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Pluton accommodation at high strain rates in the upper continental crust. The example of the Central Extremadura batholith, Spain

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Abstract

Emplacement in the tensional bridge of a stepped dextral shear zone system is proposed for the Central Extremadura batholith (Spain). The country rocks show a pervasive anisotropy that conditioned the style of the structures developed as a consequence of the transference of displacement from the stepped shear zones to the releasing area. The kinematic evolution of the resulting megakink fold provided the volume increase necessary for the granite emplacement. Thermal and kinematic models suggest that the growth of individual plutons took place in periods of no more than several hundred to a few thousand years. Fast strain rates (10^{-10}–10^{-11} s^{-1}) must concentrate in local structures (e.g. initiation of kink folds) even in zones deforming as a whole under typical strain rates ($10^{-14\pm1}$ s^{-1}). Granite plutons might be used as strain-rate gauges for syn-plutonic structures.

1. Introduction

Emplacement of granite plutons in areas of local extension associated with strike-slip faults and shear zones is a mechanism consistent with the main structural and petrological features of many batholiths (e.g. Castro, 1986; Tikoff and Teyssier, 1992; Vigneresse, 1995). A major point of debate about the applicability of this mechanism arises in the comparison between the time scale of granite emplacement and the common rates of regional deformation (Paterson and Fowler, 1993; Hanson and Glazner, 1995; Vigneresse, 1995). Ascent velocities of magmas are typically faster than tectonic strain rates. Consequently, models are developed that imply coalescence of multiple dikes or small igneous events separated by periods of magmatic quiescence (Petford et al., 1993). This multiple-dike mechanism is not supported by field relationships and geochemical data of granite plutons, in which only a few magma pulses make up big granite bodies (e.g. Paterson and Fowler, 1993). Numerical models (Hanson and Glazner, 1995; Yoshinobu et al., 1998) suggest that shallow chambers may be maintained at the typical slow rates of deformation in extensional settings. Fast strain rates seem to be the alternative mechanism to originate the observed relationships. In this paper we analyze the role that localized, fast strain rates played in the development of the Central Extremadura batholith, a group of km-scale plutons emplaced in association with a dextral shear zone of the Variscan Iberian massif.

2. Geological setting of the Central Extremadura batholith

The Central Extremadura batholith (CEB) is located in the central part of the Iberian Massif (Fig. 1). The different granitic plutons that constitute the batholith have been described by Corretgé (1971), Castro (1984, 1986), Corretgé et al. (1985), Pérez del Villar (1988)

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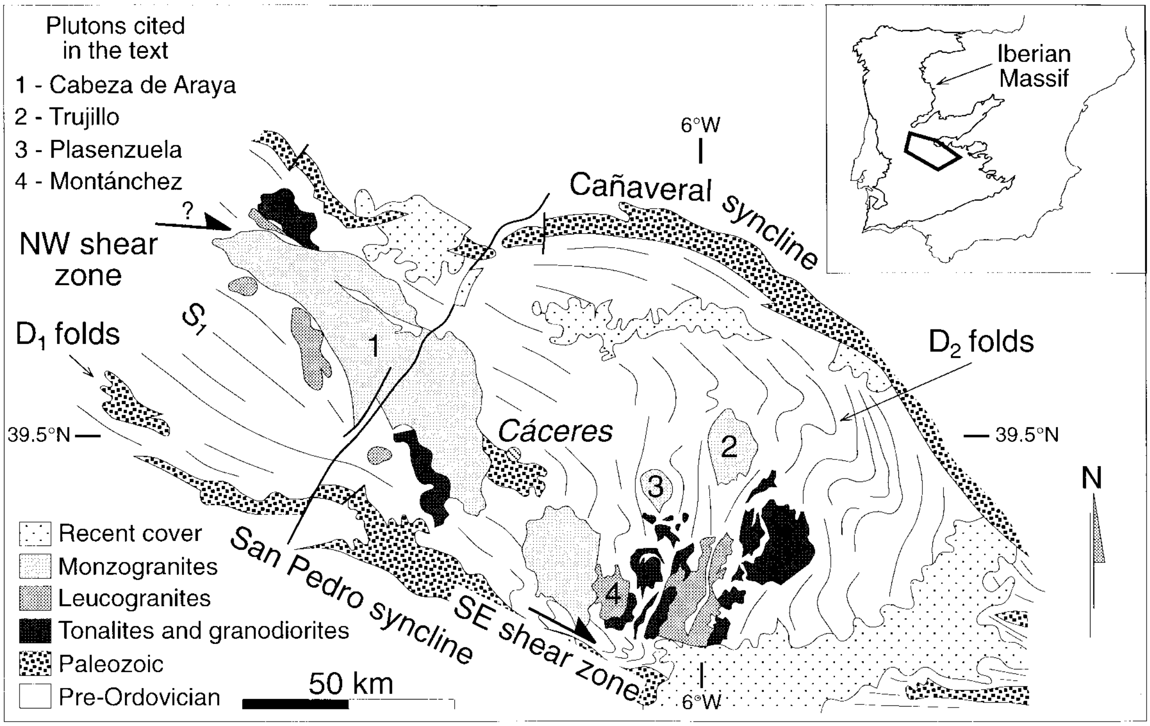

Fig. 1. Geological map of the Central Extremadura batholith. The inset shows the location of the batholith in the Variscan Iberian massif. Numbers refer to the plutons referred to in the text.

and Vigneresse and Bouchez (1997), among others. The geochemical, petrological, geophysical and structural characteristics of the batholith are described at length in these works and they will not be reproduced here.

The plutons intruded a low-grade pelitic metasedimentary series at pressures of around 200 MPa (Castro, 1984). These homogeneous schists and metasandstones are of lower Cambrian–upper Precambrian age and were deformed during the Variscan orogeny. The first deformation phase (D_1) originated kilometre-scale upright folds trending in a NW–SE direction (Fig. 1). A penetrative regional foliation (S_1) developed parallel to the axial plane of the D_1 folds. As a result of this deformation the metasedimentary rocks became anisotropic over regional volumes in the middle to upper crust. This change predates granite intrusion so that granite magma found a bulk anisotropic host rock during its ascent. The contact metamorphism in the aureoles is synchronous with a second deformational phase (D_2); the complex relationships between the D_2 folds and the shape of some plutons in the CEB led Castro (1984, 1986) and Castro and Fernández (1998) to propose that the granites are synkinematic with respect to D_2.

The Cabeza de Araya pluton is a NW–SE elongated body of more than 1400 km^2 in areal extent (Fig. 1). The other plutons in the CEB are east and southeast of the Cabeza de Araya pluton. The trace of S_1 in this area is roughly N–S, rather than parallel to the regional NW–SE trend, most common in the central part of the Iberian Massif. Therefore, these plutons were emplaced in the short limb of a large-scale asymmetric fold of S_1, that was originated during the D_2 folding (Fig. 1).

3. Geological inferences for a model of emplacement

According to Vigneresse and Bouchez (1997) the Cabeza de Araya pluton was intruded along a double-gash opening (Fig. 2a). The gashes show opposite concavities and Vigneresse and Bouchez (1997) interpreted them as the result of a dextral regional shear parallel to the S_1 foliation (i.e. NW–SE), with the centre of the pluton acting as a relay zone (Fig. 2a). We suggest that these gashes developed in a dextral E–W to NW–SE shear as tensional fractures in a transtension produced by a linked system of two overstepping, dextral strike-slip shear zones (Fig. 2b), in agreement with the theoretical work by Segall and Pollard (1980). Evidence for discrete strike-slip, dextral shear zones in the CEB is observed to the southeast of the Cabeza de Araya pluton (Fig. 1). Far to the southeast, in the Los Pedroches batholith, similar structures also accommodate massive granite intrusions (Aranguren et al., 1997).

Since this tectonic regime seems to work for the

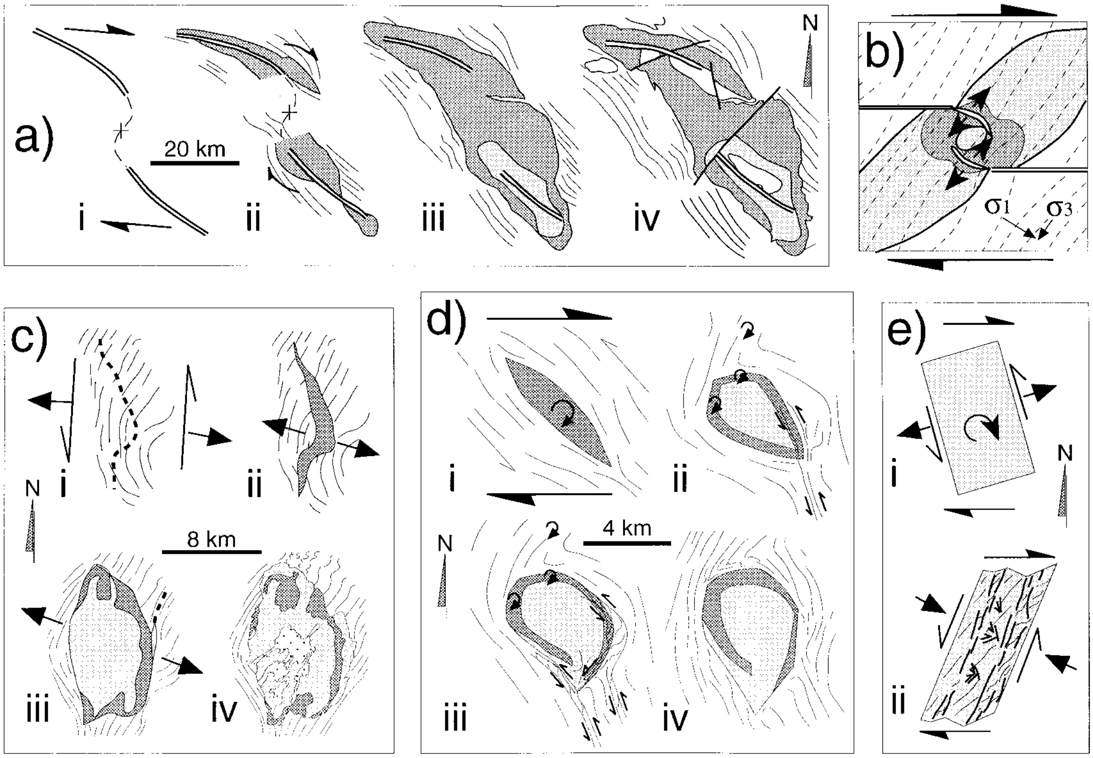

Fig. 2. Kinematic evolution of some representative plutons in the Central Extremadura batholith. Dotted and gray patterns represent different granitic facies in each pluton. See text for explanations. (a) Four stages (i–iv) in the development of the Cabeza de Araya pluton (from Vigneresse and Bouchez, 1997). (b) Stress trajectories and shape of tension-gashes developed in the releasing zone of an overstep dextral fault system (from Segall and Pollard, 1980). The dark gray pattern limits the area where tensional fracturing can take place. (c) Progressive evolution (i–iv) of the Trujillo pluton. (d) Progressive evolution (i–iv) of the Plasenzuela pluton (from Castro and Fernández, 1998). (e) Intrusion (i) and deformation in the fully crystallized state (ii) of the Montánchez pluton.

Cabeza de Araya pluton, it must also explain the emplacement kinematics of the other plutons in the CEB. Stepping transtensional fault systems generate releasing stepovers (see, for example Davison, 1994 and Woodcock and Schubert, 1994 for the terminology). The fault displacement is often transferred to the releasing area or tensional bridge as rotation of the whole zone comprised between the two fault planes (Peacock, 1991). Complexities in the response of this area as a consequence of the presence of previous anisotropies (S_1) are expected. The maximum compressive axis (Fig. 2b) was applied parallel to the pervasive anisotropy, providing the mechanical condition to favour the buckling of S_1. This observation, together with the kinematic tendency of the releasing zone to rotate in a clockwise sense can account for the large, asymmetric D_2 fold that includes most of the plutons in the CEB (Fig. 1). The large D_2 fold may be considered as a megakink fold, at least at a first order geometrical approximation. Similar map-scale megakinks have been described by Powell et al. (1985). Kink bands exhibit complex evolutions that include: (i) simple shearing parallel to the kinked surfaces, i.e. a rotational, non-coaxial component of the deformation history (sinistral simple shearing parallel to S_1 in this case); (ii) relative rotation of the rock volume comprised between the kink surfaces, i.e. a spin component of the deformation history (clockwise rotation of the sector with S_1 striking N–S); and (iii) a volume change that follows the relationship of Ramsay (1967) and Ramsay and Huber (1987):

$$\Delta = (\sin\beta/\sin\alpha) - 1, \qquad (1)$$

where Δ is the volume change within the kink band that depends on the angles that S_1 forms with the kink plane inside (β angle) and outside (α angle) the kink band. If $\alpha<\beta$ (a common situation), volume increase is predicted within the kink zone. According to Ramsay and Huber (1987) volume increase may occur in a number of ways including the formation of dilational veins parallel to or cross-cutting the kinked anisotropy planes.

The feasibility of our model may be tested in the CEB observing the relationships between the geometry of S_1 and the pluton margins. As an example, consider the Trujillo pluton, shown in Fig. 2(c). The arcuate traces of the disrupted S_1 show similar concavities at both sides of the same pluton, indicating that S_1 was slightly folded before the intrusion. S_1 is not parallel

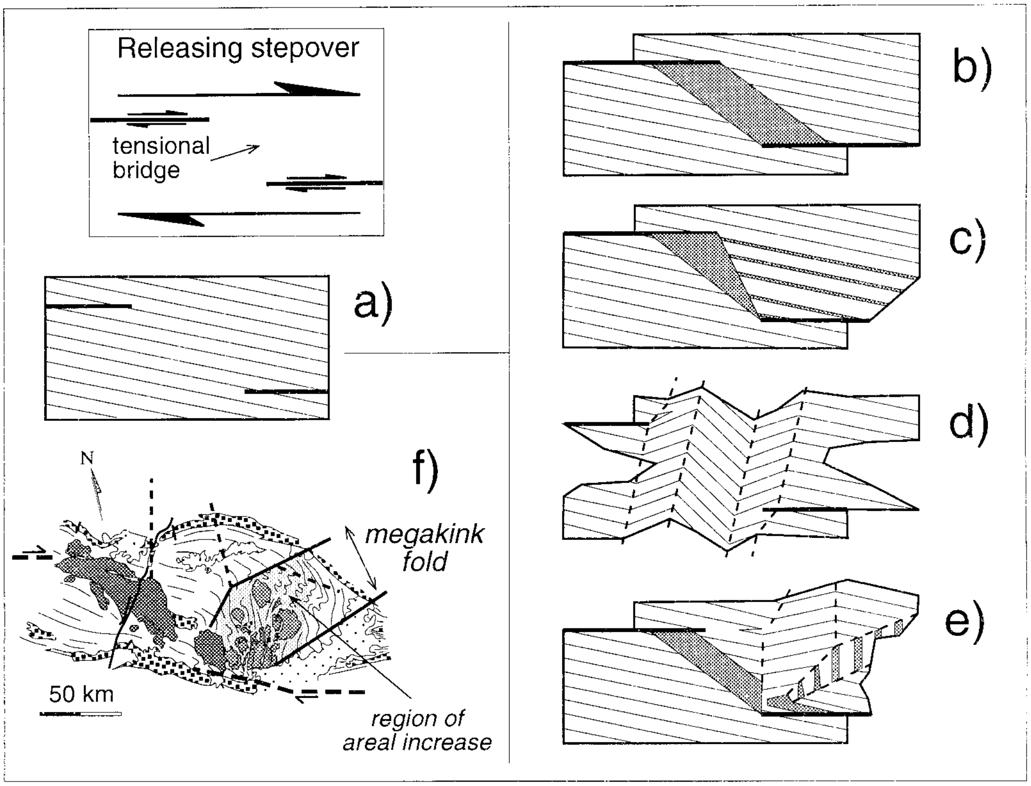

Fig. 3. Geometrical evaluation of the emplacement of the Central Extremadura batholith in a releasing stepover of a dextral strike-slip fault system (inset). (a) Initial two-dimensional sketch with an anisotropic material. (b) Isotropic model where the slip on the upper fault is transferred to the lower one by originating a rhomboidal space in the releasing area. (c) Model that allows the single domains to separate along the inextensible fibres so to partially accommodate the exceeding areal increase. (d) Model with folding in the releasing area, so that no areal increase is required as the external boundaries are allowed to easily deform. This is very similar to the basic models of twinned domains by Cobbold and Gapais (1986). (e) Model in which the block in the lower left part of the area was fixed and remained undeformed and only the upper right block was allowed to deform so that it develops a complex fold geometry and voids of distinct shape and size depending on their position in the model. See text for details on the basic assumptions of these models. (f) Map of the Central Extremadura batholith with representation of axial traces of the main folds. Compare (f) with models (b–e). Dark gray patterns in the models represent voids supposedly filled with granitic magmas.

to the margins of the plutons, as required by the ballooning or diapirism models. The simplest way to create the final geometry is to open a tension gash mostly oblique to the arcuate pattern of S_1 as a result of the volume increase and sinistral simple shearing components of the regional deformation history; this fracture was used by granite magmas to ascend, to broaden the initially planar gash and finally to give place to the pluton after the intrusion of a few magma pulses (Fig. 2c).

Evidence for the coeval activity of spinning, volume increase and simple shearing parallel to S_1 comes from the Plasenzuela pluton. The kinematic evolution of this pluton has been explained with some detail by Castro and Fernández (1998). In this case a space parallel to S_1 developed in response to the volume increase within the rotating folding domain; as volume increase and clockwise spinning components continued to operate in the incipient pluton, folds and simple shear zones developed on the host-rock and also affected the pluton. These folds and shear zones favoured the widening of the initial room and new magma pulses ascended to occupy the newly generated space (Fig. 2d). Similarly, in the Montánchez pluton the three components of the rotational deformation acted coeval to the granite emplacement (Fig. 2e). However, the solid-state deformation includes a weak component of bulk inhomogeneous flattening. This can be explained as a consequence of the rotation of the pluton past the critical β values which produce the closing of the formerly open spaces (Fig. 2e, ii).

4. Geometrical evaluation of the model

The geometrical feasibility of the model of granite emplacement in a strike-slip releasing structure was evaluated through the following two-fold approach:

1. The areal extent occupied by the granites at their present level of erosion was measured. The result was compared to the predictions of the kink model

using Eq. (1) with $\alpha = 40°$ and $\beta = 65°$ (angles estimated from the map of Fig. 1). Both values were found to be very similar (800 and 750 km^2, respectively).

2. A forward geometrical reconstruction in two dimensions of the stepover evolution was elaborated (Fig. 3) considering the following basic constraints:
    (i) a right dextral stepover fault system with a tensional bridge (inset in Fig. 3);
    (ii) an anisotropic medium consisting of single elongate domains separated by pervasive heterogeneity planes at a low angle with respect to the direction of the faults (Fig. 3a);
    (iii) the anisotropy surfaces (S_1) are considered as inextensible fibres in the sense of Cobbold and Gapais (1986) and Gapais and Cobbold (1987); and
    (iv) the external boundaries of the model are considered as perfectly deformable lines.

As long as the anisotropy surfaces are vertical in the BEC and the assumed deformation is a horizontal, dextral simple shear, the two-dimensional model seems a good representation of the three-dimensional real situation. The sketch in Fig. 3(a) was subjected to variable amounts of dextral slip on the upper left fault, and the final result depends on the way in which the releasing zone accommodates the deformation imposed by the upper left fault. Four contrasted cases were considered and the final sketches were geometrically constructed with the assumption of length balance along the inextensible fibres (Fig. 3b–e). The choice of geometrical parameters (amount of displacement in the upper left fault, size of the rhomboidal void) and type of releasing zone deformation (kink bands with area increase) for the fourth model (Fig. 3e) was planned to fit the geometrical features observed in the CEB (Fig. 3f).

Strike-slip regimes are a very common tectonic context for pluton emplacement within the anisotropic upper crust, so that the models of Fig. 3 may be taken as possible end-members for pluton geometries in releasing zones.

5. The rates of pluton emplacement

The growth rate of plutons fed by dikes can be estimated from numerical models (e.g. Petford et al., 1993) and then compared to the average tectonic strain rates. Therefore, the critical dike width (w_c), the horizontally averaged velocity of magma (V_{av}) and the time to fill each pluton (Δt) were computed according to the equations by Petford et al. (1993). The choice of parameters necessary for these estimations is explained below and follows the assumptions of Petford et al. (1993). Magma densities and viscosities were estimated following the method by Shaw (1972), using 66 whole-rock analyses of the distinct granitic facies outcropping in the batholith, and assuming a crystal-free melt at 800°C. The wt% H_2O was obtained from the analyses, so that it must be considered as a minimum estimation of the real H_2O content in the melt. Phase relations in the aureoles indicate a pressure of about 200 MPa, but the plutons extend for more than 6–10 km down the present level of outcrop (Vigneresse and Bouchez, 1997), so that a mean lithostatic pressure of 300 MPa was considered. Results range from $\sim 3 \times 10^8$ Pa s (granites) to $\sim 1 \times 10^7$ Pa s (tonalites) for the viscosities, and from ~ 2480 kg m^{-3} (granites) to ~ 2520 kg m^{-3} (tonalites) for the magmatic densities. Separate estimation of critical dike width and magma velocity are obtained for each pluton in the CEB. Latent heat was taken as 300 kJ kg^{-1} and specific heat as 1.2 kJ kg^{-1} °C^{-1}. Initial temperature in the country rock was 300°C (Castro, 1984), and magma freezing temperature 750°C. Results for w_c vary from 25.6 to 57.0 m in the Plasenzuela pluton and from 54.6 to 64.3 m for the Cabeza de Araya pluton. Similar values are obtained for the other plutons in the batholith. Velocities are faster for tonalitic melts (~ 0.7 cm s^{-1}) and slower for granites (~ 0.1–0.2 cm s^{-1}). The time to fill each pluton may be calculated following the equation of Petford et al. (1993):

$$\Delta t = Q / V_{av} w_c l, \tag{2}$$

where Q is the pluton volume, and l is the lateral extent of the feeder dike. In order to compute Δt, the relative volumes of the distinct facies are considered, and the geometry at depth was obtained from gravity models (e.g. Vigneresse and Bouchez, 1997). The lateral extent of the feeder was varied from the length of the long axis of each pluton (a reasonable estimation according to the results by Vigneresse and Bouchez, 1997) to 1 km. Results indicate a time to fill the Plasenzuela pluton of about 120–222 y. The other plutons show similar times, with most of the values varying in the range between 10^2 and 10^3 y. These growth rates are to be considered only as an order-of-magnitude estimate, because large uncertainties can be assigned to the chosen parameters. For instance, considering that the real H_2O content in the melt was higher, the time span to fill the plutons would be substantially reduced. The converse can be said if crystal-bearing magmas are considered so that average viscosities increase.

The geometrical model of the releasing zone (Fig. 3e) implies a finite strain of $R_s \approx 2.2$ (R_s = axial rate of the finite strain ellipse) for the D_2 deformation. Assuming simple shear, steady state flow and common values of the conventional strain rate (Pfiffner and Ramsay, 1982), this finite strain would arise over a time interval of about 1.3 Ma for a reasonable strain rate of $10^{-14}\,s^{-1}$. The time of pluton growth (10^2–10^3 y) is then considerably smaller than the time of the coeval deformation ($>10^6$ y), a result that has been already observed by many other authors (e.g. Paterson and Fowler, 1993).

One can hypothesize that individual plutons were accreted after a number of small pulses separated by periods of scarce or null magma flow. If this was the case, we can consider the Plasenzuela pluton to be the result of the amalgamation of a number of individual pulses of 57 m thick. Seventy pulses like this are necessary to build up the pluton and the average time recurrence of the pulses is of about 18 000 y. Taking apart the absence of field evidences concerning such an episodic growth (Castro and Fernández, 1998), simple thermal models may be used to dismiss this possibility. The host rock surrounding the Plasenzuela pluton exhibits a field contact aureole of about 300 m (Castro and Fernández, 1998). Simple solutions of the conductive heat equation for a dike intrusion (e.g. Carslaw and Jaeger, 1959; Jaeger, 1964; Furlong et al., 1991) show that a body of 4000 m thick can produce a field aureole of about 250 m, whereas a dike of 57 m across does not give place to any noticeable field aureole. The long average time interval between pulses excludes the possibility of progressive heating of the crust. Therefore, the hypothesis of multiple pulse supply of magma to generate plutons seems to be in contradiction with the observation of important contact aureoles in the CEB.

The Plasenzuela pluton, of about 4000 m thick, was filled in a time span of 120–222 y. This gives a rate of transversal growth of 18–33 m y^{-1}. Similar values can be obtained for other plutons in the CEB, yielding a range of transversal growth of 10^1–10^2 m y^{-1}. This represents the opening rate of the tensional fractures controlling the magma emplacement, and it contrasts with the typical values of slip rate in faults and shear zones (less than 4 cm in a year, e.g. Vigneresse, 1995; Yoshinobu et al., 1998).

6. Final comments

According to the data presented in the previous section, several hundred to a few thousand years may be sufficient to generate a pluton more than 300 km^3 in volume. The subsequent thermal evolution of these instantaneously (from a geological point of view) emplaced plutons lasts for more than 1×10^5 y and it may produce an appreciable contact aureole. However, it is hard to envisage how large plutons might experience such a rapid growth when the bulk conventional strain rate is only $10^{-14\pm1}\,s^{-1}$. Considering the strain associated with the pluton emplacement, and the time span to fill each pluton, strain rates for the opening of the tension gashes allowing magma emplacement in the CEB can be estimated to be between about 10^{-10} and $10^{-11}\,s^{-1}$. This is two to five orders of magnitude faster than typical strain rates. Experiments on nucleation and propagation of kink folds indicate that the initiation of kink bands is associated with a stress drop and appears to be a quite rapid phenomenon (Weiss, 1968; Ramsay and Huber, 1987). Accordingly, we suggest that, although the bulk deformation in the releasing zone resulted from moderate strain rates, instabilities related to the nucleation of megakink folds in an anisotropic crust led to unusually large strain rates in localized areas (tensional fractures opening at rates faster than 10 m in a year). Spaces originated in these areas were rapidly occupied by granitic magma.

Following the terminology by Vigneresse (1995), the local structures developing at fast strain rates coincide with the near-field deformation conditions, while the bulk tectonic scenario deforming at typical strain rates and controlling the general evolution of a batholith corresponds to the far-field deformation. Tension gashes associated with the nucleation of megakink bands are only one possible kind of near-field, fast-developing structures that accommodate pluton intrusion in the anisotropic upper crust; others may include intersecting fractures (Dehls et al., 1998), subhorizontal magma traps formed by high magma driving pressures (Hogan et al., 1998), or laccoliths emplaced in the hinge zone of buckle folds (Roig et al., 1998).

Are these fast-developing structures more common than is usually thought? We suggest that some granite plutons might be used as a sort of speedometer to constrain the rate at which a given structure developed. To do this we have to work on new numerical and analogue models that must be tested against the structural, petrological and geophysical characteristics of natural examples.

7. Conclusions

Geometrical and kinematic considerations indicate that sufficient room for granite plutons can be created in overstepping strike-slip zones. The necessary volume appeared in megakink-bands formed in the releasing zones as a consequence of deformation transfer in an anisotropic medium. Field features and thermal inferences suggest rapid filling (hundreds of years) of plutons several hundred km^3 in volume. Inferred strain rates in the near-field structures controlling the emplacement of plutons (10^{-10}–$10^{-11}\,s^{-1}$) were from two to five orders of magnitude faster than typical strain rates in the crust ($10^{-14\pm1}\,s^{-1}$).

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