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Modes and timing of fracture network development in poly-deformed carbonate reservoir analogues, Mt. Chianello, southern Italy

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ABSTRACT

Structural and paleostress analyses carried out on a kilometre-sized outcrop of allochthonous shallow-water carbonate units of the southern Apennines allowed us to unravel a superposed deformation pattern associated with plate convergence. The reconstructed tectonic evolution involves: (i) early extensional faulting and fracturing associated with bending of the foreland lithosphere during forebulge and foredeep stages (including the development of both 'tangential' and 'radial' normal fault and tensile fractures; Early-Middle Miocene); (ii) large-scale thrusting and folding (Late Miocene); (iii) transcurrent faulting (including two distinct sub-stages characterized by different remote stress fields; Pliocene-Early Pleistocene), and (iv) extensional faulting (late Quaternary). Stage (i) normal faults – generally occurring as conjugate sets – and related fractures and veins are variably deformed and overprinted by later horizontal shortening. Despite having experienced such a long and complex structural history, the studied carbonates are characterized by a 'background' fracture network – including two joint/vein sets orthogonal to each other and to bedding – that appears to be associated with the early fault sets that formed during the first (foredeep/forebulge-related) deformation stage. Therefore, away from younger (Late Miocene to Quaternary) fault zones, the permeability structure of the studied carbonates appears to be essentially controlled by the early, inherited fracture network. As a similar fracture network is likely to characterize also the buried Apulian Platform carbonates, representing the reservoir units for major oil fields in southern Italy, our results also bear possible implications for a better understanding of fluid flow in the subsurface and related hydrocarbon production.

1. Introduction

The fundamental role of structural inheritance and reactivation processes in rock deformation at all scales is well established. For example, pre-existing faults control styles and modes of basin inversion during shortening of formerly passive continental margins (e.g. Cooper and Williams, 1989; Buchanan and Buchanan, 1995), and precursor brittle features control shear zone development in granitoid rocks (Pennacchioni and Mancktelow, 2007; Mazzoli et al., 2009). Among the wide range of pre-existing structures controlling subsequent tectonic processes, a peculiar type is represented by tensile fractures and normal faults associated with flexure of the foreland lithosphere during foredeep and forebulge development at convergent plate margins. In foredeeps, turbiditic sedimentation occurs on top of a previously – or synchronously – stretched substratum. 'Tangential' (i.e. parallel to basin strike) normal faults and tensile fractures develop in response to lithospheric bending (Tankard, 1986; Sinclair, 1997), whereas 'radial' (i.e. normal to basin strike) normal faults and tensile fractures form due to the arcuate shape of the foredeep, inducing arc-parallel stretching (e.g. Doglioni, 1995). 'Tangential' normal faults in foredeep and forebulge settings show both foreland-ward and hinterland-ward dips (e.g. Maillard et al., 1992; Scisciani et al., 2001; Krzywiec, 2001; Tavarnelli and Peacock, 2002; Bolis et al., 2003; Tinterri and Muzzi Magalhaes, 2011) forming half-grabens, grabens and horsts heavily controlling the distribution and accumulation of foredeep deposits (e.g. Casnedi, 1988; Tinterri and Muzzi Magalhaes, 2011). Foredeep extensional structures, particularly 'tangential' faults and associated basin depocentres and structural highs, are well known to play a key role in subsequent tectonic processes associated with thrust propagation into the foredeep (e.g. Butler, 1989; Scisciani et al., 2001; Mazzoli et al., 2002; Tavarnelli and Peacock, 2002). Although the control

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exerted by such inherited foredeep and forebulge features in fold and thrust belt architecture is well established, the role of associated fracture networks in controlling the structural permeability of potential reservoir rocks is far less known. We anticipate that unravelling the superposed deformation pattern characterizing a kilometre-sized carbonate outcrop in the southern Apennines allowed us to document not only the role of pre-thrusting extensional structures developed during foredeep/forebulge stages, but also the occurrence of a related fracture network. This appears to control 'background' fracture intensity outside fault damage zones associated with later thrusts, strike-slip and normal faults. Therefore, away from such younger fault zones, fluid flow within the rock volume would be essentially controlled by the fracture network that formed, in association with both 'tangential' and 'radial' normal faults, during foredeep/forebulge stages. As the studied carbonate succession of Mt. Chianello represents an outcropping analogue to major oil reservoirs in southern Italy (e.g. Shiner et al., 2004), our observations provide new insights into the prediction of preferential fluid pathways in such rock units, also bearing possible implications for implemented reservoir management.

2. Geological setting

The southern Apennines are a NE-directed fold and thrust belt, with the Apulian promontory representing its orogenic foreland (e.g. Cello e Mazzoli, 1998; Butler et al., 2004; Ascione et al., 2012 and references therein). According to recent studies (e.g. Mazzoli et al., 2008; and references therein), the Apennine chain consists of two main parts (Fig. 1): (i) the Apennine accretionary wedge and (ii) the buried Apulian Platform Inversion Belt (APIB). The former is made of the HP-LT metamorphic Frido unit (Spadea, 1982; Knott, 1994; Bonardi et al., 1988), characterized by oceanic and thinned continental crust slices covered by a basin succession, and some sedimentary units, detached from their original substrata, probably deposited onto a transitional crust (Nord-Calabrese, Parasicilide and Sicilide units; Ogniben, 1969; Bonardi et al., 1988; Mattioni et al., 2006; Vitale et al., 2010, 2011; Ciarcia et al., 2009, 2012), and deformed sedimentary successions of continental margin origin. These include thick Triassic to Miocene shallow-water and slope carbonates (Apennine Platform) as well as pelagic (Lagonegro Basin) successions. As a result of NE-ward thrusting (e.g. Cello and Mazzoli, 1998), each original paleogeographic domain experienced a tectonic evolution involving fast subsidence in a foreland basin subsequently filled by turbiditic calciclastic and siliciclastic deposits. The latter, in turn, were affected by thrusting and folding, followed by the deposition of coarse clastic deposits in wedge-top basins (Bonardi et al., 2009) whose age reach the early Messinian. Subsequent buttressing of the accretionary wedge against the western margin of the Apulian Platform, wedge uplift and its emplacement on top of the foreland carbonates are marked by

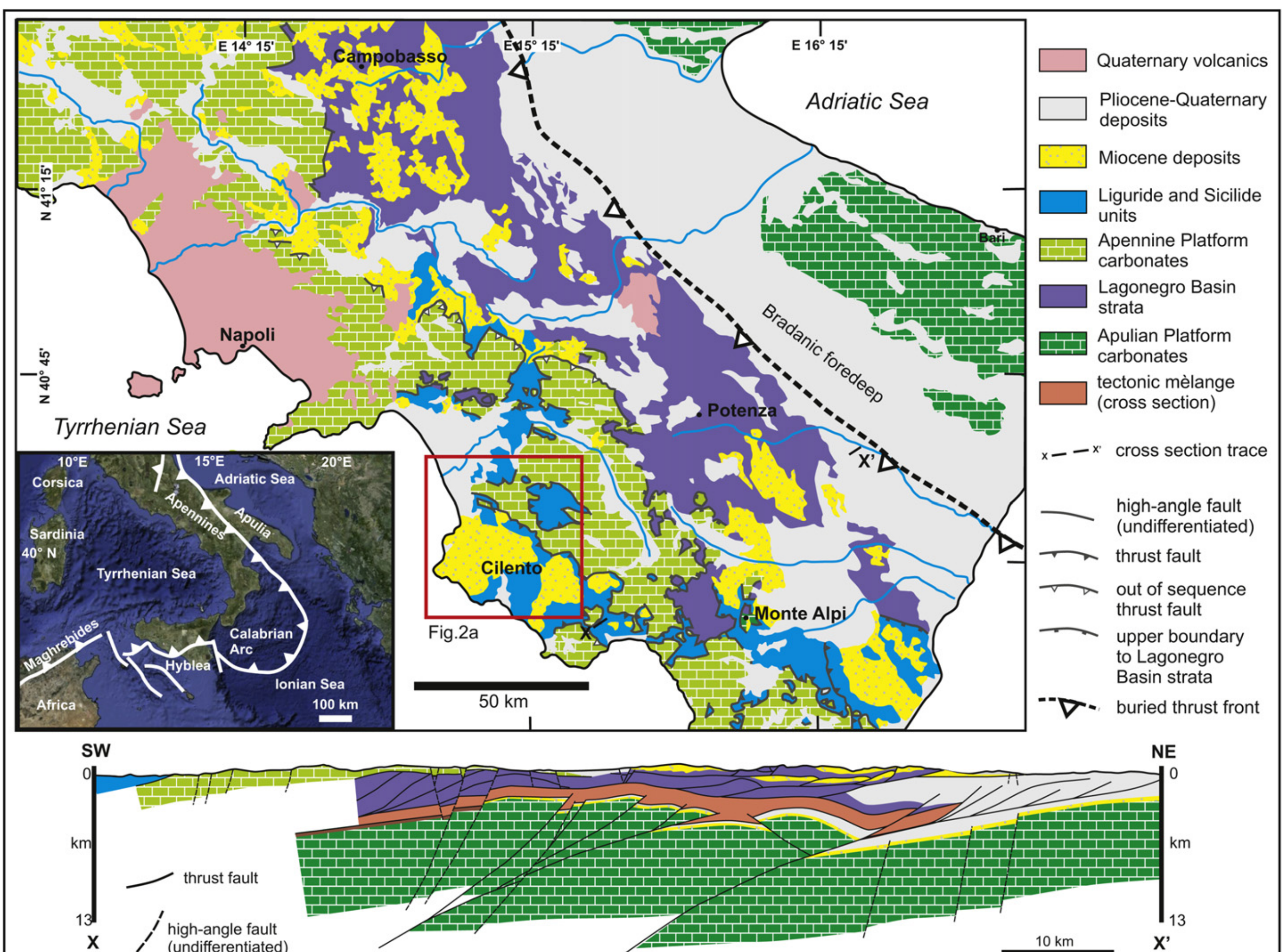


Fig. 1. Geological sketch map of the southern Apennines, showing regional cross-section X–X′.

vigorous exhumation recorded by apatite fission track data (cooling ages clustering around 5.5 Ma; Corrado et al., 2002, 2005; Mazzoli et al., 2008). This is consistent with a generalized Messinian emersion of the thrust belt (Ascione and Cinque, 1999).

Surface geology coupled with abundant subsurface data from the oil industry point out that the accretionary wedge forms an allochthon that has been carried onto a footwall of foreland strata continuous with those exposed in the Apulian promontory to the NE (e.g. Mostardini and Merlini, 1986; Shiner et al., 2004). The detachment between the allochthon and the buried Apulian Platform carbonates is marked by a mélange zone penetrated by numerous oil wells and described in detail in Mazzoli et al. (2001). Beneath the mélange zone, under a variable thickness of Messinian evaporites and, more to the east, progressively younger Pliocene shales and arenites (Fig. 1), are Mesozoic-Tertiary shallow-water carbonates of the Apulian Platform. This tectonically buried portion of the Apulian Platform was involved in the final shortening phases, giving rise to the subsurface APIB. This has been penetrated by numerous oil wells. In fact, the buried APIB consists of reverse-fault-related, open, long-wavelength folds that form the hydrocarbon traps for the significant oil discoveries in southern Italy (Shiner et al., 2004). Recent geophysical studies have provided evidence that deep-seated reverse faulting within the buried APIB is characterized by involvement of the underlying basement (Improta and Corciulo, 2006; Steckler et al., 2008). Consistently, cross-section balancing and restoration of the buried APIB, carried out by Shiner et al. (2004) based on high-quality seismic data and well logs, favour an inversion tectonics model involving reactivation of pre-existing (Permo-Triassic) basement normal faults. The related deformation is characterized by limited horizontal displacements (Mazzoli et al., 2000; Menardi Noguera and Rea, 2000; Turrini and Rennison, 2004), all of them based on subsurface data sets provided by the oil industry. Therefore, a switch from thin-skinned thrusting to thick-skinned inversion appears to have occurred in the southern Apennines as the Apulian Platform carbonates, and the underlying thick continental lithosphere, were deformed (Mazzoli et al., 2000; Butler et al., 2004). As a corollary, the different tectonic evolution and burial conditions experienced by the Apennine Platform with respect to the Apulian Platform carbonates need to be taken into account in a cautious application of the results of analogue studies based on the former in reservoir management applied to the latter (Guerriero et al., 2010, 2011).

The rocks analysed in this study, forming part of the Apennine Platform domain, crop out at Mt. Chianello (Fig. 2a). This forms, together with Mt. Soprano and Mt. Vesole, a carbonate ridge separating the Cilento area, located to the SW, from the Torrente Pietra Valley to the NE. The Mt. Soprano-Mt. Chianello ridge comprises a more than 1300 m thick succession of Lower Cretaceous to Lower Miocene (Aquitanian) platform carbonates, stratigraphically overlain by upper Burdigalian siliciclastic foredeep deposits. These, in turn, are tectonically overlain by the basin deposits of the Parasicilide Unit (Fig. 2a–b). From a structural point of view, the Mt. Soprano-Mt. Chianello ridge is formed by the NE dipping forelimb of a regional anticline whose backlimb is downfaulted to the SW. This structure is well imaged by the CROP 04 seismic profile (Fig. 2c) tied with well logs. The regional fold may be interpreted as a ramp anticline sitting in the hanging wall of a main thrust fault whose footwall includes the Alburni Mts. to the NE; (Berardi et al., 1996; Castellano and Schiattarella, 1998; Cippitelli, 2007, Fig. 2d).

3. The stratigraphic succession

The stratigraphic succession of Mt. Chianello, as described by Bravi et al. (2004), has been integrated by our own sedimentological observations (Fig. 3). The lithostratigraphic terminology introduced in a recent geological map (A.P.A.T., 2005), although not used in this study in favour of that now in use for the entire Apennine Platform (Di Stefano et al., 2011), is shown in Fig. 3.

The lower part of the Mt. Chianello succession (Fig. 3) is characterized by more than 600 m of well-bedded, *Requienidae*- and *Gastropoda*-bearing limestones, dolomitized limestones and dolomites of Neocomian-Cenomanian age ('Calcari a Requienie e Gasteropodi' Fm). Marly levels and chert beds, replacive of former evaporites, occur in the lowermost part, whereas dolomite beds prevail upward. In the upper part there are some 80 m of well-bedded, organic rich dolomites (*platy dolomites*; Bravi et al., 2004) followed by an upper Cenomanian marker horizon consisting of selectively dolomitized and bioturbated beds, passing laterally into calcareous shell mounds. The overlying 'Calcari a Radiolitidi' Fm is more than 600 m thick, and starts with discontinuous bodies of dolomitized calcareous breccias and bedded limestones with chert bands. Most of the succession is made up of *Radiolitidae*-bearing, well-bedded limestones. The succession continues, above a paraconformity surface, with the Paleocene-Middle Eocene strata of the Trentinara Fm (Selli, 1962), consisting of a 100 m thick alternance of calcarenites with *Spirolina* sp., calcilutites and green marls. Above a further paraconformity, marked by residual red clay lenses, the Aquitanian-Burdigalian biolithoclastic glauconitic calcarenites of the Roccadaspide Fm (Selli, 1957; Carannante et al., 1988) cap the whole carbonate succession. The overlying upper Burdigalian foredeep deposits of the Bifurto Fm (Selli, 1957) consist of quartzarenites and intercalated brownish marls.

4. Structural analysis

The analysed carbonate succession is characterized by a deformation pattern resulting from the superposition of several sets of structures including fractures, faults and folds. Based on crosscutting and overprinting relationships that will be described in detail below, the observed structures (Figs. 4 and 5) have been divided into four main groups: (i) early normal faults and associated fracture and vein sets; (ii) folds and thrusts; (iii) strike-slip faults and associated structures; and (iv) late normal faults.

The whole succession is characterized by the occurrence of well-developed fracture (and vein) sets orthogonal to bedding (Fig. 4a). As the succession is characterized by alternating limestones and dolomites showing variable textures and thicknesses, and affected by various major structures – faults and folds – the fracture pattern is greatly heterogeneous (e.g. Guerriero et al., 2011). However, a large number of observations made away from major fault zones and from areas of relatively intense local folding (Fig. 2b and Fig. 5) allowed us to recognize a 'background' fracture network that is well developed throughout the whole study area. The characterization of such 'background' fracture network has been carried out in well-exposed carbonates along two roads (from Monteforte Cilento to Roccadaspide, for the Cretaceous succession, and from Trentinara to Monteforte Cilento for the Paleogene Trentinara Fm) and in the Roccadaspide village area for the Roccadaspide Fm (Fig. 2a). Two main types of fractures have been recognized: (i) stratabound fractures (*sensu* Odling et al., 1999) that affect single mechanical layers, their tips lying at layer boundaries; and (ii) non-stratabound fractures (*sensu* Odling et al., 1999) that are not limited to a single bed, either because their length is less than bed thickness, or because they crosscut several beds. Both stratabound and non-stratabound 'background' fractures occur into two sets that tend to be perpendicular to each other at any single location. Similar fracture systems, defining roughly NNE-SSW (set 1) and WNW-ESE (set 2) striking sets, have been detected in Cretaceous carbonates

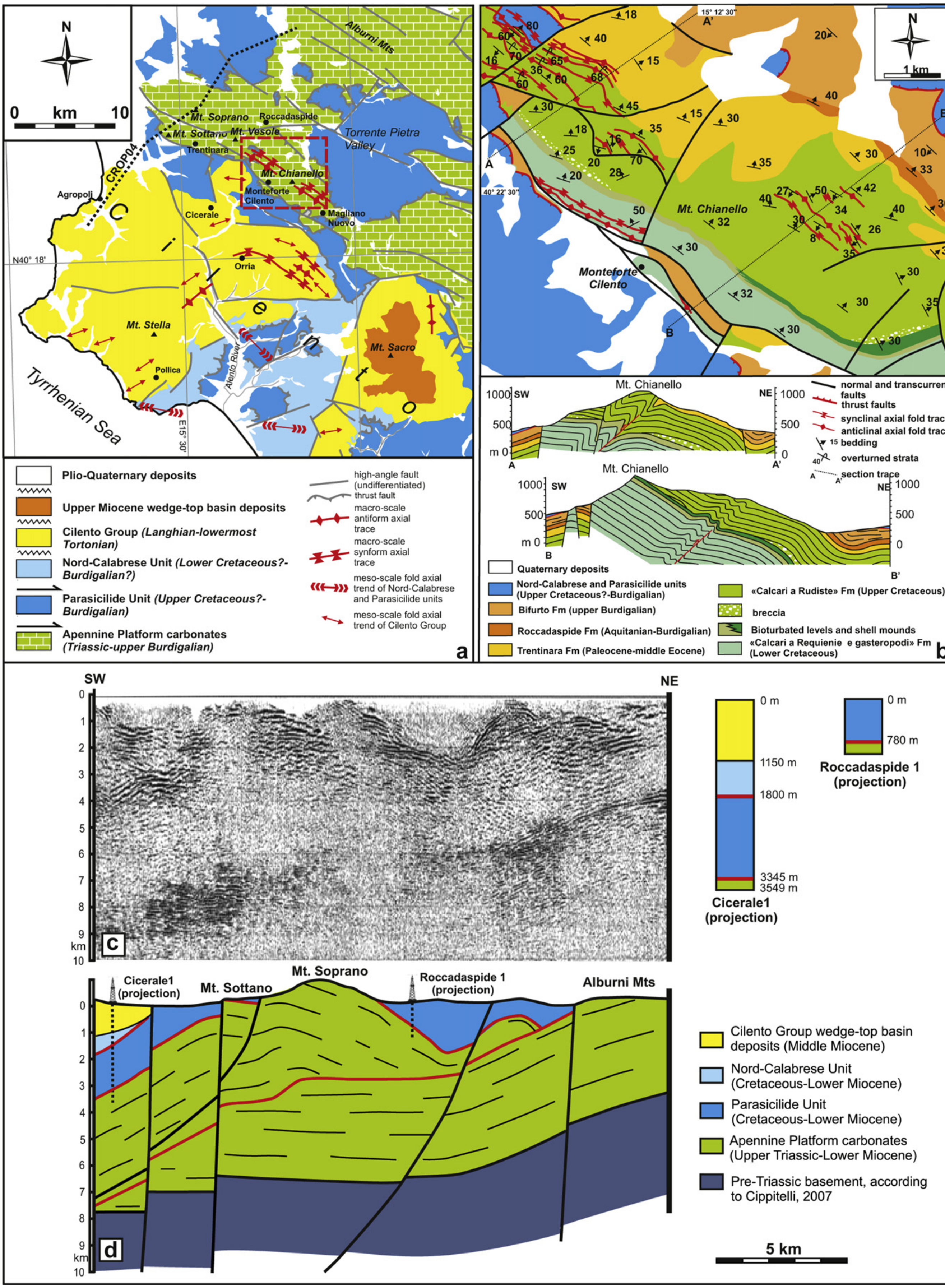


Fig. 2. Geological framework. (a) Geological sketch map of the Cilento and Torrente Pietra Valley areas, showing trace of seismic profile (CROP04). (b) Geological sketch map of field study area (after A.P.A.T., 2005, modified) and cross-sections through the Mt. Chianello ridge. (c) Part of the CROP 04, depth-converted seismic reflection profile (from Patacca and Scandone, 2007). (d) Geological interpretation of the depth-converted seismic profile, tied with stratigraphic logs of the Cicerale1 and Roccadaspide1 wells (Società Geologica Italiana, 2010).

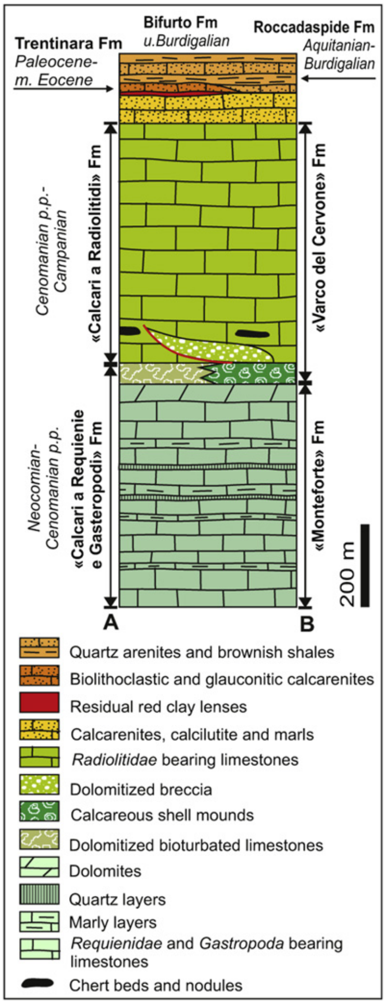


Fig. 3. Schematic lithostratigraphic log of the analysed succession, showing terminology by Di Stefano et al. (2011) to the left (A) and by A.P.A.T., (2005) to the right (B) of the column.

(Fig. 6a), in Paleogene strata (Fig. 6b) and in Lower Miocene calcarenites (Fig. 6c). The whole sedimentary succession forms a dominantly NNE dipping rock panel within the study area (Fig. 2b). Restoring bedding to horizontal, the analysed fracture sets become vertical, the data clusters defining two almost orthogonal mean planes striking N113°E and N17°E (Fig. 6e and f). The two fracture sets are roughly parallel to the bisector planes of the acute dihedral angle of two conjugate fault sets occurring in the study area (Fig. 4b, c and f). The bisector plane of the acute dihedral angle between conjugate fault pairs is always orthogonal to bedding, even when the latter attains high angles of dip (Fig. 4c and f). Conjugate faults show dominant extensional kinematics in horizontally restored bedding, defining horsts and grabens mainly characterized by a NW-SE maximum extension direction (set 1) and subordinately by roughly NE-SW extension (set 2) (Fig. 6i). Generally these faults show minor displacements and are characterized by small damage zones (not exceeding 1 m in thickness). In order to analyse the geometric relationship between background fractures and normal fault zones, the attitude of fractures located within the damage zone has been recorded for two of these faults (Fig. 4c and f). Restoring bedding to horizontal, the rotated fracture data define two main sets roughly orthogonal to each other (the fracture set striking parallel to the investigated NE trending faults being clearly more developed). The two detected damage zone-related fracture sets are consistent, in terms of orientation, with those occurring in the host rock (i.e. the background fracture sets). The transition from country rock to fault damage zones is characterized by an increasing number of fractures, which however maintain a constant orientation.

Field relationships indicate that these extensional structures, normal faults and related fractures, represent early tectonic features that have been deformed by later shortening. Clear evidence is provided by the indentation of footwall and hanging-wall blocks (Fig. 4c) accompanied by pressure solution along fault planes (Fig. 4d) and along early vein and fracture walls (Fig. 4e). Most early veins, also away from normal faults, show evidence of pressure solution along their edges and of internal deformation in the form of mechanical twinning of their sparry calcite filling (e.g. Fig. 4g). These veins are orthogonally crosscut by younger veins, parallel to bedding, best interpreted as resulting from bedding-parallel shortening. The occurrence of dissolution teeth oblique with respect to vein walls on which they developed (slickolites; Ramsay and Huber, 1983) suggests that horizontal shortening was not always perfectly orthogonal to one of the pre-existing fracture sets. Early normal faults are also locally deformed/displaced by bedding-parallel shear planes. Movement along such bedding-parallel slip surfaces is consistent with flexural slip, which appears to be the dominant mechanism accommodating folding within the studied carbonates, where tens of centimetres- to tens of metres-wavelength, chevron to rounded, mostly overturned folds occur (Fig. 5a and b). Mesoscale fold hinges are mostly sub-horizontal to gently plunging and show a scattered pattern (Fig. 6m and n); however, a dominant NW-SE trend occurs. Axial planes are mostly sub-horizontal or gently dipping (Fig. 6o and p). Fold hinge zones are often characterized by the occurrence of high angle, dominantly reverse and subordinately strike-slip and normal faults (Fig. 6q).

NE-verging, macroscale fold amplification appears to have been localized and associated with dominantly reverse faulting (Fig. 2b and Fig. 6k). Statistical analysis of poles to bedding indicates sub-cylindrical folding around a theoretical π-axis plunging 14° towards 296°N (Fig. 6d).

Shortening of the studied succession is manifested also by the occurrence of thrust faults including: (i) pre-buckle thrusts with minor displacements, affecting thin calcareous strata embedded in pelitic layers (Fig. 5d); (ii) minor thrust faults (Fig. 5f) often associated with accommodation folds at their terminations (Fig. 5a); and (iii) thrusts characterized by relatively large displacements (e.g. producing the tectonic superposition of Cretaceous limestones on top of Paleogene marls; Fig. 5b and c). Thrust faults often show a ramp-flat geometry (Fig. 5f), especially in the Trentinara Fm where flats occur in marly layers, and frequently display associated S-C structures (Fig. 5e). Thrust faults show scattered slip vectors with a prevalence of ENE-WSW trends (Fig. 6k).

All previously described structures are deformed by several fault sets showing prevailing strike-slip kinematics. These structures have been grouped into two main families, based on relative chronology: an earlier Group 1, including dextral, N-S striking, and sinistral, NE-SW and NW-SE trending faults (Fig. 6r); and a later Group 2, formed by dextral, E-W oriented, and sinistral, NW-SE striking faults (Fig. 6t). Locally, in areas of vertical bedding (pre-existing steep fold limbs), vertical folds are associated with strike-slip faults (Fig. 5g).

The youngest structures are represented by dominantly NW-SE and subordinately NE-SW striking normal faults (and oblique-slip faults with prevailing extensional components; Fig. 6v). Locally, these structures appear to reactivate pre-existing brittle features such as the NW-SE tending transcurrent faults.

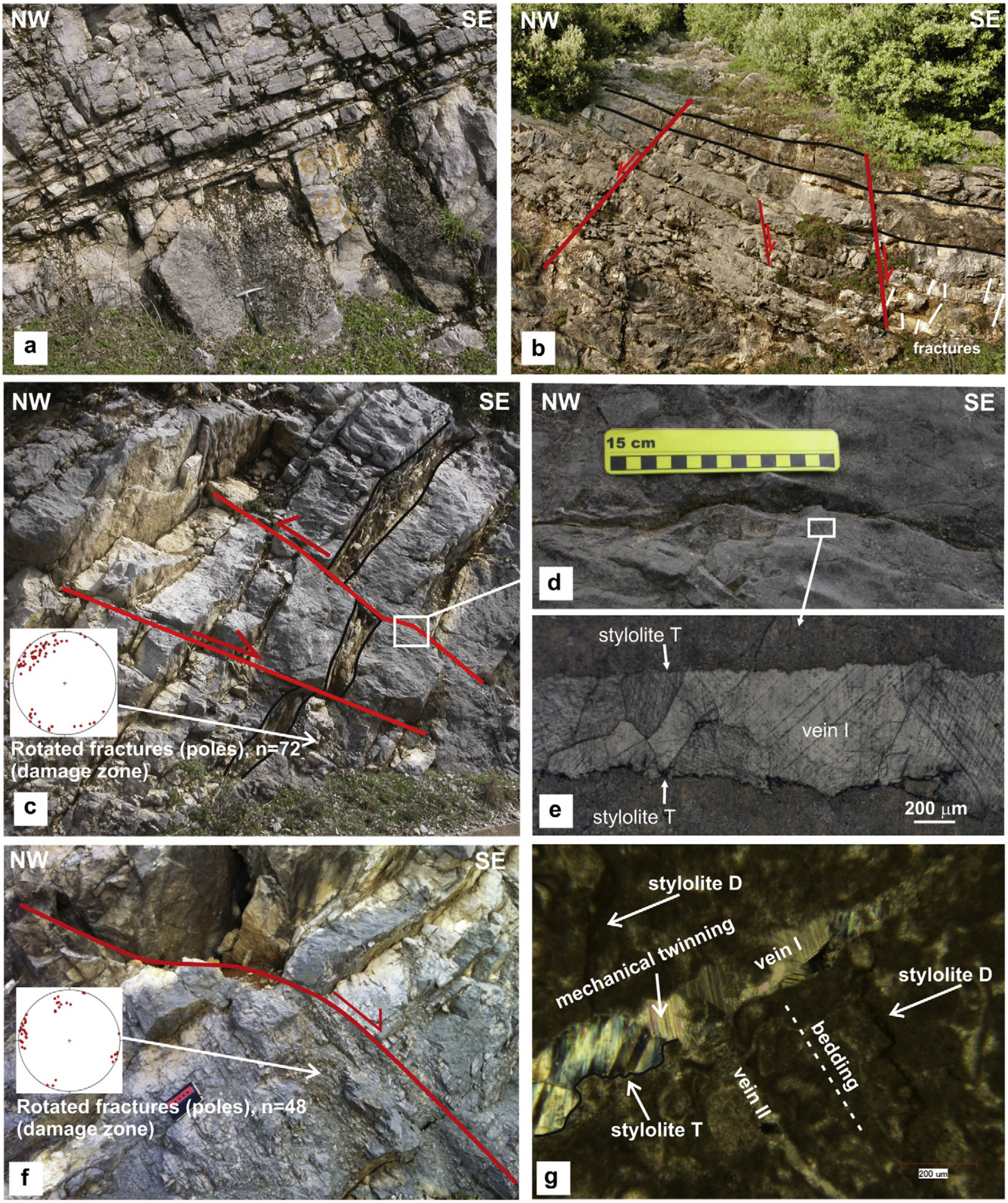


Fig. 4. Examples of early (i.e. pre-thrusting), locally reworked structures. (a) Early fractures (set 1) orthogonal to bedding ("Calcari a Radiolitidi" Fm). (b) Tilted minor horst ("Calcari a Requienie e Gasteropodi" Fm). (c) Tilted minor graben ("Calcari a Requienie e Gasteropodi" Fm). (d) Detail of tilted normal fault from previous diagram; note fault deformation and overprinting by pressure solution. (e) Detail (acetate peel) of the area close to the tilted normal fault from previous diagram; note vein walls affected by pressure solution. (f) Tilted normal faults showing a few centimetres displacement and associated *c.* 1 m-thick damage zone. (g) Microphotograph of a thin section showing two orthogonal sets of veins as well as bedding-parallel, diagenetic (D) and tectonic (T) stylolites. Note early vein orthogonal to bedding (vein I) is reworked by pressure solution (stylolite T) and crosscut by younger bedding-parallel vein (vein II) compatible with layer-parallel shortening.

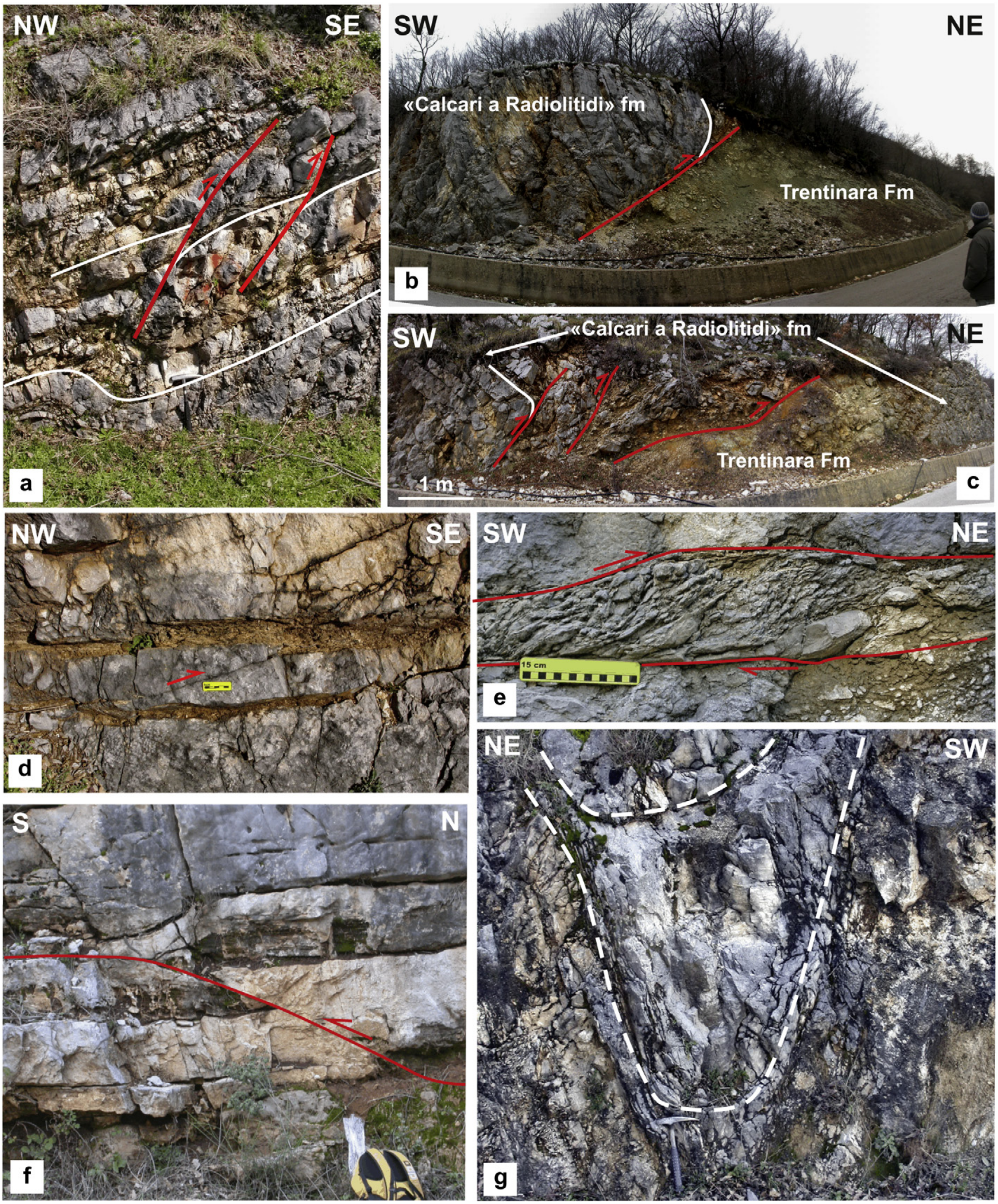
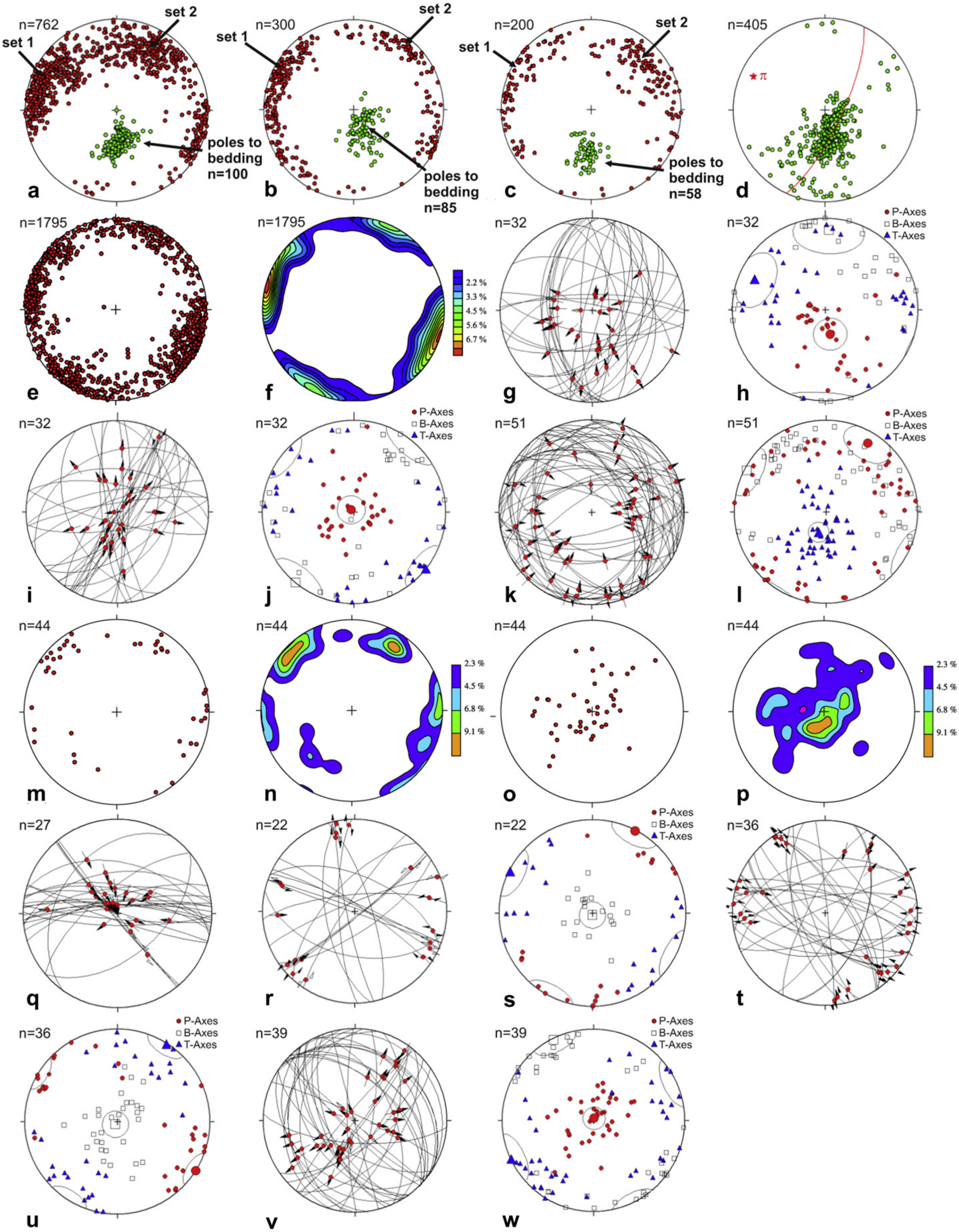


Fig. 5. Field examples of thrusting- and wrenching-related structures. (a) Minor folds and thrusts in the "Calcari a Requienie e Gasteropodi" Fm. (b), (c) Examples of thrust faults carrying the Cretaceous "Calcari a Radiolitidi" Fm on top of Paleogene marls of the Trentinara Fm. (d) Pre-buckle thrust in the "Calcari a Requienie e Gasteropodi" Fm. (e) S-C structures along a thrust flat segment in marls of the Trentinara Fm. (f) Ramp-flat thrust fault ("Calcari a Radiolitidi" Fm). (g) Vertical fold associated with a strike-slip fault ("Calcari a Requienie e Gasteropodi" Fm).


n=762
set 1
set 2
poles to bedding n=100
a
n=300
set 1
set 2
poles to bedding n=85
b
n=200
set 1
set 2
poles to bedding n=58
c
n=405
π
d
n=1795
e
n=1795
2.2 %
3.3 %
4.5 %
5.6 %
6.7 %
f
n=32
g
n=32
P-Axes
B-Axes
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h
n=32
i
n=32
P-Axes
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j
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k
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T-Axes
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n=36
t
n=36
P-Axes
B-Axes
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u
n=39
v
n=39
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5. Paleostress analysis

In order to obtain information on the paleostress field controlling the development of the various faults sets, the P-B-T technique (Angelier and Mechler, 1977) has been applied to the analysis of fault slip data. Paleostress analysis provides the orientations of the three principal stress axes $\sigma1$, $\sigma2$, and $\sigma3$ (with $\sigma1 \geq \sigma2 \geq \sigma3$) and the stress ratio $R = (\sigma2 - \sigma3)/(\sigma1 - \sigma3)$ (Angelier, 1979). The P-B-T method furnishes, for each single fault (plane attitude, slip orientation and kinematics), the three principal axes of strain: *P* (direction of maximum shortening), *T* (direction of maximum stretching) and B (intermediate axis, orthogonal to the P-T plane). In order to calculate the orientation of each principal strain axis, this method uses a common defined fracture angle θ for all fault-slip data. The software TectonicsFP 1.6.5 (by Reiter and Acs, 1996–2003), used in this analysis, allows one to further calculate the best-fit angle (θ) minimizing the sum of all misfit angles between the measured slip direction and the calculated maximum shear stress.

Inversion of early normal fault slip data by means of the P-B-T method applied to the dataset gathered in the field does not furnish a well-defined solution (Fig. 6h). However, once the data are rotated (by restoring bedding to horizontal at each measurement site), stress inversion provides an extensional stress field characterized by a sub-vertical *P* axis and a SE-NW oriented *T* axis (Fig. 6j). The results obtained by applying the P-B-T method to mesoscale thrust faults are characterized a large scatter of the *P* axis (Fig. 6l), this being consistent with the occurrence of a wide range of thrust fault attitudes and slip vectors.

For strike-slip faults, the P-B-T method indicates a transcurrent stress field characterized by a dominant NNE-SSW oriented P axis for Group 1 structures (Fig. 6s), and a transcurrent stress field with an ESE-WNW trending P axis for Group 2 faults (Fig. 6u).

Finally, for late normal faults, stress inversion provides an extensional stress field characterized by a dominant NE-SW subhorizontal extension (Fig. 6w).

6. Discussion

Tensile joints and veins form a 'background' fracture network homogeneously distributed within rock volumes. Their study is of notable importance as (i) the integrated analysis of 'background' fracture networks and larger scale fault systems provides useful information on the tectonic context in which the observed structures developed, and (ii) because fracture networks at several scales form a hierarchical system of permeable structures controlling the hydraulic properties of the rock mass (Guerriero et al., 2011). Tensile fractures are ubiquitous in rocks and usually show random spatial distribution, whereas shear fractures (including faults) appear notably clustered over a range of scales (e.g. Gillespie et al., 1993). For a stress field characterized by horizontal maximum extension, tensile and shear fractures/faults provide two alternative strain-accommodating mechanisms, the former being significantly more abundant than the latter. Caputo (2010) discussed, by means of a numerical simulation, the main factors – depth, pore-fluid pressure, tensile strength and its statistical spatial distribution – controlling the joint/shear fracture ratio. This ranges over several orders of magnitude above unity. Typically, tensile fractures occur into two main coeval sets being roughly orthogonal – or at a high angle – to each to other. As suggested by Caputo (1995) and supported by means of numerical simulations by Bai et al. (2002), the occurrence of orthogonal joint sets do not imply by itself a rotation of the remote stress field, as it may be produced by local swaps between the intermediate (σ_2) and the minimum (σ_3) stress axes in the vicinity of growing fractures (here the term 'local' is referred to the joint spacing scale, which ranges from the centimetre to the crystal scale; e.g. Guerriero et al., 2011). It is well established that, in an extensional stress regime, failure orthogonal to the σ_3 axis occurs when the tensile rock strength is locally reached, and that a subsequent stress drop takes place near the newly-formed fracture due to stress release. When the magnitude of σ_3 rises above σ_2, a swap between principal stress axes occurs and, in case a failure condition is newly reached, a second fracture develops perpendicular to the previous one (Caputo, 1995; Bai et al., 2002). Therefore, for similar orthogonal fracture sets, a unique remote stress field can be inferred. This is particularly applicable to foredeep/forbulge settings characterized by coeval arc-perpendicular and arc-parallel stretching (e.g. Doglioni, 1995).

The occurrence of forebulge-related normal faults and associated fractures have been documented both in orogenic belts (e.g. Geraghty Ward and Sears, 2007; Lash and Engelder, 2007; Casini et al., 2011) and in present-day foreland domains not involved in thrusting and folding. This is the case for the Apulian and Hyblean (SE Sicily) foreland carbonate successions, where conjugate normal faults and fractures forming two sets orthogonal to each other have been related to lithospheric flexure (e.g. Billi and Salvini, 2003; Billi, 2005). Tensile fractures in forebulge settings generally form in the flexure outer arc (i.e. atop of the forebulge; Turcotte and Schubert, 2001). Theoretical bending stress magnitudes, calculated for the Apulian and Hyblean forelands considering an effective elastic thickness of *c.* 11 km (Turcotte and Schubert, 2001; their Figs. 3 and 11), largely exceed the tensile strength of carbonates under ambient conditions (Billi and Salvini, 2003; Billi, 2005). Laboratory studies indicate that such tensile stresses can deform a carbonate succession down to a depth of 5 km (Billi et al., 2006; and references therein). Therefore, bending-related tensile fractures are expected to have developed in the whole carbonate succession cropping out in the southern Apennines (a value of 5 km being comparable to the mean thickness of the entire Apennine Platform; e.g. Scrocca et al., 2005). Widespread, intense fracturing of the 1.2 km thick Cretaceous to Miocene succession of Mt. Chianello was probably enhanced by the fact that it represents the upper part of the stratigraphic succession, which was sitting in the outer arc of a homogeneously flexed plate during the forebulge stage.

It is well known that tensile fractures may form also in association with meso- to macroscale folds in orogenic belts. Commonly they develop into four sets (Hancock, 1985): two sets parallel and orthogonal to the fold hinge, and two further orthogonal sets forming an angle of 45° with the fold hinge. On the other hand,

Fig. 6. Orientation data (lower hemisphere, equal-area projections), contour plots and results of paleostress analysis (P-B-T method) for the analysed structures. (a) Poles to fractures and bedding planes in Cretaceous carbonates. (b) Poles to fractures and bedding planes in Trentinara Fm. (c) Poles to fractures and bedding planes in Roccadaspide Fm. (d) Poles to bedding from the whole study area (also showing best-fit great circle and π theoretical fold axis). (e) Rotated poles to fracture planes from the whole study area (bedding restored to horizontal). (f) Contour plot of the data shown in previous plot. (g) Early normal faults. (h) Results of paleostress analysis on early normal faults (mean vectors and stress ratio R are: P 169/67, 67%; B 003/14, 27%; T 294/18, 33%. (i) Rotated early normal faults (bedding restored to horizontal). (j) Results of paleostress analysis on rotated early normal faults (mean vectors and R are: P 310/87, 74%; B 220/01, 50%; T 128/01, 60%). (k) Thrust faults. (l) Results of paleostress analysis on thrust faults (mean vectors and R are: P 031/14, 34%; B 298/04, 37%; T 200/71, 78%). (m) Minor fold hinges. (n) Contour plot of data shown in previous plot. (o) Poles to fold axial planes. (p) Contour plot of data shown in previous plot. (q) Faults in fold hinge zones. (r) Group 1 strike-slip faults. (s) Results of paleostress analysis on Group 1 strike-slip faults (mean vectors and R are: P 028/01, 75%; B 183/88, 85%; T 297/02, 72%). (t) Group 2 strike-slip faults. (u) Results of paleostress analysis on Group 2 strike-slip faults (mean vectors and R are: P 122/00, 76%; B 217/87, 75%; T 032/01, 70%). (v) Late normal faults. (w) Results of paleostress analysis on late normal faults (mean vectors and R are: P 015/88, 79%; B 334/02, 61%; T 245/00, 52%).

faults and tensile fractures associated with forebulge/foredeep settings are normally parallel and orthogonal to the thrust front, as suggested by Doglioni (1995) (Fig. 7). Therefore, it may be difficult to distinguish which structures formed in forebulge/foredeep settings and which are related with later fold development (even though in the Mt. Chianello succession the two oblique sets are missing). In our instance, the interpretation of background fractures being essentially early (i.e. pre-folding) structures is suggested by: (i) the stability of fracture set attitudes, which are independent of fold hinge orientation (this, as well as the attitude of related thrust faults, being rather variable within the study area; Fig. 6j and l), and (ii) the widespread evidence of subsequent shortening overprinting fracture and vein walls. The homogeneous spatial distribution and attitude of joints observed in the study area is compatible with an early fracturing process. 'Background' fracture and vein sets, and related conjugate faults, predate folds and thrusts as shown by field evidence discussed in a previous section. Taking into account that these brittle structures affect also the Aquitanian-Burdigalian Roccadaspide Fm, and that thrust faults and folds formed in Late Miocene times in this sector of the Apennine chain (see below), the timing of development of the 'background' fracture network is constrained to the Early-Middle Miocene. More precisely, the age of this deformation is bracketed between the late Burdigalian (age of the Bifurto Fm) and the early Tortonian (age of the subsequent thrusting phase). This extensional event, characterized by both ENE-WSW and NNE-SSW oriented extension (in present-day coordinates) produced horst and graben systems orthogonal and parallel to the thrust front (Doglioni, 1995). Bending of the foreland plate caused the formation and migration of the foredeep basin and of the related forebulge (Beaumont, 1981; DeCelles and Giles, 1996). Both of these regions were affected by stretching; however, in the peripherical bulge extension was accompanied by emersion and erosion. Accordingly, the model proposed in this work (Fig. 7a and b) envisages the development of normal faults and associated tensile fractures striking both parallel to the foredeep axis – associated with bending of the foreland plate – and orthogonal to it as consequence of the arcuate shape of the convergent system (Fig. 8). Most of the extension in the analysed succession was accommodated by tensile fractures and subordinately by normal faults (with the set orthogonal to the thrust front being more developed than that parallel to it). This is marked also by limited fault displacements and by the development of small fault damage zones, in analogy with those observed in foreland domains (e.g. Billi, 2005).

The NW-SE trending fracture set, roughly parallel to the present-day strike of the Apennine belt, is assumed to have been

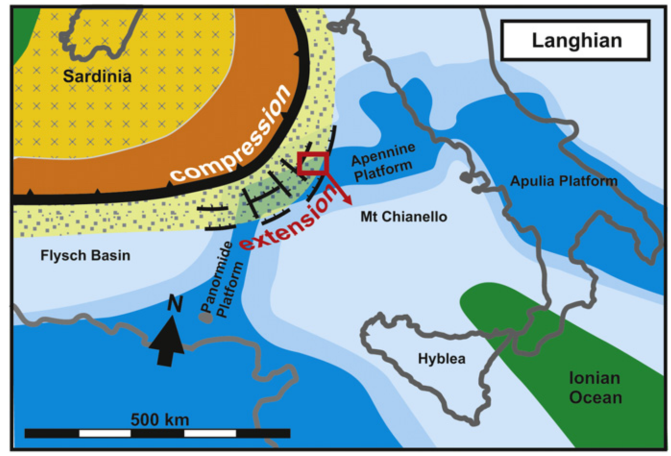

Fig. 8. Paleogeographic map of the central Mediterranean area in the Early Miocene, showing pattern of extension in the foreland.

parallel to the thrust front and to the foredeep axis in Miocene times. Taking into account the large counterclockwise rotations unravelled by paleomagnetic studies (e.g. Gattacceca and Speranza, 2002), in the paleogeographic reconstruction of Fig. 8 such a fracture set – as well as the thrust front and the foredeep axis – are shown with their likely original NNE-SSW strike. The Early-Middle Miocene foredeep stage was followed by the inclusion of the study area in the Apennine accretionary wedge, accompanied by large-scale folding and thrusting of the Mt. Chianello carbonates. The outcropping NE limb of the regional anticline (Fig. 2d) is deformed by localized kink folds and associated thrust faults (Fig. 2b and Fig. 5a, b, c and f). The paleostress field obtained from thrust fault slip data by means of the P-B-T method is characterized by a dominant NE-SW oriented horizontal compression. NW-SE trending kink folds (Fig. 2b) are also consistent with dominant NE-SW shortening. These folds, characterized by a main NE vergence, are consistent in terms of style and orientation with those affecting the Apennine Platform carbonates at Mt. Cervati (Castellano and Schiattarella, 1998) NE of our study area. These structures may also be correlated with folds affecting the wedge-top basin deposits of the Cilento Group (Fig. 2a), as well as with late-stage folds occurring in the Nord-Calabrese and Parasicilide units (Vitale et al., 2010, 2011; Ciarcia et al., 2012). All of these folds developed during the Late Miocene (e.g. Zuppetta and Mazzoli, 1997; Castellano and Schiattarella, 1998; Vitale et al., 2011; Ciarcia et al., 2012).

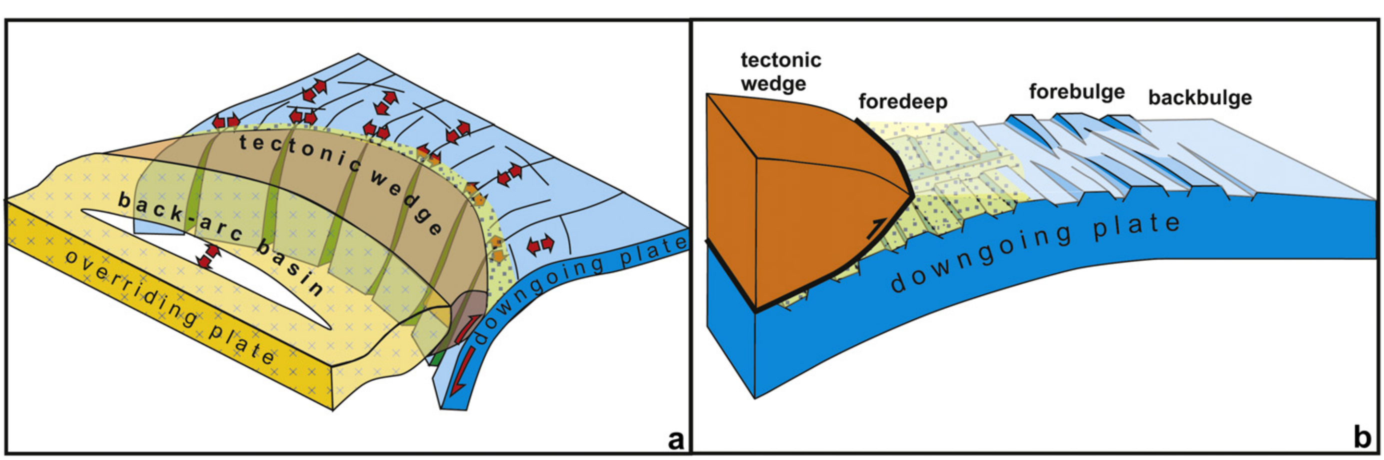

Fig. 7. (a) Cartoon of collisional plate margins and related extensional structures after Doglioni, 1995, modified. (b) Detail of previous diagram, showing stretched downgoing plate.

Two main groups of strike-slip fault sets occur in the study area, crosscutting and overprinting thrust faults and folds. Stress inversion methods applied to strike-slip fault sets indicate dominant SW-NE shortening and NW-SE extension for the earlier structures (Group 1), and prevailing NW-SE shortening and NE-SW extension for later features (Group 2). Group 1 fault sets, being characterized by a shortening direction consistent with the NE vergent Apennine belt, could be related to the final tectonic wedge building stages. Tectonic wedge thickening and consequent increase of the lithostatic load, increasing $\sigma 3$, may have triggered a permutation with $\sigma 2$, resulting in a switch from thrusting to a strike-slip tectonic regime. On the other hand, Group 2 fault sets appear to be associated with a subsequent tectonic event involving the development of N120° to N150° trending, left-lateral strike-slip faults that have been recognized in the whole southern Apennines (e.g. Turco and Malito, 1988; Turco et al., 1990; Berardi et al., 1996; Caiazzo et al., 2006) and have been related with Late Pliocene to Early Pleistocene SE migration of the Calabrian Arc (Ascione and Cinque, 1996; Hippolyte et al., 1994; Caiazzo et al., 2006; Spina et al., 2011).

Stress inversion carried out on the latest structures – post-orogenic normal faults – occurring in the study area outline an extensional stress field characterized by a dominant NE-SW tending $\sigma 3$. This is consistent with the late Quaternary and active stress field dominant in the southern Apennines, where crustal shortening ceased and a new tectonic regime was established in the chain and adjacent foothills around the early-middle Pleistocene boundary (c. 0.7 Ma; e.g. Cello et al., 1982; Cinque et al., 1993; Hippolyte et al., 1994; Montone et al., 1999). The structures related to this new regime, characterized by a NE-SW oriented maximum extension, include dominantly extensional faults that postdate and dissect the thrust belt. Such faults, locally bounding late Quaternary continental basins, also control active tectonics and seismogenesis in the southern Apennines (e.g. Caiazzo et al., 2006; Ascione et al., 2007).

The main stages of deformation reconstructed for the study area and the related remote stress field are summarized in Fig. 9. Our results suggest that 'background' fracture sets developed essentially during the first of the depicted deformation stages (bending of the foreland plate). Therefore, away from younger fault zones, fluid flow within the studied carbonates would be essentially controlled by the fracture network that formed during the foredeep/forebulge stages. It is worth noting that extensional deformation associated with bending of the foreland plate is imaged by seismic profiles also in the buried Apulian carbonates in the subsurface of the outer Apennine belt (e.g. Shiner et al., 2004; their Fig. 17), syn-rift strata documenting this process being clearly younger there (i.e. of Messinian to Pliocene age; refer to the cross-section in Fig. 1). As the early (pre-thrusting) fracture network controls 'background' fracture density and the related permeability structure in the allochthonous, far-travelled Apennine Platform carbonates, it is likely to be even more so in the much less deformed and little displaced reservoir carbonates of the APIB. As a matter of fact, extensional faults coupled with Messinian syn-rift strata and associated fracture sets related with the foredeep stage have been

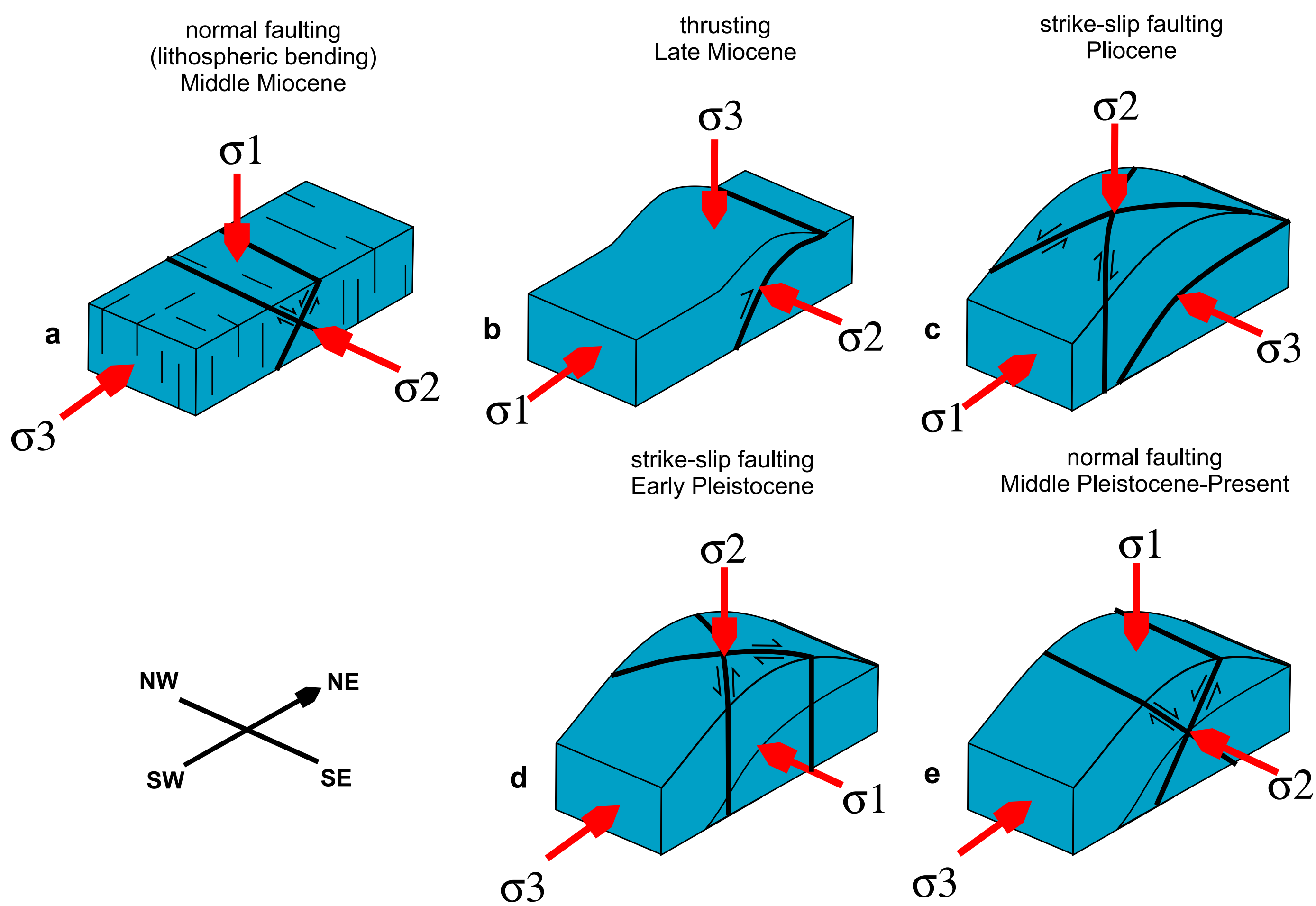

Fig. 9. Cartoon showing main structural stages and related remote stress field during convergent plate margin evolution in the study area.

extensively documented at Monte Alpi (Fig. 1), which represents the unique surface exposure of Apulian Platform carbonates within the southern Apennine thrust belt (e.g. Mazzoli et al., 2006; and references therein). Fault and fracture networks occur also in the Apulian Platform carbonates of the foreland (i.e. Apulia) region and have been related with bending of the foreland plate (e.g. Doglioni et al., 1996; Billi and Salvini, 2003). In summary, although the oil fields of southern Italy are clearly compartmentalized by recent and/or reactivated major faults (e.g. Shiner et al., 2004), it is likely that fluid flow within the 'background' fracture network is controlled by the occurrence of early (pre-thrusting) joint sets similar to those observed in the outcropping carbonates of Mt. Chianello analysed in this study. This has major implications for the analysis of fluid flow in the subsurface and related hydrocarbon production, because: (i) despite the different tectonic evolution and burial conditions experienced by the reservoir carbonates of the APIB with respect to coeval Apennine Platform units, these latter are likely to represent a good analogue in terms of 'background' fracture network characteristics; and (ii) the development of 'background' fractures would be essentially independent of structural position within large-scale folds controlling hydrocarbon structural traps in the APIB.

7. Conclusions

The structural analysis carried out in this study points out that, despite a superposed deformation history including thrusting over tens of kilometres, subsequent strike-slip faulting and final normal faulting, the 'background' fracture network controlling the permeability structure of the shallow-water carbonates of Mt. Chianello was acquired during a pre-thrusting deformation event. This was probably associated with the development of both 'tangential' and 'radial' normal faults and tensile fractures during foredeep/forebulge stages. A similar fracture network characterizes also Cretaceous carbonates of the Sorrento Peninsula (Guerriero et al., 2010, 2011), thus suggesting that it may represent a common feature in Apennine Platform carbonates of southern Italy. On the other hand, normal faulting related with bending of the foreland plate is seismically imaged in the buried Apulian Platform carbonates, which constitute the reservoir units for major oil fields in southern Italy. A 'background' fracture network is much likely to be associated with such an extensional deformation in the buried Apulian Platform carbonates, as it is observed in those exposed in the foreland (Apulia and Hyblea) regions. Therefore, our results from Mt. Chianello, besides contributing to a better understanding of the modes and timing of deformation of allochthonous carbonates of the southern Apennines, may also provide new insights into the prediction of preferential fluid pathways in subsurface reservoir carbonates.

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