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Development of strike-slip faults in the dolomites of the Sella Group, Northern Italy

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Abstract

The dolomites in the Sella Group, Northern Italy, were intensely jointed and faulted during the Alpine orogeny. Field observation of joints, joint-zones, and faults are the basis for a model for fault development in dolomite. We propose that joints developed parallel to the maximum compressive stress direction and were homogeneously distributed throughout the Sella Group before faults became localized (fault pre-nucleation stage). With ongoing deformation, the joints were localized into en-échelon arrays also called joint-zones. These joint-zones are incipient faults and are characterized by small dilation ($\ll$1 mm) of the individual joints, narrow joint spacing (1–15 mm), a high number of joints in the array (up to thousands), high joint-overlap, and joint-array angles between 10° and 40°. The next stage in fault development involves the break up of the rock bridges in the joint-zones and the localization of shear. Joint-zones with pockets of breccia are the smallest faults encountered and accommodate strike-slip offsets of 5–7 mm, whereas joint-zones with a continuous breccia zone accommodate offsets of 1–3 cm. Faults with offsets of more than 1 m are characterized by a breccia zone 0.5–15 m wide, and high joint densities in the wall-rock. The absence of a distinct granular structure of the dolomites of the Sella Group and the shallow depth of burial during Alpine deformation (less than 1000 m) may have promoted the growth and localization of joints, their linking via cross-joints, and the formation of continuous faults. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

The Sella Group is a dolomitized carbonate reef complex in the central part of the Dolomites (Bosellini, 1991). While Alpine deformation has affected the northern and eastern parts of the Dolomites with pervasive thrusting, the central part has remained relatively undisturbed (Bosellini and Neri, 1991; Cadrobbi et al., 1995). The structures in the Sella Group have, therefore, not received much attention, and are usually dismissed because of the 'small' strains they accommodate (Bosellini and Neri, 1991; Cadrobbi et al., 1995). An exception is the work done to describe the sub-horizontal thrust at Piz Boe' (Doglioni, 1985; Cadrobbi et al., 1995).

This thrust is a typical example of the 'Gipfelfaltungen' or 'Scorrimenti di vetta' (Leonardi, 1967; Cadrobbi et al., 1995) that have displaced the tops (Gipfel in German and Vetta in Italian) of some mountains in the Dolomites. Our observations away from the Piz Boe' thrust show that the Sella Group is intensely deformed by faults, joints, and other fractures. The offsets across the joints and most faults are not very large and consequently the total amount of shortening accommodated by the structures is small in comparison to other sites affected by Alpine deformation; however, the fracture density is extremely high and deserves attention and explanation.

Three sets of strike-slip faults occur in the Sella Group where a 'set' consists of sub-parallel strike-slip faults. The offset across the faults ranges from a few mm to 200 m. The dolomites are heavily jointed with spacing never exceeding 4 cm in areas between the

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strike-slip faults. One of the reasons that the importance of the structures in the Dolomites has been overlooked so far is that offset is not easily detected across the strike-slip faults. Another reason is that these faults may have evolved from en-échelon arrays of joints into complex fault zones with breccia: a mechanism not recognized before in the dolomites of the Sella Group. For that reason, the purpose of this paper is to present a model for fault development in dolomite on the basis of the observed fault structures and rock mechanical principles.

The way in which natural faults develop, and the resulting architecture, varies strongly with rock type and geologic setting (Gross, 1995; Caine et al., 1996). Many field studies contain observations on a certain type of fault (e.g. normal or reverse) with a limited range of offsets in a particular rock type and/or setting. Therefore, many such studies are needed to understand generally how faults develop from the microscale to the continental scale.

Fault development in porous sandstone is relatively well understood. Offsets of 1 mm or less are accommodated by thin cataclastic zones, also called deformation bands (Engelder, 1974; Aydin, 1978; Underhill and Woodcock, 1987; Antonellini and Aydin, 1994). With ongoing deformation, more cataclastic zones are localized close to one another, and a slip plane develops that can accommodate up to tens of meters of displacement (Aydin, 1978; Antonellini and Aydin, 1994). Veins, arranged in en-échelon arrays, have accommodated shear in different rock types, such as carbonate (Rothery, 1987), graywacke (Smith, 1996) and sandstone (Rickard and Rixon, 1983). In some cases the en-échelon arrays of veins develop in previously unfractured host-rock (Beach, 1975; Ramsay and Huber, 1983, pp. 235; Rickard and Rixon, 1983; Rothery, 1987; Willemse et al., 1997). Additional deformation can be taken up by the formation of slip planes along solution seams at the tips of the veins in the array (Willemse et al., 1997).

In other cases slip along a pre-existing fracture such as a vein or joint (Pollard et al., 1982; Nicholson and Pollard, 1985), or along a fault propagating into a less competent layer (Smith, 1996), results in the formation of en-échelon arrays of veins. Also, in other rock types, slip often localizes along pre-existing structures inherited from previous tectonic events. In granite, slip along pre-existing joints resulted in the formation of joints at the tip of the reactivated joint (tail cracks) and caused the fragmentation of the rock bridges in between the slip planes (Segall and Pollard, 1983; Granier, 1985; Martel et al., 1988; Martel, 1990). Complex fault zones result when subsequent generations of slip planes and tail cracks develop.

A similar mechanism is observed in sandstone. Tail cracks form as the result of slip along pre-existing joints (Cruikshank, 1991) or pre-existing en-échelon arrays of joints (Myers and Aydin, 1996). Complex structures at the tips of faults do not only form where slip occurred along pre-existing fractures but also at the tip of faults that form in undeformed rocks. For example, joints or tail cracks are observed at the tip of faults along bedding planes in sandstone (Cooke et al., 1999) and in siliceous shale (Dholakia et al., 1998). Compaction bands or stylolites occur in the compressional quadrant at the tips of faults in both sandstone (Mollema and Antonellini, 1996) and limestone (Rispoli, 1981). Other styles of deformation at fault tips observed in carbonates, silt and siltstone include branching and the formation of en-échelon arrays of fractures (McGrath and Davison, 1995).

Experiments using photoelastic techniques (Brace and Bombolakis, 1963), liquid metal porosity (Zheng et al., 1989; Myer et al., 1992), acoustic emissions (Lockner et al., 1992a) and computerized image analysis (Moore and Lockner, 1995) have shown that tensile microcracking often precedes the development of continuous faults in various rock types. Our observations of outcrops supplemented with microstructural work include several elements of the mechanisms described above.

2. Geologic setting and history

The Dolomites (Fig. 1) are part of the South Alpine mountain range which is bounded to the north by the Insubric lineament, to the west by the Giudicarie line, and to the south by the south-verging Valsugana overthrust (Doglioni, 1987; Bosellini, 1991). The Sella Massif stands out as one of the most impressive carbonate complexes of the Western Dolomites. The carbonate deposits of the Sella Massif range in age from Ladinian (Early Triassic) to Neocomian (Early Cretaceous) and are arranged in a broad synformal structure with an east–west axis and dips not exceeding 10°.

The massif represents an exhumed atoll composed of two different carbonate complexes, one on top of the other. The lower complex (1), of Carnian age, progrades radially from an elevated central Ladinian nucleus (Bosellini, 1982; Bosellini and Neri, 1991) and has a diameter of 7–8 km and a thickness of 400 m. For simplicity we combine the following formations in Complex 1: the Schlern Dolomite, the Cassian Dolomite, the Durrenstein Formation, and the Conglomerate of Val Gardena. The upper complex (2), on the other hand, represents the peritidal deposits of an aggregated carbonate platform margin with a total thickness of 300 m (Bosellini and Hardie, 1988; Bosellini, 1991). This complex consists of the Dolomia Principale or Haupt Dolomit. Complex 1 is separated from Complex 2 by the Raibl Formation that forms a

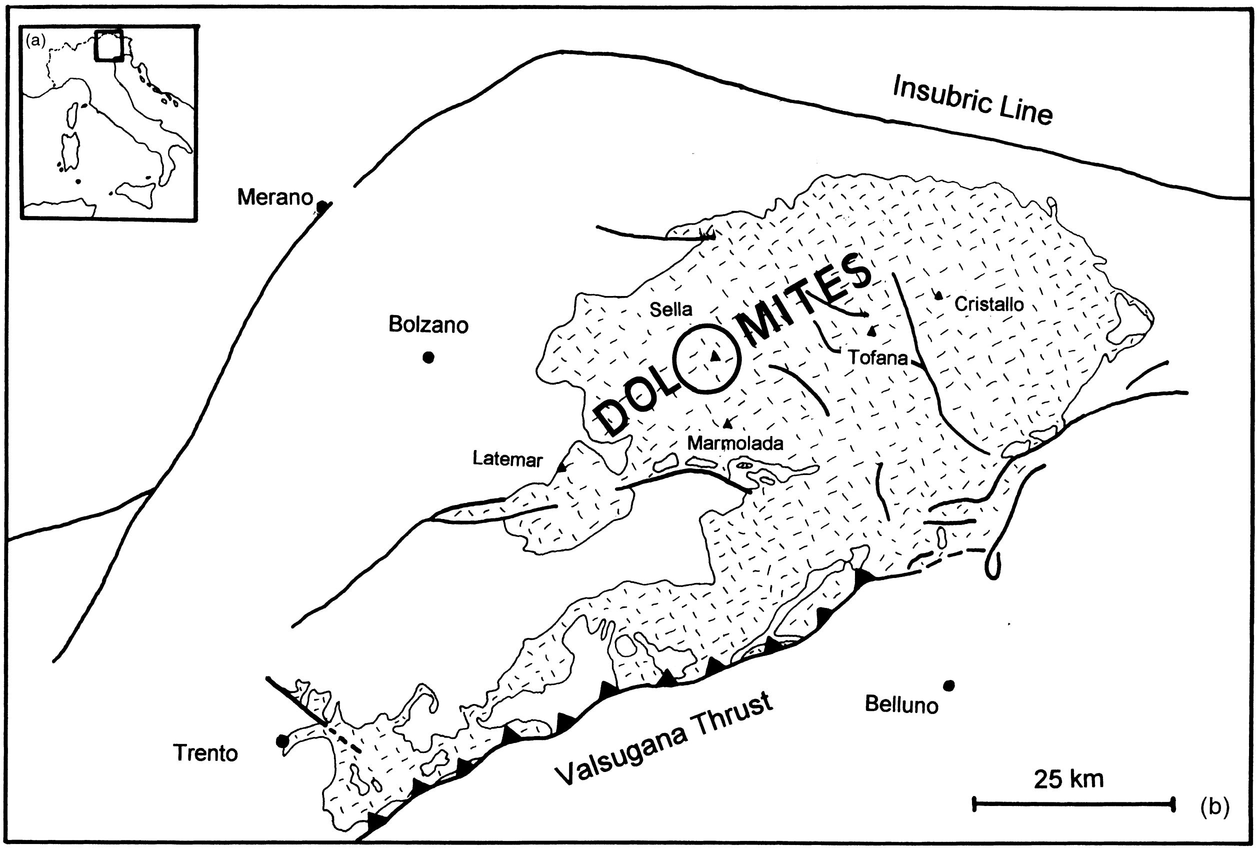

Fig. 1. (a) Location map of the Dolomites, northern Italy. (b) Simplified geologic map of the Dolomite region showing its northern (Insubric Line) and southern (Valsugana Thrust) tectonic boundaries and major faults. The circle indicates the location of the Sella Group (study area).

typical ledge in between the two steep cliffs of dolomite (Fig. 2). Most of our field observations are made in the Cassian Dolomite (Complex 1) and the Dolomia Principale (Complex 2).

The deposition of the stratigraphic units in the Sella Group was related to a sequence of tectonic phases (Doglioni, 1984; Castellarin et al., 1988; Bosellini, 1991); however, no structures are left in the Sella

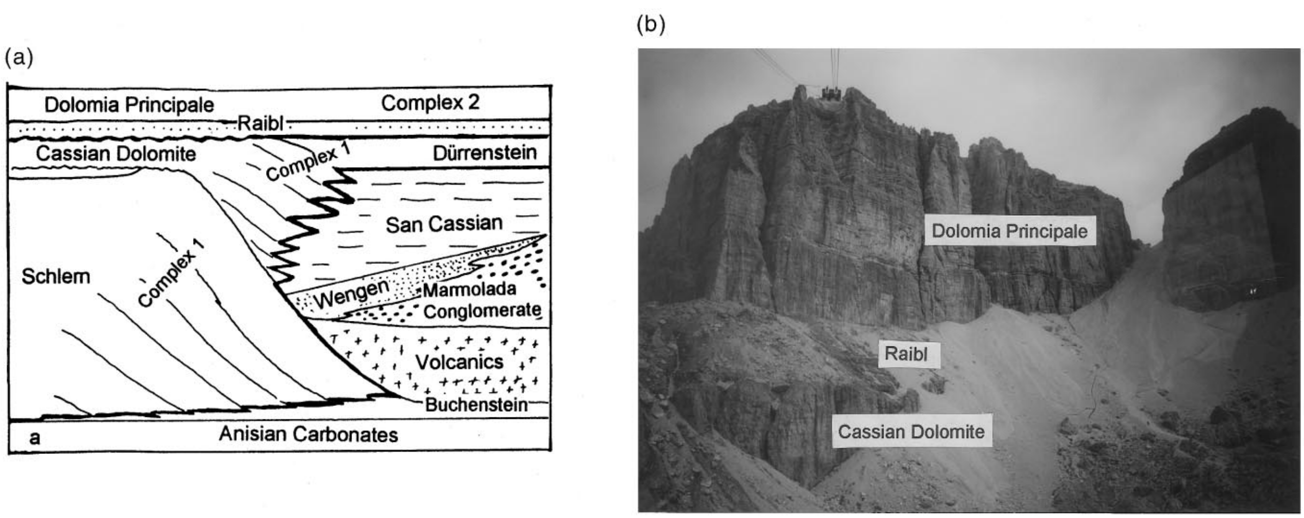

Fig. 2. Carbonate complexes in the Sella Group, modified after Bosellini (1991). (a) Main lithologic units shown with their relative thickness. The thick line represents the outline of complex 1. (b) Lithologic units as exposed at the Forcella Pordoi in the Sella Group. Lowermost formation is the Cassian Dolomite. The ledge-forming formation is the Raibl and the high cliffs are the Hauptdolomit or Dolomia Principale. View is to the North.

Group, except for the structures related to the last tectonic phase. In the Neogene, the Alpine Orogeny (fourth and last tectonic phase) caused a N–S- to NNW–SSE-trending direction of compression in the Dolomites, which was recorded by the orientation of the major overthrusts (e.g. the Valsugana overthrust) and structures described in this paper. The current uplift of the Dolomites is still related to the ongoing Alpine orogeny.

On the basis of the stratigraphic thickness, we can postulate that the depth of burial at the base of Complex 1 has never exceeded 1000 m (about 26 MPa). Therefore, rock deformation during tectonics has always occurred in regimes of moderate to low confining pressure. The (un-dolomitized) Dachstein Limestone occurs in stratigraphic continuity with the Dolomia Principale. This constrains the age of dolomitization in the Sella Massif to a period before the Late Triassic (before deposition of the Dachstein) and before the development of the strike-slip faults described in this study. Dolomitization in the Sella Group is pervasive; no rocks, except shale inclusions, are un-dolomitized. Faults, joints, and joint-zones do not have haloes of diagenetic alterations and, therefore, were not the pathways for the dolomitizing fluids. This confirms that fractures were formed after dolomitization.

2.1. Lithology

The lithology of the Cassian Dolomite (Complex 1) and Dolomia Principale (Complex 2) consists of buff-colored, coarsely crystalline dolostones, commonly vuggy and massive, with rare biogenic structures (Bosellini, 1991). Recognizable primary textures can rarely be identified in the crystalline dolomite rock.

The Cassian Dolomite has an apparent clino-stratification. Individual strata range from 1 m to 10–15 m in thickness. The Dolomia Principale has well developed sub-horizontal layers which range in thickness from 8 to 55 cm with a mode of 20–25 cm. In the Dolomia Principale, layers of syndepositional breccia occur with clasts of dolomite mudstone or shale. Other layers are very rich in macrofossils that have been completely replaced by dolomite and often form large vugs in the rock. Sub-rounded nodules of hardened dolomite, usually intensely fractured, are present throughout, often adjacent to fault zones.

3. Description of structures

3.1. En-échelon array of joints (joint-zones)

Joints (opening mode I fractures, Pollard and Aydin, 1988) are the most commonly occurring types

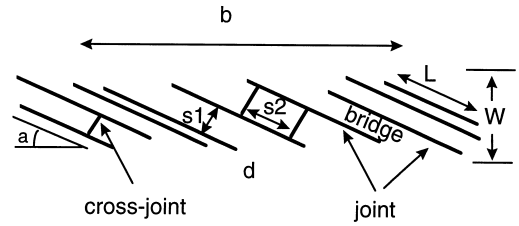

Fig. 3. Sketch showing geometric properties of a joint-zone. s_1 = spacing between joints in en-échelon array (1–2 mm); s_2 = spacing between cross-joints (1–2 mm); L = length of joints in en-échelon array (4–10 cm). b = length of en-échelon array (1–15 m). a = joint-array angle (typically 25°). d = dilation of joints in array (0.005–0.6 mm).

of fractures in the Sella Group. In many places they are localized into what we define as 'joint-zones', characterized by en-échelon arrays of narrowly spaced (mm) joints, which we suspect to be incipient fault zone structures (see Discussion).

The joints within and outside the joint-zones have a very small opening ($\ll$1 mm) compared to their length which is typically between 2 and 150 mm inside the joint-zones and up to 30 cm outside (Figs. 3 and 4). They are planar with straight parallel walls and have a typical spacing within the joint-zones from 1 to 15 mm and outside the joint-zones from 1 to 4 cm (Figs. 3 and 4). The rock volumes between the joints of an array are called bridges (Figs. 3 and 4). The angle between the joints within the joint-zone and the joint-zone itself (the joint-array angle) varies from 9° to 55° (the most common values are between 10° and 40°); in a few cases we observed angles up to 65° (Fig. 5). The joints in the array overlap for most of their length. Commonly, the orientation of the joints in the joint-zone is the same as the joints outside the joint-zones. In a few cases a small variation in orientation has been detected but not greater than 5–10°.

In most places a second joint system is observed, oriented perpendicular to the joints of the initial array (Figs. 3 and 4) without cutting across them. They are, therefore, interpreted to be younger than the joints in the en-échelon array. Some of the cross-joints end only on one side at an en-échelon joint and have a sigmoidal or arcuate shape. The cross-joints typically have a spacing of 1–5 mm. Outside the array, joints with orientations similar to the cross-joints are present only within 10–15 cm of the array boundary, but with spacing of the order of 1–3 cm. The cross-joints within the array are very short (1–7 mm) whereas outside the array (in a 15 cm wide band), their length varies from 5 to 40 mm (Fig. 4). The angle between the en-échelon joints and the cross-joints varies from 10° to 90°; values around 90° are the most common and they

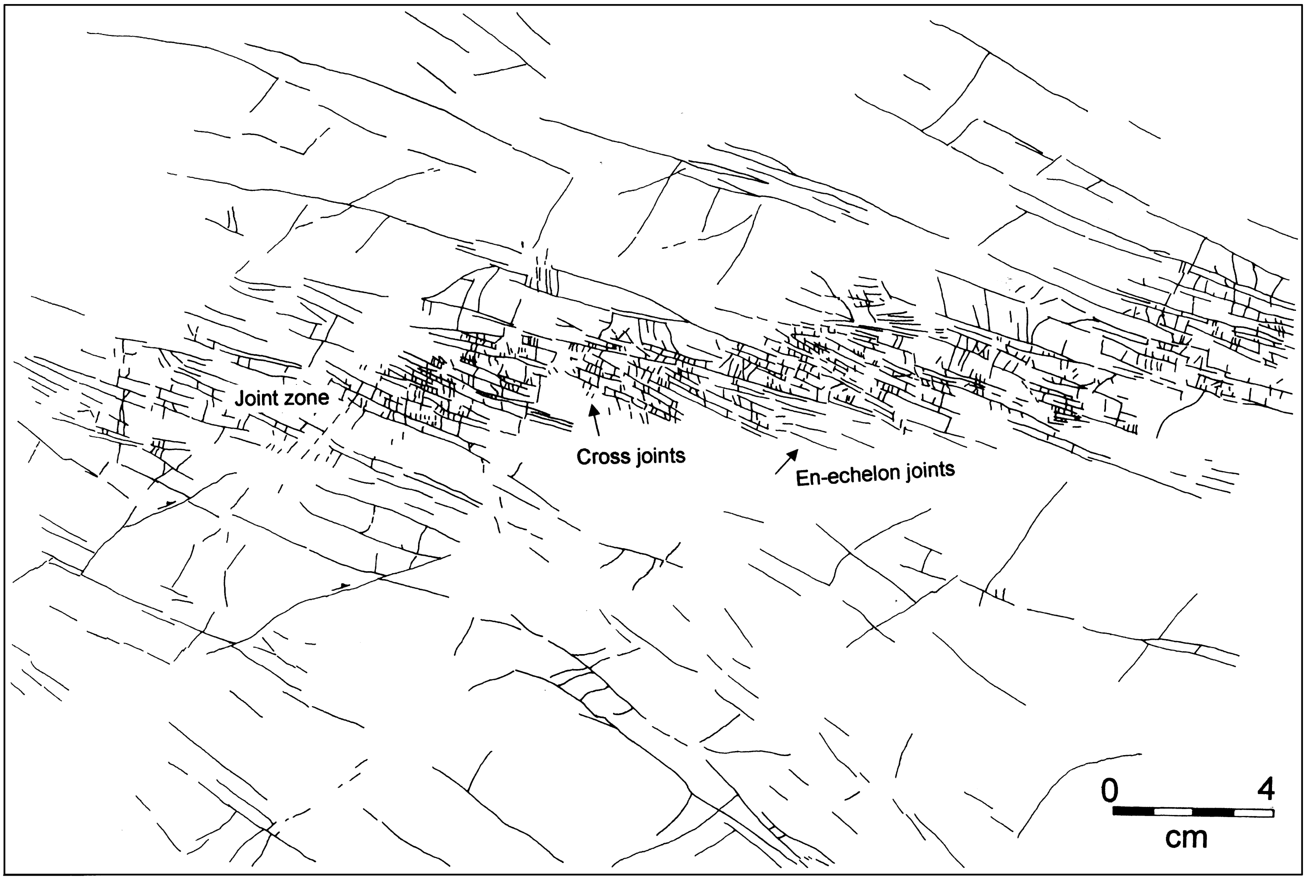

Fig. 4. Map of an en-échelon array of joints. Both en-échelon joints and cross-joints are indicated. Structure is in agreement with a right lateral sense of shear. Geometric properties are explained in Fig. 3.

are the rule where the spacing between the joints of the array is in the order of 1–2 mm. These joints, as with the joints forming the array, have a dark coloration and very small apertures. No measurable lateral offset across joint-zones with cross-joints is detected.

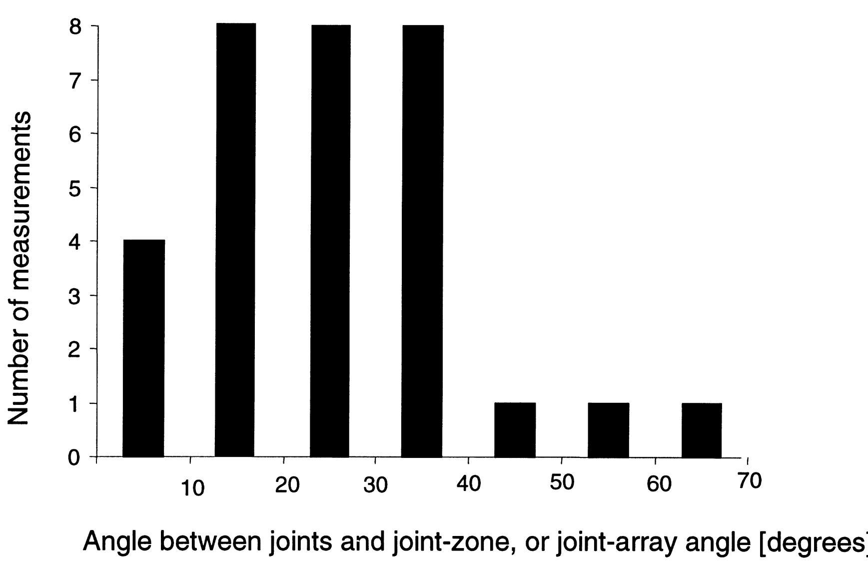

Fig. 5. Histogram of angles between joint-zones and joints within the joint-zone, measured in the field. Angles vary between 9° and 65°, but most joint-array angles are between 10° and 40°.

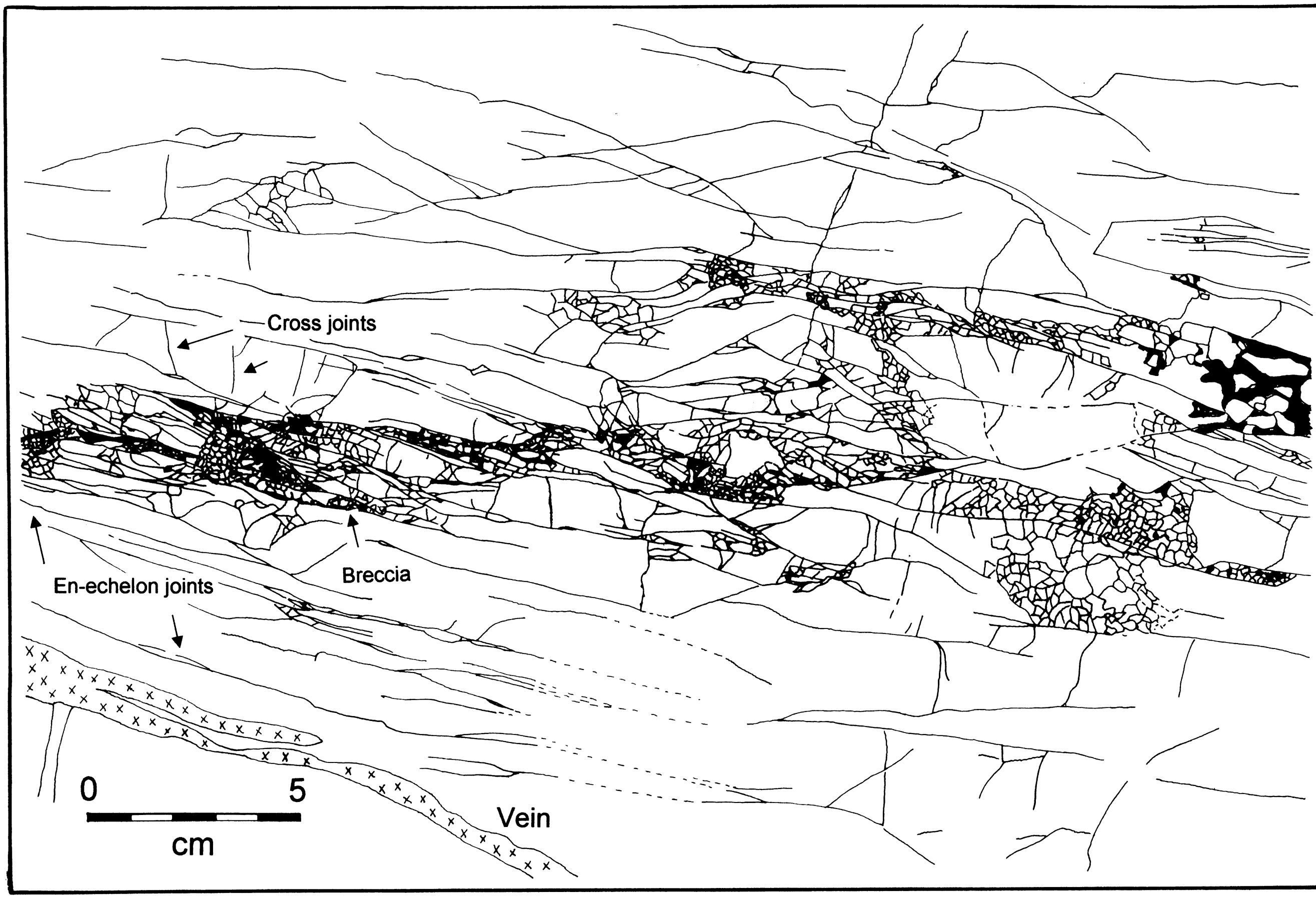

Fig. 6. Map of a joint-zone (right-lateral sense of shear). Note the pockets of breccia in between and parallel to the joints in the array.

3.2. Joint-zones with breccia pockets (strike-slip offsets of 5–7 mm)

The smallest faults we observed have a strike-slip offset of 5–7 mm and are characterized by elongated pockets of breccia, 1–2 cm wide and 3–6 cm long, parallel to en-échelon joints, also organized in en-échelon fashion (Fig. 6). Rock fragments are bounded by en-échelon joints and by cross-joints. Cross-joints perpendicular to the en-échelon joints break up the thinner bridges (1–2 mm) whereas, in the thicker bridges (0.5–2 cm), an intricate (mm spacing) network of cracks with random orientation is developed in addition to the cross-joints (Fig. 6). These networks also occur in the bridges at the boundary between the fault zone and host-rock.

3.3. Small faults with continuous breccia (strike-slip offsets of 1–3 cm)

Faults with an offset of a few cm typically have a continuous zone of breccia. The zone of breccia is up to 3 cm wide and parallel to the joint-zone. On the sides of the faults and in parts of the breccia, one can recognize the en-échelon joints and the cross-joints (Fig. 7). The joint density next to the faults in a zone 10–25 cm wide is high with spacing between 0.3 and 1 cm. The breccia is separated from the host-rock by one or more abrupt boundaries with periodic jogs (Fig. 7). We suggest that the boundaries formed along the traces of en-échelon joints and cross-joints.

3.4. Large faults (offsets of 1–200 m)

The larger faults with strike-slip offsets of up to 200 m are recognized by their wide (0.5–15 m) zones of breccia. Fig. 8 shows a block diagram of a large left-lateral strike-slip fault. The core of the fault zone contains breccia, the structure of which varies from fault to fault and with location along the same fault. For example, the breccia close to the tip of fault 647 (offset < 10 m) is very coarse with angular fragments varying in diameter from clay size (in the matrix) to 15 cm (Fig. 9a, location A on Figs. 10–12). Along the same fault, where the offset is 10–15 m (location B on Figs. 10–12) there is a seam of very fine whitish material (1–15 cm thick) on one side of the breccia zone. This seam consists of anastomosing bands of crushed material (see microstructures, Fig. 13c). The breccia of the 'Parafora del Sella', sampled in the vicinity of

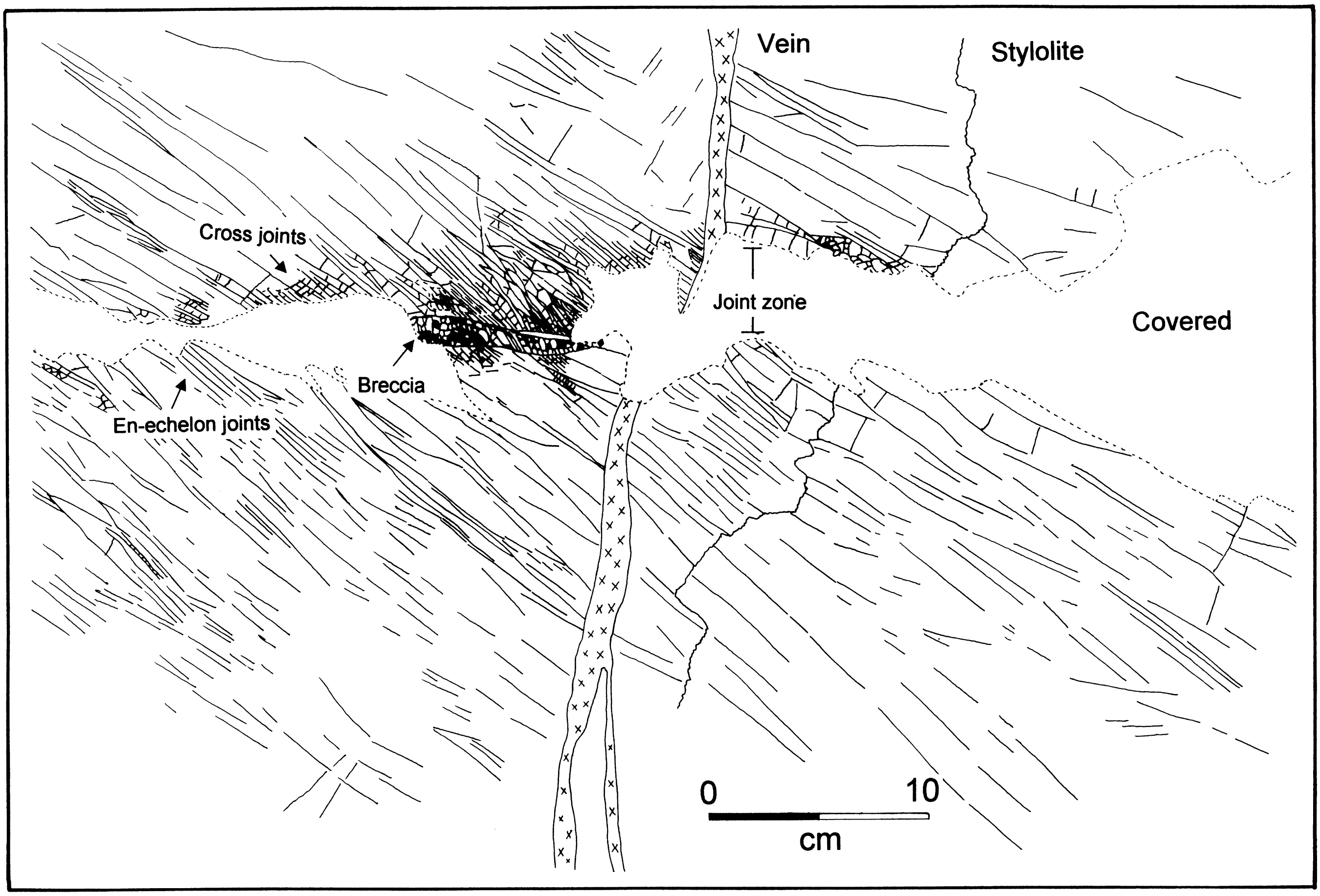

Fig. 7. Map of a small fault in dolomite. Note the zone of breccia parallel to the boundaries of the joint-zone and the two slip planes bounding the breccia. A vein and a stylolite are offset in a right-lateral sense by 3 cm. At the edges of the joint-zone and within the breccia the en-échelon geometry of joints with cross-joints can be recognized.

Rifugio Boe' where the estimated offset is 200 m (location C in Figs. 10–12), has smaller clast sizes ranging from < 1 mm to 2 cm (Fig. 13d). In this location, a possible slip surface (Fig. 9b) is recognized and open joints occur parallel to the fault plane within the breccia (Fig. 9c). At the edge of the breccia zones (fault 647, locations A and B), pieces of less fragmented host-rock project a few cm into the breccia zone (Fig. 9a).

Next to the breccia in the large faults, there is typically a zone of high joint density about 0.5 m wide (Fig. 8). These joints are oriented at an angle of 10–15° to the boundary of the breccia and are sub-vertical; their spacing varies from 1 mm to 0.5 cm. At a distance of about 20 cm from the edge of the breccia, the joints are oriented at a slightly larger angle (20–25°) to the plane of the fault and they have a spacing of 0.5–2 cm. A system of cross-joints is observed within 0.5 m of the wall of the fault. Small faults occur parallel to the en-échelon joints in the host-rock within 1.5 m from the boundary between breccia and host-rock. These small faults offset fossils approximately 1–5 mm (Fig. 9d) and have planar parallel walls. They have the morphology of joints and appear to be 'faulted joints'. The width of these faults is about 1 mm, and the space between the two fault planes has been filled by a mineral precipitate. Stylolites are very rare, and are observed only in the host-rock within one meter from the boundary between the host-rock and breccia zone. Both veins and joint-zones (with and without breccia) are typically localized parallel to, and within 15 m of the large faults. Joint density decreases with distance from the fault, from 300 m^{-1} next to the breccia to 50 m^{-1} about 15 m away.

3.5. Microstructures

To study the microstructure of faults in dolomite, 20 thin sections were cut from 15 hand-size, oriented samples that were collected during the fieldwork. The rock samples were impregnated with blue epoxy to show their porosity. The thin sections were then examined with an optical microscope using standard techniques.

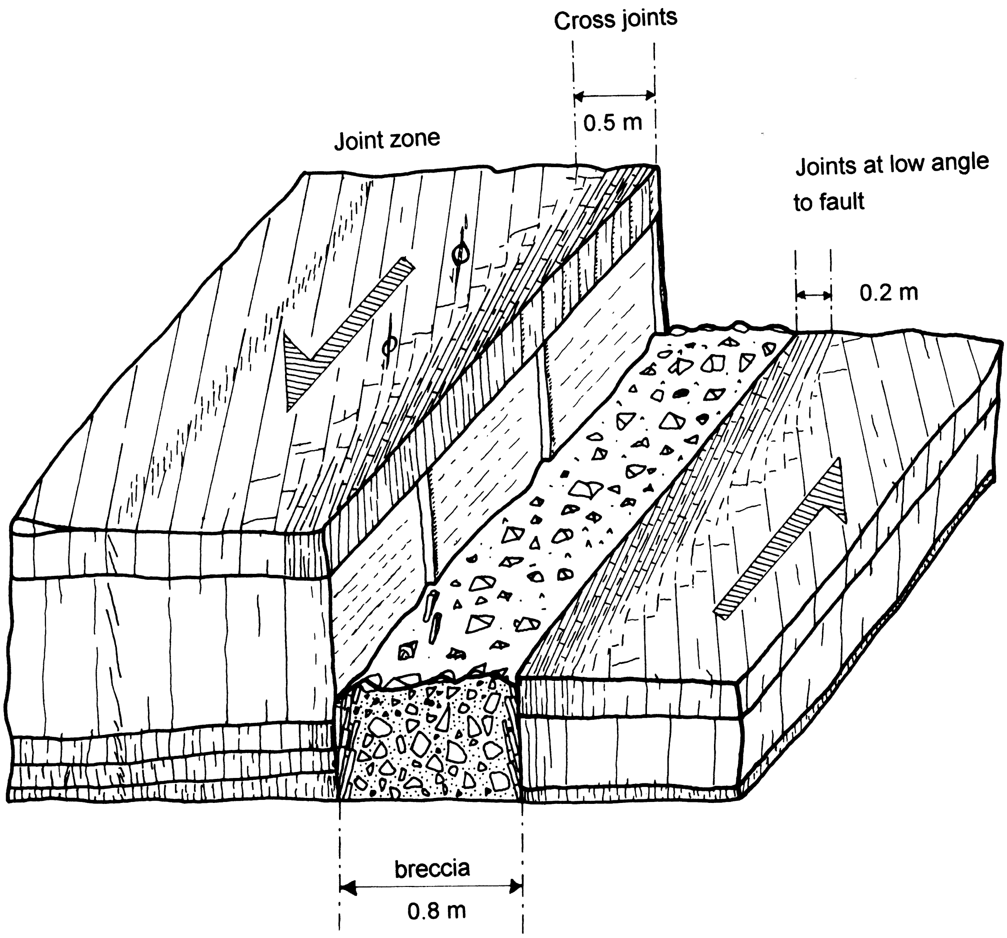

Fig. 8. Block diagram of the characteristic structure of a large (offset > 1 m) left-lateral brecciated fault zone in dolomite. The center of the fault consists of breccia. Next to the breccia there are zones of high joint density. Some of the joints are reactivated in shear. See text for further explanation.

3.5.1. Host-rock

The unfractured dolomite rock (host-rock) in the samples consists of dolomitic mudstone and crystalline dolomite. The dolomite mudstone is formed by microcrystalline dolomite, limestone shell fragments, and foraminifera replaced by dolomite. It is commonly associated with deposits of syndepositional breccia. The crystalline dolomite is formed of dolomite crystals ranging from 0.01 to 0.05 mm in diameter and is the most common lithology. Relatively large pores with diameters of 1–30 mm occur locally in the host-rock. Many of these pores are partially filled by crystalline dolomite with a drusy structure composed of a lining of crystals that project inward towards a commonly dolomite-free center.

3.5.2. Joints

Field observations on incipient fault zones in the dolomites of the Sella Group suggest that they consist of an array of joints, that is, opening mode I fractures, with no filling. Microstructural observations tell us, however, that most joints have a filling. By comparing the joints in the thin sections with the joints in the rock samples, it is apparent that the joints without filling at the surface of the sample correspond to the filled fractures in the thin sections of fresh host-rock. The joints are free of fillings up to depths of 0.5–2 cm from the surface. This and the fact that a few unfilled fractures in the thin sections show remnants of a filling, led us to believe that all joints were originally filled but that weathering in the field or epoxy impregnation in the samples caused the filled joints to open. We continue to use the term ‘joints’ to be consistent with our macroscopic observations. The joints are thin; their width is typically 0.005–0.0125 mm but occasionally up to 0.6 mm. The walls of the joints are straight and planar.

The dolomite crystals filling the joints are usually larger than the dolomite crystals in the host-rock, their size ranging from 0.005 to 0.5 mm. A few joints are open, but they have crystalline material along their border that may represent remnants of a filling similar to that of the completely filled joints (Fig. 13a); this crystalline material is usually on one side of the open

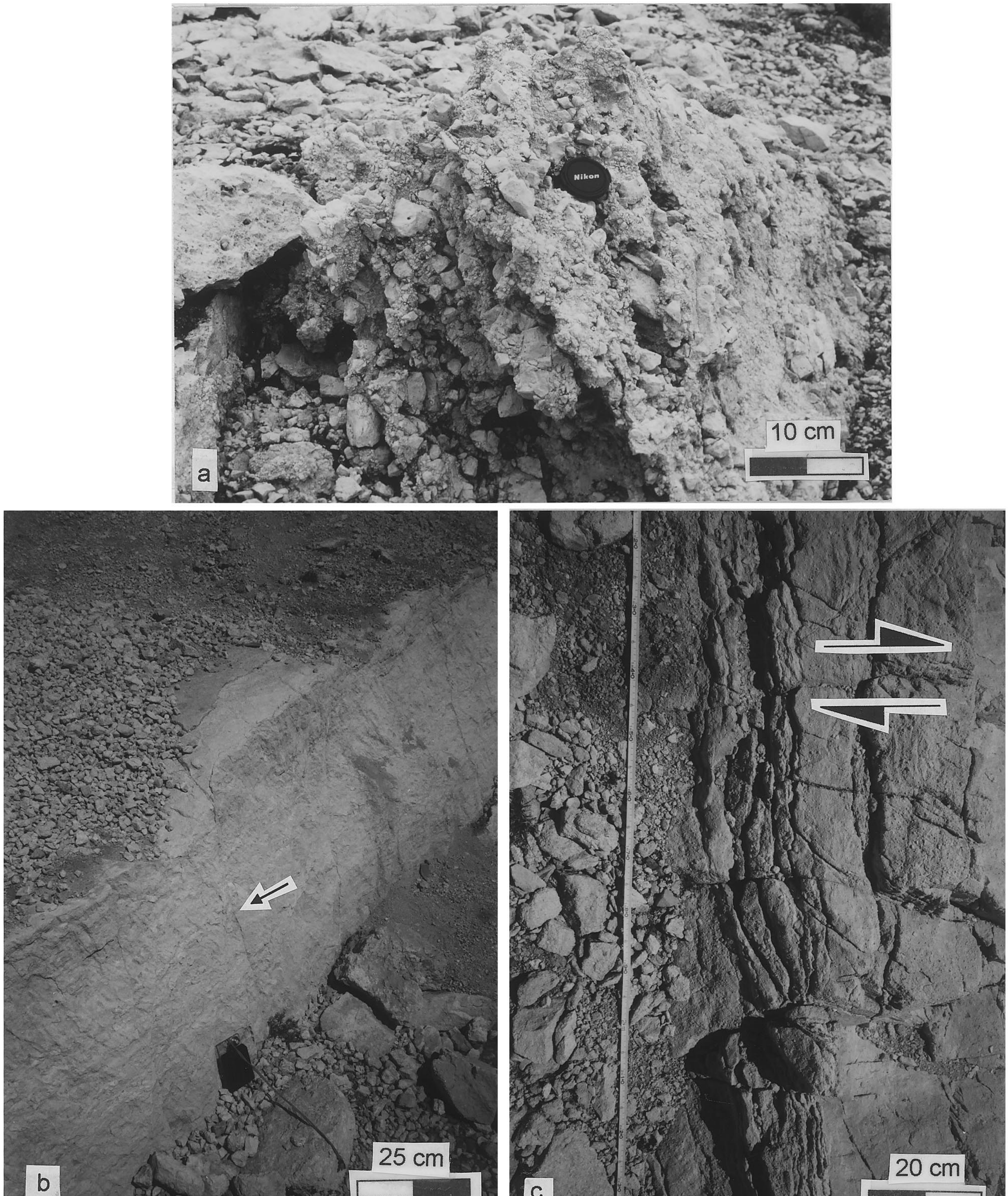

Fig. 9. (a) Coarse breccia at the termination of fault 647 where the offset is about 1 m. (b) Breccia zone in the 'Parafora del Sella' at Rifugio Boe'. Note the small strike-slip faults that cross-cut the breccia (trace of cross-cutting faults between arrows). View to NW. (c) Top view of breccia of Parafora in the vicinity of Rifugio Boe'. Note open fractures in the breccia parallel to the fault plane. (d) Shell of a fossil offset left laterally 2–3 mm by a fault. The fault is probably a faulted joint now filled by cement. This fault is 1.5 m away from the breccia of fault 647. (e) Two sets of joints, related to two different joint-zones intersect, fragmenting the rock.

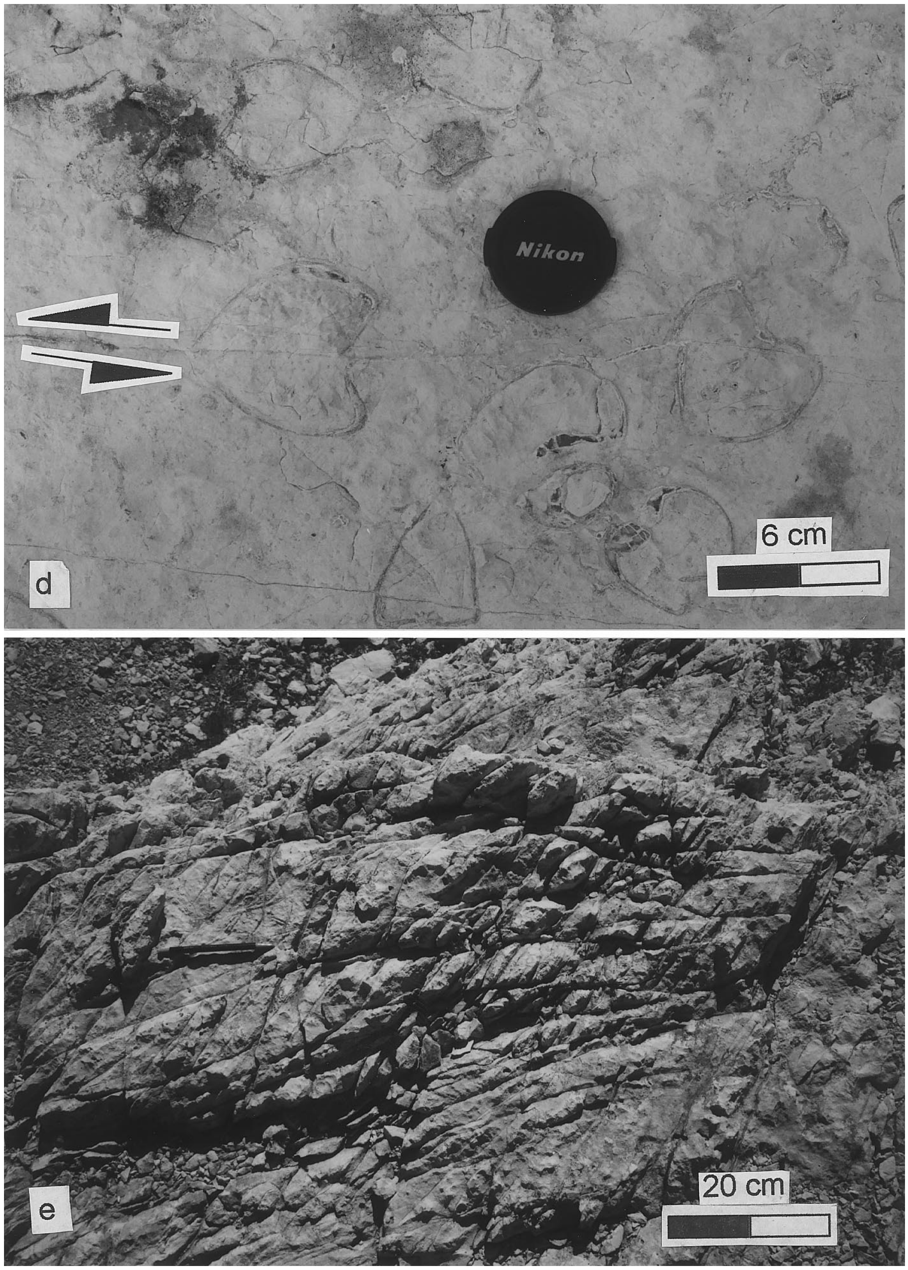

Fig. 9. continued.

joint and is continuous along the fracture. A few filled fractures show a shear offset in the order of 1–2 mm (Fig. 13e). These filled fractures cross-cut older veins and highlight the existence of at least two generations of mineral precipitation in the dolomites of the Sella Group; one that filled the veins, and one that filled the joints. The absence of cataclasis along the filled fractures, and the fact that the filling is not deformed, suggests that they were originally open joints that have been sheared and later filled by crystalline dolomite, in which case they should be called 'faulted filled joints'.

3.5.3. Fault breccia

The coarse breccia at the termination of fault 647 (location A in Figs. 10–12) contains clasts varying from clay size to 10–15 cm in diameter (Fig. 13b). In between the clasts and the matrix, we observe large pores (up to 2 cm in diameter), often with a drusy structure. The clasts and pores are homogeneously distributed and no aligned fabric is observed. The breccia in fault 647 at location B, where the offset is about 10 m, contains pockets of coarse-grained breccia without fabric, and seams of whitish material with a strong

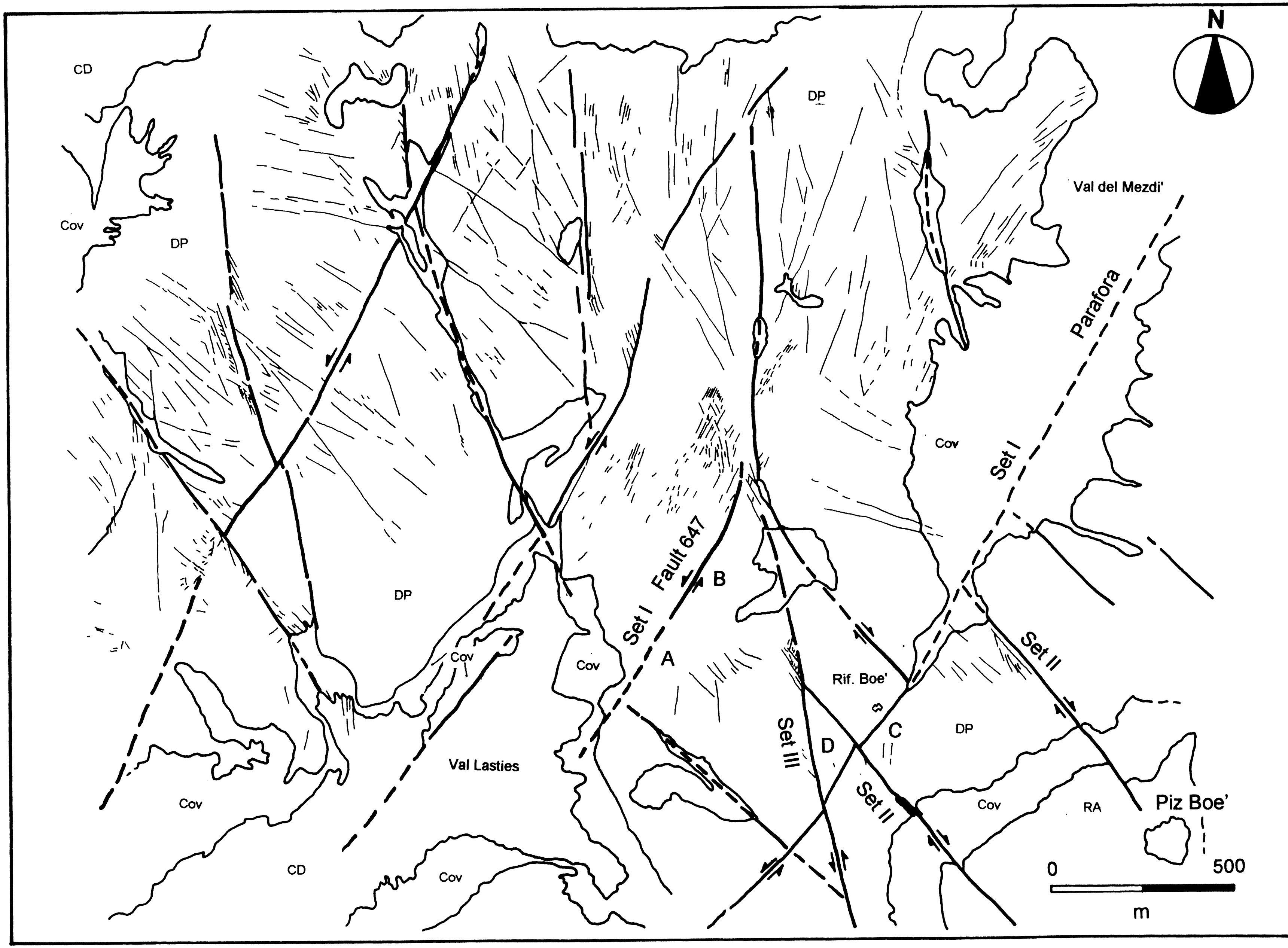

Fig. 10. Map from aerial photo and field control of the Pian delle Meisules and central part of the Sella Group. Thick lines represent faults where the arrows indicate sense of slip. The thin lines are joints and joint-zones. Cov, covered, not exposed. RA, Rosso Ammonitico. DP, Dolomia Principale. CD, Cassian complex (1). A, B, C and D are locations referred to in text. A few faults of Sets I, II and III are labeled.

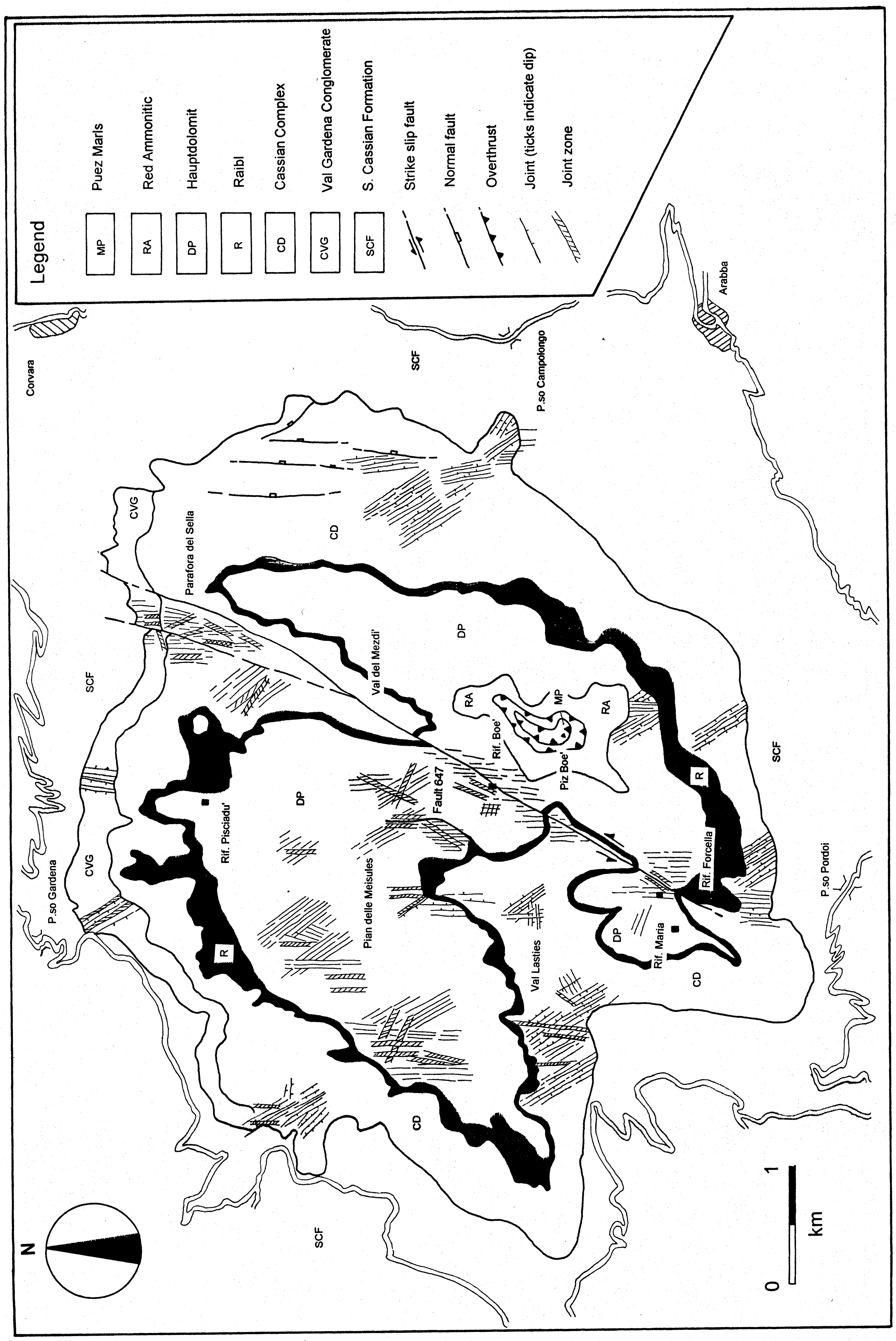

Fig. 11. Schematic map of joint orientation in the Sella Group. The map shows two dominant orientations for the joints and three for the joint-zones.

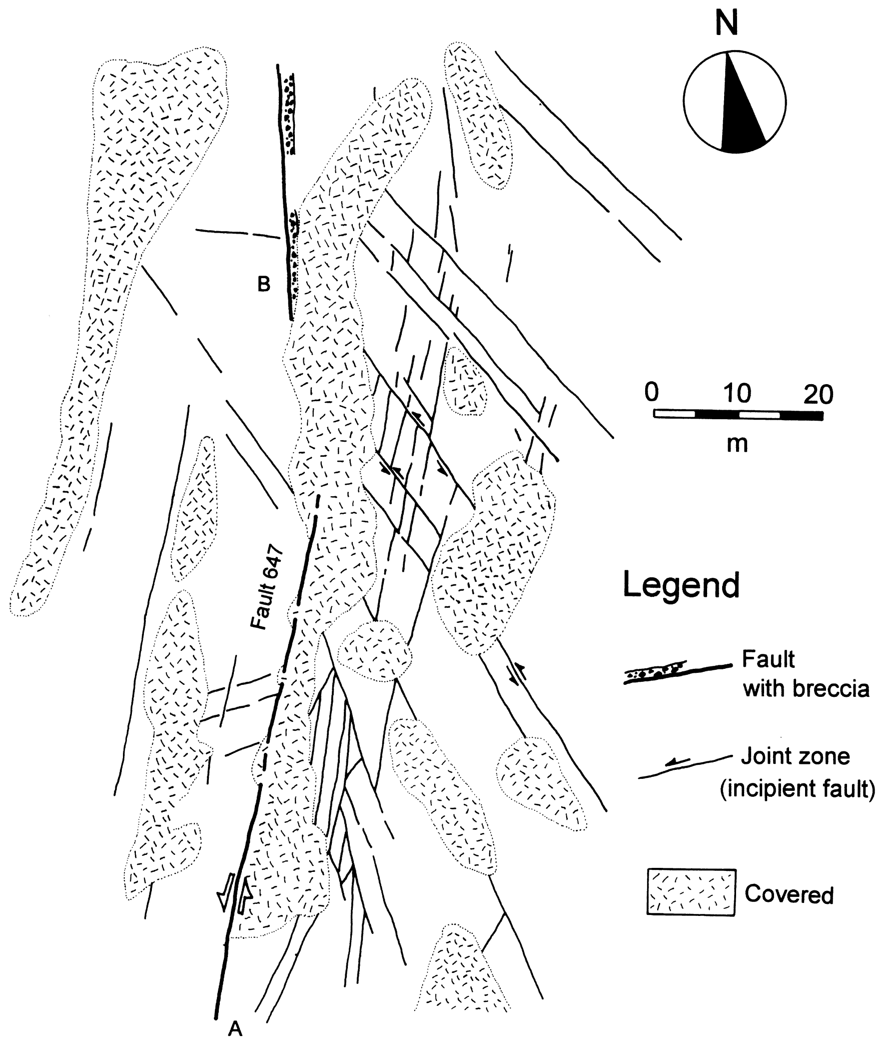

Fig. 12. Map of area around fault 647. Two sets of joint-zones are present. One set is typically shorter and abuts against the other.

fabric defined by anastomosing bands of fine grained dolomite (clay size).

Two sets of bands can be distinguished based on their orientation. One set of continuous bands is aligned sub-parallel to the fault plane and is longer than a second set of discontinuous bands that lie at low angles with respect to the first set (Fig. 13c). The width of the bands is 0.025–0.5 mm. The spacing is 0.1–0.5 mm for the first set and 0.05–0.1 mm for the second set. The pockets of crystalline dolomite in between the bands are intensely fractured by opening mode cracks. The breccia of the 'Parafora del Sella' exposed at the Rifugio Boe' (location C) consists of a homogeneous breccia zone with very poor grain sorting and no distinctive fabric (Fig. 13d). Clasts from clay size to 2–3 cm in diameter. Locally the clasts are fractured, especially the larger clasts (> 2–3 mm). Intragranular fractures cross-cut the grains or extend from the clast boundary inwards and terminate. No localization of intragranular cracks at grain contacts is observed.

3.5.4. Veins

The systematic veins oriented parallel to fault 647 have a thickness of 0.2–3 cm. Their walls are not straight or parallel to each other everywhere. They are composed of superposed linings of dolomite crystals that are parallel to the vein wall. The center of some veins are empty and have drusy structures.

3.6. Regional distribution of faults and fractures

3.6.1. Large faults

The large faults in the study area can be classified as three sets of sub-vertical strike-slip faults (Fig. 10). The joint-zones between the major faults typically are oriented parallel to one of these three sets. The oldest set of strike-slip faults (Set I) has a left-lateral slip component, a small vertical slip component and an

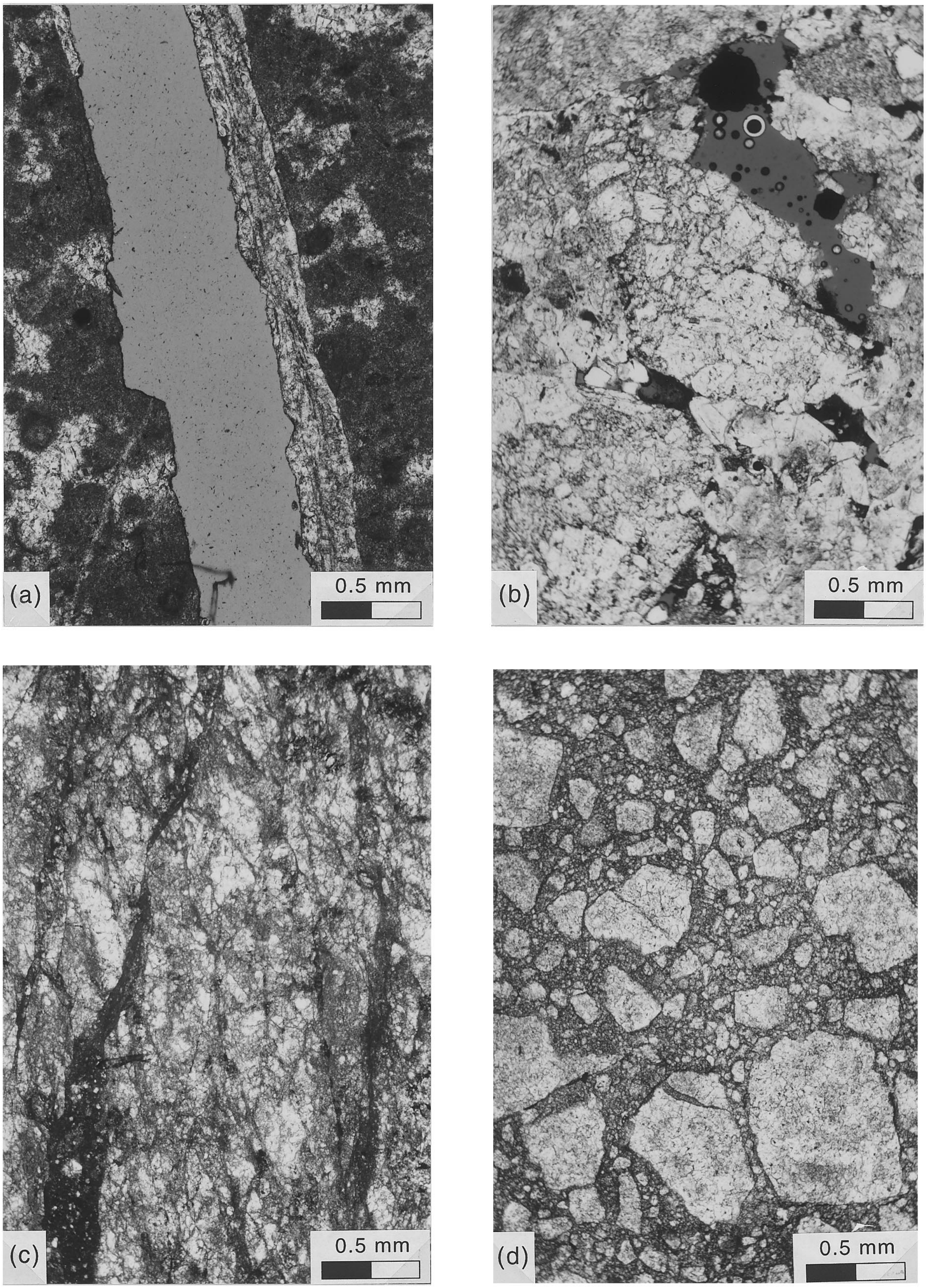

Fig. 13. (a) Epoxy filled joint along previously dolomite-filled joint (crossed nicols). (b) Coarse breccia at the termination of fault 647. Offset ~1 m. (c) Fault rock from fault 647. Amount of slip is about 10 m. Note the cataclastic shear bands and the intensely fractured dolomite. (d) Homogeneous breccia zone without fabric from the 'Parafora del Sella'. (e) Faulted filled joints, left lateral offset is apparent on two faults.

Fig. 13. continued.

average strike of 035°. A second set of faults (Set II) has a right-lateral sense of offset and an average strike trending 135°. This set offsets Set I. For example at location D on Fig. 10, the trace of the 'Parafora' is offset by a major fault of Set II and the breccia of the Parafora is cross-cut by small faults of this set (Fig. 9d). Faults with a trend 170° and a left-lateral sense of shear form a third set of strike-slip faults (Set III). This set is younger than Set I but the age relation with Set II is unclear. The 'Parafora' (Set I) is offset 10 m left-laterally by a major fault of Set III in the area south of Rifugio Boe' (location D, Fig. 10). The spacing between the large strike-slip faults of the same set ranges between 250 and 500 m.

3.6.2. Joint-zones

Joint-zones typically are localized near and sub-parallel with large faults. The sense of shear is generally the same as the sense of shear across the closest parallel major fault if they are from Set I or II. The joint-zones parallel and next to large faults of Set III have right-lateral offset in some places and left-lateral offset in others. Joint-zones with breccia occur closer to the large faults than the joint-zones without breccia. The spacing between joint-zones close to large faults is typically 0.5–1 m and up to 10–15 m further away. Locally, two sets of joint-zones are present in the area between two large faults (Fig. 12). A cross-cutting relationship can be inferred from the map pattern. Fig. 12 shows joint-zones parallel the large fault (Set I) on the west side of the map and joint-zones parallel to a large fault of Set III, that is outside the map to the east. The joint-zones of Set I are shorter and abut against the joint-zones of Set III. The joint-zones of Set I are interpreted to be older than Set III which agrees with the offset relationship between the large faults of Sets I and III in the Rifugio Boe' area (location D). The joint-zones without any detectable offset locally change along strike into faults where the offset is clear. Where two joint-zones with different orientations intersect, two sets of joints are present and fragment the rock. The joints either abut or crosscut each other. Depending on the orientation and the sense of slip across the joint-zones, the overprinting pattern of the joints varies from anastomosing to a rectangular grid (Fig. 9e). This partly explains the very high joint density in both the Cassian Dolomite and Dolomia Principale. The density is up to 300 joints m^{-1} next to the large faults, 100 joints m^{-1} within the joint-zones, and at least 30 joints m^{-1} everywhere else. The joints measured throughout the Sella Group in both the Cassian Dolomite and the Dolomia Principale have similar strikes. Two orientations can be recognized (Fig. 11) with south and southeast strikes, respectively.

3.6.3. Veins and joint-zones

Two types of veins are observed: systematic and non-systematic. A systematic set of veins is observed adjacent to and sub-parallel with large faults of Set I. These veins are fairly straight and continuous over 3–10 m. Locally, these veins are sheared and change along strike into joint-zones (Fig. 14). The joint-zones of Sets II and III (Fig. 7) offset the systematic veins. The non-systematic veins are irregular in shape and appear to represent a filling of previously-formed fractures or large vacuoles.

In summary, the fracture sets in the Sella Group are related in age from oldest to youngest in the following sequence: (1) Non-systematic veins (syndepositional or at time of dolomitization), (2) systematic veins striking 035°, (3) joint-zones and large faults in Set I, striking 035°, (4a) joint-zones and large faults in Set II, striking 135°, (4b) joint-zones and large faults in Set III, striking 170°, (5) non-systematic veins.

4. Discussion

4.1. Model for faulting

We propose that the structures described (joint-zones, small and large faults) represent steps in the process of fault development within dolomite (Fig. 15).

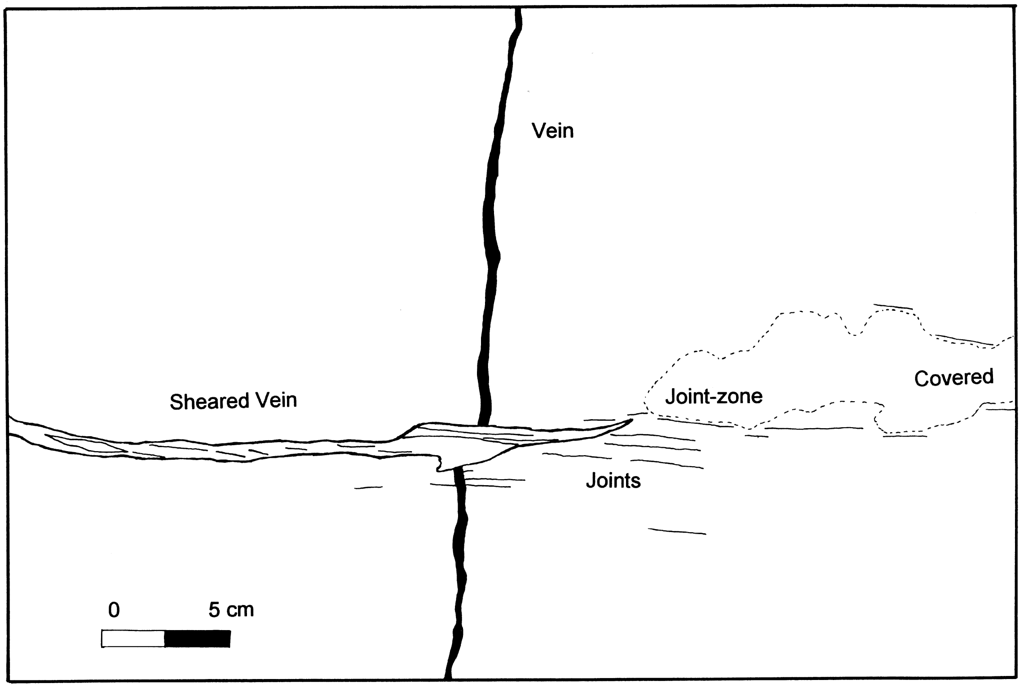

Fig. 14. Map of sheared vein that changes laterally into a joint-zone.

Joints form parallel to the direction of maximum compressive stress (Fig. 15a) and start to become localized into en-échelon arrays (Fig. 15bi) with ongoing deformation, to form joint-zones. The latter form locally at the tips of sheared veins (Fig. 15bii). A second set of joints, referred to as cross-joints develops in the joint-zones (Fig. 15c) perpendicular to the first set. Next the rock bridges between the en-échelon joints break up and pockets of breccia develop (Fig. 15d). At this stage the joint-zones accommodate 5–7 mm of strike-slip offset. More strain is localized within the joint-zones and a continuous zone of breccia develops that can show 1–3 cm of lateral offset (Fig. 15e). With continuing deformation, the breccia zone progressively widens and the faults accommodate offsets of 1–200 m.

In order to evaluate the geomechanical validity of our model we will discuss each step and compare it with similar observations of others. Most structures have been described before, but rarely together in the same rock type and geologic setting.

4.2. En-échelon array

Most outcrop observations of en-échelon arrays of fractures described in the literature consider veins, in either limestone or sandstone. We begin by comparing our observations of en-échelon arrays of joints with those of veins. Both veins and joints are opening mode I fractures so in a mechanical sense they are similar (Pollard and Segall, 1987). In general, three processes are believed to result in en-échelon arrays of veins. One process involves the formation of en-échelon arrays of veins within a pre-existing shear zone; with progressive deformation in the shear zone, the veins rotate and become sigmoidal (Beach, 1975; Ramsay and Huber, 1983). The second process was illustrated by Olson and Pollard (1991) with boundary element numerical experiments. They showed that en-échelon alignment is the preferred geometry for cracks growing from a random distribution of microcracks, due to mechanical interaction between neighboring microcracks. The microcracks initially form parallel to the maximum compression direction (Olson and Pollard, 1991). A similar nucleation of cracks in planar arrays and propagation along straight paths into en-échelon configuration is proposed by Beach (1975) as an alternative to the shear zone mechanism, but no mechanical explanation is offered. The third process is slip along a pre-existing 'parent crack', where the tip breaks down into en-échelon array of veins (Pollard et al., 1982; Rothery, 1987).

For the en-échelon arrays of joints in the dolomite we can rule out the shear zone process. The joints observed in the Sella Group do not have the sigmoidal shapes that are often recognized in shear zones. Also, the formation of breccia within the joint-zones with increasing offset indicates that the en-échelon arrays form prior to the localization of shear, and not after, as suggested for the shear zone process (Beach, 1975). Finally, the shallow burial conditions for the dolomite make ductile deformation in shear zones unlikely.

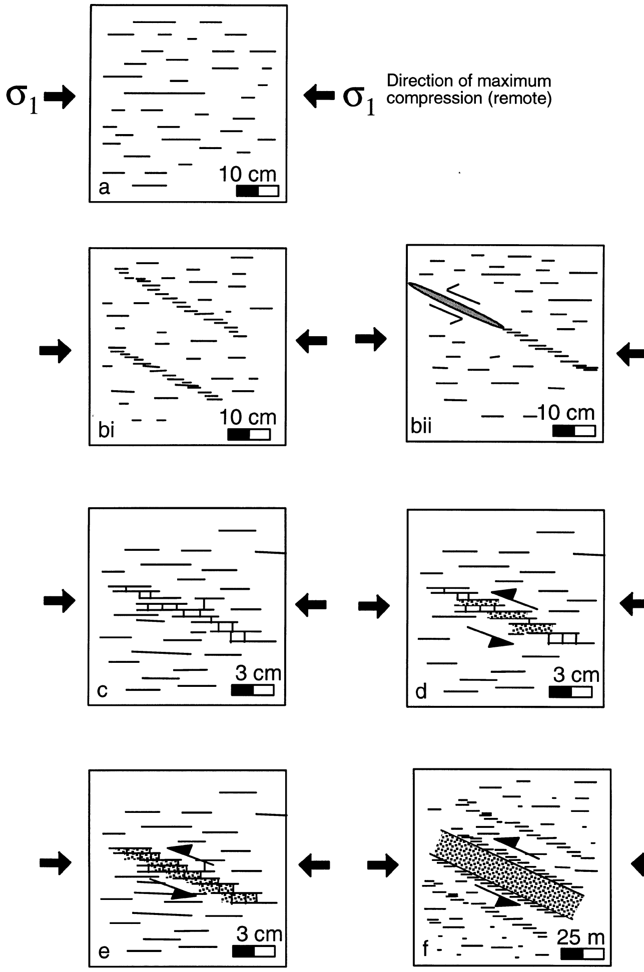

Fig. 15. Model for fault development in dolomite. (a) Microcracking and jointing parallel to maximum compressive stress direction. (bi) Localization of joints in en-échelon array, due to mechanical interaction. (bii) Localization of joints at tip of sheared vein. (c) Formation of cross-joints. (d) Formation of breccia pockets in arrays. (e) Continuous zone of breccia parallel to joint-zone. (f) Large wide cataclastic fault zone, joint-zones sub-parallel to the main fault and high joint density next to large fault.

In our field area, some of the joint-zones change along strike into veins or vice-versa. These veins are possible 'parent cracks' that broke down at their tip into the joint-zones. However, only in a few cases could we identify a possible parent crack. We therefore believe that in most cases the joint-zones formed independently of pre-existing fractures, consistent with the theory of Olson and Pollard (1991). The presence of many joints between joint-zones and between faults and which have an orientation similar to joints within the joint-zones supports this. We suggest that these joints formed before joint-zones were localized and, therefore, conform to the microcracks observed in experiments on granite and other rocks (Zheng et al., 1989; Lockner et al., 1992b; Myer et al., 1992; Moore and Lockner, 1995). The orientations of the joints in the Sella Group are consistent with maximum compressive stress directions that agree with the Alpine thrust direction.

The following geometric characteristics of the en-échelon joints in the Sella Group are different from those of vein arrays described in the literature (e.g. Beach, 1975; Pollard et al., 1982; Ramsay and Huber, 1983; Rickard and Rixon, 1983; Nicholson and Pollard, 1985; Rothery, 1987; Smith, 1996). The dilation of the individual joints ($\ll$1 mm) is smaller than that of veins (Fig. 3). The spacing between the joints is very small (1–15 mm) compared to the vein spacing in en-échelon arrays. The overlap between the joints is large. The number of joints within the array (thousands) and the total length of the joint-zones (up to 15 m) is typically much greater than the comparable properties in vein arrays.

The theoretical model of Olson and Pollard (1991) shows that certain geometries of cracks aligned in en-échelon fashion will favor fracture growth through enhancement by the mechanical interaction between neighboring cracks. In general, a low vein-array angle ($<50^\circ$) and small separations ($S/L<5$, see Fig. 3 for S and L) promote growth of the fractures (Olson and Pollard, 1991). Growth will occur until the fractures overlap and a resistance to growth (due to interaction between neighboring fractures) hinders further development (Pollard and Segall, 1987). The present geometry of the joint-zones reflects these predictions.

The observed joint-array angles in this study are smaller than 50°, and separations (S/L) are small, both which favor growth (Olson and Pollard, 1991). In fact the separations are much smaller (0.01–0.04) than discussed in Olson and Pollard (1991). However the joint-zones in the Sella Group reflect the final stage when growth of the fractures stopped, while Olson and Pollard (1991) discuss initial microcrack geometries. When the joint-zones in the dolomites of the Sella Group started to develop and joint lengths were small, S/L ratios were higher. The present joint-zone geometry shows a large overlap between fractures, in agreement with the prediction that growth of the joints in the array will stop once there is overlap (Pollard et al., 1982).

4.3. Cross-joints and brecciation

Many en-échelon arrays of veins are well preserved in the rock. There are few references in literature to structures that develop when deformation continues after the localization of veins into en-échelon arrays.

Willemse et al. (1997) describe en-échelon arrays of veins in the limestone of the Bristol Channel in which additional strain is accommodated by slip along solution seams that formed at the tip of the initial veins. The second stage in fault development in the dolomites of the Sella Group causes the formation of a set of cross-joints at high angles to the first set of en-échelon joints. These cross-joints apparently accommodate strain in the bridges between the joints in the array. The growth of the cross-joints was predicted by Nicholson and Pollard (1985), on the basis of mechanical considerations. The bridges between the en-échelon joints will bend with ongoing deformation and produce high bending strains. If cracks propagate straight, the bending strains are higher (Nicholson and Pollard, 1985) and cross-joints are more likely to form. The joints in our joint-zones are straight suggesting that bending strains were high and cross-joints could develop.

In our model, after the cross-joints form, ongoing deformation is taken up by the fragmentation of the rock, first in pockets within the joint-zone and then progressively in wider and more continuous zones. Similar processes of localization and linking of opening mode fractures, followed by macroscopic failure along a fault surface, are observed by others in both experiments and outcrops. Two different mechanisms are recognized. If there are favorably oriented pre-existing discontinuities, such as microcracks or joints or bedding planes, they may slide under compression and form mode I cracks at their tip, also called wing or tail cracks. The wing cracks link the sliding cracks and a continuous failure plane forms. This mechanism is modeled based on experiments on glass by Horii and Nemat-Nasser (1985), is recognized in experiments on granite (Granier, 1985), in outcrops of granite (Segall and Pollard, 1983; Martel, 1990), in outcrops of sandstone (Myers and Aydin, 1996) and in outcrops of siliceous shale (Dholakia et al., 1998). If there are no favorably oriented pre-existing discontinuities, a through-going fault may form by the linking up of microcracks via grain boundaries in granite (Moore and Lockner, 1995) or by breaking up of the bridges between the en-échelon microcracks in limestone and sandstone (Zheng et al., 1989; Myer et al., 1992). The model for faulting in dolomite more closely resembles this last mechanism since no potential pre-existing microscale discontinuities or wing cracks are observed.

Most experiments show that the presence of grains and grain boundaries influences the localization of microcracks. Zheng et al. (1989) mention six different mechanisms: bending of grains, cracking at pore boundaries caused by the relatively soft inclusion of the pore, point loading at grain contacts, cracking parallel to grain boundaries, compressive loading across a grain (as in a Brazilian test) and sliding of pre-existing cracks. The dolomites of the Sella Group do not show microcracking at the size of grains. The dolomites are very homogeneous, probably due to the dolomitization that obliterated the original grain framework of the rock and the primary sedimentary structures. This may explain why in the dolomites of the Sella Group, the shear zones form at a relatively large scale of centimeters after en-échelon and cross-joints break up the pristine rock. In the experiments on granite, limestone and sandstone, shear zones form at a much smaller scale (cm) (Zheng et al., 1989; Myer et al., 1992; Moore and Lockner, 1995), which is probably controlled by the grain size.

Experiments and field observations suggest that localization and the linking of opening mode fractures followed by macroscopic failure along a fault surface, may occur under a wide range of confining pressures. The experiments of Moore and Lockner (1995) were performed under 50 MPa confinement while Zheng et al. (1989) used up to 4 MPa confining pressure. Zheng et al. (1989) show that a low or absent confining pressure promotes the growth and localization of joints in bands while at high confining pressure (4 MPa), the cracks are shorter and more homogeneously distributed. These observations suggest that the shallow burial of the dolomites in the Sella Group during Alpine Orogeny allowed for the localization of joints and the development of the strike-slip faults according to the mechanism presented in this paper.

There are no laboratory experiments that show what happens after a continuous fault becomes localized, because of the small size of the samples. In the faults of the Sella Group, we recognized sharp boundaries between host-rock and breccia in the joint-zones and slip planes in the larger faults in the Sella Group. Deformation is, however, not solely localized along these surfaces. The relation between the width of the breccia zones and the maximum offset observed across the faults suggests that with ongoing deformation, more and more of the host-rock is aggregated to the fault zone in the form of breccia. This is different, for example, from faulting in porous sandstone, where large displacements (>1 m) are very much localized along thin slip planes and the fault zone width does not increase with increasing displacement (Aydin, 1978; Antonellini et al., 1994; Goodwin and Haneberg, 1996).

5. Conclusions

We observed joints and faults with a large range of offsets in the Dolomites of the Sella Group, northern Italy. The joints occur in high density (maximum spacing 4 cm) and, in many places, are localized in en-échelon arrays called joint-zones. These joint-zones locally show brecciation and they form the smallest strike-slip faults observed in the Sella Group, with offsets of 5–7 mm. Joint-zones with a continuous zone of breccia accommodate offsets from 1 to 3 cm.

The geometry of the joint-zones is characterized by joint-array angles between 10° and 40°, small

(≪1 mm) dilation of the 0.2–15 cm-long joints, narrow spacing between joints in the array (1–15 mm), a high number of joints in the array (> 1000), and a high overlap between joints. Typically a set of cross-joints exists in the central part of the joint-zones. Larger faults with offsets greater than 1 m consist of a breccia zone (1–15 m wide) and localization of joint-zones and joints in the host-rock next to the breccia. Three sets of strike-slip faults are recognized. These observations form the basis for a model for fault development containing the following stages: (1) Pervasive jointing parallel to the maximum compressive stress direction; (2) localization of joints in en-échelon arrays (joint-zones); (3) formation of cross-joints; (4) formation of breccia pockets; (5) formation of continuous breccia zone and slip planes.

The comparison of this model with observations on outcrops and experiments involving various lithologies, suggests that the lack of pre-existing favorably oriented flaws (micro- or macroscale), the lack of a profound granular structure in the rock, and a low-confining pressure during deformation, promoted the growth and localization of joints and the development of through-going faults with widths at a scale of centimeters to meters.

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