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Granite intrusion by externally induced growth and deformation of the magma reservoir, the example of the Plasenzuela pluton, Spain

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Abstract—The Plasenzuela pluton in the Central Extremadura batholith in the southern Iberian Massif, is an example of permissive emplacement in relation to the tectonic development of extensional fractures in the upper continental crust. Paradoxically, this pluton has a concordant structural pattern which is classically attributed to diapirism or ballooning. This pattern consists of the following elements: (a) nearly elliptical shape in the horizontal section; (b) conformity of the pre-existing aureole structures to the shape of the pluton contacts; and (c) development of a crenulation cleavage, parallel to the contacts, in the vicinity of the pluton walls. All these features have been interpreted in many plutons as resulting from the pushing-aside of the country rock structures due to the expansion of the pluton. However, the detailed structural relationships in the aureole do not favour a forceful emplacement mechanism. By contrast, these relationships constitute prime evidence of permissive intrusion in extensional fractures. According to this interpretation, the concordant shape of the pluton was acquired by syn-plutonic opening of a mixed tensional-shear fracture, parallel to the main foliation in the host rocks, and by folding of the fracture walls together with the previous anisotropy of the country rocks. This is a growth–deformation process that can operate at local conditions in the upper continental crust giving rise to concordant syn-tectonic plutons. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

One of the main problems related to the ascent and emplacement of plutons in the continental crust focuses on how the space now occupied by the magma was created. This problem is particularly important in certain areas of the continental crust in which granite batholiths constitute a large proportion of the surface outcrop. Questions related to the so-called ‘room problem’ raised by H. H. Read (1948, 1957), have not always been satisfactorily answered with unambiguous natural examples. Questions include the following: (1) Where is the crust left by granite intrusions? (2) Is this indicative of country rock replacement by fluids or magmas? (3) Do granites really deform the country rocks and push-out the pre-existing structures creating, by its emplacement dynamics, the room that they actually occupy?

Mechanisms of ascent and emplacement of plutons such as stoping (Daly, 1903), diapirism (Buddington, 1959; Weinberg and Podladchikov, 1994), dyking (Lister and Kerr, 1991; Clemens and Mawer, 1992; Petford *et al.*, 1993), accommodation in faults and shear zones (Pitcher, 1979; Hutton, 1982, 1988; Castro, 1986; Hutton *et al.*, 1990; Petford and Atherton, 1992) and *in situ* ballooning (Holder, 1979; Ramsay, 1989) are familiar to those interested in the geology of granites. These have been classically grouped into two main categories: (1) permissive mechanisms in which the magma plays a passive role (stoping, accommodation in extensional faults); and (2) forceful mechanisms in which the magma pushes aside the pluton walls and deforms the country rocks creating by itself the room it will occupy (diapirism and ballooning). These two categories must be seen as end-member processes and a multiplicity of different mechanisms are considered to interplay in the emplacement of any given pluton (Paterson and Vernon, 1995). In general, plutons are emplaced by a combination of magma flow and tectonic movements. The main problem is to determine the degree to which each end-member mechanism contributed to the final emplacement. The problem of pluton emplacement can be addressed in different, but complementary ways. Mechanical approaches (e.g. Marsh, 1982), experimental and numerical scale models (e.g. Ramberg, 1970; Berner *et al.*, 1972; Dixon, 1975; Cruden, 1988, 1990, among others), geophysical modeling (e.g. Ameglio *et al.*, 1997) and field geology relationships are the four main ways in which this important problem is being addressed by different researchers. Detailed field geology has turned out to be one of the most efficient ways to supply new insights on the granite emplacement problem.

Many examples of plutons accommodated within opening cracks have been reported with support from field and structural relationships (e.g. Hutton, 1982, 1988; Castro, 1986; Hutton *et al.*, 1990) and geophysical surveys (e.g. Vigneresse and Bouchez, 1997). In all the cases there is a magma which fills the opening crack, implying some equilibrium between the rate of fracture opening and the rate of magma production.

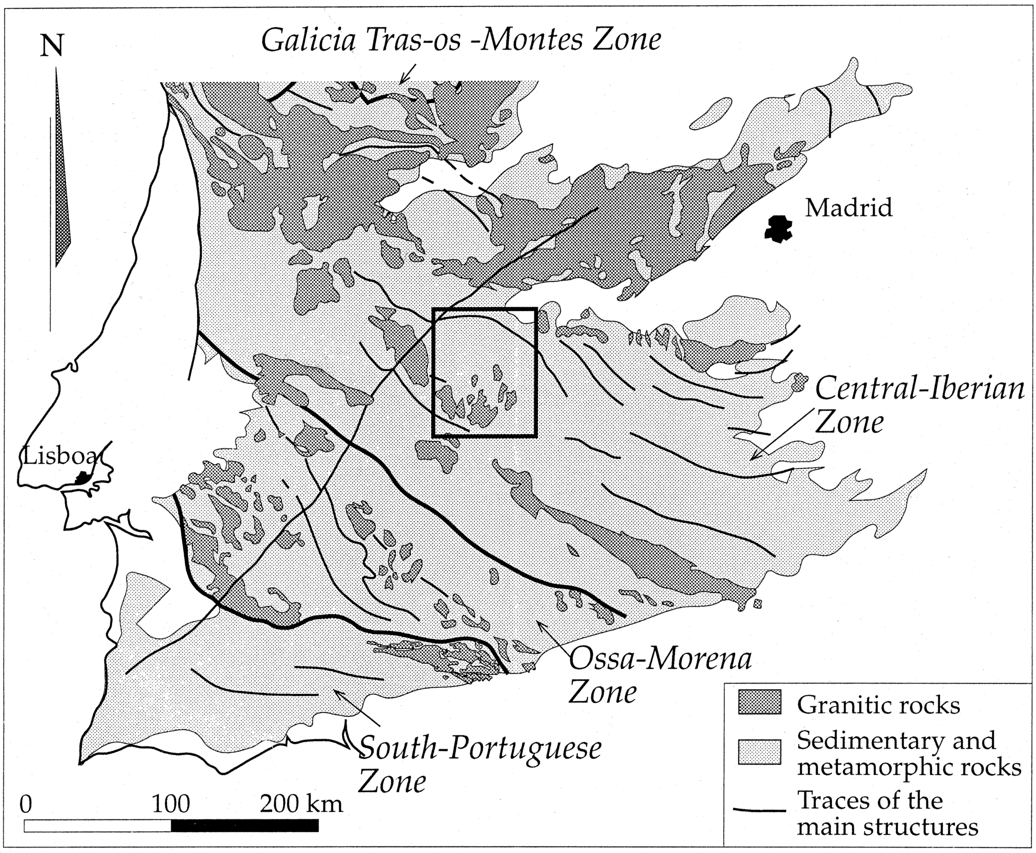

Fig. 1. Southern part of the Iberian massif. The marked area corresponds to the inset in Fig. 2.

These observations may be extended to almost every pluton, independent of the actual mechanisms involved in its emplacement, thus suggesting that nearly all the granites are syn-tectonic.

Our experience suggests that the relationships between the geometry of a pluton, its mode of emplacement and the structures of the country rocks are normally complex. The observation that plutons composed of the same type of granitic rock, with the same age and emplaced in the same batholith may have very different structural patterns, led Castro (1987) to propose that the shape, concordant or discordant, is mainly determined by tectonic factors. One of the plutons in which these observations were made is the Plasenzuela pluton in the Central Extremadura batholith (Spain), in which a recent investigation of the country rocks in its vicinity has revealed a complex history of magma emplacement and pluton growth resulting from tectonic movements related to a crustal-scale shear zone. These results are presented in this paper. The clarity of geological observations for Plasenzuela makes this pluton an ideal place in which many of the enigmatic aspects of the 'room problem', related to the emplacement of granite magmas in the upper continental crust, can be examined and tested. A mechanism for the ascent and emplacement of the pluton is developed from field observation and may be generally applicable to granite magma emplacement.

GEOLOGICAL SETTING

The Plasenzuela pluton, initially mapped by Corretgé *et al.* (1981), is part of the association of intrusive bodies that comprises the Central Extremadura batholith (Castro, 1986), a major plutonic association appearing in the Central Iberian zone (Julivert *et al.*, 1972) of the Hercynian massif of Iberia (Fig. 1). This batholith was emplaced into Precambrian metasedimentary rocks (schists and greywackes) previously deformed and metamorphosed at greenschist facies (Fig. 2). The plutons are elongated bodies parallel to the regional tectonic foliation (S_1) in the host rocks, although more complex relationships occur, such as pluton margins cross-cutting the external foliation. Conversely the S_1 is locally deflected by plutons in a nearly horizontal section. Contact metamorphism developed near the granitic bodies and overprints the mineral assemblages associated with S_1. Therefore, the intrusion took place well after D_1 in the country rocks. Solid-state deformation affected the pluton margins where it developed S–C mylonites (Berthé *et al.*, 1979). The country rocks are also deformed coeval with the granite intrusion. The main structures generated in the metasedimentary rocks are chevron folds, minor shear bands and a crenulation foliation (S_2). The D_2 structures in the host rocks are not concentrated near the pluton margins, but instead

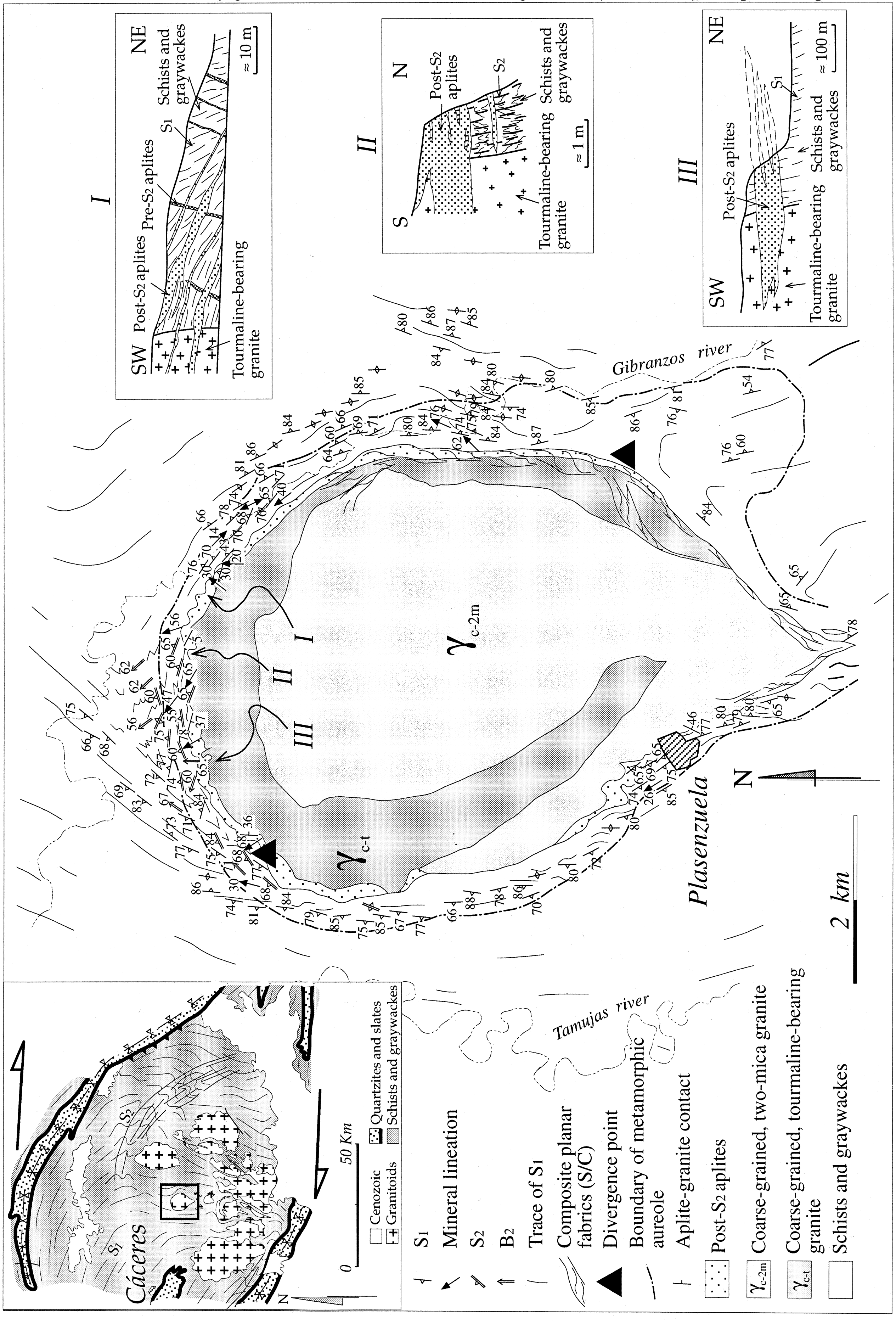

Fig. 2. Geological map of the Plasenzuela pluton. The inset shows the central and eastern parts of the Central Extremadura batholith.

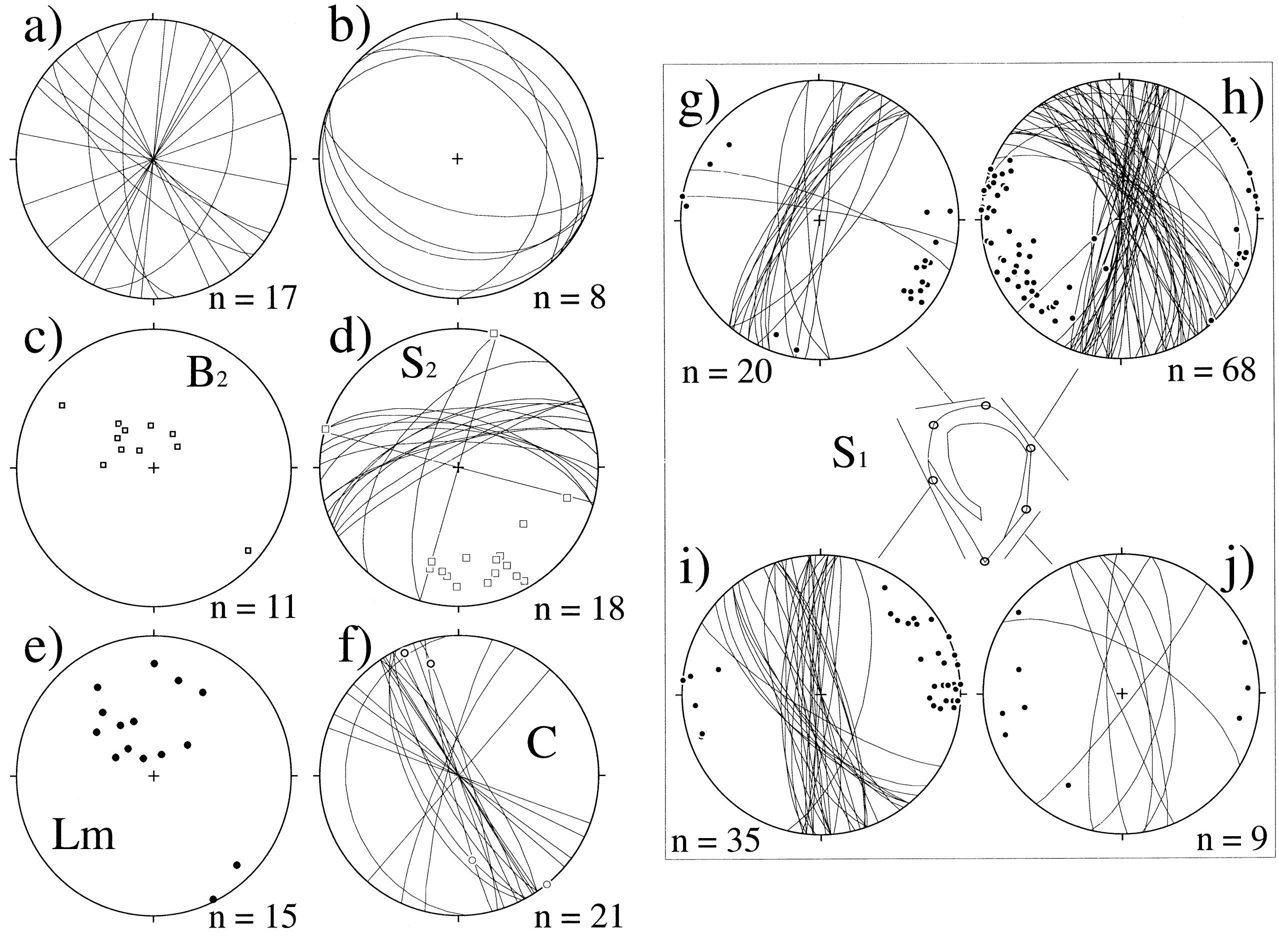

Fig. 3. Equal-area, lower-hemisphere projection of structural data of the Plasenzuela pluton. (a) Radial aplitic dykes. (b) Annular aplitic dykes. (c) Fold axes of the D_2 deformation phase (B_2). (d) Great circles and poles to the S_2 foliation. (e) Mineral lineation defined by the preferred orientation of cordierite nodules in the contact aureole. (f) Shear planes (great circles) and stretching lineations (open circles) of shear zones in the southern contact of the pluton. (g–j) Great circles and poles to the S_1 foliation for different areas in the host rock around the pluton. Open circles in the geological sketch represent inflection points in the external outline of the pluton.

show a heterogeneous development. At a larger scale, the plutons outcrop in an area where S_1 in the host rocks is deflected from its original position, defining a huge Z-shaped fold structure (Fig. 2). According to the pattern of structures in both the granites and the metasedimentary host, Castro (1986) proposed that emplacement of plutons of the Central Extremadura batholith and the large-scale rotation and folding of the S_1 foliation were controlled by a deep-seated D_2 dextral shear zone, oriented E–W (inset to Fig. 2), which favoured the formation of ascent conduits along extensional fractures and the rotation and deformation of the granitic bodies. The Plasenzuela pluton was emplaced and rotated in a dextral sense relative to its initial position, approximately NW–SE, towards the present-day N–S position.

This ascent and emplacement model accounted for most of the observed structures in both pluton and host. However, the way the plutons grew and evolved from extensional fractures to their nearly rounded final shape was not explained. A recent study of the Plasenzuela pluton, including a detailed map of the contact shape, the internal distribution of granitic facies and the structures of the country rocks in the vicinity of the pluton, reveals important new aspects of the precise mechanism by which the pluton grew.

STRUCTURAL RELATIONSHIPS IN THE PLASENZUELA PLUTON

The study of the structure in and around the Plasenzuela pluton reveals several points of interest that must be taken into account for the interpretation of the mode of emplacement. These are as follows.

1. *Shape*. From the map of Fig. 2 it can be appreciated that the shape of the pluton is more polygonal than rounded. Several inflection points can be marked on the map as illustrated in the sketch of Fig. 3. Two of these inflection points coincide with the locations at which the trajectories of the foliations in the country rocks change abruptly, diverging to give way to the granite pluton (black

triangles in Fig. 2). These *divergence* points are of prime kinematic importance and will be described in detail later, in the section devoted to the structures in the aureole.

2. *South tail and shear zones*. The southern termination of the pluton in a wedge, in contrast with the rounded shape of the north border, resembles the shape of an inverted drop, the typical shape of diapirs in experimental models (e.g. Berner *et al.*, 1972; Cruden, 1988, 1990). As this apparent drop-shaped geometry is shown in a horizontal section, the interpretation of the pluton as a diapir implies that the ascent was oblique towards the north or, alternatively, that the pluton was tilted after emplacement. The presence of a minimum in the gravity anomaly map, located at the centre of the pluton (Campos *et al.*, 1993), invalidates the existence of an oblique ascent or later tilting, as in both cases the minimum would be displaced towards the south. When analysed with some detail, this peculiar shape is identified as resulting from the intersection between a shear zone acting at the time of emplacement and one of the walls of the pluton that is displaced in a sinistral sense. This shear zone really displaced a divergence point opposite to that of the northwest contact. This displacement was crucial in creating most of the room occupied by the granite magma. The magnitude of the apparent displacement in the horizontal section is easily measured from the map as the distance between the south tip and the divergence point of the southeastern margin (3–4 km). Structures such as drag folds of the S_1 foliation and *S–C* mylonites within the marginal facies of the granite are in agreement with this kinematic interpretation (Figs 2 & 3c). There is an apparent contradiction between the fact that the *S–C* mylonites were developed at high temperature and the granites emplaced at shallow levels (pressure in the aureole is about 200 MPa, computed from mineral equilibria in the contact aureole). A possible explanation for this apparent contradiction is that the mylonites developed during granite emplacement when the granite magma was crystallizing (Castro, 1984). In this sense, these ductile, high-temperature structures developed at a shallow level may be indicative of synchronism between pluton emplacement and regional deformation. These N–S-oriented sinistral shear zones are not just local to the Plasenzuela pluton, but appear in many other places of the batholith affecting other granite complexes (Castro, 1986). They have been interpreted as rotated antithetic shears that accommodated the reorientation of the S_1 foliation in the interior of the regional, E–W-oriented, dextral shear zone (D_2).
3. *Internal contacts*. The scarcity of internal structures is the dominant feature of the Plasenzuela pluton. With the exception of the ductile shear zones of the southern and southeastern margins, there is no apparent orientation of minerals within the rest of the granite pluton. The mutual contacts between the two facies distinguished on the map are always transitional over more than 100 m in which small changes in the modal content of biotite, muscovite and tourmaline occur. The contacts of both facies with the country rocks are always sharp. A remarkable fact is the virtual absence of country rock xenoliths and any kind of enclave, within the granites, even in the marginal facies.
4. *Aplitic dykes*. The Plasenzuela granite belongs to the group of leucogranites and two-mica granites of the Central Extremadura batholith widely represented in the Iberian massif (Capdevila *et al.*, 1973; Corretgé *et al.*, 1977; Corretgé and Castro, 1997). Apart from the peraluminuous composition, these granites are characterized by having crystallized from fluid-rich magmas. Tourmaline-rich facies, aplite and aplo-pegmatitic complexes are a common feature of this kind of granite. In Plasenzuela, aplites are very common, forming large dykes near the margins of the pluton. These aplitic dykes appear in two main families: one forms radial dykes, and the other concentric dykes. Radial dykes are concentrated close to the contacts, at the contact itself and within the country rocks near the contact. Their thickness ranges from few centimetres to less than 1 m. They are subvertical (Fig. 3a), normally deformed by D_2 (vertical axis folds) and cross-cut by the concentric dykes (Fig. 2, section I). The latter are subhorizontal dykes, 10–100 m thick, outlining the pluton as they appear only at the contacts. The dip angle is normally less than 20° (Fig. 3b) towards the interior of the pluton at the northwestern contact (Fig. 2, sections II and III) and away from the pluton at the northeastern contact (Fig. 2, section I). Most of the aplites in the map of Fig. 2 correspond to a single concentric dyke extending over most of the contact.
5. *Structures in the aureole*. One of the most salient features of the Plasenzuela pluton is the parallel orientation of the S_1 subvertical foliation of the country rocks to the pluton contacts (Figs 2 & 3g–j). When studied in detail, this reorientation of the regional foliation parallel to the pluton is only apparent. In fact, the bend traced by the S_1 foliation on the northeastern corner of the pluton aureole is part of a vertical axis fold (D_2) that continues with other folds towards the north of the pluton (Fig. 2). The D_2 fold axes are subvertical (Fig. 3c) and a local S_2 axial-plane foliation is developed (Figs 2 & 3d). The above observations in the southern tip of the pluton imply that intrusion and folding of the S_1 foliation occurred at the same time. In this way, adaptation of the walls to the vertical axis folds is produced at the same time as magma intrusion, and this is the reason why the

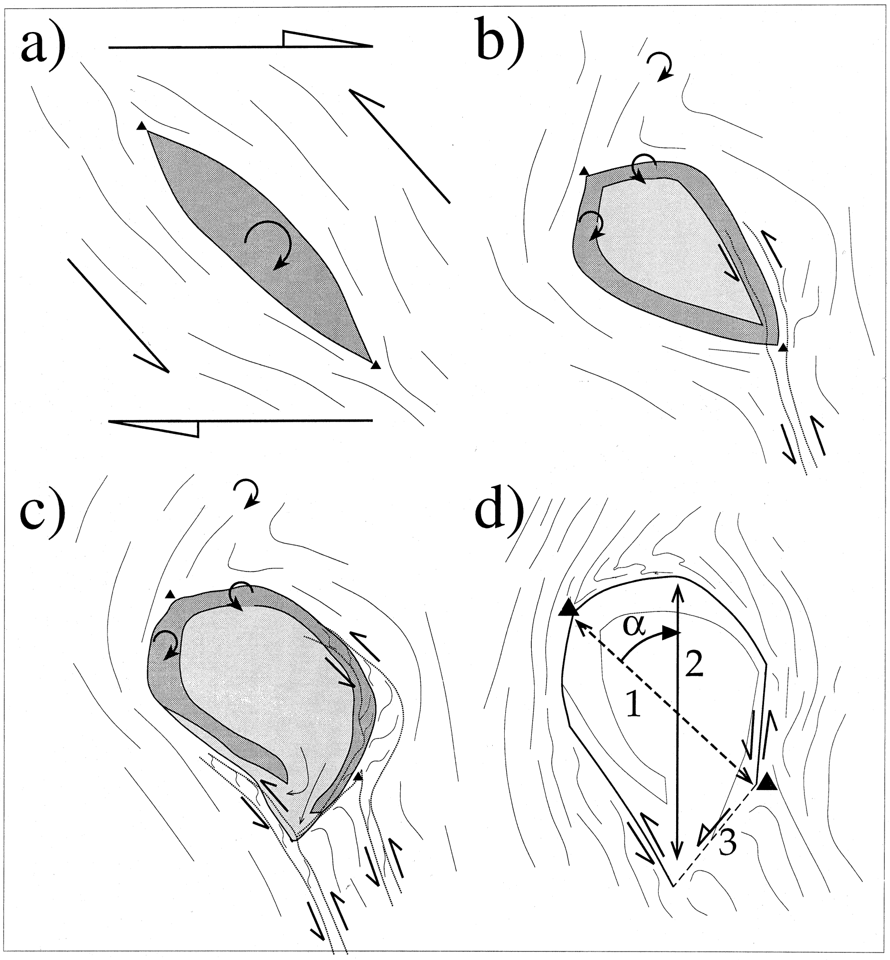

Fig. 4. A possible reconstruction of the size and shape evolution with time (from a to d) of the Plasenzuela pluton, based on the structure of the aureole (for more explanation, see text). In (d), 1 represents the initial orientation of the long axis of the pluton; 2 is its present long axis, the curved arrow marked with α indicates the rotation sense of pluton, and 3 is the shear zone that aided in the growth of the pluton. The large arrows in (a) reflect the regional D_2 dextral shear, while the other minor sinistral shear zones are a response of the S_1 foliation to the imposed dextral rotation. The vorticity indicators indicate the rotation of the granite body (a), the opening of the walls of the magma-filled fracture (b & c) and the rotation of the S_1 foliation in the limbs of the D_2 folds (b & c).

walls of the pluton are curved but do not exhibit solid-state fabrics: they were magma at the time of folding. During this survey, a detailed map of the aureole was made as the only way with which to reveal the relationships between pluton shape and aureole folding. Our first target was to find the point at which the regional foliation separated allowing the granite to be accommodated in a supposed extensional crack opened parallel to the S_1 foliation. However, these divergence points were not found where expected: the north divergence point was found at the northwestern inflection point (Fig. 2). Surprisingly, one of the flanks departing from the point at which the foliation was opened was strongly folded in a nearly isoclinal D_2 fold (Fig. 2). Again, this means that the opening crack was rotated and folded during opening and that this process occurred at the same time as magma emplacement. The position of the other divergence point was equally surprising and hence illustrative of the process. It was displaced by the sinistral shear zone mentioned above. The opening of the crack was not accommodated by folding, but rather by displacement of the divergence point. This mechanism considerably increases the volume of the opening crack as the wall surface was increased with the displacement (Fig. 4c & d). If this displacement is eliminated and the divergence point to the south is carried back to its initial position (Fig. 4b), the lengths of the walls measured between the two divergence points coincide. This is important because it implies that all the room occupied by the Plasenzuela granite was gained by externally induced opening of an extensional fracture.

6. *Contact metamorphism.* Cordierite and andalusite are the common minerals in the contact aureole of the Plasenzuela pluton. Cordierite forms polycrystalline aggregates, 2–5 mm in length, which in some places appear elongated. These aggregates define a linear fabric in a narrow, few metre wide band close

to the contacts (Fig. 2). In this band the lineation is nearly subvertical (Fig. 3e). Note that the mineral lineation is parallel to the B_2 axes (Fig. 3). This might be used as evidence of regional stretching parallel to the direction of fold axes. Nevertheless, the spatial association between the mineral lineation and the granite contact, as well as the lack of other markers of vertical stretching far from the granite body, strongly suggest that the lineation is a consequence of the emplacement mechanism, and it is possibly related to the dragging of the pluton over its country rock.

DISCUSSION

Emplacement of the Plasenzuela pluton

All the above structural relationships described from the Plasenzuela pluton are the consequence of a particular mechanism of emplacement. From these relationships it is clear that the parallelism of the regional structures with respect to the pluton shape is not a consequence of pluton expansion. The vertical lineations in a band around the pluton recall the predictions of the power-law diapiric model (Weinberg and Podladchikov, 1994), but the deformed area is too narrow so that this model can only account for a small part of the pluton volume (Paterson and Fowler, 1993). The structures in the country rocks, the absence of apparent fabrics within the granite, the local low-angle obliquity between the crenulation cleavage and the pluton contacts at the northern margin, and the disposition of the divergence points, suggest a mechanism of emplacement in which the final shape of the pluton was reached predominantly by folding of the walls of a dilatant fracture. The granite magma occupied the room created by an originally linear fracture which was progressively deformed and finally transformed in an equidimensional space. The rounded shape, therefore, represents an equilibrium geometry at which the volume is a maximum. This emplacement mechanism is sequentially illustrated in Fig. 4.

The first stage of pluton emplacement is the opening of an extensional fracture along a direction nearly parallel to the S_1 foliation. This extensional fracture is associated with an E–W, dextral, regional shear zone (D_2) that produced the folding of the D_1 structures in the region (Castro, 1985, 1986). A second pulse of magma intruded into the core of the first pulse. The core is the most feasible place for the addition of more magma. Magma solidification started from the walls and progressed towards the core of the pluton. The growth of the pluton is accompanied by a bulk dextral rotation. The S_1 foliation had two ways in which to accommodate the imposed dextral shear sense: (1) folding; and (2) rotation, assisted by the development of antithetic shear zones parallel to the foliation. The first mechanism prevailed in the northern part of the pluton, whereas the second one acted at the southern tip (Fig. 4b). One of these antithetic shear zones produced the displacement of the divergence point at the southern end of the pluton (Fig. 4c). Consequently, the volume of the pluton was increased and the intrusion of the second magma pulse engulfed the part of the first pulse separated from the wall. This observation implies that the early pulse of granite magma was completely consolidated at this stage of pluton growth and behaved as a rigid carapace. This is the reason the marginal zone of the Plasenzuela pluton is devoid of any magmatic foliation parallel to the walls. Finally, the major axis of the pluton reached the N–S position (Fig. 4d), the aplitic dykes were developed at the margins and the second foliation (S_2) appears as an axial-plane foliation associated with the vertical axis folds developed during pluton emplacement.

In a general case, the volume of the intrusion is predetermined by the original length of the extensional fracture. However, in Plasenzuela this final volume was further increased by the displacement of the southern divergence point from its initial position towards the north. This displacement is evidenced by the sinistral shear zone that appears on the east margin, affecting the granite and host rocks, and by the disposition of the regional foliation around the pluton in the southeastern margin (Fig. 2).

Geological implications

The emplacement mechanism proposed here for the Plasenzuela pluton is relevant in addressing the room problem in granite emplacement. The interpretation proposed here, based on detailed geological observations in a natural granite pluton, does not assume an *a priori* particular role, neither passive nor active, for the granite magma. We interpret the possible changes in size and shape of the intrusion only from the observation of structures in its aureole. Possibly, the granite magma contributed to the growth of the magma reservoir which evolved from a dish-shaped vertical dyke (Fig. 4a) to a rounded body (Fig. 4d), with an overpressure resulting from the density inversion and gravity instability. This shape evolution, with the consequent increase in pluton volume, is only possible if granite magma is available from the source continually during the activity of the shear zone and is injecting and filling the growing magma reservoir. This implies that the rate of magma segregation is controlled by the rate of tectonic deformation and growth of the magma reservoir. That is, the granite melt is segregated from the source at the rate of tectonic movements (Sawyer, 1996). Consequently, granite melts extracted rapidly from the source, due to high-rate tectonic activity, will be more heterogeneous and will have abundant disequilibrium textures compared with granites extracted more slowly from the source.

In other words, for similar chemical diffusion rates (i.e. similar P,T and volatile content) the homogeneity of granite rocks is controlled by the rate of the tectonic episode by which the magma ascended and was emplaced in the continental crust. However, the comparison must be made between granites emplaced at similar depths. Shallow-level granites are normally more homogeneous than deep-level granites. In this case the differences are imposed by the distance travelled by the magmas, rather than by the tectonic rate; distances are shorter for deep-seated shear zones and plutons.

This emplacement mechanism, which accounts for the structural patterns found in many concordant granitoid plutons, has further implications for the three-dimensional reconstruction of granite bodies: the classical view of plutons as inverted drops in vertical sections must be revised. Concordant plutons emplaced by a mechanism of growth and deformation (G–D) of the magma reservoir may have a fish-shape geometry in vertical sections, with tails at both ends.

Growth–deformation (G–D) processes: resulting shapes and structural patterns

The structural pattern of the Plasenzuela pluton is the result of a combination of the emplacement mechanism, initiated as an opening fracture (dyke), and the mutual relationships between the orientation of the early fracture and the pre-existing anisotropy of the country rocks, in this case a subvertical foliation.

Other possible combinations are depicted in Fig. 5. Two sets of possible combinations are shown: one in which there is no rotation of the extensional fracture during opening and growth of the magma reservoir, and another in which there is a rotation of the extensional fracture. The last situation is more likely to occur in orogenic environments in which the development of extensional fractures is associated with strike-slip shear zones allowing granite magmas to intrude in locally extensional sites (fractures) developed in zones under compression (e.g. a continental collision). Note that appreciable diversity of final structural patterns

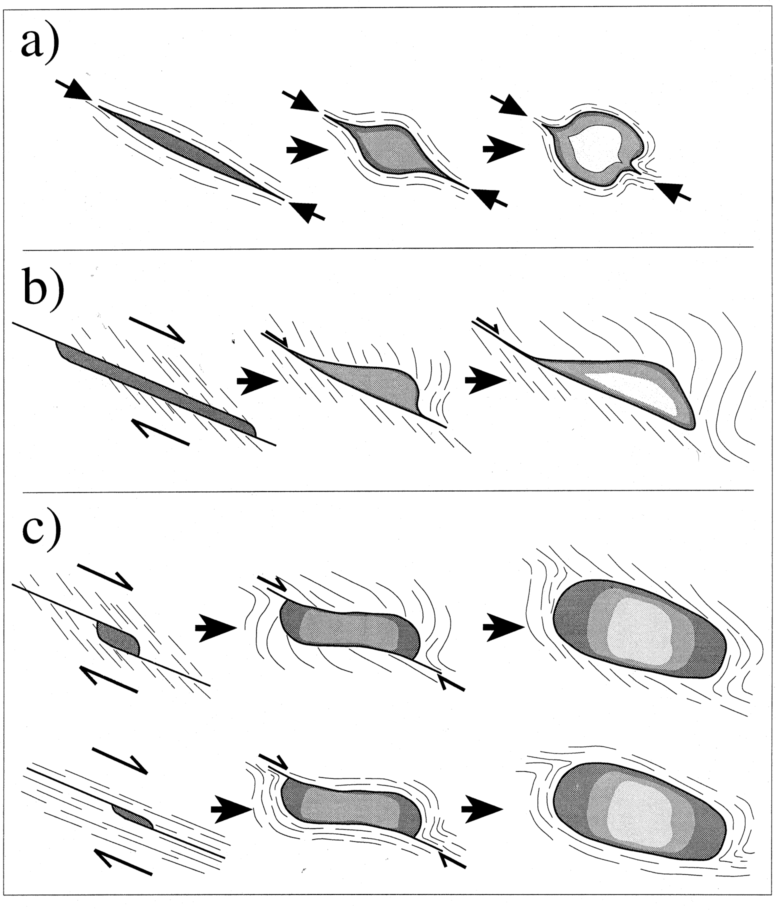

Fig. 5(a–c)—*Caption opposite*

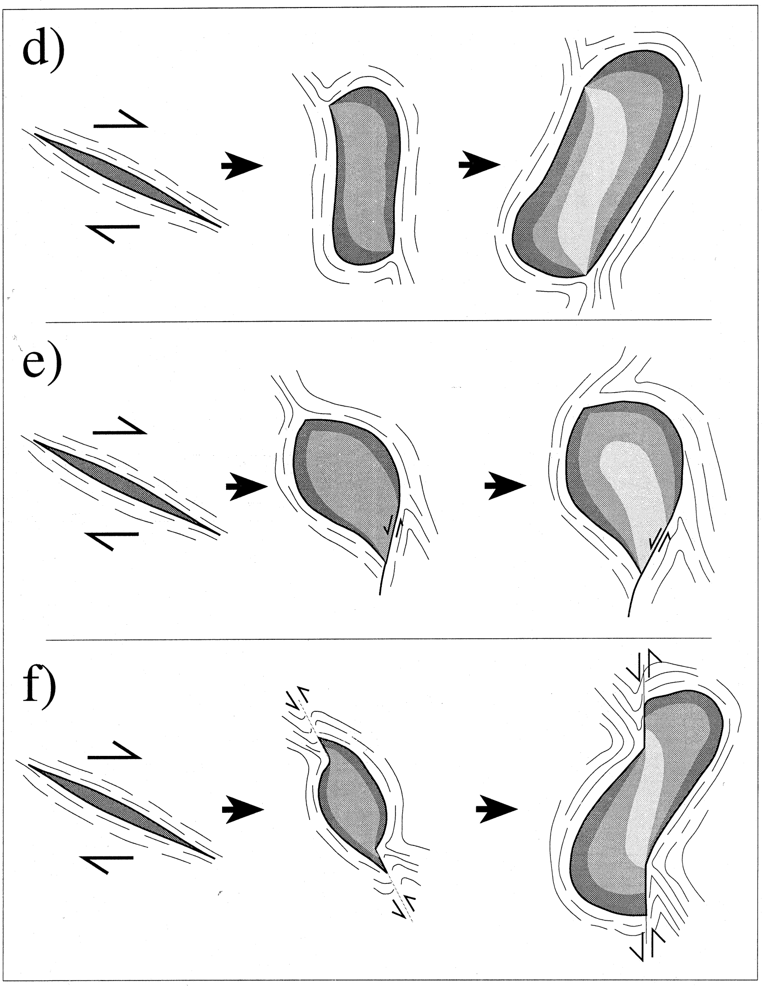

Fig. 5. Structural sketches resulting from possible combinations of fracture orientation and folding of the walls. (a) Two-wall folding during pluton growth of an extensional fracture developed parallel to a pre-existing anisotropy. (b) One-wall folding and growth of a pull-apart cavity oblique to a pre-existing anisotropy. (c) Two-wall folding and growth of a pull-apart cavity oblique and parallel to a pre-existing anisotropy. (d) Two-wall folding with growth and rotation of the extensional fracture and no displacement by shear of the divergence points. (e) One-wall folding with growth and rotation of the extensional fracture and displacement by shear at one of the tips. (f) The same as (e) but with shear at both tips.

develops from the same starting case of a dyke-like fracture, depending on the external deformation regime (Fig. 5). A further inference is that the most informative data by which to identify the emplacement mechanism come from the structures in the aureole of the pluton and how this relates to the overall pluton geometry. An important factor in reconstructing the time evolution of pluton growth is to identify the distribution of granitic facies inside the pluton. In this sense, geochemical and isotopic studies are crucial for a complete understanding of the mechanism and sequence of emplacement of a particular pluton.

CONCLUSIONS

From the structural relationships studied in the Plasenzuela pluton, it can be concluded that some concordant plutons appearing in the upper continental crust may be the result of a permissive emplacement mechanism. The concordant shape of the Plasenzuela pluton was acquired by syn-plutonic opening of a mixed tensional-shear fracture, parallel to the main foliation in the host rocks, and by folding of the fracture walls together with the previous anisotropy of the country rocks. This growth–deformation (G–D) process can operate at local conditions in the upper continental crust giving rise to concordant syn-tectonic plutons. This implies that the rate of magma segregation is conditioned by the rate of the tectonic accident responsible for the creation of opening fractures filled with granite magma in the upper continental crust.

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