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The Morphotectonic map of Mt. Etna

CARMELO MONACO (*), GIORGIO DE GUIDI (*) & CARMELO FERLITO (*)

ABSTRACT

The Morphotectonic Map of Mt. Etna (see attached table) is based on detailed field survey of morphologic and structural features outcropping on the volcanic edifice, supported by detailed analysis of orthophotos, stereo-pair photographs and satellite images. It helps to define more completely and accurately than previously done the structural network of active features that characterizes the volcanic edifice, and the relationships between faulting, fissuring and dyke swarms. Morpho-structural data are drawn on a schematic geological map where the main sedimentary and volcanic units have been reported. Morphotectonic analysis shows that Mt. Etna volcano exhibits active extensional features represented by normal faults and eruptive fissures which are related to shallow low-energy seismicity. These accommodate WNW-ESE striking extension, deduced from structural analysis and seismological data, related to incipient rifting processes at regional scale. The fault segments generally control the present topography and show steep escarpments with very young, mostly Late Pleistocene to Holocene, morphology. The most important structures are located along the eastern base of the volcano (Timpe fault system), where NNW-SSE striking normal faults with dextral-oblique component of motion represent the northern end of the Malta Escarpment system. In the north-eastern slope of the volcano these fault system swings to a NE trend which it keeps northwards along the Ionian Coast to Taormina and as far as Messina Straits. The major fissural eruptions occur along well defined, feeder-dykes and spatter cones belts that cut the upper slopes of the volcano, on the footwall of the Timpe fault system. They form NE trending pure extensional swarms along the NE sector of the volcano and en-échelon systems of N-S to NNE-SSW oriented fractures along NNW-SSE trending oblique-dextral shear-zones in the southern and south-eastern slopes. Such summital eruptive fissuring appears to result from the same ESE-striking regional extensional stress that drives active faulting at the base of the volcano suggesting a common tectonic origin.

KEY WORDS: *Mt. Etna volcano, tectonics, geomorphology*.

RIASSUNTO

La Carta Morfotettonica del Monte Etna.

La carta Morfotettonica dell'Etna (titolo in italiano: Carta Geologica Schematica del Monte Etna; v. tavola allegata) è basata sul rilevamento di dettaglio dei caratteri morfologici e strutturali affioranti sull'edificio vulcanico, supportato dall'analisi dettagliata di foto aeree a scala 1:10.000, ortofoto e immagini da satellite. Il prodotto, supportato da un data-base su piattaforma GIS, mostra in modo più completo e accurato rispetto a quanto pubblicato in passato il sistema di strutture attive che caratterizza l'edificio vulcanico e le relazioni tra faglie, fratture e dicchi di alimentazione. L'insieme dei dati è stato inoltre utilizzato per correlare l'evoluzione strutturale dell'Etna con il presente contesto tettonico regionale della Sicilia orientale. I dati morfo-strutturali sono stati tracciati su una carta geologica schematica dove sono state riportate le maggiori unità tettoniche e sedimentarie.

Per quanto riguarda la successione stratigrafica, i prodotti vulcanici sono stati distinti dal substrato sedimentario del vulcano. Quest'ultimo è costituito, nei settori settentrionali e occidentali dell'edificio vulcanico, dalle unità tettoniche frontali della catena Maghrebide e dalle loro coperture neogeniche, mentre nei settori meridionali e orientali è rappresentato dalle successioni sedimentarie pleistoceniche d'avanfossa contenenti livelli di vulcaniti tholeiitiche. I prodotti vulcanici dell'Etna sono correlati all'attività di differenti centri eruttivi che sono stati raggruppati in cinque unità vulcano-stratigrafiche, qui denominate «*Basal Tholeiitic volcanics*» (500-200 ka), «*Timpe volcanics*» (200-100 ka), «*Valle del Bove volcanics*» (100-60 Ka), «*Ellittico volcanics*» (60-15 ka) e «*Mongibello volcanics*» (15-0 ka).

L'analisi strutturale ha evidenziato che per una lunghezza di circa 30 km lungo il basso versante orientale del vulcano, tutti i segmenti del sistema di faglie delle Timpe, con direzione NE o NNW, mostrano evidenza di prevalenti meccanismi normali. Questo è il risultato di un estensione orientata ~ N100°E, correlata a processi di *rifting* incipienti a scala regionale. I segmenti di faglia orientati NNW-SSE mostrano una componente obliqua, laterale-destra, di movimento. I segmenti di faglia controllano la topografia attuale e sono caratterizzati da scarpate ripide e rettilinee («Timpe»), prevalentemente immergenti verso est, formatesi a partire dal Pleistocene medio-superiore. La marcata differenza d'altezza delle scarpate cumulative di faglia è dovuta al differente rigetto di prodotti vulcanici di età variabile accumulatisi su diversi settori delle strutture analizzate. I tassi di movimento delle faglie principali sono stati determinati utilizzando profili topografici di dettaglio attraverso le maggiori scarpate, rapportando la loro altezza all'età dei prodotti. Ciò ha consentito di stimare tassi di movimento verticale di 1-2 mm/a per la maggior parte dei segmenti di faglia. Queste strutture sono sismicamente attive, avendo dato luogo a terremoti superficiali di bassa magnitudo negli ultimi 150 anni, localizzati principalmente a cavallo dei segmenti orientati NNW-SSE. Le maggiori eruzioni fissurali dell'Etna sono avvenute lungo fratture eruttive che sono ubicate nelle parti alte dell'edificio vulcanico al letto del sistema di faglie delle Timpe, con direzione prevalente SW-NE, nel versante nord-orientale, e da N-S a NW-SE in quello meridionale. Queste fessure eruttive, talora disposte en-echelon nel versante meridionale, sono il risultato dello stesso regime tettonico regionale che, con direzione d'estensione WNW-ESE, determina la formazione di faglie attive lungo il basso versante orientale del vulcano. A livello più dettagliato, la geometria e il senso di movimento della maggior parte delle principali strutture attive presenti sul vulcano, sia le faglie, normali o oblique, che le fratture, eruttive o secche, sono cinematicamente compatibili e dunque possono essere riferiti ad un'origine tettonica comune. Tali affinità geometriche e cinematiche suggeriscono che la maggior parte degli elementi estensionali del vulcano si collegano in profondità e rappresentano l'espressione superficiale di una zona di faglia normale profonda, crostale o litosferica, determinata dalla separazione tettonica dei blocchi ionico e ibleo (sistema della scarpata di Malta), riattivata durante il tardo Quaternario.

TERMINI CHIAVE: *Vulcano Etna, tettonica, geomorfologia*.

INTRODUCTION

A detailed fieldwork, integrated by accurate analysis of 1:10,000 and 1:33,000 scale stereo-pair photographs, LANDSTAT and SPOT satellite images and 1:10,000-1:25,000 scale topographic maps, was carried out to define the morphologic features of Mt. Etna volcano, the distribution of active faults, eruptive fractures, vents and the

(*) Dipartimento di Scienze Geologiche, Università di Catania, Corso Italia, 55 - 95129 Catania. E-mail: cmonaco@unict.it

determination of their deformation rates. All these elements have been traced on the «Morphotectonic map of Mt. Etna» (see attached table), where the main stratigraphic units have also been reported. The topographic model has been obtained by elaboration of 1:10,000 scale digital terrain data reproduced at scale 1:75,000, with 50 m contour interval. The shaded relief orographic representation of DEM (Digital Elevation Model) has been draped with geological and morphological features of Mt. Etna. Moreover, a reconstruction of the sedimentary basement of the volcanic edifice was also produced by the analysis of the available well-logs and by interpretation of geophysical data. Taking into account that the accumulation of volcanic products since about 200 ka ago permitted to record the tectonic activity occurred along the Mt. Etna slopes, in this paper we have also tried to determine the deformation rates of fault systems (fig. 1). Finally, the data set is used to relate the structural evolution of Mt. Etna to the regional, active tectonic framework of eastern Sicily.

GEODYNAMIC SETTING

Mount Etna (fig. 1) is a Quaternary composite volcano, characterized by Na-alkaline magmatism, which has grown to its present elevation of 3320 m by accumulation of lavas and pyroclastics, erupted during the last 200 ka (GILLOT *et alii*, 1994). It is located in central-eastern Sicily at the front of the Maghrebian thrust belt. The eastern and southern sectors of the volcano lie mostly on an Early-Middle Pleistocene foredeep clayey succession deposited on the flexured margin of the Pelagian block (LENTINI, 1982; BEN AVRAHAM *et alii*, 1990). During the Late Quaternary, the contractional structures of the orogen were superseded by extensional faults, which form a currently active tectonic belt characterized by strong seismicity and active volcanism (Siculo-Calabrian Rift Zone or SCRZ, see inset in fig. 1; MONACO *et alii*, 1997; MONACO & TORTORICI, 2000). Active faulting contributes to a continuous extensional deformation from eastern Sicily to western Calabria. The ESE-WNW extension direction is deduced from structural analysis (TORTORICI *et alii*, 1995; MONACO *et alii*, 1997; JACQUES *et alii*, 2001; FERRANTI *et alii*, 2007), seismological data (CELLO *et alii*, 1982; GASPARINI *et alii*, 1982; ANDERSON & JACKSON, 1987; CMT 1976-2006 and RCMT 1997-2006 Catalogues) and from VLBI (WARD, 1994) and GPS (D'AGOSTINO & SELVAGGI, 2004; GOES *et alii*, 2004; MATTIA *et alii*, 2009) velocity fields. In eastern Sicily the normal faults are mostly located offshore and controls the Ionian coast from Messina to the eastern lower slope of Mt. Etna, joining southwards to the system of the Malta Escarpment, a Mesozoic discontinuity separating the continental crust of the Pelagian Block (Hyblean Plateau; BUROLLET *et alii*, 1978) from the oceanic crust of the Ionian Sea (MAKRIS *et alii*, 1986). Offshore fault activity is related to historical seismicity characterized by intensities of up to XI-XII MCS and M ~7, such as the 1169, 1693 and 1908 events (BARATTA, 1901; POSTPISCHL, 1985; BOSCHI *et alii*, 1995). The Mt. Etna area is part of the footwall of the Late Quaternary east-facing crustal scale normal fault system (ELLIS & KING, 1991; CONTINISIO *et alii*, 1997; MONACO *et alii*, 1997; HIRN *et alii*, 1997; BIANCA *et alii*, 1999; NICOLICH *et alii*, 2000; ARGNANI & BONAZZI, 2005) which has partially reactivated the Malta Escarpment.

Extensional tectonics have been the dominant mode of deformation controlling the time-space evolution of magmatism at Mt. Etna. In fact, the location on the footwall of a regional normal fault system, together with favourable conditions for melting in the mantle (HIRN *et alii*, 1997; TANGUY *et alii*, 1997; CLOCCHIATTI *et alii*, 1998), and the volcano-tectonic features and seismicity along the eastern flank of the volcano (MONACO *et alii*, 1995, 1997, 2005; GRESTA *et alii*, 1997; AZZARO, 1999; PATANÈ *et alii*, 2004) suggest that volcanism of Mt. Etna could be a direct consequence of WNW-ESE trending regional extension related to incipient rifting processes (SCRZ, see inset in fig. 1; TAPPONNIER, 1977; ELLIS & KING, 1991; CONTINISIO *et alii*, 1997; MONACO *et alii*, 1997). Alternatively, the extensional processes could be related to vertical motion of asthenospheric material at the south-western border of the roll-backed Ionian slab subducting beneath the Tyrrhenian lithosphere (HIRN *et alii*, 1997; GVIRTZMAN & NUR, 1999; DOGLIONI *et alii*, 2001).

Analysis of both historical and instrumental seismic data shows that more than 80% of the earthquakes on Mt. Etna are very shallow (h<5 km), and mainly located on the eastern side of the volcano (GRESTA *et alii*, 1990; 1998). In this sector of the volcano the shallow seismicity mostly originates from the NNW-SSE trending seismogenic structures (see below). Conversely, swarms of deeper (h>10 km) earthquakes occur on the western side of the volcano, with foci distribution mostly trending along NNW-SSE and SW-NE directions (GRESTA *et alii*, 1990; PATANÈ & PRIVITERA, 2001).

Focal mechanism analyses and stress tensor computations indicate a dominant NNW-SSE orientation of P axis and a maximum compressive stress (σ_1) in the lower crust (h≥10 km) beneath the western sector of the volcanic edifice (COCINA *et alii*, 1997; LANZAFAME *et alii*, 1997; PATANÈ & PRIVITERA, 2001). This is consistent with the regional pattern characterizing central and western Sicily (MONACO *et alii*, 1996; CACCAMO *et alii*, 1996; FREPOLI & AMATO, 2000; LAVECCHIA *et alii*, 2007), related to the Africa-Europe convergence (WARD *et alii*, 1994; GOES *et alii*, 2004; FERRANTI *et alii*, 2008). This compressive domain coexists with the ESE-WNW extensional regime that produces the coseismic faulting along the lower eastern slope of the volcano edifice (HIRN *et alii*, 1997; GRESTA *et alii*, 1997; MONACO *et alii*, 1997; AZZARO, 1999).

STRATIGRAPHIC SUCCESSION

The sedimentary substratum of Mt. Etna is constituted by the frontal tectonic units of the Maghrebian chain (fig. 3a) and their Neogene covers in the northern and western sectors of the volcanic edifice and by foredeep Pleistocene sedimentary sequences containing several horizons of tholeiitic volcanics in the eastern and southern sectors (LENTINI, 1982). The volcanic products of Mt. Etna are related to the activity of distinct eruptive centers, which have been grouped in five main volcano-stratigraphic units here dubbed «Basal Tholeiitic volcanics» (500-200 ka), «Timpe volcanics» (200-100 ka), «Valle del Bove volcanics» (100-60 ka), «Ellittico volcanics» (60-15 ka) and Mongibello volcanics (15-0 ka)

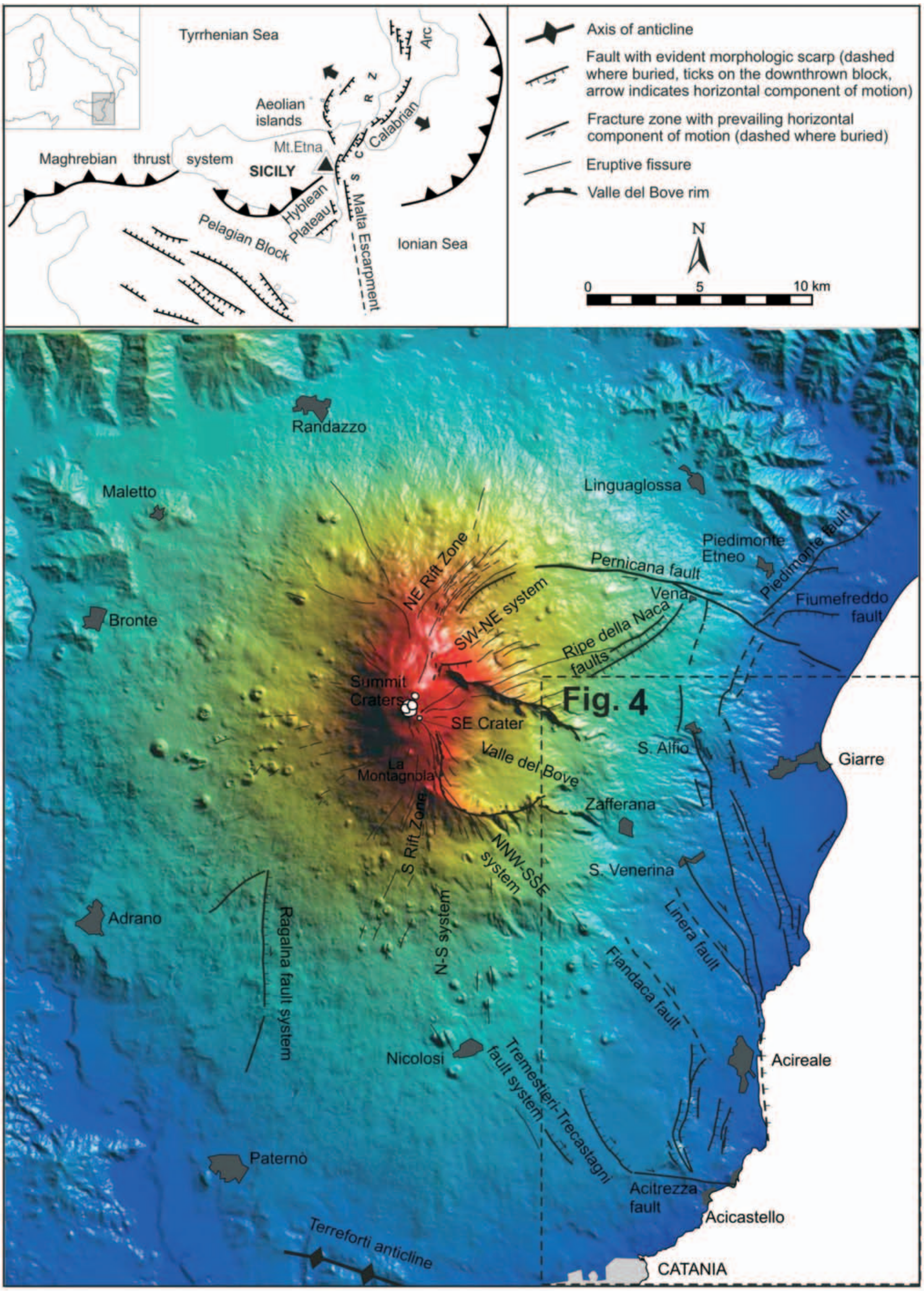
Tyrrhenian Sea
Aeolian islands
Mt.Etna
SICILY
Maghrebian thrust system
Hyblean Plateau
Pelagian Block
Malta Escarpment
Calabrian Arc
Ionian Sea
Axis of anticline
Fault with evident morphologic scarp (dashed where buried, ticks on the downthrown block, arrow indicates horizontal component of motion)
Fracture zone with prevailing horizontal component of motion (dashed where buried)
Eruptive fissure
Valle del Bove rim
N
0 5 10 km
Randazzo
Maletto
Bronte
Linguaglossa
Piedimonte Etneo
Piedimonte fault
Pernicana fault
Vena
Fiumefreddo fault
NE Rift Zone
SW-NE system
Ripe della Naca faults
Summit Craters
SE Crater
Fig. 4
S. Alfio
Giarre
La Montagnola
Valle del Bove
Zafferana
S Rift Zone
NNW-SSE system
S. Venerina
Adrano
Ragalna fault system
N-S system
Linera fault
Fiandaca fault
Acireale
Nicolosi
Tremestieri-Trecastagni fault system
Paternò
Acitrezza fault
Acicastello
Terreforti anticline
CATANIA

Fig. 1.

(Rittmann, 1973; Romano, 1982; Chester *et alii*, 1985; Gillot *et alii*, 1994; Branca *et alii*, 2004, 2007; De Beni *et alii*, 2005). The detailed description of the stratigraphic succession, from the bottom to the top, follows.

Sedimentary succession of the Etnean substratum

Tectonic units of the chain and Neogene sedimentary covers (Cretaceous-Early Pliocene)

The sedimentary rocks outcropping at the bottom of the northern and western sectors of the volcanic edifice along the Simeto river and Alcantara river valleys, respectively, include tectonic units of the chain front and Neogene deposits filling piggy-back basins (Lentini, 1982; Roure *et alii*, 1990). Along the upper valley of the Simeto river they are represented by Upper Oligocene-Lower Miocene pelitic-arenaceous successions with intercalations of quartzarenitic banks (Numidian Flysch, fig. 3a) and by Cretaceous-Palaeogene Varicoloured Clays. Along the lower valley of the Simeto river, between Adrano and Paternò, these tectonic units are unconformably overlayed by Tortonian marly sandy deposits (Terravecchia Formation), by the Messinian gypsum-sulphur succession (the so called «Serie Gessoso-Solfifera») and by Lower Pliocene whitish marly limestones («Trubi»). Along the Alcantara river valley the tectonic units are represented by Varicoloured Clays and by pelitic-arenaceous successions with intercalations of arenitic banks, that are the Cretaceous-Palaeogene Monte Soro Flysch and the Upper Oligocene-Lower Miocene Capo d'Orlando Flysch (Lentini, 1982).

Marly clays, sands and conglomerates (Early-Middle Pleistocene)

In the area to the south of Mt. Etna (the «Terreforti» hills) and locally along the Ionian shoreline, at the front of the thrust belt, the Quaternary sedimentary substratum of the volcanic edifice outcrops. It is made up of a Lower-Middle Pleistocene foredeep succession (Wezel, 1967; Di Stefano & Branca, 2002) of bluish marly silty clays with rare intercalations of fine-grained sands, up to 600 m thick, upward evolving to some tens of meters of cross-bedded yellowish quartzose sands with intercalations of rare levels of whitish pumices and frequent lenses of poligenic conglomerates, containing volcanic clasts with tholeiitic composition, interpreted as channel fillings in a fluvial-deltaic environment. These deposits, referred to the Mindel-Riss interglacial stage by Kieffer (1971), are unconformably overlain by terraced sands and/or conglomerates (Kieffer, 1971; Chester & Duncan, 1982; Monaco, 1997) of coastal alluvial origin (see below). In the Terreforti area, there are evidence of the Etnean submarine to subaerial fissural early activity (Romano, 1982), represented by products of tholeiitic-transitional affinity (the «pre-Etnean volcanism»). These products, coeval or following the deposition of the Mt. Etna Quaternary substratum sediments, are constituted by the lava flows (350-250 ka; Gillot *et alii*, 1994) outcropping east of Paternò at the top of sands and conglomerates of the oldest terrace, and by the neck of Motta Sant'Anastasia, intruded in the same terraced deposits (see below).

Products of the Mt. Etna volcanic district

Basal tholeiitic volcanics (500-200 ka)

The oldest volcanic product of the area are represented by lava flows, pillow lavas, hyaloclastites and subvolcanic bodies, with tholeiitic composition, related to the fissural activity of the period preceding the formation of the early Etnean alkaline centers. Lavas show columnar joints and porphiritic texture with phenocrysts of plagioclase and olivine (Romano, 1982; Cristofolini & Romano, 1982).

The oldest tholeiites (500-400 ka, Gillot *et alii*, 1994) are constituted by pillow lavas and hyaloclastites, outcropping at distinct levels of the Pleistocene marly clays along the Acicastello-Acitrezza coast (fig. 2), and by the subvolcanic body of the Ciclopi islands, intruded in the Pleistocene marly clays (Corsaro & Cristofolini, 1997, 2000). In the south-western sector of the volcano, more recent products outcrop between Adrano and Paternò, forming tabular lava banks hanging 350 m above the Simeto valley (350-250 ka, Gillot *et alii*, 1994) that overlies an alluvial terrace (330 ka old paleo-Simeto terrace, Monaco *et alii*, 2002), gently dipping to the south-east, located at altitudes between 600 and 430 m a.s.l, covered in turn by terraced alluvial deposits (see below). The most recent volcanics are represented by transitional products locally outcropping at the bottom of the Timpa of Acireale (225 ka; Gillot *et alii*, 1994) and by the neck of Motta Sant'Anastasia (~200 ka, Del Negro *et alii*, 1998) (fig. 2).

Timpe volcanics (200-100 ka)

The Timpe volcanics (Branca *et alii*, 2004) have been emitted by isolated centres (e.g. Calanna, Paternò, Romano, 1982; Valverde, Monaco & Ventura, 1995) or by fissures located along the present shoreline (e.g. Timpa di Acireale) during the early activity of the Mt. Etna volcanic district (fig. 2). They correspond to the ancient alkaline centers of Romano (1982) and are constituted by light grey massive lava banks, locally showing columnar joints, with intercalations of levels of yellowish cinders and brown-reddish scoriae. The composition is usually hawaiitic to basaltic even if some basal lava banks of the Timpa of Acireale show transitional affinity (Romano, 1982). The lava texture is porphiritic with phenocrysts of pyroxene, olivine and plagioclase.

North of Catania and in the San Gregorio-Valverde-Acitrezza area they form tabular lava banks that overlies fluvial-coastal terraces located at altitudes between 300 and 170 m a.s.l. (Kieffer, 1971; Monaco, 1997; Monaco

Fig. 1 - Map of active tectonics of Mt. Etna. Inset shows the central Mediterranean area and the location of Mt. Etna within the Siculo-Calabrian Rift Zone (SCRZ; Monaco & Tortorici, 2000); large arrows indicate mean, regional extension direction; lines with barbs correspond to main Quaternary normal faults, lines with triangles indicate the front of the Siculo-Maghrebian thrust system.
– Mappa delle strutture tettoniche attive del M. Etna. Il riquadro mostra l'area del Mediterraneo centrale e l'ubicazione del M. Etna lungo la Siculo-Calabrian Rift Zone (SCRZ; Monaco & Tortorici, 2000); le frecce indicano la direzione di estensione regionale media, le linee con i trattini corrispondono alle principali faglie normali quaternarie, le linee con i triangoli il fronte del sistema a thrust Siculo-Maghrebide.

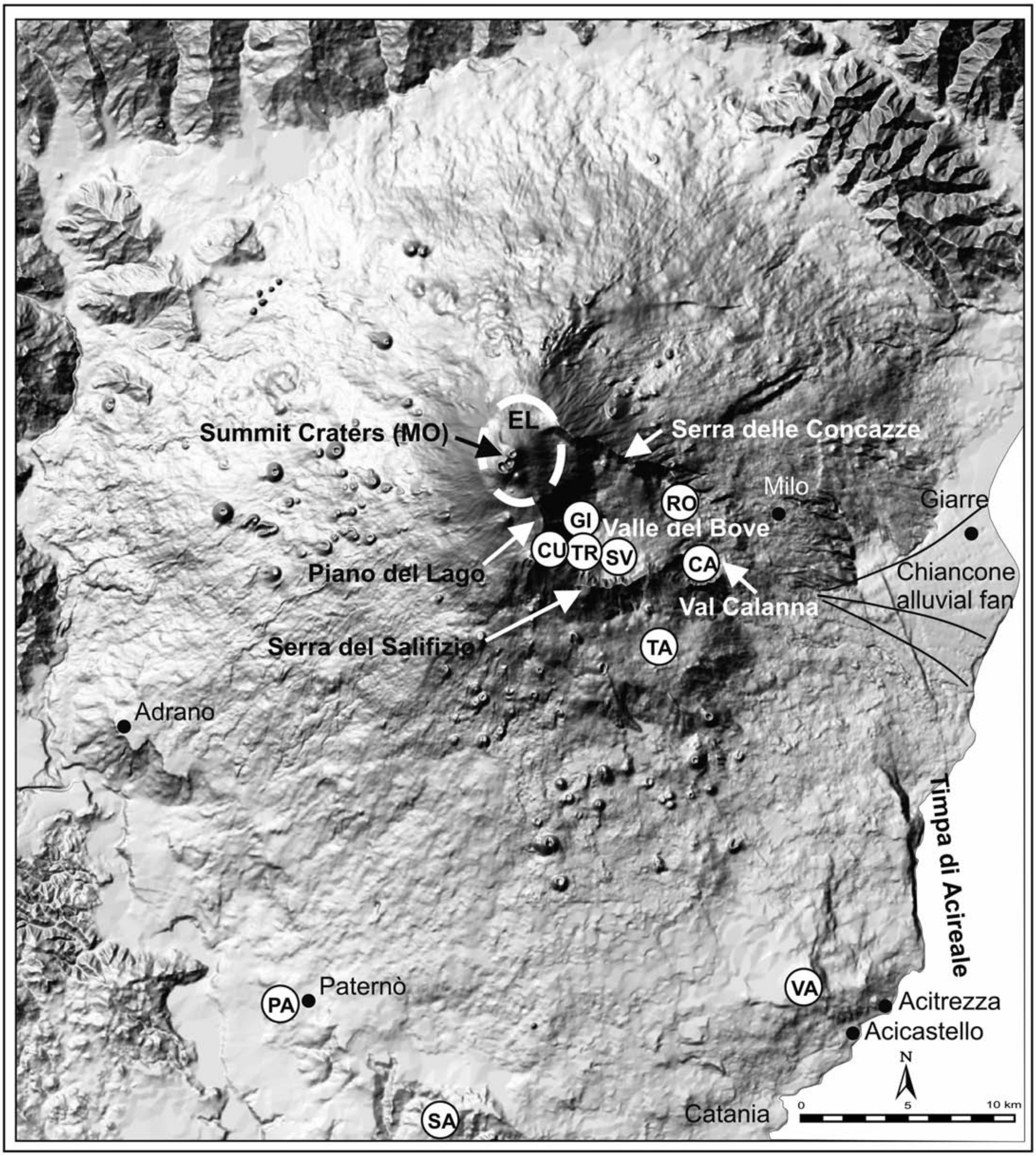

Fig. 2 - Map showing the main eruptive centers active during the distinct volcanic phases of Mt. Etna (see text for explanation): CA, Calanna; CU, Cuvigghiuni; EL, Ellittico; GI, Giannicola; MO, Mongibello; PA, Paternò; RO, Rocche; SA, Motta Sant'Anastasia; SV, Salifizio-Vavalaci; TA, Tarderia; TR, Trifoglietto; VA, Valverde (ROMANO, 1982; BRANCA *et alii*, 2004).
– *Mappa mostrante i principali centri eruttivi attivi durante le distinte fasi vulcaniche del M. Etna (vedi testo per ulteriori spiegazioni): CA, Calanna; CU, Cuvigghiuni; EL, Ellittico; GI, Giannicola; Mo, Mongibello; PA, Paternò; RO, Rocche; SA, Motta Sant'Anastasia; SV, Salifizio-Vavalaci; TA, Tarderia; TR, Trifoglietto; VA, Valverde (ROMANO, 1982; BRANCA* et alii, *2004).*

et alii, 2002), covered in turn by terraced alluvial deposits (see below). The outcropping scarps represent marine palaeo-cliffs developed during the Middle-Late Pleistocene marine high-stands. In particular, in the northern outskirts of Catania these products overlay cemented layers or banks of arenitic to ruditic brown-blackish epiclastics. Along the Timpa of Acireale (FERRARA, 1976; CORSARO *et alii*, 2002) they outcrop at the bottom of the cliff where they dip at about 10° toward the west and are overlaid by an interval of volcanoclastic products accumulated either in a continental (conglomerates and caotic breccias) or marine environment (whitish fossiliferous tufites).

As regards the period of activity, the transitional products locally outcropping at the bottom of the Timpa of Acireale have been dated 225 ka (GILLOT *et alii*, 1994), whereas absolute age determinations for the alkaline Timpe volcanics yielded an oldest age of about 180 ka (GILLOT *et alii*, 1994) and a youngest one of about 100 ka (GILLOT *et alii*, 1994; BRANCA *et alii*, 2004, 2007; DE BENI *et alii*, 2005).

Valle del Bove volcanics (100-60 ka)

The Valle del Bove volcanics (BRANCA *et alii*, 2004) are constituted by alternances of lava flows and scorias, breccias and lapilli levels cropping out along the western and southern walls of the Valle del Bove (see below). These products are related to the activity of the Rocche, Trifoglietto, Giannicola, Salifizio-Vavalaci and Cuvigghiuni eruptive centers, whose axes are located inside the Valle del Bove (fig. 2) (LO GIUDICE, 1970; RITTMANN, 1973; LO GIUDICE *et alii*, 1974; ROMANO, 1982; CHESTER *et alii*, 1985; BRANCA *et alii*, 2004). According to BRANCA *et alii* (2004), also the activity of the Tarderia center, located south of the Valle del Bove, can be related to this phase of activity. All these volcanics partially correspond to the Trifoglietto Unit of ROMANO (1982). The composition is usually more evolved than the present-day volcanics, being the products mugearitic and benmoeritic (CRISTOFOLINI & ROMANO, 1982; CRISTOFOLINI *et alii*, 1991). The lava texture is porphiritic with phenocrysts of plagioclase, pyroxene and subordinately kaersutitic anphibole. In this unit are included the subvolcanic bodies of Serra Cuvigghiuni and Serra Giannicola, a few hundreds meters thick, characterized by massive texture and columnar joints.

Absolute dating of these products suggest a starting period at about 100 ka along the eastern sector of the Valle del Bove (Trifoglietto and Rocche) or to the south (Tarderia; BRANCA *et alii*, 2004, 2007); successively, between 80 and 60 ka, the eruptive activity migrated to the western sector, where the collapsed remains of the other eruptive centers outcrop (GILLOT *et alii*, 1994).

Ellittico volcanics (60-15 ka)

The Ellittico volcanics are constituted by lava flows and volcanoclastic deposits related to the effusive and explosive activity of the Ellittico eruptive center, whose axis is located inside the homonymous caldera (fig. 2). Thick alternances of lava flows and levels of scorias and breccias outcrop along the western and northern walls of the Valle del Bove. The composition is variable from hawaiitic to mugearitic-benmoreites. The lava texture is porphiritic with phenocrysts of plagioclase, pyroxene and olivine.

Peripheral portions of Ellittico lava flows outcrop at the northeastern, northern and western boundary of the volcanic edifice, where they form large tabular lava banks overlying alluvial terraces and hanging above the Alcantara and Simeto river valley. One of these is represented by the Barcavecchia lava flow that north of Adrano flowed into the Simeto valley and, following the river course, widened as far as the confluence with the Salso river where, presently, it appears intercalated in alluvial deposits. K/Ar dating of this lava flow yielded ages of 35 ka (GILLOT *et alii*, 1994) and 41 ka (BLARD *et alii*, 2005).

The top portion of this unit is constituted by products with trachitic composition such as the 15 ka old (K/Ar dating; GILLOT *et alii*, 1994), autoclastic lava dome outcropping at Monte Calvario, north-east of Biancavilla, the reddish foam lava flows outcropping in Punta Lucia area and volcanoclastics (COLTELLI *et alii*, 2000). These latter include i) piroclastic fall deposits constituted by cinders, scoriaceous lapilli, reddish unwelded breccias and yellowish pumices, with hawaiitic to benmoreitic-trachitic composition, outcropping in the Pizzi Deneri area, west of Giarre and between Acireale and San Gregorio, ii) unwelded breccias with trachitic composition, produced by pyroclastic flow, outcropping between Ragalna and Biancavilla and iii) debris flow deposits and epiclastics constituted by eterogeneous lava blocks up to metre in size with silt-arenitic matrix, outcropping in the same area. Radiocarbon dating on coal fragments included in the Ragalna-Biancavilla pyroclastic flow revealed an age of about 15 ka (KIEFFER, 1979; ROMANO, 1982; CORTESI *et alii*, 1988).

The overall age of the ellittico volcanics (60-15 ka) can be deduced by its stratighaphic position and by absolute dating (KIEFFER, 1979; ROMANO, 1982; CORTESI *et alii*, 1988; GILLOT *et alii*, 1994). The pyroclastic fall and flows products are related to the final collapse of the Ellittico caldera, whose border is presently located at about 2900 m a.s.l., occurred about 15 ka ago (ROMANO, 1982).

Fluvial-coastal terraced deposits (Middle-Late Pleistocene)

Between the southern border of the volcano and the Catania Plain, a flight of coastal alluvial terraces of the Simeto River with inner edges located at altitudes between 300 and 45 m a.s.l., carve the foredeep clayey deposits. They are constituted by cross layered brown-yellowish sands containing pebble levels, fragments of mollusc shells and arenitic-ruditic blackish epiclastic levels, generally passing upwards to polygenic conglomerates of alluvial origin. The morphotectonic evolution of the foredeep area has been coeval to the distinct stages of the pre-Etnean and Etnean volcanism. So, the terraced alluvial and marine conglomerates occurring south of Mt. Etna contain volcanic clasts of Etnean origin as well as sedimentary clasts deriving from the erosion of the Siculo-Maghrebian Chain. In particular, the different terraces are characterised by associations of volcanic clasts whose petrologic features depends on the volcanic stage during which they were involved in the sedimentary processes. On the basis of petrographic determinations and consequent attributions of the volcanic clasts to the different Etnean volcanostratigraphic units (see MONACO, 1997; MONACO *et alii*, 2000, 2002), whose age has been determined by GILLOT *et alii* (1994), we related the coastal alluvial terraces to the different Marine Isotopic Stages (MIS) stages corresponding to sea-level high-stands of the eustatic curve (WAELBROECK *et alii*, 2002 and references therein). This method (BOSI *et alii*, 1996) allowed us to constrain the age of the terraces at 330-40 ka and consequently to estimate the chronology of the structures in which the terraces are involved, such as the large anticline (the Terreforti anticline) outcropping between the lower southern slope of Mt. Etna and the Catania Plain (see below).

Along the Ionian coast, the uplift of the region since the Middle-Late Pleistocene is confirmed by flights of marine terraces. NW of Acitrezza, beach deposits containing basaltic conglomerates, sands and fragments of shells, have been found at 175 m a.s.l. interposed between the Timpe volcanics (MONACO, 1997). Taking into account the age of the lava flows, this horizon has to be related to the 125 ka Tyrrhenian high-stand (MIS 5.5). The distribution of the other paleo-shorelines observed in the area (KIEFFER, 1971), at an altitude of 265 m, 125 m, 100 m and 60 m, suggests the correlation of these with the 200 ka, 100 ka, 80 ka and 60 ka high-stands, respectively. A similar distribution has been observed ten kilometres to the south in the urban area of Catania, where the stratigraphy has been reconstructed by the integration of field data with bore-hole and seismic information (MONACO *et alii*, 2000). Here, a Lower-Middle Pleistocene marine clayey succession is carved by a flight of five marine terraces and dissected by deeply entrenched valleys, filled with lava flows belonging to the Mongibello volcanics (see below). The marine terraces, located at elevations between 170 m and 14 m a.s.l., have been correlated with sea level high-stands between 125 ka and 40 ka by relationships with dated Etnean lavas and volcanic clasts (see MONACO *et alii*, 2002 and references therein).

Along the valleys of the Alcantara and Simeto rivers, Late Pleistocene fluvial deposits, constituted by pebbles, sands and clayey silts, are terraced in distinct orders and elevations. In the area between Adrano and Paternò, deposits of travertine are associated to the terraced alluvial sediments.

Mongibello volcanics (15-0 ka)

The most recent and widely outcropping volcanic products of Mt. Etna are represented by lava flows and volcanoclastic deposits related to to the effusive and explosive activity of the summit craters and/or lateral vents of the Mongibello eruptive center (fig. 2). It grew immediately after the collapse of the Ellittico volcanic center (see above) inside the previous caldera (see cross-section in the attached table). Lava surfaces generally present a scoriaceous morphology with aa and block flows and subordinately pahoehoe flows. Composition is variable, from hawaiitic to mugearitic, texture from aphiric to strongly porphiritic with phenocrysts of plagioclase, pyroxene and olivine. Vulcanoclastic deposits are represented by fall pyroclastics (bombs, scoriaceous lapilli and sands) forming the numerous flank cones or by debris flow deposits cropping out on the eastern slope of the vulcano, between Milo and Giarre (COLTELLI *et alii*, 2000). Lava flows and volcanoclastics with certain age (see also ROMANO & STURIALE, 1982; CHESTER *et alii*, 1985; TANGUY & KIEFFER, 1993; BRANCA & DEL CARLO, 2004; TANGUY *et alii*, 2007) and/or well preserved surface morphology and well defined flow boundaries have been distinguished from those with degraded surface morphology and poorly defined flow boundaries.

A large gently-sloping alluvial fan, presently inactive, fills a structural depression in the easternmost slope of the volcano (fig. 2), between Giarre-Riposto and Pozzillo (*Chiancone*). It is constituted by volcanoclastic deposits, pebbles and blocks, coarsely layered, from centimetre to metre in size, with sandy matrix. Along the coastline they form an up to 20 m high cliff, prone to rapid marine erosion. As regards the age, morphotectonic and stratigraphic remarks, together with radiocarbon dating (5-7 ka; KIEFFER, 1979; CALVARI & GROPPELLI, 1996), suggests that the alluvial fan formed after the Last Glacial Maximum (LGM), because of the post-glacial abundant rain-fall. Moreover, the location of the fan apex immediately east of the opening of the Valle del Bove, a large collapsed area occurring in the eastern flank of the volcano, suggests a tight relationships between the post-glacial erosion of this depression, the Ellittico collapse and the feeding of the Chiancone deposits (CALVARI *et alii*, 2004).

Recent and present-day alluvial and shoreline deposits (Holocene)

Pebbles, sands and clayey silts constitute the present-day bed or the lateral deposits of the main rivers. Pebbles and coarse sands form the main beaches along the Ionian shoreline. They have been deposited during the last climatic cycle and along the coastal areas are related to the present base level. As a whole, they form the coastal-alluvial plain of the Alcantara and Simeto rivers, located northeast an south of the Mt. Etna volcanic edifice, respectively.

MORPHOTECTONIC FEATURES

The morphotectonic evolution of the Mt. Etna area during the Late Quaternary is characterized by the coexistence of contractional structures at the front of the Siculo-Maghrebian thrust system and extensional structures along the Ionian onshore and offshore (LABAUME *et alii*, 1990). Contractional processes have been followed by

Fig. 3 - a) Numidian Flysch sequence at the front of the Maghrebian Chain (Mt. Etna on the background); *b*) 1879 eruptive fissure along the NE Rift; *c*) Aerial view of the 200 m high scarp («timpa») of the Acireale fault between Acireale (on the footwall) and Santa Tecla (on the hangingwall); *d*) Aerial view of the San Leonardello graben; the entrenched valley of the Fago river is evident; *e*) Ground rupture along the Santa Venerina fault caused by the earthquake of 29/10/2002 at San Giovanni Bosco; *f*) Fissured 2nd world war bunker on the top of the 10 m high scarp of the Trecastagni fault between San Giovanni la Punta and San Gregorio; *g*) Fissure in stone building along the Acitrezza fault caused by the 2002 creep event at Acitrezza; *h*) Left-lateral offset of ~40 cm in the asphalt of the road S.P. 59 (near Vena) along the Pernicana fault, caused by the earthquake of 27/10/2002.

– a) *Successione del Flysch Numidico al fronte della catena maghrebide (M. Etna sullo sfondo);* b) *Fessura eruttiva del 1879 lungo il Rift di NEt;* c) *Veduta aerea della scarpata («timpa») alta 200 m della faglia di Acireale tra Acireale (al letto) e Santa Tecla (al tetto);* d) *Veduta aerea del Graben di San Leonardello; è evidente la valle reincisa del Torrente Fago;* e) *Rottura del terreno lungo la faglia di Santa Venerina causata dal terremoto del 29/10/2002 a San Giovanni Bosco;* f) *Bunker della II guerra mondiale fessurato in cima alla scarpata alta 10 m della faglia di Trecastagni tra San Giovanni la Punta e San Gregorio;* g) *Fessura in muro in pietra lungo la faglia di Acitrezza causata dall'evento di creep del 2002 ad Acitrezza;* h) *Rigetto sinistro di ~40 cm nell'asfalto della S.P. 59 (nei pressi di Vena) lungo la faglia della Pernicana, causato dal terremoto del 27/10/2002.*

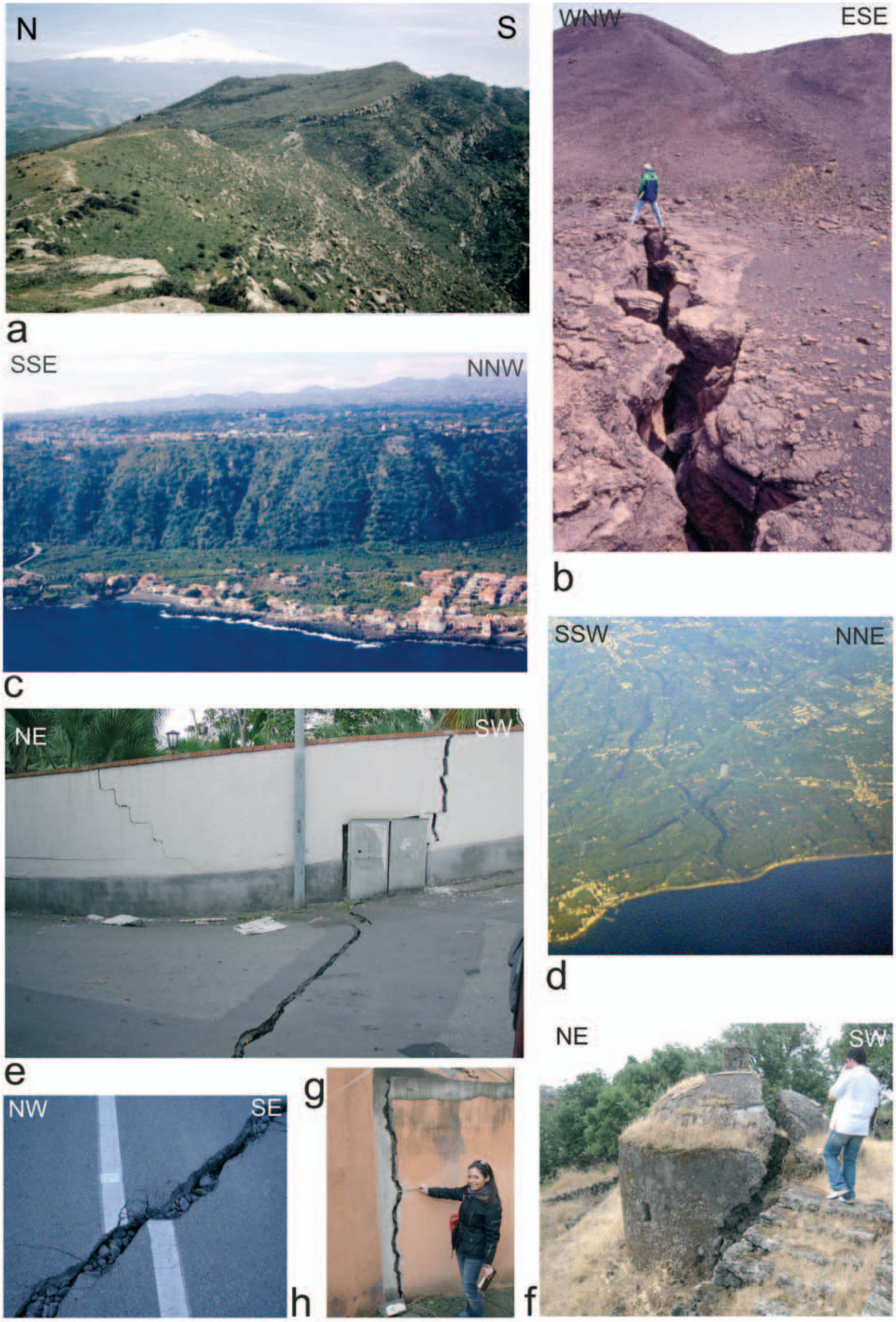

Fig. 3.

a deeper entrenchment of the drainage system, which propagated from the Ionian coast inland, as consequence of the Late Quaternary increase of the regional uplifting rate related to rifting processes (MONACO *et alii*, 2002). Basically, the volcanic edifice exhibits active extensional features (fig. 1) that are represented by normal faults and eruptive fissures accommodating the WNW-ESE striking regional extension and are related to shallow low-energy seismicity (see above). The most important structures are located along the eastern base of the volcano where NNW-SSE striking normal faults, with dextral-oblique component of motion, represent the northern end of the Malta Escarpment system. In the north-eastern slope of the volcano these fault system swings to a NE trend which it keeps northwards along the Ionian Coast to Taormina and as far as Messina Straits. The summit area of the volcano is characterized by eruptive and dry fissures, which show NNE to NE directions in the north-eastern slope and N to NNW directions in the southern slope.

LATE QUATERNARY CONTRACTIONAL STRUCTURES

In the area to the south of Mt. Etna (the Terreforti hills), the Lower-Middle Pleistocene sedimentary substratum forms an E-W trending, about 10 km long, fault propagation fold (the Terreforti anticline, fig. 1) at the front of the Siculo-Maghrebian thrust system (LABAUME *et alii*, 1990; BORGIA *et alii*, 1992; MONACO, 1997). This structure also deform the 240 ka old terrace (MONACO *et alii*, 2002) that, largely outcropping to the south of the volcano at an altitude ranging between about 350 m (along the crest of the anticline) and 150 m a.s.l. (the inner edge is located at 270 m a.s.l.), is younger than the early tholeiitic products of the south-western slope of Mt. Etna (320-250 kyr; GILLOT *et alii*, 1994). In the same area, between Paternò and the Ionian coast, west of Catania, a flight of coastal alluvial terraces of the Simeto River with inner edges located at altitudes between 250 and 45 m a.s.l., carve the western extension and the southern limb of the Terreforti anticline. Taking into account the ages of the last folded terrace (240 ka) and of the first undeformed one (200 ka), the growth of the Terreforti anticline ended about 200 ka (MONACO *et alii*, 2002), before the formation of the present Mt. Etna edifice. Younger contractional structures, related to Late Pleistocene-Holocene Africa-Europe convergence (LAVECCHIA *et alii*, 2007; FERRANTI *et alii*, 2008) are also observed in the foredeep-foreland domain (CATALANO *et alii*, 2006).

ERUPTIVE FISSURES

The main eruptive fissures of Mt. Etna cut the north-eastern, south-eastern and southern flanks of the volcano, forming three major systems striking SW-NE, NNW-SSE and N-S, respectively (fig. 1).

On the north-eastern flank, the main fissures distribute from the summit area along a NE direction, forming a 5 km-long, 1 km-wide topographic ridge made up of lavas and pyroclastics, known as the «Northeast Rift Zone» (KIEFFER, 1975; LO GIUDICE *et alii*, 1982; GARDUNO *et alii*, 1997; TIBALDI & GROPPELLI, 2002). During the last two centuries, it has been reactivated by several volcano-tectonic event (e.g. 1809, 1874, 1879, 1911, 1923, 1947, 1981, 2002) (fig. 3b). This zone is part of wider fissure system (the SW-NE system; fig. 1) which develops to the south, between the SE Crater and the northern rim of the Valle del Bove, where scattered historical eruptive vents (e.g. 1865, 1928, 1971, 1978, 1979, 1986 and 1989 events) occur. This system has been particularly active during the last two centuries and is confined to the north by the WNW-ESE striking left-lateral Pernicana fault (fig. 1; see below), which transfers most of the extension to the east (MONACO *et alii*, 1997).

South of the summit area, two faults and fissures zones, the NNW-SSE and N-S systems occur (fig. 1). The NNW-SSE system develops between the SE Crater and the south-western rim of the Valle del Bove along a SSE direction, and then continues south-eastwards as the rim swings to an easterly direction (fig. 1). The upper part of this zone forms a narrow belt of closely spaced normal faults that bound elongated grabens or small pull-apart depressions within dilational jogs. In the lower part, left-stepping en-echelon dyke swarms are clearly recognizable. The overall geometry of the NNW-SSE system implies a right-lateral component of motion, as observed on fracture fields developed during the 1989 and the 1991-93 reactivations (MONACO *et alii*, 1997).

The N-S system cuts through the southern slope of the volcano and forms a more diffuse set of N-S to SSW-NNE striking fissures extending from the Montagnola area to Nicolosi (fig. 1), a distance of about 10 km. Such fissures are typically about 1-2 km long and marked by aligned spatter cones which coalesce at places to form volcanic ridges (South Rift Zone of KIEFFER, 1975). South-east of Nicolosi, a more localised fissure and fault zone extends for about 10 km towards the south-east, composed of left-stepping, en-echelon segments, clearly indicative of a component of dextral displacement (see below).

Some other eruptive fissures and alignments of volcanic vents are radially distributed on the western slope of the volcano (fig. 1). Their geometry suggests that they are linked to a local field component induced by the hydraulic load of the magmatic column in the central conduit (VILLARI *et alii*, 1988).

FAULT SYSTEMS

Normal faults occur mostly on the eastern flank of Mt. Etna, along the Ionian coast (fig. 1), where they form a 30 km long system dipping towards the Ionian Sea. The system trends SSW-NNE on the lower north-eastern flank, where the Piedimonte-Fiumefreddo fault system occurs, and bends to NNW-SSE direction on the lower south-eastern flank (fig. 4), where the Sant'Alfio-Guardia, San Leonardello-Trepunti, Acireale-Santa Venerina and Acicatena-Valverde fault systems show a slight right-lateral component of motion (LO GIUDICE & RASÀ, 1986, 1992; MONACO *et alii*, 1995, 1997; LANZAFAME *et alii*, 1996; AZZARO, 1999, 2004). Southwards, this normal fault system extends offshore at the base of the Malta Escarpment (see inset in fig. 1) where it bounds NNW trending Late Quaternary wedge-shaped basins, as shown by reflection seismic profiles (MONACO *et alii*, 1995; HIRN *et alii*, 1997; BIANCA *et alii*, 1999). To the north, Late Quaternary fault segments run along the Ionian coastline, strongly uplifting the onshore, reaching the Straits of Messina to continue along the Tyrrhenian side of the Ca-

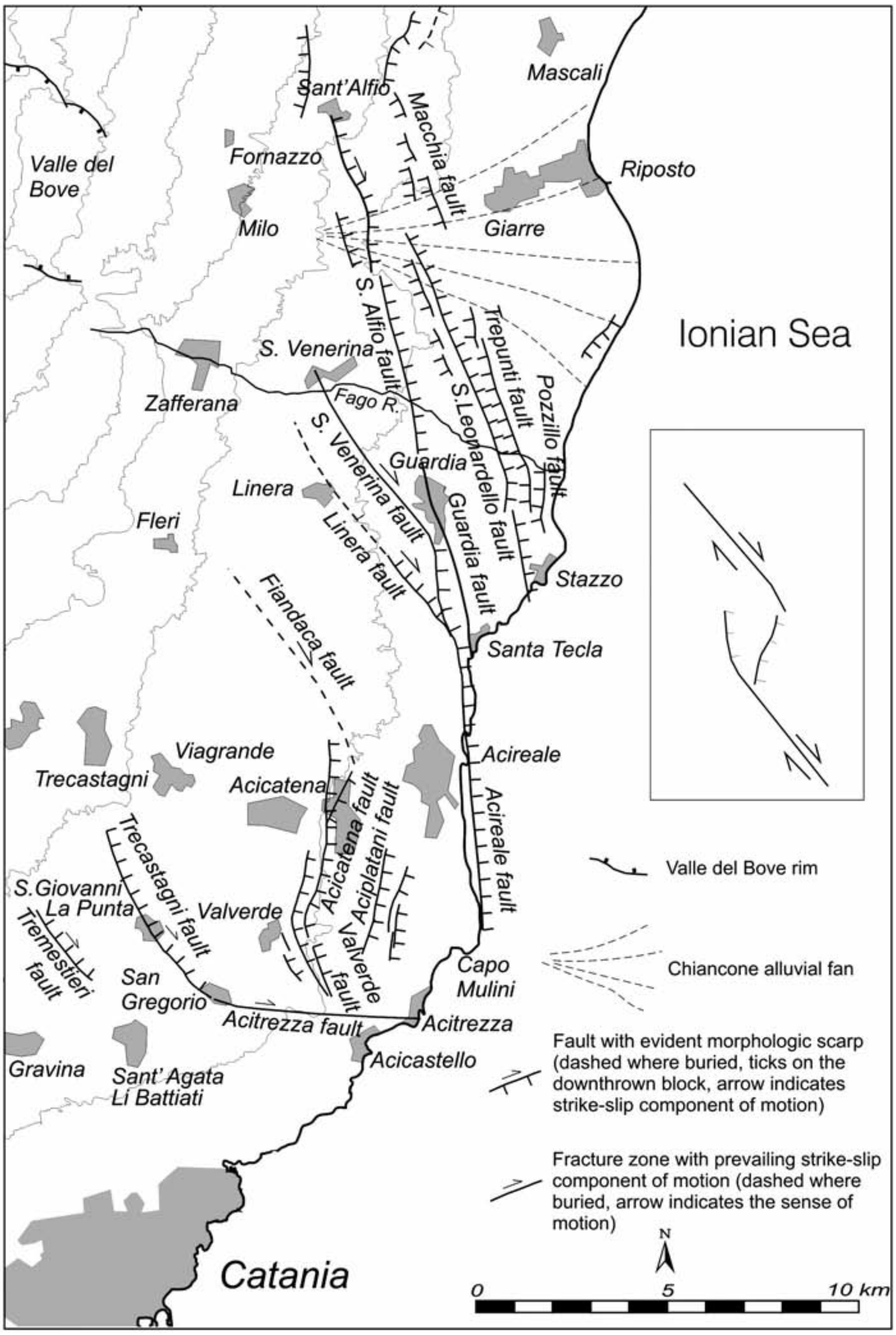

Fig. 4 - Detailed map of active structures on south-eastern flank of Mt. Etna (location in fig. 1). Inset shows the kinematic model of pull-part structures (WOODCOCK & SHUBERT, 1996 and reference therein).
– Mappa dettagliata delle strutture attive del versante sud-orientale del M. Etna (ubicazione in fig. 1). Il riquadro mostra il modello cinematico di strutture di tipo pull-apart (WOODCOCK & SHUBERT, 1996 e relativa bibliografia).

labrian Arc (STEWART *et alii*, 1997; MONACO & TORTORICI, 2000; CATALANO & DE GUIDI, 2003).

The fault segments control the present topography and drainage network and show steep escarpments («Timpe», see fig. 3c) with very young, mostly Late Pleistocene to Holocene, morphology. The most impressive scarps, up to 200 m high, extend discontinuously for about 20 km from Sant'Alfio to Acireale (fig. 1), where they affect sedimentary and volcanic rocks ranging in age from Early Pleistocene to historical times, as the 396 B.C., IX century, 1284, 1329, 1408, 1689 lava flows (AA.VV., 1979; TANGUY & KIEFFER, 1993; MONACO *et alii*, 1997; CORSARO *et alii*, 2002). In this sector, normal faulting is associated with shallow-depth (<5 km) seismicity, including the occurrence of several earthquakes with M~4.5 (AZZARO *et alii*, 2000).

Secondary structures are represented by the NW-SE striking Linera and Fiandaca faults, that extend upslope with poor morphologic evidence (fig. 4). In the southern flank of the volcano, between Nicolosi and Catania, a less pronounced fault system occurs, composed of NW-SE striking segments (Tremestieri-Trecastagni fault system), characterized by a component of dextral displacement. To the west, the isolated N-S striking Ragalna fault also shows oblique-dextral component of motion (fig. 1).

The normal fault system occurring in the eastern flank of Mt. Etna is confined to the north by the WNW-ESE striking left-lateral Pernicana fault and to the south by the Acitrezza fault (fig. 1). These structures transfer most of the extension to the east toward the master faults of the Siculo-Calabrian Rift Zone (MONACO *et alii*, 1997).

The Piedimonte-Fiumefreddo fault system

The northern branch of the normal fault system develops north of Sant'Alfio, where the Piedimonte-Fiumefreddo fault system shows a SSW-NNE direction which it keeps northwards along the Ionian Coast to Taormina (fig. 1). In the Mt. Etna area this system is represented by the Ripe della Naca, Piedimonte and Fiumefreddo faults. The SW-NE striking and 5 km long *Ripe della Naca fault* is located upslope where it forms a 100 m high scarp on Timpe volcanics, mostly mantled by Mongibello volcanics. The main fault of the system is the 10 km-long *Piedimonte fault* (MONACO *et alii*, 1997), that in its southern sector is mantled by the large 1651 AD and 1928 AD lava flows. Near Piedimonte this normal fault exhibits a 60 m high cumulative escarpment across the 60-15 ka-old Ellittico volcanics. The Piedimonte fault also offsets the Lower-Middle Pleistocene pre-Etnean claystones that outcrop at up to 600 m of altitude in the footwall.

To the east, the Piedimonte fault is flanked by a synthetic normal fault, the *Fiumefreddo fault*, whose southern sector is also partially mantled by recent lava flows. West of Fiumefreddo it is characterized by a 20 m high scarp on Mongibello volcanics, accompanied by up to 1 dm wide open fractures at the bottom. In the Fiumefreddo area it veers to the east, losing its morphologic evidence. Here, it has been the site of aseismic creep events, characterized by oblique-sinistral motion, that caused damages to buildings and roads.

The Sant'Alfio-Guardia fault system

South of Sant'Alfio (figs. 1 and 4), the normal fault system swings to a NNW-SSE trend which it keeps southwards along the Ionian Coast to Acireale and as far as the Catania-Siracusa offshore. The N160-170°E striking and ENE dipping *Sant'Alfio fault* develops between the Sant'Alfio village to the Torrente Fago. It bounds to the west a basin filled by the Chiancone alluvial fan (see above). At its northern end the fault offsets 130 ka old Timpe volcanics (DE BENI *et alii*, 2005) and shows a 120 m high cumulative scarp (Timpa di Miscarello) characterized by trapezoidal facets suggesting that the drainage network deeply incised the uplifting footwall during the Late Pleistocene-Holocene. At the scarp bottom, near a mineral water factory, the 1689 AD lava flow is cut by a 2 m-wide brittle shear zone showing cataclastic structure, indicative of active movement on the fault. As a matter of fact, this fault has been reactivated during the 1865, 1911 and 1971 seismic events (I = VIII-IX; M = 4.1-4.5), which were accompanied by ground ruptures with vertical offset between 20 and 70 cm (GRASSI, 1865; RICCÒ, 1912; RIUSCETTI & DISTEFANO, 1971; POSTPISCHL, 1985). The structural analysis along the cataclastic zone showed the occurrence of a set of ENE dipping shear planes characterized by slickensides indicating dextral-oblique normal motion. The fault scarp decreases toward the south where it is mantled by prehistoric and historic lava flows. Offsets of 1.5 m and 5 m have been measured in the Macchia area on the 1284 lava flow and east of Santa Venerina (fig. 4) along prehistoric lava flows (5-2.4 ka, MONACO *et alii*, 1997), respectively.

Between the Fago river and Santa Tecla (fig. 4), the Sant'Alfio fault, here named *Guardia fault*, loses its morphologic evidence. This sector has been reactivated during the 2002-2003 eruptive event (earthquake of 29/10/2002; 16.39 GMT; M = 4) with oblique-dextral motion observed in the Guardia village, characterized by a vertical and horizontal components of 2 and 3 cm, respectively (MONACO *et alii*, 2005).

The San Leonardello graben

East of Sant'Alfio-Guardia (fig. 4) a system of NNW-SSE striking minor sinthetic (San Leonardello fault) and anthitetic (Macchia, Trepunti and Pozzillo faults) structures form the *San Leonardello Graben* (fig. 3d). The *San Leonardello fault* shows an up to 25-30 m high linear scarp, which cuts the Chiancone fanglomerate and the overlapping lava flows, younger than 15 ka. The ~10 km-long, ~500-1000 m-wide San Leonardello graben since the late Wurm strongly modified the drainage network of the Fago and Macchia rivers (ADORNI & CARVENI, 1993). East of Guardia (fig. 4), the San Leonardello fault offsets by 25 m the entrenched channel of Torrente Fago forming a perched valley on the footwall since 14-18 Ka ago (MONACO *et alii*, 1997). To the south the San Leonardello fault is mantled by a prehistoric lava flow and by a 9th century flow (TANGUY & KIEFFER, 1993), disappearing offshore of S. Tecla (fig. 4); these lava flows are in turn offset by 5-6 m and ~1.5 m, respectively.

The San Leonardello fault has been reactivated during the 1881, 1920, 1950 e 1989 seismic events (I = VIII-IX; M = 4.0-5.1), which caused ground ruptures with vertical throw up to 50 cm (SILVESTRI, 1883; PLATANIA, 1922; CUMIN, 1954; POSTPISCHL, 1985; AZZARO *et alii*, 1989a). In the last 20 years it has been characterized by aseismic slip with vertical rates of 1 cm/yr, causing the subsidence of the Stazzo harbour (fig. 4).

The Acireale-Santa Venerina faults

The *Acireale fault* forms a NNW-SSW striking, up to 200 m high (fig. 3c), rectilinear scarp between Santa Tecla and Capo Mulini (fig. 4) where it offsets a volcanic sequence mostly made of the 200 to 100 Ka-old Timpe volcanics. A polished fault surface on volcanoclastic products is well exposed west of Santa Tecla; here oblique slickensides and Riedel fractures with pitches ranging between 30° and 50°, indicate a right lateral component of slip. Between Santa Tecla and Acireale the fault scarp is largely covered by the 394 BC lava flow which forms a large fan toward the sea. These products do not appear offset by the buried fault. South of Acireale the fault runs along the coast forming the up to 120 m high coastal cliff of «La Timpa», whose altitude decreases towards Capo Mulini.

The Acireale fault has been reactivated along its northern sector (Timpa di Santa Tecla) during the February 1986 earthquakes (I = V-VII; M ≤ 3; LO GIUDICE & RASÀ, 1992; PATANÈ *et alii*, 1994) that caused slight damages to the San Giovanni Bosco (south of Guardia, fig. 4) buildings and small ground fractures (well visible on the road asphalt). North-west of Santa Tecla, the Acireale fault is characterized by progressively minor offsets and it loses its morphologic evidence between San Giovanni Bosco and Santa Venerina where it is called *Santa Venerina fault* (fig. 4). This N150°E striking segment has been reactivated with dextral-oblique motion for a length of 5 km during the 2002-2003 eruptive event (earthquake of 29/10/2002, 10.02 GMT; M = 4.4; MONACO *et alii*, 2005). Ground ruptures with vertical throw up to 10 cm and horizontal throw up to 7 cm have been observed on buildings, road walls and asphalt in the San Giovanni Bosco area (fig. 3e). To the north, in the Santa Venerina-Bongiardo area, ruptures were represented by several N-S oriented *en-echelon* tension cracks, up to 1 cm wide, mainly observed on the road asphalt. These fractures confirm the dextral component of motion along a NNW-SSE oriented shear zone (MONACO *et alii*, 2005). Similar macroseismic effects have been reported during the 26/05/1879 earthquake (I = VIII; M = 4.1) between Bongiardo and Guardia (BLASERNA *et alii*, 1879).

The Linera and Fiandaca faults

Another structure, here named *Linera fault,* branches off from the Acireale fault in correspondance of the Timpa di Santa Tecla scarp (fig. 4). This structure extends with N150°E direction between Santa Maria degli Ammalati (west of Santa Tecla) and Zafferana showing poor morphologic evidence being covered by several historical and prehistoric lava flows. Notwithstanding, this structure has been often reactivated during the last two centuries. Extensional fractures with oblique-dextral component and vertical throw up to 50 cm have been observed all over the fault on buildings, road walls and ground during the 08/05/1914 earthquake (I = IX; M = 4.5; PLATANIA, 1915; AZZARO, 1999) and the 1952 seismic events (I = VI-VIII; M = 3.5-3.9; CUMIN, 1954; PATANÈ & IMPOSA, 1995; AZZARO, 1999). In the southern sector of the Linera fault (Santa Maria degli Ammalati area), similar fractures have been detected during the 1865 (GRASSI, 1865), 1973 (PATANÈ, 1975) and September 1981 (I = VI-VIII; M = 3.4-3.9; LO GIUDICE & RASÀ, 1986; 1992; PATANÈ & IMPOSA, 1995; AZZARO, 1999) seismic events.

To the south, between Fleri and Acicatena (fig. 4), the 5 km long and NNW-SSE striking *Fiandaca fault* steps to the right relative to the Linera fault (AZZARO, 1999). Similarly to the Santa Venerina and Linera faults, it is characterized by poor morphologic evidence and extensional motion with oblique-dextral component. Ground ruptures and building damages have been detected also on this fault during seismic events in the last two centuries. In particular, extensional fractures with oblique-dextral component and throws of 4-20 cm have been detected along the southern sector of the fault, between Pennisi and Santa Maria la Stella, during the 1875 (DE ROSSI, 1875), 1907, 1914 (PLATANIA, 1915), 1919 (PLATANIA, 1920) 1931 (CAVASINO, 1935), 17 and 19/06/1984 (PATANÈ & IMPOSA, 1995), and 1997 seismic events, all characterized by intensity between V and VII and magnitude between 3.0 and 3.7 (AZZARO, 1999). The 1894 Fleri earthquake (I = VII-VIII; M = 3.9; RICCÒ, 1894, AZZARO, 1999) and the 25/10/1984 seismic event (I = VIII; M = 4.1; LO GIUDICE, 1984; AZZARO, 1999), were accompanied by the development, at the north-western fault end, of dm-long NNW-SSE oriented oblique-dextral fractures and N-S oriented *en-echelon* extensional fractures.

The Acicatena-Valverde fault system

To the south, the NNE to NNW trending *Valverde fault* (San Nicolò fault of RASÀ *et alii*, 1996; Nizzeti fault of MONACO *et alii*, 1997) steps to the right relative to the Fiandaca fault (fig. 4). The linear, up to 100 m high, cumulative scarp of this fault, together with a minor parallel conjugate structure upslope, truncates the Timpe volcanics, represented in this area by 120 Ka-old (BRANCA *et alii*, 2007) lava flows capping Eutyrrhenian (MIS 5.5) marine conglomerates (KIEFFER, 1971; MONACO *et alii*, 2002). To the north, this structure links to the southern end of the Fiandaca fault by a system of east-dipping normal fault splays (the Acicatena faults), with direction between N-S and SSW-NNE (fig. 4), partially mantled by historical and prehistoric lava flows. They buried the cumulative scarps but are in turn offset up to 5 m (MONACO *et alii*, 1997). The Valverde fault has been seismically active in historical times (e.g. 1866-1899; M = V-VII; IMBÒ, 1935) and recently (17/12/1988; AZZARO *et alii*, 1989b) has been the site of aseismic creep that caused the development of ground fractures and faults with centimetric offset and damages on buildings along a NW-SE trending belt, 500 m long and 70-80 m wide, in the San Nicolò area (east of Valverde, fig. 4).

The N-S striking *Acicatena fault* also truncates the Timpe volcanics forming an up to 70 high scarp. To the north it is mantled by historical and prehistoric lava flows, disappearing below the 394 a.C. The analysis of historical catalogs suggests that this structure has only been the site of aseismic creep events that damaged the Acicatena building and roads (LO GIUDICE & RASÀ, 1986; RASÀ *et alii*, 1996). These repeatedly occurred since the beginning of the last century at the bottom of the main fault scarp and of a secondary 30 m high fault scarp that branches off, with a SSW-NNE direction, from the Acicatena fault (fig. 4). During the creep episodes of the August 1980, October 1984 and April 1985, open fractures with vertical throw of 3-10 cm and horizontal throw of 15-20 cm have been observed on buildings, road walls and asphalt (RASÀ *et alii*, 1996). These aseismic creep episodes were coeval or immediately subsequent to seismic crisis along other tectonic structures of the eastern slope of the volcano.

To the east, a minor coniugate structure, the *Aciplatani fault,* develops between Reitana and Aciplatani forming a 10 m high scarp (fig. 4). This 3 km-long, SSW-NNE striking and east dipping structure has been the site of aseismic creep during the second half of the 19th century (June 1879, June 1886, April 1889) that caused the development of centimetric open fractures (ARCIDIACONO, 1893; SILVESTRI, 1893; DE FIORE 1908-11; IMBÒ, 1935; RASÀ *et alii*, 1996).

The Tremestieri-Trecastagni fault system

West of the Valverde fault, other two northeast-dipping and NW-SE striking oblique faults occur, the Trecastagni and the Tremestieri faults. The 5 km-long *Trecastagni fault* extends with NNW-SSE direction from Trecastagni to San Giovanni la Punta where it veers to the southeast towards San Gregorio (fig. 4). It forms an up to 10 m high scarp (fig. 3f), partially mantled by the 1408 lava flow that in turn is offset by recent activity. In fact, this structure has been reactivated during the earthquakes of the 16 and 28 September 1980 (I = VI; M = 3.4; LO GIUDICE & LONGO, 1986; AZZARO, 1999), when ground fractures, characterized by centimetric normal motion, were detected on buildings and road walls. More recently, this fault has been reactivated by the 21/11/1988 (I = VI; M = 3.4; AZZARO, 1999) and 31/10/2005 (I = VII; M = 3.6; AZZARO *et alii*, 2006) earthquakes, with centimetric oblique-dextral motion detected along road walls and asphalt.

The 3 km-long, *Tremestieri fault* is characterized by a 10 m high scarp in its northern sector, whereas in the Tremestieri town it shows poor morphologic evidences, even though several buildings are damaged by recent activity. Ground fractures at the bottom of the scarp along the northern sector of the fault have been associated to the 30/04/1908 (I = V-VI; M = 3.2; MARTINELLI, 1911; AZZARO, 1999), 21/08/1980 (I = V; M = 3.0) and 23/08/1980 (I = VI; M = 3.4; LO GIUDICE & LONGO, 1986; AZZARO, 1999) earthquakes. These latter were characterized by oblique-dextral motion (RASÀ *et alii*, 1986). Aseseimic creep episodes are reported during the 1883 eruptive event (SILVESTRI, 1883), and accompanied the reactivation of the Fiandaca and Acireale faults during the 1984 and 1986 seismic events, respectively (see above, RASÀ *et alii*, 1996).

According to AZZARO (2004), the Tremestieri fault extends to the NW, as far as Nicolosi, without morphological evidence («hidden fault»). Evidences of coseismic ground ruptures inside the village of Nicolosi dates to 29/09/1885 (I = VII, SILVESTRI, 1886; AZZARO, 2004) and 11/05/1901 (I = VII, ARCIDIACONO, 1901; AZZARO, 1999; 2004), whereas systems of NNW striking tensional cracks, ca 0.9 km long, developed south of Nicolosi during the 29/01/1986 (M = 3.4; AZZARO *et alii*, 1989b) and 22/05/1998 (M = 3.5; AZZARO, 1999) earthquakes.

The Acitrezza fault

Following the November 1988 seismic event along the Trecastagni fault (see above), a fracture field developed at the south-eastern tip of this structure between the villages of San Gregorio and Acitrezza (fig. 4). In particular, during the month of December 1988, creep processes were observed in the Ficarazzi and Acitrezza roads and buildings where WNW-ESE striking discontinuous and anastomoused fractures developed (PATANÈ & IMPOSA, 1995). According to testimonies of the elderly inhabitants, damages on walls and building along this alignment have already occurred in the past. Aseismic slip along this fracture zone also occurred after the October 2002 Timpe seismic sequences (Franco Cavallaro, personal communication). A 40 m wide and 600 m long belt was clearly observed, characterized by discontinuous extensional fractures (with millimetric offset) on road asphalt and walls and on concrete and stone buildings (fig. 3g). Another similar documented deformation episode occurred after the April-May 2009 seismic sequences in the Ficarazzi-Acitrezza sector. GPS velocity field showed that it was accompanied by a large displacements in the lower eastern slope of Mt. Etna (Mario Mattia, personal communication).

Actually, the field survey of the San Gregorio-Acitrezza alignment revealed the occurrence of a 5 km-long fracture zone, here called *Acitrezza fault* (fig. 4), without morphologic evidence being characterized by discontinuous segments showing prevalent right-lateral motion. A maximum normal-dextral offset of about 5 cm has been observed on 1960' buildings in the San Gregorio village, probably representing the cumulative effect of several creep episodes. They can be mostly interpreted as the post-seismic accommodation of movements along the Trecastagni faults. Minor cumulative offsets have been observed on the eastern sector of the Acitrezza fault on building of the same period, suggesting that the deformation is progressively adsorbed to the east, where this structure seems to accommodate also movements of the Timpe faults. According to CAVALLARO *et alii* (2008), this structure could extend offshore as far as the Lachea island.

The Ragalna fault system

To the west, the N-S striking and 8 km-long *Ragalna fault* (RUST & NERI, 1996; RUST *et alii*, 2005) is a normal fault characterized by a oblique-dextral component of motion (fig. 1). The northern sector shows a 5 km long and up to 20 m high fresh scarp developed on the upper interval of the Ellittico volcanics (15 ka). Gravity-induced open fissures can be observed south of Masseria Cavaliere at the top of this scarp, probably related to recent creep episodes as that occurred 8 months after the end of the 2002-2003 eruptive event (RUST *et alii*, 2005). At its southern end, this segment is characterized by the occurrence of cinder cone aligned in a N-S direction. To the south, the fault loses its morphologic evidence and a 3 km long fracture zone develops with a NNW-SSE direction towards the village of Santa Maria di Licodia. These fractures are well visible on concrete road walls and show millimetric oblique-dextral offset probably related to the 06/05/1987 earthquake (I = V-VI; M = 3.2; PATANÈ & IMPOSA, 1995; AZZARO *et alii*, 2000).

Small SW-NE striking ground fractures occurring at the northern end of the Ragalna fault have been related to coseismic effects of the 27/03/1983 earthquake (I = VI; M = 3.4; PATANÈ & IMPOSA, 1995). Here, a 3 km long fault occurs, characterized by prevalent dip-slip motion producing poor morphological evidence (*Calcerana fault*, AZZARO, 1999). Minor SW-NE striking coseismic extensional fractures also developed in the villages of Santa Maria di Licodia and Ragalna during the 14/05/1898 (I = VII; M = 3.7; RICCÒ, 1899-1900) and 04/06/1982 (I = VI; M = 3.4; AZZARO, 1999) earthquakes, respectively.

The Pernicana fault

On the northeastern flank, none of the eruptive fissures extends much beyond the prominent, E-striking, Pernicana fault (fig. 1). This ~10 km-long fault thus appears to connect the northeastern extremity of the NE Rift Zone to the Piedimonte-Fiumefreddo fault system. To the west, the Pernicana fault displays a sharp, linear, south-facing scarp. It has been the site of several, shallow depth ($h < 4$ km), earthquakes with $2 < M < 4$, of which some were accompanied by surface breaks with a clear left-lateral component of slip (AZZARO *et alii*, 1988; LO GIUDICE & RASÀ, 1992; AZZARO *et alii*, 1998; OBRIZZO *et alii*, 2001; MONACO *et alii*, 2005). Predominant sinistral movement along much of the length of this fault is attested by fresh offsets of roads, walls and houses that cross its trace. Near the eastern end of the south-facing fault scarp, the side walls of the provincial road (S.P.59) from Linguaglossa to Zafferana (1.5 km northeast of Vena; fig. 1), built around 1940 AD, show a left-lateral offset of ~140 cm. About 200 m west of the road, the fault offsets by ~400 cm several stone walls built at the beginning of the 19th century. These walls, together with reinforced concrete buildings built in 1975 AD about 500 m farther east along the fault trace, were displaced sinistrally, by ~30 cm, during the 1981 earthquake sequence, which included three main shocks, with MKS intensities ranging from IV and VIII, between January 8 and October 11 (AZZARO *et alii*, 1989b). This sequence was coeval with the March 1981 eruption that started in the NE Rift Zone, suggesting a direct relationship between fissuring along that rift and coseismic slip on the Pernicana fault. In fact, at the onset of the 2002-03 eruptive event, the epicentre time pattern showed a northeast-ward migration of earthquakes along the Northeast Rift. From the early morning of 27 October (01.28 GMT), seismicity (depth max = 3.5 km b.s.l.; M_{max} = 3.8) involved the western tip of the WNW-ESE trending Pernicana fault on the north-eastern flank of the volcano, destroying the Piano Provenzana tourist station. Large ENE-WSW trending coseismic fractures developed in the large parking area of Piano Provenzana and downslope the fault, between Piano Provenzana and the village of Vena, left-lateral movement occurred. In general, ground deformation was characterised by an anastomoused pattern of E-W trending fractures. Along the «Mareneve» road that crosses the Pernicana Fault at altitudes of 1370 m and 1450 m a.s.l., left-lateral motion of about 1 m was observed on concrete walls and asphalt. To the east, near Vena, the road S.P. 59 showed again a left-lateral offset of ~40 cm (fig. 3h). The same displacement was observed on the reinforced concrete buildings and walls about 500 m farther east along the fault trace. During the following months, postseismic slip of ~20 cm was observed in the same buildings and road. Between the S.P. 59 and Vena (fig. 1), the deformation was accommodated by a splay fault which transferred left-lateral motion of the main structure to the south, offsetting road side walls and triggering a rock fall. According to NERI *et alii* (2004), after 29 October fracturing propagated to the ESE along N80°E trending fault segments, with horizontal displacement decreasing from 8 cm in the Mascali area to 2 cm at the coastline.

In conclusion, taking into account that the left-lateral movement on the Pernicana fault accommodates the extension of the NE Rift (see also RASÀ *et alii*, 1996; GROPPELLI & TIBALDI, 1999) and that since the beginning of the 19th century about ten eruptive events occurred along the Rift (AA.VV., 1979; ROMANO, 1982; GARDUNO *et alii*, 1997), the 400 cm offset measured in the stone walls along the eastern sector of the fault should be a cumulative effect of related slip events, each characterized by 30-40 cm of motion.

Fault slip-rates

A quantitative assessment of the consequently variable offsets of dated units yields remarkably consistent vertical slip-rates of 1 to 2 mm/yr for most segments of the Timpe fault system (MONACO *et alii*, 1997) and for the Ragalna fault (RUST & NERI, 1996). Such segments appear to be seismically active, with shallow earthquakes of only moderate magnitude (4-6) in the last ~150 years, located mostly east of the S. Alfio-Guardia and San Leonardello-Trepunti fault traces (AZZARO *et alii*, 2000). The throw-rates obtained are typical of major tectonic normal faults worldwide.

Offsets along the Pernicana fault imply a sinistral slip-rate of 2 cm/yr in the last 200 years, about ten times faster than on the Timpe fault systems. The time-span over which they accrued is too short to decide whether they are representative of long-term slip or, perhaps more likely, of a shorter-term centennal pulse of volcanic activity and eruptive fissuring along the NE Rift Zone.

Taking into account the fault arrangement and the oblique motion on the fault segments, the vertical slip-rates can be converted in extension-rates. Average values of 3-4 mm/a have been estimated, compatible with extension rates obtained by permanent GPS velocity field along the Siculo-Calabrian Rift Zone (CATALANO *et alii*, 2008).

ASEISMIC CREEP AND ORIGIN OF EASTERN FLANK INSTABILITY

Normal and oblique faulting at the eastern flank of Mt. Etna is usually related to crustal seismicity, but also aseismic creep processes locally occur (see RASÀ *et alii*, 1996 for a complete review). For example, aseismic creep along the eastern sector of the Pernicana fault (AZZARO *et alii*, 2001) accommodates coseimic slip of the western sector of the structure and extension along the NE Rift, whereas the Acitrezza fault accommodates coseimic slip along the Trecastagni fault (see above). Similarly, the Acicatena and Aciplatani faults (fig. 4) are characterized by slow extensional motion that usually accomodates coseismic strike-slip deformation along the Fiandaca fault (see 1914, 1919 and 1984 seismic events). At its southern tip this structure depicts a *pull-apart* geometry, typical of transtensional domains (WOODCOCK & SHUBERT, 1996 and reference therein), together with the Acicatena and Valverde structures (see kinematic model in the inset of fig. 4). As a matter of fact, the 1980 and 1988 creep events along the Acicatena-Valverde fault system (see above) followed seismic crises along independent structures, respectively the Tremestieri and Trecastagni faults. Similarly, 1984 and 1986 aseismic ruptures along the Tremestieri fault followed seismic events along the Fiandaca and Acireale faults and 2002 and 2009 aseismic creep events along the Acitrezza fault followed seismic events along the Timpe fault system (see above). These relations suggest that aseismic creep could be also triggered by shaking related to earthquakes along nearby seismogenic structures in a context of eastward flank sliding ruled by gravity (RASÀ *et alii*, 1996).

Structural, morphological and ground deformation studies suggest that the eastern flank of Mt. Etna is spreading seaward (RASÀ *et alii*, 1996). Deformation is confined to the west by the NE and S Rift zones, to the north by the left-lateral Pernicana fault and to the south by the right-lateral San Gregorio-Acitrezza fracture zone, which transfers most of the extension to the east. Three contrasting models have been proposed: deep-seated spreading, shallow sliding and tectonic block movements (see FIRTH *et alii*, 1996 for a complete review).

According to the deep-seated spreading model (BORGIA *et alii*, 1992; RUST & NERI, 1996; TIBALDI & GROPPELLI, 2002; NERI *et alii*, 2004; RUST *et alii*, 2005), both the volcanic edifice and its uppermost basement (down to a 5 km depth) are spreading eastwards because of magma inflation processes. Deep sliding wedges would produce a belt of active contractional structures bordering the volcano at the foot of its southern and eastern flanks and deforming Middle Pleistocene sediments. However morpho-structural studies and geomechanical considerations seems to exclude the possibility of thrust faulting induced by magma intrusion. In fact, the continuity of coastal emergence between the volcanic edifice and its southern and northern basement, at rates exceeding 1.5 mm/yr, is incompatible with the differential uplift predicted by the deep-seated spreading model which emphasizes the independent nature of Mt. Etna's mobile flank (FIRTH *et alii*, 1996). Moreover, the occurrence of the ramp of a 5 km depth decollement, triggered by the push from magmatic intrusion, does not find support on seismic data along the Ionian offshore where only extensional structures have been observed (ARGNANI & BONAZZI, 2005). As regards the on-land fold structures occurring southwards, being former than the formation of the present Mt. Etna edifice which occurred since about 200 ka, they cannot be the result of deep-seated spreading (MONACO *et alii,* 2002). On the contrary, they must be interpreted as a thrust-propagation fold related to the last phase of migration of the Maghrebian chain front (see also LABAUME *et alii*, 1990). The compression at the base of the volcanic edifice is also invoked by BORGIA *et alii* (1992) and RUST & NERI (1996) to explain the structural setting of the pillow lavas outcropping under the Norman castle of Acicastello (fig. 1) that are hastily interpreted as overturned to the south-east. On the contrary, detailed field investigation of the Acicastello castle rock outcrop (CORSARO & CRISTOFOLINI, 2000) suggests complex emplacement conditions for both the pillows lavas and related hydroclastic rocks depending on the pre-existing topography, output rate, degree of interaction with sea water and underlying unconsolidated sediments, but does not support the idea of a significant tilt of the whole succession that, on the contrary, appears little disturbed. From a mechanical point of view, models borrowed from thrust tectonics (DAVIS *et alii*, 1993) show that compression 4-5 times higher than gravitational body forces is necessary to move crustal wedges. This is incompatible with stress induced by individual dikes intruding the volcano basement.

According to the shallow sliding model (LO GIUDICE & RASÀ, 1992; RASÀ *et alii*, 1996), the eastern mobile sector would be dismembered into minor sub-blocks of volcanics slowly sliding eastwards under their own weight, accommodated by seaward dipping detachment surfaces at different levels within the volcanic edifice or the sedimentary basement. This model is compatible with geomechanical models and is supported by the distribution patterns of the residual between GPS observed and modelled deformations that show the high mobility of eastern and south-eastern flanks with respect to the rest of the volcano (BONFORTE & PUGLISI, 2003; PUGLISI & BONFORTE, 2004). Problematic is the lacking of seismological evidences supporting the occurrence of shallow sliding planes (PATANÈ *et alii*, 2004, 2005).

The geometry and senses of motion of most of the major active features that affect the eastern sector of the volcanic edifice are kinematically compatible and thus appear to have a common tectonic origin (MONACO *et alii*, 1997). Such striking geometrical affinities suggest that most of the extensional tectonic features of Etna merge together at depth and represent shallow splays of a deep, normal fault zone driven by tectonic separation of the Ionian and Iblean blocks, reactivated during the Quaternary (CONTINISIO *et alii*, 1997; HIRN *et alii*, 1997; NICOLICH *et alii*, 2000). The tectonic block model is also supported by recent seismological models based on 3D seismic tomography (PATANÈ e*t alii*, 2002, 2003, 2006). However, deformation rates obtained by local GPS data and SAR interferometry (FROGER *et alii*, 2001; LUNDGREN *et alii*, 2003, 2004; BONFORTE & PUGLISI, 2003; PUGLISI & BONFORTE, 2004; PALANO *et alii*, 2006) suggest rates up to 10 times higher than that obtained by structural morpho-structural estimations and by permanent GPS velocity field along other sector of the incipient regional rift zone. This suggests that local shallow sliding phenomena can be triggered in the eastern slope of Mt. Etna but they must be framed in the morpho-structural setting of the edifice and in the crustal seismological models.

THE VALLE DEL BOVE

On Mt. Etna the only places where ancient volcanic products are well exposed and can be easily studied are the cliffs cut by the erosion on the eastern flank of the volcano. Among these natural rockwalls the Valle del Bove is by far the most important. This depression has a horseshoe shape and stretches E-W for ~6 km and N-S for ~5 km (fig. 2). It is carved on the eastern upper slopes of the volcanic edifice, from 1000 to 2700 m a.s.l. and closed by steep slopes on its northern, southern and western flanks. These slopes have a variable height reaching 1000 m on the wall buttressing Piano del Lago and closing the depression to the west. To the south, the slopes culminate into the E-W stretching ridge of Serra del Salifizio, which downward to the east bifurcates to enclose the small (~1 by 2 km) depression of Val Calanna. To the north, the slope terminates on the arcuated ridge of Serra della Concazze (fig. 2).

Contrasting hypotheses have been proposed to explain the mechanism of formation of the Valle del Bove depression (see CALVARI *et alii*, 1994 for a complete review). The most probable mechanism is slope failure under gravity and gradual enlargement of primordial depressions formed by the Valle del Bove eruptive centers (see above). Since about 15 ka ago, this process has been accentuated by the collapse of the Ellittico eruptive center and by the post-glacial accentuated erosion of the resulting depression (CALVARI & GROPPELLI, 1996; CALVARI *et alii*, 2004). According to the authors, this collapse produced the debris flow deposits cropping out between Milo and Giarre (see also COLTELLI *et alii*, 2000) and abundant clastic deposits subjet to fluvial reworking and deposition in the Chiancone alluvial fan (fig. 2).

The Valle del Bove slopes are not regular but are crossed by several ridges formed the stocks of dykes. Dikes mostly outcrop on the southern and western walls of Valle del Bove, where they show NNW-SSE prevalent direction. Their arrangement mimics the structural trend of faults and fissures on the eastern sector of the volcano, showing SW-NE direction on the northern wall. The most prominent dike ridges are Serra Perciata, Serra Cuvigghiuni and Serra Giannicola Grande. This last devides the Valle del Bove into two main portions to the south and to the north. The northern portion in its uppermost section is covered by the lava flows of the recent activity, the last remains have been completely buried by the products of the 2004-2005 eruptive activity, and only close to the ridge of Serra delle Concazze are exposed older formations. The ridges and steep slopes of the Valle del Bove display excellent rock exposures, which allow the reconstruction of the relationships between products of the various eruptive centers recognised in the area (see above). In particular, from the bottom and for a thickness of ~300 m are exposed the thick vulcanoclastic sequence, interlayered with thin lava flows, belonging to the Trifoglietto eruptive center, above it are the thin lava flows forming a ~400 m sequence of the Vavalaci eruptive center and finally, on the western slope crops out a 600 m thick alternance of tephra and lavas referred to to the Ellittico eruptive center (KLERKS, 1970; CRISTOFOLINI & LO GIUDICE, 1969; KIEFFER, 1970, 1977; RITTMANN, 1973; LO GIUDICE, 1970; LO GIUDICE *et alii*, 1974; ROMANO & STURIALE, 1975; ROMANO, 1982; AA.VV., 1979; MCGUIRE, 1982; GUEST, 1980; GUEST *et alii*, 1984; FERLITO & CRISTOFOLINI, 1989; FERRARI *et alii*, 1989; COLTELLI *et alii*, 1994; CALVARI *et alii*, 1994).

CONTOUR LINES OF THE SEDIMENTARY SUBSTRATUM

A reconstruction of the sedimentary basement of the volcanic edifice was produced by the analysis of the available well-logs and by interpretation of geophysical data mainly represented by SEV (CASSA PER IL MEZZOGIORNO, 1983). The product is represented by a map showing the contour lines of the top of the substratum (see inset in the attached table). This probably reaches altitudes of about 1400 and 1700 m a.s.l. in the summit area and in the Pizzi Deneri area, respectively. Normal faults clearly bounds eastwards sectors characterized by steep slopes along the Ionian coast. The map also shows the occurrence of palaeo-valleys completely filled by volcanic products. The most pronounced palaeo-valley is located east of the Valle del Bove in correspondence of the apex of the Chiancone alluvial fan. This deep incision should have formed after the LGM when strong erosional processes dismantled the Valle del Bove and fed the alluvial fan which filled a structural depression in the easternmost slope of the volcano. The map of the sedimentary substratum also show a wide terraced surface located at about 300 m a.s.l. in the south-eastern sector of the volcano between San Gregorio, San Giovanni La Punta, Viagrande and Aci S. Antonio. The formation of this surface, completely covered by Timpe, Ellittico and Mongibello volcanic products, should be related to one of the marine high-stands occurred during the Middle Pleistocene (330 or 240 ka; MONACO *et alii*, 2002).

PLUMBING SYSTEM

Mount Etna volcano is characterized by a continuous magma rise throughout an articulated set of vertical, to sub-vertical structures, which is known as «plumbing system». The development of the structures beneath the edifice is revealed by numerous lines of evidence. Seismic tomographic reconstructions (HIRN *et alii*, 1991, 1997; CARDACI *et alii*, 1993; DE LUCA *et alii*, 1997; VILLASENOR *et alii*, 1998; LAIGLE *et alii*, 2000; ALOISI *et alii*, 2002; CHIARABBA *et alii*, 2004; PATANÈ *et alii*, 2002, 2003, 2006) of the crustal structure of the Mt. Etna region reveal the occurrence of a high-velocity body beneath the eastern flank of the volcano (Valle del Bove; fig. 1). A more detailed investigation allowed better constraints to high velocity anomalies located between 0 and 18 km (CHIARABBA *et alii*, 2000), which have been interpreted as cooled batches of magmatic intrusions. In addition, two anomalies with high b-values of the frequency-magnitude relationship beneath Mt. Etna has been interpreted (MURRU *et alii*, 1999) as magma batches located 2 km east of the top of volcano, at a depth of 10.5±3 km b.s.l., and WSW of the summit craters, at a depth of 3.5±2 km b.s.l. Furthermore, on the southeastern flank of the volcano the occurrence of an almost aseismic, NNW-SSE trending volume, extending at depth from 5 to 25 km, has been interpreted as the conduit for rapid rise of upper-mantle deriving melts (GRESTA *et alii*, 1998). Based on the radionuclides activity of ^{210}Pb, ^{210}Bi and ^{210}Po, LE CLOAREC & PENNISI (2001) presented a sophisticated evaluation of the volume of the shallow degassing magma reservoir. They proposed that for the period 1983-1995 only 15-20% of degassing magma was erupted. This un-erupted magma solidifies at depth forming large high-velocity bodies of frozen dikes and crystal cumulates, extending vertically across the sedimentary basement. Recently, the simultaneous eruption of compositionally distinct magmas during the 2001 and 2002-2003 events has evidenced that rising magma can involve different storage volumes and conduits that developed independently from each other (CLOCCHIATTI *et alii*, 2004; MÉTRICH *et alii*, 2004; VICCARO *et alii*, 2006; SPILLIAERT *et alii*, 2006a, 2006b; FERLITO *et alii*, 2008, 2009a, 2009b). These two eruptions indicate that at Mt. Etna the ascent of magma, as well as the accommodation of deformation, when triggered by tectonic activity is strongly dominated by local extensional structures that are connected to regional systems.

DISCUSSION AND CONCLUSIONS

Morphotectonic analysis shows that Mt. Etna volcano exhibits active extensional features represented by normal faults and eruptive fissures which are related to shallow low-energy seismicity. These accommodate WNW-ESE striking extension, deduced from structural analysis and seismological data, related to incipient rifting processes at regional scale (see also VLBI and GPS velocity fields in Southern Italy). The most important structures are located along the eastern base of the volcano (Timpe fault system), where NNW-SSE striking normal faults with dextral-oblique component of motion represent the northern end of the Malta Escarpment system. In the northeastern slope of the volcano these fault system swings to a NE trend which it keeps northwards along the Ionian Coast to Taormina and as far as Messina Straits.

The major fissural eruptions occur along well defined, feeder-dykes and spatter cones belts that cut the upper slopes of the volcano, on the footwall of the Timpe fault system. They form NE trending pure extensional swarms along the NE sector of the volcano and en-échelon systems of N-S to NNE-SSW oriented fractures along NNW-SSE trending oblique-dextral shear-zones in the southern and south-eastern slopes. In this tectonic context, the left-lateral Pernicana fault and the right-lateral Acitrezza fault are interpreted as transfer structures linking the NE and the South rift zones, respectively, with the Timpe fault system. Such summital eruptive fissuring appears to result from the same ESE-striking regional extensional stress that drives active faulting at the base of the volcano suggesting a common tectonic origin. These tectonic structures probably merge together at depth and represent shallow splays of a deep, crustal or lithospheric normal fault zone driven by the incipient rifting processes that govern the tectonics of eastern Sicily. Fracturing on both the upper areas and the eastern sector of the volcano is in fact produced by dilational strain on the footwall of east-facing crustal normal faults located along the Ionian shore (e.g. Timpe fault system and offshore faults; see ELLIS & KING, 1991). The mere existence of a central conduit is to be ascribed to the maximum extension occurring at the summit crater region. There, the cracking system feeding the main conduit undergoes a bend of 120°, turning from a SSE to a NE direction, and ESE regional extension is accommodated by pure opening. A good correspondence between field structural data and recent seismological models based on 3D seismic tomography has been observed, especially in the south-eastern upper slope of the volcanic edifice where the occurrence of an high-velocity body seems to be related to repeated fracturing along the NNW-SSE system.

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