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Structural evidence for Neogene rotations in the eastern Sicilian fold and thrust belt

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Abstract

A geological and structural analysis carried out on a sector of the eastern Sicilian fold and thrust belt pointed out the occurrence of two systems of structural associations, typical of collisional fronts. In particular, the Mesozoic–Serravallian succession of the Mt. Judica unit, outcropping in three W–E- to WNW–ESE-striking distinct ridges, is characterized by two fold systems with sub-perpendicular axes, the first plunging towards 010–040 at angles of 30–55°, the second one with sub-horizontal axes trending 090–115. The different angular values of plunging suggest that the folds of the first system underwent the effects of severe tectonic deformation following their formation. Moreover, the distinct ridges were uplifted by south-verging thrusts and relative back-thrusts coaxial to the second system of folds. Conversely, the Upper Tortonian–Lower Pliocene deposits of Mt. Pulicara show only one fold and thrust system, WNW–ESE-trending, roughly coaxial to the second system recognized in the Mt. Judica unit succession. The structural analysis carried out in the two areas, compared with published eastern-central Sicily palaeomagnetic data, suggest that the Mesozoic–Serravallian succession of the Mt. Judica Unit recorded both major 70° Langhian–Late Tortonian clockwise rotations and locally 30° Pliocene clockwise rotations. So, the structures formed during the first deformation stage were totally rotated up to 100°. Conversely, structures of the Mt. Pulicara Upper Tortonian–Lower Pliocene deposits were involved only in the Pliocene clockwise rotation. From a geodynamic point of view, the Neogene clockwise rotation in the eastern Sicily fold and thrust belt is related to the regional framework of the Africa–Europe convergence.

Keywords: Folds; Thrusts; Rotations; Neogene; Sicily

1. Introduction

The Sicilian–Maghrebian chain is composed of a thin-skinned south-verging foreland fold and thrust system developed during the Neogene to Quaternary Africa–Europe collision (Dewey et al., 1989; Ben Avraham et al., 1990). Together with the Gela–Catania foredeep and the Hyblean foreland (Fig. 1), it represents one of the structural domains of the eastern Sicily collisional belt, which is a portion of the alpine orogen (Roure et al., 1990). The frontal portion of this thrust system overthrusts the flexured foreland, whose top, made up of Lower Miocene carbonates, was reached by oil exploration wells at a depth of 3000 m (Bianchi et al., 1987; Lickorish et al., 1999; Bello et al., 2000).

The W–E-trending Siculo–Maghrebian segment of the orogenic belt is linked to the NW–SE-trending southern Apennines by the Calabrian Arc (Fig. 1). This latter is made up of crystalline basement units that represent the inner portions of the orogenic system. The arc shaped geometry of the Calabrian Arc was interpreted as the result of indentation processes of the Pelagian block and consequent Tyrrhenian basin rifting along the suture zone between the Sardinia–Corse and Adria blocks (Tapponnier, 1977; Boccaletti et al., 1990; Catalano et al., 2004). The consequent lateral extrusion of the Calabrian Arc towards the Ionian oceanic domain was attained by counter-clockwise and clockwise rotations of the Apennines and Sicilian sectors, respectively (Channel and Tarling, 1975; Channel et al., 1980, 1990; Channel, 1992; Sagnotti, 1992; Scheepers et al., 1993; Speranza et al., 1997). In particular, the thrust migration along the Sicilian sector of the chain has been accompanied by clockwise rotations, revealed by structural (Giunta et al., 2000; Avellone and Barchi, 2003; Guarnieri, 2004; Nigro and Renda, 2005) and palaeomagnetic data (Channel et al., 1980, 1990; Grasso et al., 1987; Oldow et al., 1990; Speranza et al., 1999). New palaeomagnetic data on Upper Trias to Lower–Middle Pliocene sediments reveal

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a major 70° clockwise rotation (see Fig. 1) that took place in central-eastern Sicily between the Langhian and the Late Tortonian, followed by a further 30° clockwise rotation that occurred after the Early Pliocene (Speranza et al., 2003).

A detailed structural analysis was carried out in the Mt. Judica area, at the front of the Sicilian–Maghrebian chain (Fig. 1), in order to define the tectonic evolution of the area in relation to the rotation episodes that have occurred in central-eastern Sicily since the Middle Miocene. The structural analysis was concentrated on the Mt. Scalpello and Mt. Judica–Mt. Turcisi ridges (Fig. 2), where the Upper Triassic–Serravallian sedimentary succession of the Mt. Judica tectonic unit (Lentini, 1974) is well exposed, and in the Mt Pulicara area (Leonforte–Centuripe Basin; see also Fig. 1), where top-thrust Neogene terrigenous covers outcrop, in order to compare tectonic structures of different ages. In order to recognize the main structures and to define their geometry, the detailed structural field analysis was supported by the elaboration of a 3D topographic digital elevation model of the area and by the analysis of 1:33,000 scale aerial photographs. Structural data (slickensides on fault surfaces, fold axes, fracture systems) collected on several measurement stations were processed to better define the geometric and kinematic features of the structures occurring in the area.

2. Geological setting

The Sicilian–Maghrebian chain (Fig. 1) is formed by several thrust sheets deriving from the oceanic realm of the Neotethys and from the Africa continental palaeo-margin (Bianchi et al., 1987; Lentini et al., 1990; Roure et al., 1990; Bello et al., 2000; Catalano et al., 2000). The oceanic units are represented by broken formations and melange terranes (Sicilide units) constituting distinct portions of an original accretionary wedge tectonically overlain by crystalline rocks (Calabride units) belonging to the European palaeo-margin. The Meso-Caenozoic successions of the Africa palaeomargin are represented by distinct thrust sheets derived from the deformation of carbonate platform (i.e. Panormide units) and pelagic (i.e. Imerese and Mt. Judica units) domains.

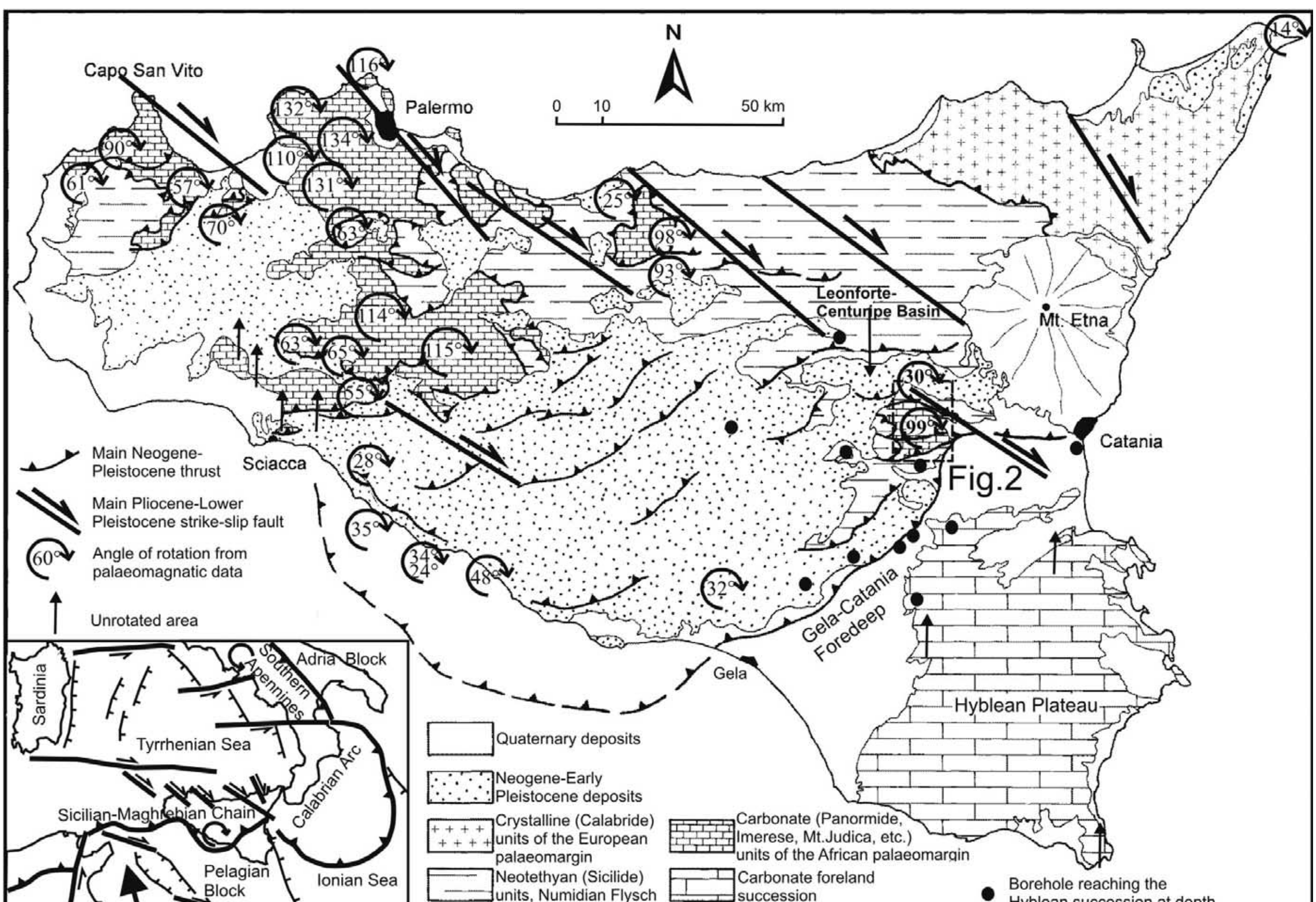

Fig. 1. Schematic geological map of Sicily. Circular arrows (and the enclosed angle) indicate the amount of clockwise rotations calculated by palaeomagnetic analyses (from Speranza et al., 1999, 2003 and references therein). Vertical arrows indicate unrotated areas. Borehole location from Bello et al. (2000). The inset shows a simplified model of lateral extrusion of the Calabrian Arc produced by the indentation of the Pelagian Block and by consequent opening of the Tyrrhenian Basin (from Catalano et al., 2004, modified). The large arrow shows the Late Tortonian to Present direction of convergence between Africa and Europe (from Mazzoli and Helman, 1994); circular arrows indicate the clockwise and counterclockwise orogen-scale rotations of the Sicilian–Maghrebides and Southern Apennines, respectively. Lines with triangles represent the front of the chain; lines with arrows the main Plio-Pleistocene strike-slip faults; lines with barbs the main Quaternary faults.

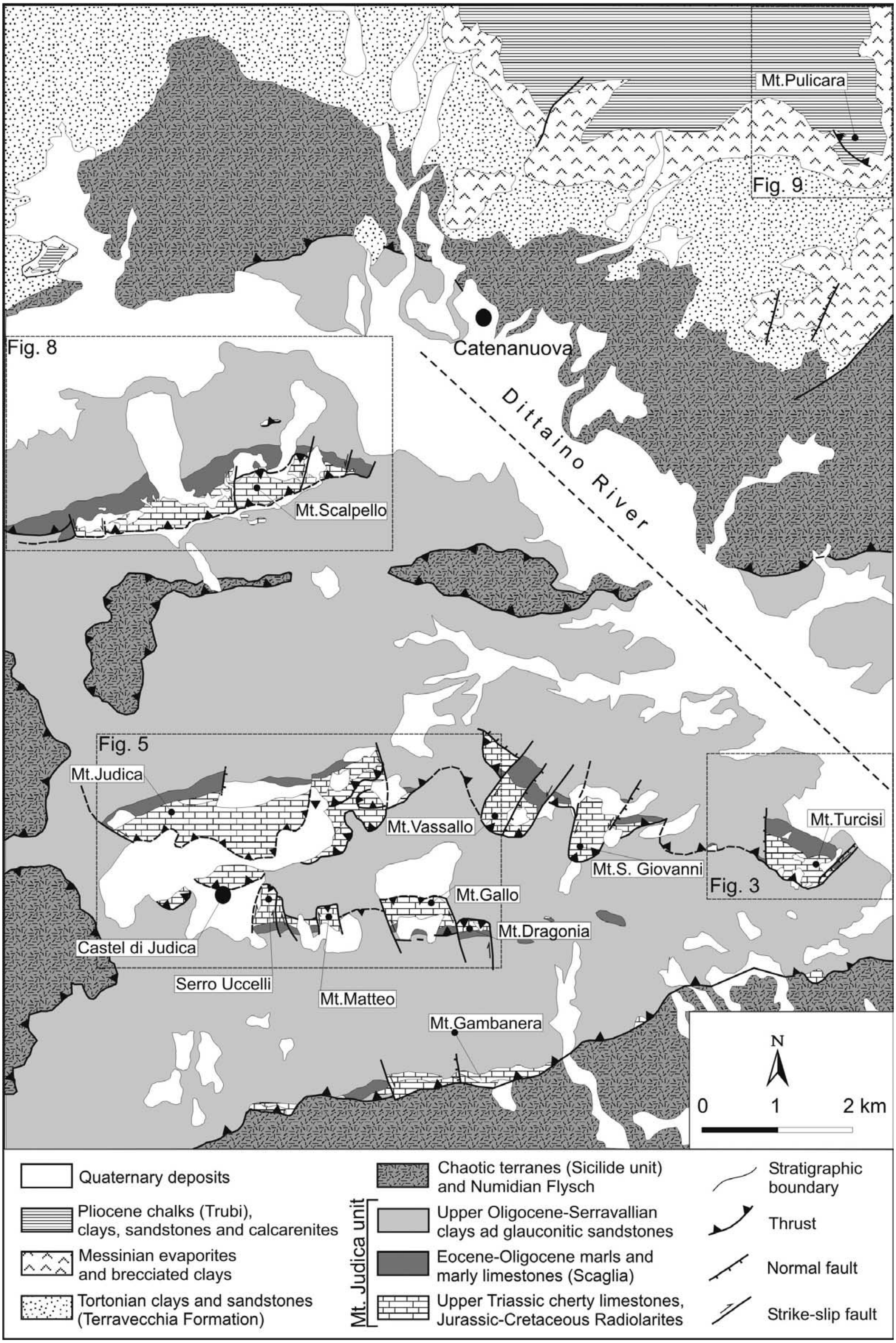

Fig. 2. Geological map of the Mt. Judica–Mt. Pulicara area (see Fig. 1 for location).

As a whole, the chain shows a duplex geometry with horses formed by the sedimentary cover of the African palaeo-margin that are contained between two main shear zones: a roof thrust represented by the Sicilide units and a floor thrust represented by the detachment level of the sedimentary cover from the subducting African basement, regionally located along the Upper Triassic Mufara Formation (Lentini et al., 1990). Collisional processes have involved the African palaeo-margin since the Middle Miocene giving rise to thrust migration characterized by piggy-back propagation of SSE-verging flat and ramp thrusts (Bianchi et al., 1987; Lentini et al., 1990; Roure et al., 1990; Bello et al., 2000; Catalano et al., 2000). During the Neogene, the Neotethyan units, together with the Numidian Flysch units, overthrust more external domains reaching the front of the chain (Fig. 1). The Numidian Flysch represents the Upper Oligocene–Lower Miocene turbiditic cover of the Sicilide, Panormide and Imerese domains, detached from the Mesozoic–Palaeogene successions during the thrust propagation (Lentini et al., 1990).

Since the Late Miocene, the frontal thrusting of the chain over the flexured Hyblean foreland was accompanied by out-of-sequence thrusting (Lentini et al., 1990; Bello et al., 2000) and by the development of syntectonic marine basins in the depressions at the rear (i.e. the Leonforte–Centuripe Basin, Fig. 1). The occurrence of NW–SE- and WNW–ESE-striking en-échelon right-lateral strike-slip fault systems characterized the post-Tortonian stages of the orogenesis (Lentini et al., 1991). During their Neogene propagation the distinct thrust sheets underwent strong clockwise rotations (Speranza et al., 1999, 2003 and references therein).

The study area is located in a sector of the chain bounded by the Leonforte–Centuripe Basin to the north and by the frontal thrust to the south (Fig. 1), where the Monte Judica unit extensively outcrops (Fig. 2). The bottom of the Monte Judica Unit succession is constituted by strongly deformed Middle–Upper Carnian clays, limestones and sandstones (Mufara Formation), locally outcropping at the southern lower slope of Mt. Scalpello. They are overlain by 300-m-thick Upper Triassic cherty limestones passing upwards to 100-m-thick Jurassic–Cretaceous radiolarites (Lentini, 1974; Lentini et al., 1991). The Mesozoic succession is covered by 100-m-thick Eocene–Oligocene marls and marly limestones ('Scaglia'), passing upwards to 500-m-thick Upper Oligocene–Serravallian clays and glauconitic sandstones. The Mt. Judica succession was tectonically overlain by chaotic terranes of Sicilide unit and Numidian Flysch (Fig. 2) during the Middle Miocene collisional event (Lentini, 1974; Bello et al., 2000). The Monte Judica unit forms an imbricate thrust system composed of three main E–W-striking thrust ridges reaching elevations of about 700 m a.s.l., named from the north to the south as Mt. Scalpello, Mt. Judica–Mt. Turcisi and Mt. Gambanera (Fig. 2). They overthrust the Lower Pliocene foredeep deposits at the front of the chain (Bianchi et al., 1987).

The tectonic units are unconformably covered by Neogene sedimentary successions (Fig. 2) that, to the north of Mt. Scalpello, are represented by Upper Tortonian clays and sandstones (Terravecchia Formation) by strongly folded Messinian evaporites with levels of brecciated clays and by unconformable Lower Pliocene chalks ('Trubi'). These latter pass upwards to clays, sands and calcarenites, deposited in the Lower–Middle Pliocene Leonforte–Centuripe Basin (Fig. 1) and deformed by large W–E-trending folds (Di Grande et al., 1976).

3. Structural analysis

In order to reconstruct the tectonic events that occurred in the area, a detailed structural analysis of fold systems was carried out on the Upper Triassic–Oligocene rocks of the Mt. Judica unit exposed both at Mt. Scalpello and at the main ridges along the Mt. Judica–Mt. Turcisi alignment (Fig. 2). Rare thrusts and faults characterized by clear and evident surfaces for measuring dip and slickensides have been projected on the Schmidt lower hemisphere. By comparison, the tectonic structures on the Upper Tortonian–Lower Pliocene unconformable successions of the Leonforte–Centuripe Basin (Mt. Pulicara, Fig. 2) were analysed. All these tectonic structures are typical of the frontal zone of collisional chains, being represented by folds, thrusts and associated fault systems (Ghisetti and Vezzani, 1980).

3.1. Mt. Judica–Mt. Turcisi alignment

The structural setting of the Mt. Judica–Mt. Turcisi alignment (Fig. 2) is characterized by the occurrence of a W–E oriented triangle zone, comprised between the Mt. Judica–Mt. Turcisi south-verging main thrust to the north and the Serro Uccelli–Mt. Dragonia back-thrust to the south. These structures, with associated coaxial folds, have cut and/or tilted first generation folds and have truncated and/or reactivated pre-existing faults that consequently play the role of lateral ramps or transfer faults. In general, ridges formed by the south-verging thrust show complete stratigraphic successions of the Mt. Judica unit dipping northwards at 10–55° (Mt. Judica, Mt. Vassallo, Mt. San Giovanni and Mt. Turcisi). Conversely, ridges formed by the back-thrust are made up of Upper Triassic cherty limestones and Eocene–Oligocene marls and marly limestones ('Scaglia') dipping southwards at about 35° (Serro Uccelli, Mt. Matteo, Mt. Gallo and Mt. Dragonia). In the following, the most representative structural sites of the Mt. Judica–Mt. Turcisi alignment are described.

Mt. Turcisi is the easternmost ridge of the investigated area (Fig. 2) and reaches an elevation of 303 m. The stratigraphic succession is made up of cherty limestones, radiolarites and 'Scaglia' (Fig. 3). The major structure is made up of a ramp thrust with orientation 110/30NE that evolves to the east to a SW–NE striking sinistral lateral ramp. Two main fold systems with orthogonal axes have been found: the first shows axes plunging towards 010–040 at angles of 30–55°, the second one characterized by sub-horizontal axes trending 090–115 (diagram in Fig. 3). The first system is well visible in the cherty limestones outcropping in the southern flank of the ridge where large parallel folds are cut downslope by the basal thrust (Fig. 4). The second system is more diffused on the northern

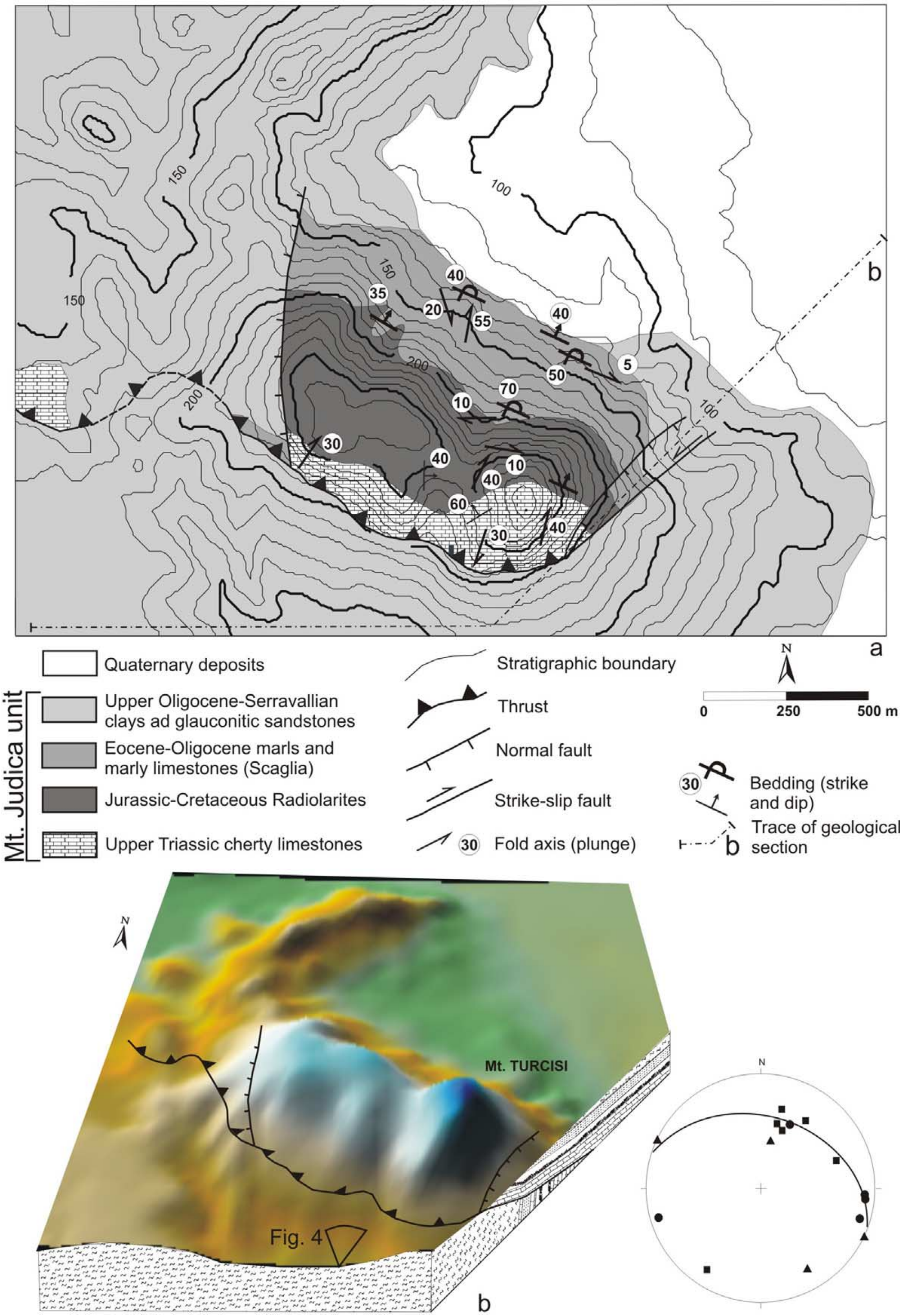

Fig. 3. (a) Geological–structural sketch map of Mt. Turcisi (see Fig. 2 for location); (b) view from the south of Mt. Turcisi ridge by the 3D prospective projection mode of a Digital Elevation Model (DEM). The stereoplot (Schmidt, lower emisphere) shows projections of the basal thrust and of beta fold axes on Calcari con selce (squares), radiolarites (triangles) and Scaglia (circles).

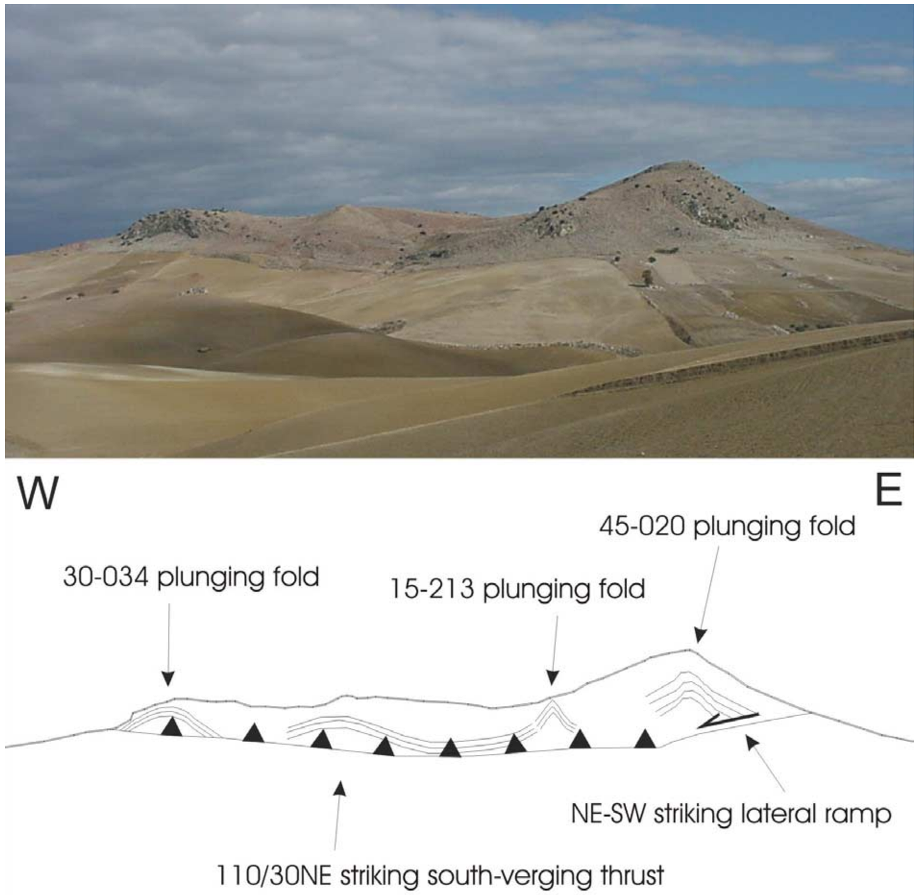

Fig. 4. Panoramic view of the southern slope of Mt. Turcisi (see Fig. 3 for location). The folds of the first phase, truncated by the basal thrust, are evidenced.

slope where radiolarites and 'Scaglia' layers are locally deformed by northwards overturned parallel folds related to blind antithetic back-thrusts. The axis direction of the second phase folds is roughly coaxial to the basal thrust (diagram in Fig. 3).

The Mt. Judica ridge is located in the westernmost sector of the alignment (Fig. 2) and reaches an elevation of 763 m. The steep southern slope is made up of cherty limestones dipping northwards at 5–10° and passing upwards to radiolarites and 'Scaglia' that in the northern slope dip at 45–55° (Fig. 5). The major structure is represented by a south-verging and 080/35NW oriented ramp thrust, associated with a large thrust propagation anticline and with a minor thrust fault (070/25NW) which splays out southwards. The main structure is truncated to the west by a WNW–ESE striking dextral lateral ramp, whereas to the east it is off-set by two N–S striking sinistral transfer faults. Also in this area two main fold systems with orthogonal axes have been found: the first characterized by axes plunging towards 340–045 at angles of 10–40°, the second by sub-horizontal axes trending 090–125 (diagram (a) in Fig. 5). The first system is represented by large open folds in the cherty limestones, while the second system mostly deforms radiolarites and 'Scaglia' that in the northwestern slope are characterized by northwards overturned parallel folds related to a blind antithetic back-thrust.

The Mt. Gallo–Mt. Dragonia ridge is located in the central sector of the Mt. Judica–Mt. Turcisi alignment and reaches an elevation of 535 m (Fig. 2). The stratigraphic succession is made up of cherty limestones unconformably covered by 'Scaglia' (Fig. 5). The main structure is represented by a north-verging and 090–100 striking back-thrust, bounded by two 170 striking lateral ramps. A transfer fault with the same direction separates the two peaks. Two main fold systems with orthogonal axes have been found in the cherty limestones: the first one shows axes plunging towards 180 at angles of 10–25°, the second one is represented by folds with axes trending 090–115 and plunging at angles of 0–25° (diagram (b) in Fig. 5). In particular, Mt. Gallo forms in its entirety a ramp anticline, coaxial to the back-thrust, which refolds a large pre-existing syncline plunging to the south at 20° (Fig. 6). At Mt. Dragonia, parallel folds show axes plunging to the SW at angles of 10–20° (diagram (b) in Fig. 5) and, together with an associated pre-existing reverse fault (205/70SE), are cut and tilted southwards by the basal back-thrust (Fig. 7).

3.2. Mt. Scalpello ridge

The northernmost thrust sheet of the Monte Judica unit thrust system is represented by the Mt. Scalpello ridge (Fig. 2), which reaches an elevation of 583 m. The major structure

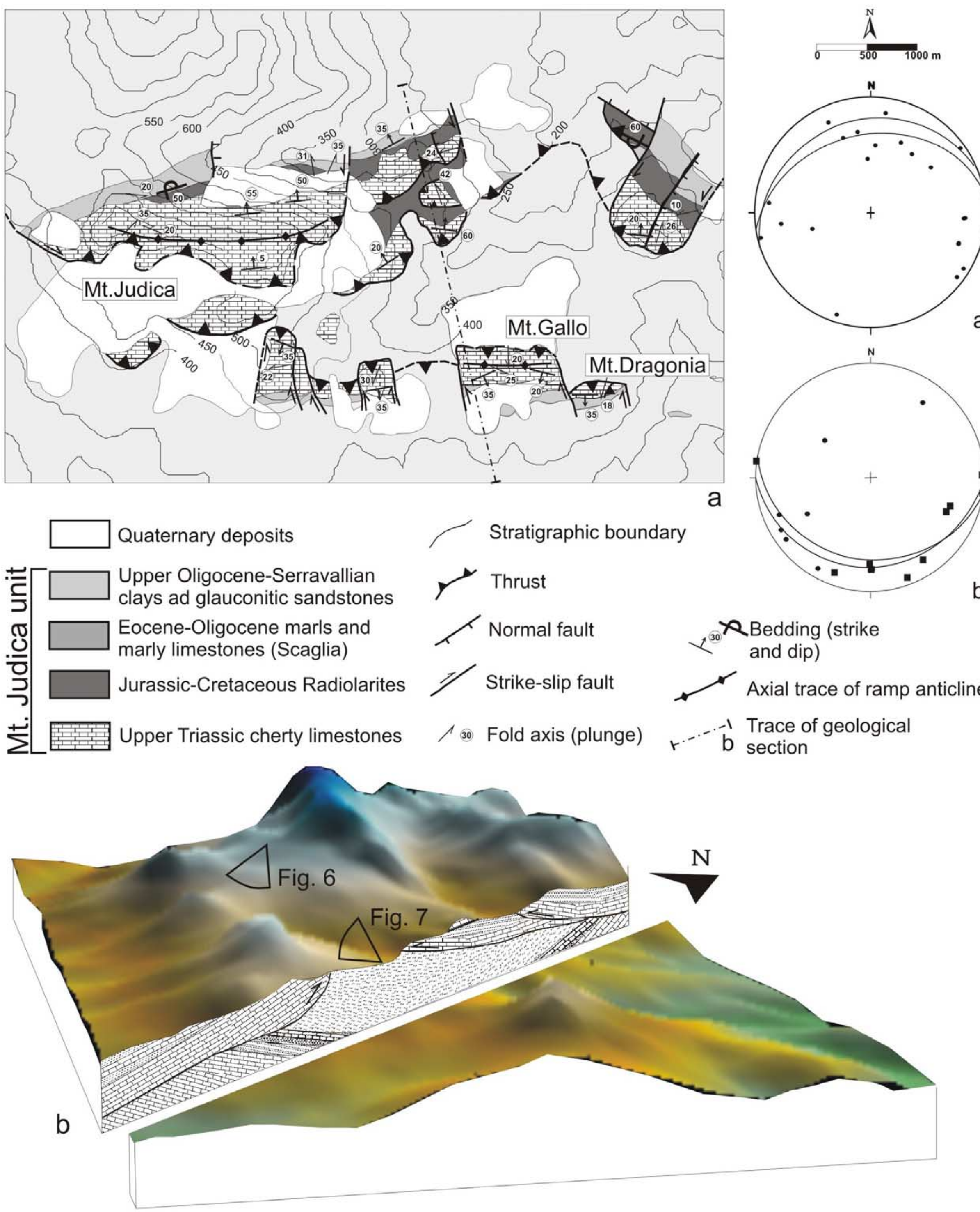

Fig. 5. (a) Geological–structural sketch map of the area between Mt. Judica and Mt. Dragonia (see Fig. 2 for location); (b) view from the south of the Mt. Judica–Mt. Dragonia area by the 3D prospective projection mode of a Digital Elevation Model (DEM). Stereoplot a (Schmidt, lower emisphere) shows projections of the basal thrusts and of beta fold axes collected at Mt. Judica; stereoplot b shows projections of the basal thrusts and of beta fold axes collected at Mt. Gallo (squares) and Mt. Dragonia (circles).

is made up of a south-verging and E–W striking ramp thrust, dipping northwards at 30°. In the eastern sector (Fig. 8), an antithetic back-thrust, laterally bounded by two transfer faults, gives rise to a pop-up structure. In the western sector, the thrust sheet forms a monocline mostly made up of cherty limestones dipping to NNW at 15–25° (Fig. 8). In the northwestern slope they pass upwards to radiolarites, while the 'Scaglia' unconformably cover the Mesozoic succession through a metre-thick level of intrabacinal breccias that seal Upper Cretaceous extensional structures with orientation 060/55SE.

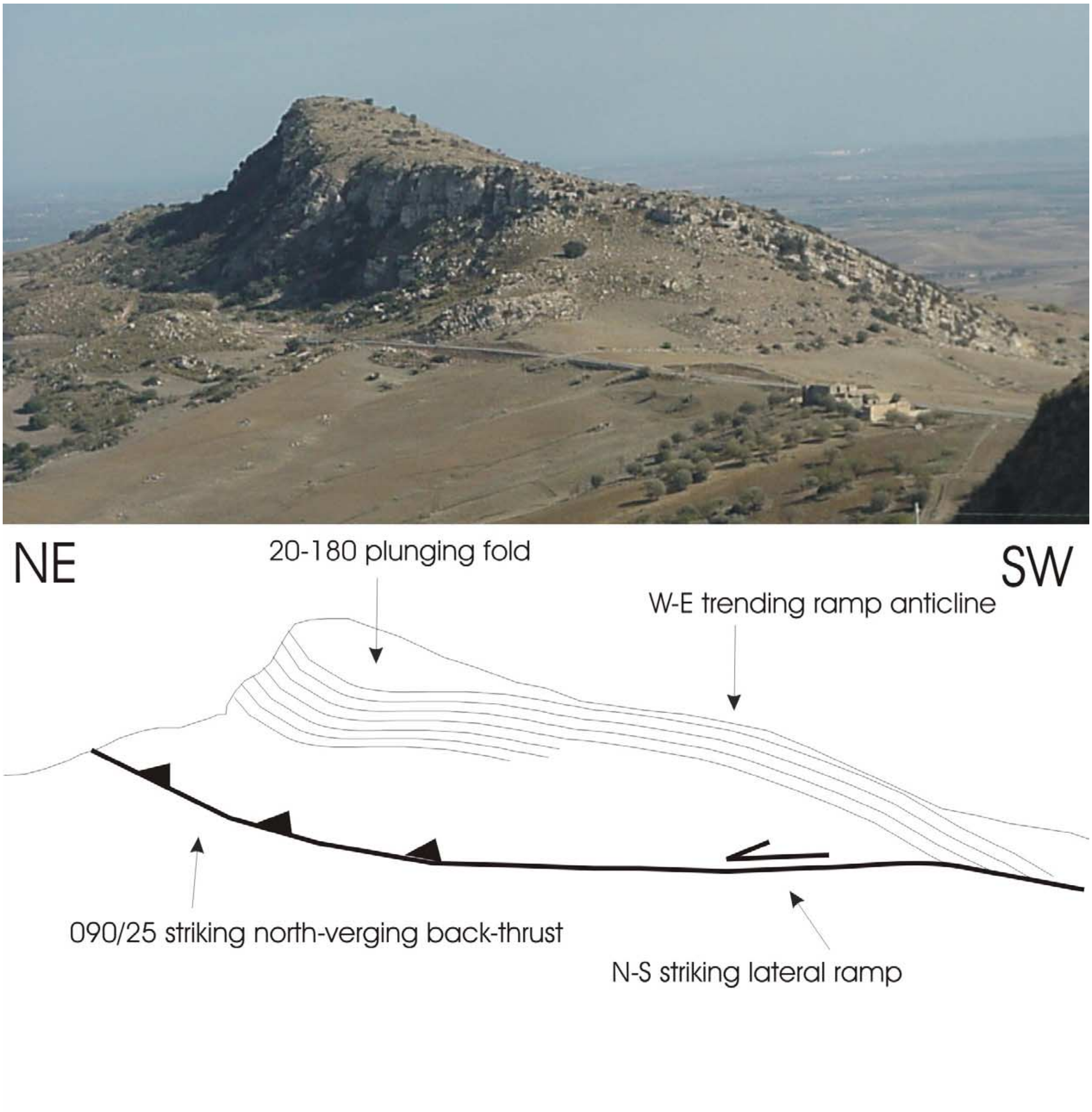

Fig. 6. Panoramic view of the northern slope of Mt. Gallo (see Fig. 5 for location). The fold of the first phase, refolded by the ramp anticline of the basal back-thrust, is evidenced.

Also along the Mt. Scalpello ridge two main fold systems with sub-orthogonal axes have been found: the first one shows axes plunging on average to the north at angles of 30–55°; the second one is characterized by axes trending on average E–W and plunging at angles of 0–10°. In particular, in the western sector the folds of the first system plunge towards 320–030, while the folds of the second system trend from SW–NE to WNW–ESE (diagram (a) in Fig. 8); in the eastern sector a small clockwise rotation was observed, as the folds of the first system plunge towards 355–050, while the folds of the second system trend from WNW–ESE to NW–SE (diagram (b) in Fig. 8). The superposition of the two systems gives rise to rare ‘dome and basin’ interference structures.

Shear structures sub-orthogonal to the main thrust were observed along the Mt. Scalpello ridge. In the western sector they are mostly represented by normal faults (diagram (a) in Fig. 8), while the eastern sector is characterized by several left-lateral transfer faults (diagram (b) in Fig. 8).

3.3. Mt. Pulicara area

The Mt. Pulicara area is located 10 km northeastwards of Mt. Scalpello (Fig. 2) and reaches an elevation of 470 m. In this area Neogene deposits outcrop, unconformably covering the chain units. They are made up of Upper Tortonian clays and sandstones, Messinian evaporites and Lower Pliocene chalks

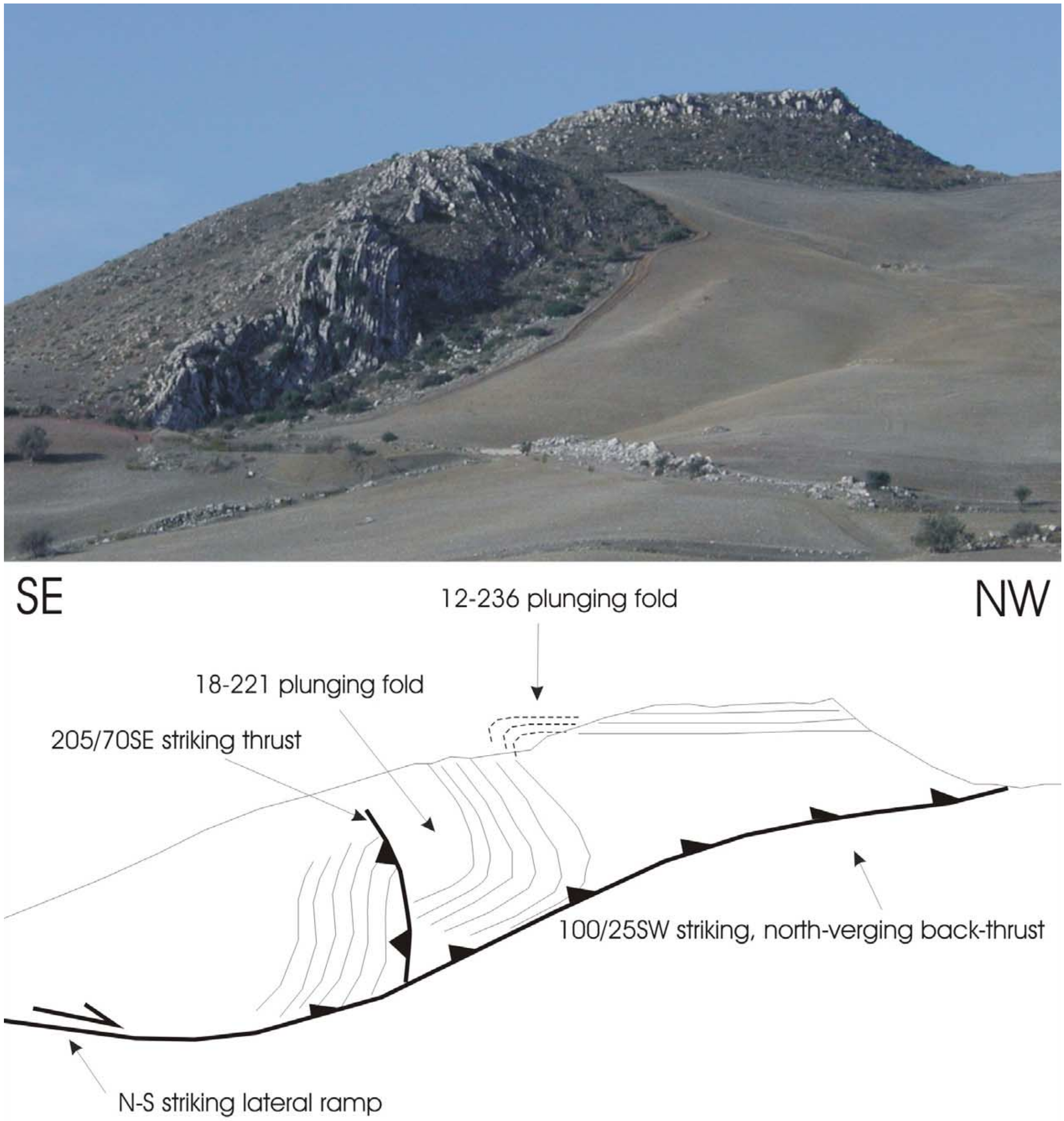

Fig. 7. Panoramic view of the northern slope of Mt. Dragonia (see Fig. 5 for location). The folds and thrust of the first phase, truncated by the basal back-thrust, are evidenced.

(Fig. 9). Evaporites and chalks are strongly deformed by several thrust propagation folds. A dispersion of fold axis poles around WNW–ESE directions was recognized in the two formations (diagram in Fig. 9). Major thrust faults, coaxial to the folds, outcrop on the western slope of Mt. Pulicara, where they cause the thickening of the stratigraphic succession (Fig. 9).

4. Data analysis

The geological–structural analysis carried out in the Mt Judica and Mt. Pulicara areas pointed out the occurrence of contractional structural associations (folds and thrust) typical of collisional fronts, caused by Africa–Europe convergence. Fold structures, with parallel geometry, in well-bedded multilayered successions suggest that folding occurred in shallow crustal domains, mostly related to thrust detachment and propagation.

The Mesozoic–Serravallian succession of the Mt. Judica unit (Figs. 3, 5 and 8) is characterized by two fold systems with sub-perpendicular axes. In the western sectors (Mt. Judica, Mt. Gallo and western portion of Mt. Scalpello), the early and the second systems roughly trend N–S and W–E, respectively. In the eastern sectors (Mt. Turcisi, Mt. Dragonia and eastern portion of Mt. Scalpello), the two systems are slightly rotated clockwise (10–30°) as they roughly trend SSW–NNE

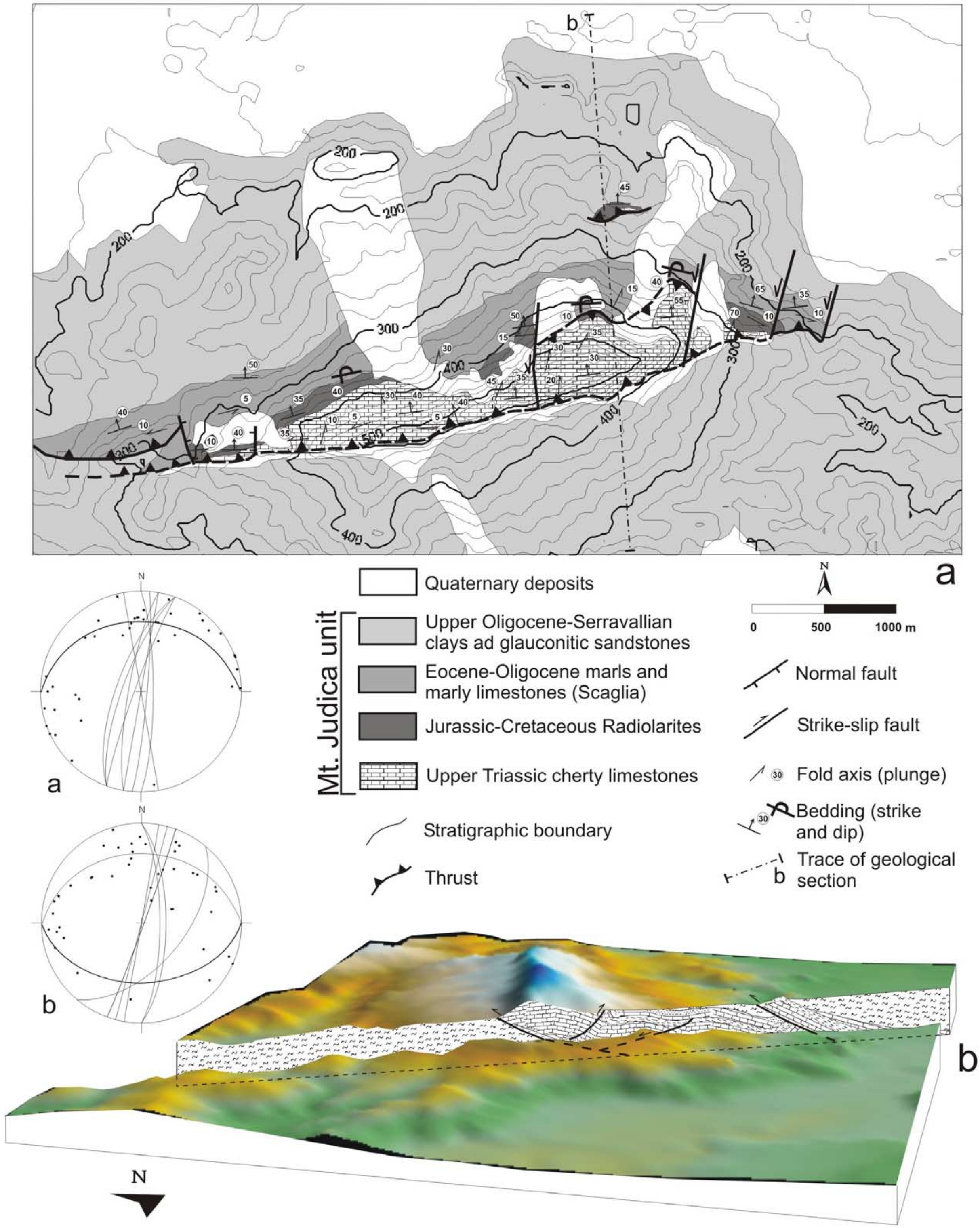

Fig. 8. (a) Geological–structural sketch map of Mt. Scalpello (see Fig. 2 for location). (b) View from the south of Mt. Scalpello ridge by the 3D prospective projection mode of a Digital Elevation Model (DEM). Stereoplot a (Schmidt, lower emisphere) shows projections of the basal thrust, normal faults and beta fold axes of the western sector of the ridge; Stereoplot b shows projections of the basal thrusts, left lateral ramps and beta fold axes of the eastern sector.

and WNW–ESE, respectively. In both sectors the axes of the first system plunge on average at 35° to the north, while the second system is characterized by sub-horizontal axes. The azimuthal clockwise rotation could be related to dragging caused by a Pliocene–Lower Pleistocene NW–SE-trending right-lateral strike-slip fault, masked by the alluvial deposits of the Dittaino River (Fig. 2; see also Lentini et al., 1991). The different angular values of plunge of the two systems suggests

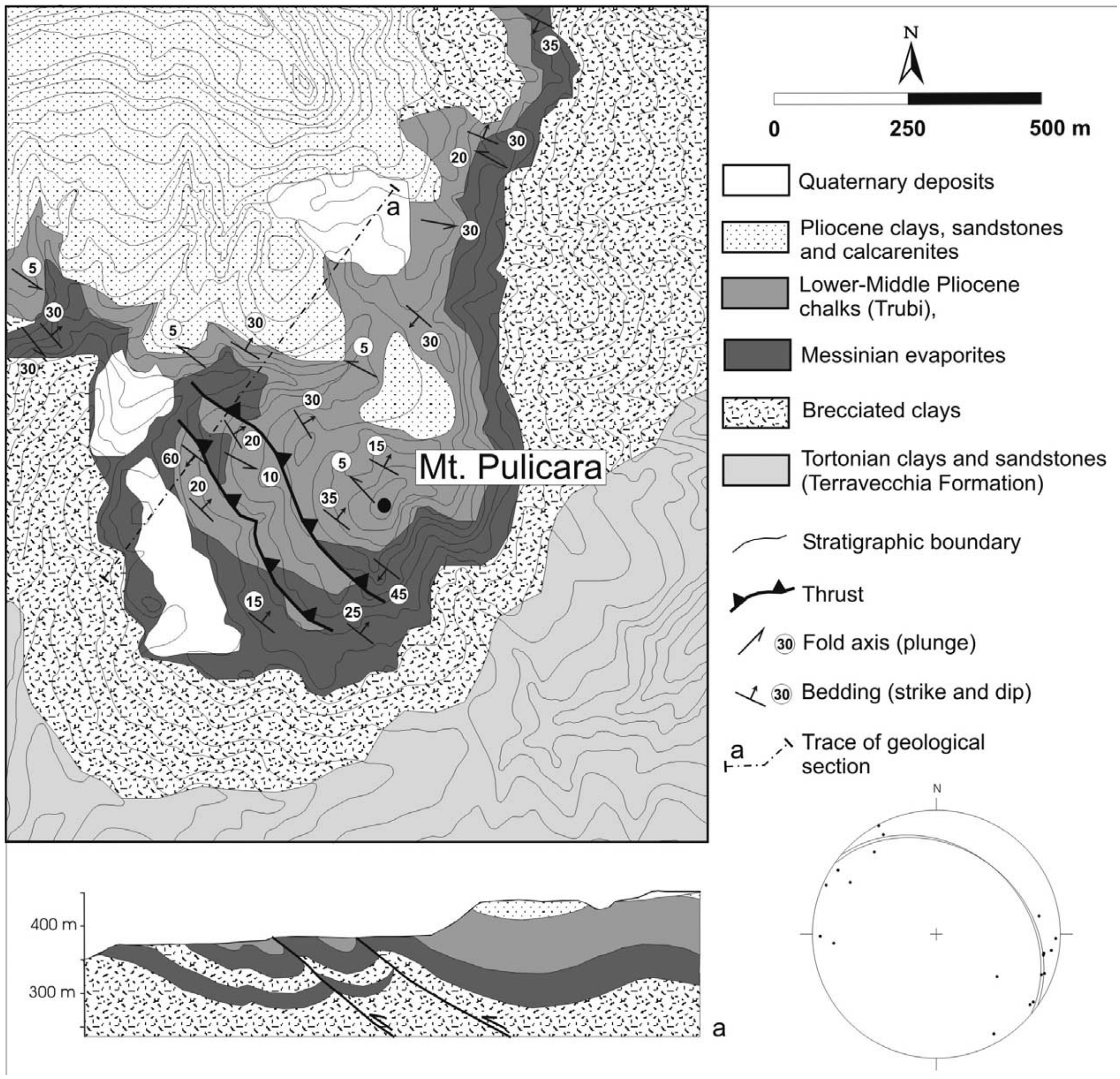

Fig. 9. Geological–structural sketch map of Mt. Pulicara (see Fig. 2 for location). The stereoplot (Schmidt, lower emisphere) shows projections of beta fold axes and of thrust planes.

that only the axes of the first fold system underwent strong, mostly northwards, tilting deformation. Sometimes, the superposition of the two fold systems gives rise to 'dome and basin' interference structures (Ramsay, 1967). As regards the shear structures, the distinct ridges were uplifted by south-verging thrust and conjugate back-thrust, showing W–E and WNW–ESE orientation in the western and eastern sectors, respectively. It is worth noting that these directions are coaxial to the second fold system. All the thrust ridges are characterized by the occurrence of normal faults, with directions ranging from N–S to SSW–NNE, perpendicular and kinematically compatible (Ghisetti and Vezzani, 1980) to the main south-verging thrust faults.

Conversely, the Upper Tortonian–Lower Pliocene deposits of Mt. Pulicara (Fig. 9) are characterized by only one fold and thrust system, WNW–ESE-trending, coaxial to the second system found in the eastern sector of the Mt. Judica area.

It is worth noting that along the Mt. Judica–Mt.Turcisi alignment, ridges formed by the complete succession of the Mt. Judica unit alternate with depressions where only the higher clays and glauconitic–sandstones outcrop (Fig. 2). This structural setting is interpreted as the result of the occurrence of first-phase faults that caused the second phase thrust propagation along distinct stratigraphic levels of the Mt. Judica succession. This implies that depressions and ridges should represent the downthrown and uplifted blocks, respectively, of first phase faults (Fig. 10). In particular, the reverse fault of Mt. Dragonia (Fig. 7) can be associated with the first system folds. These structures were deformed and tilted as a whole by the basal back-thrust that, conversely, should be associated with the second system folds.

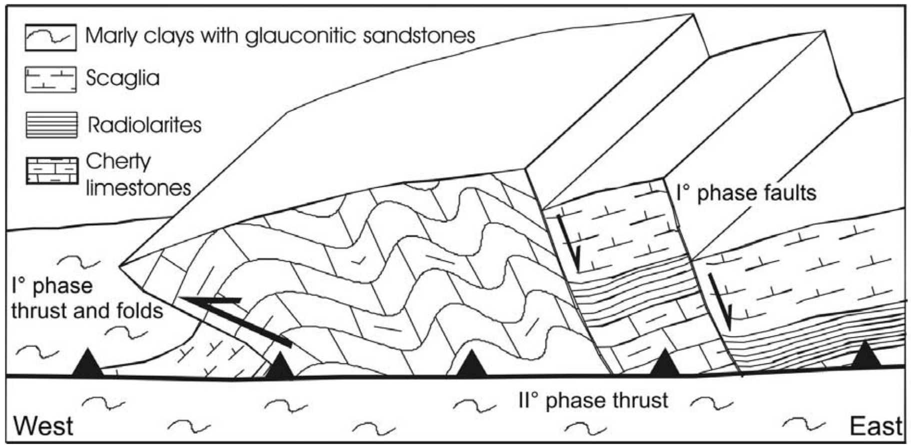

Fig. 10. Simplified kinematic model of relationships between first phase structures and basal thrust (second phase) along the Mt. Judica–Mt. Turcisi ridge; the latter propagates along different stratigraphic level.

5. Discussion and conclusions

The structural analysis carried out in central-eastern Sicily shows the occurrence of two fold and fault systems, with sub-perpendicular axes, related to two distinct tectonic phases. The second and more recent one is also responsible for the piling up of the Mesozoic–Serravallian succession of the Mt. Judica unit to form a south-verging thrust-system and for the folding and thrusting of the Upper Tortonian–Lower Pliocene unconformable deposits. The discontinuity of the ridges along the Mt. Judica–Mt. Turcisi alignment is interpreted as a consequence of the superposition of the second phase basal thrust on a pre-existing sub-perpendicular fold and fault system that gave rise to structural highs, represented by the distinct ridges, and to longitudinally interposed structural depressions (Fig. 10).

The occurrence of two contractional structure systems with sub-orthogonal axes can be variously interpreted. The superposition could be related to a ∼90° azimuthal rotation of the stress field or, alternatively, could be the result of ∼90° rotation of the first phase structures under a quasi-constant stress field characterized by a roughly N–S oriented maximum horizontal compression. New palaeomagnetic data (Speranza et al., 2003) on Upper Triassic–Lower Pliocene sediments of central-eastern Sicily (including the Mt. Judica Unit and the Mt. Pulicara succession), reveal that in this area a major 70° clockwise rotation with respect to the Hyblean foreland took place between Langhian and Late Tortonian times, followed by a further 30° clockwise rotation since the Lower–Middle Pliocene. This latter could be related to block rotation around vertical axes caused by Pliocene–Lower Pleistocene NW–SE striking right-lateral strike-slip faults occurring in the area (see Figs. 1 and 2). As a matter of fact, clockwise rotations related to Pliocene–Lower Pleistocene dextral strike-slip faulting are documented all over northern Sicily (Lentini et al., 1991; Giunta et al., 2000; Guarnieri, 2004; Nigro and Renda, 2005).

Taking into account that during the pre-Tortonian collisional events Africa–Europe convergence was about NNE–SSW oriented (Dewey et al., 1989), the first phase contractional structures of the Mt. Judica unit could be formed with roughly WNW–ESE directions (Fig. 11a). They have been affected by 70° clockwise rotation (Fig. 11b) between Serravallian (age of the Mt. Judica unit top level) and Late Tortonian time (Speranza et al., 2003), assuming the about N–S orientation observed in the Mesozoic–Serravallian Mt. Judica unit succession. Successively, during the Early–Middle

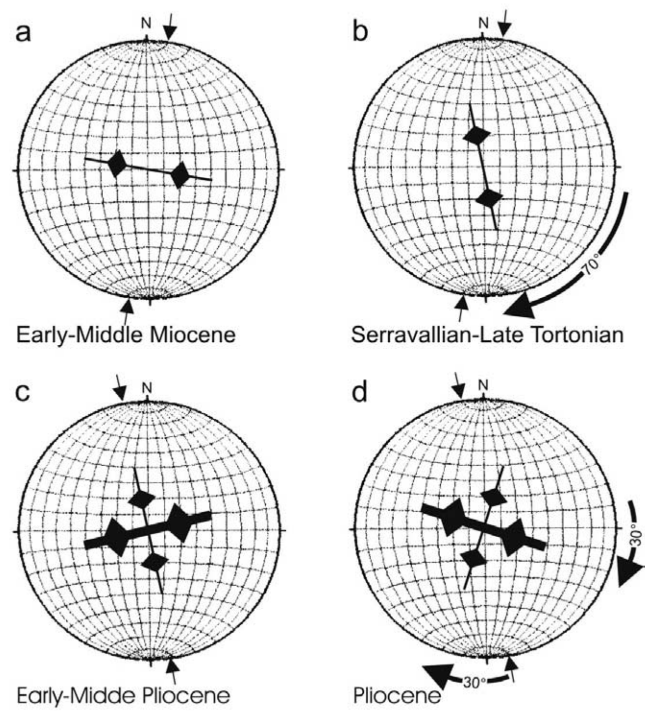

Fig. 11. Timing and geometry of contractional deformation and rotation steps of the Mt. Judica unit succession and overlying Neogene covers: (a) formation of WNW–ESE-trending folds and thrusts induced by SSW–NNE oriented Africa–Europe convergence during the Lower–Middle Miocene early collisional stage; (b) 70° clockwise rotation of first phase structures between Serravallian and Upper Tortonian; (c) formation of ENE–WSW-trending fold and thrust structures induced by NNW–SSE oriented Africa–Europe convergence during the Lower–Middle Pliocene collisional stage; (d) further 30° clockwise rotation of first and second phases structures after the Lower–Middle Pliocene. The arrows indicate the Africa–Europe convergence direction (Dewey et al., 1989; Mazzoli and Helman, 1994); amount and timing of rotation from Speranza et al. (2003).

Pliocene, a second major tectonic event, documented in all of eastern Sicily (Lentini et al., 1996), occurred. It was related to the post-Tortonian Africa–Europe collisional processes, characterized by a NNW–SSE convergence direction (Mazzoli and Helman, 1994), which caused the formation of WSW–ENE-trending folds and SSE-verging thrusts (Fig. 11c). These second phase structures were superimposed on the first system giving rise to interference structures and causing the prevalently northwards tilting of first phase fold axes. During and following this tectonic event, the two superimposed structure systems were involved in a further up to 30° clockwise rotation with respect to the Hyblean foreland (Speranza et al., 2003), resulting in the present tectonic setting observed at Mt. Turcisi, characterised by approximate SSW–NNE and WNW–ESE axial directions (Fig. 11d).

As regards the Upper Tortonian–Lower Pliocene deposits of Mt. Pulicara, structural analysis showed the occurrence of only one system of WNW–ESE-trending thrust propagation folds. These structures developed during the Lower–Middle Pliocene deformation event with structural axes trending WSW–ENE and, together with the structures observed in the Mt. Judica unit, were affected by a further 30° clockwise rotation. This was recorded on Lower Pliocene–Lower Pleistocene deposits of central-eastern Sicily (Speranza et al., 1999, 2003).

The structural analysis carried out in the Mt. Scalpello ridge and along the Mt. Judica–Mt. Turcisi alignment suggest that the Mesozoic–Serravallian succession of the Mt Judica unit recorded both 70° clockwise rotation occurred between Langhian and Tortonian times and, locally, up to 30° clockwise rotation occurred after the Lower Pliocene. In fact, the first phase structural axes observed in the Mt. Judica unit show up to 100° clockwise total rotation, value comparable with the palaeomagnetic data measured by Speranza et al. (2003) in Upper Triassic–Lower Pleistocene sediments of central-eastern Sicily. Structures observed in the Upper Tortonian–Lower-Pliocene deposits of Mt. Pulicara were only involved in the post-Lower Pliocene rotation (up to 30° according to palaeomagnetic data of Speranza et al. (2003)), which produced the present WNW–ESE orientation of the second phase structural axes.

In conclusion, our study shows structural evidence for Neogene rotations in the eastern Sicily fold and thrust belt comparable with palaeomagnetic data collected along the entire Sicilian orogenic belt (Channel et al., 1980, 1990; Grasso et al., 1987; Oldow et al., 1990; Speranza et al., 1999, 2003). According to these authors, the clockwise rotation accompanied thrusting processes since the Middle Miocene, when the Africa–Europe collision triggered the extensive southwards migration of large carbonate nappes and a general oroclinal bending. In our opinion, the clockwise rotation should be associated with the activation of a system of NW–SE striking right-lateral strike-slip faults, with en-échelon arrangement (Fig. 1), along the roughly W–E-trending Sicilian–Maghrebian chain, which accommodated the lateral extrusion of the Calabrian Arc towards the Ionian oceanic domain and consequent spreading of the Tyrrhenian sea (Tapponnier, 1977; Boccaletti et al., 1990; Faccenna et al., 1996; Catalano et al., 2004). This right-lateral strike-slip fault system favoured block rotations around vertical axes and, in general, the advancing of the internal tectonic units towards the eastern sectors of the island under a quasi-constant stress field, related to the N–S Africa–Europe convergence. In this dynamic and kinematical context a problem is raised by the timing: the Pliocene–Lower Pleistocene activity is well documented on field (Ghisetti and Vezzani, 1984; Lentini et al., 1991; Finetti et al., 1996; Giunta et al., 2000; Renda et al., 2000; Guarnieri, 2004), but the Middle–Upper Miocene activity is not clear and needs to be deeply investigated.

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