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Segmented, curved faults: the example of the Balduini Thrust Zone, Northern Apennines, Italy

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Abstract

Meso- and micro-structural studies of the well-exposed Balduini Thrust (Northern Apennines, Italy) indicate that the structure formed during a single folding event, contemporaneous with diagenesis, and is a zone comprising curved, en-échelon fault segments. The geometry of each segment is arcuate with pure compression at one end and right-lateral displacement along the other. The thrust developed during the Tortonian within a single mud-rich formation, the Upper Eocene–Upper Oligocene Scaglia Cinerea, but rheological variations within the unit led to differences in deformation style; zones of scaly fabric are discontinuous and calcite veins vary in abundance. The mesoscopic morphology of the veins and the distribution of calcium carbonate along the formation indicate variations in the distribution of fluids at the time of deformation, which affected both diagenesis and the structural response of the material. Systematic variations of mechanical properties within the thickness of the Scaglia Cinerea Formation account for the curvature of the propagating thrust. Together with the heterogeneity of the stress field, the confinement of the arcing thrust to this single, weak unit lead to repeated initiation of new fractures and hence segmentation of the propagating thrust. Geometric analysis of the calcite veins and their microscopic characters suggests that hydrofracturing was involved, with the Scaglia Cinerea Formation experiencing high fluid pressure followed by rapid water expulsion. The Balduini Thrust is therefore an example of a fluid-driven, refracted compound shear zone. The analysis presented here provides insights into the three-dimensional arrangement of fault zones and fluid-migration patterns during regional faulting. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

In the classical view, faults are envisaged as continuous, planar surfaces, although there is growing evidence that many examples are zones of discontinuities, with each segment showing orientation variations both along strike and down dip (e.g. Segall and Pollard, 1980; Mandl, 1987; Aydin, 1988; Peacock, 1991; Peacock and Sanderson, 1991, 1994; Treagus and Lisle, 1997; Willemse, 1997). Commonly, however, inadequate exposure restricts any analysis of the degree of segmentation, or of curvature, and hence understanding of the mechanisms that are responsible. This paper reports on a structure in the Northern Apennines, called here the Balduini Thrust, that is excellently exposed on an irregular surface and that allows geometrical problems to be addressed.

Three-dimensional description of natural faults has been approached from different viewpoints. The question of whether the faults, together with other surfaces such as cleavages and veins, should be approached as a mathematical or geometrical problem (Segall and Pollard, 1980; Mandl, 1987; Peacock, 1991; Peacock and Sanderson, 1991, 1994) or as a mechanical issue (Robin and Cruden, 1994; Willemse, 1997) is still active. Treagus and Lisle (1997) argued that in three dimensions, stress and strain can lack definable principal surfaces, so that geometrical indicators such as fractures and fabrics become unreliable. They also pointed out problems of definition and nomenclature that follow from this; for example, a deformation that lacks continuous principal surfaces should not necessarily be regarded as a discontinuous event. Therefore,

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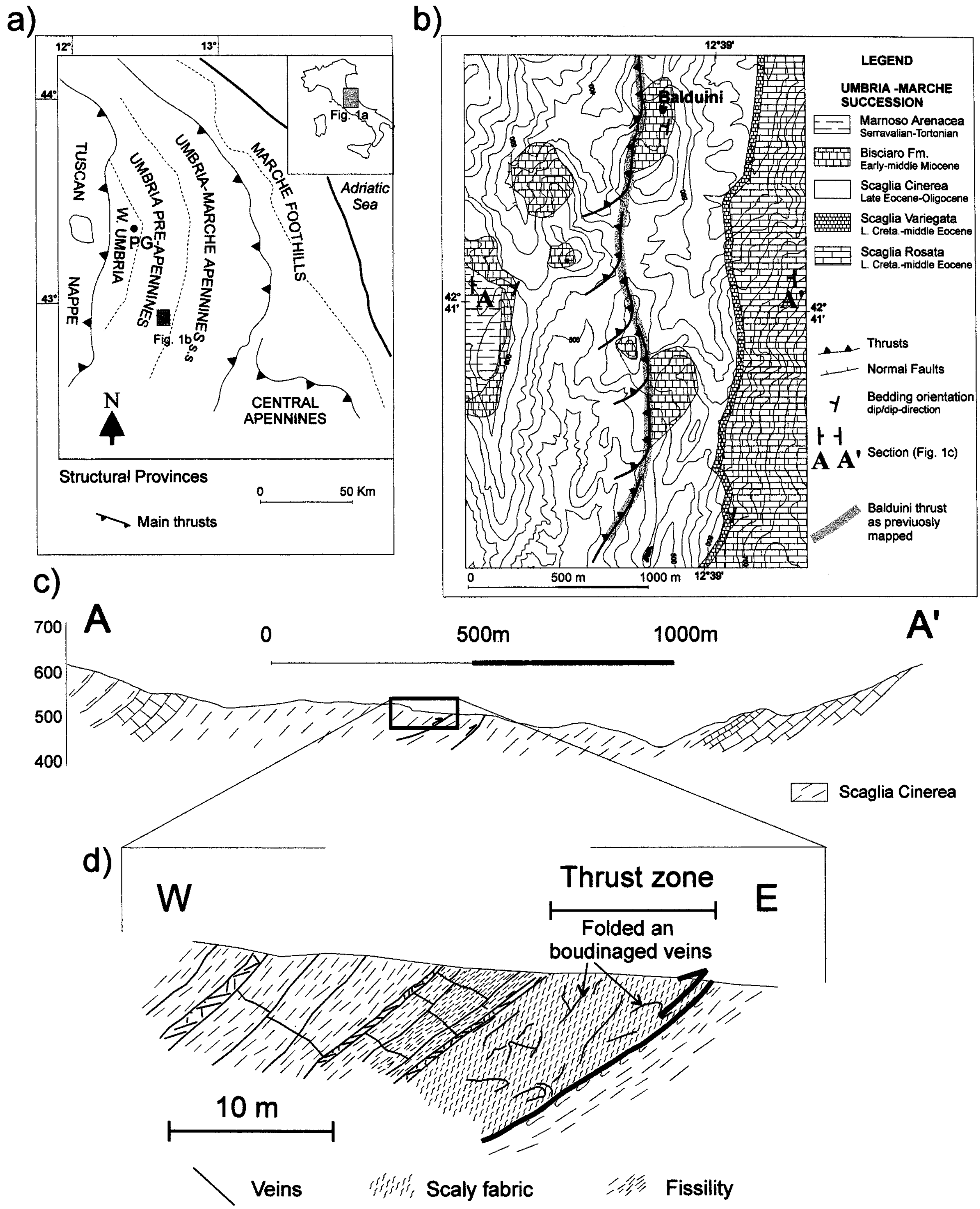

Fig. 1. (a) Structural provinces of the Umbria–Marche Apennines. (b) Geological map of the Balduini Thrust. The curved and segmented thrust traces occur entirely within the Scaglia Cinerea Formation in the eastern limb of a synclinal fold having the hinge closure toward the south (the fold axis is not shown in the figure). (c) Geological cross-section across the study area. (d) Schematic cross-section of the study zone, showing veins, fissility and scaly fabric distribution. Vein sizes are exaggerated to allow their representation.

since the concept of discontinuity can be misleading, attention here will be focused on the geometry of the fault segments that combine to form the thrust zone and, in particular, their separated, curviplanar nature will be considered.

Two questions can be addressed regarding the discontinuous nature of faults: the first relates to why fractures should develop in a segmented arrangement; the second concerns whether the ruptures developed as curved surfaces or were affected by later folding. The answers involve the influence of the mechanical properties and the fluid-flow patterns in the partially lithified sediment as the thrust evolved. A qualitative model for rupture in dewatering sediments, based on differential diagenesis, is proposed which can account for the segmentation of a propagating thrust and for primary curvature of the surfaces. The well-documented field example of the Balduini Thrust provides a key for understanding the progressive growth and orientation of rupture surfaces in lithifying sediments.

2. Geological setting

The Umbria–Marche Apennines are characterised by a fold-and-thrust geometry followed after the collision of the Adria and European plates starting from the Oligocene (Boccaletti et al., 1980; Treves, 1984; Coward and Dietrich, 1989; Deiana and Pialli, 1994; Barchi et al., 1998). Structural and geophysical data allow the distinction of four tectonic provinces in the Umbria–Marche Apennines: the Western Umbria, the Umbria pre-Apennines, the Umbria–Marche Apennines and the Marche Foothills (Fig. 1a) (Deiana and Pialli, 1994; Barchi et al., 1998). The area examined in this paper is part of the Umbria pre-Apennines (Fig. 1a). In the classical view the tectonic style of the Umbria pre-Apennines is characterised by thin-skinned thrusts detached on a regionally extensive décollement (Koopman, 1983; Bally et al., 1988; Calamita et al., 1994; Deiana and Pialli, 1994). More recent studies (Barchi et al., 1998) suggest the presence of multiple detachments located at different stratigraphic levels.

The outcropping sedimentary sequence belongs to the Umbria–Marche Succession whose oldest unit is a Triassic platform limestone. The rocks below the Triassic limestones do not outcrop in the Umbria–Marche Apennines, but Triassic evaporites, mainly anhydrite and dolomite, have been drilled (Anelli et al., 1994). In the Liassic several normal faults cut the carbonate platform, producing a differentially subsiding 'horst-and-graben' type basin, characterised by pelagic limestone sedimentation during the Middle Lias–Tithonian interval. Starting in the Aptian–Albian an increasing amount of shale was deposited. Marly sediments were deposited during the Early Miocene, when turbiditic episodes became regionally important.

The sedimentary succession was involved in four recognisable deformation events (Lavecchia et al., 1994; Brozzetti and Lavecchia, 1995; Tavarnelli, 1997; Barchi et al., 1998):

- Fold and shallow thrusts—a Tortonian system of asymmetric and commonly recumbent E-verging folds, tens of kilometres wide, cut by thrusts developed along cores or limbs. The relationship between folds and thrusts has been widely discussed. Tavarnelli (1997) interpreted the folds as 'fault propagation folds', while Calamita (1990) suggested a two-stage evolution with early folds later accompanied by faulting;
- Evaporite-basement thrusts—a Tortonian–Early Messinian system of E- to NNE-verging thrusts detached above the evaporites, along the base of the Triassic carbonate platform (Bally et al., 1988; Deiana and Pialli, 1994; Barchi et al., 1998);
- Strike-slip faults—two Tortonian–Early Messinian systems of NNE, dextral, and ESE, sinistral trending strike slip-faults, that cut the previous structures;
- Normal faults—Plio-Pleistocene en-échelon NW–SE- and SSW–NNE-trending normal faults (Calamita et al., 1979; Centamore et al., 1980).

The nature of the thrust-induced deformation developed during the fold and shallow thrusts phase, in fold limbs or cores, varies, and reflects the different mechanical behaviour of the sediments involved in the fold (Tavarnelli, 1997). The studied Balduini Thrust affects one limb of a 5–7-km-wide synclinal fold (Brozzetti and Lavecchia, 1995). According to the geometrical evidence the Balduini Thrust is contemporaneous with the first phase of folding. The oldest rock in the fold is the Triassic carbonate-platform limestone, which is overlain by other Mesozoic carbonate-rich formations. The Balduini Thrust is intra-formational and only occurs within the Scaglia Cinerea Formation (Fig. 1b), though it is difficult to estimate the total displacement. The Upper Eocene to Upper Oligocene Scaglia Cinerea (Monaco et al., 1987) is the first formation to record an increasing amount of clay in the Umbria–Marche Succession. In the study area, the Balduini Thrust is not modified by later deformation events such as evaporite-basement thrusts, strike-slip or normal faults.

The Mesozoic carbonate-rich formations commonly show evidence of early diagenetic processes such as dissolution-induced compaction of sediments (using the definition of Berner, 1980). In particular the limestones, that deformed together with Scaglia Cinerea Formation during the fold and shallow thrusts phase, and constitute the footwall of the Balduini Thrust (Fig. 1b, c) show only brittle deformation features.

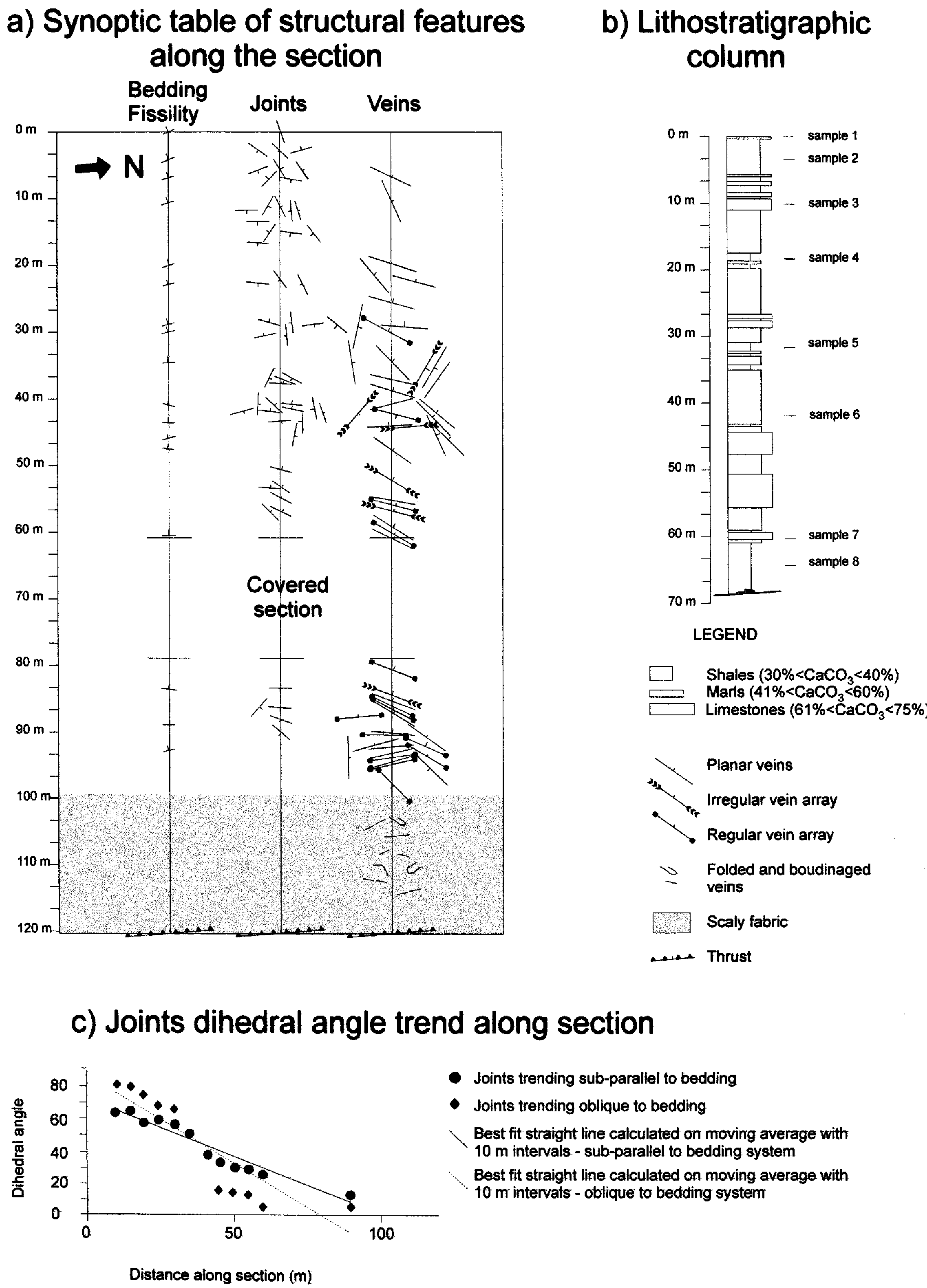

Fig. 2. Structural (a) and stratigraphic (b) synoptic representation of a section of the Scaglia Cinerea Formation across the thrust. The structural data are represented projected on a horizontal plane, so that it is a plane view. The outcrop is subdivided in two parts: the thrust zone, in grey, and the zone above. The veins have been differentiated on the mesoscopic morphology. The stratigraphic section has been drawn showing the relative amount of calcium carbonate and the location of samples. (c) Graph of the joint systems dihedral angle variation along the section.

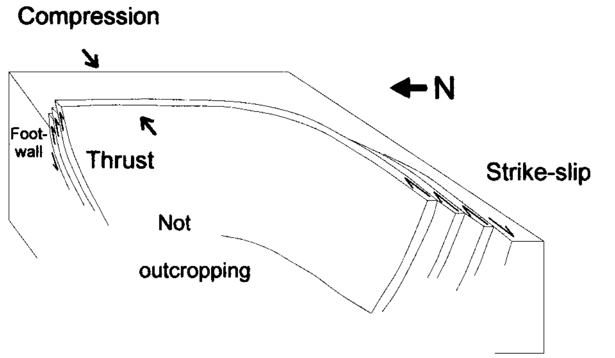

Fig. 3. Block-diagram of a representative segment of the Balduini Thrust. The vertical development of the surfaces and how they are rooted is not detectable from the outcrops.

3. The Scaglia Cinerea Formation

The Scaglia Cinerea Formation has marly and calcareous marly beds alternating with shales. Three sections of the Scaglia Cinerea Formation across the Balduini Thrust have been chosen for the detailed structural study, where bedding/fissility joints and veins have been recorded (Fig. 2a). The study of the deformation along the three studied sections has been accompanied by the analysis of the relative amount of calcium carbonate. Pressure-solution widely affected the Scaglia Cinerea Formation (e.g. Koopman, 1983). The orientation of the pressure-solution seals is parallel to bedding and they increase in number towards

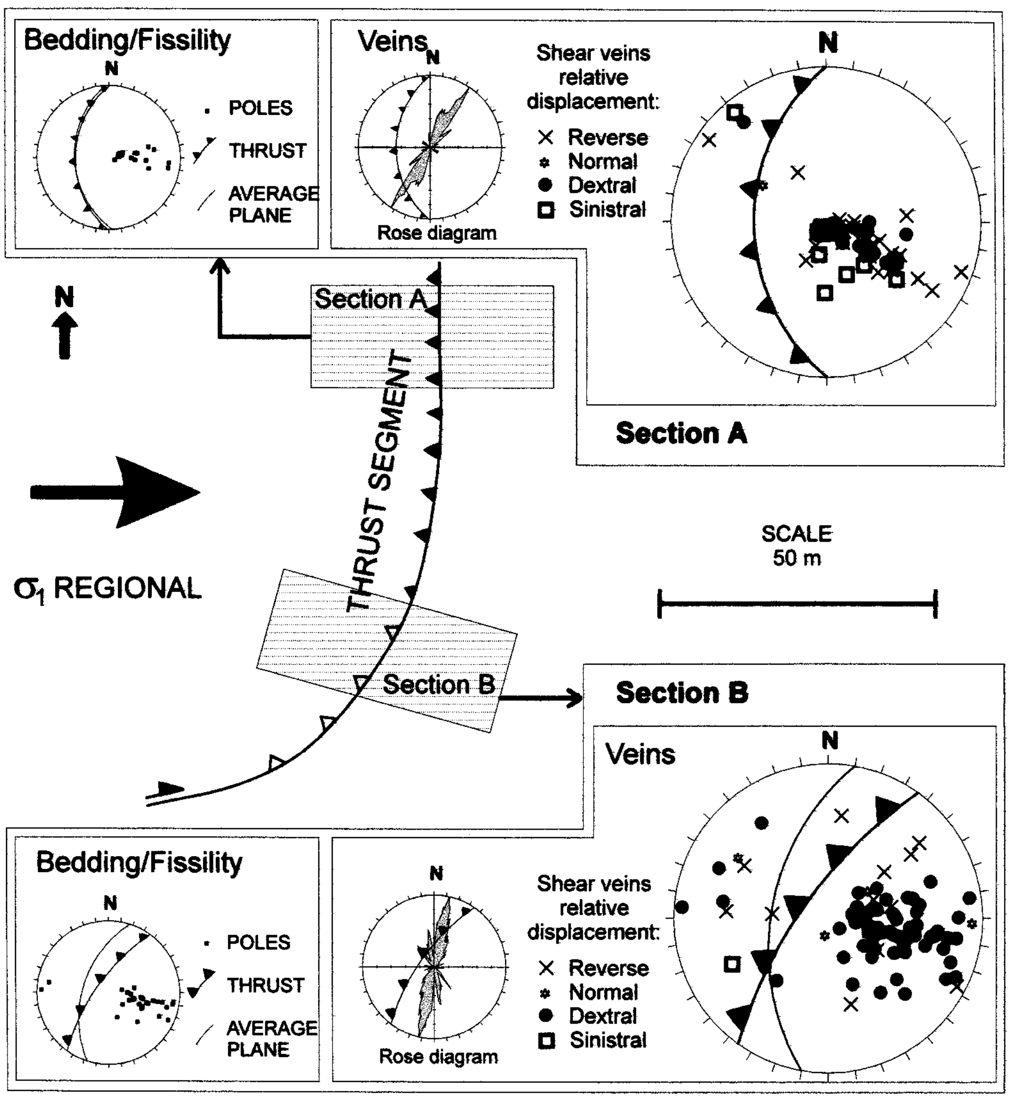

Fig. 4. Schematic planar trace of a segment of the Balduini Thrust. Along the segment the sense of slip changes from transpressional, with a right-lateral component of movement (empty triangles), to pure contraction (black triangles). A and B are two real sections projected along the segment. The stereoplots show equal angle, lower hemisphere projection of the bedding/fissility and veins. Each projection has the thrust orientation and the relative movement recorded by the shear veins fibres. A rose diagram with vein azimuth data helps in defining the vein systems.

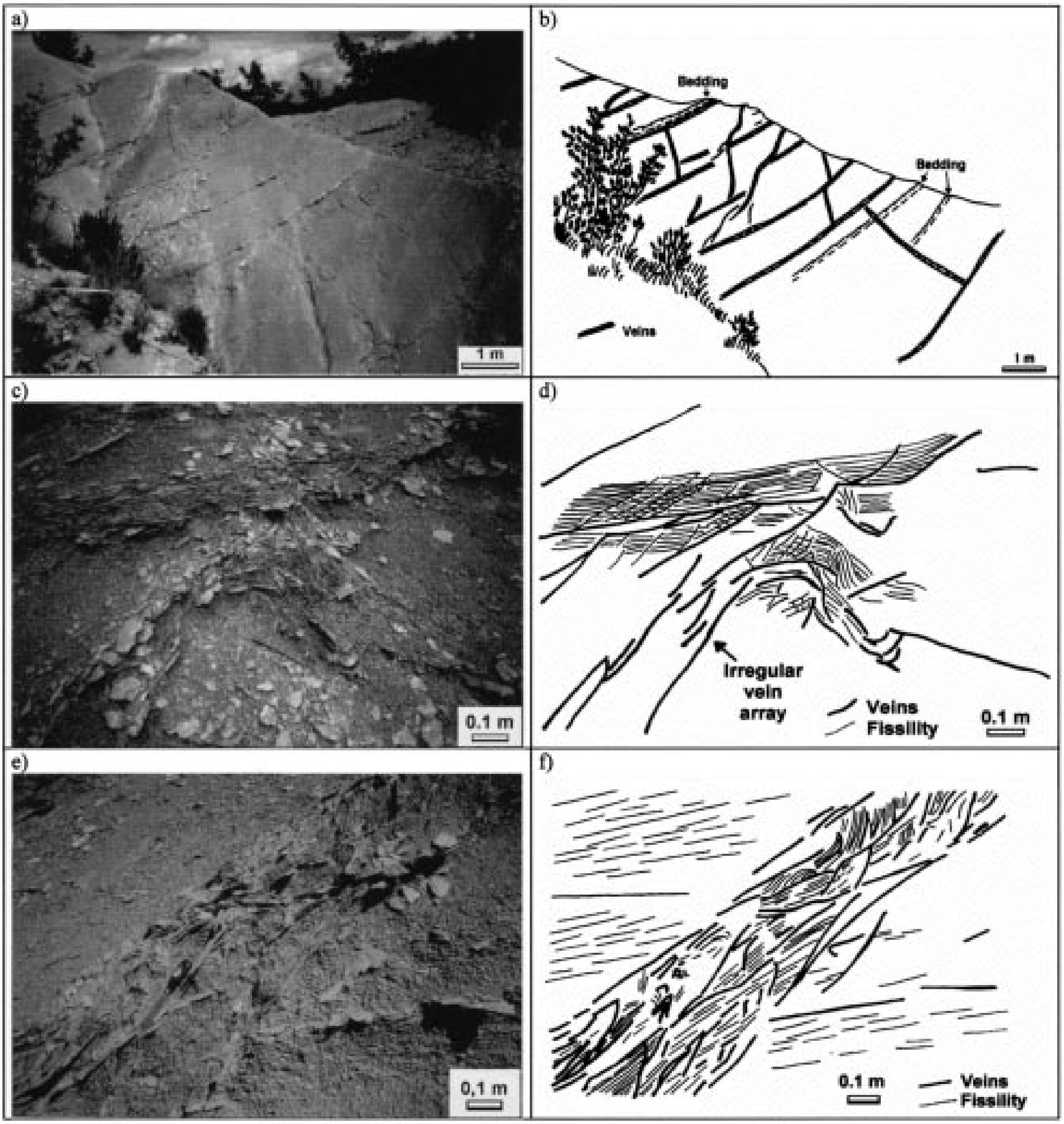

Fig. 5. (a, b) Photograph and sketch of badlands with calcite veins from the outcrop of section A in Fig. 4. Veins both sub-parallel and oblique to the bedding/fissility are present. (c, d) Photograph and sketch of a multiple calcite vein, 10 m from the detachment surface, with calcite sheets organised in a regular array (shear band). (e, f) Photograph and sketch of an irregular vein array cut by another multiple vein formed by parallel tabular calcite sheets.

the thrust zone. The 32 samples collected for carbonate analysis were carefully chosen away from pressure-solution seals. The average $CaCO_3$ concentration is about 65%wt, but varies from 30 to 70%wt. Fig. 2(b) shows $CaCO_3$ pattern. The general trend is a decrease in $CaCO_3$ toward the thrust, which is located in a shaly level.

The calcium carbonate distribution along the formation is the result of primary lithological variations in addition to the secondary processes as testified by the wide occurrence of pressure-solution in the Scaglia Cinerea Formation. Undeformed sections located near the studied outcrops confirm the presence of levels where calcium carbonate varies in relative abundance.

In order to evaluate temperature conditions during thrusting, clay mineral analyses have been carried out on the same samples used to determine the $CaCO_3$ relative abundance. The clay mineral composition is constant along the entire section (average abundance: smectite: 10%; illite–smectite: 20%; chlorite: 15%; chlorite–vermiculite: 15%; illite: 20%; kaolinite: 20%). The inferred temperatures reached during deformation in the Scaglia Cinerea Formation are below 200°C (Hayes, 1970).

4. The Balduini Thrust

4.1. Geometry of the Balduini Thrust

In the Balduini area (Fig. 1), the fabric changes caused by deformation of the Scaglia Cinerea Formation are clearly seen in three dimensions, because of the badland style of erosion. The outcrops show that the Balduini Thrust is not a single continuous 'fault surface', but consists of at least five en-échelon fault segments (Fig. 1b). In plan view, each surface forms a semi-arc where the front is aligned with a general N–S trend and the other end curves up to 60° from that trend describing a wing (Figs. 1b, 3 and 4). The length of each semi-arc along fault varies from 50 to 100 m. The dip of a single surface varies along strike from a 50° average in the frontal part to a 70° average in the lateral parts. Thrust segments typically curve both in plan view and in cross-section (Fig. 3). Thrust segments are arranged left-lateral and en-échelon (Fig. 1b). Kinematic indicators suggest that displacement directions vary along each semi-arc fault surface: slickenlines, fibres of calcite veins, and drag folds indicate a reverse movement on the semi-arc front, and right-lateral transpression along the wing (Fig. 4). The alignment of the straight frontal parts of the curved surfaces forms the overall Balduini Thrust (Fig. 1b).

4.2. Structural sections along the thrust segments

Three structural sections have been studied across different segments of the Balduini Thrust. Fig. 2(a) shows a planar view of one of the sections measured through the frontal part of the thrust, where the types, frequency and strikes of different structures are presented. Based on the deformation style all the studied sections can be subdivided along their lengths into two parts, one including the thrust zone and material immediately below it, and the other above the thrust zone (Figs. 1d and 2a). Above the thrust zone the orientation of bedding/fissility does not show abrupt change through all the section, and the maximum angle formed by azimuths is 40° (Figs. 2 and 4).

Calcite veins are common and their occurrence is closely linked to the thrust zone, as they are not present in undeformed outcrops of the Scaglia Cinerea Formation. Veins have four orientations: one set sub-parallel to the bedding, one set sub-perpendicular to the bedding with the same strike angle, and two sets oblique to the bedding. Based on cross-cutting relationships veins can be grouped into two different systems, each system composed of two conjugate sets, according to whether they are striking sub-parallel or oblique to the bedding (Fig. 5a, b). The dihedral angles between the conjugate sets gradually decrease toward the bottom of the sections where the thrust zone is located. Cross-cutting relations reveal that the two systems of veins are contemporaneous. The number of veins increase toward the bottom of the sections: the veins striking oblique to bedding are more common in the upper part of the section, while veins striking sub-parallel to bedding tend to increase toward the thrust zone. The calcite shows that each vein has both shear and extension, and very rarely is only one mechanism present. Pitch values of the vein fibres are different if measured in sections striking through the frontal part of the segment or through the lateral part (Fig. 4). In the frontal part, veins with reverse movement are more common, while in the lateral part dextral veins are dominant.

The distribution and shape of the veins differ between the outside and the inside of the thrust zone (Fig. 1c). The veins are most abundant 5 m above the thrust zone. Outside the deformation zone, veins are uniformly distributed, lenticular in shape and persist for a distance along strike of 30–50 m. Within the thrust zone, calcite veins are commonly disrupted, showing folding and boudinage.

The morphology of the veins above the thrust zone progressively changes. Near to the thrust zone dominant veins have a constant thickness of about 0.5 m and they consist of calcite sheets organised as tension gashes associated with a top and a bottom vein (Fig. 5c, d). These veins have a shear zone geometry and they are called regular. Calcite sheets are often truncated and rotated suggesting a progressive evolution of the array. Going away from the thrust zone veins become more irregular with highly variable thickness. Irregular veins form an anastomosing array in three dimensions (Fig. 5e, f). Finally, far from the thrust zone the dominant calcite veins consist of single, tabular veins less than 10 mm thick. Similar morphological characters have been observed in calcite veins from other thrust-fault zones (Vannucchi, 1995) and in veins

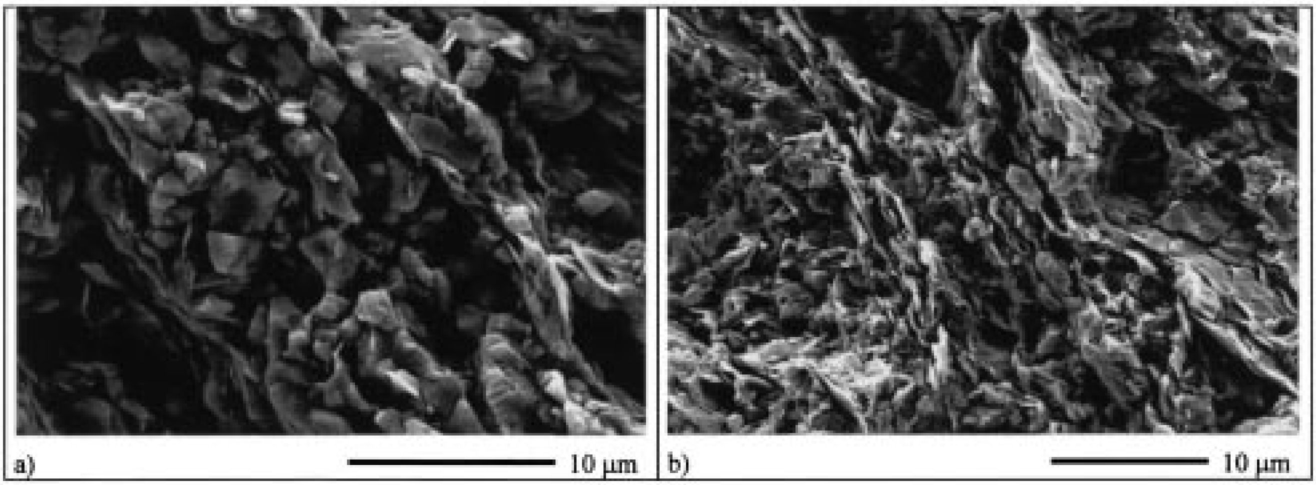

Fig. 6. SEM photomicrographs (secondary-electron mode) of the Scaglia Cinerea Formation: (a) undeformed marls showing calcite cement and the fine laminations, some with parallel clays, that account for the mesoscopic fissility; (b) deformed marls from the thrust zone showing the irregularly distributed domains.

in cores from Japan Trench, ODP Leg 87 (Knipe, 1986).

Joints are present throughout the section above the thrust zone, decreasing in number toward the thrust (Fig. 2a). Joints are organised in the same geometrical pattern as veins, with two systems, each with two sets, trending sub-parallel and oblique to the bedding/fissility. The dihedral angle among each set decreases toward the thrust zone (Fig. 2c) even more markedly than in the veins.

A 5–10-m-thick zone of disrupted shales in which the fabric passes from a regular planar fissility with about 10 mm spacing into a scaly fabric (Fig. 1c) marks the thrust zone. Microscopically, away from the thrust zone the fissility can be seen to result largely from the primary sedimentary layering, a fine alternation of clay-rich laminae and biogenic material (Fig. 6a). Biogenic grains, consisting mainly of nannofossils a few microns across, give a 'silty' appearance to the sediment and occupy as much as 30–40% of the sediment. A well-developed calcium carbonate cement forms up to 75% of the material but decreases towards the thrust zone, where it drops to 30%. Clay minerals are poorly oriented, with a void ratio of 2.1–2.3. Within the thrust zone, thinner and denser (face-to-face contact instead of edge-to-face) clay horizons define irregularly distributed domains, corresponding to the mesoscopic scaly partings (Fig. 6b). They lack persistence and terminate abruptly, and only occasionally show fine striations. Secondary shear surfaces are present, but not common. Fractures and signs of displacement are seen parallel to the strongly oriented clay mineral horizons. Cementation is present but less intense than in the undeformed section. The void ratio is here less than 1.

The biogenic and clay-rich laminations alternate finely and imbue a marked mechanical anisotropy. Consequently, as deformation progressively intensified the sedimentary laminations and their parallel fissility were a dominant influence on the shearing, although there was reorientation of clay minerals. The microscopic appearance of the clay mineral horizons indicates breakage along partings parallel to the grain orientation. Such discontinuous and local deformation is typical of overconsolidated sediment (Bolton and Maltman, 1998). The high degree of cementation, which tended to lock the sediment, prohibited continuing clay rotation and the development of a strong scaliness such as that of Barbados (Labaume et al., 1997). Hence incipient cataclasis and fracture is dominant, and, microscopically, the scaly fabric only reached an embryonic stage. This scenario for the fabric resembles that described from the Applachians by Lash (1989).

Mesoscopically the change from fissility to scaly fabric is abrupt and bounded by calcite veins (Fig. 1d). Outside the thrust zone the Scaglia Cinerea contains only joints, calcite veins, and fissility, while within the thrust zone the marly shales have developed non-cylindrical folds with a radius of curvature of about 0.5 m (Fig. 1c). The deformation style abruptly changes from brittle in the marls above the thrust zone to ductile in the thrust zone. Even mesoscopically scaly fabric does not pervade the entire deformed volume, but is concentrated in discrete horizons. Zones in which scaly fabric is folded alternate with others where shales have a very closely spaced (2–3 mm), but not pervasive, fissility. In both cases, the discontinuity surface is slickensided. The fissility defines open drag folds linked to the detachment surface. In the thrust zone, calcite veins are either continuous or folded and

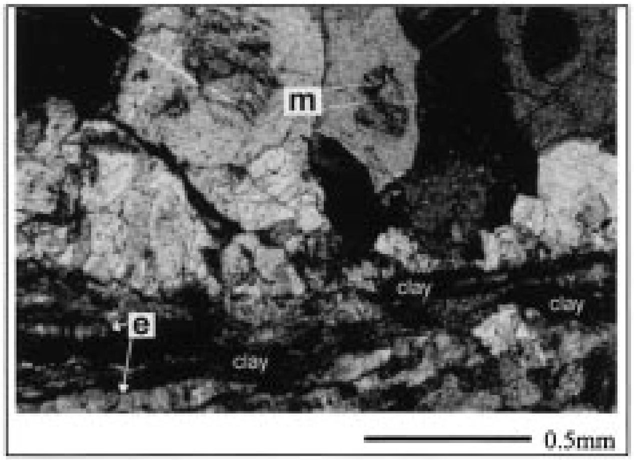

Fig. 7. Photomicrograph of a tabular calcite vein where both the extensional fibrous generation of calcite (e) and mosaic calcite (m) are present. The extensional fibrous calcite alternates with clay layers, dark in the photo. The mosaic calcite crystal centres show inclusions causing 'dirty' cores. The growth pattern of the vein is toward the top of the picture (cross-polarised light).

boudinaged. There is no evidence of any later deformational events affecting the area.

4.3. Calcite veins accompanying the Balduini Thrust

The veins have been developed over a number of several opening events where extension and shear alternate (Fig. 7). Cross-cutting relationships, differing crystal morphologies and progressive deformation allow reconstruction of a vein crystallisation history (Vannucchi and Maltman, 1999).

Starting from the first event each vein shows a network of extensional veinlets of fibrous calcite, '*S–C*'-like calcite organised in bands and fibres, brecciation and mosaic calcite with mud injections, extensional fibrous calcite alternating with shear fibrous calcite, and, finally, pressure-solution parallel to the veins (Vannucchi, 1998; Vannucchi and Maltman, 1999). Mosaic crystals testify that the constrained opening that generated the fibrous calcite, is replaced by free open channels, where calcite approached an equilibrium fabric as mosaic or foam structure. Mosaic calcite is then cut, indicating that the system went back to the previous, constrained conditions of opening (Fig. 7).

The crystallisation pattern is similar in the two vein systems, but in the sub-parallel-to-bedding veins the extensional generations are more developed than the shear ones. Clean calcite extension fissure in the outer fold arc and disruption of the calcite veins in the thrust zone reveals that they were deformed after their precipitation. Isotope analyses on the veins and the host sediments show that the calcite of the veins is locally derived (Vannucchi, 1998).

5. Discussion: veins and fluid flow

In line with the observations of Maltman (1994) and references therein, the bedding-parallel arrangement of mineralised veins is typical of hydrofracturing. The

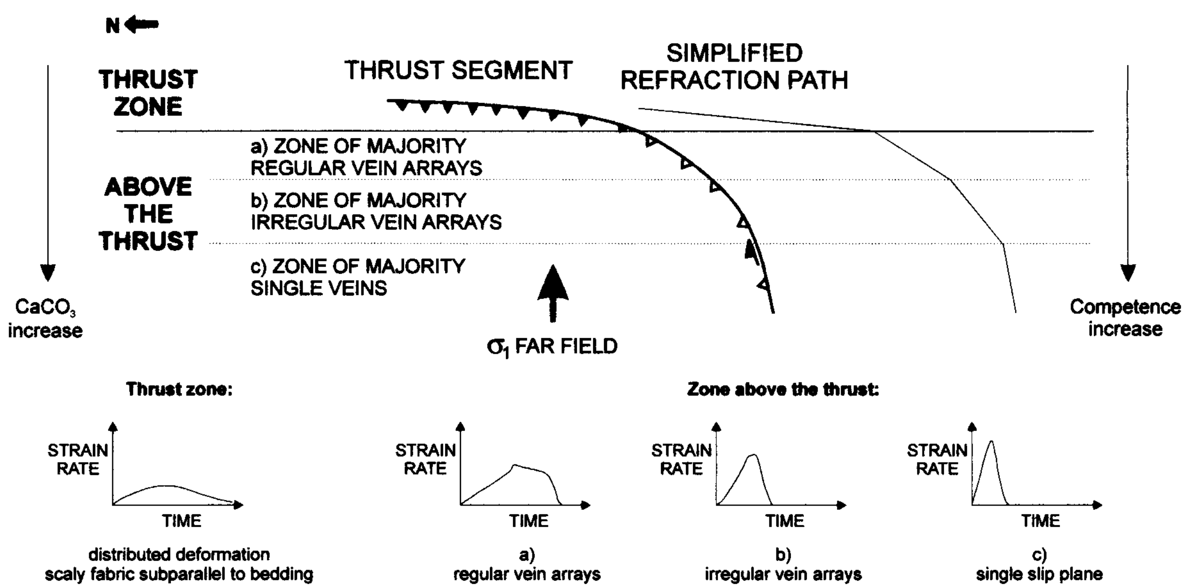

Fig. 8. Distribution of vein types in strain rate/time space along the sediment column. The different features and vein morphologies reflect competence contrast which in turn affects the thrust geometry. The refraction path is here simplified for scale reasons (after Knipe, 1986).

extensional fibrous calcite (Fig. 5c) and the generation of mosaic calcite (Fig. 5c) further confirm the existence of a high fluid pressure. The deformation of veins in the thrust zone, testifies to their precipitation before or during the thrust growth and evolution. These veins developed because the fluid pressure exceeded the stress normal to the bedding by an amount greater than the cohesion of the sediment. The matter of whether the fluid overpressure was related to ongoing consolidation and dewatering or to the tectonic regime is beyond the scope of the paper, but the localisation of the veins only at the thrust zones supports a tectonic origin. Mud injections in between mosaic crystals indicate the sediments were poorly lithified during vein development, which therefore occurred early in the strain history of the Scaglia Cinerea.

The progression of fibrous and mosaic calcite, ending with pressure-solution, implies that during the deformation event vein production, strain rate and the fluid pressure increased, reached a maximum, and then decreased. The only step out of this trend is the brecciation, where cataclasis took over from opening of fractures for veins. The reason for this apparent drop in the fluid pressure, or increase in the strain rate, could have been the improved connectivity of the vein system to promote drainage, the transient nature of the fluid pressure pulses, or a peak in the shearing activity.

The calcite crystal morphology and the morphology of the veins themselves indicate variations in strain rate during the deformation event (i.e. the strain rate/time path). Knipe (1986) shows that variations in regularity and planarity of veins may reflect evolution of the deformation, and in this case of the dilation, during differing strain rate/time paths (Fig. 8). In relatively lithified material, for example, the strain rate builds up very rapidly and the development of a single fracture is promoted, which concentrates shearing, as suggested by the displacement along the veins (Fig. 8). In relatively unlithified material, the strain rate is low and the material can accommodate deformation over a greater volume of sediments, ending up with distributed shear either as grain boundary sliding or particulate flow (Fig. 8).

Vein orientations and microstructures account for fluid pressure behaviour while the vein morphology defines the strain rate and fluid pressure variation along the Scaglia Cinerea (Fig. 6). The cross-cutting relationships between veins testify that strain rate and fluid pressure variation occurred simultaneously in the whole deformed volume. Together with the vein morphology other features systematically vary along the examined sections of Scaglia Cinerea. Summarising from the outside of the thrust zone to the inside: the calcium carbonate content decreases from an average of 70% to 35%; the number of veins increases; the value of conjugate veins and joints dihedral angles increases (Fig. 2). The peak in vein abundance just above the thrust zone records the zone with the greatest dewatering. Moreover in the thrust zone, whose upper limit is defined by an abrupt surface outlined by calcite veins, structures are typical of a ductile regime, with folds and scaly fabric, and without brittle structural features. Data and observations, reflecting various stage of lithification, reveal systematic variations across the Scaglia Cinerea Formation that are in line with the presence of a gradient in degree of diagenesis.

Three important controlling factors of the deformation have been defined: fluid pressure, strain rate, and degree of diagenesis. Variations of such factors occurred simultaneously and interactions between them have been inferred. All the three factors are linked to physical properties, such as strength, bulk density and pore pressure, that are difficult to evaluate for the time when the deformation took place. Observations on the Balduini Thrust aim to establish how the interactions qualitatively affect the deformation.

The Balduini thrust segments have a general curved shape at the macroscale (100 m) and at the same scale the lithology and vein morphology variations are indicative of a trend going from high strength, far from the thrust, to low strength, near the thrust. At the mesoscale (1 m) the sedimentary section (Fig. 2b) is composed by alternations of relatively carbonate-rich and carbonate-poor layers. Veins also alternate and the detachments are composed of a series of refracted surfaces (Fig. 3). The regular curvature representing the Balduini Thrust (for example Fig. 4) is the result of considering the average surface of the refracted planes.

6. Discussion: thrusting mechanism

The tectonic setting of the area and the meso-microstructural analysis show that the Balduini Thrust developed as a segmented feature and that each thrust segment developed with a primary curvature. There is no evidence of later deformation or that the curvature is due to later folding. Along the curvature, slickenlines show different movement senses (Fig. 4).

The deformation took place early in the burial history of the sedimentary sequence, while the deforming material was poorly lithified. The deformation is concentrated in the Scaglia Cinerea Formation while the formations above and below showed strong resistance to the movements, as they were relatively well-lithified. The explanation of why the Balduini Thrust propagated entirely within the Scaglia Cinerea Formation, and in a segmented, curved arrangement, lies in the mechanical nature of this formation, and its poorly lithified state at the time. The distribution and dissipation of pore-fluids are intimately involved with the mechanical behaviour. Fluid expulsion has an important influence on the strength, pore pressure, and hence mechanical response of sediments undergoing lithification and deformation. In particular, fluid expulsion influences fracturing and affects the generation and propagation of detachment surfaces (Cloos, 1982, 1984; Bangs et al., 1990; Behrmann, 1991; Henry and Wang, 1991; Breen and Orange, 1992; Wang et al., 1994; Moore et al., 1995a, b; Morgan and Karig, 1995). The effects are best known in submarine accretionary complexes, where geophysical analyses image variations in bulk density, strength, and pore pressure, responsible, for example, for the upward convexity of the décollement (Zhao et al., 1986; Breen and Orange, 1992). On-land detachment zones have been much less investigated, because of difficulties in imaging them seismically and in quantifying physical properties at the time of deformation when sediments were not already lithified.

Isotope analysis carried out on the veins and the marls of the Scaglia Cinerea Formation shows that the calcite is derived from the pore-fluids of the host material (Vannucchi, 1998). The record of high fluid pressure in the veins testifies that pore-fluids were locally overpressured. Every rupture surface present at the time presents a preferential dewatering channel. The migration of fluids towards channels helps give rise to heterogeneities in the pore-fluid distribution in the formation, superimposed on those due to the differences in the primary lithology. Consequently, the relationship between the bulk densities, pore-pressures and strengths of the sediments vary at different levels within the Scaglia Cinerea Formation. The response to heterogeneous fluid overpressure is shown by the varying degree of veining, i.e. fracturing and dilation, observed in the studied sections. The dewatering of the Scaglia Cinerea Formation proceeded at different rates at different levels in the unit, further enhancing the heterogeneities already mentioned.

The formation of a shear zone is by itself a reason to progressively change the physical properties of the sediments in the zone, leading to deformation-induced competence contrast (Ramsay, 1982). The sediment in the shear zone became less competent than that in the walls, a process of strain softening, which in turn affected the Mohr–Coulomb friction angle (Ramsay, 1982).

In a uniform stress field, a fault cutting across sediments with uniform lithology, but different friction angles φ, changes its orientation with respect to a constant σ_1-direction, in accordance with the Mohr–Coulomb theory. This has been demonstrated in experiments (Wunderlich, 1957) and analytically through the study of heterogeneous stress fields related to the significance of fracture propagation (Treagus 1983, 1988; Foster and Hudleston, 1986; Treagus and Lisle, 1997). Treagus's (1983) analytical model implies that stress refraction is required to maintain stress and strain continuity at the contact between layers with different material properties. In a sediment volume with smoothly varying competence contrast the progressive refraction of strain results in curved rather than planar trajectory (Treagus, 1988). Foster and Hudleston (1986) adapted the model to fracture propagation, so that with decreasing relative competence of sediments, fracture surfaces should refract towards the bedding plane and increase in intensity. In layers of exceptional incompetence, fractures may be an intense foliation sub-parallel to bedding (Treagus, 1983; Foster and Hudleston, 1986; Treagus and Lisle, 1997). This theoretical model well applied to the Balduini Thrust where the sub-parallel to bedding orientation of the scaly fabric confirms the incompetence of the material of the thrust zone.

Mandl's (1988) two-dimensional finite-element analysis of a thrust sheet of uniform mechanical properties, which rests in frictional cohesive contact with a thin band of homogeneous weaker material attached to a rigid block, produces a curved detachment surface. Mandl's model does not take into account fluid migrations, which can result in strain hardening and strain softening (Bolton et al., 1998). In the Balduini Thrust case, the thrust zone, characterised by a scaly fabric, represents the weak, low competence level where sub-parallel pervasive foliation is developed. Moreover fluid migration is, in this case, related to the zones of scaly fabric development alternating with the zones where the fabric is not present. A similar effect was reported from the Barbados décollement (Labaume et al., 1997).

Although refraction explains the curvature of the faults (Fig. 8), it does not account for their lack of continuity. According to Mandl (1987) and in the framework of the Mohr–Coulomb theory, incipient and early stages of failure are expected not to form continuous faults, but numerous, discrete segments, because of the heterogeneous three-dimensional stress field (no plane stress) and of the concentration of shear in narrow domains. Changes in local stress regime, caused by heterogeneities, are adjusted by en-échelon arrays of smaller faults playing the role of transfer zones (Aydin, 1988).

The Balduini area has two major sources of discontinuities: one inside the Scaglia Cinerea Formation, namely the variations in lithology, dewatering rate and stress field, and one due to the geological setting. The regional setting of the area may have enhanced the effects of lithology and dewatering. The Balduini Thrust lies in a synclinal core whose limbs are formed by limestones that show early diagenesis with respect to the shales of the Scaglia Cinerea Formation. The fold cores, acting as 'rigid' blocks, complicated the far-field stress pattern.

The geological frame of the Balduini area shows that the propagating fracture cannot continue to arc upwards, passing out of the Scaglia Cinerea Formation into the overlying strong material, and so an adjacent new fracture is initiated. The Balduini Thrust being restricted to the Scaglia Cinerea horizon and the inhomogeneity of the tectonic stress field result in the segmentation of the thrust. The disrupted veins in the Balduini Thrust zone record a simple shear process that progressively involved new volumes of sediments, along with the progressive growth of the thrust zone itself.

The geometry of the Balduini Thrust, and its difference from other thrusts in the area that show a single, continuous thrust surface, is also referable to properties of the Scaglia Cinerea Formation and particularly to the diagenesis/time ratio. The lithology of the Scaglia Cinerea Formation is the major factor responsible for the geometry of the thrust. Mud-rich formations are characterised by a delay in diagenesis in comparison with limestones (Byrne, 1994). Mandl (1987) recognised that the early stages of fault development are likely to produce discontinuous features. The Balduini Thrust formed in weak, poorly lithified mud-rich material and its shape reveals that it propagated quickly, never reaching a mature stage. Thus the Balduini Thrust is, in this respect, preserved as a feature in its early stages of development; its singularity in the regional context is related to a balance between time, strain intensity and diagenesis.

7. Conclusions

The Balduini Thrust occurs within the mud-rich Scaglia Cinerea Formation and cuts the recumbent limb of a synclinal fold that involved the entire Umbria–Marche Succession. Excellent exposure has allowed geometric and kinematic analysis of the thrust, which demonstrates that it consists of several curved, en-échelon segments.

Stratigraphic sections across the Scaglia Cinerea Formation reveal a decreasing amount of sedimentary calcium carbonate toward the thrust zone. Discontinuous zones of scaly fabric and extensional and shear calcite vein systems oriented both parallel and oblique to the bedding represent deformation adjacent to the thrust. The veins have a different mesoscopic morphology along the outcrops: far from the thrust they are single, tabular veins, then they become multiple, with an irregular geometry and, just above the thrust zone, they form a regular array. These differences in mesoscopic characters suggest a difference in rheology across the formation thickness. The bedding-parallel vein system, together with the micromorphological characteristics of the calcite crystals, is evidence for high fluid pressure in the sediment.

The Balduini Thrust propagated through a poorly lithified zone with systematically varying mechanical properties. Even though the mechanism of strain refraction has been proposed before (e.g. Treagus, 1983, 1988; Foster and Hudleston, 1986; Mandl, 1987), the example discussed here has some new implications. The role of fluids, the compressibility of the layers, as a result of porosity loss and diagenesis, and the nature of propagating fractures in poorly lithified material are documented for the first time. Fault zones that consist of curved segments may be more common than exposure reveals. In the case of the Balduini Thrust example, its genesis is due to a particular balance between time, strain intensity and diagenesis.

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