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Extensional tectonics of the Toledo ductile–brittle shear zone, central Iberian Massif

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ABSTRACT

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The Toledo mylonite in the central area of the Iberian Massif represents a major ductile shear zone, only a small part of which has been exposed to view. Mylonites derived largely from migmatite occupy a 300–350 m thick, gently S-dipping zone along the southern margin of the Toledo Crystalline Massif. The upper plate comprises Palaeozoic lower-grade metasedimentary rocks intruded by a late Hercynian pluton. The juxtaposition of the upper and lower plates with different structural and metamorphic conditions indicates that the shear zone is a significant structure with a large displacement. Progressive simple shear under conditions of a clearly decreasing confining pressure and temperature is supported by a microbrecciated mylonite, cataclasite and ultracataclasite sequence overlying the mylonites. The top of the ledge of cataclasites corresponds to the detachment-fault part of the shear zone.

Structural relations, combined with meso- and micro-structural evidence (stretching lineations and asymmetric shear sense indicators), support the conclusion that the mylonites and cataclasites associated with the detachment faulting formed during a continuous extensional deformation. Detachment-fault models developed for the formation of metamorphic core complexes can be applied in the Toledo Massif. We propose a model that implies a transition from ductile to brittle deformation associated with extension at greater structural depths, during lower Permian time.

Introduction

A geological study of the central area of the Iberian Massif by Llopis and Sanchez de la Torre (1963) suggested that the Toledo Migmatite Complex is separated from Palaeozoic metasediments by an unconformity. Subsequently, Aparicio (1971) proposed that the abrupt jump in metamorphic grade between the migmatitic rocks (amphibolite facies) of the Toledo Massif and the Palaeozoic metasediments (greenschist facies) is due to the low-angle faulting. The rock products of this shear zone can be explained by a quasi-plastic behaviour of the migmatites, generating mylonites considerably later than the regional Hercynian metamorphism (Aparicio, 1971; Hernández Enrile, 1976, 1981). The Toledo Shear Zone is considered to be a classic example of a large-scale ductile dislocation zone of late Hercynian age in the Hercynian basement of the Central Iberian Massif (Fig. 1).

The direction and sense of movement in the Toledo Shear Zone has been the subject of considerable controversy. Two distinct views are held. Aparicio (1971) considered this shear zone to be a normal fault on the basis of the outcrop distribution of metamorphic facies with respect to the fault zone, and the mylonitic lineation.

As a consequence of the limited kinematic criteria available, other interpretations about the direction and shear sense of the Toledo fault zone were sought. Martínez Garcia (1986) identified the "Morille and Alcudia terranes" as part of two different lithospheric "plates". In addition, he suggested that the Toledo Crystalline Massif, part of the "Morille terrane", is separated from the "Alcudia terrane" (Palaeozoic metasediments) by the Toledo Mylonite Belt. Strike-slip movement was proposed for the Toledo ductile shear zone, followed by a regional tilt to the south.

This paper reports a kinematic model of the

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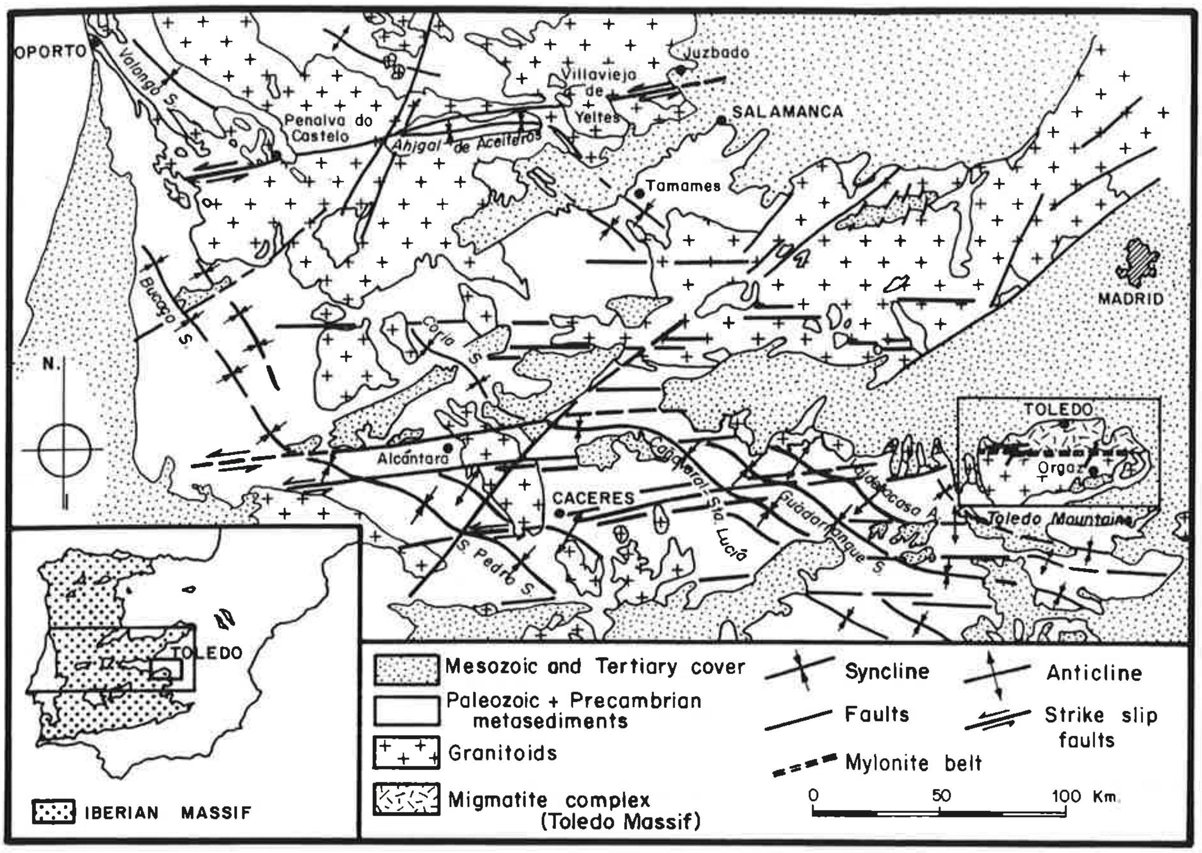

Fig. 1. Simplified map showing the location of the migmatite complex of the Toledo Massif, the Toledo mylonite belt (outlined) and the geological setting.

Toledo Shear zone on the basis of mesostructural field observations combined with microstructural studies. Attention is draw to the significance of this crustal shear zone in explaining the present position of the migmatite complex of the Toledo Massif.

Summary of the regional geology

The Toledo Crystalline Massif is located in the southern part of the Central Iberian Zone, where sediments and igneous rocks have been highly deformed and metamorphosed during the Hercynian orogeny. This massif comprises a migmatite complex with banded quartzofeldspathic schists, mica schists and layered anatectic zones with granular textures. These migmatitic rocks have been described (Aparicio, 1971) as originating from high-grade regional metamorphism accompanying the main compressional phases of the Hercynian orogeny.

Structural outline of the Migmatite Complex

In the Migmatite Complex of the Toledo Massif, both pre-Hercynian and Hercynian structures have been recognized. Assuming an early Hercynian age for the migmatization, pre-existing structures observed in the field appear to be of pre-Hercynian age, as suggested by previous workers (Martín Escorza and López Martínez, 1978)

Three phases of Hercynian syn-metamorphic structures have been observed. Occasional non-coaxial folding in these phases results in the development of interference patterns (Ramsay, 1967). Additionally, the geometries of the F_1 and F_2 folds vary in adjacent compositional bands and along layers of different thicknesses.

The migmatites developed during the syn-metamorphic deformation event F_1. In the quartzofeldspathic zones within the migmatites, metamorphism to amphibolite facies accompanied feldspar augen texture development and the formation of a mineral lineation defined by the grain shape preferred orientation of feldspars. Simultaneously, melanocratic bands of biotite and garnet micaschist were formed. Felsic and mafic-rich layering, designated S_m, may represent F_1 metamorphic segregations. Generally, small-scale F_1 folds are tight to isoclinal, and NW–SE-trending with an axial planar foliation S_1 parallel to S_m, resulting in a composite S_m/S_1 foliation. The L_1 mineral lineation plunges to the southeast (Fig. 2).

The E–W-trending mesoscopic F_2 folds have an axial-planar foliation S_2 defined by a grain shape preferred orientation of biotite and muscovite. The S_2 foliation intersects the metamorphic layering S_m in the hinge zones to produce a lineation L_2, which is parallel to the E–W-trending F_2 folds. Furthermore, the F_1 folds and the S_1 foliation are refolded during F_2 fold development such that F_1 folds plunge northwest and southeast, with an apparent vergence towards the southwest. Syn-metamorphic F_2 deformation is additionally responsible for the dispersion of the L_1 mineral lineations trends (Fig. 2).

Post-metamorphic F_3 folds are characterized by a general N–S trend (Fig. 2). These structures appear to be responsible for the larger-scale variations in the fold hinge directions and lineations generated by earlier F_1 and F_2 events.

Structural outline of the Palaeozoic metasediments

A sedimentary sequence of Cambrian and Ordovician age outcrops to the south of the migmatite complex. The difference in the structural style between these lower-grade sediments and higher-grade rocks of the Toledo Massif is a response to deformation under different conditions at different crustal levels.

The lower-grade metasediments exhibit three sets of folds, the trends of which are similar to those in deeper-level migmatites (Fig. 2). Lower

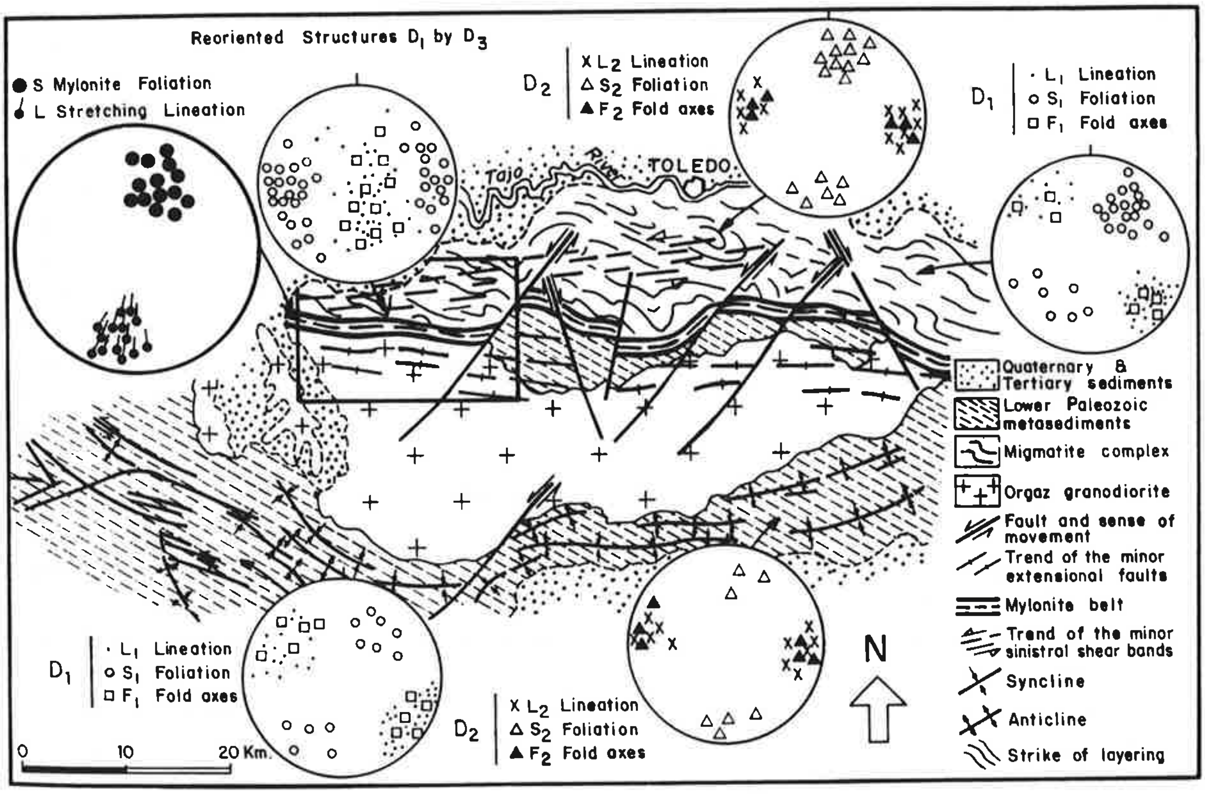

Fig. 2. Geological sketch map showing the location of the main area studied (outlined) in the Toledo Shear Zone. Synoptic equal-area projections (lower hemisphere) are given, indicating the principal structural elements for the different Hercynian deformation events and the mylonitization of the TSZ.

Ordovician quartzites show features characteristic of ideal concentric folds. Their hinge orientations trending WNW–ESE and their NE vergence are consistent with F_1 folds in less competent lithologies, where an axial planar cleavage S_1 is well developed and dips moderately to steeply southwest. Reverse faulting occurred during the later stages of the first folding episode. Examples of reverse mesoscopic faults have listric fault planes, and macroscopic faults may curve likewise. These faults are approximately coincident with the axial planes of major and mesoscopic F_1 folds, and cut upwards through the cores of these folds.

The second deformation event in the metasediments is responsible for E–W-trending axial surfaces of macro- and mesoscopic scale folding, which is approximately coaxial with the first folding phase (Fig. 2). These F_2 fold are asymmetric, with gently dipping axial planes trending N90°E to N100°E. A spaced axial planar cleavage S_2 crenulates the earlier S_1 cleavage. This generally plunges to the east, but is locally variable due to later deformation events and according to variations in the initial attitude of layering arising during F_1.

The third deformation phase is defined by folds with a N–S trend. A weak S_3 fracture cleavage is developed as an axial planar surface to these upright folds, which accentuates the dispersion of pre-existing lineations and fold axes.

The metasedimentary Palaeozoic sequence is intruded by the Orgaz granodiorite which outcrops south of the Toledo Massif (Figs. 1 and 2). This granodioritic pluton, which does not show any foliation, transects the Hercynian polyphase structures, generating contact metamorphism in the metasedimentary country rocks. These relations suggest a late Hercynian age for the Orgaz granodiorite intrusion.

Structural setting and age of the Toledo Mylonite

Mylonites occur within Toledo Shear Zone separating two discrete structural and metamorphic units of the Central Iberian Massif: the Toledo Migmatite Complex unit to the north, and the Palaeozoic metasediments intruded by the Orgaz granodiorite to the south (Fig. 1 and 2). This mylonite zone outcrops for a distance of 50 km (both ends are covered by Tertiary sediments) with E–W to N100°E trend and a gently southward dip.

Mylonite and cataclasite zones with similar orientations to the Toledo Mylonite are localized in the Central Cordillera (Capote et al., 1987; Doblas, 1987a,b) and in the Toledo Mountains (San José Lancha, 1969) respectively. They extend approximately 100 km in outcrop length and represent large-scale E–W-trending plastic and brittle faults respectively within the Central Iberian Massif. Alia (1972) described a large-scale faulting zone (Toledo Structural Belt) which extends from Portugal to the Levante region with an E–W trend. Alia (1972) proposed a long history of movement for this fault zone, from late Hercynian to Alpine and even recent times.

The Toledo Shear Zone is situated in an older transcurrent faulting zone (Alcantara–Toledo shear zone) with a N75°E to N80°E orientation (Fig. 1). These shear zones lie within the Toledo Structural Belt. The generalized geological map of Fig. 1 shows a sense of deflection of the Hercynian regional fold trends along the Alcantara–Toledo shear zone. It permits the deduction of a sinistral sense of movement for this transcurrent fault system. A similar sinistral geometry has been inferred from field observations of N70–80°E-trending shear bands deflecting the minor folds and S_1 and S_2 foliations (Fig. 2). The planar fabrics of the Toledo mylonite zone clearly transect and overprint these earlier shear bands, the similarity of orientation of which is believed not to have any genetic significance.

In addition, the older Alcantara–Toledo Shear Zone is comparable in orientation and movement picture to another fault zone (Fig. 1) which extends from Juzbado to Traguntia (Province of Salamanca; García de Figuerola and Parga, 1968) continuing to the Penalva do Castelo area in Portugal (Iglesias and Ribeiro, 1981). The Juzbado–Penalva shear zone (JPSZ) has a long history of movement. Iglesias and Ribeiro (1981) argued that it developed during early Hercynian times. Later, Jiménez Ontiveros and Hernández Enrile (1983) inferred that this shear zone was active under amphibolite to greenschist facies metamorphic conditions from the late Carboniferous to early Permian period (300–280 Ma). The JPSZ is cross-cut by a post-kinematic granite (e.g. Villavieja del Yeltes) which is comparable to the Villar de Ciervo granite, the age of which is 280 ± 10 Ma (García Garzon and Locutura, 1981; Carnicero et al., 1986)

The geometry and sinistral movement picture reported for the JPSZ, which trends N70–80 ° E, is identical to the one which has been found for the Alcantara–Toledo Shear Zone. Thus, a possibility exists that these fault zones may be coeval (late Hercynian, 300–280 Ma).

If, on the other hand, the Toledo Mylonite was cut by a new NE–SW transcurrent fault system (Fig. 2) of late Hercynian age (Parga, 1969), and the upper age limit of which is 250 Ma (Arthaud and Matte, 1975), the above evidence could be consistent with a lower Permian age (280–250 Ma) for the Toledo Mylonite.

Moreover, on the south side of the Toledo Shear Zone, the Orgaz granodiorite has suffered an initially ductile deformation later overprinted by brittle processes, resulting ultimately in cataclasites. This pluton may be comparable in age to the Villavieja de Yeltes granite (280 ± 10 Ma), and to the Cabrera granites (288 ± 12 Ma) (Vialette et al., 1981).

The mylonites in outcrop: geometry and mesostructures

Well localized mylonite outcrops are best developed in host rocks of quartzofeldspathic composition, but the ductile deformation of the Toledo Shear Zone also occurs in the Palaeozoic metasediments, especially when quartzite beds are present.

The present study was carried out mainly in the outlined data of the map (Fig. 2), which shows the migmatite complex of the Toledo Massif separated from the Orgaz granodiorite by a major E–W-trending fault zone. The latter is a quartzofeldspathic mylonite belt with a constant outcrop width of approximately 1 km and the true thickness of 300–400 m.

Along the northern boundary of the mylonite Zone a relatively broad zone of transition (100–150 m) exists from host migmatites to mylonitic rocks. This transition is marked by discrete slip surfaces, which are well developed only at the margins of the mylonite zone. They are accompanied by an incipient foliation which is usually defined by a coarse mineral binding. This foliation is clearly precursory to the mylonitic rocks because all transitions can be seen between them.

However, the transition between host granodiorites and mylonites is very abrupt. Structural analysis (Hernández Enrile, 1976, 1981) revealed that the mylonites were progressively overprinted by brittle deformation, which is particularly well developed along the southern boundary of the Toledo Shear Zone.

The host granodiorites, up to 1 km away from the mylonite and cataclasite zones, exhibit discrete and widely spaced slip surfaces separated by undeformed rocks. These bands of shearing extend along E–W to N100 ° E trends for several kilometres (Fig. 2). Thus, these slip features display a range of orientations similar to the Toledo Shear Zone, but dipping most steeply than the mylonitic foliation. The slip surfaces are interpreted to be related to later brittle episodes which developed in the upper plate (Lower Palaeozoic metasediments and Orgaz granodiorite) of the Toledo fault zone.

Within the mylonite zone a marked grain shape fabric and associated grain-size reduction generated a strong foliation which is observable on a mesoscopic scale. This foliation is defined by a colour banding of alternating fine-grained quartzofeldspathic aggregates and mica. It marks a planar anisotropy which microstructurally shows a mineral-shape preferred orientation of the grains. Hence, alignment of feldspar porphyroclasts contributes to the foliation expression as well. This planar fabric is though to nearly parallel the X–Y plane of the finite strain ellipsoid, and has been interpreted to represent the S-surfaces (Berthé et al., 1979a). The mylonite foliation strikes N85 ° E to N100 ° E and dips gently, 15–30 ° to the south (Fig. 2).

A second set of irregularly spaced surfaces (C-planes) is equally visible on the mesoscopic scale. They are defined by fine-grained domains of biotites and quartz, and occasionally trails of feldspar

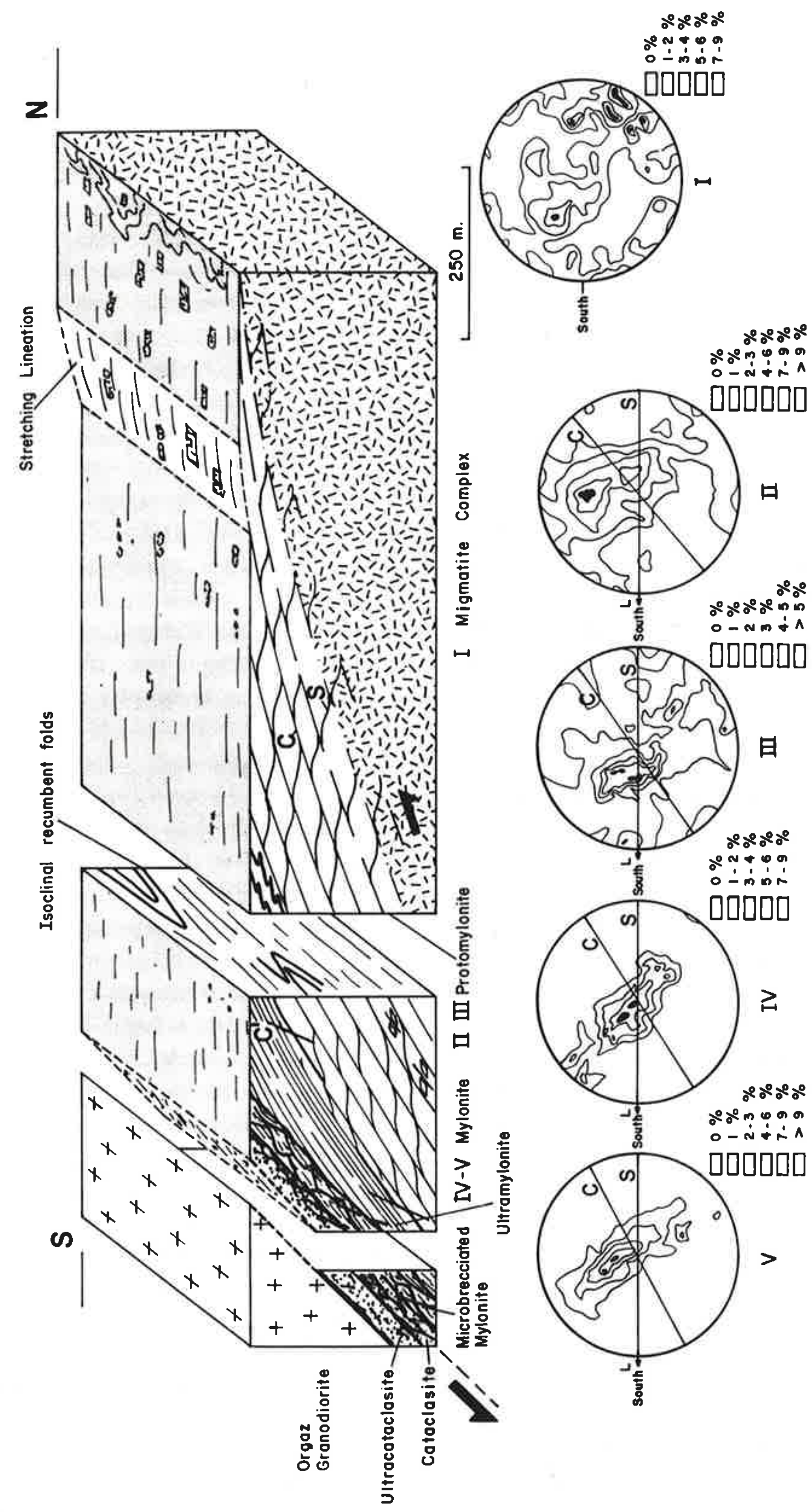

Fig. 3. Idealized section through the Toledo ductile–brittle shear zone, showing the distribution of the fault rocks, the structures and the pattern of preferred orientation of quartz (c-) axes in mylonites. The asymmetry of the single girdle discloses the sinistral sense of shear southward.

porphyroclasts. These *C*-planes develop parallel to the margins of the Toledo Shear Zone with a constant E–W to N100 ° E orientation across the whole mylonite zone. These *C*-surfaces dip 40 ° or less towards the south, but dip more steeply than the *S*-planes.

In higher deformed zones of the mylonite belt, field evidence also includes late discontinuous and irregularly spaced shear bands which transect and break up the mylonitic foliation. Microstructurally, they consist of millimetre-scale zones defined by the preferred orientation of biotite and fine-grained recrystallized quartz. Micro-shearing planes, oriented obliquely to the preferred orientation of the fractured feldspar porphyroclasts and to the *C*-surfaces, also contribute to define the shear bands. These planar structures develop at low angles to the *C*-surfaces and dip 30–40 ° S, indicating a N–S component of movement parallel to the mylonitic lineation (Fig. 3). Such structures have similar origins and geometries as the *C*′-shear bands which have been reported in different mylonite types (Berthé et al., 1979b; Watts and Williams, 1979; White, 1979).

A penetrative mineral lineation is marked by elongated quartz grains and by the preferred orientation of the long axes of feldspars, which are commonly fractured perpendicularly to the elongation. This stretching lineation, trending N190 ° E to N200 ° E, lies on the foliation planes and plunges gently to the south-southwest (Fig. 2).

At the margins of the shear zone, a mineral lineation with a N–S trend is exposed as a result of deflection and rotation of the regional migmatitic layering. This lineation is defined by the long axes of the feldspars that are almost parallel to the mylonitic stretching lineation which shows fractured pulled apart fragments (Fig. 3).

Slickenside striations can be seen on the *C*-planes with dominant N190 ° E to N200 ° E trends, and plunging to the south-southwest. They are parallel to the mineral lineations, indicating a kinematic relationship between them.

At the most advanced stages of deformation, the Toledo Mylonite also shows small-scale fold structures, commonly affecting the compositional banding or foliation (Fig. 3). Intrafolial fold occur at varying angles to the stretching lineation of the mylonite. It is probable that such folds were initiated with their axes almost at right angles to the lineation, and during progressive slip they became overturned in a direction related to the sense of shear. At higher shear strains, sheath folds (Carreras et al., 1977; Cobbold and Quinquis, 1980) are observed on sections perpendicular or at a high angle to the mylonitic lineation.

The sense of movement of the Toledo Shear Zone

From geological mapping, a number of observed features, such as the regional banding and the lineation deflection of the host rock banding, the presence of *L–S* tectonites and asymmetric minor folds of the mylonitic foliation, are useful criteria for the deduction of the sense of movement in the Toledo Mylonite Zone. In addition, microstructural and textural features indicative of the direction of shearing were also observed. Thus, the mylonite zone geometry, combined with meso- and microstructural evidence as shear sense indicators, allowed the sense of movement of the Toledo Shear Zone to be determined.

Mesoscopic shear criteria indicators

The N185–200 ° E orientation of the mineral lineation and the slickenside striations developed on the mylonite foliation (*S*-surfaces) and *C*-planes respectively, indicate that the direction of tectonic transport was not perpendicular to the E–W trend of the slip *C*-surfaces. This implies that the movement has a weak dextral component along the E–W trend in the Toledo Shear Zone (Fig. 2).

S–C type mylonites are spectacularly developed in the TSZ from the migmatite complex. The configuration and angular relationship between *S*- and *C*-surfaces defines a normal shearing sense towards the south (Fig. 3). In addition, a set of *C*′ shear bands show displacement synthetic with the sense of movement described above.

The relationship between the asymmetry ("*S*" pattern) of intrafolial folds and the shear sense is consistent with other field observations of shear sense criteria. Such folds indicate a normal slip sense of shear directed toward the south (Fig. 3).

Boudinage of competent mylonite layers is related to synthetic movements on shear bands, showing a stretching in an approximately N–S direction. Furthermore, at the margins of the TSZ, close extensional fractures within the megacrystals and porphyroclasts of feldspar are seen, with orientations strictly perpendicular to the direction of the mylonitic stretching lineation, often given rise to fractured pulled-apart pieces, accommodating a N–S extensional strain.

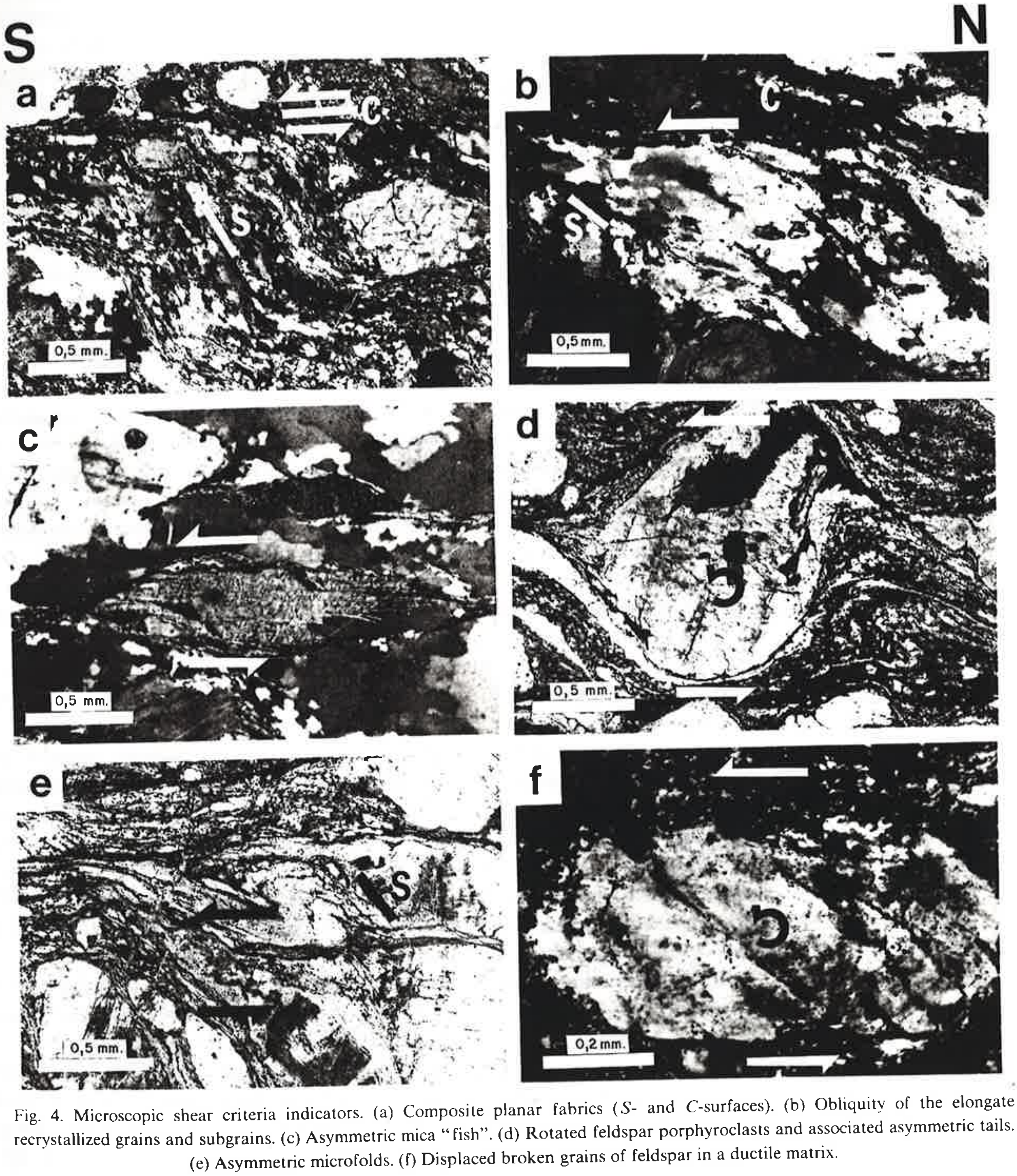

Fig. 4. Microscopic shear criteria indicators. (a) Composite planar fabrics (*S*- and *C*-surfaces). (b) Obliquity of the elongate recrystallized grains and subgrains. (c) Asymmetric mica "fish". (d) Rotated feldspar porphyroclasts and associated asymmetric tails. (e) Asymmetric microfolds. (f) Displaced broken grains of feldspar in a ductile matrix.

Some *C*-surfaces show slickenside striations plunging 30° with a trend of N185–200°E parallel to the dip direction of the stretching lineations, which are also consistent with a slip to the south.

Along the southern edge of the TSZ, brittle deformation is superposed on the mylonitic rocks. As a consequence of this later brittle deformation, orientations of recognizable *L–S* tectonics within the brecciated mylonite are strongly disrupted. Hence the kinematics of later brittle faulting within the TSZ have been determined from a number of lines of evidence, such as: (1) normal displacement to the south on small-scale fault planes; (2) the direction and sense of rotation of the pre-existent mylonite foliations, suggesting a southward-directed movement of the upper plate; and (3) dip-slip trends of striations on E–W striking minor cataclastic faults, indicating a N–S normal-slip translation.

These kinematic data reveal that the direction and sense of tectonic transport during the brittle faulting was nearly parallel to the direction and the same sense of movement deduced for the pre-existing mylonitic rocks. Thus, mylonites and cataclasites formed as a common response to the extensional tectonic regime of the Toledo Shear Zone.

Microscopic shear criteria indicators

On the microscopic scale, some of the most useful and consistent criteria for the deduction of the sense of shear are observable in *X–Z* oriented thin sections parallel to the lineation of the quartzofeldspathic mylonites of the TSZ. The microscopic kinematic criteria used in this study include the following:

(1) *S–C* angular relationships (Berthé et al., 1979a,b; Simpson and Schmid, 1983; Lister and Snoke, 1984): the mylonitic foliation marked by fine-grained quartzofeldsphatic aggregates are deflected into the *C*-surfaces, indicating a sinistral sense of shear (Fig. 4a).

(2) The obliquity of elongate recrystallized grains and subgrains of quartz to the main foliation or shearing plane (Fig. 4b) (e.g. Simpson and Schmid, 1983; Lister and Snoke, 1984).

(3) Asymmetric mica "fish" trails (Lister and Snoke, 1984) are observed (Fig. 4c) and they indicate the same normal sense of shear to the south.

(4) An identical sense of movement is determined from asymmetric pressure shadows and tails (e.g. Passchier and Simpson, 1986) in porphyroclasts (Fig. 4d).

(5) The vergence and the "*S*" pattern of asymmetric microfolds suggest an overall sinistral sense of shear to the south (Fig. 4e).

(6) Displaced broken grains of feldspar and micas in a ductile matrix show the effects of a large N–S extensional deformation. The rotation of broken and displaced grains of feldspar (Fig. 4f) is similar to a sheared cards model (Etchecopar, 1977), also indicating a sinistral shearing sense to the south or normal faulting.

(7) Asymmetric quartz *C*-axes fabrics: the patterns of preferred orientations of quartz *c*-axes belong to four main types. In Fig. 3 a N–S progressive variation of the asymmetric quartz *c*-axes fabric with increasing strain is shown. Additionally, the asymmetry of fabrics about the lineation and foliation of the mylonitic rocks is consistent with southward sense of shear inferred from other microstructural indicators. Thus, the assemblage of mesoscopic and microscopic shear sense indicators is remarkable reliable in these mylonites.

Crustal conditions during extensional tectonics of the Toledo Shear zone

Previous microstructural studies of the quartzofeldspathic mylonites (Hernández Enrile, 1976, 1981) assumed that the ductile deformation of the Toledo Shear Zone formed under greenschist facies metamorphic conditions. Moreover, faulting was inferred to have occurred at a depth of 7–10 km.

These metamorphic conditions of extensional faulting are clearly superimposed on the regional metamorphism of the migmatite complex, which formed under transitional amphibolite to granulite facies conditions (Aparicio, 1971). It is to be expected that the effects associated with the shearing of the migmatites, such as tectonic reduction of the grain size, were accompanied by a metamorphic retrogression to mineral assemblages and microstructures indicative of less extreme environmental conditions.

Later lower-grade faulting effects, defined by cataclasites and breccia zones, are present in the brittle upper plate, overlying the ductilely deformed migmatitic rocks (Hernández Enrile, 1976, 1981, 1983). Therefore, it is also reasonable to expect that these brittle shear zones are zones of further metamorphic retrogression.

Aparicio (1971) argued that the syn- and post-kinematic granite intrusions were a consequence of the high temperatures that occurred during the Hercynian regional metamorphism. In an attempt to make generalizations on the occurrence of late Hercynian granites in the Central Iberian Zone, Corretge et al. (1977) strongly supported the view that the intrusion of granitic rocks (García de Figuerola and de la Peña, 1964; Suarez, 1970) occurred by partial melting of deep-crustal rocks and led to the Permian–Carboniferous plutonic activity of the Central Iberian Massif.

If, on the other hand, the high temperatures (600–700 °C) suggested by Aparicio (1971) prevailed after the deformation events had ceased, the low temperatures related to the Toledo extensional faulting (250–350 °C) inferred by Hernández Enrile (1981) would imply a rapid cooling after the emplacement of the Orgaz granodiorite and during the time that the area was subjected to regional extension. The crustal extensional tectonics of the Toledo Shear Zone may have initiated a period of rapid cooling related to an uplift of the rocks which had remained deeply buried since Palaeozoic times.

A shear zone model for the structural evolution of the migmatite complex of the Toledo Massif

Any model that attempts to explain the present position and deformational history of the migmatite complex of the Toledo Massif must account for the following observations:

(1) The geometrical data given above are consistent with a general model in which a low-angle ductile shear zone cut discordantly the pre-existing rock fabrics of both the hanging-wall (Palaeozoic metasedimentary rocks of lower grade intruded by late Hercynian granodiorite) and the footwall (migmatite complex).

(2) On a gravity profile (see Santa Teresa et al., 1983) of the Orgaz granodiorite and adjacent areas, the upper and lower plates of the TSZ have been recognized. The most significant feature of this model is that the upper and lower plate are separated by a gently dipping surface which decreases in dip in the direction of upper-plate transport. This suggests that the TSZ may display a listric geometry, flattening at a depth of 6–10 km. In addition, a seismic reflection profile (Banda et al., 1981) across the Central Iberian Meseta, has shown a gently dipping reflector situated between 7 and 11 km, which appears to be the in-depth continuation of the TSZ.

(3) The geometric and microstructural relations described above suggest that the Toledo Shear Zone consists of a largely ductile lower part defined by gently dipping mylonites. As a result of progressive deformation and displacement, these ductile fault rocks were transformed, near their upper surface, into microbrecciated mylonites, indicating a superimposed episode of retrogressive shearing. In this later brittle regime, cataclasites developed and formed an upper ledge. Such a juxtaposition of the cataclastically deformed hanging-wall with a plastically deformed footwall displays a geometry which may be explained by the effects of a large displacement on a normal fault.

(4) The orientation of the mylonitic foliation under the brittle upper plate is more steeply dipping than the foliation of the nearest mylonites exposed on the migmatite complex. Moreover, the original orientation of disrupted relict foliation within microbrecciated mylonites and cataclastic zones displays a steeper dip than the mylonitic foliation in the lower ductile plate (Fig. 3). This figure displays a departure from the original listric geometry, which might be interpreted in terms of a progressive rotation and warping of the lower ductile plate.

Many of the essential features of detachment faults in metamorphic core complexes of the North American Cordillera (see Coney, 1974, 1980; Davis and Coney, 1979; Crittenden et al., 1980; Wernicke, 1981; Davis, 1983) might be recognized in the TSZ as described above. The evidence presented in this paper favours a model of continental extension (Rehring and Reynolds, 1980; Wernicke, 1981, 1985; Davis, 1982; Davis et al., 1986;

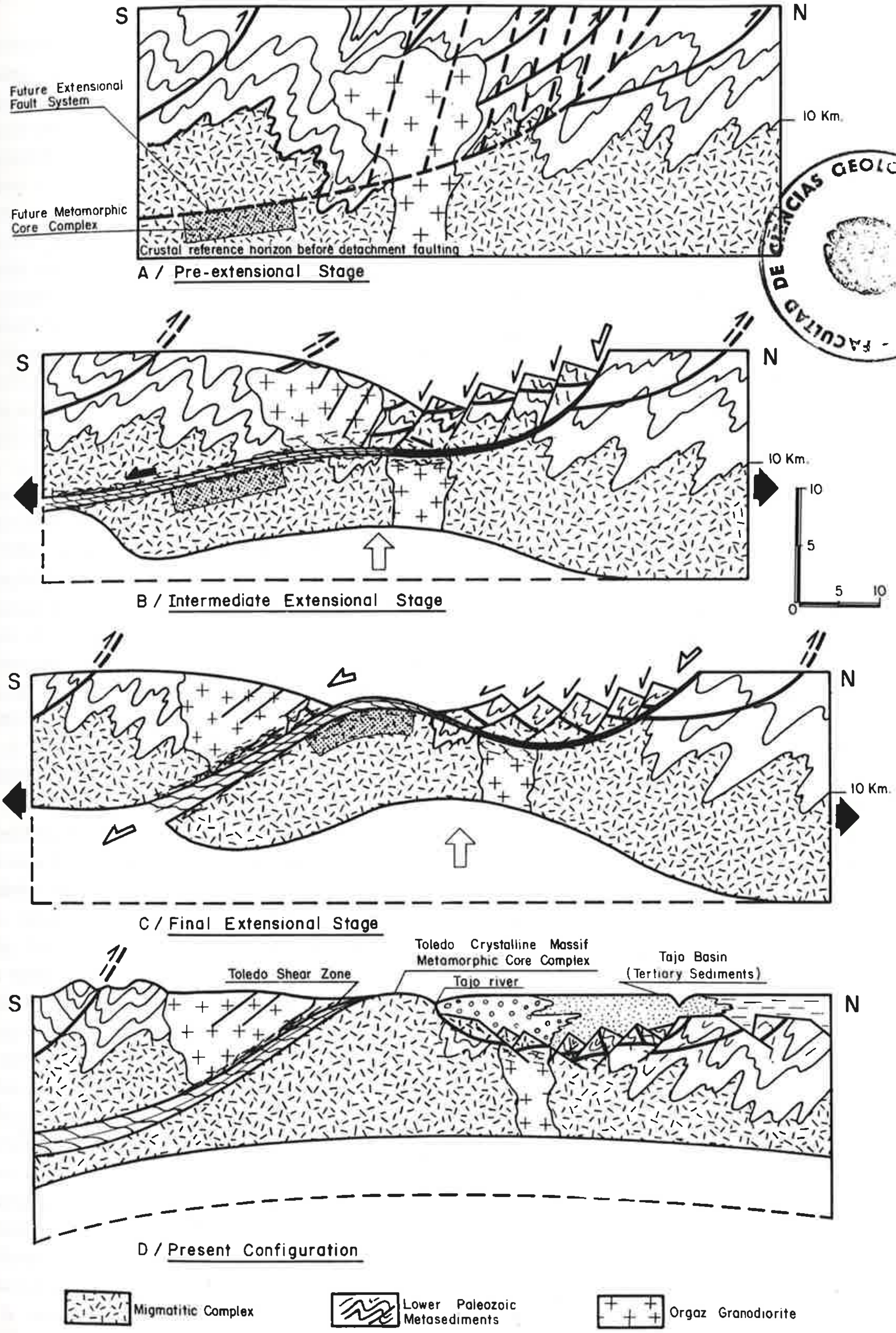

Fig. 5. Schematic evolution of the extensional Toledo Shear Zone, outlined in the text.

Coward et al.. 1987) that involves a shallow-dipping major ductile shear zone. To apply this model, we have to assume the mylonites in the lower plate of the TSZ were progressively drawn upwards from beneath overlying crustal levels. In other words, with continued extension, mylonite rocks were transported above the plastic to cataclastic transition. This structural succession for rocks that have moved from a metamorphic environment to surface conditions is the order observed in core complexes (Davis and Coney, 1979; Crittenden et al., 1980; Rehring and Reynolds, 1980; Davis et al., 1986; Coward et al., 1987). In this way, we propose a model involving a detachment fault with a brittle upper plate superposed on a ductilely deformed migmatite basement, which might be interpreted in terms of a metamorphic core complex.

This model is tentatively depicted as a series of simplified cross-sections in Fig. 5, interpreting the geometric evolution of the Toledo detachment fault as a result of the extensional tectonics. The geometric evolution suggested here is partially based on the concepts and ideas of Wernicke (1981, 1985), Davis (1983) Spencer (1984), Davis et al. (1986), Coward et al. (1987) and Doblas (1987).

In this model, the extensional fault system would have initially cut steeply down-section from the headwall domain in the northern area of the Toledo region, and flattened at a depth of 8–12 km, under what is now the Toledo Mountains (Fig. 5a). With continued extensional deformation the ramp of the detachment fault (Figs. 5b and c) would have been arched upwards, uplifted and progressively denuded, as a result of the evolution of detachment systems (see Spencer, 1984). These extensional processes are accompanied by a significant crustal thinning. Meanwhile, synthetic steeply dipping normal faults with strikes ranging from E–W to N110°E cut the allochthonous rocks (hanging-wall). Continued movement along the detachment fault surface, accompanied by upward arching processes, define a series of stacked/rotated allochthonous blocks.

A simple gravity sliding model or simple unloading for tectonic denudation of terrains seems unlike to account for all of the uplift. In the TSZ, the extensive areal dimension of deformation and undirectional transport (to the south) complicates the interpretation of a simple breakaway and shearing geometry, as might be expected with gravity sliding. Thus, evidence that the Toledo metamorphic core complex reached surficial levels during denudational faulting and the large amplitude and short wavelength of the warp suggest that the base of the crust was similarly domed along this narrow belt (Fig. 5c). It implies that the flexural rigidity of the crust was low during *lower Permian* denudational faulting. This low flexural rigidity might be explained as a result of a thermal anomaly related to the intrusion of the Orgaz pluton, very close to the lower Permian extensional event. This anomaly was probably active during most of this extensional episode. This interpretation has been advocated for a mainly granitic province with a similar extensional scheme in the Spanish Central System by Doblas (1987).

The present configuration of the Toledo Crystalline Massif is depicted in a schematic way in Fig. 5d. In the northern area, the structure of stacked/rotated blocks is covered by the Tajo Basin Tertiary sediments. These sediments were affected by alpine fracturing tectonics. This fracturing was recognized on gravity data, and has been interpreted as the result of a partial reactivation of the previous lower Permian extensional fractures. Additionally, the cortical thickness and apparent lack of gravimetrical anomalies might be explained by the action of Alpine compressional tectonics.

Conclusions

The zone of quartzofeldspathic mylonites and mylonitized migmatite in the southern part of the Toledo Massif represents a major ductile shear zone, only a small part of which has been exposed to view. This shear zone separates lower-grade metasedimentary rocks intruded by a late Hercynian pluton from a ductilely deformed migmatitic basement.

In the Toledo Massif we have evidence for the following sequence of deformational events:

(1) The Hercynian migmatite complex was involved in progressive ductile shearing under

greenschist metamorphic conditions, forming penetrative S–C mylonites with an E–W trend and a gentle dip to the south. Thus the migmatites are roofed by the ductile lower part of the TSZ. Depth estimates of 8–10 km are based on mineralogy and microstructures which suggest that the mylonites are the products of shearing of upper-middle crust.

(2) The mylonites of the TSZ are overprinted by brittle shearing. The structural distinctiveness of the microbrecciated mylonites, cataclasites and ultracataclasites provided the basis for the identification of a later brittle detachment fault as a result of a continuous progressive deformation.

(3) Kinematic studies in the TSZ, using both mesoscopic and microscopic structures, revealed that the direction of tectonic transport during the detachment faulting was approximately parallel to and in the same normal sense as the ductile shear deduced for the underlying mylonites. It implies a kinematic continuity of the extensional shearing from middle-upper crustal to surficial levels. The structural succession for rocks that have moved from a metamorphic environment to surface conditions suggests that models developed for Cordilleran core complexes can be applied in the Toledo Massif.

The structural evolution of the Hercynian migmatite basement of the Toledo Massif can be explained in terms of major detachment faulting that accommodated lower Permian crustal extension. Migmatites and mylonites were drawn out from beneath the cataclastically extending upper plate and they were uplifted through the plastic to cataclastic transition. Finally, apparent uplift may have been increased by later high-angle normal faulting.

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