the migmatite nomenclature of Mehnert (1968), we identify two main types of migmatites.

'Metatexites' exhibit a pronounced foliated and/or layered structure, which is commonly defined by biotite-rich layers representing the principally solid framework of the rock. Leucosome layers are usually thinner than the mesosomes and vary in width from a few millimetres to a few centimetres. Locally, concentrations of biotite form dark rims, which are termed 'melanosomes'. Metatexites include migmatites with layered ('stromatic'), brecciated ('agmatic') and dilatation ('surreitic') structures. They all imply a low melt component (leucosome).

'Diatexites' consist of foliated xenoliths of the original source-rock ('restites') dispersed in leucosome material of successive generations (and slightly different composition), as well as intrusive granite and pegmatite. Xenoliths constitute 'rigid' fragments that may locally preserve from full recrystallization, or localize strain in the leucosome producing a weak, contorted foliation defined by mafic (refractory) minerals, restitic xenoliths and 'schlieren' (irregular streaks with diffuse boundaries enclosed in the leucosome). Diatexites appear as rocks having lost their strain-supporting skeleton, which is broken and transected by leucosomes that constitute nearly a third or more of the outcrop. They encompass migmatites with fleck ('stictolithic'), raft ('schollen'), streak ('schlieren'), reticulate ('diktyonitic') and ghost-like ('nebulitic') structures.

Petrological and rheological background

Petrological studies have convincingly shown that migmatites result from melting followed by later *in situ* crystallization whether this is isochemical (Ashworth 1976, Johannes & Gupta 1982) or not (Olsen & Grant 1991). The first melt in quartzofeldspathic rocks appears at grain boundaries, with experimentally obtained dihedral angles of 45–60° (e.g. Jurewicz & Watson 1984). A granitic rock is saturated for a melt fraction of 2–4%, when the equilibrium melt morphology becomes an interconnected network along triple junctions with melt-free grain boundaries (Jurewicz & Watson 1985). At this critical amount of melt, and at natural strain rates, there is a switch from dominantly dislocation creep to dominantly melt-enhanced diffusion creep (Dell'Angelo & Tullis 1988) and melt migration may take place. Although density and viscosity data are scarce for granitic melts under deep crustal conditions (Bottinga & Weill 1972, Kushiro 1980), silicate liquids are less dense and less viscous than the solid from which they are produced (Jurewicz & Watson 1984, 1985), which is regarded as an important crustal separation process by McKenzie (1984). The melt fraction tends to migrate from zones of high pressure to zones of low pressure (Robin 1979, Van der Molen 1985a), such as thermally-induced and extensional microcracks (Paquet *et al.* 1981). As a consequence of the viscosity of silicic liquids, anatectic felsic melts will not be segregated over distances greater than approximately 1–10 m, according to McKenzie (1984).

With increasing proportion of melt, the mechanical properties of rock change from elastic-plastic to viscous (Arzi 1978, Van der Molen & Paterson 1979). Convoluted folding in migmatitic terrains (e.g. Hopgood 1980, 1984) has been related to the superimposition of complex flow behaviours in partially melted rocks (Holland & Lambert 1969, McLellan 1984). Arzi (1978) pointed out that a drastic decrease in effective viscosity occurs at a rheological critical melt percentage (RCMP) of around 20–30%. The rapid fall in strength seen in Arzi's experiments represents the threshold beyond which the rock does no longer behave as a solid with an intergranular, interstitial liquid. The rock changes from a granular framework to a dense suspension with effective fluid properties (Van der Molen & Paterson 1979, Wickham 1987).

The following rheological consequences can be inferred: (1) metatexites have a dominantly plastic behaviour because the solid skeleton largely takes up the deformation; (2) diatexites, the solid framework of which has been disrupted, are dominated by the granitic melt rather than by the solid component; therefore, they should have an overall viscous behaviour and the ability to develop gravitational instabilities; and (3) the metatexite to diatexite transition may be an important migmatite boundary in which it is primordial to determine whether upward migmatitic motion has occurred.

Structural tools

Melt can theoretically be separated from rocks with a low melt-fraction during ductile deformation of layers of differing composition (Robin 1979, Van der Molen 1985b). Therefore, large and small structures in migmatite are largely controlled by the rheological contrast between the melt and solid fractions. In particular, density and viscosity contrasts enable the melt to migrate. We use the spatial distribution and shape of leucosomes (inferred to be segregations of granitic liquid) to determine structures that can be interpreted in terms of melt migration on a small scale.

Three primary melt migration mechanisms are driven by a solid–liquid density and viscosity contrast, namely: (1) percolation, which is the movement of a liquid through a solid matrix; (2) diapirism, which is body migration by intrusion and strain; and (3) fracturing, which results in the formation of a vein network in the rock. Percolation (i.e. diffusional transport) is mainly achieved by intergranular flow and results in the bulk compaction of the solid matrix (McKenzie 1984, 1987). Diapirism and fracturing occur along discontinuities and locally create sites of collection (Clemens & Mawer 1992). If gravity impels a relative upward migration of the less dense melt, a collection of leucosomes under relatively impermeable layers produces asymmetric leucosome features that have been inferred to indicate the polarity of the migmatite at the time of formation by Burg (1991). These can be used as way-up criteria (Fig. 1) which, in turn, allow an interpretation of the large structures developed during and after the crystallization of migmatites.

Syn-migmatization way-up criteria

Asymmetric vein-clusters are leucosome veins crystallized along the lower boundary of competent layers (Figs. 2a & b). They are interpreted by us as granitic melts trapped underneath the competent and impermeable layer during their ascent, as the melt fraction percolated through the deforming parent rock. Leucosome vein-clusters may display segregation of tourmaline-rich pegmatoids along their consistently-assumed top boundary, directly below the competent layer.

Cauliflower structures characteristically appear along one, assumed to be the upper, boundary of leucosome layers (Fig. 3a). They are typically lobate features with imbricated wavelengths, which are characteristic of the local amplification of a gravitational instability (Ramberg 1968, de Brémond d'Ars & Davy 1991). They may indicate buoyant ascent of small pockets of melt, which is possible if layering was initially horizontal and viscosity contrasts with the country rock were low (Fyfe

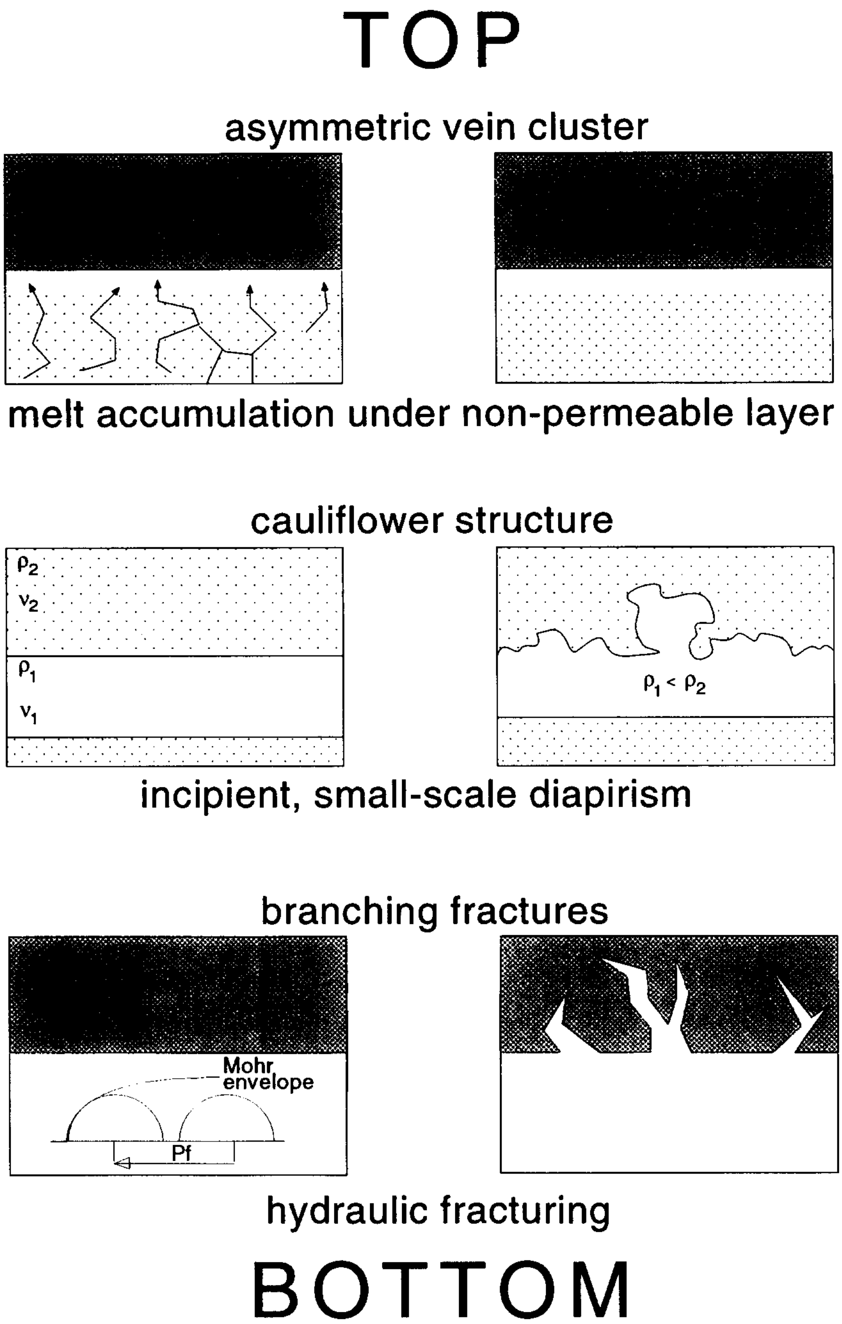

Fig. 1. Sketch of syn-migmatitic way-up criteria and interpretation. ρ and ν are density and viscosity, respectively. Pf is pore pressure of the fluid.

1973). On the scale of a single leucosome layer, differentiation may occur, with segregation of tourmaline-rich pegmatoids toward the top, lobate boundary.

Layer-parallel leucosome veins with a smooth boundary on one side can be associated on the other side with branching fractures that terminate into a ductilely deformed, more competent layer (Fig. 3b), which we take as the upward termination of the fracture network. Our interpretation is as follows. Although these rocks are in the ductile regime, hydraulic fracturing can occur at any depth of the crust, provided pore fluid pressure is high enough (Jaeger & Cook 1979). The accumulation of a high-viscosity silicate melt results in a rise of the local fluid pressure that may become greater than the tensile strength of the competent layer (Shaw 1980, Clemens & Mawer 1992). If hydraulic fracturing occurred at the bottom of an impermeable layer, it would create a pressure gradient in the rock responsible for the movement of melt drawn into a crack of this type. Upward fracture propagation will take place into the impermeable, competent layer until disruption is reached, with the formation of brecciated (agmatic) migmatites. Intermediate stages of upward fracture propagation, where preserved, provide another way-up criterion.

THE VELAY DOME

Regional setting

The 300 Ma Velay anatectic complex (Caen-Vachette *et al.* 1981, 1982, Mougeot 1991) is a 120 × 100 km granite–gneiss dome that formed below the major eclogite- and amphibolite-bearing thrust sheet of the eastern French Massif Central, about 60 Ma after Variscan thickening (Burg & Matte 1978). Dupraz & Didier (1988) have given a detailed account of the petrogenesis of these granitoid and migmatite bodies. Two competing models are: (1) *in situ* melting with inherited structures that are preserved during upwelling of the dome (Weisbrod 1970, Weisbrod *et al.* 1980, Macaudière *et al.* 1987); and (2) deep-seated, immature diapirism with partial melting of the host rocks (Dupraz & Didier 1988). In addition, the Late Variscan tectonic setting of the Velay dome is actively debated. Mattauer *et al.* (1988) inferred post-orogenic extension from ductile normal faults on the northern limb of the Velay dome. On the other hand, Lagarde *et al.* (1990) related its formation to large conjugate strike-slip faults at the end of the compressional Variscan history.

Our field study is focused on the southern limb of the Velay dome in order to: (i) document structural relationships between the surrounding regions and the migmatitic–granitic dome; (ii) better understand the dome structure; and (iii) elucidate structural mechanisms involved in doming.

The southern limb displays a continuous N–S section from the core of the dome to the Cévennes metamorphic series (Fig. 4). The transition from mica-schist to gneiss, migmatite and granite occurs over 10 km. Lithologic contacts are parallel to the main-foliation planes and delineate the grossly concentric shape of the Velay dome.

On the basis of observations and terminology discussed in the preceding section, three structural domains are recognized: (1) the low- to medium-grade Cévennes metamorphic rocks; (2) a transitional domain comprising metatexites that have developed a synmigmatitic foliation; and (3) a domain within the dome that comprises diatexite and granitoid bodies that have diapirically risen with respect to the Cévennes metamorphic rocks.

Structural domains

The Cévennes series is composed of polyphase, quartzopelitic schist and orthogneiss, increasing in metamorphic grade from low-grade muscovite–chlorite–garnet schists in the south to andalusite–biotite schists in the north (Weisbrod 1970, Laumonier *et al.* 1991). The main foliation, S_{1-2}, includes two regionally parallel foliations derived from a transposed sedimentary layering (the general trend of which defines the dome shape) and contains a down-dip mineral lineation, L. However, sedimentary structures such as graded bedding are locally preserved. Asymmetric quartz lenses and tails around various clasts indicate a top-to-the-south sense of shear, which is a result of normal faulting, since most foliation planes dip to the south. A crenulation cleavage S_3 is seen in hinge regions of cm- to km-scale, S-facing chevron folds. S_3 increases in intensity northward and is almost parallel to S_{1-2} in the intermediate, nearly vertical domain where sedimentary structures indicate a southward younging direction.

The beginning of the transition zone is marked by small lenses and very thin layers of felsic minerals scattered throughout the schist and paragneiss. Felsic lenses become broader and more abundant with an increase in the metamorphic grade toward the north, and are composed of leucosome rimmed by melanosome selvages. Leucosome bodies are contained by, and flattened within, the composite foliation S_{1-2}, which has not lost its coherence. The minerals are quartz, K-feldspar, plagioclase and biotite, with minor constituents epidote, sphene, ilmenite, apatite, zircon, secondary chlorite and muscovite. Fold interferences have a consistent orientation that can be directly correlated to regional S_2 and S_3 structures. Conjugate shear bands indicate late coaxial strain with a N–S-oriented flattening direction. Consistency of structures in these metatexites, with a low percentage of melt, suggest that they had a dominantly solid-state behaviour, which did not differ greatly from that of entirely solid rocks, because the crystals formed a continuous aggregate through which stress was transmitted.

A distinction between diatexites and metatexites, as defined above, has been used in order to delineate the southern boundary of the domal domain (Figs. 4 and 5). The metamorphic sequence culminates in garnet–sillimanite-bearing diatexite with cordierite-rich leucosome bodies and granite that occupy much of the core of the dome. Thermobarometric calculations based on garnet–plagioclase–sillimanite–quartz assemblages imply that extensive, water-saturated crustal anatexis occurred at 3–5 kbar (Montel *et al.* 1992). Xenoliths are metres to kilometres in size and represent all types of the host rocks and earlier mafic magmas. Besides these inherited structures, overprinting criteria and contrasting deformational styles reveal several entangled deformational and migmatitic events (Laumonier *et al.* 1991). In detail, folds of the diatexite layering can be related to diapiric granitic intrusions and cannot be related to regional structures. Here, syn-anatectic deformation resulted in disharmonic and non-cylindrical folds with great variations in wavelength and amplitude, diagnostic of viscous fold types (McLellan 1984). Failure of previous structural analyses in the Velay area to consider the mechanical implications of melting, such as the possibility that intersecting fold axial directions may be products of a single deformational event, to which the migmatite responded largely by melt migration, casts doubt on their conclusions.

The Rocles two-mica granite intrusion between the Cévennes and intermediate domains has subsolidus- and solidus-stage foliations both of which are parallel to the main foliation of the migmatitic sequences (Weisbrod *et al.* 1980). This suggests that intrusion took place during the late stages of regional deformation, and the granite is dated at 302 ± 4 Ma using the Rb/Sr whole-rock method (Caen-Vachette *et al.* 1981). The sub-vertical compositional layering indicates that the pluton floor is to the

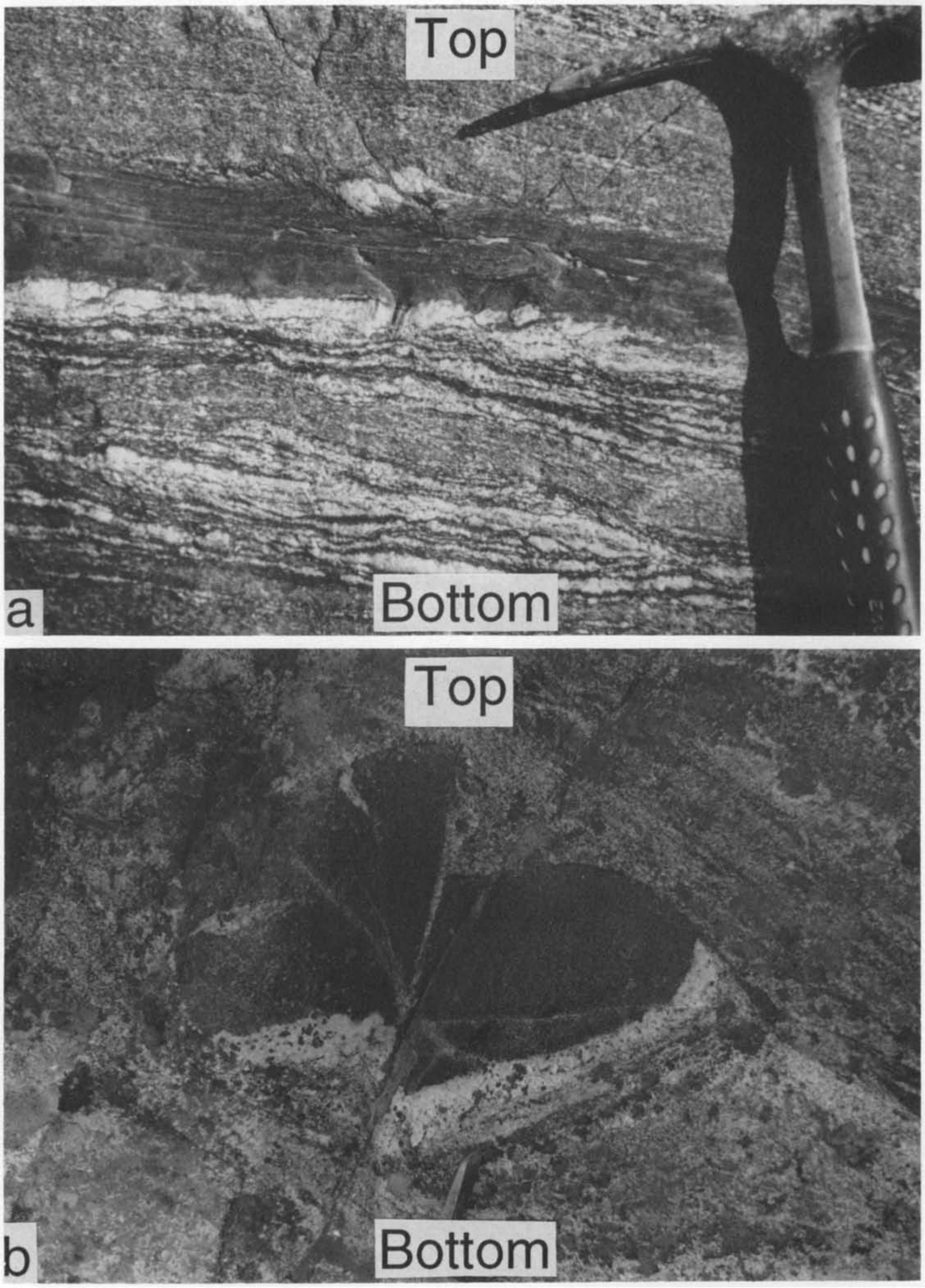

Fig. 2. (a) An asymmetric vein cluster in metatexites of the southern limb of the Velay dome (Ardèche river: locality, La Levade). (b) An asymmetric vein cluster in metatexites of the southern limb of the Velay dome (Volane river: locality, Les Terrets). Note boudinage of both the early leucosome and the impermeable dioritic layer.

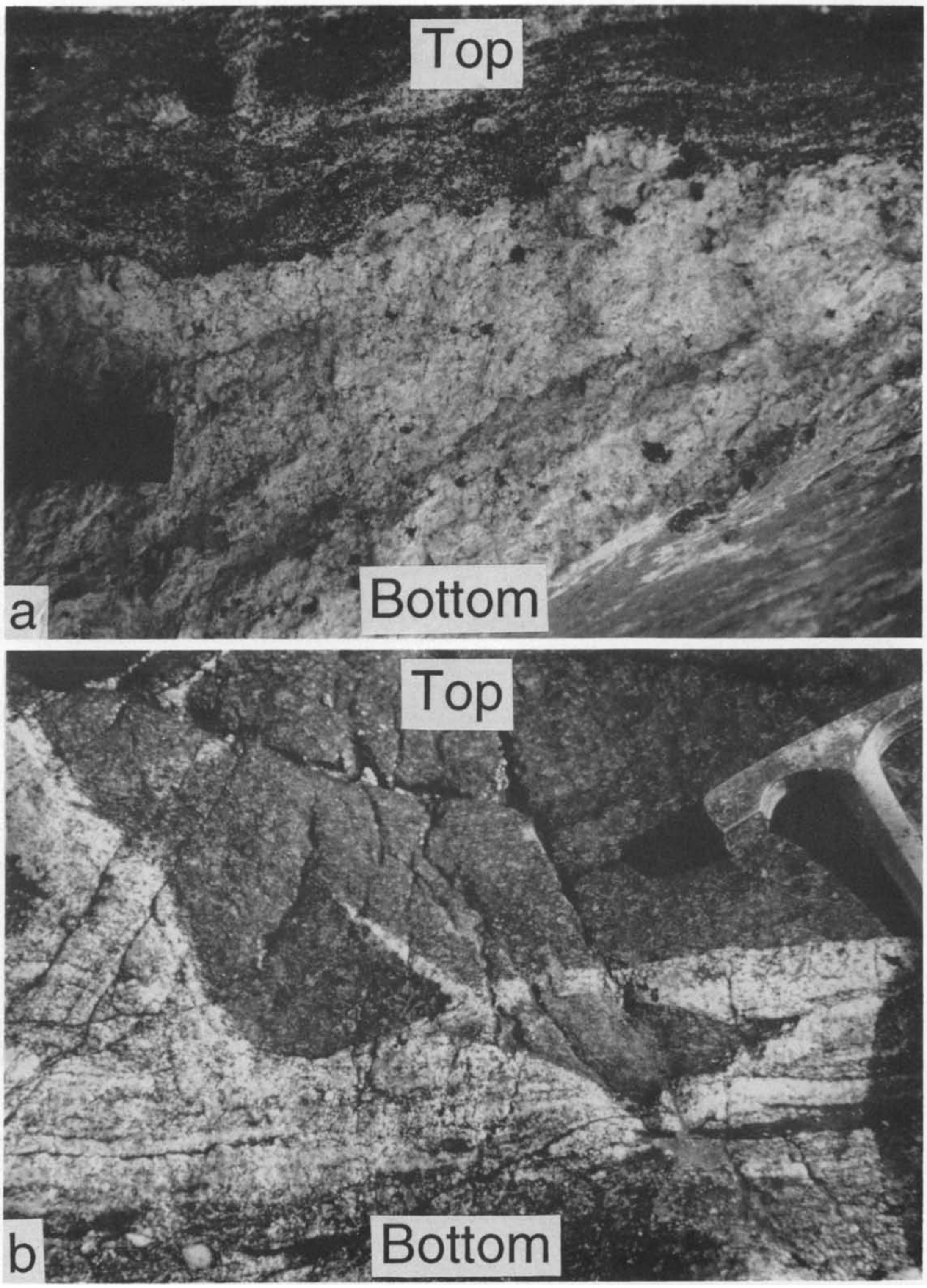

Fig. 3. (a) A cauliflower structure in metatexites of the southern limb of the Velay dome (Volane river: location, Antraygues bridge). (b) Branching fractures in metatexites of the southern limb of the Velay dome (Ardèche river: locality, La Levade).

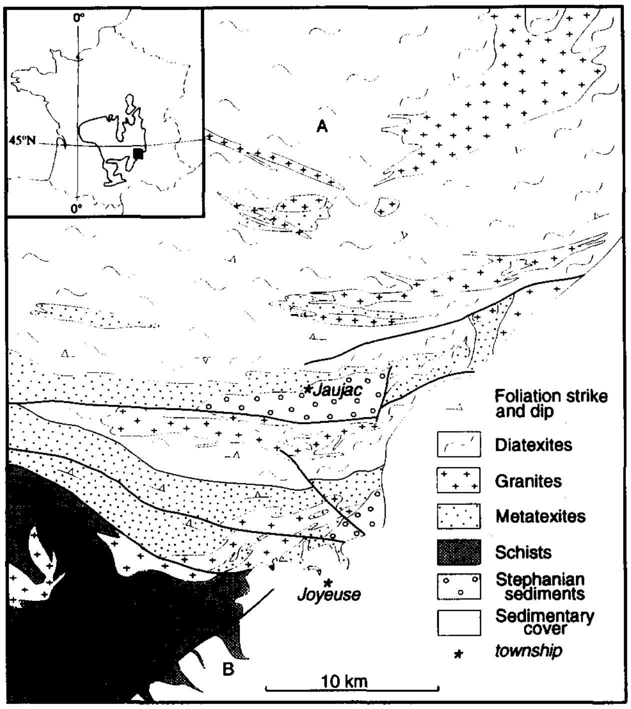

Fig. 4. Simplified geological map of the southern limb of the Velay dome. A–B = section of Fig. 5.

north and the roof to the south (Caen-Vachette *et al.* 1981).

Syn-migmatization way-up criteria

Syn-migmatization way-up criteria are best preserved in the transition zone. Representative cauliflower structures, asymmetric vein clusters and branching fractures are shown in Figs. 2 and 3. More than 50 have been recorded in the study area. They all reliably and consistently indicate a top-to-the-south on subvertical to N-dipping foliation planes. Assuming they are gravity driven features formed while the foliation was close to horizontal, we conclude that the main foliation has been tilted to vertical and was locally overturned. Close to the dome domain, S-facing second order chevron folds also indicate southward movement with overturning of way-up criteria on steeply dipping long limbs and less steeply or shallowly dipping short limbs. This is consistent with (1) way-up sedimentary criteria seen in the Cévennes schists to the south and (2) the roof of the Rocles pluton that is facing south. Therefore, the southern limb of the Velay dome appears to be an overturned sequence of low melt-content migmatites surrounding a diapiric dome of diatexites and granite.

DISCUSSION

The geometrical relationships between mesosome and increasing amount of leucosome can be interpreted as a two-step process. First, the interstitial melt percolated through the solid framework at the grain-scale in a connected network to form leucosome lenses within, and contained by, continuous mesosomes. Second, coalescence of leucosome bodies occurred parallel to the mesosome layering that geometrically controlled melt mobility, preventing migration by diapirism from macroscopic to regional scales as long as the mesosome framework was not broken by deformation processes such as boudinage.

We have documented changes in deformational response from essentially plastic metatexites to complexly deformed diatexites in which melt-flow dominated. The change in deformation response may be explained by a transition from regional to body forces controlling strain features in the migmatitic levels of the crust. Break-up of the solid framework via *in situ* melting, infiltration and mechanical penetration of mesosomes by leucosomes has permitted regional doming of rocks with viscous behaviour into rocks with plastic behaviour. A high pore fluid pressure in leucosome and subsequent hydraulic fracturing may explain how melt-dominated rocks penetrated plastic rocks with several order of magnitude lower viscosity, a melt-enhanced process that has yet to be understood in the natural case. In principle, fluid motion will be most effective along the direction parallel to the axis of least compressive stress and towards regions where the melt is already concentrated (e.g. Stevenson 1989, Cooper 1990), which is not necessarily vertical and upward. Our field observation so far in Canada, the Alps, Bulgaria, Greece and other places has convinced us that although we do not know the actual bulk direction of melt migration, some upwards migration apparently controlled by the gradient of litho-

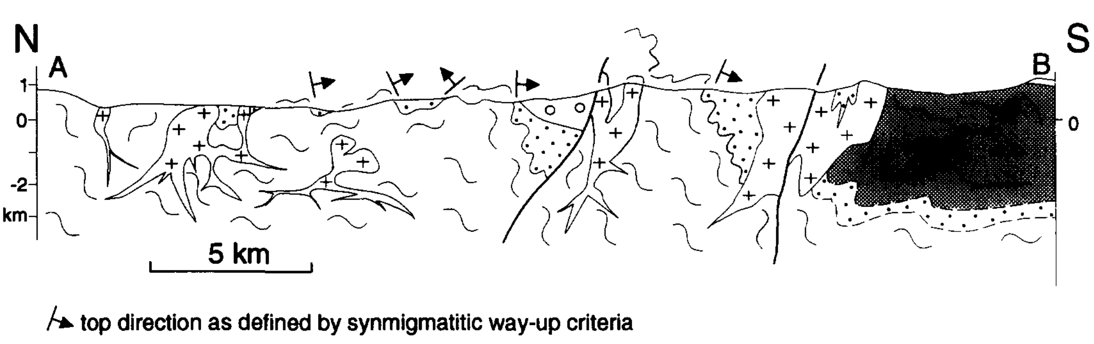

Fig. 5. Cross-section indicated in Fig. 6 with syn-migmatitic way-up criteria shown.

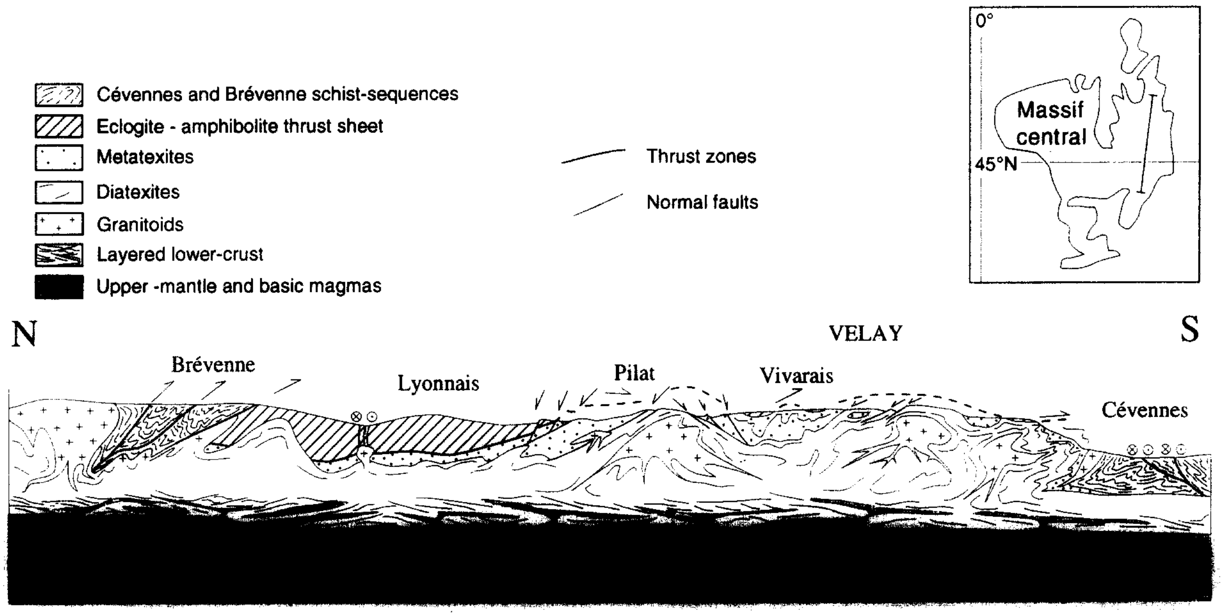

Fig. 6. Synthetic section across the entire Velay dome. Thickness of the layered lower-crust and depth of the Moho inferred from seismic data.

static pressure is recorded and forms way-up criteria as those used in this study.

Post- to syn-migmatitic layering with S-facing way-up criteria, asymmetric syn-migmatitic folds and magmatic layering in the Rocles granite all indicate a S-directed overturning of the southern limb of the Velay dome, whereas the northern boundary developed as a N-dipping normal ductile fault (Mattauer *et al.* 1988). Syn-migmatitic criteria lead us to consider a pre-doming section of the crust in which a flat-lying, partially molten level with migmatite and granite occurred below a ductile middle crust and a brittle upper crust. The very high thermal gradients implied by the condensed sequence of low- to high-grade metapelitic rocks support the interpretation of an upwelled migmatitic–granitic dome rimmed by ductile metatexites and gneisses. The west and east margins are nearly vertical (Dupraz & Didier 1988), giving the Velay dome an asymmetric N–S shape (Fig. 6) that can be explained by the following two end-member models. (1) The asymmetric development of a gravitational instability may have been caused by either lateral density and viscosity gradients or an inclined interface between the source layer and a cover level that obstructed diapiric upwelling (Talbot 1977). This cover level could be the eclogite- and amphibolite-bearing thrust sheet of the French Massif Central. (2) Doming of the ductile middle crust that has taken place into a pinch zone opened by post-orogenic, regional extension of the brittle upper crust (Wernicke & Axen 1988, Van Den Driessche & Brun 1992), as it is suggested in the field area by the Stephanian basin reported in Fig. 6. We attribute S-facing doming to these distinct yet combined phenomena. The late-orogenic extension and associated normal faulting has boudinaged the upper-crust, hence nucleating mechanical instabilities in the ductile lower-crust and the ensuing development of the large domal structure. Due to thermal relaxation and subsequent heating (England & Thompson 1984, 1986), increasing amounts of partial melt products lead to the upwelling of successive magma generations. As a result, associated diatexites developed a syn-anatectic strain field around the Velay dome. The history is consistent with S-facing oblique diapirism and tectonic denudation of the back, northern margin of the Velay.

CONCLUSIONS

(1) The anatexis of metamorphic rocks, inducing the growth of a magmatic phase partly moved by gravity is a process of major rheological and tectonic importance because the mechanical properties of rocks change from elastic–plastic to viscous.

(2) Features of upward melt migration are consistent with sedimentary geopetal structures and top-side indicated by granitic compositional layering. They provide syn-migmatization way-up criteria that may be used as a regionally reliable structural tool in migmatite terrains.

(3) Continuity of the solid framework of migmatites helps to separate regions that record plastic (stable) deformations from regions that record viscous (unstable) deformations. Accordingly, complex structures in migmatites can be related to the variety of flow behaviour of partially molten rocks. Metatexites have a dominantly plastic behaviour because the solid skeleton largely takes up the deformation. Diatexites display complex structures appropriate to melt-dominated behaviour and may develop gravitational instabilities.

(4) Our case study reveals overturning of the southern limb of the Velay dome.

(5) We argue that the place where melting first occurs, grows and develops mechanical instabilities is an important factor in localizing regional-scale migmatitic terrains and associated structures. Consequently, the regional distribution of granitoid intrusions of anatectic origin in an orogenic belt may be more strongly con-

trolled by compositional variations in the protoliths (because the melting temperature depends on the bulk chemical composition of the rock) than by changes in the pressure–temperature paths along the orogenic belt.

Acknowledgements—The Centre National de la Recherche Scientifique and the Bureau de Recherche Géologiques et Minières have financed this work. C. Teyssier and B. Tikof are thanked for their comments on, and improvement of, a first text. The manuscript was reviewed by Paul Dirks and Ron Vernon, and we thank them for their excellent job.

REFERENCES

Arzi, A. A. 1978. Critical phenomena in the rheology of partially melted rocks. *Tectonophysics* **44**, 173–184.

Ashworth, J. R. 1976. Petrogenesis of migmatites in the Huntly–Portsoy area, north-east Scotland. *Mineralog. Mag.* **40**, 661–682.

Bottinga, Y. & Weill, D. F. 1972. The viscosity of magmatic silicate liquids: a model for calculation. *Am. J. Sci.* **272**, 438–475.

Burg, J.-P. 1991. Syn-migmatization way-up criteria. *J. Struct. Geol.* **13**, 617–623.

Burg, J.-P. & Matte, P. 1978. A cross section through the French Massif Central and the scope of its Variscan evolution. *Z. dt. geol. Ges.* **129**, 429–440.

Caen-Vachette, M., Couturié, J.-P. & Fernandez, A. 1981. Age westphalien du granite de Rocles (Cévennes, Massif Central français). *C.r. Acad. Sci., Paris* **293**, 957–960.

Caen-Vachette, M., Couturié, J.-P. & Didier, J. 1982. Ages radiométriques des granites anatectiques et tardimigmatitiques du Velay (Massif Central français). *C.r. Acad. Sci. Paris* **294**, 135–138.

Clemens, J. D. & Mawer, C. K. 1992. Granitic magma transport by fracture propagation. *Tectonophysics* **204**, 339–360.

Cooper, R. F., Kohlstedt, D. L. & Chyung, K. 1989. Solution-precipitation enhanced creep in solid–liquid aggregates which display a non-zero dihedral angle. *Acta metall.* **37**, 1759–1771.

Cooper, R. F. 1990. Differential stress-induced melt migration: An experimental approach. *J. geophys. Res.* **95**, 6979–6992.

de Bremond d'Ars, J. & Davy, P. 1991. Gravity instabilities in magma chambers: rheological modelling. *Earth Planet Sci. Lett.* **105**, 319–329.

Dell'Angelo, L. N. & Tullis, J. 1988. Experimental deformation of partially melted granitic aggregates. *J. metamorph. Geol.* **6**, 495–515.

Dupraz, J. & Didier, J. 1988. Le complexe anatectique du Velay (Massif central français): structure d'ensemble et évolution géologique. *Bull. BRGM, Série "Géologie de la France"* **4**, 73–88.

England, P. & Thompson, A. B. 1984. Pressure–temperature–time paths of regional metamorphism. Part 1. Heat transfer during the evolution of regions of thickened continental crust. *J. Petrol.* **25**, 894–928.

England, P. & Thompson, A. B. 1986. Some thermal and tectonic models for crustal melting in continental collision zone. In: *Collision Tectonics* (edited by Coward, M. P. & Ries, A. C.). *Spec. Publs geol. Soc. Lond.* **19**, 83–94.

Fyfe, W. S. 1973. The generation of batholiths. *Tectonophysics* **17**, 273–283.

Henkes, L. & Johannes, W. 1981. The petrology of a migmatite. *Neues Jb. Miner. Abh.* **141**, 113–133.

Holland, J. G. & Lambert, R. St. J. 1969. Structural regimes and metamorphic facies. *Tectonophysics* **7**, 197–219.

Hopgood, A. M. 1980. Polyphase fold analysis of gneisses and migmatites. *Trans. R. Soc. Edin. Earth Sci.* **71**, 55–68.

Hopgood, A. M. 1984. Structural evolution of the Svecokarelian migmatites, southern Finland: a study of Proterozoic crustal development. *Trans. R. Soc. Edin. Earth Sci.* **74**, 229–264.

Jaeger, J. C. & Cook, N. G. W. 1979. *Fundamentals of Rock Mechanics*. Halsted Press, New York.

Johannes, W. & Gupta, L. N. 1982. Origin and evolution of a migmatite. *Contr. Miner. Petrol.* **79**, 114–123.

Jurewicz, S. R. & Watson, E. B. 1984. Distribution of partial melt in a felsic system: the importance of surface energy. *Contr. Miner. Petrol.* **85**, 125–129.

Jurewicz, S. R. & Watson, E. B. 1985. The distribution of partial melt in a granitic system: the application of liquid phase sintering theory. *Geochim. cosmochim. Acta* **49**, 1109–1121.

Kushiro, I. 1980. Viscosity, density, and structure of silicate melts at high pressures, and their petrological applications. In: *Physics of Magmatic Processes* (edited by Hardgraves, R. B.). Princeton University Press, Princeton, New Jersey, 93–120.

Lagarde, J. L., Dallain, C. & Capdevilla, R. 1990. Contexte tectonique de la fusion crustale post-collision dans la chaîne hercynienne: l'exemple du complexe anatectique du Velay (Massif central français). *C.r. Acad. Sci., Paris* **311**, 477–484.

Laumonier, B., Marignac, C., Cheilletz, A. & Macaudière, J. 1991. Relations entre tectoniques superposées, migmatitisations et mise en place des granites sur l'exemple de la bordure sud du dôme du Velay (région de Laviolle, Ardèche, France). *C.r. Acad. Sci., Paris* **313**, 937–944.

Macaudière, J., Marignac, C. & Weisbrod, A. 1987. Grandes nappes synschisteuses collisionnelles dans la catazone hercynienne des Cévennes médianes (Massif Central France). *C.r. Acad. Sci., Paris* **304**, 1195–1199.

Mattauer, M., Brunel, M. & Matte, P. 1988. Failles normales ductiles et grands chevauchements. Une nouvelle analogie dans l'Himalaya et la chaîne hercynienne du Massif Central français. *C.r. Acad. Sci., Paris* **306**, 671–676.

McKenzie, D. P. 1984. The generation and compaction of partially molten rock. *J. Petrol.* **25**, 713–765.

McKenzie, D. P. 1987. The compaction of igneous and sedimentary rocks. *J. geol. Soc. Lond.* **144**, 299–307.

McLellan, E. L. 1984. Deformational behaviour of migmatites and problems of structural analysis in migmatite terrains. *Geol. Mag.* **121**, 339–345.

Mehnert, K. R. 1968. *Migmatites and the Origin of Granitic Rocks*. Elsevier, Amsterdam.

Montel, J. M., Marignac, C., Barbey, P. & Pichavant, M. 1992. Thermobarometry and granite genesis: the Hercynian low-P high-T Velay anatectic dome (French Massif Central). *J. metamorph. Geol.* **10**, 1–15.

Mougeot, R. 1991. Géochronologie U-Pb sur minéraux accessoires. Applications à la bordure Sud du Velay (Massif Central Français). Unpublished DEA thesis, Montpellier.

Olsen, S. N. & Grant, J. A. 1991. Isocon analysis of migmatization in the Front Range, Colorado, USA. *J. metamorph. Geol.* **9**, 151–164.

Paquet, J., François, P. & Nedelec, A. 1981. Effect of partial melting on rock deformation: experimental and natural evidences on rocks of granitic composition. *Tectonophysics* **78**, 545–565.

Ramberg, H. 1968. Instability of layered systems in a field of gravity. *Phys. Earth & Planet. Interiors* **1**, 427–474.

Robin, P.-Y. F. 1979. Theory of metamorphic segregation and related processes. *Geochim. cosmochim. Acta* **43**, 1587–1600.

Shaw, H. R. 1980. Fracture mechanisms of magma transport from the mantle to the surface. In: *Physics of Magmatic Processes* (edited by Hardgraves, R. B.). Princeton University Press, Princeton, New Jersey, 201–264.

Stevenson, D. J. 1989. Spontaneous small-scale melt segregation in partial melts undergoing deformation. *Geophys. Res. Lett.* **16**, 1067–1070.

Talbot, C. J. 1977. Inclined and asymmetric upward-moving gravity structures. *Tectonophysics* **42**, 159–181.

Van Den Driessche, J. & Brun, J.-P. 1992. Tectonic evolution of the Montagne Noire (French Massif Central): a model of extensional gneiss dome. *Geodinamica Acta* **5**, 85–99.

Van der Molen, I. 1985a. Interlayer material transport during layer-normal shortening. Part 1. The model. *Tectonophysics* **115**, 275–295.

Van der Molen, I. 1985b. Interlayer material transport during layer-normal shortening. Part II. Boudinage, pinch-and-swell and migmatite at Søndre Strømfjord Airport, West Greenland. *Tectonophysics* **115**, 297–313.

Van der Molen, I. & Paterson, M. S. 1979. Experimental deformation of partially-melted granite. *Contr. Miner. Petrol.* **70**, 299–318.

Weisbrod, A. 1970. Pétrologie du socle métamorphique des Cévennes médianes (Massif Central Français). Reconstitution sédimentologique et approche thermodynamique du métamorphisme. Thèse Doctorat ès Sciences, Nancy (3 volumes).

Weisbrod, A., Pichavant, M., Marignac, C., Macaudière, J. & Leroy, J. 1980. Relations structurales et chronologiques entre le magmatisme basique, les granitisations et l'évolution tectonométamorphique tardi-hercynienne dans les Cévennes Médianes, Massif Central Français. *C.r. Acad. Sci., Paris* **291D**, 665–668.

Wernicke, B. & Axen, G. J. 1988. On the role of isostasy in the evolution of normal fault systems. *Geology* **16**, 848–851.

Wickham, S. M. 1987. The segregation and emplacement of granitic magmas. *J. geol. Soc. Lond.* **144**, 281–297.