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Morphologically ductile criteria for the sense of movement on slickensides from an extensional detachment fault in southern Spain

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Abstract—New criteria for the sense of movement on slickenside surfaces displaying evidence for mesoscopic ductility are described in the Neogene Jaloche extensional detachment fault in southern Spain. This detachment develops spectacular slickensides and fault gouges, and four of the criteria for the sense of movement observed along the highly polished slip surfaces are new to the literature. They are: (1) synthetic secondary fractures with hangingwall drag-effects in the form of roll-over microsynclines; (2) metre-scale oval-shaped asymmetric culmination and depression features; (3) microthrusts verging towards the direction of motion of the opposite block and dragging/overthrusting previous planar elements on the fault surface; and (4) flakes of fault-surface material trailed and plastered in the direction of the missing block. The geometry and microstructure of these features reveal that they deformed in a morphologically ductile manner by the coupled processes of cataclastic flow and shear localization, probably during aseismic sliding. During transient seismic pulses, deformation occurred along shiny/polished slickenside fault planes occasionally bearing jigsaw implosion breccias. Fluids under high pressure present initially may have promoted distributed cracking, whereas the process of dilatancy hardening may have served to facilitate cataclastic flow in the deformation history. © 1997 Elsevier Science Ltd.

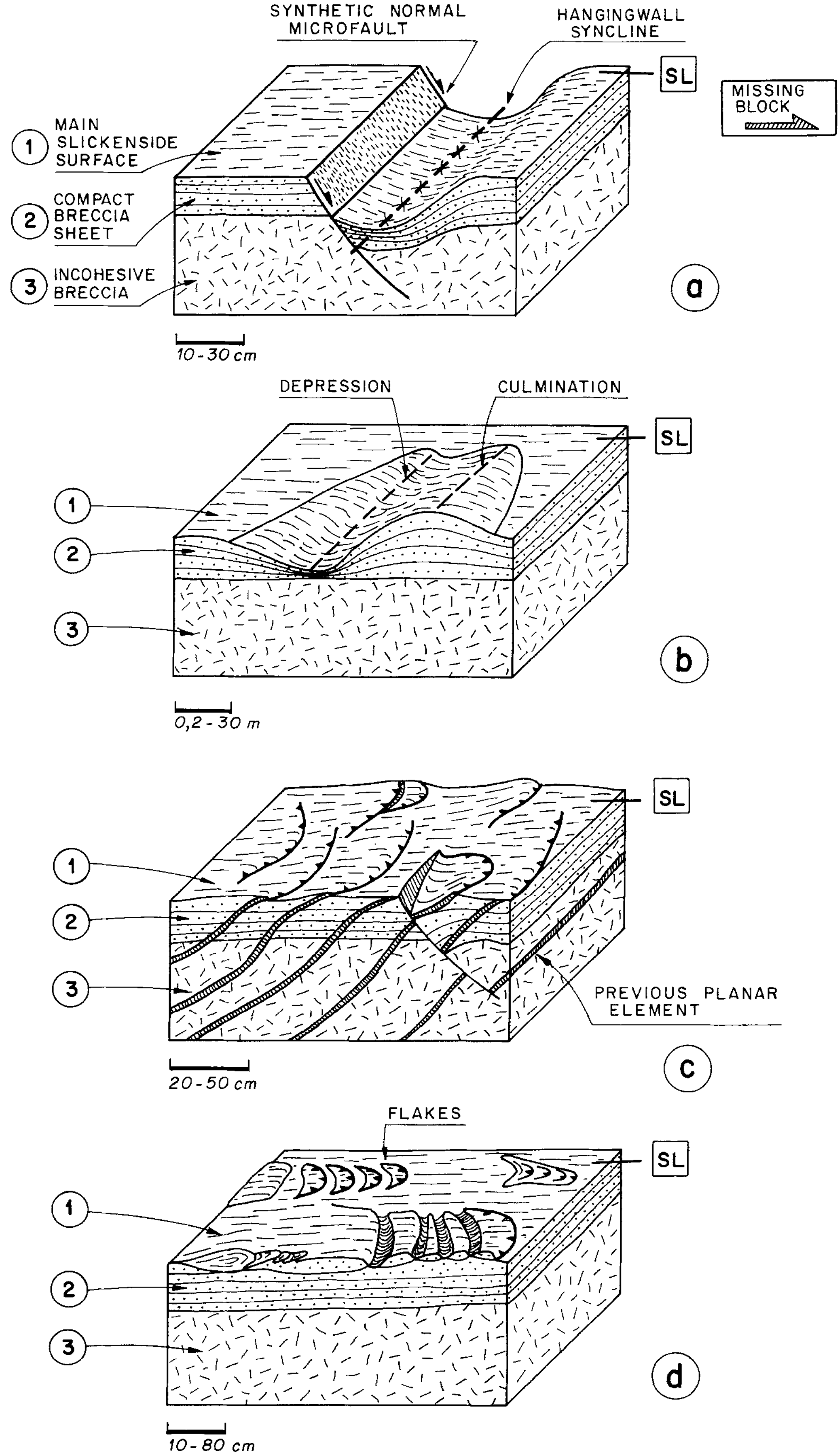
INTRODUCTION

Slickensides have been described under a wide variety of brittle to ductile crustal conditions (Petit *et al.*, 1983; Doblas, 1987; Means, 1987), including unusual environments such as shallow hydroplastic or pedogenic synsedimentary ones (Petit and Laville, 1987; Gray and Nickelsen, 1989) and conditions related to the igneous flow of magmas against their wall rocks (Doblas *et al.*, 1988).

In this paper, we describe four new criteria for the sense of movement on slickensides showing evidence of mesoscopic ductility from the Jaloche extensional detachment fault in southern Spain (Fig. 1), infer their conditions of formation and postulate on the mechanisms responsible for their development.

The study area is within the Betic cordilleras, the westernmost branch of the Alpine Mediterranean orogenic system (see inset in Fig. 2). Three main units are recognized within the Internal Zone of the Betics and these increase in metamorphic grade with depth (Torres-Roldán, 1979). They are (from bottom to top) the Nevado-Filábride, the Alpujarride and the Maláguide complexes. The orogen results from lower Cretaceous–early Miocene compressional tectonics and it is overprinted by Neogene extensional detachments (Doblas and Oyarzun, 1989a,b).

The Jaloche detachment fault, which constitutes a subhorizontal contact affecting Triassic dolomitic marbles, dolomites and undifferentiated Palaeozoic and Triassic mica-schists, was previously interpreted as an Alpujarride compressional thrust (IGME, 1981). However, later works (Doblas and Oyarzun, 1989a,b; Doblas *et al.*, 1993, 1995) and detailed unpublished mapping show the unequivocal extensional character of this contact. This is also corroborated by the presence of abundant field structures, such as vertical extension gashes and shear bands, and by the NNE-directed sense of displacement of the hangingwall observed along this detachment (Doblas *et al.*, 1993, 1995). Compressional thrusts in the region generally show an opposite S-directed sense of movement (IGME, 1981). In the outcrops described in this paper the Jaloche detachment fault displays higher angles of dip than the usual regional low-angle attitude, probably as a result of later Tertiary–Quaternary tilting and faulting, which is well documented in this part of the Betics (Doblas *et al.*, 1993).


SYNTHETIC NORMAL MICROFAULT
HANGINGWALL SYNCLINE
SL
MISSING BLOCK
1 MAIN SLICKENSIDE SURFACE
2 COMPACT BRECCIA SHEET
3 INCOHESIVE BRECCIA
a
10-30 cm
DEPRESSION
CULMINATION
SL
1
2
3
b
0,2-30 m
SL
1
2
3
PREVIOUS PLANAR ELEMENT
20-50 cm
c
FLAKES
SL
1
2
3
d
10-80 cm

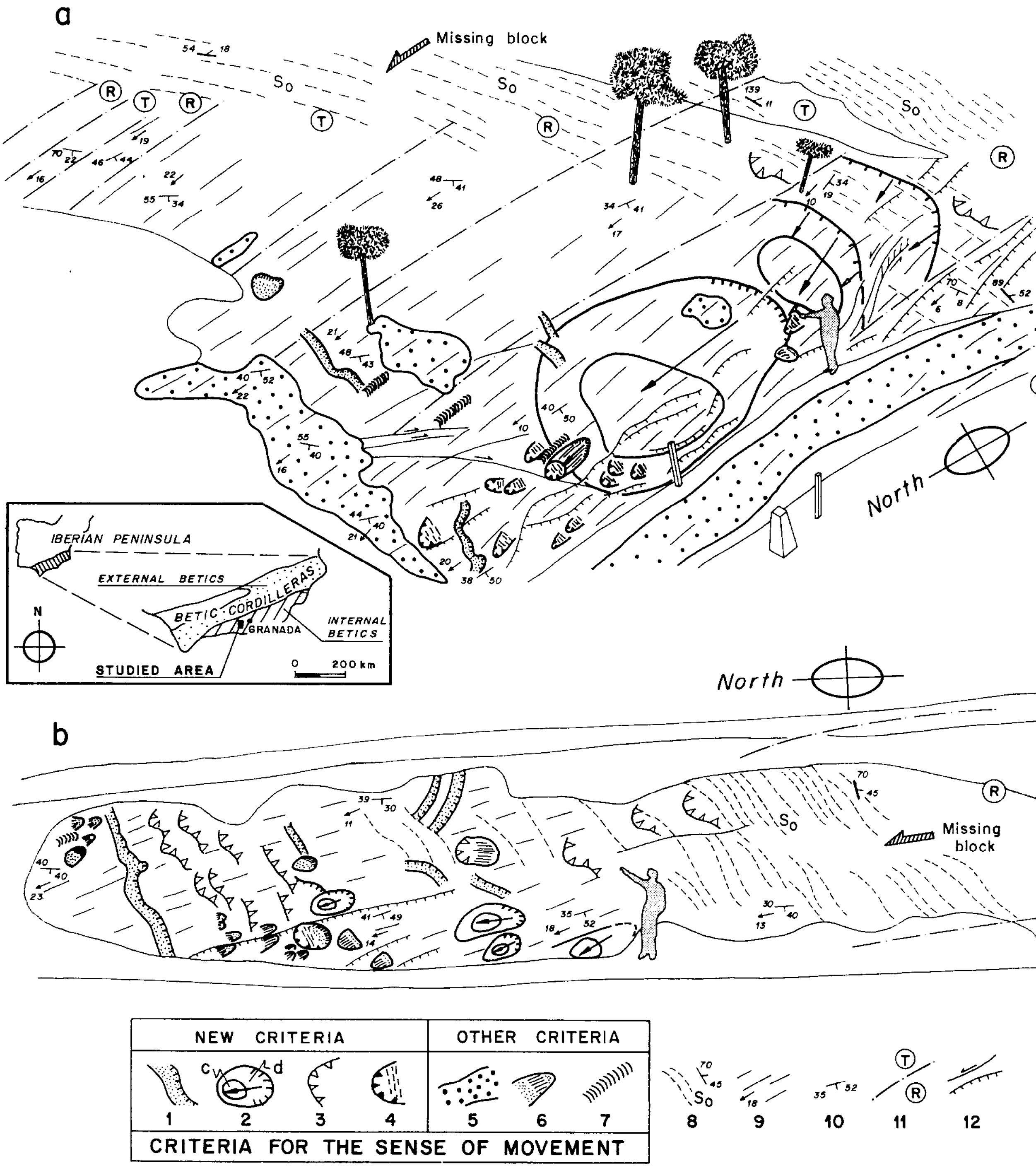


Fig. 2. Structural sketches (a & b) of the two studied exposures of the Jaloche detachment fault highlighting the new criteria recognized in this study (1, 2, 3, 4), as well as some other kinematic indicators (5, 6, 7). Criteria for the sense of movement: (1) synthetic secondary fractures with hangingwall microsynclines; (2) culmination (c) and depression (d) features (the arrows indicate the direction of transport of fault material from d towards c); (3) microthrusts verging towards the motion of the opposite block and dragging/overthrusting previous planar elements on the fault surface; (4) flakes of fault material trailed and plastered in the direction of the missing block; (5) foliated fault gouge; (6) asymmetric depressions with congruous steps; (7) trains of synthetic R_1 Riedel fractures along narrow channels with crescentic markings showing concavities facing towards the movement of the opposite block. Other symbols: (8) trace and attitude of the S_0 stratification planes; (9) direction and value of plunge of the slickenside lineations; (10) attitude of the slickenside surfaces; (11) lineation-parallel ridges (R) and troughs (T); (12) late/secondary high-angle wrench and normal fractures. The inset shows the location of the studied area in southern Spain. Scale is represented by the person standing close to the outcrops (height: 1.75 m).

Fig. 1. Schematic block diagrams depicting the four morphologically ductile criteria for the sense of movement on the slickenside surfaces of the Jaloche detachment fault. (a) Synthetic secondary fracture with hangingwall drag-effect in the form of a roll-over microsyncline. (b) Asymmetric culmination and depression features. (c) Microthrusts verging towards the direction of motion of the opposite block and dragging/overthrusting previous planar elements on the fault surface. (d) Flakes of fault-surface material trailed and plastered in the direction of the missing block. Note the different ranges of scales in each case, and the slickenside "stratigraphy" (1, 2, 3). SL, slickenside lineation.

The two exposures of the Jaloche detachment fault displaying the most spectacular slickenside surfaces have been schematically represented in Fig. 2 and they are shown in the photographs of Fig. 3. The rock consists of massive dolomites with occasional stratified dolomitic marble layers cut by the sliding surfaces, where bedding (S_0) dips between 11° and 52° in the opposite direction to the sense of movement of the missing block (Figs 2 & 3). The Jaloche detachment fault in this zone is oriented N19°E to N70°E, dipping from 8° to 26° to the NNW, while the trend of the lineations ranges between N11°E and N26°E (Fig. 2). This detachment fault is characterized by spectacular slickensides with shiny, polished, smooth surfaces (Fig. 3), and a "stratigraphy" (*sensu* Means, 1993) below the slip surface consisting of a compact breccia sheet, a zone of incohesive breccia and the fresh rock (Fig. 1). The shiny slickenside planes are commonly deformed by the ductile-looking features that are the kinematic indicators described in this paper. In some sectors of the exposed Jaloche fault, the slickensides have been eroded away. Metre-scale, low-amplitude, lineation-parallel ridges and grooves—megacorrugations—are also observed (Fig. 2), and these seem to be typical features associated with other normal faults (Hancock and Barka, 1987). Isolated patches of fault gouge with thicknesses ranging from a few mm to 50 cm are observed on top of the slickenside surface (Figs 2 & 3a), but erosion has removed them in most of the exposures. These fault gouges are foliated, providing spectacular criteria for the sense of movement (Fig. 4a), and they are well indurated and cemented, showing conspicuous stretching lineations. As a whole, the slickenside surface and the overlying fault gouge are interpreted to have formed coevally as they display similarly oriented lineations and the same sense of movement, that is a consistent NNE-directed sense of displacement of the hangingwall as clearly revealed by all the criteria for the sense of movement. Finally, a set of late secondary wrench and normal high-angle fractures disrupt the Jaloche detachment (Fig. 2), some of them bearing jigsaw implosion breccias which indicate the existence of transient seismic events.

CRITERIA FOR THE SENSE OF MOVEMENT ON THE SLICKENSIDE SURFACES OF THE JALOCHE DETACHMENT FAULT

We will now describe the four new kinematic criteria which show evidence of mesoscopic ductility related to the coupled processes of cataclastic flow and shear localization, together with other additional indicators which clearly reveal a NNE-directed sense of displacement of the hangingwall.

(1) The first criterion is based on the presence of synthetic secondary fractures which dip toward the movement direction of the missing block and show ductile-looking hangingwall drag-effects in the form of cm-scale roll-over microsynclines where the main slickenside fault surface is actually folded (Figs 1a, 2, 3b & 4b). These roll-over microsynclines, resulting from a congruous drag-effect, have a different mechanical origin than the classical hangingwall anticlines which are the result of shape adaptations of the upper block of a listric normal fault that flattens at depth. The secondary fractures described here are similar in many respects to R_1 *Riedel fractures* (Riedel, 1929) or to other *synthetic normal fractures* described in the literature (Norris and Barron, 1969; Engelder, 1974; Petit *et al.*, 1983; Petit, 1987). However, our synthetic secondary fractures make a greater angle with respect to the fault-zone boundary (approximately 30–60°), similar in that respect to the *hybrid synthetic fractures* of Hancock (1985) and Doblas *et al.* (1997). The secondary fractures described here are unique in that they show the ductile-looking drag-effect-related microsynclines.

(2) The second criterion for the sense of movement consists of metre-scale oval-shaped asymmetric culmination and depression features (Figs 1b, 2, 3a, c & 4c). In these structures there is ductile-looking material transport of cataclastic particles which are removed from the depression and transported by movement along the fault to form a culmination ahead of the depression in the movement direction of the hangingwall. It should be noted that these features are different to natural undulations which are usually encountered in slickenside planes, in that: the features described here are of a larger scale; deformation in them is discontinuous; they have a kinematic significance related to their asymmetry; and they have a different mechanical origin. They are probably related to the indentation effect of blocks contained in the hangingwall thrusting ahead fault material with a behaviour which might be compared to the granular flow of loose sand under stress states too small to cause fracturing, a mechanism which has been described as a form of cataclastic flow (Rutter, 1993). In contrast, the symmetric megacorrugations parallel to the slickenside lineations which have also been described in the Jaloche detachment fault (ridges and troughs; Fig. 2) represent continuous deformations of the sliding surface. This may be due to the same process described in normal faults in Turkey (Hancock and Barka, 1987) where propagating slip planes seek undemanding pathways through heterogeneous fault-precursor breccias. Both *symmetric depressions* with no kinematic significance (Suter *et al.*, 1995) and *asymmetric depressions* with conflicting senses of movement (Vialon *et al.*, 1976; Hancock and Barka, 1987) have been described in slickensides, but they bear little ressemblance to the paired depression–culmination features described here.

(3) The third criterion is characterized by microthrusts verging towards the direction of motion of the hangingwall and which often drag and overthrust, in a ductile manner, previous planar elements such as the

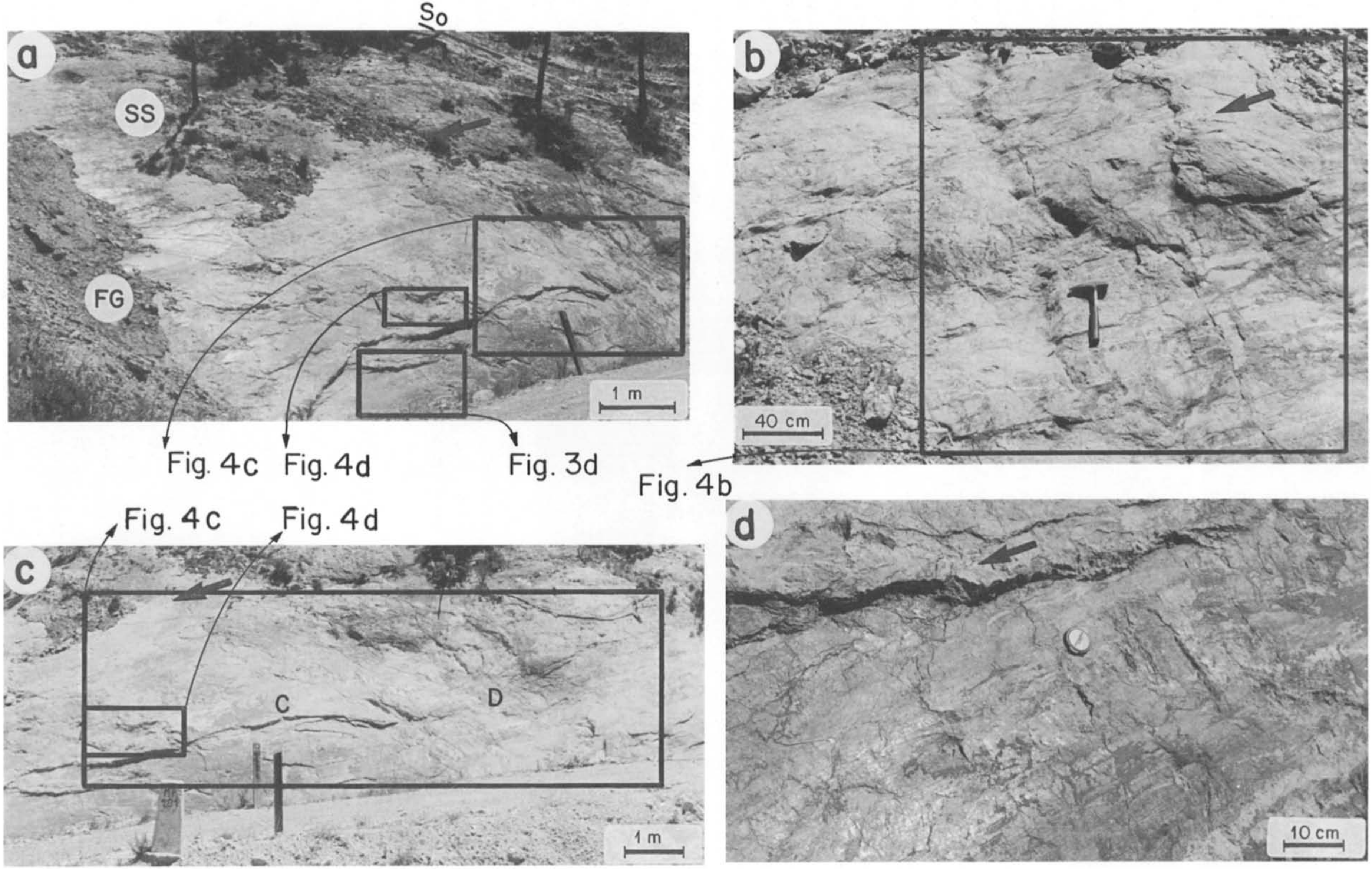
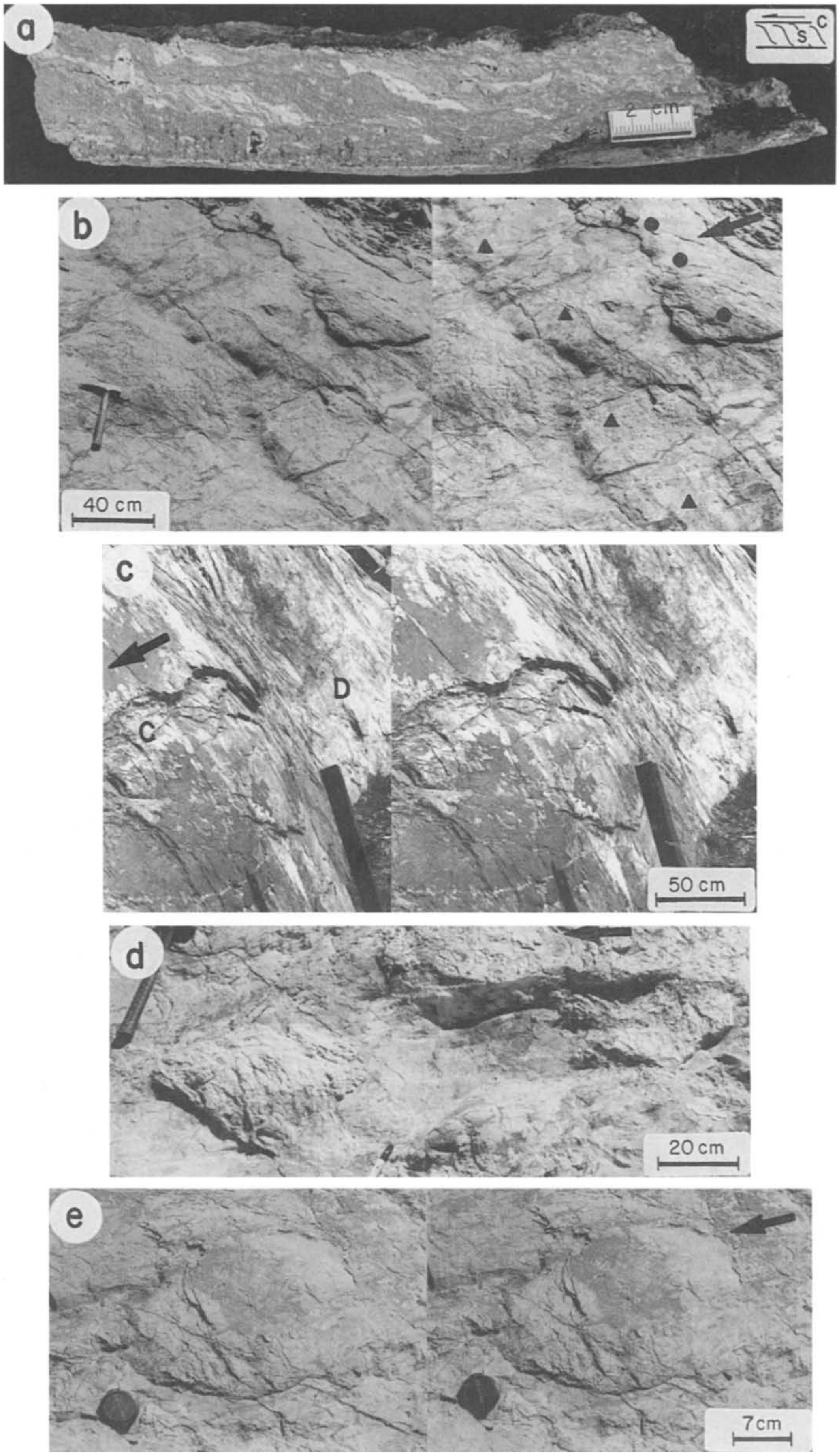


Fig. 3. The two studied exposures of the Jaloche detachment fault. (a) Partial view of the first outcrop which is schematically depicted in Fig. 2(a) (FG, fault gouge; SS, slickenside surface). (b) Partial view of the second exposure which is schematically depicted in Fig. 2(b). (c & d) Details of some of the features observed along the shiny and polished surfaces of the Jaloche detachment fault in the first outcrop (C and D in Fig. 3c: culmination and depression). Arrows indicate the movement direction of the missing block. The location of some of the photographs shown in the figures are outlined in (a)–(c).


a
C
S
2 cm
b
40 cm
c
D
C
50 cm
d
20 cm
e
7cm

original S_0 stratification on the fault surface (Figs 1c, 2, 3b & 4b). These overthrusted elements are firmly cemented to the slickenside surface. Similar microthrusts have been described in the slickenside literature as S_1 *pinnate shears* (Tjia, 1967), *synthetic reverse fractures* (Norris and Barron, 1969; Vialon *et al.*, 1976), *microthrusts* (Doblas, 1987) or *P fractures* (Lee, 1991). However, the structures described in the literature never involve previous planar elements dragged in a ductile manner on the fault surface in the movement direction of the missing block.

(4) The fourth criterion comprises flakes of fault-surface material trailed and plastered in the direction of the missing block, and showing evidence of mesoscopic ductility (Figs 1d, 2, 3a & c, 4d & e). These flakes of fault material are torn away/trailed in the direction of the missing block, with frontal microthrusts and tensile fractures both in the back and in the front of the thrusted pads. These flakes are strongly attached and bonded by a carbonate cement to the substrate, and it is hence impossible to pick them off without the use of a hammer. Amounts of displacement are of the order of mm to cm and, hence, it is easy to recognize from where these flakes originated. Even if the conditions of formation and most of the geometric characteristics are different, these features bear some slight similarity to a series of structures described previously by other authors: *microscopic flakes* (Doblas, 1987; Bossière and Sellier, 1993); *debris trails or bruises* (Willis and Willis, 1934; Tjia, 1967; Jackson and Dunn, 1974; Vialon *et al.*, 1976; Doblas, 1987); *congruous accretion steps* (Dzulynski and Kotlarczyk, 1965; Norris and Barron, 1969; Gay, 1970); *trailed fault material* (Doblas *et al.*, 1997); *tappering grooves* and *thrusted pads* of hydroplastic slickensides (Petit and Laville, 1987); soft-sediment *glacial grooves* (Savage, 1972); synsedimentary erosional *flute-* or *groove-casts* (Roberts, 1991); and *lava grooves* generated while the volcanic rock was still plastic (Nichols, 1938).

Occasionally, complex structures which represent intermediate cases between the four criteria described here might be observed along the Jaloche detachment fault (e.g. trailed flakes with culmination and depressions, or flakes of thrusted previous planar elements).

Additionally, other criteria for the sense of movement previously described in the literature have been found in the Jaloche detachment fault. These include: (i) spectacular foliated fault gouges (Fig. 4a) with *S*- and *C*-planes; (ii) asymmetric depressions with congruous steps similar to the ones described by several authors (Dzulynski and Kotlarczyk, 1965; Vialon *et al.*, 1976; Doblas *et al.*, 1995); and (iii) trains of synthetic R_1 Riedel fractures along narrow channels (analogous to the *R criterion* of Petit, 1987), and with crescent-shaped marks with concavities facing towards the movement of the opposite block (the *"arcatures"* of Sellier and Bossière, 1993).

DISCUSSION

We will discuss the conditions of formation of the Jaloche detachment fault, as the new criteria described here may be a product of the particular mechanical evolution of this fault. The temperature of formation of this detachment has been semi-quantified using calcite–dolomite geothermometry and illite crystallinity index. The geothermometry using the $MgCO_3$ content of the calcite (Sheppard and Schwarz, 1970), and the mole fraction values of the $MgCO_3$ based on the 2θ angle of the calcite peak (Goldsmith *et al.*, 1961), yields temperatures between 290 and 327°C. These temperatures are within the range of the low-grade metamorphic event defined on a regional scale for this part of the Betic cordilleras (Aparicio *et al.*, 1995). Microstructural analysis of the measured calcite grains indicates that they correspond to a recrystallized phase, probably associated with the generation of the fault gouge. The mineralogical composition of the fault gouge determined using X-ray diffraction is as follows: 40% illite–muscovite, 35% calcite, 20% quartz, 5% dolomite and traces of haematite. The crystallinity index of the illite according to Kubler (1968) shows values between 4.5 and 5 mm (anchi- to epizone) and 2.25 and 2.5 mm (epizone).

All the features described occur within pervasively fractured dolomite, which has phyllosilicate-rich fault gouge lying directly above it. The four criteria for the sense of movement on slickensides described here formed as a result of coupled cataclastic flow and shear localization, as indicated by the morphology of these features and also the brittle nature of the microstructure (Fig. 5a–d). Despite the relatively high temperature of formation, dolomite remains brittle over a wide range of conditions, although some static recrystallization of the dolomite is evident on a microscopic scale in isolated areas. Microstructural studies of the dolomite have shown intact angular polycrystalline fragments of varying sizes contained within a matrix of cata- to ultracataclasite (Fig. 5a & b), characteristic of distributed cataclastic flow.

Cementation of the dolomite by calcitic cements can also be seen (Fig. 5d), although only one episode can be identified clearly as no cataclastic damage of the cement

Fig. 4. Examples of some criteria for the sense of movement on the slickenside surfaces of the Jaloche detachment fault. (a) Section of the foliated–indurated fault gouge parallel to the slickenside lineation and perpendicular to the fault surface (the sense of movement is revealed by the *S*- and *C*-planes). (b) Stereopair showing an example of a synthetic secondary fracture with a hangingwall drag-effect in the form of a roll-over microsyncline (triangles). This photograph also shows an example of microthrusts dragging/overthrusting the S_0 stratification planes on the fault surface (circles; see also Fig. 3b for the location of this photograph). (c) Stereopair showing a metre-scale culmination–depression (C/D) feature (see also Fig. 3a & c for the location of this photograph). (d & e) Flakes of fault-surface material trailed and plastered in the direction of the missing block (e is a stereopair). See also Fig. 3(a & c) for the location of Fig. 4(d). Arrows indicate the movement direction of the missing block.

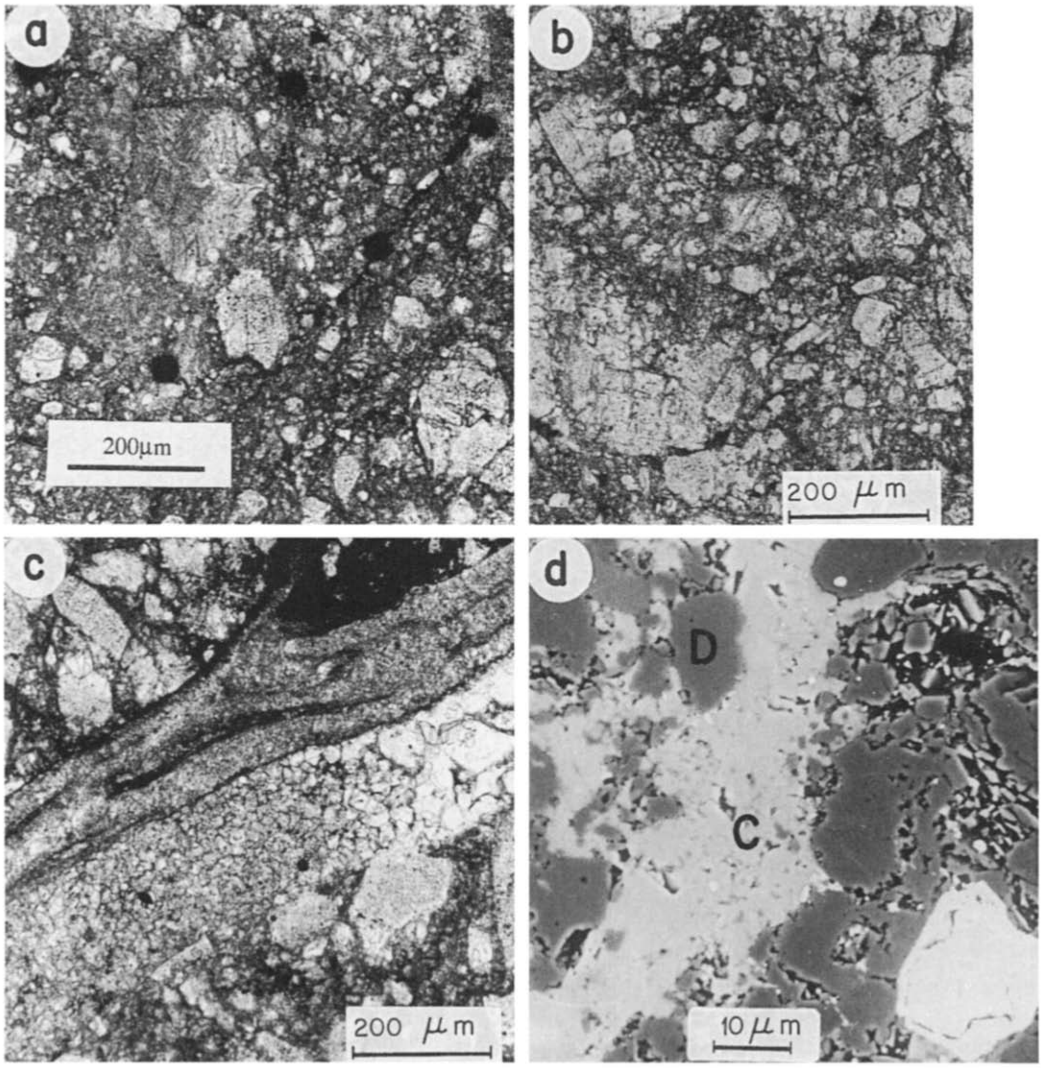


Fig. 5. Different photomicrographs of the fault rocks of the Jaloche detachment fault. (a & b) Photomicrographs showing angular polycrystalline fragments of dolomite contained within a matrix of cataclasite to ultracataclasite (these features are characteristic of cataclastic flow); (c) photomicrograph showing angular fragments of cataclastic dolomite, and a narrow zone where deformation is localized and two phases of movement can be recognized: one where the finer grained cataclasite is seen, and the second where the ultracataclasite has developed; (d) scanning electron microscope photomicrograph showing angular dolomite clasts (D), cataclastic damage and one phase of calcitic cement (C). The grains/cement structures seen within the dolomite clasts are a product of early cementation and are not relevant to the deformation history of the fault rock.

can be found. The presence of the cement indicates that a fluid flux existed within the dolomite, although this may only have been after the major phase of deformation.

Cataclastic flow of rocks has been described in both nature and experiments (e.g. Stearns, 1968; Hadizadeh and Rutter, 1983; Hirth and Tullis, 1989; Evans *et al.*, 1990; Zhang *et al.*, 1990; Rutter and Hadizadeh, 1991). Several conditions have been recognized as important to facilitate deformation by cataclastic flow as opposed to the more common mode of failure, brittle localization. Among these are: a high effective pressure (defined here as total pressure minus pore pressure, Bernabe and Brace, 1990); high porosity (Rutter and Hadizadeh, 1991); the presence of a weak second phase (Byerlee, 1968); and contribution from some crystal-plastic mechanism (Fredrich *et al.*, 1989).

In terms of what is seen in the microstructures of the Spanish dolomites, there was no presence of a weak second phase, and a contribution from crystal plastic mechanisms is not evident (no undulatory extinction, no subgrains seen). In addition, high initial porosities are not observed in the protolith, which would suggest that a high confining pressure and low pore pressure were necessary to favour cataclastic flow and inhibit localization. This inferred mechanical state, whereby high effective stresses were present, may seem paradoxical considering that we are dealing with movement on a low-angle extensional detachment. To promote sliding on such a surface, low effective stresses are usually assumed. Two possibilities exist to explain this paradox: (1) a high effective stress was perhaps only transient, and pore pressure increased as the porosity was steadily sealed up by cementation; or (2) once dilatancy hardening had occurred in the dolomites, subsequent movement on the fault was further accommodated within the phyllosilicate-rich gouge, which would require much lower effective stresses for sliding. Indeed, movement within this gouge may have helped promote some of the features described by the drag-effect of the gouge on the slickenside plane deforming it into a complex surface. The existence of only one phase of undamaged calcite cement suggests that fluid flux through the dolomites during deformation was not great, and that precipitation of the cement occurred after the deformation.

The initial pore pressures may have been high within the dolomites, as the "cap" of phyllosilicate-rich fault gouge would have provided a low permeability barrier to fluids moving upwards, and intact dolomites would have provided a barrier downwards. This sealed-in pressurized fluid would have served to reduce the initial stress required to induce cracking and, during progressive cataclasis, the process of dilatancy hardening may have occurred (Brace and Martin, 1968; Rutter, 1972). Initial hydrofracturing of dolomite is possible if fluid pressures exceeded the least principal stress, but this would have produced oriented cracks for which there is no evidence in the microstructure, perhaps due to overprinting of later cataclastic damage. This cataclasis would have reduced the pore pressure within the dolomites as more porosity was created by the dilatancy effects, which in turn would have steadily increased the effective pressure, facilitating cataclastic flow.

This cycle of events, whereby pressurized fluids are sealed into the fault zone by progressive cementation, inducing cracking and dilatancy hardening effects promoting cataclastic flow, could occur many times, allowing large strains to be achieved. In this case, it appears that the cycle occurred once, as only one cementation event can be clearly recognized. Other studies of naturally deformed rocks have shown that similar processes can accommodate large strains. However, the processes highlighted here have yet to be explored in detail by experimental studies.

Although one of the major deformation processes occurring within the dolomites has been shown to be cataclastic flow, it is clear from the field structures and the microstructures that some localization did occur as shown by the existence of the brittle secondary fractures associated with the ductile-looking roll-over microsynclines, and by some of the tension fractures related to the flakes and microthrusts (Fig. 5c). Hence, deformation accommodated by cataclastic flow may only have been transient.

It has been recognized that distributed deformation such as the one characterizing the steady-state evolution of fault gouge typically forms during stable aseismic sliding, whereas deformation occurring along highly polished slickensides tends to be the result of unstable seismic slip (Moore *et al.*, 1988; Miller, 1996; Spray, personal communication). In the Jaloche detachment fault rates of slip seem to have cycled over time from seismic to aseismic (as is usually the case in most faults; Scholz, 1990): the highly polished shiny slickensides and the jigsaw implosion breccias are probably indicators of transient seismic episodes, while the foliated–indurated fault gouges and the ductile-looking slickenside features might represent times of aseismic creep and cataclastic flow (Spray, personal communication). Furthermore, this seismic–aseismic behaviour might have coexisted occasionally along contrasted domains along the Jaloche detachment fault, which displays patches of gouge overlying highly polished slickensides: as suggested by Miller (1996), portions of fault zone without gouge tend to be stronger and they are more likely to slide unstably than portions with gouge.

Contrary to the assumption that low-angle normal faults tend to creep aseismically (Jackson, 1987), the recognition that extensional detachments commonly fail in large earthquakes (Wernicke, 1995) has significant implications regarding seismic hazards which may be seriously underestimated in extending areas such as the one described in southern Spain. In fact, the seismogenic map of this part of the Betic cordilleras only considers the earthquake risks associated with high-angle normal and wrench faults (IGN, 1992).

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