SC DEFORMED GRANITOIDS IN THE SAN VICENTE RANGE (CENTRAL SPAIN)

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ABSTRACT

SC deformed granitoids are found in the San Vicente Range in Central Spain. Three deformation features appear in them: S planes, C planes, and lineations on the C planes. The rocks occasionally display ultramylonites. A complex temporal succession of deformation episodes affected these granitoids: i) a magmatic intrusion, during which an S_1 foliation developed on the borders of the pluton; ii) a tectonic extensional episode, with NNE-dipping C_2 shearing planes; iii) a tectonic transcurrent sinistral regime, triggering a WNW/ESE-oriented band with C_3 shearing planes; iv) an intrusion of leucogranites within the transcurrent band, developing S_4 and C_4 deformation planes. Three types of deformed granitoids are defined, according to the presence of S and C planes together: S_1C_2 granitoids, in the area of extension; S_1C_3 and S_4C_4 granitoids, in the transcurrent band. On the basis of these data, some controversial issues related to the larger group of SC deformed rocks can be discussed.

Key words: SC deformed granitoids, Shear criteria.

RESUMEN

Se describen ejemplos de granitoides SC presentes en la Sierra de San Vicente, en la zona central de España. En ellos aparecen tres estructuras de la deformación: planos S, planos C, y lineaciones en los planos C. Las rocas presentan ocasionalmente ultramilonitas. Estos granitoides sufrieron una compleja sucesión de deformaciones: i) una intrusión magmática, durante la cual se desarrolla una foliación S1 en los bordes del plutón; ii) un episodio distensivo, con formación de planos de cizalla C_2 buzantes al NNE; iii) un episodio transcurrente-senestral generando una banda WNW/ESE con planos de cizalla C_3; iv) una intrusión de leucogranitos en la banda transcurrente, que desarrollan planos S_4 y C_4 al deformarse. En función de la presencia de S y C juntos en las rocas, se definen tres tipos de granitoides cizallados: granitoides S1C2 en la zona de extensión, y granitoides S_1C_3 y S_4C_4 en la banda transcurrente. En base a todos estos datos, se discuten algunos puntos controvertidos en relación con el grupo general de rocas deformadas SC.

Palabras clave: Granitoides deformados SC, Criterios del sentido de movimiento.

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1. INTRODUCTION

Deformed granitoids with composite planar fabrics have been abundantly described in the literature after the papers of Berthe et al. (1979 a,b), and they are now commonly used as kinematic indicators.

However, the use of SC fabrics to deduce the type of deformation is a point which needs discussion, since many factors play a role, such as intrusive or tectonic-related stresses, pure or simple shear regimes, relative timing of the S and C planes, etc.

There are four main objectives in this paper: the description of the deformational fabrics, the application of shear sense criteria to them, the deduction of their origin and relative timing, and the discussion of some issues related to SC deformed rocks as a whole.

The San Vicente Range (Casquet, 1975; Doblas et al., 1983), forms an isolated outcrop of metamorphic

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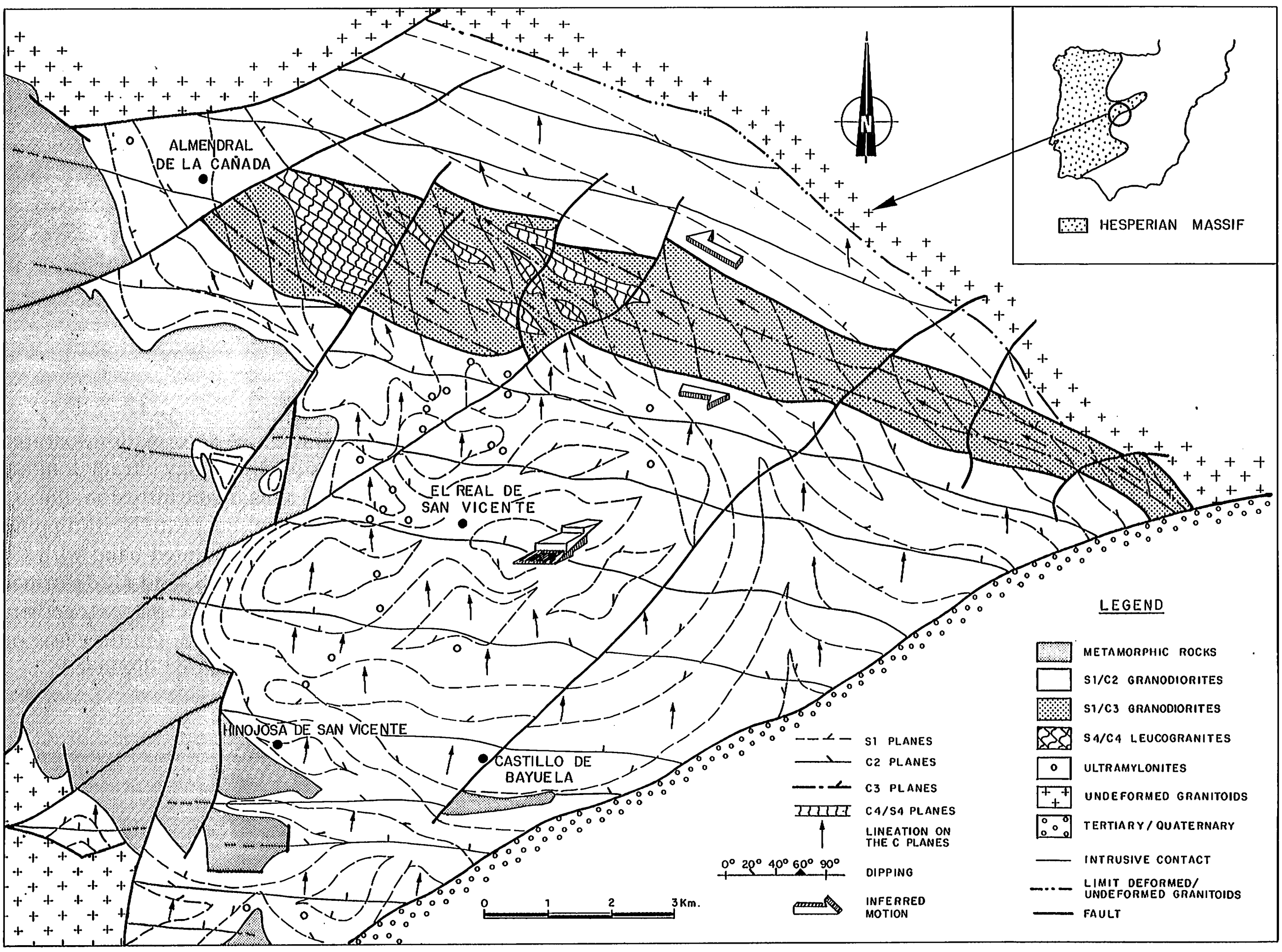

Fig. 1.—Structural map of the different deformation features displaid in the San Vicente granitoids.

Fig. 1.—Esquema estructural de las características estructurales de las rocas graníticas de San Vicente.

rocks, surrounded by granitoids, in the southwestern Spanish Central Range, pertaining to the Hesperian Massif (Fig. 1).

Both deformed and undeformed granitoids are observed in the area (Fig. 1). Deformed granitoids are either porphyritic granodiorites, or leucogranites outcropping as minor lensoidal bodies. They display three deformation features: S planes, C planes, and lineations on the C planes. Ultramylonites appear occasionally in discrete zones of higher strains within the granitoids. The S and C terminology is used after Berthe et al. (1979 a,b), and the subscripts refer to the proposed temporal succession (S_1, C_2, C_3, and C_4/S_4).

2. SC DEFORMED GRANITOIDS

There are two types of S planes: S_1 planes, affecting the granodiorites, and S_4 planes, found within the leucogranites (Figs. 1 and 2a). The S_1 planes constitute a regionally penetrative ductile foliation, defined by a compositional banding of micas with preferred dimensional orientation, and by elongated quartz ribbons curving around feldspar porphyroclasts. The S1 planes have the following characteristics (Fig. 1): i) the structures in them reveal a positive strain gradient in the direction of the granitic/metamorphic interface (the fabrics evolve from ultramylonitic near the interface, to standard S_1-type mylonitic, and undeformed, toward the N, NE, and E); ii) the number of metamorphic inclusions in them increases toward this interface; iii) they parallel the granitic/metamorphic interface in its vicinity; iv) their regional trend shows complex convolute patterns; v) they are sigmoidally deformed by C shearing planes. The S_4 planes appear as N/S-oriented and subvertical sigmoids within the leucogranitic bodies.

The C planes, as a whole, are non-penetrative shear surfaces with a semi-ductile behaviour (there are slickenside features, but some metamorphic minerals as sillimanite, and garnet appear along them), and they have the following characteristics: i) they display uniform (90°-110°) regional trends; ii) they are unaffected by the vicinity of the granitic/metamorphic interface (they intersect it at a high angle, and do not show any strain gradient toward it); iii) some C planes (C_2) are found within the metamorphic rocks, as late crenulation cleavages; iv) they have constant lineation directions, defined by slickenside striations (N for C_2, and WNW for C_3/C_4); v) they sigmoidally deform the S planes under simple shear conditions (Doblas, 1985), as revealed by the dominance of congruent mineral rotations, the absence of flattening

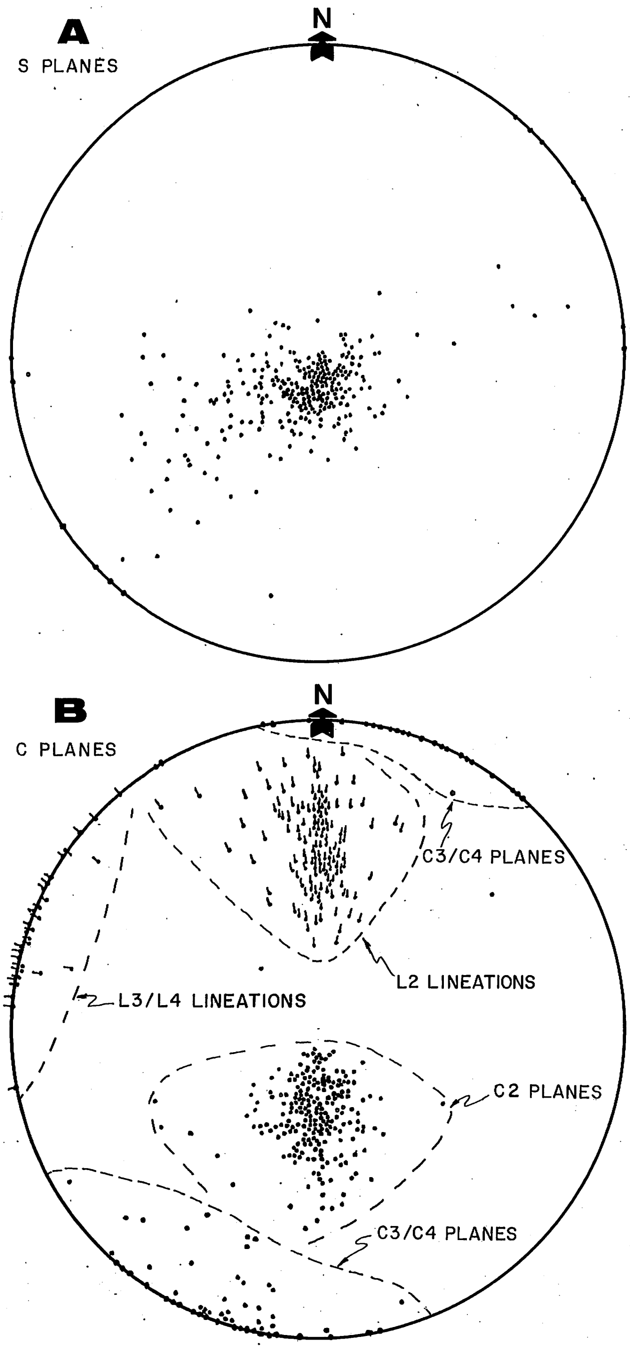

Fig. 2.—Stereograms showing main structural data of the San Vicente deformed granitoids. (a) Poles to S planes. (b) Poles to C planes and associated L lineations.

Fig. 2.—Estereogramas con los datos estructurales mas importantes de las rocas graníticas deformadas de San Vicente. (a) Polos de planos S. (b) Polos de planos C y lineaciones L asociados.

normal to C, and the abundance of slickenside striations. Three types of C planes are distinguished (figs. 1 and 2b): CS planes, dipping 30°/50° to the NNE with constant northward lineations (L_2), and vertical C_3 and C_4 planes, with constant horizontal lineations (L_3 and L_4), defining a WNW/ESE trending band. The C_4 planes are restricted to the leucogranitic bodies in this band, where it is possible to observe C_2 planes overprinted by later C_3 planes.

According to the presence of the S and C planes together, the deformed granitoids define three structural domains (Fig. 1): a large area with S_1C_2 deformed porphyritic granodiorites, a WNW/ESE band with S_1C_3 deformed granodiorites, and the western part of this band, with S_4C_4 deformed leucogranites.

The S_1C_2 granitoids show C_2 shear planes which sigmoidally deform the S_1 planes, in a way indicating a top-to-the-N displacement (Fig. 3a). On the outcrop and regional scales, these two planar features rarely coincide in orientation. In these rocks, there is no clear pattern relating increasing strain to decreasing C/S angles (as described by Berthe et al., 1979 a,b), and this is due to the heterogeneity of the deformations. At the sample scale, the irregularity of the C_2 planes is often dependent on the abundance of porphyroclasts (Hanmer, 1979). In some cases where higher strains developed, S_1 and C_2 become parallel, and a third C'_2 foliation appears (Berthe et al., 1979 a,b), oblique to C_2, and dipping opposite to S_1. The highly porphyritic character of these granitoids allows us to define two types of deformed phenocrysts (Fig. 4): «grains with pressure-shadows», and «broken displaced grains» (Simpson and Schmid, 1983). The grains with pressure-shadows may be «locked» (Fig. 4a) or «rotated» (Fig. 4b). The broken displaced grains show «shear-steps» (Fig. 4c), and «pull-aparts» (Fig. 4d). In these rocks there is continuing deformation/recrystallization of feldspar phenocrysts, from S_1, to C_2 and the ultramylonites (Doblas, 1985).

In the S_1C_3 granitoids, S_1 is sigmoidally deformed in a sinistral way, this time by the more penetrative C_3 planes (Fig. 3b). The non-coeval character of S_1 and C_3 is revealed by a number of leucocratic veins only affected by the later C_3 planes.

The S_4C_4 leucogranites display similar sigmoidal relationships, with a sinistral dragging along the WNW/ESE-oriented C_4 planes.

The ultramylonites are dark rocks occurring randomly within the S_1C_2 granitoids. They result from high strains localized in specific zones of the granitoids, having the same mineralogy as these, with all the elements comminuted. They form wide bands paralleling C_2, or irregular vein-like patterns. Some of these ultramylonites are old pseudotachylites, recrystallized (Doblas, 1987). The initial granitic fabric in them has been obliterated by strong deformations. However, the wide bands develop an «SR foliation» (S-type foliation defined by quartz ribbons; Fig. 3c). SR indicates a top-to-the-N displacement along the bordering C_2 planes, by its obliquity and inclination to these planes. As described by previous authors (Sibson, 1980; Carreras & Losantos, 1982; Passchier, 1984), ultramylonites are a common phenomenon in the deformation behaviour of granitoids.

3. SHEAR SENSE CRITERIA

Two different shear sense criteria have been used in these granitoids, SC sigmoidal relationships, and mineral deformations.

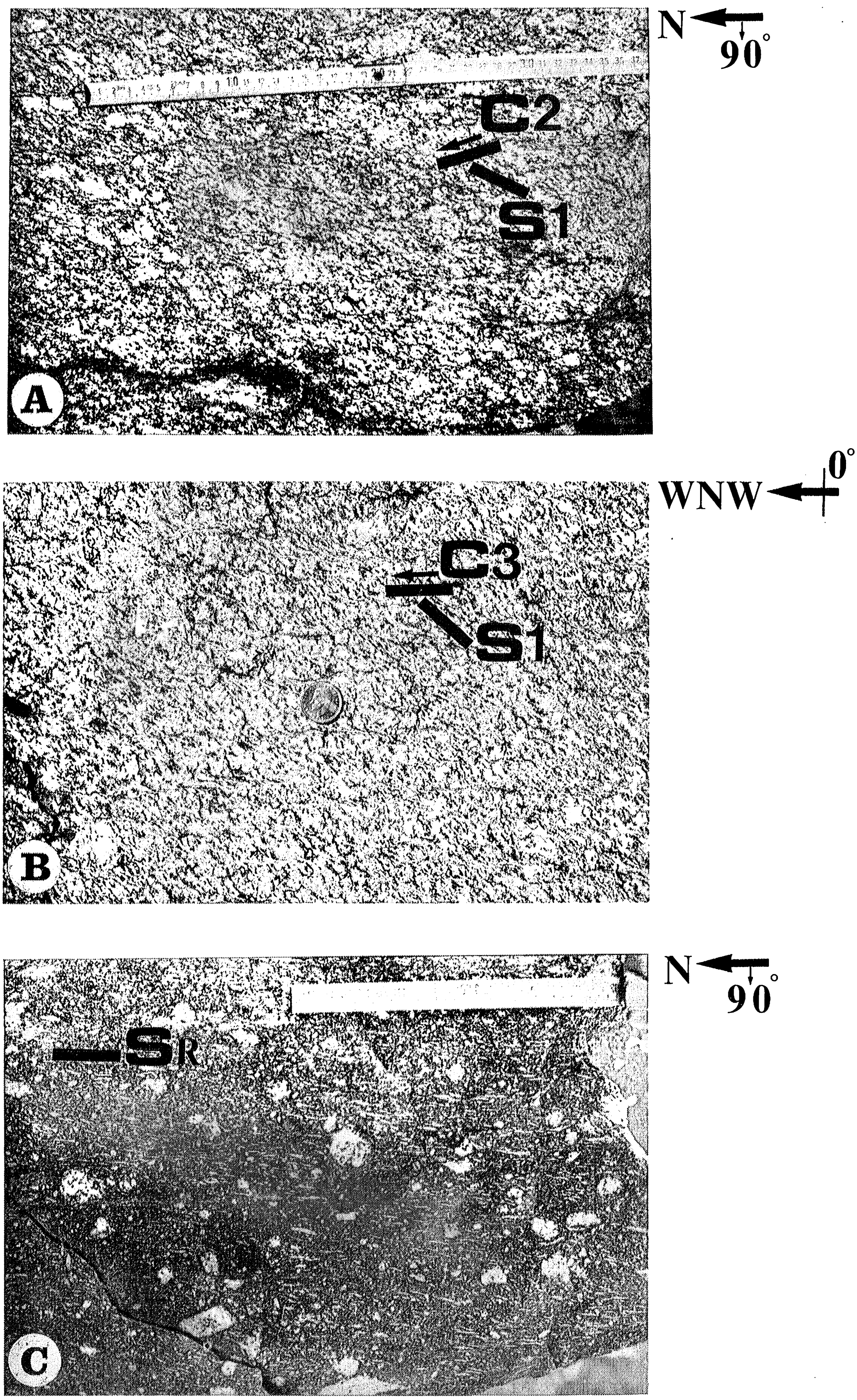

Fig. 3.—Deformed granitoids. (a) Vertical outcrop of S_1C_2 granitoid. (b) Horizontal outcrop of S_1C_3 granitoid (coin diameter: 2 cm). (c) Ultramylonite with quartz ribbons, defining an SR foliation.

Fig. 3.—Rocas graníticas deformadas. (a) Afloramiento de un plano vertical de la roca S_1C_2. (b) Afloramiento de un plano horizontal de una roca S_1C_3 (diámetro de la moneda: 2cm). (c) Ultramilonita con «ribbons» de cuarzo que definen una foliación SR.

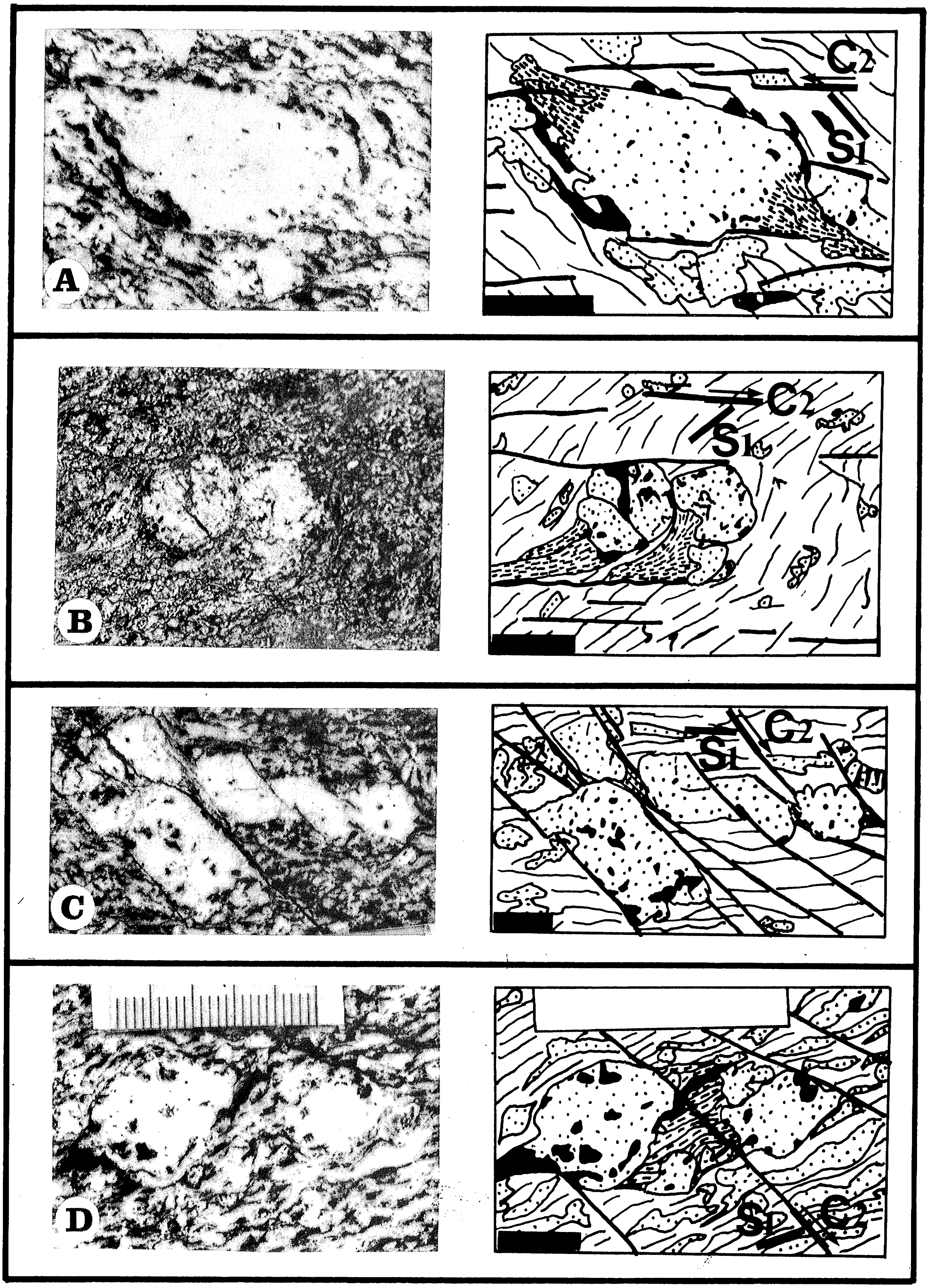

Fig. 4.—Main types of phenocryst deformations in the S_1C_2 granitoids. (a) Locked phenocryst with pressure-shadows. (b) Rotated phenocrysts with pressure-shadows. (c) Shear-stepped phenocryst. (d) Pulled-apart phenocryst. Scaled bars: 1 cm. Arrows indicate the shear sense.

Fig. 4.—Principales tipos de deformación de fenocristales en rocas S_1C_2. (a) Fenocristales bloqueados con rombos de presión. (b) Fenocristales girados con sombras de presión. (c) Fenocristales con escalones de cizalla («shear steps»). (d) Fenocristal roto por estiramiento. Escala de las barras: 1 cm. Las flechas indican el sentido de la cizalla.

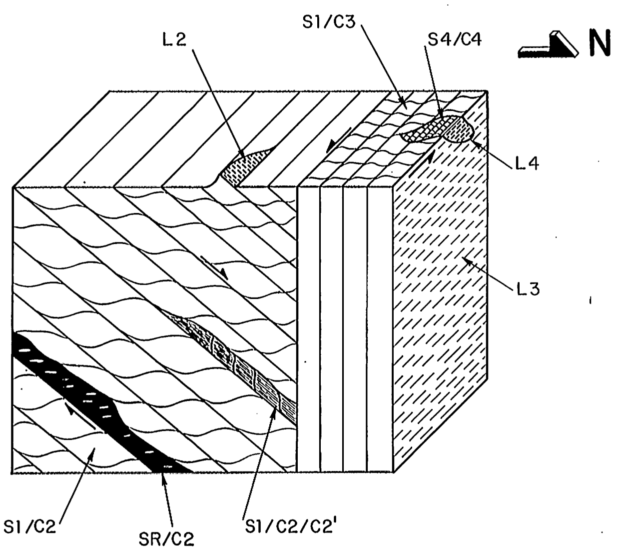

Fig. 5.—Schematic block diagram of the area representing the SC sigmoidal relationships indicative of shear senses on the C planes.

Fig. 5.—Bloque-diagrama esquemático del área que representa las relaciones sigmoidales SC indicativos de los sentidos de cizallamiento en los planos C.

Six SC sigmoidal relationships indicate the sense of movement on the C planes (Fig. 5). The top-to-the-N shear sense along the C_2 planes (in the direction of L_2) is deduced from three SC sigmoidal relationships: S_1C_2, SRC2, and $S_1C_2C_{'2}$. The sinistral shear sense in the WNW/ESE band (in the direction of L_3/L_4) is deduced from three SC sigmoidal relationships: S_1C_3 S_4C_4, and, on a map scale, the oblique orientation of the S_4C_4 leucogranitic bodies to the band boundaries (Fig. 1).

Mineral deformations have often been used for the deduction of shear senses. Two types of textures might reveal them at the mesoscale: asymmetric augen and shear-steps. Asymmetric augen have been used as shear sense indicators in a similar way to the «locked grains with pressure shadows» described in Fig. 4a. They represent phenocrysts that have been strained on opposite edges by motion on the C planes (the pressure-shadows point in the direction of the shear movement). This criterion is statistically useful in our rocks, but it is not always safe to use for individual crystals: locked and rotated grains are easily misinterpreted, and in them, the pressure-shadows point in opposite directions. Moreover, Simpson and Schmid (1983) noted that rotated grains occasionally show confusing pressure-shadow orientations. Shear-stepped phenocrysts have been used as shear sense indicators by Etchecopar (1977) and Simpson and Schmid (1983), who described their behaviour as a «deck of cards» when strained: they show a sense of shear opposite to the external one, and the internal shears, highly oblique to the C planes, should dip against the motion. However, the different varieties of shear-steps found in the San Vicente Range, suggest that this criteria may only be applicable statistically (Doblas 1985).

Under the microscope, two main types of shear sense criteria can be observed, oblique and asymmetric features (Fig. 6). Some of the classical criteria used as shear sense indicators under the microscope are not always reliable, at least for individual crystals. According to Lister & Snoke (1984), oblique listric normal microfaults are indicative of shear motion, with the microfaults always dipping toward it. However, we have found listric normal microfaults dipping both against and toward the motion. Asymmetric «mica fishes» have been described as typical shear sense indicators by Lister and Snoke (1984), with the elongated edges pointing toward the motion. Nevertheless, contrary senses have also been observed in our samples.

4. DISCUSSION

We will now discuss the origin and relative timing of the deformational structures found in the San Vicente deformed granitoids, which are schematically summarized in Fig. 7.

Different arguments indicate that the S_1 planes are related to the intrusion of the granodiorites (Fig. 7b), representing strong subsolidus deformations of the nearly cold granitic border against the country rocks, by a continuing directional emplacement of the unexposed molten granitic core: they display regional trends with complex convolute patterns; different factors in them are dependent on the proximity of the granitic-metamorphic interface, such as the degree of deformation, the orientation, and the abundance of metamorphic inclusions.

This is the first deformational episode in the granitoids, as the S_1 planes are deformed both by the C_2 planes, and by the different structures associated with the transcurrent band.

The data indicate that the C shearing planes, as a whole, are genetically different from the S_1 planes, representing «tectonic-related» deformations: they display uniformly oriented trends (90°/110°) and lineations (N for C_2, and WNW for C_3/C_4), they are unaffected by the proximity of the granitic/metamorphic interface which they intersect at a high angle, they deform the S planes under simple-shearing conditions, and some C planes are found within the metamorphic rocks as late crenulation cleavages.

The WNW/ESE-oriented C_2 planes belong to the second deformational episode (they deform S_1 and they are overprinted by the transcurrent band), and the shear sense criteria indicate that it is an extensional event with a top-to-the-N motion (Fig. 7c). The ultramylonites also formed during this episode. Extensional episodes have been rarely described in SC deformed granitoids (Burg et al., 1984).

The third deformational episode (Fig. 7d) generated a WNW/ESE-oriented transcurrent band with a sinistral movement along C_3 planes, which sigmoidally drag the S1 foliation, and overprint the C_2 planes.

This event was accompanied by the syntectonic intrusion and deformation of S_4C_4 leucogranites, in the western/wider portion of the WNW/ESE band (Fig. 7d). Similarly to what Davies (1982) proposes for some Pan-

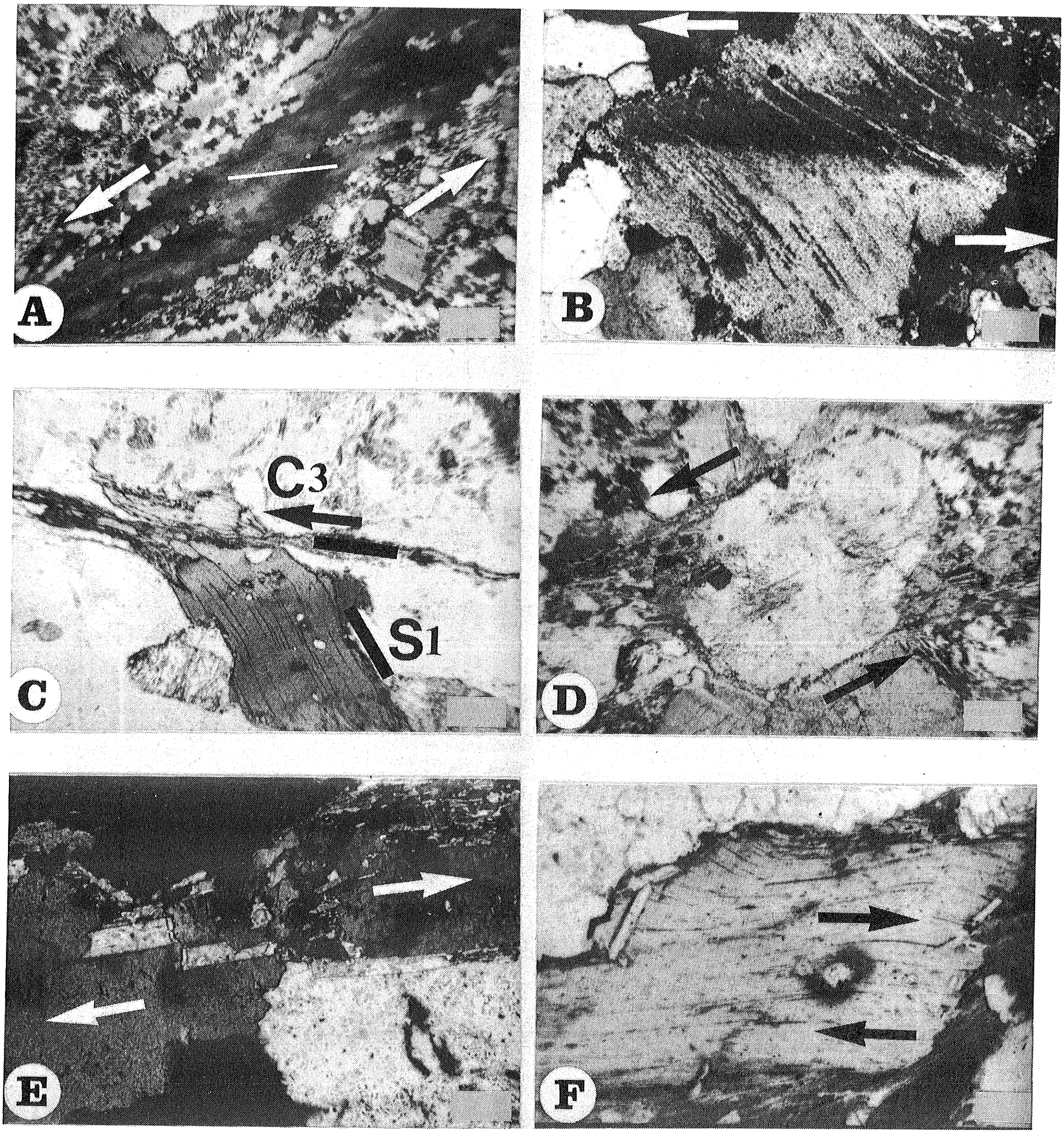

Fig. 6.—Examples of some shear sense criteria under the microscope. (Arrows indicate the shear senses. Scale bars: 0.44 mm in (a), (c), and (d); 0.22 mm in (b), (e), and (f). Crossed polars in (a), (b), and (e), and parallel polars in (c), (d), and (f)). (a) Obliquely recrystallized quartz ribbon in an ultramylonite. (b) Oblique drag-effect on the cleavage planes of a biotite grain, along a ductile microfracture. (c) S1C3 oblique relationships. (d) Locked plagioclase augen with asymmetric pressure-shadows. (e) Asymmetric pull-apart with recrystallization of micas in the gaps. (f) Zircon with asymmetric pleochroic haloes, included in a deformed biotite grain.

Fig. 6.—Ejemplos de algunos criterios del sentido de cizallamiento al microscopio (las flechas indican el sentido de la cizalla). Escala: 0,44 mm en (a), (c) y (d) 0,22 mm en (b) (e) y (f). Nicoles cruzados en (a), (b) y (e) y paralelos en (c), (d) y (f). (a) Cinta («ribbon») de cuarzo recristalizado oblicuamente en una ultramilonita. (b) Efecto de arrastre oblicuo en los planos de explotación de un grano de biotita, según una microfractura ductil. (c) Relaciones de oblicuidad S_1C_3. (d) Megacristal de plagioclasa bloqueado con sombras de presión asimétricas. (e) Rotura por estiramiento asimétrica con recristalización de micas en los huecos. (f) Circón con halos pleocroicos asimétricos incluido en un cristal deformado de biotita.

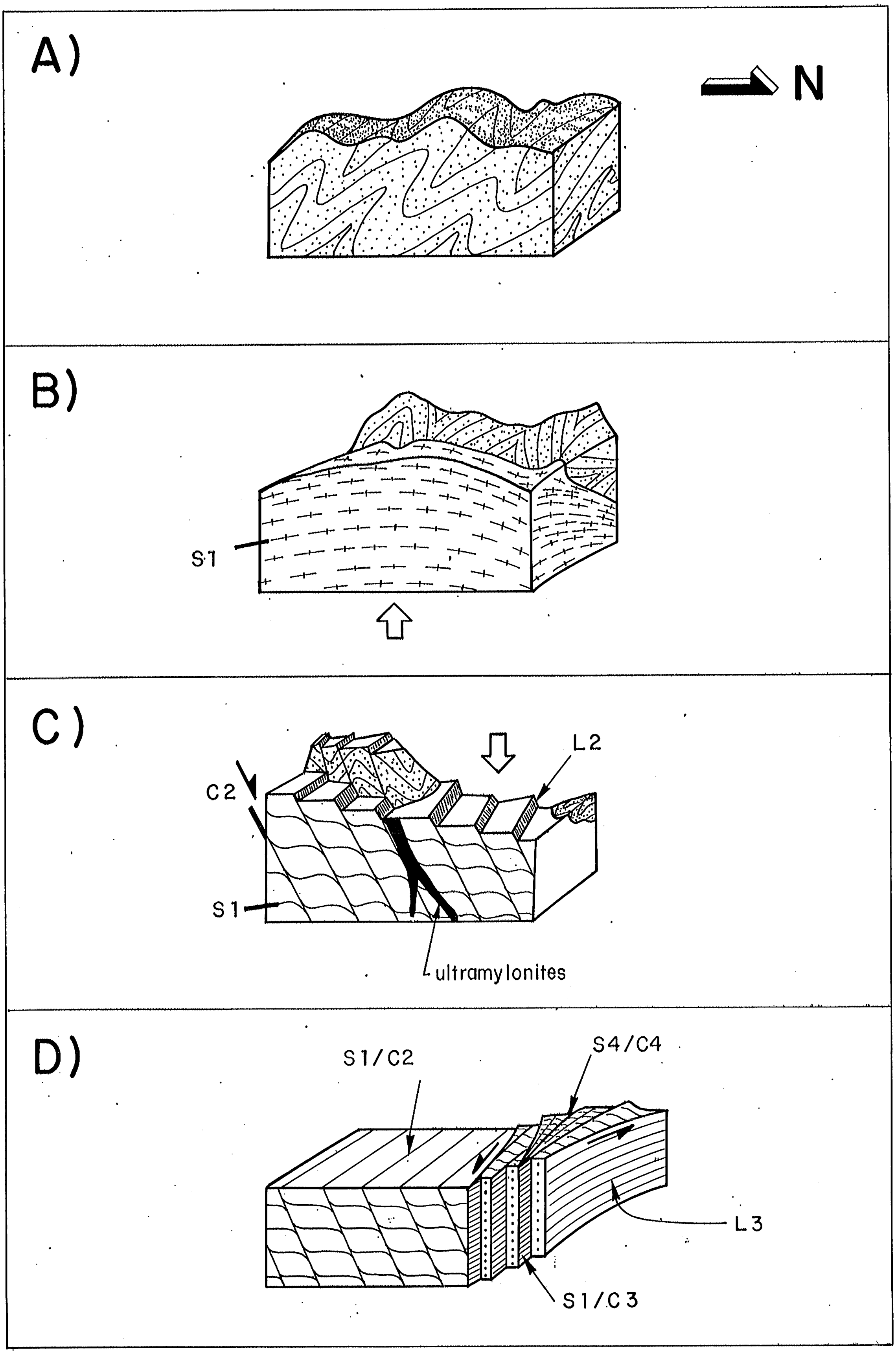

Fig. 7.—Deformational history proposed for the San Vicente Range. (a) Previous metamorphic history. (b) Intrusion and formation of the S_1 planes. (c) Extensional episode with C_2 planes and ultramylonites. (d) Sinistral transcurrent episode with C_3 planes and intrusion/deformation of S_4C_4 leucogranites.

Fig. 7.—Esquema de la secuencia de deformación en la Sierra de San Vicente. (a) Historia metamórfica anterior. (b) Intrusión y formación de los planos S_1. (c) Episodio distensivo con planos C_2 y ultramilonitas. (d) Episodio de desgarre sinistral con planos C_3 e intrusión y deformación de los leucogranitos S_4C_4.

African granites, we suggest that these leucogranites represent late intrusions that filled voids created in response to tectonic volume changes in the transcurrent band (at the same time that they were intruded, they were deformed into S_4C_4 fabrics by the continuing sinistral motion). All these events (C_3 deformation, leucogranitic intrusions, and SC deformation of the leucogranites), may be enhanced by «anatectic-tectonics» processes, in which there is a continuing feedback between tectonic deformation and melting (Hollister and Crawford 1986).

The three types of SC deformed granitoids are genetically very different: while S_1C_2 and S_1C_3 deformed by two successive non-coeval events, one intrusion-related (forming S_1), and the other tectonic-related (forming C_2 or C_3), S_4C_4 represent «true SC deformed granitoids» in the sense of Berthe et al., (1979 a,b), both planes being coeval and tectonic-related. SC granitoids formed by two non-coeval deformational events are rarely described in the literature (López Plaza, 1980; López Plaza & Corretge, 1980).

Metamorphic terrains often show crenulation cleavages (S_2) cutting previous foliations (S_1). The genetic mechanism was thought to be one of pure shearing for both foliations, and in two separate deformational events. Berthe et al. (1979 a,b) first described SC deformations in granitic rocks, which, at the outcrop scale, sometimes show a similar fabric to the S_1S_2 metamorphic deformations, but in this case a mainly simple-shearing mechanism was suggested, with only one deformational event. Since then a multitude of papers have described SC deformed granitoids, with wide possibilities of pure/simple shear and coeval/non-coeval deformations (Iglesias Ponce de León and Choukroune, 1980; Jegouzo, 1980; Simpson et al., 1982; Brown and Murphy, 1982; Bouchez et al., 1981; Burg et al., 1981; Lagarde and Choukroune, 1982; Vernon et al., 1983; Choukroune and Gapais, 1983; Doblas et al., 1983; Burg et al., 1984; Simpson, 1984; Rhodes and Hyndman, 1984; Burg and Iglesias Ponce de León, 1985; Doblas, 1985).

Some controversial issues related to SC sheared rocks have been raised by the deformations found in the San Vicente Range.

Most interesting is the relative timing of the S and C planes. The «coeval and non-coeval S and C planes» views are represented, respectively, by the Berthe et al. (1979 a,b) model, and by the classical S_1S_2 crenulation cleavages model. However, a number of recent papers suggest that these composite planar fabrics can form in any of the two ways (Vernon et al., 1983; Doblas et al., 1983; Lister and Snoke, 1984). In the San Vicente Range the SC deformed granitoids show both non-coeval (S_1/C_2 and S_1/C_3), and coeval S and C planes (S_4/C_4).

The origin of the stresses involved in the S and C deformations might also be confusing as both tectonic and intrusion-related stresses may trigger SC fabrics. In the Berthe et al. (1979 a,b) model, S and C are tectonic-related. In the San Vicente Range we propose a mixed origin, with S_1 planes related to intrusion stresses and C_2/C_3 planes to tectonic stresses. Several authors describe granitoids where both S and C planes form as a result of intrusion-related stresses (López Plaza, 1980; López Plaza and Corretge, 1980; López Plaza, 1983; Bouchez et al., 1983; Castro, 1983; Franco and Castro, 1983).

A main issue is whether the inclination and shape of the S sigmoids are valid shear sense indicators along the C planes. According to Berthe et al. (1979 a,b) they are indeed, and this is what makes SC granitoids so interesting, as it is the only kinematic picture available from these rocks. In the San Vicente Range, the S sigmoids are also valid shear sense indicators. However, in many other cases this is not so. Under pure shearing conditions, as for the S_1S_2 crenulation cleavages in metamorphic rocks, the S_1 sigmoids do not reflect any shear sense. Lister and Snoke (1984), Platt and Vissers (1980), and Platt (1984), noted that local C planes may occur with motions antithetic to the general picture («extensional crenulation cleavages»). These sigmoids might also be intrusion related, and then are only indicative of the modality of the intrusion, and do not reflect any type of tectonic movement (López Plaza, 1980; López Plaza and Corretge, 1980; Bouchez et al., 1981; Franco and Castro, 1983; López Plaza, 1983; Castro, 1983).

The angle between S and C was associated by several authors (Berthe et al., 1979 a,b; Iglesias Ponce de León and Choukroune, 1980; Jegouzo, 1980; Burg et al., 1981; Simpson, 1984) with the shearing strain (the higher the strain, the lower the angle). However, when S and C are non-coeval as in the San Vicente Range, this angle will also depend on the initial orientation of the S planes. Finally, Means (1981) and Hanmer (1984) described oblique «steady-state foliations» that are strain-insensitive.

5. CONCLUSIONS

Using SC deformed granitoids, we have shown the existence of a complex deformational history in the San Vicente Range, a granitic area previously considered as undeformed.

Three different events are proposed: an early intrusion episode, a later extensional regime with a top-to-the-N movement, and a final WNW/ESE sinistral episode accompanied by intrusion of leucogranites.

A possible contribution of this paper is the description of SC deformed granitoids with composite planar fabrics resulting from two non-coeval different deformational episodes, one intrusion-related, and the other tectonic-related. The description of C shearing planes in granitoids formed under extensional episodes is also uncommon.

The variety of deformations present in these rocks make them useful for studying shear-sense criteria, on all the scales. We have argued that some shear sense criteria might be confusing if applied to individual crystals, such as asymmetric augens with pressure-shadows, shear-stepped phenocrysts, oblique listric microfaults, and mica fishes.

Finally, we discuss different controversial issues related to the larger group of SC deformed rocks.

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