PERGAMON

Journal of Structural Geology 21 (1999) 1125–1130

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

Should felsic magmas be considered as tectonic objects, just like faults or folds?

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Received 13 January 1998; accepted 23 April 1999

Abstract

Integrated studies that correlate gravity data with magmatic structures or geochemical analysis reveal that the organization of granitic plutons (shape and feeder) varies according to the tectonic regime (brittle or ductile) and type (extension, strike-slip or compression) under which magma was generated. Deformation clearly controls granite emplacement. It also has influence during the ascent, segregation of melt and indirectly during the phase of initial melting. Because of the contrast of viscosity between melt and its plastic matrix, strain partitioning develops during magma ascent that facilitates melt flow, which bears consequences for the chemical evolution of the magma. Fast rate of melt extraction out of the source may lead to chemical disequilibrium. At a larger scale, petrochemical zoning of plutons is described as a dynamic process that results from the competition between the rate of magma emplacement (the rate of the room provided by deformation) and the rate of magma delivery.

1. Introduction

Classically, (e.g. in the Webster sense), granite is defined as "a very hard natural igneous rock formation of visibly crystalline texture", referring to its mineralogical composition. The IUGS classification also refers to a plutonic rock with relative amounts of quartz, plagioclase and alkali feldspar. Accordingly, granites have been studied looking primarily at their mineralogical or chemical variations. Here, I suggest that granites are subject to deformation all along their history and should be described as other tectonic objects like faults or folds.

Granites are felsic rocks, made of quartz, feldspars and ferro-magnesian minerals, plus some accessory minerals. The relative content of calco-sodic or alkaline minerals and the saturation of aluminium yields a letter-based typology (I, S types) which soon revealed insufficient, leading to the addition of new types (A, C, M, H…) (Pitcher, 1982). A genesis history could then be traced according to a specific composition. Trace elements diagrams that correlate granite chemistry to a specific tectonic environment (Pearce et al., 1984) also reveal controversy since chemical anomalies due to magma mixing can obliterate the original tectonic signature. Hence mineralogy and geochemistry adequately identify granitic types and variations, but fail to explain their mode of generation.

Structural geologists attempted to distinguish between pre-, syn- or post-tectonic granites, but a debate soon occurred in which most granites were said to be syn-tectonic (Karlstrom, 1989). In fact, granites are found in all tectonic settings, despite a common assumption, formulated by many as a very simplistic equation

$$\text{felsic magma intrusion} = \text{extension}. \qquad (1)$$

The association of granitic intrusion to any period, or style, of deformation does not imply that granites result from deformation. Indeed, the succession of the various phases leading to granite generation are directly associated with deformation, whatever the type or regime of deformation.

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0191-8141/99/$ - see front matter
PII: S0191-8141(99)00102-9

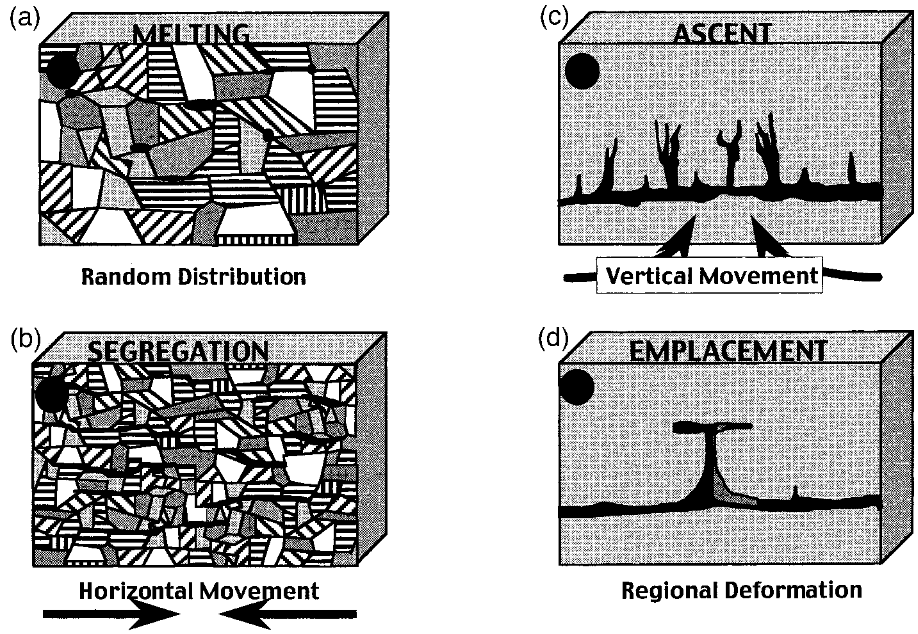

Fig. 1. Schematic representation of granite genesis. Scale varies from cartoon to cartoon. (a) Initial melting (in black) at grain boundaries. Scale is about 10 cm. (b) Magma segregation. Horizontal movement of melt is favored by strain partitioning at the melt/matrix interface. Scale is about 1 m. (c) Vertical ascent of magma possibly by diapirism in the lower crust, but tapped at the brittle/ductile transition. Scale is about 1 km. (d) Pluton emplacement into the upper brittle crust, with several batches of magma (in black and grey) leading to petrographic zonation. Scale is about 50 km.

The present paper came out from a reflection issued after many geophysical surveys conducted over granites, in conjunction with structural or geochemical studies (Bouchez et al., 1997). Granites are emplaced in any tectonic setting, but the influence of deformation is predominant along their whole history, from melting to emplacement. I propose that all granites are syn-tectonic, in that sense that *granites need deformation* to be generated. During each of the four stages of granite generation, i.e. melting, segregation, ascent and emplacement (Petford et al., 1997), deformation plays an active role and becomes more and more important. In that sense, felsic intrusions are (partly) the result of deformation. In what follows, the generic term of granites or granitic magmas represents all kind of intrusive rocks derived from the continental crust and having a felsic composition.

2. Influence of deformation on granite genesis

2.1. Incipient melting

To generate granite, a fertile source must be heated to reach fusion. Melting is primarily controlled by heat which proceeds either from diffusion of the heat generated by radioactive-elements (U, Th and K), or by advection through the heat generated in the asthenosphere, transported throughout the mantle and the crust. In common conditions, the temperature of the continental crust hardly reaches values high enough to fuse crustal minerals. Additional sources of heat are required which indirectly result from tectonics. Several mechanisms are commonly admitted that can warm the crust enough so that a temperature appropriate to intense melting (at least 850°C) is reached. One mechanism is crustal thickening, thus increasing the amount of crustal heat production which results first in a lower, but soon in a higher thermal gradient. Crustal thinning, because it condenses the isotherms resulting in a steeper gradient, can also achieve crustal melting, but the amount of melt remains low. The second type of mechanism to reach fusion is the intrusion into the crust of mantle derived material that disturbs the geotherm. As soon as the solidus temperature of the fertile source is achieved, melting starts at appropriate mineral grain boundaries (Fig. 1a). This process occurs at the mineral scale.

Deformation is therefore indirectly necessary to increase the heat generated in the crust, since it controls the rate of crustal thickening, thinning or the rate of mafic intrusions in the crust. Deformation here refers to the far-field stresses that cause crustal thickness variations or mantle upwelling.

2.2. Melt segregation

Before magma can ascend towards the upper crust, magma must segregate from melt pockets at grain boundaries toward veins. This process takes place between the Liquid Percolation Threshold and the Melt Escape Threshold (Vigneresse et al., 1996), that is at melt percentage ranging between 8 and 20–25%. At higher melting percentage, all the melt plus the matrix can move. Melt segregation and local melt movement are observed in migmatites. They occur on a scale ranging from decimetric to decametric. Deformation largely activates melt segregation. Since melt and its plastic matrix have a different viscosity, strain partitioning develops, which induces vorticity in the less viscous material (Vigneresse and Tikoff, 1999). Due to the strain partitioning, melt is easily segregated in local shear zones, as observed in migmatites. Melt segregates horizontally faster than it would do vertically, if the material was only under the influence of the gravity forces due to melt buoyancy (Fig. 1b).

During horizontal melt segregation, the rate of deformation, if one considers fracture, is usually fast during a brief time, but slow on a large scale. In comparison, the rate to which gravity forces develop, induces a constant, but slow buoyant movement of melt. In addition, the vertical movement of melt is controlled by the plastic deformation of the matrix which gives place to melt ascent. Thus the ratio of the horizontal to vertical movement of melt could, in a first order, be proportional to the ratio of the fracture propagation velocity to plastic deformation rate.

2.3. Magma ascent

Magma has now been collected in large enough amounts and viscosity/density instabilities developed, as well as the occurrence of magma veins expelled by shear forming feeders and dykes (Fig. 1c). The ascent may be diapiric in the lower ductile crust, though the matrix response should be fast enough to accommodate magma displacement. This process certainly applies for magmas that remain within the lower crust (Barnichon et al., 1999). It certainly cannot apply to intrusion into the upper brittle crust. The strength of the continental crust at the brittle/ductile transition is about 200–600 MPa, depending on whether normal or reverse faults are generated, and also on the bulk thermal regime of the crust. The stress level is one order of magnitude, if not two, larger than the buoyancy forces, which are of the order 4–6 MPa/km of the granitic magma column (Vigneresse, 1995a). Consequently, magma cannot intrude the brittle upper crust only by its internal forces. It requires additional forces to initiate fractures at the base of the brittle crust. If not, then magma could be trapped at this level, as observed through bright spots on seismic sections (Ross and Brown, 1999). This level apparently determines the place where the floors of granitic plutons change from a gently dipping slope to a tiny vertical feeder, at least as deduced from gravity data inversion.

A second consequence of deformation is that it locally controls the place where magma can intrude the upper crust. Those places are evidently locally extensional. Thus, Eq. (1) remains valid, but only on a local scale. The reason for that is the lower strength required to induce normal faulting compared to other types of faults. Whatever the regime of deformation, it is always easier to open local fractures in mode I, in locally extensional areas. These local zones of extension exist whatever the deformation regime because the crust is not homogeneous.

2.4. Granite emplacement

Magma emplacement in the upper brittle crust is strongly controlled by deformation (e.g. Hutton, 1992). This is clearly evident when examining the number, place and orientation of the feeder zones in a granitic pluton. Feeders are interpreted as being the places where gravity indicates a steep deepening of the floor, and where magmatic structures are vertical. They may correlate with late evolved facies (Améglio et al., 1997). Several cases exist, mostly coming out from surveys realized in the European Hercynian belt (Vigneresse, 1995b and references therein), which refer to different tectonic settings, as well as different crustal levels, allowing us to correlate the emplacement either to a specific regime (brittle or plastic) or condition (extensional, strike-slip shear or contractional) of deformation (Fig. 1d).

In the case of strike-slip deformation, plutons are located either within overlapping shear zones (e.g. Mortagne, Brittany) or adjacent to a major shear plane (e.g. Pontivy, Brittany). In the first case, the walls of the massifs are steep and are controlled by the fracture planes. The massif is deep, down to 8–10 km, over most of its area, with vertical foliation planes. Clearly, movement along the strike-slip faults controls granite emplacement. Conversely, in the case of a massif adjacent to a strike-slip fault, its root is not within the shear plane and trends at a high angle to the major stress component (σ_1) direction. It can be as deep as 6–8 km, compared to the gently dipping floor of the rest of the massif (2–4 km). The feeder is within a local extensional sector relative to the deformation field, aligned with the stretching direction as assumed in a plastic deforming crust. By comparison, an intrusive within a brittle crust, the massif of Guitiriz, NW Spain (Vigneresse, 1995b) trends globally N–S, in between two strike-slip faults, one dextral, the other sinistral, but not connected together. Structural directions within the massifs are mostly with low plunge and also trend N–S. The root zones are very shallow, only 4 km, and are E–W, that is parallel to the major stress component (Vigneresse, 1995b). The orientation of the root, along with their shallow depth, agrees with the Andersonian theory of fracture opening in a brittle deforming crust.

In the French Massif Central, the Saint Sylvestre and La Marche units are thin (2.6 km in average) compared to the preceding massifs, with structures showing horizontal or low dipping foliations over most of the massif. They are both peraluminous with biotite (±muscovite) facies evolving to muscovite + biotite facies and late fine grained intrusives. In those fine-grained facies, about 1–3 km^2 in area, magmatic structures, formerly subhorizontal, change to steeply plunging lineations carried by more or less concentric foliation planes. Detailed gravity measurements show that those local areas may be as deep as 6 km. Such a tabular morphology with numerous local roots reflects that the main facies was emplaced in a ductile crust and then was perforated by the more evolved magma at the onset of extension. Surrounding ductile faults show a normal component. But these ductile faults do not control the emplacement. For instance, the floor of the main Saint Sylvestre unit is normally faulted by about 500 m on its western side. Ductile deformation acted shortly after the granite emplacement as shown by the large scale ductile deformation of the foliations while the magma was not yet fully crystallized (Vigneresse, 1995b).

Massifs emplaced during compression (e.g. Flamanville, France or Piute Mountains, CA) show a small volume (about 500 km^3 compared to usual 1500 km^3). Hence, they cannot develop enough stress by their own buoyancy and their internal heat cannot warm up the crust during the ascent. They present a thin shape with a tiny root zone not discernible from gravity data inversion at depth about 3–4 km only. In Flamanville, the granitic floor is controlled at depth by the plunging of Cambrian limestones and the root shapes an extensional gash opened along the anticlinal axis of those rocks.

3. Chemical consequences of deformation

The consequences deformation bear on the chemical variations in a granitic magma have not yet been fully explored (Hecht et al., 1997). Chemical variations in the magma are commonly assigned to fractional crystallization or differentiation, and in a few cases to mixing or mingling of different types of magmas, often mafic and felsic. However, at a smaller scale, the dynamic interaction between a not yet fully crystallized magma and a second batch of more fractionated melt is not always considered as a possible source of chemical variations.

3.1. Incipient melting

Crustal melting is basically controlled by minerals, including water, associations and temperature. At grain scale, melt initiates according to the anisotropy of wetting of grain boundaries (Laporte and Watson, 1995), but under deformation melt is displaced from its source. Depending on the relative rate of deformation compared to melt production, high deformation rate displaces the melt out of its source and induces disequilibrium melting (Knessel and Davidson, 1996).

3.2. Melt segregation

Because the melt segregates at a nearly constant temperature, it has time to re-equilibrate chemically, explaining its relative homogeneity. However, if melt segregation is fast, due to active deformation, disequilibium melts can be generated and upwelled, inducing variations in their chemical or isotopical composition (Sawyer, 1994). This has serious consequences for geochronology.

3.3. Magma ascent

Magma ascent rate has indirect influence on magma evolution. The duration of the ascent is fast enough not to induce chemical variations, except local wall assimilation (Petford et al., 1994). However, the rate to which magma is delivered from the source has consequences on the petrographical zonation of a massif (e.g. Fichtelgebirge, Germany). Chemical evolution of the magma varies according to the distance of the sampling point to the place of the feeder (Hecht et al., 1997).

In a granitic intrusion, petrographic zonation can be either normal, that is more evolved toward the center (e.g. the older unit, OIC, from Fichtelgebirge) or inverse, that is less evolved, or basic at the center (e.g. the younger unit, YIC, from Fichtelgebirge). When plotted according to the distance of the sampling point to the place of the feeder (Hecht et al., 1997), chemical evolution of magma reflects how magma evolved while being emplaced. In a normally zoned granitic massif, magma evolution increases linearly toward the root zone. When facies show concordant structures, it reflects a continuum of magma emplacement, more and more evolved, which pushes aside the former emplaced magma, provided it is not yet fully crystallized. In the case of inverse zoning, with discordant structures between facies, the output of magma is tectonically controlled. Due to this control, magma emplacement occurs in discontinuous pulses. If the rate of magma emplacement is low, the next sequence of magma is emplaced beside the former because the former batch of magma is already solid when the new one comes out. Reverse zoning results that reflects a geometrical disposition of successive magma batches.

3.4. Pluton emplacement

Finally, during the late stage of emplacement, local magma segregation still occurs. It essentially results from dilatant shear zones which are the unique way to achieve a closer packing of crystals (Vigneresse et al., 1996). During this late reorganization, melt is expelled out of the loose rigid framework of the yet formed crystals. Melt is therefore residual and is richer in incompatible elements (Th, U, Rb, Cs). Major mineralizations (U, W) are essentially associated with the contact between both types of magmas, possibly reflecting the interaction between unconsolidated framework of the yet formed crystals backbone and interstitial melts as suggested by the different Th/U behavior in each facies (Vigneresse et al., 1996).

4. Does granite generation need deformation?

The role played by deformation during granite generation seems far more important than previously estimated since it occurs during the whole cycle. Granites need deformation to be generated, which is a stronger assertion compared to the previous one stating that granites are syntectonic.

Horizontal melt segregation occurs because temperature distribution is horizontally stratified, so melt develops preferentially within that layering. The anisotropy of melt development, reinforced by the horizontal segregation, induces local concentration of melt from which magma can be expelled. It explains why magma develops as a discrete intrusive pluton rather than having a diffuse occurrence of melt veins, as found for instance during oil seepage.

Influence of deformation rules out some formerly admitted concepts such as a diapiric ascent into the brittle crust, or magma stopping at a neutral buoyant level. If gravity forces, or the density contrast between melt and the surrounding crust were the leading parameters that control ascent, then all granites should be intrusive at a more or less similar level. It is not the case, as observed from gravity data interpretation. In addition, the existence of gravity anomalies associated with felsic intrusions reflect sometimes a positive, but generally a negative density contrast between granite and its surroundings. Since the crystallized magma is denser than the melt, it would imply a still higher density contrast at the time of emplacement, which definitely rules out a neutral buoyancy level.

The shape of granitic plutons is apparently controlled by deformation. This is also the conclusion of modelling the geometry and amplitude of the stress field around a pluton (Vigneresse et al., 1999). Magma always intrudes in near-field extensional fracture planes, perpendicular to the minor stress component (σ_3) in a brittle environment. The opening plane is commonly a vertical plane in an extensional or shear deformation far-field. Magma induced stress field locally modifies the far-field stress pattern, leading to stress re-orientation. Intrusion ends in a locally compressional field, yielding opening along a horizontal plane. The switch between a vertical to a horizontal plane is reflected in the tabular shape of granitic intrusions. Their lateral extension is often large (50 km) compared to their thickness (5–7 km). However, some wedge-shaped plutons are observed which correspond to tectonic driven emplacement.

Finally, the existence of a significant stress level to accommodate granite generation also signifies that a strong crust must exist which can sustain such a stress. In other terms, granites exist because there is a rigid crust which can sustain stress, the latter being able to add significant forces to help in magma segregation and ascent. A thick crust is also required to achieve the temperature and pressure conditions for melting. As an example, granites are found in the Kerguelen Islands, which have been emplaced only after a thick crust has been generated (Giret, 1990; Recq et al., 1990).

5. Conclusions

Various shapes and structures of granitic plutons are recognized from gravity data inversion. They reflect the conditions under which they were emplaced. Each regime or type of deformation induces a specific morphology to a given pluton. It also controls the mechanism by which magma segregates and is upwelled from the lower crust. I suggest that deformation triggers the whole process of granite generation. Depending on the stress rate, a certain amount of magma is upwelled continuously or not and thus is separated from its source region. Consequently, the control deformation has on the dynamic upwelling and emplacement is partly reflected in its magmatic evolution. Since deformation is active all along felsic magmas history, I suggest that granites are deformed objects and should be considered as so.

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