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Contrasted Granite Emplacement Modes Within an Oblique Crustal Section: The Closepet Granite, South India

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Abstract. The Closepet Granite, in South India, is a large, syntectonic Archaean granitic complex. Differential erosion has exposed it from the lower (25 km) to upper crust (5 km). Four main parts are recognized from bottom to top: (i) A root zone, where magmas formed, collected and rose within active shear zones, leaving schlieren behind. The surrounding crust was highly ductile, leading to diffuse deformation. (ii) A transfer zone, where the magma was progressively enriched in K-feldspar phenocrysts during its ascent. In this part, the granite rose as a mush moving as a whole within a less ductile crust. Slow cooling was responsible for a long magma residence time under conditions favoring to fabric enhancement and strain partitioning, leading to horizontal and vertical melt migration. (iii) A "gap" (dyke complex that acted as a filter zone), were the ascent of the mush was stopped, probably due to high phenocryst load and high viscosity contrast with the wall rocks. Only crystal-poor melts could continue their ascent through the dykes. (iv) A zone of shallow intrusions, where the liquids extracted from the mush filled small, elliptical plutons, cooling quickly and developing only very weak fabrics.

1 Introduction

Ascent and emplacement of granitic magmas have been the subjects of lively debates. A large part of the discussion focused on the opposition between diapirism and dyking (Clemens, 1998, and references therein). On the other hand, recent work (Hutton et al. 1990, Brown and Rushmer 1997, Collins and Sawyer 1996, Brown and Solar 1999, etc.) emphasized the role played by deformation in the extraction and/or ascent of granitic melts out of their partially molten sources, as well as the key importance of major shear zones in focusing granitic magma ascent. However, it is generally impossible to link lower- and deeper-crustal processes, and correlate emplacement modes at different structural levels.

Due to differential erosion after its emplacement, the late-Archaean Closepet granite, in South India, can be studied at all structural levels, from granulite-facies lower to greenschist-facies upper crust. This allows us to study and compare transport and emplacement modes as a function of depth. The aim of this paper is to link field relationships and strain patterns in and around the Closepet granite, at different structural levels, with the evolution of selected physical parameters as functions of depth within the crust.

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2 Geological setting

The Archaean terrain of South India is known as the Dharwar craton. It crops out over 400,000 km^2 and presents the three typical Archaean lithological units (sea review in Chadwick et al., 2000): a basement of TTG orthogneisses (the "Peninsular gneisses"), emplaced from 3.3 to 2.7 Ga; volcano-sedimentary greenstone belts, the age of which range between 3.5 and 2.6 Ga; and late-Archaean granitic bodies cutting across all other lithologies. Several of these intrusions have been dated, with ages clustering in the 2.6–2.5 Ga interval. The Closepet granite, dated (Friend and Nutman, 1991) at 2.52 $\pm$0.01 Ga, is the largest (400 $\times$ 30km) of these granitic complexes. All granitic intrusion form N-S elongated bodies, parallel to the main structural trend of the craton.

During the late Archaean, the Dharwar craton underwent HT-LP metamorphism accompanied by both dome-and-basin developement, and transcurrent deformation along a network of ductile shear zones (Chardon et al., 1996). It has long been postulated (Drury and Holt 1980, Drury et al. 1984) that the elongated shape of the granitic intrusions was due to syn-tectonic emplacement in relation with the activity of the shear zones.

This idea has actually been demonstrated for the Closepet granite (Moyen, 2000), using mapping of the strain pattern in and around the granitic complex (Fig. 1).

The Dharwar craton preserves lower-crustal structural levels in the South (20–25 km paleodepth), and upper-crustal levels (5–10 km) in the North (e.g. Rollinson et al., 1981). This allows us to reconstruct a cross-section of the whole crust. As the tilt angle remains very low (less than 5°), the measured dip and strike of structural elements are only minimally modified.

3 The Closepet granite: main subdivisions and structural features

Based on detailed field work, coupled with anisotropy of magnetic susceptibility studies, and remote sensing (Moyen, 2000), it has been possible to describe the Closepet granite and its syn-emplacement deformation. Several distinct zones have been recognized, each one being characterized by specific structures and strain patterns (Fig. 1).

3.1 The main mass

The main mass is 250 km long, and 30 km wide. It cuts across granulite- and amphibolite-facies basement rocks. It is further subdivided in two parts.

3.1.1 The root zone

The root zone is located South of 13°N, which roughly corresponds to granulite-facies depths. It consits in a network of small dykes, plugs and sheets of granitoids injected in ductile shear zones and along foliation planes (Collins and Sawyer, 1996), into migmatized Peninsular Gneisses. A wide range of magma compositions are found there, from monzonites (SiO_2= 51 %) to granites (SiO_2= 75 %). It has been demonstrated (Jayananda et al. 1995; Moyen et al. 1997; Moyen 2000) that all magmatic facies result from magma mixing between two end-members, a mafic, mantle-derived one, and a felsic one, generated by anatexis of the surrounding Peninsular Gneisses.

3.1.2 The transfer zone

Further North, the transfer zone nearly coincides with the depths of amphibolite-facies. There, a single, continuous mass (150 × 30 km) of porphyritic monzogranite (SiO_2= 65–70 %) intrudes the gneissic basement, that becomes less and less migmatized towards the North. The monzogranite (Moyen, 2000) results from magma mixing recognized in the root zone. In some narrow areas, corresponding to high strain zones on its margins, the Closepet granite is rich in enclaves of cumulate, mafic magmatic facies similar to those observed in the root zone, and high-temperature metapelites All

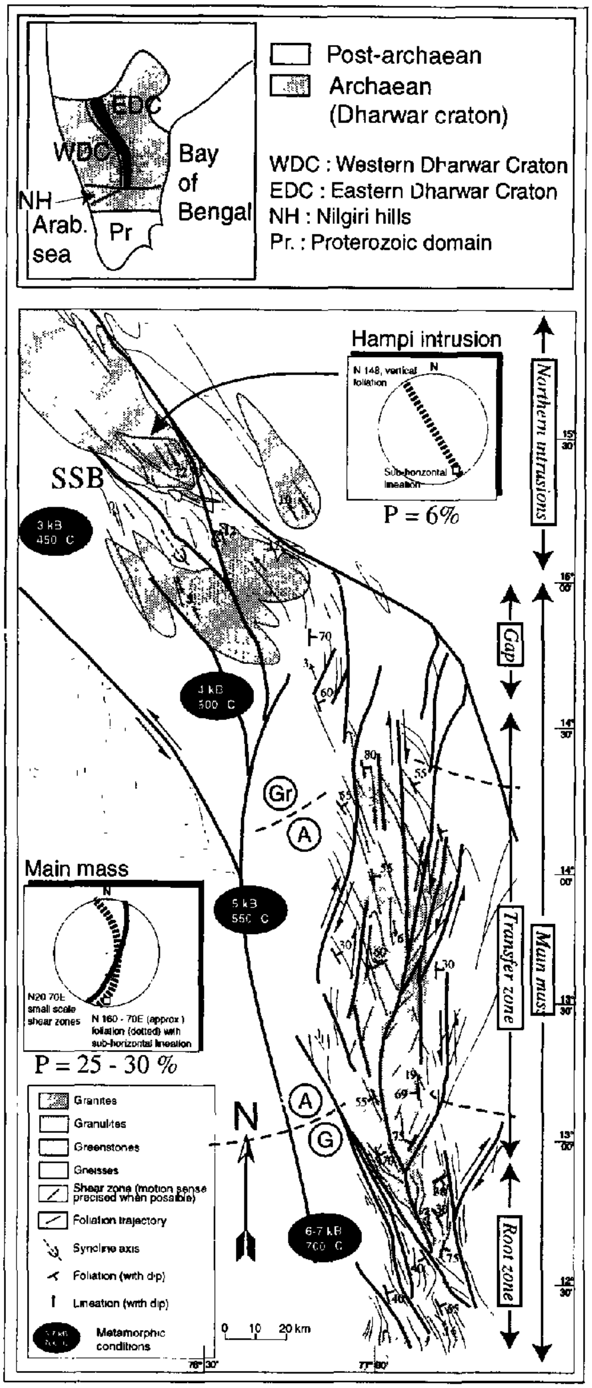

Fig. 1. Synthetic geological map summarizing the main field subdivisions in the Closepet granite, as well as the strain pattern deduced from field work, remote sensing and AMS studies.
Top: localisation map, showing the position of the Closepet granite (black) in the Dharwar craton of South India (grey).
Main map: The Closepet granite (grey). Foliation trajectories are drawn, as well as major shear zones. When individual data were avaible, they were also reported on the map (with dip). They were provided both from our field and AMS studies, except in and around Sandur Schist Belt (SSB) (data from Chadwick et al. (1996)).
The two stereograms in insets display the average foliation and lineation in the Hampi intrusion (upper right, AMS data) and in the main mass (lower left, field + AMS data (Moyen, 2000)). P (average degree of anisotropy) is indicated. Metamorphic conditions are from a compilation of data from the litterature (Moyen, 2000)); dotted line are the metamorphic isogrades (G: granulite-facies: A: amphibolite-facies; Gr: Greenschist facies).

these enclaves were carried upwards from deeper crustal levels. The same areas also commonly show K-feldspar phenocrysts accumulations.

3.1.3 Deformation

Deformation in the main mass was active during emplacement and cooling of the magmas, as evidenced by meso- and microstructures (Moyen, 2000): magmatic-state foliation with re-oriented K-feldspar phenocrysts in shear bands; shear zones invaded by aplites; ductile to solid-state shear zones. An anastomosing network of high-strain, steep to vertical, strike-slip shear zones, with a general N-S trend, is observed all along the main mass. These zones are narrow, and mainly confined to the margins of the Closepet granite in the transfer zone; they are wider and more widespread in the root zone, probably as a result of a more ductile environment. Between the shear zones are large domains of relatively low-strain that are characterized by a well-developed foliation with an average dip of 70°E and an horizontal lineation. Occasional small scale vertical shear zones cut across the foliation; the overall disposition mimics the large scale strain pattern. The fabric is generally planar (Flinn shape parameter < 1).

3.2 The northern intrusions

In a region of greenschist-facies grade, corresponding to shallow depths, the Closepet granite appears as a suite of small (commonly 10–30 km long), elliptical plutons crosscutting an unmigmatized gneissic basement with sharp contacts. Individual intrusions display mutually cross-cutting relationships. In this area, only homogeneous, enclave-free granites (SiO_2= 70–75 %) are found, at the exclusion of less differentiated facies. Porphyritic facies are rare, in marked contrast to the lower levels, where this facies is ubiquitous.

3.3 The gap

A gap separates the Northern intrusion zone from the main mass (fig. 1). It consists of a network of granitic dykes cutting the Peninsular Gneisses, that physically connect both parts of the Closepet granite.

4 Emplacement styles at different structural level

The emplacement styles can be briefly summarized (Fig. 2).

4.1 The root zone

Liquids formed by both in-situ melting (felsic), or intruded from below (mafic), are collected in active shear zones (Brown and Rushmer 1997, Collins and Sawyer 1996). They are heavily loaded with solid materials: restitic schlieren, cumulate enclaves and basement xenoliths. The variety of compositions and solid loads lead to a variety of solid-liquid transitions and solidification temperatures (Fernandez and Gasquet, 1994). Therefore, the deformation is heterogeneous, leading to the formation of an anostomosing network of relatively wide (1 – 5 km) shear zones.

4.2 The transfer zone

When rising up to the transfer zone, the deformation is localized in narrower (0.1 – 1 km) shear zones in a well-foliated and homogeneous granite. At the same time, K-feldspar phenocrysts are progressively formed from the liquid, leading to the formation of a two phase mush. The mush can move as a whole; but Vigneresse and Tikoff (1999) also demonstrated that, in a mush undergoing transpressional deformation, melt can move through the crystal network both horizontally and vertically.

4.3 The gap

The ascent of the mush is stopped at a level corresponding to the gap. A this level, only crystal-poor liquids are able to rise through a network of dykes, leaving below most crystals, and enclaves of all kinds. Fast magma ascent through the gap resulted in dissolution of whatever crystals that may have been carried upwards (Holtz and Johannes, 1994), as evidenced by textural criteria (Moyen, 2000) such as partially dissolved K-feldspar phenocrysts.

4.4 The superficial intrusions

Finally, the liquids rising to the upper crust fill small, elliptical pockets. Shear zones may have accomodated space creation for the plutons are situated at some distance from them (Fig. 1), which is compatible with the conclusions drawn from analogical modelling by Benn et al. (1999). On the other hand, as pointed by Cruden (2000, and this volume), the extraction of large amounts of magmas from the lower crust can create vacant space in the upper levels, by downward displacement of the crust below the growing intrusions.

5 Discussion

In order to better explain the different modes of emplacement, the evolution of two physical parameters within the Closepet granite has been studied (fig. 3): the first is the viscosity contrast between basement and granites; the second, called "MT# " by Olsen and Baumgartner (2000), is a dimensionless number that quantifies the relative importance of flow percolation vs. mass transfer, in the case of a mixture of solid and liquid phases. MT# is calculated as a ratio of Stokes law sinking velocity of

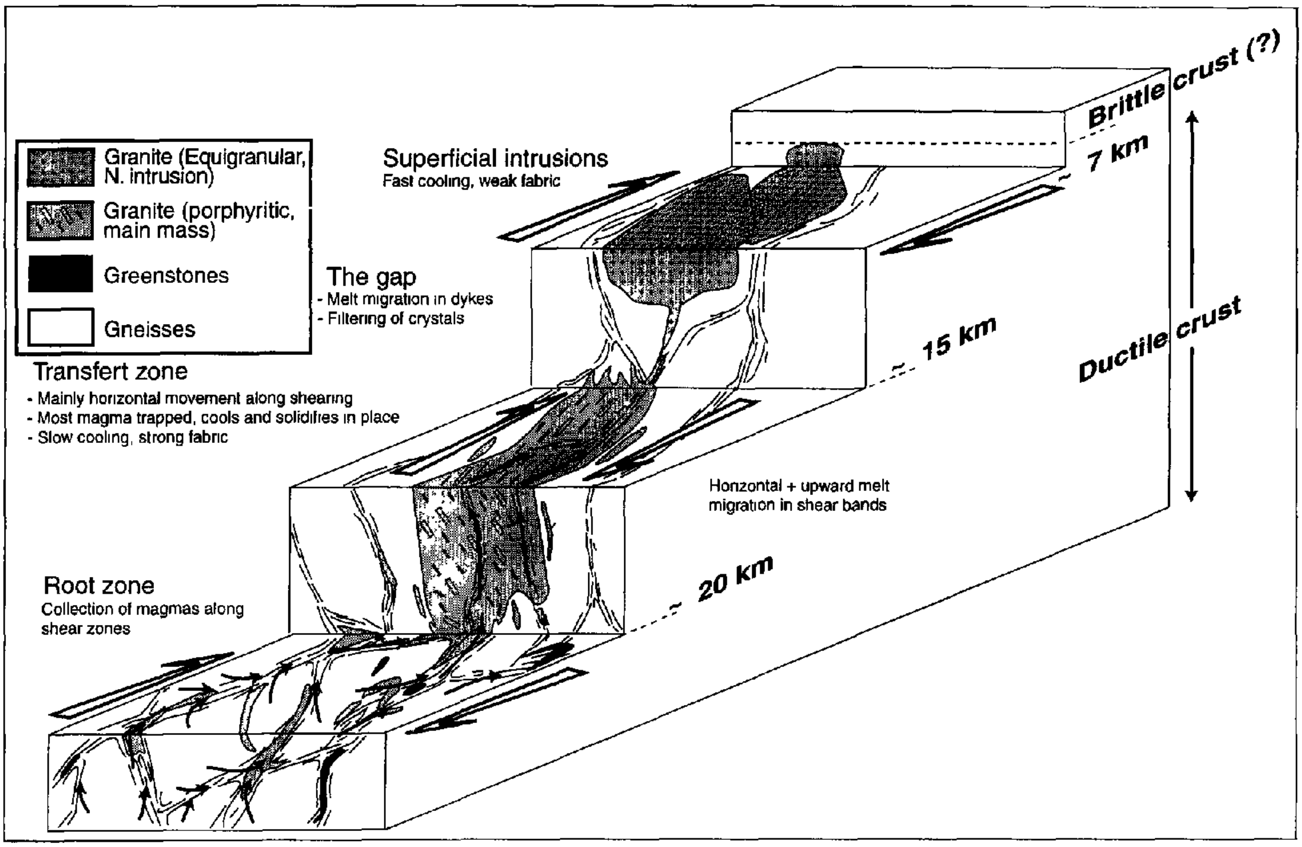

Fig. 2. Sketch drawing of the emplacement mode and strain partitioning in the Closepet granite at contrasted structural levels (Moyen, 2000). Comments in the text and on the figure. Black, thin arrows: melt movement; white, large arrows: kinematics of deformation.

solids in a magmatic liquid, versus dyke-like magma ascent (e.g. Clemens, 1998); it is a good tool to study the ascent mode of a two phase mush. More specifically the Stokes sinking velocity is

$$V_s = \frac{\Delta\rho a^2}{\mu},$$

with $\Delta\rho$ the density contrast between the sinking body and the surrounding liquid, a the size of the sinking body, μ the viscosity of the liquid, and C a constant linked to the aspect ratio of the sinking body. The mass transfer velocity is

$$V_m = -\frac{KD}{\mu_1}\Delta\rho_1 g + (1-f)V_s,$$

where D is the width of the mobile zone, μ_1 the overall viscosity of the moving material, $\Delta\rho_1$, the density contrast with the wall rock, f the proportion of solid, and K a geometric constant (Olsen and Baumgartner, 2000, and personal communication).

The emplacement style of the granite at a given depth is controlled by the physical properties of the granitic magma at the time it first arrived at a particular level; these properties controlled the major structures, whereas latter deformation during cooling controlled outcrop-scale structures. This is evidenced by the fact that the tectonic regime was the same, whatever the structural level, leading to similar structures at the outcrop scale at all depths; nevertheless map-scale structures are contrasted and strongly depend on the paleodepth. This implies that the physical parameters (functions of depth) were the key elements that controlled large scale structures.

Fig. 3 plots two physical parameters as they were at the time of emplacement, at each depth; emplacement is diachronous from bottom to top, since the lower parts of the crust evolved earlier than the upper parts. To study this evolution, we made the following assumptions. In the root zone, the granitic liquids progressively leave behind their solid load (schlieren) during ascent. In the transfer zone, K-feldspar megacrysts are progressively formed as the magma rises, up to an amount of about 30 %, roughly corresponding to the present amount of phenocrysts (which provides an upper bound for the solid load during the emplacement history). Obviously, after emplacement the granite will totally crystallize; this will happen, however, well after the granite was emplaced and will not alter the granite–basement relationships.

5.1 Viscosity contrast

Estimates of the strength of the crust under simple shear, for a strain rate of 10^{-14}, were calculated using the

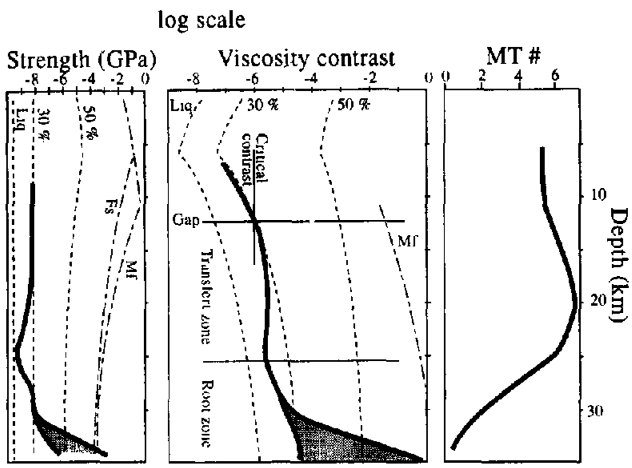

Fig. 3. Evolution of physical parameters in and around the Closepet granite, at the time of its arrival at a given depth. Left: Strength under strike-slip deformation; Middle: viscosity contrast between granitic magmas and gneissic basement; Right: MT# (Olsen and Baumgartner, 2000), which is an estimation of the relative importance of mass transfer vs. liquid percolation in a magmatic suspension.
Left and middle parts: doted lines (Liq., 30% and 50%): granitic liquid with the specified solid load. Fs. and Mf.: felsic and mafic crust. Thick line: Closepet granite magmas. The shaded field in the bottom corresponds to different situations, calculated by variation of the solid load of the magmas in deepest levels.
Right part: Thick line: Closepet magmas.

equation of Handy (1994). Viscosity of the granite, for a given depth (and hence a given solid load) was estimated on the basis of the data of Scaillet et al. (1999) for the viscosity of the crystal-free liquid; and the work of Lejeune and Richet (1995) to describe viscosity of a two phase (liquid + solid) material.

Although our calculation depend on the strain rate or tectonic regime assumed, the viscosity contrast spans 4 to 5 orders of magnitude, far more than any variation induced by those uncertainities. This allows us to be confident, at least about the qualitative evolution observed on fig. 3.

In the root zone, the viscosity contrast between the magma, at the time it reaches a given level, and the host crust remains very low. This is due both to the low strength of the gneissic basement, and to the high schlieren load of the granite. For high solid load of the magmas, it is possible to have virtually no viscosity contrast between gneisses, granite and mafic greenstone belts, leading to the observed patterns of elongated patches of rocks of all lithologies in high strain zones (fig. 2). A similar situation was described by Martelat (1998) in the granulite facies lower crust of Madagascar.

In the transfer zone, the viscosity contrast at the time of emplacement increases up to 10^{-6}, due to the disappearance of schlieren, and the increase in strength of the crust. It is interesting to note that during ascent through the crust, the magma progressively crystallizes, thus increasing its phenocryst load, and the correlated viscosity of the magma. This mechanism progressively compensates the higher strength of the crust at shallower levels. Both factors together result in the viscosity contrast beeing nearly constant through the transfer zone — a possible explanation for the very homogeneous structures all along the 150 km-long transfer zone.

Finally, near the brittle-ductile transition, the viscosity contrast rapidly increases, and reaches a critical threshold, which appears to correspond to a main change in emplacement mode, represented by the gap.

5.2 Mass transfer of the mush vs. percolation in the crystal network

The MT# displays similar patterns to the viscosity contrast. In the root zone, it is low (close to 1), meaning that percolation is as effective a process as mass transfer. This corresponds to percolation of granitic liquids between solid schlieren. In other words, schlieren remain at lower levels, while the liquid rises in the crust. When reaching the transfer zone, separation of schlieren causes a viscosity drop in the granitic magma, resulting in a higher V_m, with a V_s only slightly changing. This causes the MT# to increase dramatically (up to $10^7 - 10^8$), allowing mass transfer of the whole granitic mush (liquid + crystals together) to take over percolation between the solids. Finally at the gap, the MT# decreases, but still remains at $10^4 - 10^5$. This corresponds to a level where liquid percolation becomes an important process, that can play a quantitatively significative role. The crystals are separated because of the increasing viscosity contrast and are essentialy immobile, while the liquids, on the other hand, continue ascent. This can result in a network of more or less immobile K-feldspar, with liquid percolating in between.

6 Conclusion and implications

Each zone was recognized and defined on the field, and corresponds to a specific physical situation at the time the granite first arrived at each level. The root zone is a place where granitic liquids percolate between solid elements; this is also the place where a low viscosity contrast allows for poorly contrasted deformation modes between magmas and surrounding crust. As the emplaced magma cools, this situation is complicated by the contrasted solidification temperatures of the different magmas (monzonite to granite), leading to complicated deformation patterns (Fernandez and Gasquet, 1994). The transfer zone is an area of mass transfer of granitic mush in a considerably more viscous crust. Deformation is localized and confined to the borders of the intrusion. During further evolution, the slow cooling of the mush allows for a long residence time at a partially crystalized state under ongoing strike-slip deformation, allowing for

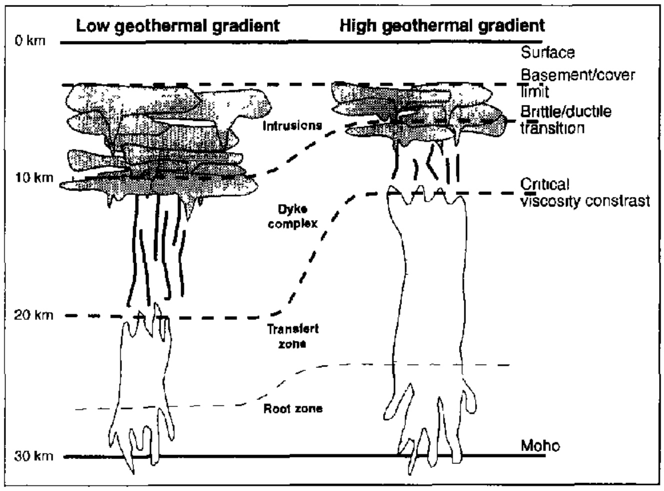

Fig. 4. Two possible end-members situations. Left: with a low geothermal gradient, the critical viscosity will be reached deep in the crust, hence producing a short transfer zone and a long dyke complex (e.g. the Flamanville granite (Brun et al., 1990)). On the other hand, the intrusion zone will be relatively thick. Right: A high geothermal gradient induces the reverse situation (e.g. the Closepet granite)

the development of a pronounced fabric (Ildefonse et al., 1997), that is related to regional deformation, rather than magma flow. Finally, when the phenocryst load becomes important enough, and when the crust viscosity is sufficiently high, ascent mode dramatically changes. Only percolation through the phenocrysts or the crust is possible, thus leading to the separation of a solid phase, that remains at deep structural levels, and a liquid phase, that rises into the upper crust up to a discontinuity that can stop ascent and form upper-level intrusions. It is worth noting that this level (the gap) does not necessary correspond to the brittle-ductile transition, but to a deeper critical level. The brittle-ductile transition itself, under such a high geothermal gradient, was probably located higher in the crust (≈ 2.5 Kb· fig. 3), which corresponds to the North of the Sandur Schist Belt —the place where most superficial intrusions are found. The filtered liquids rise and cool quickly in the upper crust, thus dissolving any crystals that may have been entrained (Holtz and Johannes, 1994); hence, they had only a very short time to develop their syn-tectonic fabric Consequently, they display isotropic textures.

It must be noted that the vertical disposition of the zones, as well as their relative importance, strongly depends on the geothermal gradient (fig 4) With a lower geothermal gradient, the critical viscosity contrast corresponding to the gap would be significantly deeper in the crust. This leads to a greater distance between the main mass and the intrusions, and hence to a longer dyke complex. Such a situation would closely correspond to what is described by Brun et al. (1990) at Flamanville (North-western France), where a deep-seated root zone is separated from upper level intrusions by a 5- to 10 km high dyke complex. The transfer zone would be considerably shorter.

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