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Structural pattern and ascent model in the Central Extremadura batholith, Hercynian belt, Spain

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Abstract—The Central Extremadura batholith constitutes an important alignment of plutonic rocks occupying part of the internal zones of the Iberian Hercynian belt. It comprises 13 plutons and numerous minor intrusions, and covers a wide compositional range from quartz–diorites to alkali–feldspar granites. Structural study of the individual plutons reveals that their internal structural patterns may be correlated. Correlation between the different structural patterns in the plutons and interpretation of the superimposed deformation in the metasedimentary host rocks indicate that the plutons were emplaced and deformed in an E–W, dextral, intracontinental shear zone developed during the second deformation phase (302–320 Ma). A qualitative ascent model has been established as follows: (1) development of extensional fractures at 45° to the E–W, dextral, shear zone; (2) intrusion of granitic magmas along these fractures and (3) rotation of the earlier intrusions, in a dextral sense, inducing antithetic shear zones (N–S sinistral) and a transverse shortening, perpendicular to the major axis of the earlier, deformed plutons as well as the forced emplacement of the later plutons.

Resumen—El batolito de Extremadura Central constituye un importante alineamiento de rocas plutónicas que ocupa parte de las zonas internas de la Cadena Hercínica Ibérica. Está constituido por 13 plutones y numerosas intrusiones menores cubriendo un amplio rango composicional desde cuarzo–dioritas hasta granitos de feldespato–alcalino. El estudio estructural de los plutones individuales revela que sus patrones estructurales pueden ser correlacionados entre sí. A partir de esta correlación estructural, y de las interpretaciones de las deformaciones superpuestas en el encajante, se puede deducir que los plutones se emplazaron y fueron deformados en una zona de cizalla intracontinental, E–W dextra, desarrollada durante la segunda fase de deformación (302–320 Ma). Se ha elaborado un modelo cualitativo de ascenso de la forma siguiente: (1) desarrollo de fracturas extensionales a 45° de la zona de cizalla E–W dextra; (2) intrusión de los magmas graníticos a favor de estas fracturas extenionales; (3) rotación de las intrusiones precoces, en sentido dextro, induciendo la formación de zonas de cizalla antitéticas (N–S senestras) y un acortamiento transversal al eje major de los plutones deformados, así como el emplazamiento forzado de los plutones más tardíos.

INTRODUCTION

UNTIL recently the study of batholiths was limited to the genesis of plutonic rocks of which they are composed together with their chemical–mineralogical evolution. However, the work of Pitcher (1977, 1979), Pitcher & Bussell (1977) and Hutton (1982), among others, on the tectonic regimes and ascent mechanisms of the individual plutons constituting a given batholith, has shown that structural studies on individual plutons may be quite useful. Such individual plutons in most cases appear to be associated spatially in large macrostructural units which may be observed in the internal parts of any orogenic belt. All this seems to indicate, as Pitcher suggested in 1979, that the association of plutons, far from being accidental, is the result of an external structural control, probably imposed by some deep-seated, localized tectonic activity (deep faults, intracontinental shear zones, etc.). This structural control can determine the ascent, emplacement and deformation mechanisms of the plutons. In this sense, all the spatially associated plutons, for which it is possible to establish a common structural control, may be considered as a single batholith according to the structural definition of batholith by Pitcher (1979).

The Central Extremadura batholith (CEB) in the Hercynian belt of Spain is a good example of structurally controlled emplacement which can be deduced from a study of the individual plutons that make up a batholith. This paper describes the structural and emplacement history of the CEB. Interpretation of structural fabric patterns of the plutons and the host rocks forms the basis for an ascent model to explain the closely linked phenomena of plutonism and deformation in the Central Extremadura area.

GEOLOGICAL SETTING

Regional geology

The Central Extremadura area (CEA) is a wide, NW–SE oriented region, more than 150 km in length, extending from Portugal to Montes de Toledo (Province of Cáceres, Central Western Spain). The rocks of the CEA are Precambrian and Paleozoic metasediments, deformed and metamorphosed during the Hercynian orogeny, and several granitoid plutons which make up the Central Extremadura batholith (Fig. 1).

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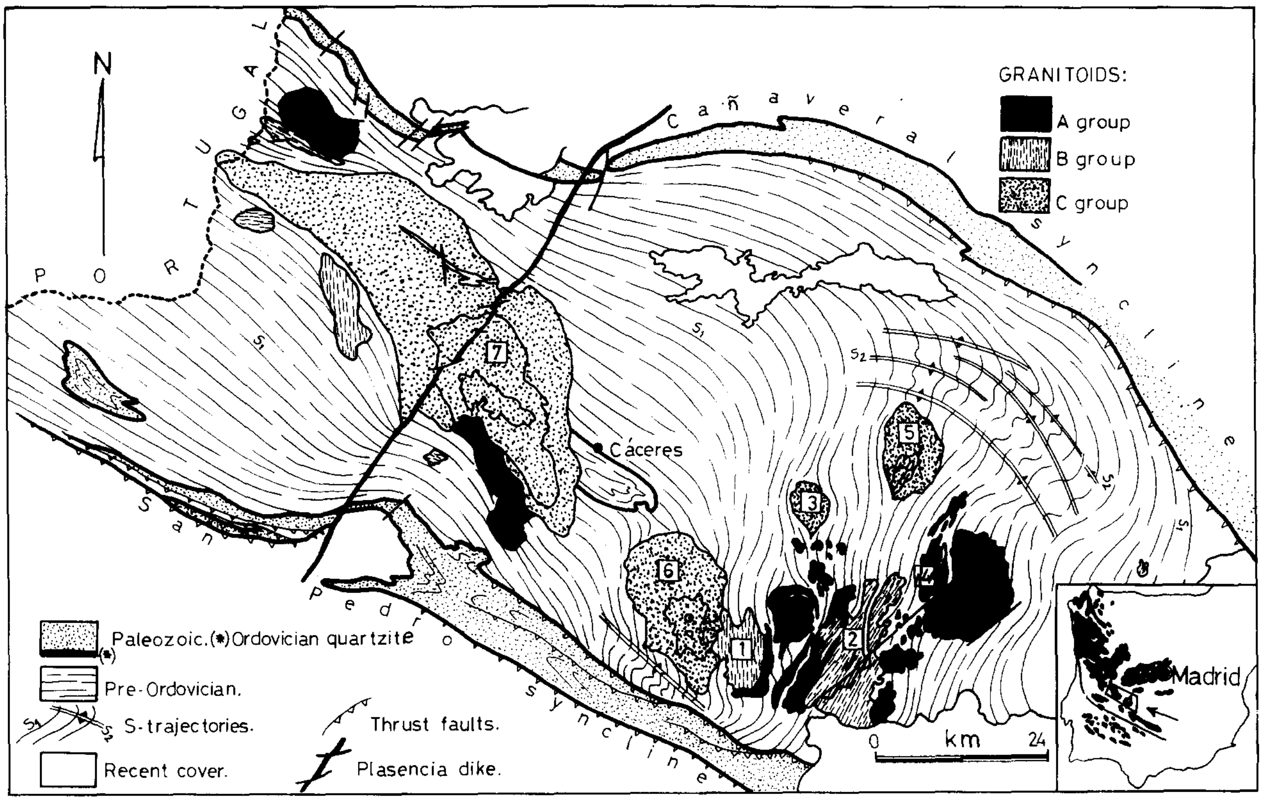

Fig. 1. Geology of the Central Extremadura area (modified after Castro 1984a, fig. 1) representing the plutons which make up the CEB and the most important structures of the area. The plutons labelled are those which are referred to later in the text: 1, Montanchez; 2, Alijares; 3, Plasenzuela; 4, Santa-Cruz; 5, Trujillo; 6, Alcuescar; 7, Cabeza-Araya.

Within the Iberic Hercynian belt, the CEA is located on the south branch of the Central Iberian zone (CIZ), according to the zonal division of Julivert *et al.* (1972, 1980). In general, the CIZ is characterized by the existence of pelitic-greywacke sedimentary rocks of Upper Precambrian age, and by the presence of plutonism in which there is a clear cut predominance of intermediate to acidic rocks over basic members (Barrera *et al.* 1981, Corretgé 1971, Corretgé *et al.* 1977, DPUS 1980). Another important aspect of the CIZ is the alternation of epizonal domains with mesozonal and catazonal ones in which, apart from the metamorphic grade, both the deformation style and the relationships of plutonism to deformation may differ.

The CEA is situated in one of the epizonal domains characterized by the presence of a first deformation phase (Lower Carboniferous) accompanied by a low-grade (Winkler 1967) regional metamorphism. A second deformation (Upper Carboniferous) was characterized in the epizonal domains by several kinds of structures superimposed on those of the first phase. The second phase may have had its origin in the large crustal shear zones, developed at depth, which can be observed in the deep domains (mesozonal and catazonal) of the CIZ (Castro 1984a, 1985).

Deformation phases

The first phase (D_1) gave rise to WNW–ESE oriented, upright folds with associated axial plane schistosity (S_1). Examples of D_1 folds are the large Paleozoic synclines which limit the CEA to the north and south (Fig. 1). Precambrian rocks outcrop between these synclines in a large D_1 anticlinorium. They are known regionally as "Complejo esquisto-grauváquico", and are in most cases the hosts to the plutons which form the CEB. The first schistosity (S_1) was deformed in a second deformational phase.

The second phase (D_2) is characterized by vertical-axis folds (Fig. 1) with associated axial plane schistosity (S_2). In the granitoids, D_2 gave rise to different kinds of structures (ductile shear zones) which will be analysed and interpreted below. In view of the close relationship, both spatial and temporal, between D_2 and the granitoid intrusions, the style of this deformation will be referred to extensively throughout this paper. The CEA granitoids constitute intrusive bodies, completely uprooted from their zones of origin, and emplaced after the first deformation phase. Granitoid emplacement may have taken place during the second deformation phase and may cover a period of 17 Ma (Castro 1984a).

Granitoid groups

Three granitoid groups are defined in the CEB on the basis of modal analysis (Castro 1984a) and the classification of Streckeisen (1976).

Group A. Granitoids of quartz–diorite affinities. These are medium-grained biotite quartz–diorites composed of quartz, zoned plagioclase (An_{20-30} at the core) and biotite. Generally, these rocks contain biotite spots (1–4 cm) which were of great help in the determination of the internal structure of certain quartz–diorite plutons.

Group B. Alkali-feldspar granites. These are coarse, medium- and fine-grained two mica granites, essentially composed of quartz, K-feldspar, albitic plagioclase, muscovite ± biotite ± cordierite ± tourmaline.

Group C. Calcalkali-feldspar granitoids of alkaline tendency. The composition of this group ranges from granodiorite to alkali-feldspar granite. Three main facies, C1, C2 and C3, may be distinguished, which in general terms present the following features: C1 are monzogranites and granodiorites of coarse to very coarse grain size, with K-feldspar megacrysts (5–10 cm). These megacrysts usually appear oriented, defining a planar or plano-linear fabric; C2 are coarse grained two-mica granites, generally lacking in K-feldspar megacrysts. Their classification ranges from syenogranites to alkali-feldspar granites. In some cases it is possible to distinguish a subfacies C'2, rich in tourmaline. C3 are aplitic granites, of fine to medium grain size.

STRUCTURAL PATTERNS IN THE PLUTONS AND HOST ROCKS

Pattern elements in the plutons

The structural pattern is determined by the different structural elements which appear associated within a particular intrusive body. This can give some idea about the history of emplacement and deformation and the mechanisms involved. Three main characteristics define the structural pattern: (1) *shape* of the pluton, (2) *internal structure* and (3) *structure of the host* near the intrusion.

Knowledge of the shape involves the construction of a detailed structural map with strict observance given to the contact dip. The distribution of the internal flow structures may yield information on the deep geometry of the pluton as well as on the eroded part (e.g. Wikström 1984).

Internal structure is determined by the internal fabric, and by the spatial distribution of granitic facies and joints. In the cases to be described below, the internal fabric has been determined from observations and measurements taken directly in the field from natural outcrops. The elements that have been chosen by the author for fabric determination are sheet silicates, K-feldspar megacrysts, non-equidimensional quartz aggregates and xenoliths. The joints which have been taken as part of the internal structure are those filled by aplites or aplopegmatites, that is by differentiation products from the granite itself. This implies that these joints were developed during emplacement; therefore, their spatial distribution may be closely related to the stress state existing during emplacement (Castro 1984b).

The structure of the host rocks in the zone adjacent to the pluton will also be considered as part of the structural pattern, since the existence of any anisotropy prior to intrusion may control the pluton's shape. Furthermore, some new structures may have developed during emplacement as a result of interaction between pluton and host. In this sense, an essential feature is the fabric associated with the contact metamorphism around the pluton. In the CEB most of the plutons, in their contact aureoles, induce the formation of cordierite aggregates (generally ellipsoidal) which serve as excellent strain markers.

Two extreme cases of structural pattern have been defined in the CEB plutons based on these elements: (i) a pattern corresponding to deformed plutons in which no structures due to emplacement remain because they have been obliterated by subsequent deformation processes and (ii) a pattern corresponding to undeformed plutons, in which the internal structure is exclusively due to the emplacement dynamics. Intermediate cases will also be considered, in which structural elements of the two kinds mentioned above appear together in the same body.

Structural pattern of the early, deformed plutons

The earlier plutons of the CEB are mainly characterized by (i) an elongate shape (in horizontal section) with axial ratios (major axis/minor axis) greater than 5 in some cases; (ii) an internal structure mainly defined by one or more planar fabrics of biotite and sheet silicates in general. The planar fabric, which usually gives a foliated aspect to the rocks, is due to ductile shearing. The deformed rocks of such plutons may generally be classified as *mylonites* according to Bell & Etheridge's (1973) definition; (iii) straight, tectonically reactivated contacts with the host rocks. These contacts are characterized by the localization of high deformation (with ultramylonites) due to simple shear. In the host rocks the ellipsoidal cordierite aggregates, developed in the contact aureole, usually define a subhorizontal linear fabric (representing the X axis of strain) which is compatible with the inferred simple shear.

The Montanchez pluton (Fig. 2) exhibits a fairly complex internal structure resulting from several superimposed ductile shear zones. The structural pattern is characterized by (1) an ovoid-shaped geometry in horizontal section and (2) an intense deformation both at the border zones (eastern border) and within the pluton (Fig. 2). Criteria of non-homogeneous strain are observable at both macro- and microscopic scale. Microscopically, the deformed rocks are characterized by the presence of ultramylonite microbands composed of fine aggregates of quartz and muscovite. Such bands, separated by a distance proportional to the feldspar size, anastomose, delimiting less deformed parts of rock in which the quartz is not extensively polygonized and shows serrated boundaries and undulatory extinction. The anastomosing geometry, also observable at macroscopic scale, is a criterion of non-homogeneous strain (Simpson 1983). Another criterion is the reduction in grain size observed in the highly deformed microbands (cf. Watts & Williams 1983).

The anastomosing planes correspond to shear planes (C planes) between which the sheet silicates are arranged

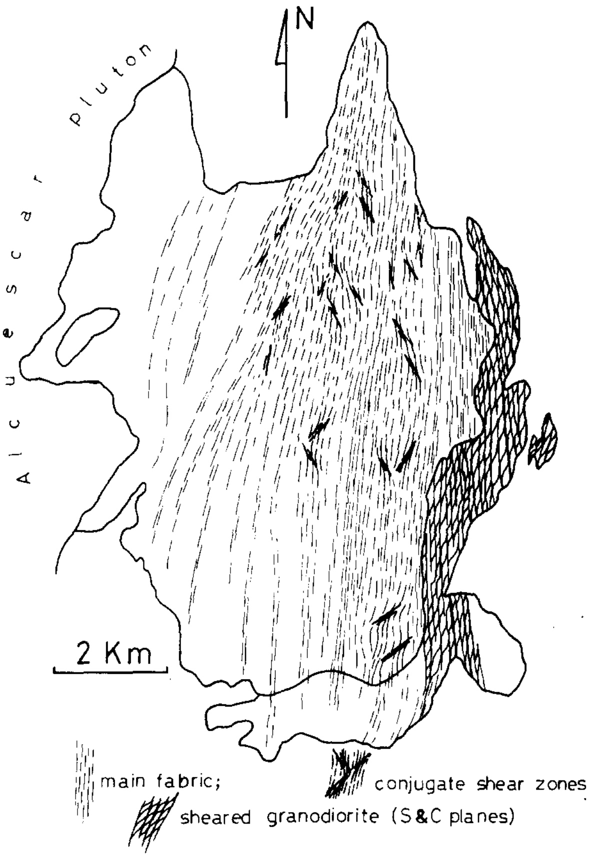

Fig. 2. Structural map of the Montanchez pluton (1 in Fig. 1).

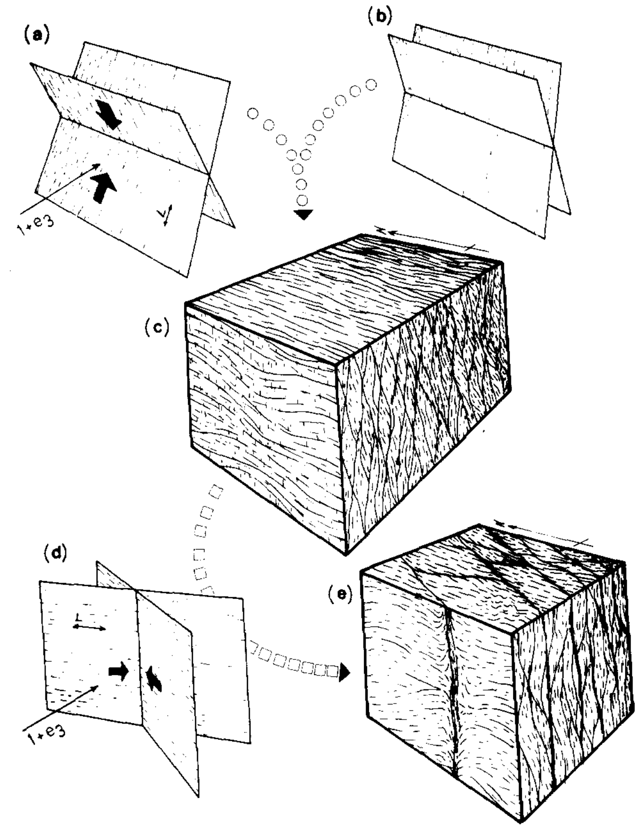

Fig. 3. Deformation by inhomogeneous flattening which gives rise to the main fabric and conjugate shears of the Montanchez pluton. (a), (b) Conjugate shears giving rise to the main fabric; $1 + e_3$: maximum finite shortening parallel to the minor principal axis (Z) of the finite strain ellipsoid. (c) Three-dimensional block illustrating the style of the main fabric observed in the field. (d) Second generation conjugate shears. (e) Three-dimensional block illustrating the appearance of outcrops after the superposition of the two deformations. L in (a) and (d) is a lineation in the shear plane.

obliquely (S planes) (Berthé *et al.*'s 1979 nomenclature) and the feldspars appear as asymmetric augen, evidencing a rotational deformation as well as the shear sense (Simpson & Schmid 1983, Simpson 1983).

Within the pluton it is possible to distinguish two types of planar fabric: (1) the main fabric and (2) vertical conjugate shear zones (Fig. 2). The main fabric is a subvertical, N–S striking planar foliation which terminates abruptly at the north and south contacts, indicating that this fabric is unrelated to the emplacement dynamics. In a vertical section, perpendicular to the foliation (XZ profile), it may be seen that this fabric is due to conjugate shear zones which act as E-verging thrust faults if they dip towards the west (dip angle always greater than 70°) or W-verging if they dip towards the east. A subvertical biotite lineation, parallel to X, is apparently associated with this planar fabric. The direction of maximum shortening (Z) deduced from such conjugate shears is approximately N100°E to N110°E.

At a later date, two new systems of ductile conjugate shear zones were developed: one with NE–SW dextral displacement and a second with NW–SE sinistral displacement indicating, as in the above case, a transverse shortening (perpendicular to the major axis of the pluton). These shear zones deform the main fabric and develop a subhorizontal mineral lineation.

Both deformations (1) and (2) could have been produced by a bulk pure shear mechanism. The conjugate shear systems may have originally formed with a dihedral angle of from 90 to 130° (Ramsay 1980) and this angle increased during the course of deformation until the present angle of 160° formed by the conjugate systems of the main fabric (Fig. 3) was attained. If the transverse shortening continued and the deformation could not be absorbed, a second generation of conjugate shears could have appeared (Figs. 3d & e). This conjugate shear mechanism is a common process in granitic rocks deformed by ductile *bulk inhomogeneous flattening* (Choukroune & Gapais 1983). In this case, the result is a transverse shortening with vertical stretching for the first generation of conjugate shears (main fabric) and with N–S to NNE–SSW, horizontal stretching for the second generation shears. The fact that the dextral, NE–SW system of the second generation predominates over the sinistral, NW–SE system does not necessarily have any special significance, since for shortening to take place one of the two systems must predominate and deform the other (Ramsay 1980).

The change in the X axis orientation from vertical during the first generation of conjugate shears to horizontal during the second generation, does not necessarily reflect a change in the tectonic regime. Both the anisotropy created during the first generation (main fabric) and the rotation of the pluton during deformation could have determined the new disposition (horizontal) for the X axis in the second generation of conjugate shear zones.

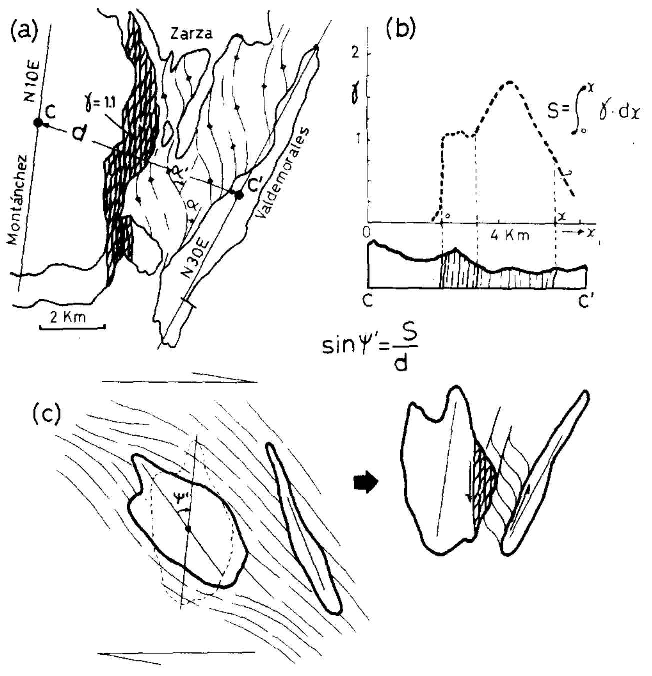

Fig. 4. Measurement of simple shear strain and displacements between the Montanchez and Valdemorales plutons. (a) Value of γ in the Montanchez shear zone and definition of the angles α and α' in the metamorphic rocks that separate the plutons. The initial angle (α) is formed by the shear direction and the S_1 schistosity near the contact of the pluton. This angle is assumed to reflect the initial, undeformed state. The shear direction is considered parallel to the major axis of the Valdemorales pluton. This idealization is necessary because of the local irregularities of the contact. (b) Plot of γ against distance (o–x) across the deformed zone along the line c–c′. In the metamorphic rocks γ is calculated from the equation $\gamma = \cot\alpha - \cot\alpha'$ (Ramsay & Graham 1970). The displacement S is calculated from the equation $S = \int_0^x \gamma\, dx$ (Ramsay & Graham 1970). (c) Value of the dextral rotation (ψ') which induced the N–S sinistral shearing.

The shear zone, located in the granodiorite on the east border of the pluton (Fig. 2), exhibits different characteristics to those described above. It is a ductile shear zone (simple shear) in which the shear planes (C planes), an oblique schistosity (S planes) and numerous criteria indicating rotational deformation are observed. The C-planes are arranged in a N–S orientation along the whole shear zone. The shear sense is sinistral and the stretching lineation (X axis) is subhorizontal or gently plunging towards the north.

A relevant aspect is that the N–S simple shearing does not continue in its direction within the host rocks. This suggests that the shear strain is due to sliding of the pluton past the host rocks. That is, the N–S sinistral shear zone could be induced by the dextral rotation of the pluton from its original site of intrusion. The value of dextral rotation (ψ') can be obtained approximately from the calculations of shear strain and displacement between the Montanchez and Valdemorales plutons. These calculations, shown schematically in Fig. 4, only give very rough indicators of displacement and strain because of the assumptions involved: (1) absence of volume change during deformation in the Montanchez shear zone; (2) passive behaviour of the S_1 schistosity and (3) the displacement along the C-planes in the Montanchez shear zone are not considered and thus a minimum displacement only is calculated.

The shear strain value (γ) is obtained in the east border of the Montanchez pluton (Montanchez shear zone) from the angle θ' between the S- and C-planes. A mean value of around 30° was obtained for θ' from several cross-sections through the shear zone. The lack of compositional variation throughout the shear zone may indicate that there was no volume change (Ramsay 1980). The equation $\gamma = 2/\tan 2\theta'$ (Ramsay & Graham 1970) may thus be applied and a mean value of $\gamma = 1.1$ is obtained. In the metasedimentary host rocks which separate the Montanchez and Valdemorales plutons (Fig. 4), the shear strain (γ) is calculated using the inflections of the S_1 schistosity between both plutons. According to the expression $\gamma = \cot\alpha - \cot\alpha'$ (Ramsay & Graham 1970), the curve of Fig. 4(b) is obtained and a total minimum displacement of around 5 km has been calculated. The obliquity between the borders of the Montanchez and Valdemorales plutons (Fig. 4a) is neglected for the calculation of shear strain and total displacement. These are calculated along section c–c′; the points c and c′ being the geometrical centres of each pluton. c–c′ is not perpendicular to the shear direction (Fig. 4a) which is N–S for the Montanchez shear zone and N30°E for the Valdemorales pluton.

The calculated displacement (5 km) yields a rotation of around 50° (Fig. 4). If this angle is used to restore the two plutons to their initial positions (Fig. 4c), their major axes are oriented approximately NW–SE, an orientation similar to those of the major axes of the later plutons (e.g. Cabeza–Araya pluton, Fig. 1).

The Alijares pluton (Fig. 5) occurs as a set of NE–SW oriented bands, in which quartz–diorite bands (group A) alternate with bands of granite composition (group B).

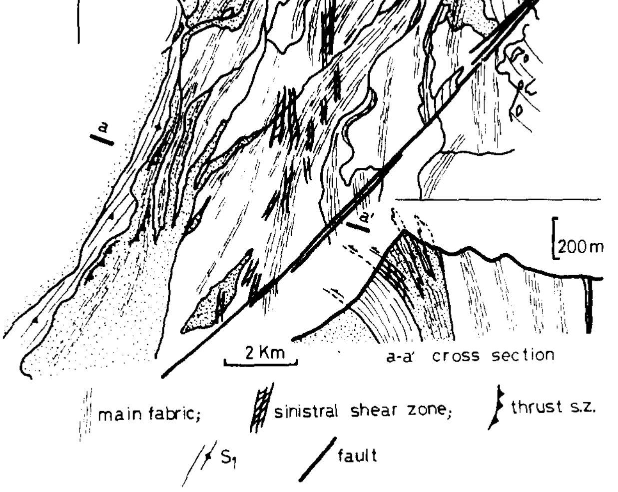

Fig. 5. Structural map of the Alijares pluton (2 in Fig. 1).

The linear disposition may be largely due to the intense deformation sustained by this pluton.

Three main types of planar structure are distinguished (Fig. 5): (i) a NE–SW subvertical foliation, (ii) N–S sinistral subvertical shear zones and (iii) shear zones of thrust sense. The first is a subvertical, planar, occasionally plano-linear fabric which contains a subhorizontal mineral lineation. It contains no fabric elements indicative of non-coaxial deformation and it may have formed as a result of pure shear strain (transverse shortening). This fabric may have developed in an original N–S position and rotated during the sinistral N–S deformation mentioned above. Alternatively, the main fabric may correspond to a component of pure shear accompanying the N–S sinistral simple shearing. According to Ingles (1983), both pure shear and heterogeneous simple shear must act simultaneously. Apparently, the N–S sinistral shear zones deform the main fabric; however, the low angle (less than 30°) between the main fabric and the shear zones supports on interpretation of simultaneous pure and simple shear (Ingles 1983).

The sinistral N–S shear zones are localized in narrow bands (1–10 m in width) in which the rocks are strongly foliated and criteria indicating non-coaxial deformation, in the *XZ* section (Fig. 6), are clearly recognizable.

Finally, the shear zones of thrust sense are preferentially located on the western border of the pluton (see cross-section a–a′ in Fig. 5) making the pluton 'override' its host rocks. These may indicate a transverse shortening. Field data are not sufficient to establish a temporal sequence between the sinistral N–S shear and the thrust shear zones. They may have acted simultaneously to form a "flower structure" as defined by Sanderson & Marchini (1984) in a simple transpression regime.

In both the Montanchez and Alijares plutons, a spatial transition is observed from the domain of thrust shear zones (with *X* subvertical) to the domain of N–S sinistral shear zones (with *X* subhorizontal). In addition, the structural pattern of Alijares is very similar to that of Montanchez; that is, there is a finite transverse shortening (perpendicular to the major axis of the pluton) and N–S sinistral simple shearing, and these may have occurred simultaneously. The N–S sinistral shear zones in the Alijares pluton may be due to the displacement and dextral rotation of the pluton from its original site of intrusion to its present position, as proposed for the Montanchez pluton.

Structural pattern of the late, undeformed plutons

This group includes those plutons which contain no evidence of shear deformation and which have an internal structure that is interpreted to reflect only the emplacement dynamics. The Trujillo and Alcuescar plutons are the most significant examples of this group (Fig. 1). They are composed of C-group granitoids and contain a concentric zonation of granitic facies in which the more evolved (felsic) facies are located near the central parts of the plutons.

The Trujillo pluton (Fig. 7) has a structural pattern defined by the following elements: (i) an elongate shape in horizontal section; (ii) a planar fabric of K-feldspar megacrysts, which parallels the contacts of the pluton; (iii) earlier joints (emplacement fractures of Castro 1984b) which indicate lateral widening during emplacement and (iv) weak deformation of the pre-existing structures (S_1) in the host rocks.

The three facies C1, C2 and C3 (Fig. 7) might have

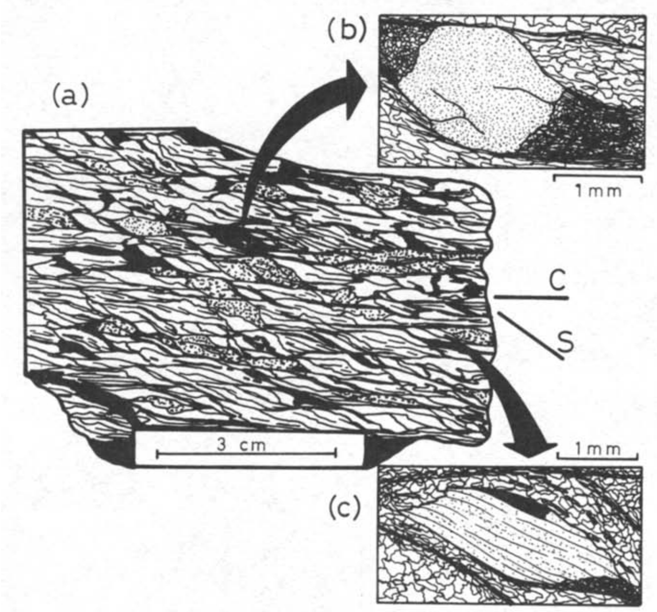

Fig. 6. Mesoscopic aspect in an *XZ* profile of the granites deformed by the N–S sinistral shear zones (two-mica granite of Alijares), showing the S- and C-planes. (b), (c) Microscopic aspect of asymmetrical K-feldspar augen and asymmetrical fish-shaped muscovite, indicating the rotational mechanism.

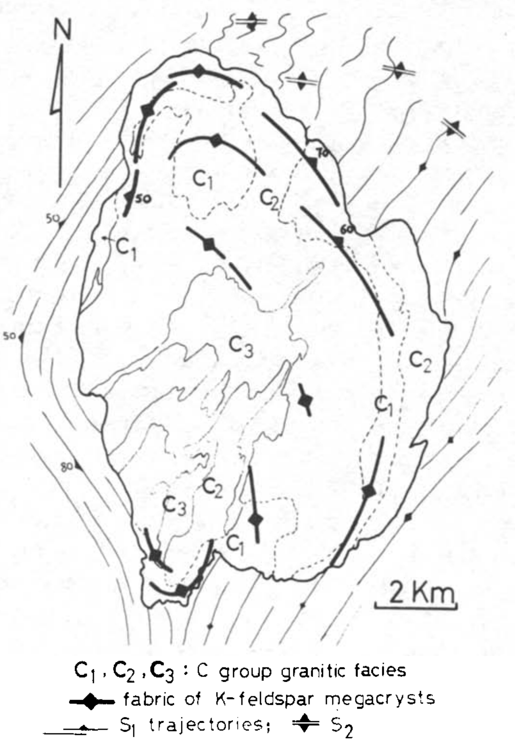

Fig. 7. Stuctural map of the Trujillo pluton (5 in Fig. 1).

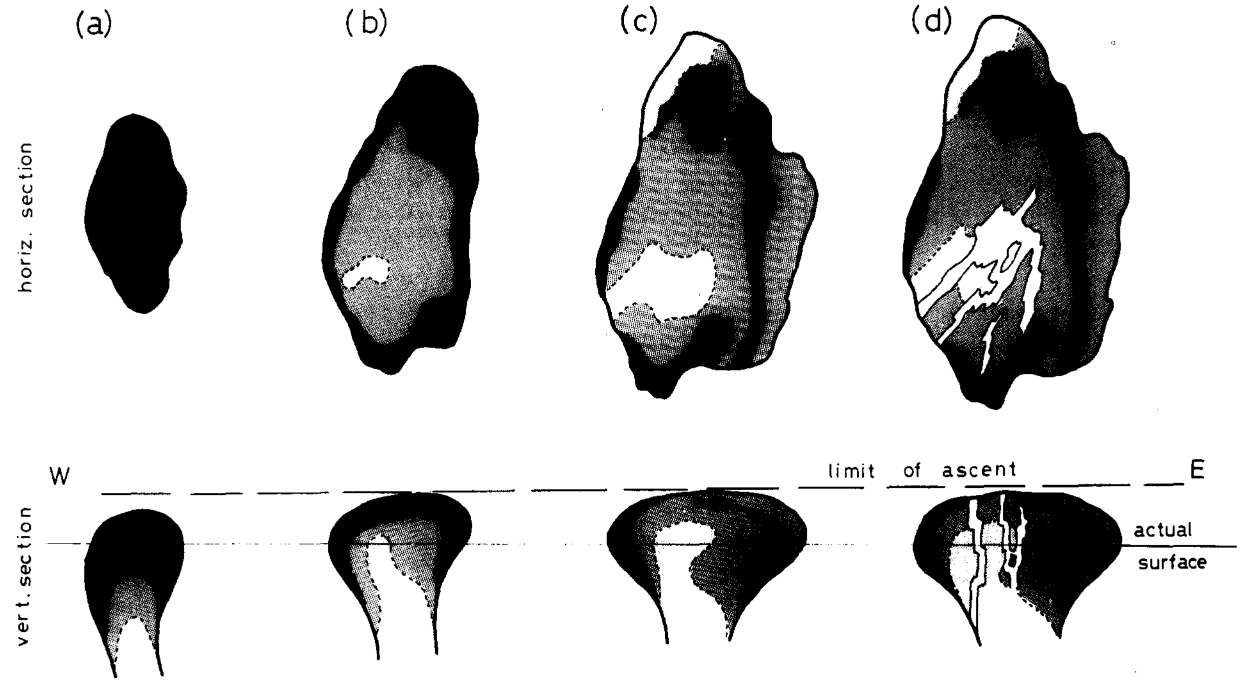

Fig. 8. Four stage, idealized representation of ascent and emplacement of the Trujillo pluton. Ascending pluton in which differentiation is produced by migration of volatiles towards the tail zone (the lighter shades of grey are the more felsic facies). (a) Early stage. (b), (c) The pluton reaches a limiting height in the crust and expands laterally by forced injection of the central facies. (d) Shattering and emplacement by stoping of the aplitic facies. The 'ascent limit' could be situated at around 8 km depth, deduced from the PT conditions of the contact metamorphism (Castro 1984a).

originated by a volatile migration-related differentiation mechanism (Corretgé *et al.* 1983). The volatiles could have migrated towards underpressured zones in the intrusion tail during ascent (Fyfe & Brown 1972, Marsh 1982). The ascent model proposed in Fig. 8 (Castro 1984a) assumes that the more evolved facies were located at the tail of the pluton during ascent (Fig. 8a). When the intrusion roof reached a limiting height in the crust, sufficiently cool to prevent further ascent, the central facies began to intrude into the central part of the pluton (Figs. 8b & c), inducing lateral widening (i.e. a ballooning process, e.g. Bateman 1984, 1985) and flow parallel to the contacts, in turn giving rise to the planar fabric of K-feldspar megacrysts. The emplacement fractures could have developed at this stage. Finally, a terminal process of shattering may have given rise to emplacement by stoping of the C3 aplitic facies (Fig. 8d).

This emplacement mechanism may account for the structural pattern of the pluton and the relationships among the facies composing it. However, the vertical push itself, resulting from the density contrast between magma and host, was not necessarily the only cause of the forced intrusion of the tail into the central part of the pluton causing the lateral widening. The transverse shortening, deduced in the deformed plutons, could also have occurred here, such that the ascent conduit became tectonically closed in a direction perpendicular to its major axis and the pluton became forcefully *extruded* upward, expanding laterally when the intrusion roof reached its limiting height in the crust (Fig. 8).

The Alcuescar pluton (Fig. 9) exhibits a structural pattern which is fairly similar to that of Trujillo. The planar fabric of K-feldspar megacrysts is parallel to the

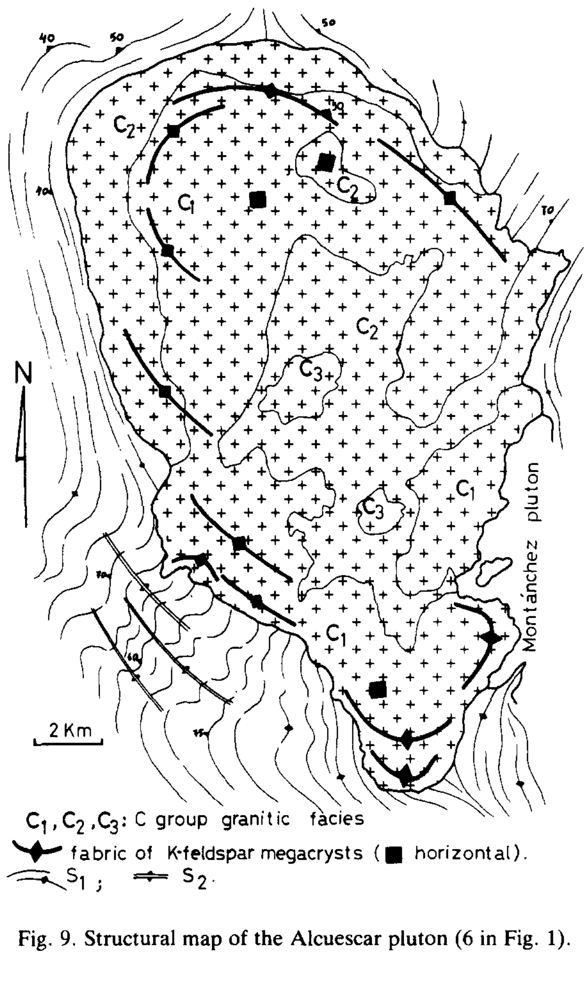

Fig. 9. Structural map of the Alcuescar pluton (6 in Fig. 1).

contacts of the pluton. This fabric may be due to a flow parallel to the contacts, which is also reflected in the orientation of xenoliths and biotite schlieren present in C1. This aspect, together with the late nature of the central facies relative to the marginal ones, means that it is possible to interpret (as in Trujillo) the existence of an emplacement mechanism with lateral widening. On the north border of the pluton, the lateral widening is more pronounced and has given rise to deformation of the host rocks in such a way that the pre-existing schistosity is parallel to the NW contact (Fig. 9). Emplacement fractures due to the lateral widening are also a common feature along this border.

Plutons with intermediate characteristics

Apart from the extreme cases of late (undeformed) and earlier (deformed) plutons, described above, there is a whole range of intermediate cases in which emplacement-related elements and deformation structures are superimposed within the same pluton. The most representative examples are the plutons of Plasenzuela, Cabeza–Araya and Santa-Cruz (Fig. 1).

The Plasenzuela pluton (Fig. 10) is mainly composed of C-group granitic facies (C1, C2 and C′2). The most significant structural elements are: (i) an elongate shape; (ii) the concentric zonation of granitic facies; (iii) contacts conformable to the regional S_1 schistosity in the host rocks and (iv) a sinistral, N–S oriented shear zone on the eastern border of the pluton.

The wedge-shaped termination of the southern border might be a result of ascent through extensional fractures. The aplitic marginal ring has been interpreted to be a result of a lateral push due to widening of the pluton

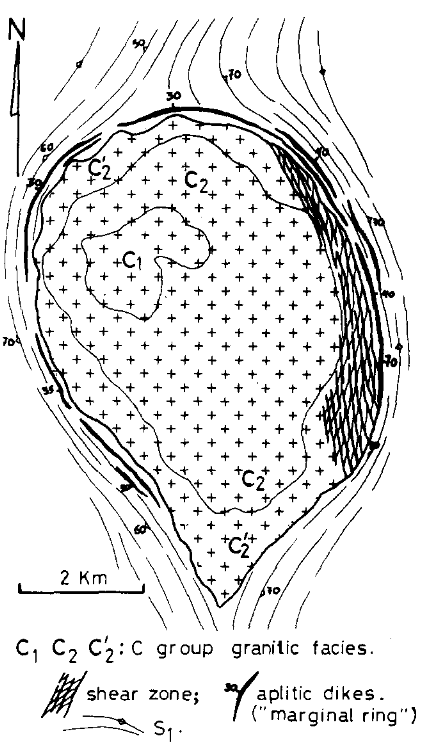

Fig. 10. Structural map of the Plasenzuela pluton (3 in Fig. 1).

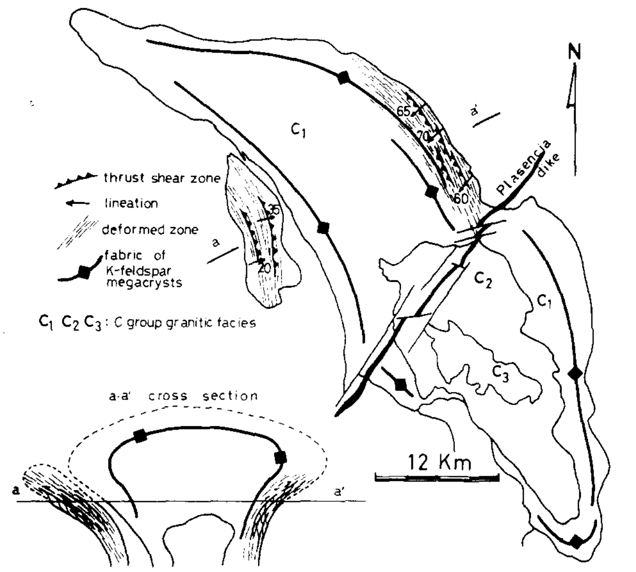

Fig. 11. Structural map of the Cabeza–Araya pluton (7 in Fig. 1) and a–a′ cross-section. Modified after Corretgé (1971).

(Castro 1984b), in a manner similar to that inferred for the Trujillo and Alcuescar plutons. The deformation of the regional S_1 schistosity may also be due to this lateral widening. The deformed zone of the eastern border (Fig. 10) is a N–S ductile shear zone developed after the emplacement of the pluton (Castro 1984b). This shear zone could have been developed by dextral rotation of the pluton, since it does not continue either to the north or to the south within the host rocks. Therefore it may have the same significance as the N–S sinistral shear zones described in the earlier, deformed plutons.

The Cabeza–Araya pluton (Fig. 11) is composed of C-group granitic facies. It exhibits characteristics of the late plutons, and deformed zones typical of the earlier plutons located on the NE border. This border is a ductile shear zone which acted as a thrust fault verging towards the external part of the pluton. There are ductile thrust faults symmetrically opposed located in the smaller pluton of Brozas, which is attached to the western border of the Cabeza–Araya pluton (Fig. 11). The Brozas pluton could have been emplaced before the Cabeza–Araya pluton and the thrust shear zones which deform it may therefore be comparable with those appearing on the NE border of the Cabeza–Araya pluton. Both thrust-shear-zone systems may indicate a transverse shortening, of the same type inferred for the early plutons (i.e. Montanchez and Alijares).

The Santa-Cruz pluton (Fig. 12) exhibits certain structural characteristics which do not appear in the other plutons of the batholith, though they may be compatible with those described above. It is composed almost entirely of A-group granitoids (quartz–diorites) rich in deformed biotite spots which faithfully reflect the internal structure of the pluton (Fig. 12a). The most significant structural elements are: (i) the elongate shape, with a termination on the northern border involving numerous quartz–diorite layers intercalated with high-grade metamorphic rocks (migmatites) developed at the con-

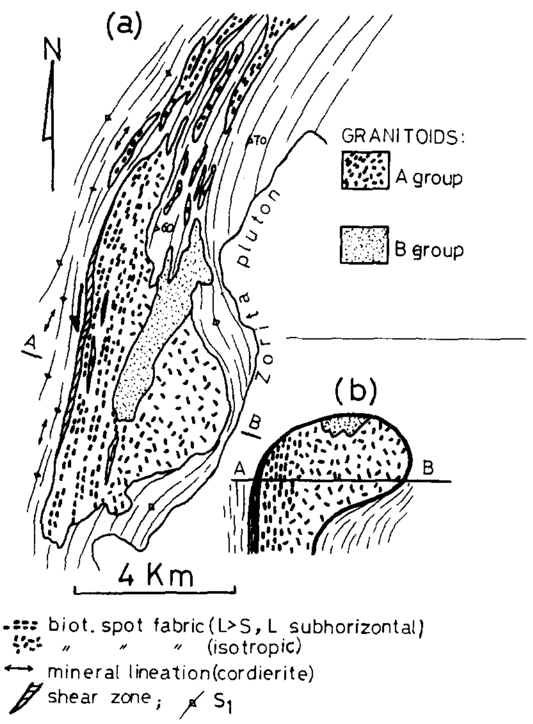

Fig. 12. (a) Structural map of the Santa-Cruz pluton (4 in Fig. 1). (b) Hypothetical cross-section A–B.

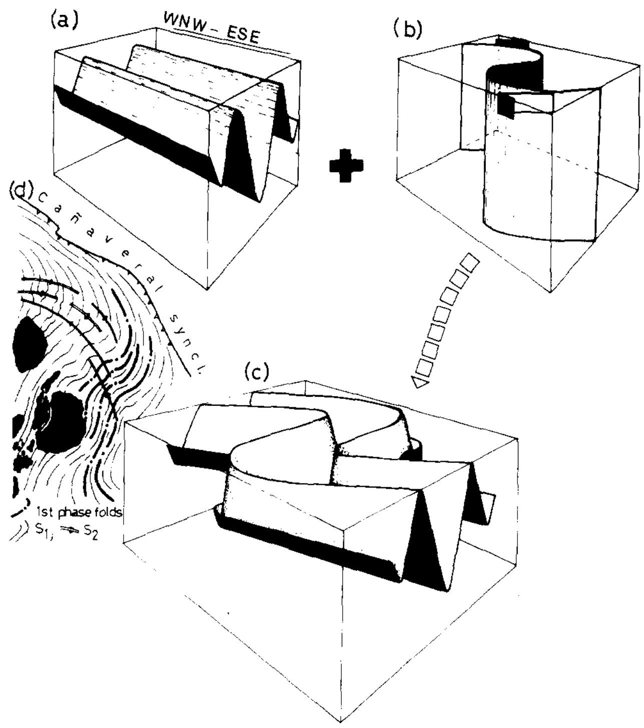

Fig. 13. Idealized model for the interference of first-phase and second-phase folds. (a) First-phase folds. (b) Superimposed folding by dextral simple shearing. (c) Resulting interference. (d) Geological sketch of the western sector of the Central Extremadura where the vertical-axis folds and associated axial-plane schistosity occur (see Fig. 1).

tact aureole; (ii) a N–S oriented, sinistral shear zone, located at the western contact, and affecting both the quartz–diorite and the host rocks; (iii) a subhorizontal lineation of cordierite aggregates developed in the contact aureole of the western border, probably related to the shear strain mentioned above and (iv) an internal structure defined by a subhorizontal linear fabric of biotite spots. There is a gradual loss of this fabric towards the eastern border where the biotite spots are randomly oriented (Fig. 12). This fabric could have developed during the shear strain which affected the western border. Since there is no intracrystalline deformation in the quartz–diorite, the magma must still have been unconsolidated when the shear strain took place.

It may be concluded that the Santa-Cruz pluton was emplaced synkinematically with the sinistral shear zone. At the same time, the ascent conduit could have been closed in a direction transverse to its major axis and the pluton could thus have expanded laterally towards the eastern border (Fig. 12b), where the sinistral shear had no effect. The shear zone at the western border does not continue into the host rocks, nor towards the north or the south. It may have been induced by the dextral rotation of the pluton during its emplacement.

Structural outline of the metasedimentary host rocks

In the first part of this paper reference was made to the major structures which owe their existence to two main deformational phases in the Central Extremadura area (CEA). Figure 13 illustrates schematically the interference effect, resulting from the first and second deformation phases, in the eastern sector of the CEA (Fig. 13d). The geometry and spatial arrangement of the first-phase (D_1) folds (Fig. 13a) may be deduced from observations in adjacent areas in which the second deformation phase (D_2) did not act. The superimposed folding could have resulted from dextral simple shearing in an oblique direction (E–W) to the main flattening (S_1 schistosity) of the D_1 folds (Fig. 13b). From the angular relationships between geometric elements of the initial and superimposed folding (angles α and β, Ramsay 1967), the resulting interference model (Fig. 13c) would correspond to Ramsay's type 2.

This may be the result of D_2 dextral shear acting at deep levels of the crust, which, at higher levels, gave rise to the superimposed folding. The rotation of the D_1 structures caused a transverse widening along a NNE–SSW structural trend and was manifested by the N-verging thrust faults located on the S limb of the Cañaveral syncline (Figs. 1 and 13d).

DISCUSSION: A QUALITATIVE MODEL FOR ASCENT

General considerations

The behaviour of the continental crust during orogenic processes is an important enigma which has received numerous tentative interpretations. The role of the fluid phase is undoubtedly one of the more important factors to be taken into account, since to a large extent it conditions the rheological behaviour of the crust during orogenic processes (Etheridge *et al.* 1983).

The fluid released during the metamorphic processes, at any crustal level, may have been retained in the rocks in intergranular spaces and microcracks (White & White 1981) so that the effective stress (effective stress equals acting stress *minus* fluid pressure, Terzaghi 1936) may have been zero in some direction. When the least principal stress is exceeded by the fluid pressure, extensional fractures may be formed independent of the depth considered (Secor 1965). Shaw (1980) has shown how such extensional fractures may have originated in the crust at depths even greater than 40 km. He contrasted such theoretical results with field data from seismically active zones in which the propagation of extensional fractures constitutes the mechanism of magma transport to the surface. Likewise, Spera (1980) arrived at analogous conclusions regarding the formation of extensional fractures at deep crustal levels.

There is nothing to prevent one from extrapolating to ancient orogens, since it is commonly accepted that the behaviour of the continental crust since the Lower Paleozoic did not differ greatly from the present day situation (Dewey & Spall 1975). Accordingly, of interest is the model of Hutton (1982) for the ascent and emplacement of the Donegal batholith in the Caledonides of Northern Ireland, in which extensional fractures, induced by a crustal shear zone, are also considered.

In the CEB, granitoid intrusions were emplaced immediately after the regional metamorphism which accompanied the first deformation phase (Castro 1984a). The metamorphic grade, which in this area is low and in the greenschist facies (Winkler 1978), could have increased towards deeper crustal levels until anatexis conditions were reached (e.g. Ugidos 1976, Garcia de Figuerola *et al.* 1983). If the D_2 deformation (shear zones) took place immediately after the regional metamorphism, it is clear that the fluids released and/or the melts developed in such a metamorphic process largely controlled the rheological behaviour of the continental crust in this sector of the chain. Therefore, extensional fracturing is the process which could have accommodated the ascent of the CEB granitoids. In addition, the correlation of the structural patterns of each pluton may be accounted for within a general model of deformation, ascent and emplacement for the whole CEB. The most salient structural events in the individual plutons can be summarized as follows.

(1) In the earlier plutons: (i) transverse shortening gave rise to the conjugate shear zones and to ductile thrust faults and (ii) dextral rotation of the plutons could have induced the development of N–S oriented sinistral shear zones (antithetic shears).

(2) In the late plutons: tectonically induced lateral widening by intrusion of the central facies probably produced the planar fabric of K-feldspar megacrysts, the emplacement fractures, and weak deformation of the host rocks.

(3) In the plutons of intermediate characteristics: (i) lateral widening *plus* dextral rotation occurred (e.g. Plasenzuela); (ii) lateral widening *plus* transverse shortening occurred (e.g. Cabeza–Araya) and (iii) emplacement occurred synkinematically with dextral rotation (Santa-Cruz).

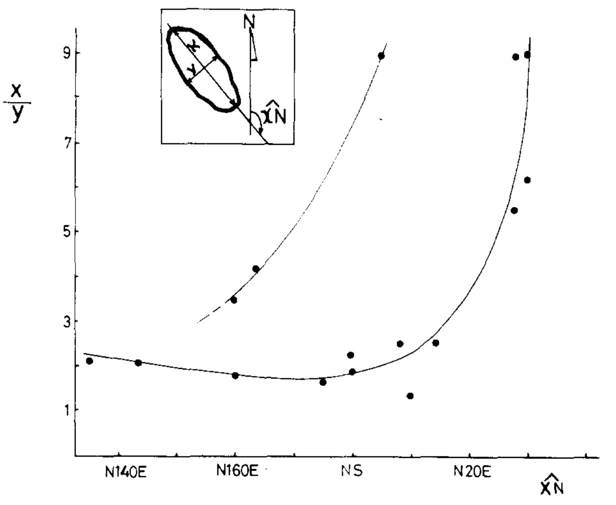

Fig. 14. Graphical representation of x/y vs the geographic position (azimuth of x) of the CEB plutons. From a N10°E orientation, the axial ratios increase due to the intense deformation which affected the earlier plutons oriented between N–S and N30E. Inset: x, y parameters and the angle $\hat{xN}$ represented on the graph.

Another significant aspect is the orientation of the major axis of each pluton. Practically all the plutons exhibit a well-defined major axis (x); however, x has a NW–SE orientation in the late intrusions and a NE–SW orientation in the earlier ones. The early, NE–SW oriented plutons exhibit axial ratios (x/y, i.e. major axis/minor axis, measured in a horizontal section) greater than those of the late plutons. Figure 14 shows x/y plotted vs geographical orientation of the major axis (x), and it may be seen that the highest values of x/y correspond to the NE–SW oriented plutons. The original x/y ratios could have increased as result of deformation during dextral rotation undergone by these earlier plutons.

An integrated ascent model

The hypothesis that all the plutons of the CEB intruded as elongate bodies in a preferential NW–SE direction therefore seems plausible. Furthermore, as has been seen, all the plutons which have an orientation other than NW–SE, exhibit structures which indicate a dextral rotation either during or after emplacement. All this suggests the existence at deep crustal levels of a dextral shear zone which caused the rotation of the intrusions and D_1 folds. This could be the driving force behind all the post-D_1 phenomena observed in the CEB.

Furthermore, if the original direction of intrusion was NW–SE, the ascent conduits may correspond to extensional fractures developed at 45° to the shear direction. That is, this shear zone could have acted at deep levels in an approximately E–W direction. This is the basis of the proposed ascent model (Fig. 15) for the Central Extremadura batholith: immediately after the first deformation phase, an E–W dextral shear zone

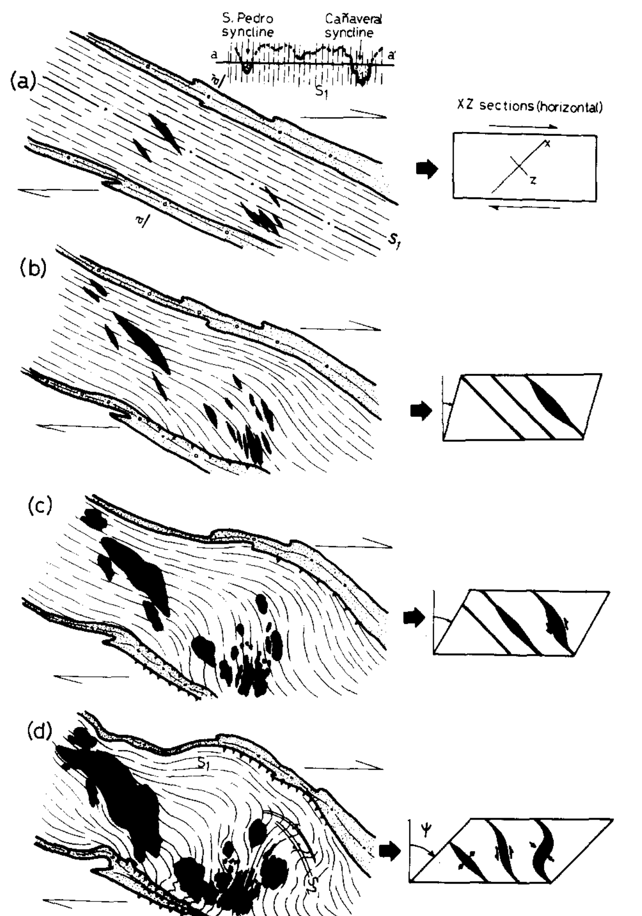

Fig. 15. Idealized representation of the qualitative ascent model. (a) The situation after the first Hercynian deformation phase, when the E–W dextral shear zone began to act at depth. (b) Intrusion of the earlier plutons through extensional fractures developed at 45° to the shear direction. (c) Dextral rotation of intrusions and first-phase structures. (d) The final situation with the appearance of the second schistosity (S_2) and thrust faults located in the Cañaveral syncline. The XZ sections, corresponding to each step, show the disposition of the principal axes (X, Z), angular shear, ψ, the orientation of the extensional fractures and their dextral rotation.

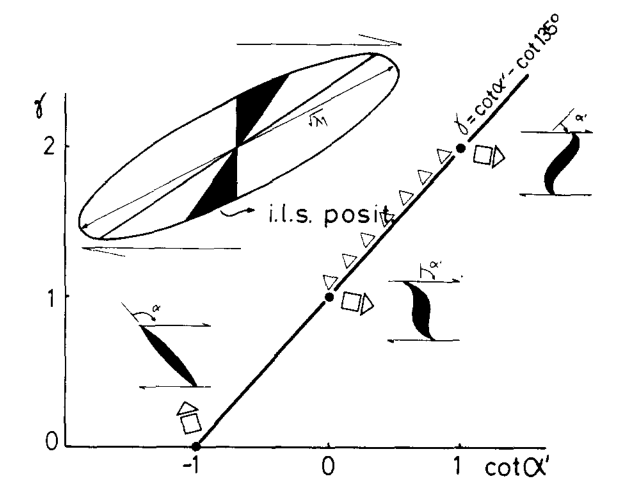

Fig. 16. Theoretical evolution of the extensional fractures from their initial position ($\alpha = 135°$) to the more evolved position ($\alpha' = 45°$). The 'fractures' change from being in zones of extension to being in zones of compression when they reach the position $\alpha' = 90°$. Inset: incremental strain ellipse associated with the E–W dextral simple shearing to show the field (black) where the infinitesimal longitudinal strain is positive. The plutons are in this field when they occupy a position between N–S ($\alpha' = 90°$) and NE–SW ($\alpha' = 45°$), and consequently these plutons appear strongly deformed.

developed, resulting in the concomitant formation of NW–SE oriented extensional fractures (Fig. 15a). These fractures were used by the granitic magmas for their ascent from their zones of origin (Fig. 15b). The shear zone itself caused the rotation of the earlier intrusions and first-phase structures, and new extensional fractures were developed (Fig. 15c). Finally, the earlier intrusions were rotated into their present position (NE–SW), and at the same time they were strongly deformed (i.e. N–S sinistral antithetic shears, conjugate shear zones, etc.). The dextral rotation of the first phase structures gave rise to the vertical-axis folds (Fig. 15d). The process could have lasted 17 Ma over the period 320–302 Ma (Castro 1984a).

Practically all the major structures and the structural pattern of the individual plutons may be accounted for by this qualitative model. When the intrusions were rotated, in a dextral sense, the N–S sinistral antithetic shears may have developed. When a pluton reached a N–S orientation during rotation, it passed through a critical field of the hypothetical incremental strain ellipse associated with the E–W shear zone (Fig. 16). The lines of positive infinitesimal longitudinal strain fall into this critical field, thereby producing the transverse shortening perpendicular to the major axis of the pluton. This shortening produced different structural patterns in early and late intrusions as illustrated in Fig. 17. The early intrusions (e.g. Alijares and Montanchez plutons) must have solidified by the time they reached a N–S position, and the N–S sinistral shear zones developed. After this position was passed, the transverse shortening took place. Both conjugate shear zones and thrust shear zones were developed in this situation. The late intrusions ascended when the earlier plutons were deforming (Fig. 17). These late, undeformed intrusions reached the N–S position and were not affected by the N–S sinistral shear zones; that is, they were still unconsolidated at this stage. Finally, when they passed the N–S position, a transverse shortening took place inducing the lateral spreading of the pluton and its tectonically forced emplacement. At this final stage the plutons were not consolidated and no deformation structures were developed (e.g. Trujillo pluton).

The intermediate intrusions (Fig. 17) are those that present a mixed structural pattern with structural elements of both early and late plutons. These must have been intruded at an intermediate stage between the early and late intrusions and thus they show the antithetic shear zones resulting from rotation (e.g. Plasenzuela).

In addition, this model implies that the late intrusions cooled more slowly than the earlier ones. All the plutons were emplaced under the same tectonic regime (E–W shear zone), but the early intrusions cooled rapidly and were ductilely deformed while the late intrusions reached a previously heated zone of the crust and cooled more slowly. Thus these late intrusions were not

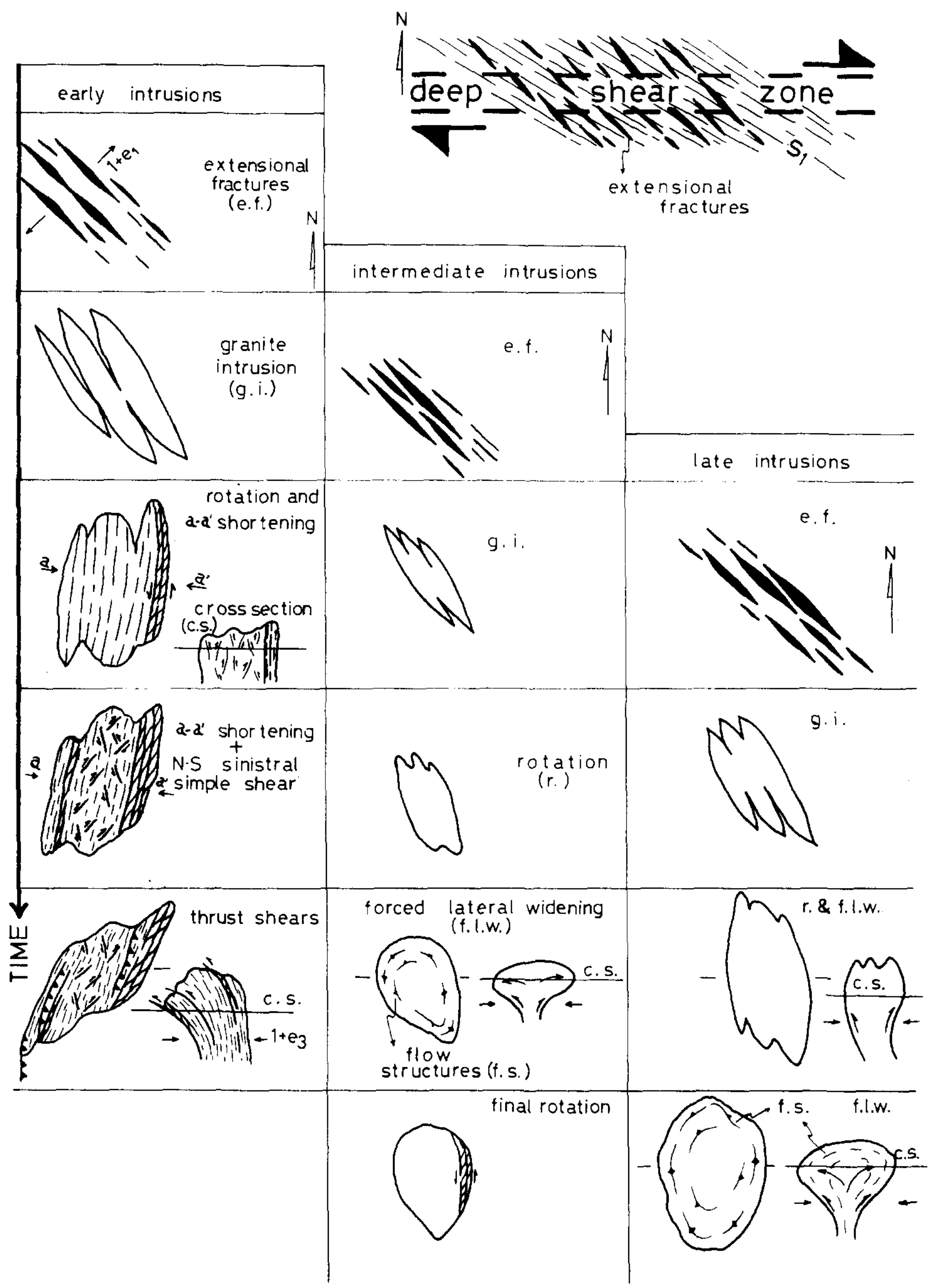

Fig. 17. General summary of the structural pattern of the individual plutons and their interpretation within the ascent model. Inset: deep shear zone which leads to the formation of extensional fractures used by the granitoids as their ascent conduits (see text for explanation).

deformed but rather experienced a tectonically forced emplacement in response to the regional tectonic regime.

Finally, it should be pointed out that the deep E–W dextral shear zone, which controlled the evolution of the CEB, may be comparable with other intracontinental shear zones in the Iberian massif. The massif itself developed during the continental collision which gave rise to the Ibero-Armorican arc (Matte & Ribeiro 1975, Burg *et al.* 1981, Castro 1985).

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