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# Deformation along the leading edge of the Maiella thrust sheet in central Italy

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ABSTRACT

The eastern forelimb of the Maiella anticline above the leading edge of the underlying thrust displays a complex system of fractures, faults and a series of kink bands in the Cretaceous platform carbonates. The kink bands have steep limbs, display top-to-the-east shear, parallel to the overall transport direction, and are brecciated and faulted. A system of pervasive normal faults, trending sub-parallel to the strike of the mechanical layers, accommodates local extension generated by flexural slip. Two sets of strike-slip faults exist: one is left-lateral at a high angle to the main Maiella thrust; the other is right-lateral, intersecting the first set at an acute angle. The normal and strike-slip faults were formed by shearing across bed-parallel, strike-, and dip-parallel pressure solution seams and associated splays; the thrust faults follow the tilted mechanical layers along the steeper limb of the kink bands. The three pervasive, mutually-orthogonal pressure solution seams are pre-tilting. One set of low-angle normal faults, the oldest set in the area, is also pre-tilting. All other fault/fold structures appear to show signs of overlapping periods of activity accounting for the complex tri-shear-like deformation that developed as the front evolved during the Oligocene–Pliocene Apennine orogeny.



## 1. Introduction

Understanding the processes of faulting and fracturing as it has occurred in existing structures provides a foundation for development of predictive models for faults and fractures, including their orientation, geometry, pattern, distribution, kinematics, and petrophysical properties. This knowledge is necessary for determining the structural framework of deformed rocks and regions and for evaluating fluid flow pathways in fractured reservoirs, especially those in low permeability carbonate rocks (Aydin, 2000; Graham Wall et al., 2006). Characterization of structural and hydraulic parameters is particularly challenging in carbonate rocks, which fail by opening mode fractures as well as by closing mode fractures. Furthermore, chemical dissolution of carbonate rocks at or near the surface further complicates direct observations by means of analog studies. Considering that vast amounts of resources, including water, oil, and gas are found in carbonate rock formations (Yose et al., 2001), understanding fractures and faults in this type of rock is all the more critical. However, there are relatively few publications on failure and faulting of carbonate rocks and their geometric and petrophysical properties in comparison to studies of similar features of silicaclastic detrital rocks.

In some carbonate rock types, fault initiation and evolution are associated with opening mode fractures such as joints and veins (see, for example, Mollema and Antonellini, 1999 for dolomite; and Rawnsley et al., 1992; Kelly et al., 1998; Gross and Eyal, 2007 for limestone). The mechanisms described by these authors are similar to those in other brittle rocks (see Segall and Pollard, 1983; Martel, 1990 for granitic rocks; Myers and Aydin, 2004; Flodin and Aydin, 2004; Florez et al., 2005 and Gonzales and Aydin, 2008 for sandstone; Dholakia et al., 1998 for siliceous shale). However, because carbonate rocks are prone to dissolution under common geological loading conditions in the upper crust, deformation and failure of carbonate rocks usually involve pressure solution (Rutter, 1983; Groshong, 1988; Engelder and Marshak, 1985). Examples of carbonate rock deformation predominantly by pressure solution and the subsequent shearing of solution seams can be found in Alvarez et al. (1978), Salvini et al. (1999), Graham et al. (2003), and Billi et al. (2003). In some cases, however, both opening and closing failure modes simultaneously played equally important roles in carbonate rock failure in certain environments (Rispoli, 1981; Petit and Mattauer, 1995; Peacock and Sanderson, 1995; Willemse et al., 1997; Graham Wall et al., 2006; Agosta and Aydin, 2006; Antonellini et al., 2008). The conditions that lead to mixed failure modes are not well understood.

Deformation of the carbonate rocks associated with the Apennine orogeny has attracted considerable interest (Alvarez et al., 1978; Marshak et al., 1982; Graham et al., 2003; Marchegiani et al.,

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2006; Tondi et al., 2006; Agosta and Aydin, 2006; Agosta et al., 2007, 2008; Antonellini et al., 2008), as has its symmetric counterpart, the Albanian fold and thrust belt on the eastern side of the Adriatic Sea (Van Geet et al., 2002; Graham Wall et al., 2006). Early interest in these areas was, in part, due to the excellent examples of natural pressure solution features in carbonates in the region but the latest projects are more related to the growing need for analogs of carbonate reservoirs in fold-and-thrust belts for research related to resource location and extraction.

Maiella (also spelled Majella) Mountain, in central Italy, offers a rich example of a marine carbonate setting, including the platform carbonates and the associated slope and basin deposits. These deposits were deformed during the Apennine orogeny and also perhaps during the post- orogenic extension. Deformations of the basin and slope deposits (alternating turbiditic grainstones and micrites) and their spatial and temporal variations as a function of lithotype were the subjects of two recent studies (Tondi et al., 2006; Antonellini et al., 2008). In this paper, we document a number of structural assemblages, with an emphasis on the geometry, distribution, and formation mechanisms of the faults in the platform carbonates exposed in the hanging wall along the leading edge of the Maiella thrust sheet, immediately west of the town of Fara San Martino. This study follows two earlier investigations carried out in the same area which focused solely on the micromechanics of normal faulting in a contractional environment (Graham et al., 2003) and the geostatistical properties of the faults and fractures in the broader area (Marchegiani et al., 2006), and which were not concerned with the structural framework at the leading edge of the thrust sheet.

## 2. Geological setting

Maiella Mountain is located about 200 km east of Rome (Fig. 1a), in the Abruzzo region, and is the easternmost of the major thrust sheets located within the Oligocene–Pliocene central Apennine fold and thrust belt (Fig. 1b, Mostardini and Merlini, 1986; Roure et al., 1991; Cello et al., 1997; Bigi et al., 1992; Ghisetti and Vezzani, 1997; Vezzani and Ghisetti, 1998; Scisciani et al., 2002; Tondi and Cello, 2003). The first-order structural feature of the Maiella thrust sheet is an elongated, kidney-shaped anticline with a steeply-dipping, curvilinear eastern forelimb and a basal thrust underlying the thrust sheet (Figs. 2a, c). Along the forelimb, the projected surface trace of the thrust fault separates the predominantly carbonate rocks of the Maiella series, which are of Lower Cretaceous to Middle Miocene age (Fig. 2b, Bernoulli et al., 1992; Eberli, 1993) from the argillaceous and silicaclastic foredeep deposits of the Messinian and Pliocene flysch (Figs. 2b, c, Ori et al., 1986).

Aside from the underlying thrust, which accommodated several kilometers of eastward motion of the thrust sheet (Scisciani et al., 2002 and references therein), the internal structures of the Maiella anticline consist predominantly of normal faults (Figs. 2a, c) with about 4 km of total offset (Ghisetti and Vezzani, 1997; 2002; Scisciani et al., 2002). Among these, the Caramanico Fault marks the trailing western boundary of the thrust sheet. Many other smaller normal faults transect the anticline at various angles. These normal faults appear to be younger than the underlying basal thrust.

The 2-km-thick carbonate succession of the Maiella series (Fig. 2b) records the conditions of Cretaceous to Miocene platform margins and the slope/basin depositional environments of the Tethys. It is capped by silicaclastic sediments of Upper Miocene–Middle Pliocene age (Bernoulli et al., 1992; Eberli et al., 1993). The surface outcrops are dominated by platform carbonate rocks, in the south, and basinal rocks in the north (Fig. 2a). In the center of the anticline, platform margin sediments are exposed along several deep gorges such as the Tre Grotte Valley (Crescenti et al., 1969; Accarie, 1988; Eberli et al., 1993; Mutti, 1995; Lampert et al., 1997; Vecsei et al., 1998; Vecsei and Sanders, 1999; Ori et al., 1986). These earlier studies identified a carbonate ramp sequence developed in post-Cretaceous times, when the platform margin ceased to be active.

In the hanging wall of the Maiella thrust to the west of the town of Fara San Martino (Figs. 2a and 3), there are excellent outcrops of Cretaceous platform carbonate rocks. These are divided into two different formations: the Morrone di Pacentro Formation, the older, and the Cima delle Murelle Formation, the younger (Figs. 2b and 3). The older formation is made up of thickly and poorly-bedded oolitic and oncolitic grainstones, intercalated by stromatolitic limestone. The younger formation consists of organic limestones and relatively well-bedded mudstone, grainstones and rudstone, and contains

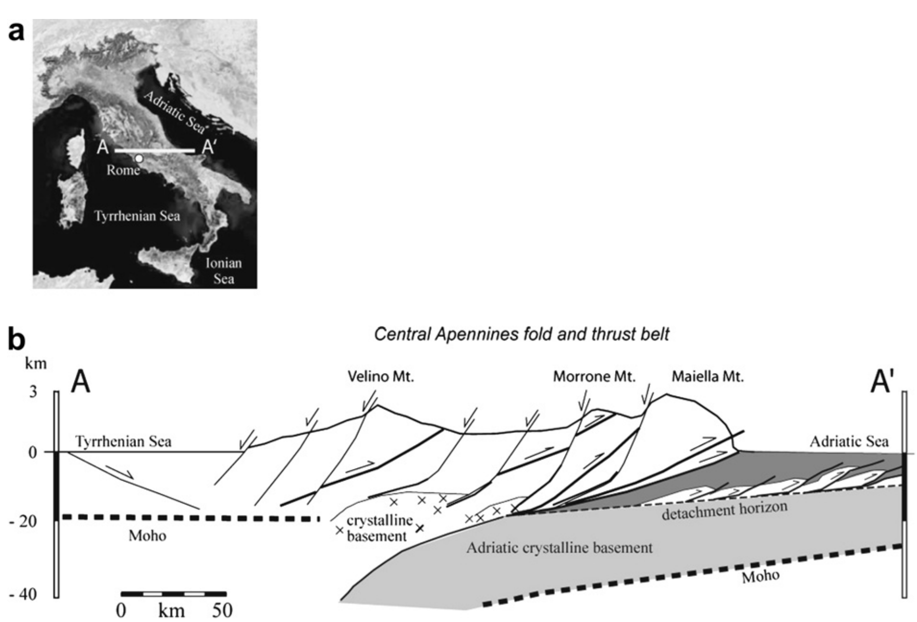


**Fig. 1.** (a) Location map and (b) a generalized E–W cross section (A–A′) showing the central Apennines fold-and-thrust belt (Ghisetti and Vezzani, 2002). The Maiella thrust sheet is the easternmost major thrust belt within this system. Also shown are the high-angle normal faults resulting from the post-orogenic Apennine extension.

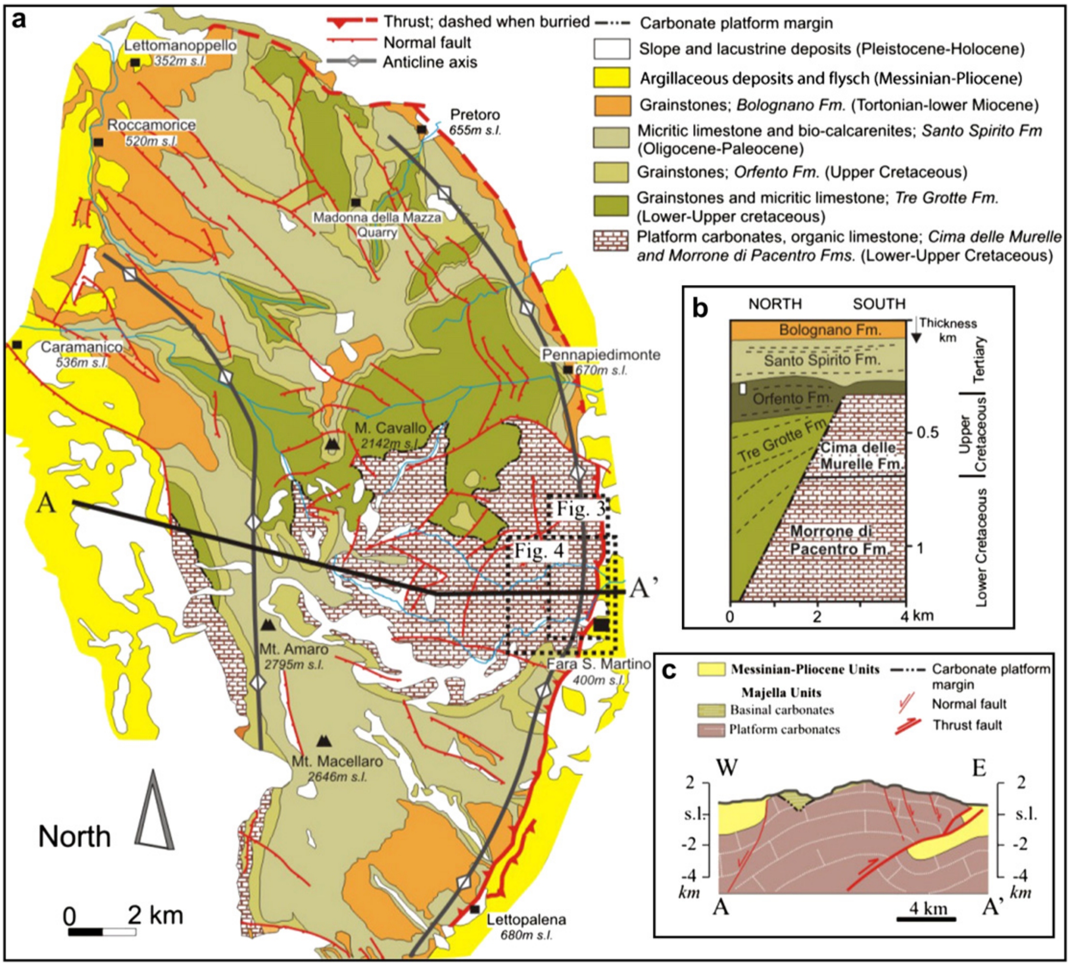


**Fig. 2.** (a) Simplified geologic map (modified from Vezzani and Ghisetti, 1998); (b) platform to basin stratigraphic section (Bernoulli et al., 1992); and (c) a generalized E–W cross section (Vezzani and Ghisetti, 1998) of Maiella Mountain. In (a), locations of Figs. 3 and 4 are also marked.

abundant rudist fragments. These formations are of Malm to Lower Cretaceous age (Vezzani and Ghisetti, 1998).

## 3. Deformation in the hanging wall along the leading edge of the Maiella thrust sheet

The study area lies along the steep eastern limb of the Maiella anticline, in between two spectacular gorges: Vallone di Santo Spirito and Vallone Del Fossato (Figs. 3 and 4). It primarily exposes carbonates of the Cima delle Murelle Formation, with bedding striking approximately N–S and dipping to the east generally between 30° and 85° (Fig. 3 inset). Although there are a few fossiliferous beds that are characterized by their depositional features, most layers in the platform carbonates are of mechanical type, defined by bed-parallel pressure solution seams (Graham et al., 2003). It is apparent that these layers exposed both at the southern and northern proximities of the study area are thinner and more systematic in the Cima delle Murelle Formation than in the Morrone di Pacentro Formation. In spite of such differences, the bed-parallel pressure solution seams are present in varying degrees within both formations.

Despite the quality of the outcrops that we have examined is exceptionally good, the field work in the study area has been highly challenging due to steep topographic gradient (nearly 1). Aerial photography of the area is prone to significant distortions due to the steep slopes and deeply incised valleys, so we relied on ground photographs and detailed sketches for structural documentation. We first introduce typical examples of different structure types seen in a panoramic picture from the southern part of the study area (Fig. 5).

The study area displays a series of kink bands and numerous faults with a variety of orientations, kinematics, and distribution patterns (Fig. 3 and insets therein): (i) thrust faults are confined within the steeper limb of kink bands approximately in strike-parallel orientation; (ii) normal faults are distributed throughout the eastern slopes of the mountain and are approximately strike-parallel, dipping generally downslope (synthetic) but also, in some cases, upslope (antithetic); (iii) left-lateral strike-slip faults are at high-angle to the front while right-lateral strike-slip faults are nearly parallel, or at very small angles to the front.

## 4. Background structures

Not visible in Fig. 5 is a system of pervasive pressure solution seams (PSSs), which we consider to be the fundamental structural elements related to the pre-tilting deformation phase. There are three different sets of these pre-tilting fundamental structural elements in the study area (Graham et al., 2003) similar to those found in platform carbonates of other thrust sheets nearby (Agosta and Aydin, 2006). There is one set of bed-parallel and two sets of orthogonal, bed-perpendicular (transverse) PSSs. The bed-parallel PSSs have spacing typically on the order of 0.5–20 cm with lengths of up to a few 10s of meters (Graham et al., 2003); these bed-parallel PSS's define mechanical layers in an otherwise massive carbonate rock. The E–W set of orthogonal transverse PSSs, perpendicular to the depositional bedding and mechanical

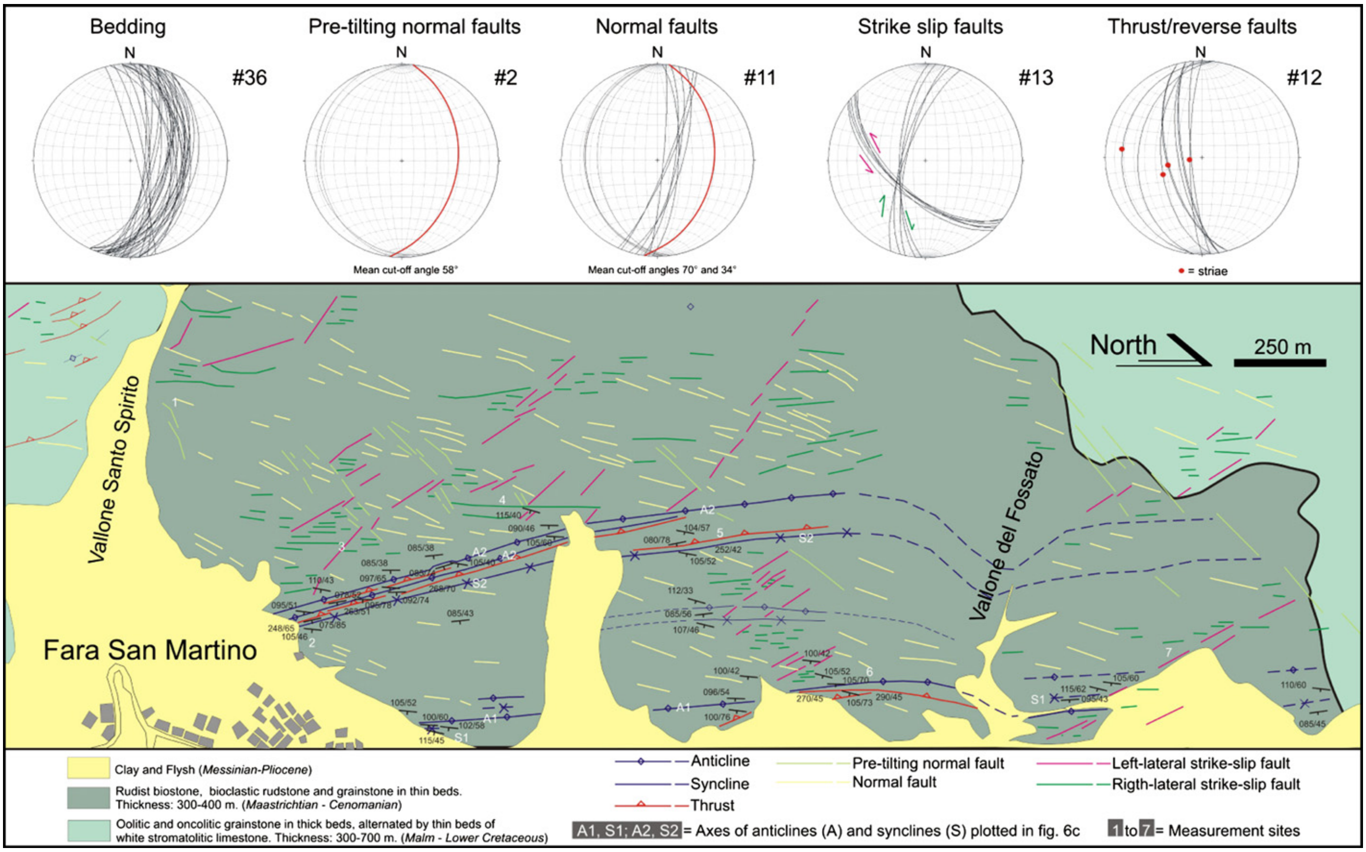


**Fig. 3.** Geologic map of the leading edge of the Maiella thrust sheet, west of the town of Fara San Martino. The thick succession of platform carbonates is divided into two units: the Cima delle Murelle Formation (dark green) and the Morrone di Pacentro Formation (light green). Also marked are two major monoclinal kink folds with associated thrust faults and three minor discontinuous kink folds. In addition, numerous normal faults, and left- and right-lateral strike-slip faults are also shown. Inset diagrams show plots of attitudes of older low-angle normal faults, younger (flexural slip) normal faults, left- and right-lateral strike-slip faults, and thrust/reverse faults using Lambert azimuthal equal-area projection. Cutoff angles for the normal faults are also shown. Counts of measurements are given in the upper right corners.

layering, is more continuous, whereas the N–S set is generally younger and truncated against the other sets and, therefore, shorter. Spacing of both bed-perpendicular PSSs is smaller than the thickness of the mechanical layers in which they occur.

### *4.1. Kink bands and the associated thrust/reverse faults*

Perhaps one of the most intriguing types of structures displayed along the eastern forelimb of the Maiella anticline is a series of kink bands (Figs. 3, 5, and 6) and the associated thrust/reverse faults with fragmented and brecciated zones (Figs. 8 and 9). These structures have attracted little attention, if any, in the literature in spite of the fact that together with the three mutually orthogonal sets of pervasive pressure solution seams, they represent the majority of actual contractional structures internal to the Maiella thrust sheet, except for the major anticline itself.

Fig. 6a, b shows two major continuous kink bands (labeled, from east to west, as K1 and K2 for simplicity) and three short and

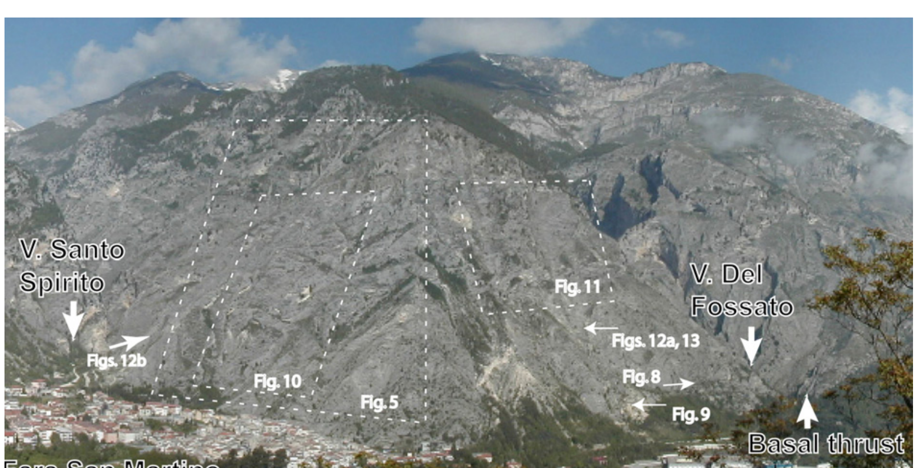


**Fig. 4.** Photograph (due WNW) showing the Maiella Mountain front between the Vallone Santo Spirito and the Vallone Del Fossato, west of the town of Fara San Martino (in the foreground). Locations of Figs. 5, 10, and 11, are delineated and locations of Figs. 8, 9, 12a, b, 13, and 15 are pointed out. The projected location of main basal thrust is also reported.

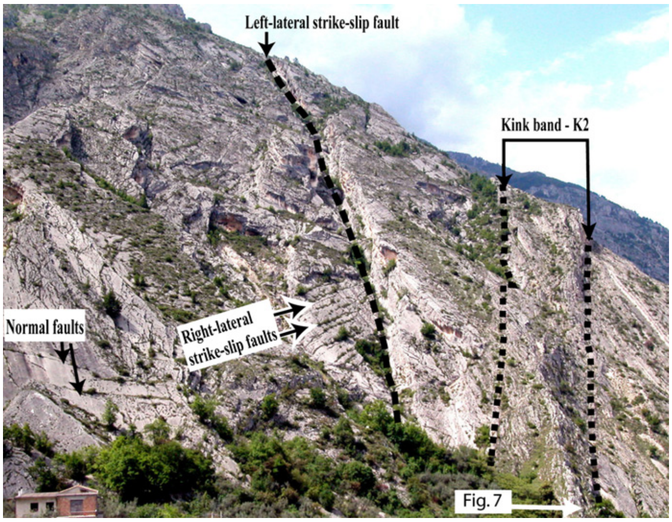


**Fig. 5.** Photograph (due WNW) of the forelimb of the Maiella anticline, immediately above the basal thrust at the base of the slope, on which typical examples of prominent major structures such as normal faults, left- and right-lateral strike-slip faults, and kink bands are highlighted.

discontinuous kink bands (marked by arrows without numbers). These kink bands trend sub-parallel to the projected trace of the main thrust at the base of the eastern slope of Maiella Mountain (Figs. 3 and 6c). The kink bands are of monoclinal type, in which the dip angles of the beds reach almost 90°, and they are overturned in a few locations. The east facing, steeper limbs of the kink bands are the locations of greater internal deformation. We identified the approximate boundaries of these zones by the antiformal and synformal axes along the two major kink bands, K1 and K2 (Figs. 5 and 6c). We also utilized detailed local observations and sketches of the points of interest to document the geometry and internal deformation of the major kink bands (Figs. 7, 8, and 9).

Fig. 5 shows the kink band, K2. The antiformal axis of the band is somewhat irregular, whereas the synformal axis is extremely sharp and well defined. The kink band geometry indicates approximately top-to-the-east shearing, which is consistent with the geometry of the Maiella anticline (Fig. 2). The steeper limb of the kink band is composed of mechanical layers dipping to the east usually at more than 50° (Fig. 6c). The width of the steeper limb shows some variability but, on average, falls between 20 and 30 m. Although we were unable to track the same stratigraphical horizon from the upper limb, through the central steeper limb, to the lower limb of the kink band, we estimated the gross top-to-the-east offset across each of the two major bands to be about 100 m, based on the bedding attitudes and the thicknesses and orientations of the kink bands. The mechanical layers are generally recognizable even within the steeper limb of K2, but they are highly fractured (Fig. 7). The fractures are of the same types as the three pervasive orthogonal pressure solution seams sets, one bed-parallel and two bed-perpendicular sets, except that they are usually sheared. Because of the shearing, splay pressure solution seams, oblique to bedding, are common (see short oblique lines in Fig. 7). In one location, what appears to be a gravity slide was also observed.

Fig. 8a shows a view due north along the antiformal axis of the easternmost kink band, K1 (see also Fig. 6c) south of Vallone Del Fossato, near the projected surface location of the main thrust underlying the Maiella sheet (see Fig. 4 for location). The cross-sectional sketch in Fig. 8b shows localized narrow zones of intense deformation along the steeper forelimb of the kink structure. Even if the antiformal fold hinge zone is well rounded, the fold axis is easily identifiable. Some reverse faults and breccia with various

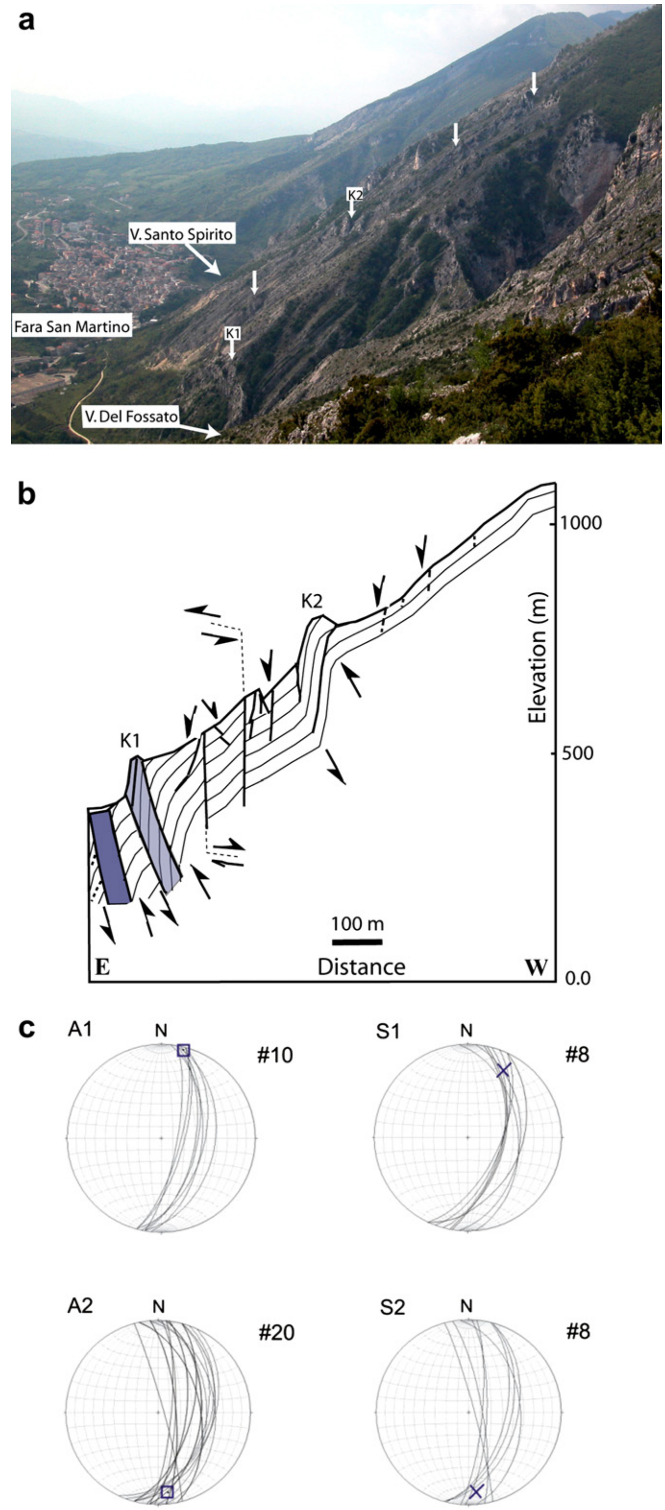


**Fig. 6.** (a) Photograph (due south) showing the hanging wall of the Maiella thrust west of Fara San Martino. Two major kink folds (K1 and K2) and three minor kink folds (vertical arrows) are pointed out. (b) Detailed E–W cross section (along the arrows in (a)) of the Maiella front, showing the two major kink folds (K1 and K2) and some faults. Other minor kink bands are present but are too subtle to be distinguished. (c) n diagrams (Lambert azimuthal equal-area projection) showing bedding or mechanical layering attitudes within anticline (A) and syncline (S) pairs that define major kink folds that are oriented approximately parallel the base of the thrust sheet. (1) and (2) denote K1 and K2, respectively. Measurement counts are also given.

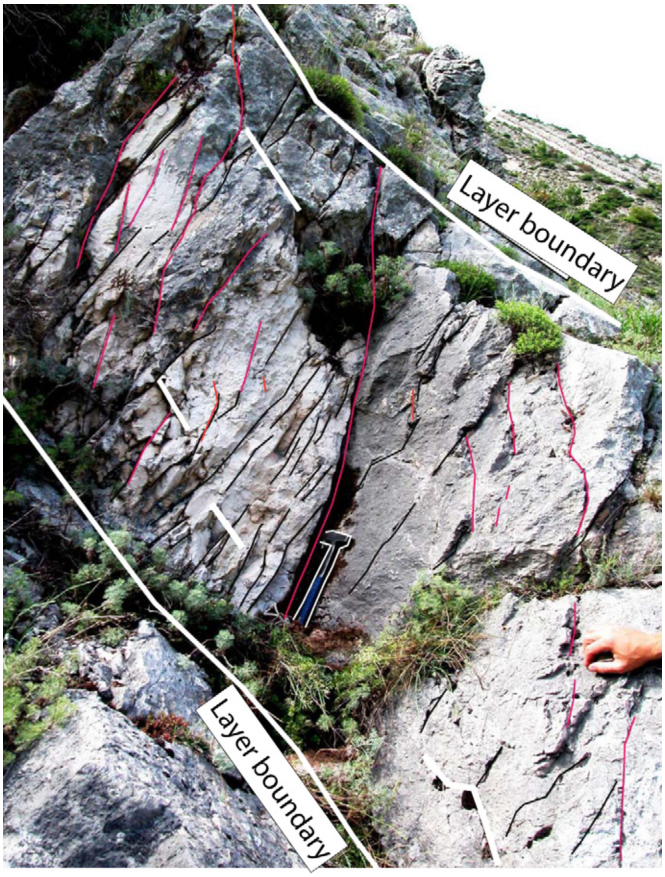


**Fig. 7.** Detailed photograph (due north) and map showing the fundamental structures (PSSs and their sheared versions) on a cross-section of the K2 kink fold across its synclinal limb (for location see Fig. 5). Sheared bed-parallel PSSs (white) and bed-perpendicular dip-parallel (black) and bed-perpendicular strike-parallel (red) PSSs are shown. Some oblique PSSs (short red) are also included within the bed-perpendicular and strike-parallel category. Hammer for scale.

degrees of deformation intensity can be observed along several distinct pockets within the steeper limb. Several high-angle faults locally utilized the bed-parallel and oblique PSSs, and have striated and polished slip surfaces (Fig. 8a, b, c). The splays/tails of these slip surfaces (identifiable in the field but difficult to see in the photograph in Fig. 8c due to the view angle) are in an orientation indicating approximately top-to-the-east motion along the faults.

The same K1 kink band can also be observed about 100 m to the south of the location shown in Fig. 8. There, the steep forelimb, nearly upright and overturned in some places (Fig. 9), displays high-angle reverse/thrust faults locally, following mechanical bed boundaries and oblique PSSs. These high-angle faults, together with sheared multiple sets of PSSs, interlaced parts of the fold limb to a degree that the rock was entirely brecciated (see cross-section in Fig. 9b). This well-developed breccia pocket is the location of a series of catchments that provide water for the world-famous pasta factories nearby. The eastern boundary of this breccia zone is covered and may possibly merge into the main thrust at the base of the Maiella sheet. The amount of top-to-the east motion associated with the major kinks alone may be at least a few hundred meters, based on the thickness of the breccia zones (>30 m) and the steep bedding orientation (~85°) therein.

### 4.2. Normal faults

A system of normal faults with traces, more-or-less, parallel to the strike of the bedding (Fig. 3 and insets) is pervasive in the study area. Some of these faults are shown in ground photographs in Figs. 5, 10, and 11. The majority of the normal fault planes are oriented down-dip with respect to bedding but some smaller normal faults are also oriented up-dip (antithetic, Fig. 12a, b). The cutoff angles for these faults were determined to be 34° for the synthetic faults and 70° for the antithetic faults (Fig. 3 inset). In a previous paper, Graham et al. (2003) studied a few selected examples of the normal faults within the platform carbonates in the eastern limb of the Maiella anticline in order to decipher their formation mechanism and internal architecture. They proposed a mechanism for the initiation and growth of normal faulting, which consisted of shearing of the bed-parallel PSSs induced by flexural slip, as shown by the rather low and high cutoff angles mentioned above. The normal faults also took advantage of the splays of sheared bed-parallel and bed-perpendicular PSSs, which are also strike-parallel (Fig. 13). These fractures fragmented the rock to form weak pockets within each mechanical layer. Eventually, fault growth was facilitated by linkage of the localized fragmentation zones within adjacent mechanical layers (Figs. 12a and 13).

The antithetic faults shown in Fig. 12a, b occur along the PSSs oriented perpendicular to the bedding and parallel to the strike of the beds. A few of the antithetic normal faults abut the dominant down-dip normal faults, indicating that the antithetic faults are generally younger.

Another set of low-angle, dip-slip faults (Fig. 10), which do not fit the normal fault group characterized earlier, is also present. Based on the abutting relationships, they appear to be the oldest structures seen in the study area. Almost all other types of structures described in this paper truncate against this group of normal faults. One relatively larger strike-slip fault appears to cut across two of these normal faults (Fig. 10), displacing them with a complex and ambiguous intersection geometry. These normal faults, at the present time, trend N–S and have low dip angles (Fig. 3 inset). However, they intersect the bedding at an angle of about 58°, which is within a range expected from normal faults formed when the beds were flat. Normal faults with similar cutoff angles were also described by Marchegiani et al. (2006) in different parts of the eastern front of Maiella Mountain.

### 4.3. Strike-slip faults

Strike-slip faults in the study area are organized primarily in two major sets (Figs. 3, 5, 10, 11 and 14). One set of these occurs at high-angle to bedding, trends WNW, and is characterized by left-lateral slip (Fig. 3 inset). The other set is right-lateral, trends roughly NNE, and also has steep dip angles (Fig. 3 inset). A potential third set of similar structures, trending nearly E–W (Fig. 10), is merely a series of lineaments without any indication for sense and amount of slip. However, these lineaments do appear to be spatially related to the first set of strike-slip faults.

The first set is generally more prominent and appears to determine the location of the second set in large scale (Figs. 10, 14a, b). Detailed observations and maps of these two relatively well-developed strike-slip fault sets suggest that they occur in hierarchical order, as documented by the sketch field map in Fig. 14c, d. The two sets display mutually-abutting relationships with dihedral intersection angles of about 60–70°. In this regard, the pattern of the strike-slip faults resembles "conjugate" shear fractures (Anderson, 1951; Stearns, 1968). However, a closer inspection of the geometry and kinematics of the faults shows a significant difference from those of classical conjugate faults: the bisector of the dihedral intersection angle coincides with the direction of extension, which is the opposite of what is seen in classical conjugate faults. This interesting issue is revisited later in this manuscript.

It is difficult to determine the magnitude of slip across many of these strike-slip faults because of the lack of marker beds and limited accessibility. Nevertheless, at one location near the end of a relatively large, left-lateral fault (see vertical arrow in Figs. 10 and

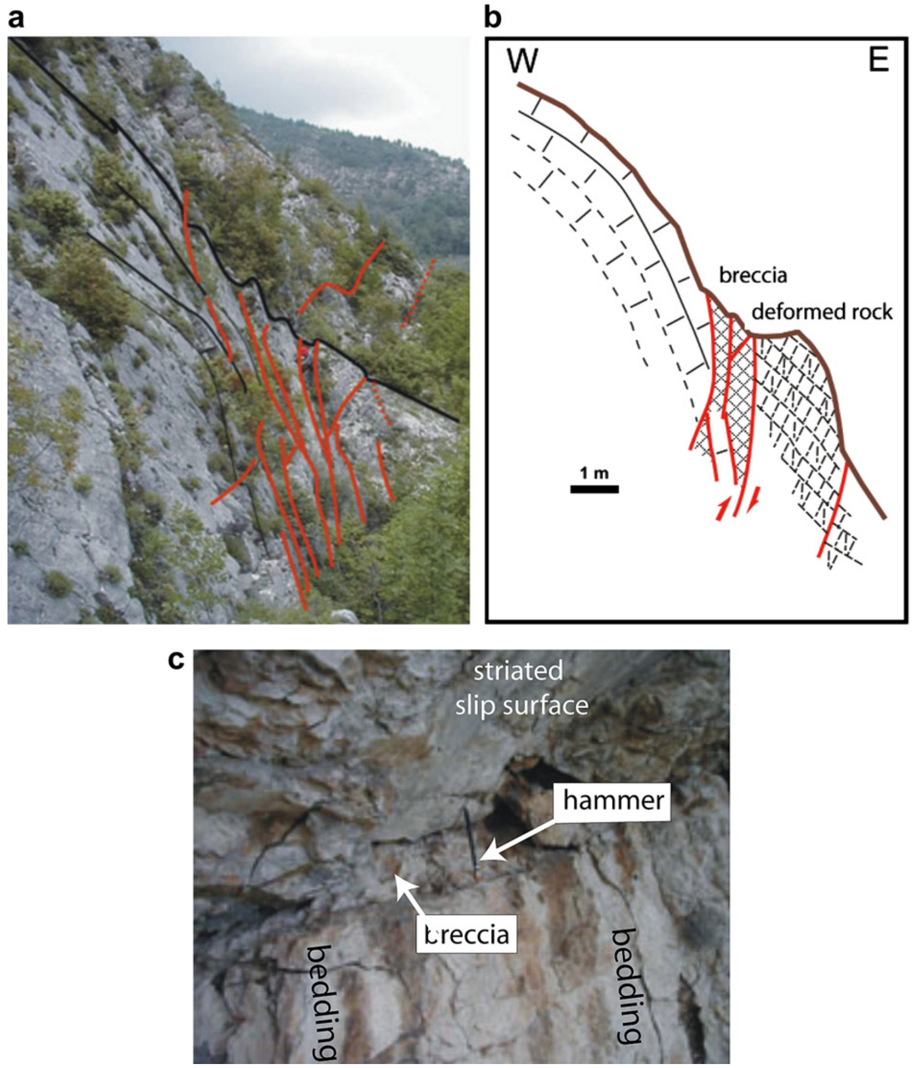


**Fig. 8.** (a) View (due north) along the easternmost kink band, K1, showing the rounded antiformal hinge zone (see Fig. 6c for bedding or mechanical layering attitudes) and associated deformation (in red) within the steeper forelimb, about 200 m south of Vallone del Fossato. All bedding interfaces show evidence of shearing. East verging thrust/reverse faults also occur. (b) A field sketch from the same perspective as in the photo in (a), depicting pockets of breccia and locally amalgamated deformation zones along the steeper limb of the kink band. (c) Photograph (due north) of a fault, as defined by a striated and polished slip surface and a breccia zone of about 12 cm. Several splay/tail PSSs, spatially connected to the fault surface, are identifiable in the field but difficult to see in the picture due to the view angle and indicate top-to-the east motion, which is consistent with that of the kink band itself. High-angle layer orientations in the footwall are also marked.

14b), a fossiliferous bed has been displaced by about 8 m. Considering that this fault appears to die out to the east, it is reasonable to estimate that the maximum slip near the central part of the fault should be significantly greater than 8 m.

Aside from the structures described above, there are some hairline cracks visible only on polished pavements. These appear to be younger than bed-perpendicular PSSs and sheared bed-perpendicular PSSs. Based upon the drastically different failure mode from all other structures described before, it is likely that these cracks may be related to the latest extension or uplift which will not be considered here.

## 5. Conceptual models

The structural elements documented above include pressure solution seams (PSSs, closingmode), cracks (openingmode), and faults with all three kinematical end members as well as kink bands. The openingmode cracks are the youngest structural features and are minor in terms of their size and spatial frequency. Therefore, they accommodate only a small amount of strain. On the other hand, the three mutually-orthogonal PSSs associated with the pre-tilting phase are closely spaced and pervasive and are, therefore, the most crucial structural elements in the sense that they introduced the initial mechanical anisotropy, forming numerous weak planes in the massive platform carbonates (Fig. 15). They initiated and led to the development of all three types of synorogenic faults, as well as the folds in this area. The bed-parallel PSSs created the mechanical layering within the platform carbonates, and are responsible for two of the most intriguing structures described in this paper, the kink bands and the normal faults. The kink bands are more common in thinly layered (by bed-parallel PSSs), laminated rocks, while the normal faults owe their existence to flexural slip along these interfaces. As pointed out earlier, the origin of most layering in platform carbonates is bed-parallel PSSs. The kink bands (Fig. 15) are approximately parallel to the projected trace of the main thrust at the base of the forelimb of the Anticline. In this model, it is envisioned that the basal thrust steepens near the surface. Unfortunately, the original thrust fault boundary was obliterated by younger normal faults, making it difficult for any quantitative comparison.

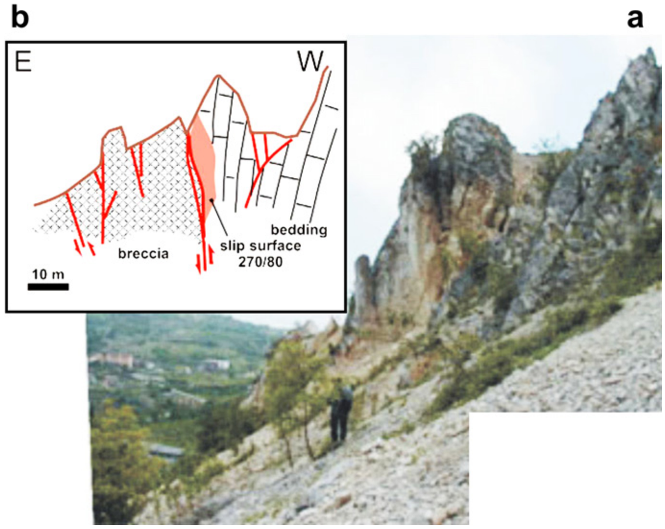


**Fig. 9.** (a) View (due south) showing the easternmost kink band, K1, adjacent to the projected locality of the main thrust fault (under the talus to the left). Location is about 100 m south of that of Fig. 8. (b) A sketch showing many high-angle reverse/thrust faults within a wide zone of breccia (~30 m) along the steeper limb of the kink band, which may extend to the projected location of the main thrust fault at the base of the slope. Man on the talus on the forefront is for scale.

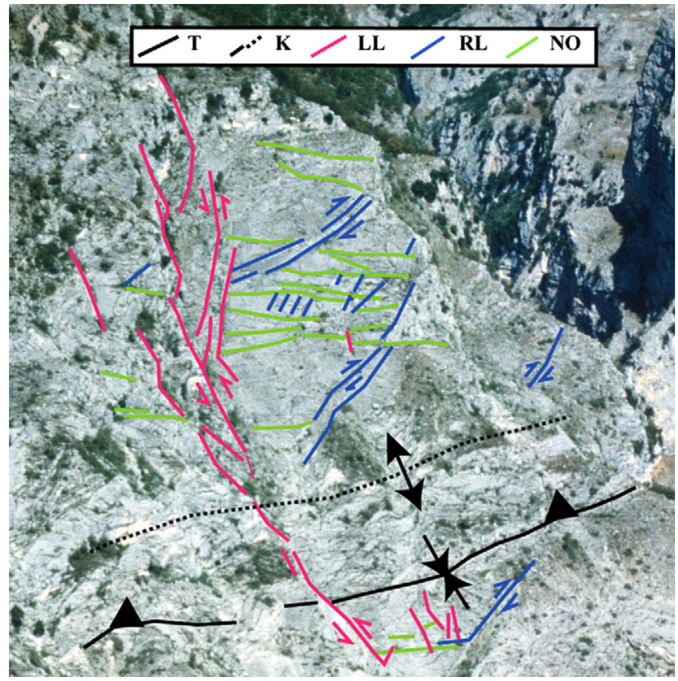


**Fig. 11.** A structural map showing the patterns of, and the intersection relationships among, the major structures (for location see Fig. 4): One kink band (K-2) is overprinted by a thrust fault along the synformal hinge zone, left-lateral (LL) and right-lateral (RL) strike-slip faults, and generally strike-parallel normal faults (NO). One relatively continuous strand of the left-lateral fault appears to be intersecting the kink band at high-angle but no appreciable offset is discernable. Some right-lateral faults abut the left-lateral faults and some other right-lateral faults abut the normal faults which, in turn, abut the left-lateral faults.

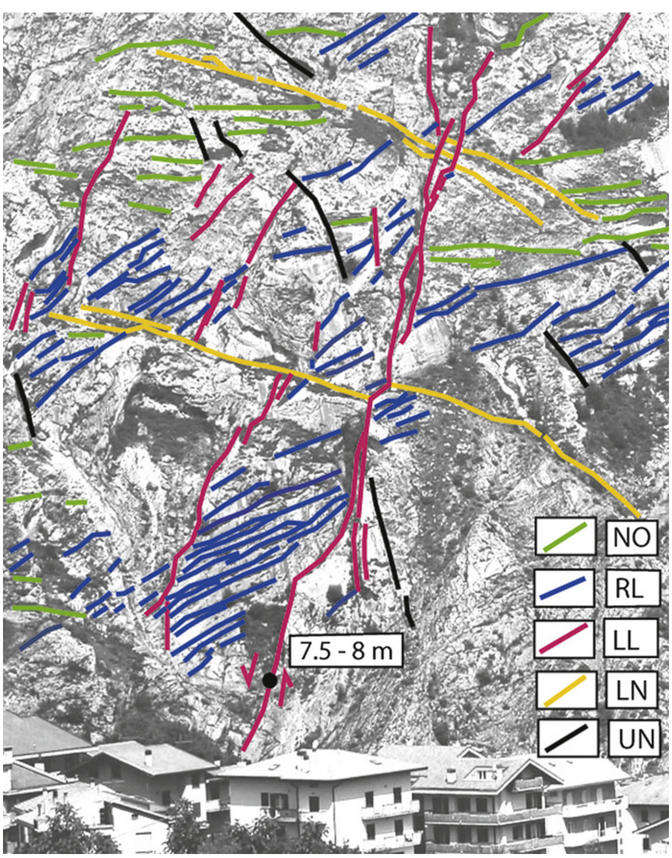


**Fig. 10.** Photograph (due west) and map showing various types of faults exposed on a steep face of the Maiella Mountain north of Vallone Santo Spirito and directly west of the town of Fara San Martino. The fault types include WNW trending left-lateral (LL) and NNE trending right-lateral (RL) strike-slip faults and generally N–S trending normal faults (NO and LN). Another set of faults (UN) with uncertain kinematics is probably related to strike-slip deformation.

Also crucial in terms of the development process of the faults are the two orthogonal, transverse sets of PSSs, oriented perpendicularly to the mechanical layers (Fig. 15). One set runs parallel to the strike, while the other set runs parallel to the dip direction. Shearing across the bed-parallel and bed-perpendicular strike-parallel PSSs is thought to be responsible for the formation of the normal faults, in the context of flexural-slip in the forelimb of the Maiella anticline (Graham et al., 2003).

The primary strike-slip faults in the study area occur hierarchically in two sets, with an apparent conjugate pattern (Fig. 15). The left-lateral strike-slip faults trend WNW, are at fairly high-angle to the projected trace of the main thrust, and appear to have been instigated by shearing of bed-perpendicular dip-parallel PSSs. Because these PSSs are short, the faults had to grow by linkage of neighboring sheared PSSs via splay PSSs, also called tails, wings, or kinks.

The right-lateral strike-slip faults trend NNE and are spatially related to the left-lateral faults (Fig. 15).

Thus, the mechanisms that produced the apparent conjugate pattern are the shearing of the pre-existing, bed-perpendicular, dip-parallel PSSs, formation of splay PSSs, and the subsequent shearing of these splays in a sense opposite (antithetic) to the earlier shear sense (Fig. 16). The resulting patterns of the faults are controlled primarily by the angle between the sheared PSSs and their PSS splays (Fig. 16a). The so-called splay angles found in nature and in theoretical models show great variability. Willemse and Pollard (1998) suggested that the angles for the pressure solutions splays, similar to the angles of opening mode splays, are up to 70.5° for Linear Elastic Fracture Mechanics models, but 45° for Cohesive End Zone models. However, a wide range of angles is possible, depending on the stress components parallel and perpendicular to the shear fractures. Thus, the angles depend on

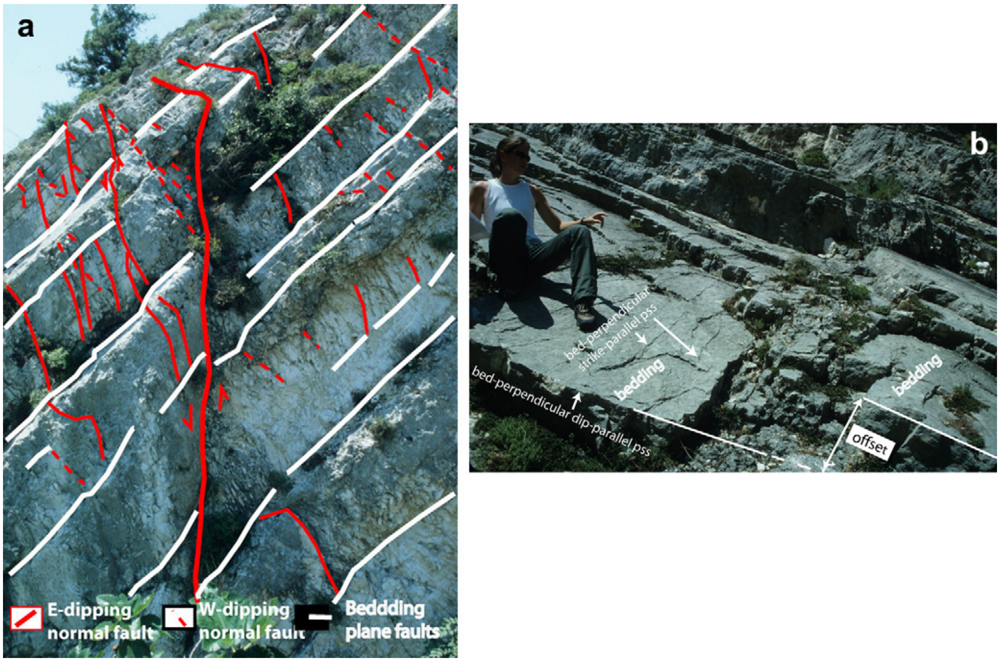


**Fig. 12.** (a) Photograph (due south) showing a normal fault system in approximately WNW section. The faults are more-or-less parallel to the bed strike but dip either to the east (solid red line) or to the west (dashed red lines). The east-dipping faults have low cutoff angles, and often merge into the mechanical layer interfaces (white lines) which are sheared in a sense consistent with that expected from flexural slip. (b) A relatively larger, west-dipping (antithetic) normal fault with about 45 cm offset and sub-parallel bed-perpendicular strike-parallel PSSs and sheared PSSs. Brita Graham Wall for scale.

the rock and fracture rheology, as well as the stress state. Splay angles seen in field observations also show a wide range of values: 40° (Billi et al., 2003), and 40–90° (Rispoli, 1981; Petit and Mattauer, 1995). The fault patterns observed in the study area suggest fault intersection angles in the range of 60–70°, implying splay angles with similar values.

The formation mechanism for the apparent conjugate strike-slip faults proposed here is essentially similar to that proposed by Florez et al. (2005) for the Andean fold-and-thrust belt and by Graham Wall et al. (2006) for the Albanian fold-and-thrust belt, except that in this proposed mechanism, the orientation for the splay PSSs is such that the bisector of the dihedral intersection angle of the strike-slip faults coincides with the direction of extension. A quick comparison between conceptual models based on splay PSSs (Scenario 1) or on splay openingmode fractures (Scenario 2) with arbitrary but equal splay angles, $a = 45^{\circ}$ (Fig. 16a) and their shearing (Fig. 16b), shows why the shortening and extension directions inferred from apparent conjugate faults formed by shearing of splay opening mode fractures or shearing of splay closing mode fractures will be different by an angle of $(90^{\circ} + a)$ measured in a clockwise sense.

## 6. Discussion

It is, perhaps, not surprising that the deformation in the hanging wall immediately adjacent to the leading edge of the Maiella thrust sheet is quite complex, as indicated by the widespread occurrences of various structure types and their reactivations: pressure solution seams, kink bands, thrust faults, normal faults, strike-slip faults, and hairline cracks. The presence of pre- tilting PSSs in three mutually-orthogonal orientations, and their subsequent shearing, k provide the fundamental mechanism for the faulting of the platform carbonates. This result is in agreement with conclusions from our earlier studies of platform carbonates in the central Apennines (Graham et al., 2003; Agosta and Aydin, 2006). The results expand on the previous ones to include a role for these structures in the initiation and deformation of kink bands.

The network of such a pervasive system of PSSs and their shearing represents, perhaps, what Elliott (1976) referred to as a "body of dissipated work by pressure solution slip" within a thrust sheet. It appears that the complexity of both kinematics and geometry of the final products reflects a progressive deformation, as evident in numerous re-activation events derived by shearing.

The kink bands in the steeper limb of the Maiella anticline are monoclinal (Reches and Johnson, 1976) and are somewhat reminiscent of the kink bands of fault-related folds described by Suppe (1985) and his former students (for example, Suppe and Medwedeff, 1990; Suppe and Connors, 2004). Since the relative timing of folding, as well as the geometry and mechanism of propagation of the underlying thrust are not certain, the above analogy is not strictly applicable in this case. Nevertheless, it is interesting to point out that the kink bands in the study area occur primarily in the Cima delle Murelle Formation rather than in the Morrone di Pacentro Formation (Fig. 3). Based on our visual observations, we would argue that the reason the kink bands are more common in the Cima delle Murelle formation is due to the more closely-spaced bed-parallel pressure solution seams in this unit, which are responsible for thin mechanical layers in the platform carbonates. Thin beds, especially with contrasting interbeds (Johnson, 1977), such as clayey residue of the bed-parallel PSSs, are more prone to kink banding. High-angle, reverse/thrust faults thus followed the formation of the kink bands that produced additional local bed-parallel slip, bed-oblique PSSs and, eventually, rock fragmentation. Reverse and thrust faults, at or near the leading edge of the main thrust, are known to occur elsewhere in layered rocks that include weak lithologies (Rodgers and Rizer, 1981; Boyer and Elliot, 1982; Mitra, 1986). In the study area, the only weak materials are the residual seams and breccias at the hanging wall immediately above the basal thrust.

Another intriguing aspect of the deformation along the forelimb of the Maiella anticline is the presence of an array of normal faults (Figs. 10, 11, 12, and 13). The occurrence of normal faults in other contractional fold and thrust belts was previously reported

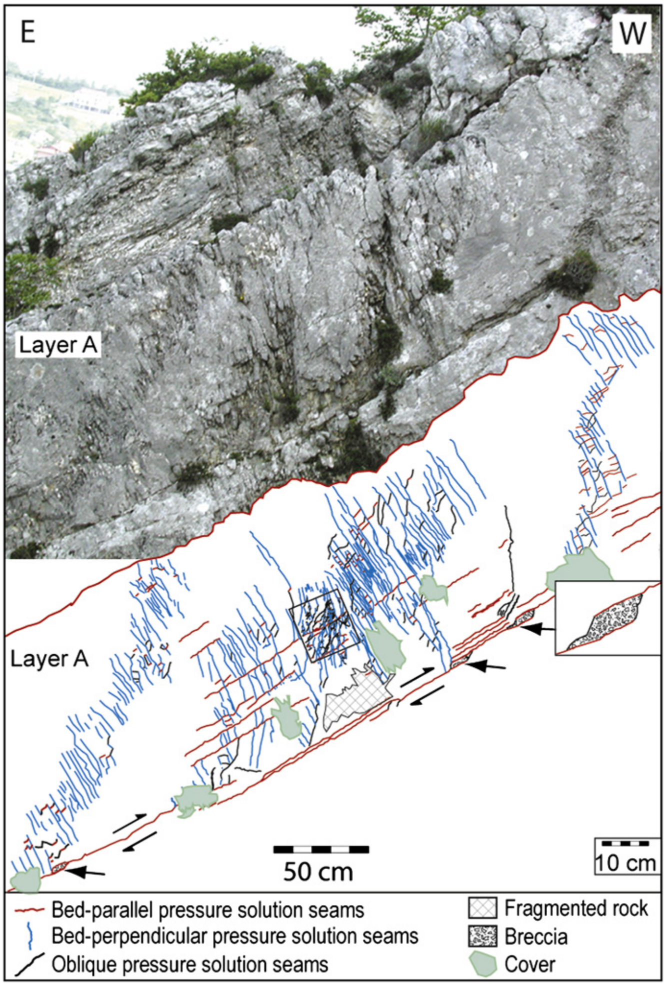


**Fig. 13.** Normal faults formed by shearing of bed-parallel PSSs, and bed-perpendicular strike-parallel PSSs. The oblique PSSs are splays generated by these shears which are top-to-the-right for bed-parallel PSSs and east-side-down for the bed-perpendicular strike-parallel PSSs. The resulting normal faults are often segmented and wavy, because they often incorporate both types of sheared PSSs and their splays. From Graham et al. (2003).

(Kilsdonk, 1989; Yin and Kelty, 1991; Ohlmacher and Aydin, 1995). The association of normal faulting and thrust faulting was observed after recent earthquakes (Magee and Zoback, 1993; Du and Aydin, 1996). Rupture kinematics associated with active thrust faults also showed that normal faults may occur within the hinge region of thrust-related anticlines (Avouac et al., 1992), which is not the case seen within the limb of the Maiella anticline. There are, of course, well-known examples of normal faults within the central Apennines (Ghisetti and Vezzani, 2002; Scisciani et al., 2002; Agosta and Aydin, 2006; Tondi et al., 2006; Marchegiani et al., 2006; Antonellini et al., 2008). Scisciani et al. (2002) put forth a broader possible mechanism for the contraction and extension relationship by including pre-, syn-, and post-contraction normal faulting in their model. Those authors, however, concluded that the normal faults at the trailing and leading edges of the Maiella structure are pre-contractional and pre-folding. That interpretation, however, may be applicable only to the oldest normal faults, presently oriented at low-angle positions within our study area. The pervasive normal faulting in the steeper limb of the Maiella anticline, on the other hand, is clearly related to flexural slip and the resulting stress perturbations and was part of the folding and faulting of the thrust sheet (Graham et al., 2003). The normal faulting associated with recent earthquakes does, however, suggest that many of the trailing edge normal faults in the central Apennine fold and thrust belt are currently active (Michetti et al., 1996; Boschi et al., 1997; Piccardi et al., 1999; Tondi, 2000), regardless of the origin of the initial break.

The occurrence of strike-slip faults within the Maiella area is curious in terms of the variations in fault kinematics and co-existence of strike-slip and thrust faults in fold-and-thrust belts. Aside from tear or transfer faults (Dahlstrom, 1970), strike-slip faulting in fold-and-thrust belt environments has not attracted much attention. Based on the field relationships described earlier, it is likely that strike-slip faulting and both thrust and normal faulting were active simultaneously at the leading edge of the thrust sheet. This possibility is based on observations that one left-lateral fault intersects one of the major kink bands, while many normal faults abut both types of strike-slip faults (Fig. 11). Coeval strike-slip faults, kink bands, and thrust faults in the orientations described in this study are more-or-less consistent with the regional structural trend mapped throughout the Apennines (Bigi et al., 1992; Tavernelli, 1997; Vezzani and Ghisetti, 1998; and Scisciani et al., 2002). Unfortunately, the lack of any data about the local geometry of, and the slip direction across, the main thrust prevents any definitive interpretation.

The temporal association among these structures is also consistent with mechanical models of folded layers: Guiton et al. (2003) proposed that during folding of a layer, stress distribution is such that there is a potential for coeval activity of strike-slip and reverse faults in orientations similar to those reported in this study. However, the simultaneous activity of the strike-slip and thrust faults at the leading edge of the thrust sheet raises an issue in terms of the Andersonian theory of faulting based on the Coulomb slip criterion (Anderson, 1951). Specifically, the issue is that the minimum principal stress is required to be vertical for thrust faulting, whereas the intermediate principal stress is vertical for strike-slip faulting. It follows that, according to the Andersonian theory of faulting, these principal stresses would have to be interchangeable for the co-development of the thrust and strike-slip faults.

Peacock et al. (2008) considered the stress state conducive to the transition from the pre-orogenic, basinal extension to the syn-orogenic, contractional phase, and subsequently to uplift and extension. They proposed that between extension (vertical maximum compressive stress) and contraction (horizontal maximum compressive stress), there is a phase in which the intermediate compressive stress needs to be vertical, tending to promote strike-slip faulting. According to these authors, this transient phase of strike-slip faulting can occur at the beginning of basin inversion, when the magnitude of one horizontal stress exceeds the overburden stress, or it can occur immediately after the main phase of the orogenic contraction, during the uplift and tectonic denudation when the vertical stress exceeds the largest horizontal stresses. Such a variation in the relative magnitudes of the principal stresses can be promoted by changes in either the overburden or in the tectonic forces.

The mechanism based on shearing of a pre-existing discontinuity, pressure solution splaying (Fig. 16a), and subsequent shearing of the splays in a sense antithetic to the first shearing (Fig. 16b), results in an unexpected apparent conjugate fault geometry where the bisector of the acute intersection angle coincides with the direction of the extension (Scenario 1 in Fig. 16b). This is in contrast to those conjugate faults with uncertain micromechanics (Anderson, 1951; Stearns, 1968) and to the apparent conjugate faults formed by openingmode splay fractures (Fig. 16a) and their subsequent shearing in an antithetic sense (Scenario 2 in Fig. 16) (Davatzes and Aydin, 2003; Flodin and Aydin, 2004; Flores et al., 2005; Graham Wall et al., 2006). The main difference between the patterns described by these authors and the one proposed here

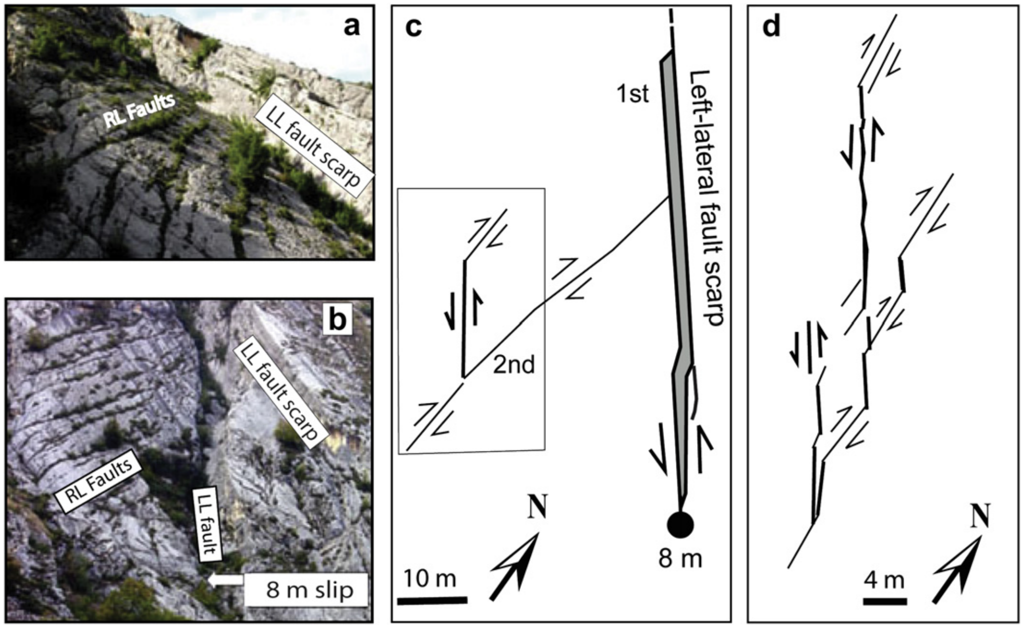


**Fig. 14.** (a,b) Two views of the strike-slip fault system in the platform carbonate succession at the leading edge of the Maiella thrust sheet, immediately above the water tanks of the town of Fara San Martino. Right-lateral fault traces and the main left-lateral fault scarp are labeled. (a) View (due NNE) along the right-lateral set highlighted by strings of vegetation in the photo. (b) View along the main left-lateral fault highlighted by a steep scarp. Also shown are the location and amount (8 m) of left-lateral slip across a fossiliferous marker bed. (c,d) Detailed sketches revealing that the two sets are spatially interrelated in the form of an apparent conjugate pattern, have mutually abutting relationships, and occur in a hierarchical manner over a broad scale. For example, what appears to be a continuous straight fault at one scale has a more intricate pattern at a more detailed scale, which is made up of several segments of both left- and right-lateral faults.

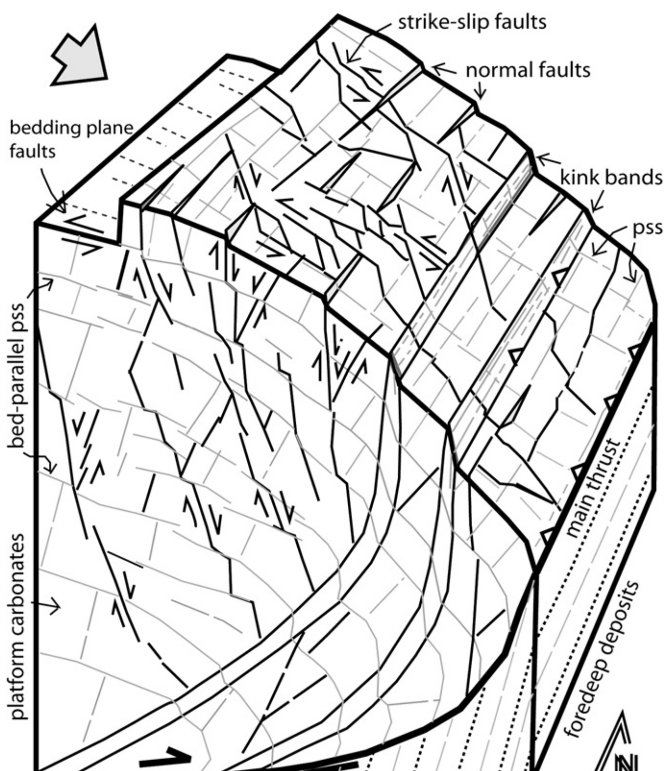


**Fig. 15.** Conceptual model for the structures and their orientation within the steeper limb of the Maiella anticline adjacent to the leading edge of the Maiella thrust sheet. Thin, light gray lines indicate the three mutually-orthogonal sets of PSSs (bed-parallel; bed-perpendicular strike-parallel; and bed-perpendicular deep-parallel) and their sheared versions. Kink folds with associated reverse faults, antithetic and synthetic normal faults, and two sets of left- and right-lateral strike-slip faults with an apparent conjugate geometry display a complex pattern of deformation in the hanging wall of the main thrust at the base of the mountain.

lies in the contrasting orientation of the kinematical axes (E1 and S1 versus E2 and S2): The kinematical axes rotate clockwise by an angle of $(90^{\circ} + \alpha)$, *a* being the splay angle.

The structural complexity described in this paper may also shed light on the nature of progressive strain within the steeper limb of thrust-cored anticlines, such as that proposed in trishear models (Erslev, 1991; Almendinger, 1998; Allmendinger et al., 2004; Johnson and Johnson, 2002). The lack of an obvious rigid basement near the surface in the study area makes the analogy to trishear models rather imperfect. Nevertheless, the study area does contain a highly

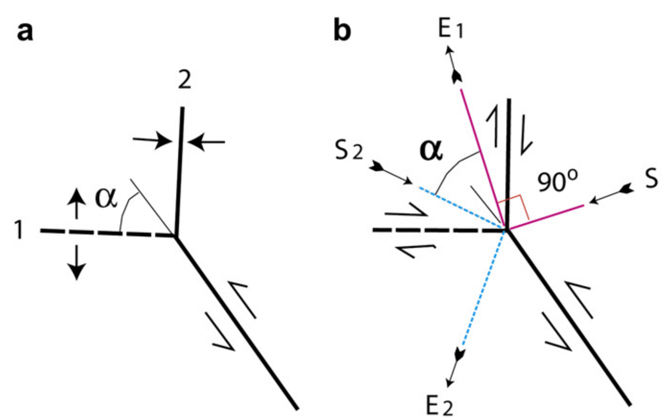


**Fig. 16.** (a,b) Conceptual model comparing formations of apparent conjugate strike-slip faults in response to shearing across a discontinuity in two scenarios depicted in the same diagrams. Scenario 1 represents the formation of splay PSSs at an angle of $-\alpha$ (thin solid line in (a)) and its subsequent shearing (thick solid line in (b)). Scenario 2 is based on the occurrence of openingmode splay fractures with a splay angle of $\alpha$ (thin dashed line in (a)) and its subsequent shearing in a sense antithetic to the main shear (thick dashed line in (b)). The orientations of the shortening (S) and extension (E) axes for the two scenarios are marked width subscripts (1) and (2) in blue and red lines, respectively, in (b), which shift about $(90 + \alpha)$ from each other in clockwise directions.

deformed zone within the steeper limb of an anticline above a basal thrust and, therefore, deserves a comparison with the published results on fracturing and faulting presented by those models. Many trishear models, including those referred to above, deal with the geometry and kinematics of deformation, but not with the distribution, type and orientation of fractures and faults. However, a few recent studies conducted in the western United States did focus specifically on fractures and faults within reverse or thrust fault-related anticlines containing primarily clastic rocks (Henning et al., 2000; Bergbauer and Pollard, 2004; Fischer and Christensen, 2004; Cooper et al., 2006; Bellahsen et al., 2006; Fiore, 2007). In those studies, the dominant deformation mechanism appears to be openingmode fracturing (jointing) and their subsequent shearing. The conceptual model proposed by Bergbauer and Pollard (2004) includes two sets of pre-existing joints formed prior to the folding. In spite of these important differences in the structural and lithological settings, which are responsible for most of the diversity in the fundamental structures and in their geometry and distribution in thrust fault-related folds investigated by the previous workers, some features of their model appear to be quite similar to the structural configurations that we report in this paper. These similarities include the strike- and dip-parallel configurations of the principal planes during the early phase of the deformations (Fischer and Christensen, 2004; Cooper et al., 2006, and the presence of strike-slip (Henning et al., 2000; Fischer and Christensen, 2004), and normal faults at the steeper limb of asymmetric anticlines and bedding plane-slip faults (Fiore, 2007).

## 7. Conclusions

We have described a wide variety of structures within the Cretaceous platform carbonates that are exposed along the eastern limb of the Maiella anticline, immediately above the leading edge of the underlying thrust fault. These structures include pressure solution seams (PSSs), normal and strike-slip faults, kink bands with their related reverse/thrust faults, and some minor hairline cracks. The assemblages of the three mutually-orthogonal pressure solution structures are pre-tilting in origin, and were instrumental in the formation of all three major types of faults as well as of the kink bands.

The majority of the normal faults in the study area is approximately parallel to the strike of the bedding, inclined to the bedding, generally dipping easterly, and is consistent with a flexural slip mechanism. Antithetic normal faults, commonly perpendicular to the bedding, are also present. The inclined faults incorporate bed-parallel and bed-perpendicular strike-parallel PSSs, as well as their splays, and have low cutoff angles. The antithetic faults appear to follow bed-perpendicular strike-parallel PSSs and have high cutoff angles. These results supports the mechanism that these types of normal faults formed after the beginning of tilting and rotation of beds in which they occur. The timing and genesis of the normal faults described here appear to be different from those reported in the previous literature, which includes the Caramanico fault at the trailing edge of the thrust sheet. The earliest normal faults inferred in this study presently have low dip-angle but they intersect bedding at an angle of about 58°. These characteristics suggest that this type of normal faulting predated the tilting associated with the Apennine orogeny as proposed by Marchegiani et al. (2006).

The left-lateral strike-slip faults in the study area are at high-angle to the main thrust, and appear to have formed in response to shearing of bed-perpendicular dip-parallel PSSs and their splays. This shearing was probably induced by either material or stress rotation. Given that the original PSSs are short, the later faults must have formed by the linking of several neighboring sheared PSSs, resulting in fault orientations veering from those of the individual PSSs. The right-lateral strike-slip faults are spatially related to the left-lateral faults in a way similar to that of a shear fracture and its closingmode splays. However, the kinematical axes inferred from the apparent conjugate left- and right-lateral strike-slip faults are opposite to those predicted in the classical conjugate fault geometries with unidentified micromechanics, as well as to the apparent conjugate faults formed by openingmode splaying and their subsequent shearing. The bisector of the dihedral angle coincides with the direction of extension rather than shortening. Locally, however, the shortening direction inferred from the strike-slip faults is SW-NE, which is more-or-less consistent with that of the NNW trend of the northern and central Apennines.

Four hundred and eighty-four reverse/thrust faults are localized within the steeper limbs of a series of monoclinal kink bands and are at least reminiscent, both geometrically and kinematically, of imbricate blind thrust faults above the basal thrust fault at the leading edge of the thrust sheet.

All three fault types have brecciated fault rocks and slip surfaces surrounded by a damage zone composed of PSSs and sheared PSSs. The widest zone of brecciated fault rock and damage zone (>30 m) is associated with the monoclinal kink bands close to the projected trace of the main thrust fault at the base of the forelimb, and provides a remarkable amount of high quality ground water.

The wide variety of structures in the idealized conceptual model in Fig. 15 exemplifies the complexity of the deformation along the forelimb of the Maiella anticline above the main basal thrust fault, and may shed light on the nature of fracturing and faulting associated with similar structural settings such as thrust fault-cored folds and trishear deformation domains elsewhere.

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This work has been supported by the Rock Fracture Project at Stanford University (for A. Aydin, M. Antonellini, and F. Agosta) and by the Faults and Fractures in Carbonates project at the University of Camerino (for E. Tondi and F. Agosta).We are grateful to Thomas. Blenkinsop and one of the two anonymous reviewers for their thoughtful comments.

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