The deformation offshore of Mount Etna as imaged by multichannel seismic reflection profiles

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A B S T R A C T
Despite the clear evidence of active flank dynamics that is affecting the eastern side of Mount Etna, the contribution of tectonic processes has not been yet understood. So far, the various models proposed to explain the observed flank deformation have been based on onshore structural data, coming from the volcanic edifice. The Ionian offshore of Mount Etna has been only recently investigated using multichannel seismic profiles, and offers the opportunity to image the structural features of the substrate of the unstable flank of the volcano. This contribution aims at describing the deformation located offshore Mount Etna using multichannel seismic profiles recently acquired during three seismic surveys. The onshore flank deformation of Mount Etna appears to be laterally confined by two tectonic guidelines, trending roughly E–W, located to the north and south of the deforming flank; the northern guideline, in particular, takes the surface expression of a sharp fault (Pernicana Fault). Though often assumed that these boundary structures continue offshore as linear features, connected to a frontal thrust ramp, the occurrence of this simple offshore structural system has not been imaged. In fact, seismic data show a remarkable degree of structural complexity offshore Mount Etna. The Pernicana Fault, for instance, is not continuing offshore as a sharp feature; rather, the deformation is expressed as ENE–WSW folds located very close to the coastline. It is possible that these tectonic structures might have affected the offshore of Mount Etna before the Pernicana Fault system was developed, less than 15 ka ago. The southern guideline of the collapsing eastern flank of the volcano is poorly expressed onshore, and does not show up offshore; in fact, seismic data indicate that the Catania canyon, a remarkable E–W-trending feature, does not reflect a tectonic control. Seismic interpretation also shows the occurrence of a structural high located just offshore the edifice of Mount Etna. Whereas a complex deformation affects the boundary of this offshore bulge, it shows only limited internal deformation. Part of the topography of the offshore bulge pre-existed the constructional phase of Mount Etna, being an extension of the Hyblean Plateau. Only in the northern part, the bulge is a recent tectonic feature, being composed by Plio-Quaternary strata that were folded before and during the building of Mount Etna. The offshore bulge is bounded by a thrust fault that can be related to the intrusion of the large-scale magmatic body below Mount Etna.

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1. Introduction
Mount Etna is a large volcano that originated in its present form ca. 15 kyr ago, following a long magmatic history that began ~500 kyr ago in an area of complex tectonics (Fig. 1; Branca and Del Carlo, 2004; Branca et al., 2004, 2008). A large set of geodetic and interferometric data collected in the last two decades shows that the eastern flank of Mount Etna is slowly moving eastward (e.g., Froger et al., 2001; Puglisi and Bonforte, 2004; Bonforte et al., 2011), supporting longer-term geological evidence (e.g., Borgia et al., 1992). Despite the clear evidence of active flank dynamics that is affecting the eastern side of Mount Etna, the contribution of tectonic processes has not been yet understood. So far, the different models proposed to explain the observed flank deformation have been based on onshore structural data, coming from the volcanic edifice (Fig. 2). The flank deformation of Mount Etna appears to be a complex system of tectonic blocks that are laterally confined by two main tectonic guidelines, trending roughly E–W in the north and roughly WNW–ESE in the south of the deforming flank (e.g., Rust et al., 2005); the northern guideline, in particular, takes the surface expression of a sharp fault (Pernicana Fault). Though often assumed that these boundary structures continue offshore as linear features, connected to a frontal thrust ramp (i.e., Borgia et al., 1992, 2000a), the occurrence of this simple offshore structural system has not yet been proven. The Ionian offshore of Mount Etna has been only recently investigated using multichannel seismic profiles, and offers...
the opportunity to image the structural features of the substrate of the unstable flank of the volcano. This contribution aims at describing the deformation located offshore Mount Etna using recently acquired multichannel seismic profiles (Fig. 2).

2. Geological setting

Mount Etna is the largest subaerial volcano in Europe and is located in an area of great tectonic complexity (Fig. 1; Hirn et al., 1997;
Monaco et al., 1997; Argnani, 2000; Nicolich et al., 2000; Doglioni et al., 2001; Argnani, 2009). The volcano is sitting on top of the Maghrebian fold-and-thrust belt, that runs W–E through Sicily, and is located on the northern prolongation of the NNW-trending Malta Escarpment, a major morphological feature of the central Mediterranean, part of which has been tectonically reactivated in Quaternary time (Argnani and Bonazzi, 2005; Argnani, 2009). The Malta Escarpment is separating the continental crust domain of the Hyblean region, in SE Sicily, from the oceanic domain of the Ionian basin (e.g., Argnani and Bonazzi, 2005 and references therein), a setting that greatly affected the subduction regime underneath Calabria (e.g., Gvirtzman and Nur, 1999; Argnani, 2009).

Moreover, the Sicli–Ragusa fault system, a large NNE-trending fault zone that bounds to the west the Hyblean plateau, is also converging toward Mount Etna. This location at a crossroads of structural trends has been often called upon to explain the origin of Mount Etna (e.g., Lo Giudice et al., 1982), although the relationships between tectonic processes and geodynamic regime have not been yet fully unraveled (Gvirtzman and Nur, 1999; Doglioni et al., 2001; Argnani, 2009; Schiapparelli, 2010).

Besides the volcanic activity of Mount Etna, the region appears to be tectonically highly active: a remarkable late Quaternary uplift affected the adjacent Peloritani and Calabrian domains (Monaco and Tortorici, 2000; De Guidi et al., 2003), and one of the largest earthquakes in Italy occurred in the Messina Straits in 1908 (e.g., Pino et al., 2009).

The geologic history of Mount Etna includes phases of submarine volcanism, shield building, formation of nested volcanic centers and calderas, and the final constructive phase of the stratovolcano in the last 15 ka (Kieffer, 1985; Corsaro et al., 2002; Branca et al., 2004; Branca and Del Carlo, 2005; Branca et al., 2008). Recent eruptions of Mount Etna are characterized by summit eruptions at the central craters, and by fissure eruptions and dike intrusions at the rift zones oriented NE, N–S and E–W. Several eruptions have occurred from both summit and flank vents in the last century (Romano et al., 1979; Behncke and Neri, 2003; Branca and Del Carlo, 2004). Additional information about historical lava flows on Mount Etna, along with a daily update of Mount Etna activity, is available on the Catania Istituto Nazionale di Geofisica e Vulcanologia Web site (http://www.ct.ingv.it).

Recent geodetic, InSAR and GPS data, clearly show that northern and western sectors at Mt. Etna are mainly characterized by uplift and radial pattern of ground deformation and by a widespread and structurally complex seaward deformation accommodated by movement of different blocks in the eastern and southern flanks of the volcano (Lanari et al., 1998; Froger et al., 2001; Lundgren et al., 2004; Bonforte and Puglisi, 2006; Solaro et al., 2010; Bonforte et al., 2011). Particularly, geological, geodetic and volcanologic investigations have identified a short term shallow deformation, mainly linked with volcanic activity (volcano inflation and emplacement of dikes), and a long term deep seated deformation due to an overall gravity instability by the volcano load (Neri et al., 2009; Solaro et al., 2010). Inversion of geodetic data shows that volcanic load (pressurized source at depth) acted at depths variable in the 3–9 km b.s.l. range (Puglisi and Bonforte, 2004; Bonforte et al., 2008). A sub-vertical high velocity body (HVB) has been imaged by seismic tomography (Fig. 2), with bottom at a depth of about 18 km and top at about 3 km (e.g., Hirn et al., 2010).
1991; Chiarabba et al., 2000; Patanè et al., 2003, 2006). This volume with positive velocity anomaly has been interpreted as a large plutonic body. Between 3 and 9 km depth the lateral extent of this body increases to about 6 km, and the estimated volume is about 3 times larger than the volcano pile, suggesting that its accretion could be responsible for destabilizing the eastern flank (Allard et al., 2006). Then most of the magma mass is actually cumulated at the shallower interface of the upper limit of the HVB and is detected by the ground deformation and gravity data analysis (Bonaccorso et al., 2011).

Sector collapses also characterized the evolution of Mt. Etna, as testified by the Valle del Bove (VDB) scar and by the occurrence of Pleistocene to Holocene debris deposits (Chiancone) cropping out on the eastern flanks of the volcano (Fig. 2). The Holocene Chiancone deposits form a seaward bulge of the coastline and consist of fluvial deposits resting upon debris avalanche deposits whose top has been dated back to about 8000 yr B.P. (Calvari and Groppelli, 1996; Calvari et al., 1998, 2004). The results of magnetic surveys carried out offshore of the Chiancone deposits have been interpreted as imaging volcaniclastic deposits and alluvium in a stretch a few km wide (Del Negro and Napoli, 2002); this volcanic-derived deposit has been attributed to the Chiancone, and it would increase the estimate of the volume of material evacuated during the Valle del Bove collapse.

Following the observation that the eastern flank of Mount Etna is moving eastward, several attempts have been made to identify a basal sliding plane, using the concepts of volcanic spreading (e.g., Borgia et al., 1992, 2000b). Several different interpretations of the basal sliding surface have been proposed on the basis of geological data. Borgia et al. (1992) proposed a detachment surface, located at about 5–6 km depth (below sea level) and slightly dipping westward, which is rooted in the plutonic complex below the volcano summit. The sub-Etnean clays have been taken as representing the detachment surface. A similar solution was subsequently adopted by several authors (Tibaldi and Groppelli, 2002; Neri et al., 2004; Rust et al., 2005). A west dipping surface located at 0–2 km a.s.l., which therefore does not extend offshore, has been also proposed (Lo Giudice and Rasà, 1992; Bousquet and LanzaFame, 2001, 2004). Moreover, in an early work (Kieffer, 1983) an offshore subhorizontal detachment was linked to the extension occurring in the Timpe fault system, and was not directly related to the flank dynamics. These different interpretations show that the geometry of the detachment plane lacks of solid constraints, despite its geological appeal. More recently, a 12° east-dipping plane was defined by inverting GPS velocities (Bonforte and Puglisi, 2006; Bonforte et al., 2008; Puglisi et al., 2008); this plane would reach the coastline at a depth of ca. 4 km below sea level. With a similar approach, Bonaccorso et al. (2011) proposed the occurrence of an eastward dipping slide surface located just at the top of the HVB at 3 km depth b.s.l. A listric fault connecting the sliding detachment with the segment of the Pernicana Fault adjacent to the NE Rift has been constructed by applying a rollover construction to (Ruch et al., 2010). However, the constraints on the geometry of the fault plane are rather loose, and the reconstructed fault plane flattens to a depth of ca. 2 km b.s.l. over a short distance (few kms), resulting shallower than the GPS-derived sliding plane.

Overall, flank instability is widespread at Mt. Etna, regardless of volcanic activity, and remains by far the predominant type of deformation on the eastern flank of the volcano. Based on geological and geodetic data, the main bounding structures of the unstable eastern flank are the E–W trending left-lateral strike–slip Pernicana Fault, to the north, with an average slip rate of 10–20 mm/yr, and the Trecastagni Mascalucia fault system, to the south, with average slip rate in the order of 1–10 mm/yr (Fig. 2; Tibaldi and Groppelli, 2002; Accocella et al., 2003; Neri et al., 2004; Accocella and Neri, 2005; Rust et al., 2005).

Seismicity in the eastern flank is rather intense and associated with the main structural features (e.g., Azzaro et al., 2008). The Pernicana Fault is characterized by intense very shallow (<3 km from surface) seismicity, especially in the western sector of the fault (e.g., Alparone et al., 2011a, 2011b this issue), and focal mechanisms mostly display sinistral strike–slip motion along the fault plane. However, although the Pernicana Fault is a sharp feature, the deformation along the southern boundary of the Etna eastern flank is rather diffuse, as indicated by the field of GPS velocities (Bonforte et al., 2011), and the displacement appears also of lesser extent. The very limited seismicity associated to this southern fault system further supports the lack of a clear boundary. Some remarkable seismicity is instead associated to the Timpe fault system, where earthquakes occur down to 10–15 km, with focal mechanisms that show dextral-oblique extensional motion (Allard et al., 2006; Neri et al., 2005a). Magnitic activity is also associated with this fault system, and the connection with magmatic outpour could be somewhat puzzling, as the magma-tapping faults should cut through the decollement surface of the sliding flank of the volcano. It should be noted, however, that the Timpe magmatism was switched off at about 130 ka (De Beni et al., 2005; Branca et al., 2008).

The huge bulge just offshore of Catania (Fig. 2), has been regarded as a large antiform and thought to be the offshore expression of the seaward volcano’s spreading (Borgia et al., 1992, 2000a). Occurrence of widespread landslide deposits offshore of Mount Etna was proven by recent multichannel seismic surveys (Argnani and Bonazzi, 2005; Pareschi et al., 2006), although major contractional structures were not documented, so far. The offshore prolongations of the Pernicana Fault and of the southern boundary of the Etna sliding flank are represented by the Fiumefreddo Canyon, to the north, and Catania Canyon, to the south, respectively (Fig. 2). It should be remarked, however, that these are mainly morphological features and so far no clear tectonic structure has been shown, although they have been interpreted as marking two regional tectonic lineaments that accommodate the basinward movements of both the submarine and subaerial flank of the volcano (Chiocci et al., 2011).

3. Seismic data

The data from three seismic surveys have been used to map the geology of the marine area offshore of Mount Etna (Fig. 3). The MESC 2001 and TAORMINA 2006 surveys were carried out in order to investigate the regional geology and active tectonics of the eastern Sicily slope and of the Messinian Straits (Argnani et al., 2002, 2008, 2009a; Argnani and Bonazzi, 2005). The INGV survey (Pareschi et al., 2006) was aimed at investigating the marine flank of Mount Etna, and seismic acquisition was planned for a higher resolution, with respect to the other two surveys. The details of seismic acquisition and processing are given in Appendix A.

4. Interpretation and discussion

Seismic profiles have been interpreted by applying the procedures of seismic stratigraphy (Payton, 1977) and the technique for identifying structural styles (Bally, 1983).

For sake of clarity the interpretation of seismic profiles is presented by subdividing the study area in three sectors: northern, central, and southern. The northern sector straddles the prolongation of the Pernicana Fault, the central and the southern sectors covers the frontal part of the bulge located offshore Etna, and its southern boundary, respectively. The seismic profiles described in this section are located in Fig. 3.

4.1. Northern sector

Seismic profiles show evidence of contractional structures in the region offshore northern Etna. In some instance, small-scale thrust sheets are imaged as detaching at rather shallow level (Fig. 4). The seismic facies in the lower part of the line shows low frequency, variable amplitude and poor continuity reflections, recalling the seismic facies of the Hylbean domain (see Central sector section, below). On the other hand, the upper seismic facies, with high frequency, good continuity reflections, resembles the response of the Plio-Quaternary
succession (e.g., Argnani and Bonazzi, 2005). The seismic data show that the strata describing these contractional structures are truncated by an erosional surface. It appears that the erosional surface has been subsequently folded with a wavelength larger than that of the thrust sheets. More than one episode of contraction is therefore recorded in the area. Considering the thickness of the folded Plio-Quaternary succession (over 400 m), and comparing it to the thickness in the adjacent areas, the older thrust faulting can have occurred sometimes within the Quaternary. The thrust faults trend NNE–SSW, but detailed mapping of their lateral extent is inhibited by their small scale and by the great complexity of the area (Fig. 5).

The erosional surface that cut the thrust and folded strata is in turn folded with a much larger wavelength. The effect of this later large-scale folding on seafloor topography can be appreciated on a ca. N–S profile (Fig. 6) where folded strata are well imaged. Fold axes trend ENE–WSW (Fig. 5). Interestingly, minor extensional faults with roughly the same trend and dipping downslope occur in this area; they are likely driven by a combination of folding and gravity. Small extensional faults with the same trend have been imaged on multibeam bathymetry, very close to the coast (see also Chiocci et al., 2011). Onshore prolongations of these features might be responsible for historical episodes of mud blow out in the coastal lagoons, known as La Gurna mud volcano (Fig. 5; Carveni et al., 2006). In this respect, it is interesting to observe that the Pernicana Fault loses its continuity toward the coastline, and is present with short NE-trending segments. Here the faults have almost normal component, and displacement is much reduced; the morphological expression of the faults and the associated seismicity are also reduced (Groppelli and Tibaldi, 1999; Acocella and Neri, 2005). High resolution multibeam bathymetry, very close to the coast, also shows that a cluster of small NNE–SSW scars, between 80 and 110 m water depth, are present on the prolongation of the Pernicana Fault (Chiocci et al., 2011). How the Pernicana Fault continues offshore is a critical question. The interpretation of seismic profiles shows that the Pernicana Fault does not continue offshore as a sub-vertical strike-slip fault with an E–W trend (Figs. 6 and 7). Therefore, models of distributed brittle deformation above a decoupling layer given by Etnean clays (Groppelli and Tibaldi, 1999) seem not likely. Rather, it seems that two broad anticline and syncline, trending ENE–WSW and at least 8 km long, interrupts the trend of the Pernicana Fault (Fig. 5).

It seems, however, that the easternmost extent of the Pernicana Fault onshore is more similar to what observed in the offshore (small NE-trending extensional faults), and one may wonder whether the large folds mapped offshore, that underline the superficial extensional faults, can continue inland, underneath the coastal plain. The change from a clear strike-slip Pernicana Fault and a different kind of deformation to the east could, therefore, be located onshore. The coastline, as it is often the case, is just an ephemeral and apparent boundary.

The left-lateral Pernicana Fault accommodates the sliding of the eastern flank of Mount Etna; therefore, the displacement along the fault is either absorbed as contractional deformation (as previously suggested, e.g., by Borgia et al., 1992), or is linked to a broader extensional system that marks the large-scale collapse of the volcanic edifice and its substrate toward the depressed region of the Ionian Sea. As the Pernicana Fault appears kinematically linked to the Rift of NE, its activity is likely comprised within the last 20 ka (last phases of Ellittico volcano and Inception of Mongibello activity; Branca, 2003; Del Carlo et al., 2004). Moreover, with the estimated (maximum) current slip rate of 15–20 mm/yr along the Pernicana Fault, the total amount of displacement...
in the last 20 kyr, 300–400 m, is much less than what observed at the thrust front, as described below.

The ENE–WSW-trending system of folds affects the sea floor morphology, suggesting a recent activity, perhaps coeval with the activity of the Pernicana Fault. The ENE–WSW fold trend, however, is at odds with a left lateral strike-slip along the Pernicana Fault, undermining the simple view of a collapsing volcanic flank where two lateral strike-slip faults are linked to a frontal thrust (i.e., Borgia et al., 1992). On the other hand, it is possible that complexity related to regional active tectonics played a role (e.g., Argnani, 2009).

The thrust fault at the front of the structural high is well imaged by seismic data (Fig. 8). The thrust plane cuts through the stratal surface which represents the base of a large-scale landslide and reaches the sea floor. Although the sea floor shows evidence of submarine erosion and mass wasting at the location where it is intersected by the thrust plane, it is likely that shortening is currently occurring. However, the observed displacement along the thrust is larger than 1 km, and therefore much larger than the maximum horizontal displacement accrued along the Pernicana Fault since its onset (300–400 m). Moreover, it seems that the large scale landslide has been triggered by the uplift caused by the initial activity of this thrust.

A remarkable character of this offshore area is the widespread occurrence of erosional features that testify the intense mass wasting along the slope (see also Chiocci et al., 2011). The scars left by mass wasting processes are well imaged in many of the profiles (e.g., Figs. 4 and 6). The most relevant feature related to mass wasting along the slope is the large scale slide at the northern boundary of the offshore bulge (Fig. 5). The body of such submarine slide is composed by stratified sediments that were deposited on the submarine slope (Figs. 8 and 9) and that, therefore, cannot be directly related to volcanic collapse. A regional profile (Fig. 9) shows the broad view of the thrust fault located at the front of the structural high, and illustrates also the large-scale slide body and the extent of mass-wasting processes which have been active along the offshore slope. The details of the large submarine slide will be given elsewhere, nevertheless, the slide deposit has been deeply eroded on the northern side, where it faces the large Fiumefreddo Canyon (Figs. 2 and 10). In fact, the flanks and the head of the wide Fiumefreddo canyon are deeply incised by smaller canyons; the dense network of gullies and canyons indicates an erosionaly mature submarine drainage, suggesting that the age of the submarine slide can be taken as older than any known historical tsunamis (Argnani et al., 2009b).

Moreover, the high resolution seismic profiles and morphobathymetric data on the northern part of our study area support previous arguments, based on geophysical data (Argnani et al., 2009b), and allow to rule out the occurrence of a recent large-scale landslide located offshore Giardini–Naxos (Fig. 5). This observation undermines the proposal of Billi et al. (2008) that the 1908 tsunami was originated by a over 20 km$^3$ large landslide in this sector of the eastern Sicily slope.

Finally, it has been recently proposed that the Etna volcanic extends eastward, for about 20 km into the Ionian Sea (Patané et al., 2009). The authors further hypothesize that the morphology of the volcanic apparatus is not directly observed because it is buried under the debris deposits of the Chiancone unit. The supposed volcanic apparatus is located in the Riposto Ridge, a marked east–west-trending features that bounds to the north the offshore bulge. This proposal, however, does not find support in our data, which show that the Riposto Ridge is composed by folded sedimentary strata, in the seismic facies of which there is no evidence of volcanic material (Fig. 6). Moreover, as discussed more in details below, the deposits belonging to the Chiancone unit do not extend as far as the locality where the volcanic apparatus is supposed to be.

4.2. Central sector

The area located offshore of central and southern Mount Etna is characterized by a marked topographic bulge that extends ca. 10 km from the coastline. On seismic profiles this region appears as a structural high that displays a thin sedimentary cover, characterized by high frequency, good continuity reflections, above a poorly reflective substrate (Fig. 10). On the other hand, well stratified and thicker sedimentary packages occur on either side of this high, on a N–S cross section (Fig. 9). Stratigraphic relationships, still partly visible on the southern and eastern sides (Figs. 9 and 10), suggest that the sedimentary strata onlapped a pre-existing topographic relief. As the strata span at least the whole of the Quaternary, it is believed that the structural high pre-existed the stabilization of the volcano feeder system and the change from fissural to central eruptions, that led to the formation of Mount Etna (120 ka; Branca et al., 2004). Whereas the strata on the...
southern side show little or no deformation, the sedimentary package to the north has been heavily folded. It is worth noting that although the folded strata to the north, which include the Riposto Ridge, contribute to the topographic bulge, this area differs substantially from the rest of the topographic high.

In the northern part, the sedimentary strata have been folded and the eastern edge of the structural high appears clearly as thrust fault (Figs. 6 and 8). The same thrust fault, although less evident, can be followed further to the south on seismic profiles, till the Catania canyon, where it turns from NNE-SSW to ca. E-W (Fig. 5).
The origin of this topographic high, which pre-existed the forma-
tion of Mount Etna, is not fully understood. However, subsurface data
in the Catania plain, south of Etna, show that a narrow stripe of units
belonging to the Hyblean plateau is entering below the eastern part of
the volcano edi-
fi-
cence (Longaretti et al., 1991). In fact, Miocene volcanics
belonging to the Hyblean succession have been found at depth less
than 700 m near Catania (Fig. 2). It seems, therefore, that the high cor-
responding to part of the bulge located offshore of Mount Etna is a
northern stretch of the Hyblean plateau (Fig. 5).

4.3. Southern sector

The southern prolongation of the Timpe Faults system has been
assumed by several authors (e.g., Monaco and Tortorici, 2000), mak-
ing the Timpe faults as part of the Malta Escarpment fault system.

A physical continuity, however, has never been proven, and previous
data suggested that it was not likely (Argnani and Bonazzi, 2005). The
current seismic coverage allows to better define this issue (Fig. 3). The
east–west-trending seismic profiles south of Mount Etna show a thick and undeformed sedimentary package that likely spans the
whole of Quaternary and possibly older sediments. This sedimentary
package covers and sutures pre-existing structures (W-dipping ex-
tensional faults) but it is not affected by faulting (Fig. 11); considering
that if the Timpe Faults were continuing southward they should pass
through this seismic profile, a direct connection between the Timpe
faults and the Malta Escarpment fault system should be rejected.
Although, it is possible that the Timpe fault system represents a W-
ward (left) stepping of the Malta Escarpment fault system, it should
be noted that the final morphology produced by this fault system
is rather different from the morphology resulted from the Malta

Fig. 7. Southern part of Line Tao 16 showing the lack of subvertical tectonic features at the seaward prolongation of the Pernicana Fault. The folded sediments on the southern portion of the profile belong to the system of folds of the Riposto Ridge (Fig. 5). Location is in Fig. 3.

Fig. 8. Line 2. Thrust fault at the front of the structural high. The thrust cuts through the surface above which a thick package of sediments (500–600 m) have slid down, originating a
large scale-slide. The intense sea floor erosion is evident on the profile. The minimum thrust displacement (ca. 1 km) is larger than the horizontal displacement possibly accrued
along the Pernicana Fault (300–400 m). Note that the basinal strata (right side) are onlapping to the west a pre-existing high.
Escarpment fault system, as the Timpe fault system does not show a steep scarp toward an eastern deep water domain. High resolution bathymetric data show that the Timpe faults offset the coastline by 10–15 m throw in their southern termination (Chiocci et al., 2011).

A large submarine canyon, the Catania Canyon, represents a major morphological feature in this last area (Fig. 5). Because of its E-W roughly linear trend in the 15 km near the coastline, the Catania Canyon has been often considered as a tectonically-controlled morphological feature. However, our seismic data suggests that no E-W trending structure occur in that area, where, instead, extensional faults with trends from NW to N have been mapped (Fig. 5). The thrust bounding the offshore bulge is passing to the north of the Catania Canyon, and the canyon is incising a subhorizontal sedimentary succession (Fig. 10). Although a more than 30 km long, WNW–ESE lineament can picked out in detailed bathymetries (Marani et al., 2004; Chiocci et al., 2011; Fig. 5), seismic data (Argnani and Bonazzi, 2005a and this study) show that the lineament is just a morphological feature that has no relationship with deep structures; in fact, a fault of the Malta Escarpment system is crossing the lineament, remaining unaffected. This evidence undermines the interpretation of Chiocci et al. (2011), that consider the Catania Canyon lineament as crustal feature bounding the offshore bulge to the south. It seems more likely that the Catania Canyon is controlled by a morphology that is inherited from previous tectonics (Fig. 10).

4.4. The Chiancone unit

An apron of prograding sediments has been observed offshore of the area where Chiancone unit is cropping out, and it may be of interest to figure out its relationship with the Chiancone deposit (Fig. 2). A N–S profile close to the coastline shows an erosional platform located just off the Chiancone outcrops (Fig. 12); this erosional surface is covered by little or no sediments, without any trace of the chaotic facies that can be attributed to the Chiancone deposits. Rather, judging from its location, this erosional surface might represent the base of Chiancone unit cropping out onshore. This widespread erosional surface can be followed all along the shelf and can be attributed to the last sea level lowstand (ca. 20 ka). Moreover, the prograding unit imaged by E–W profiles (Fig. 13) is affected by the erosion that originated the subhorizontal platform, indicating that the prograding unit was older than the Chiancone unit, from which it may be physically detached (Fig. 14). Although it is possible that the sedimentary wedge located offshore has been fed by the dismantling of the Etna eastern flank, there is no relationship with an abrupt event such as the collapse of the Valle del Bove, and deposition appears to be due to regular and continuous sedimentation. This observation questions some results obtained from marine magnetic survey offshore Mount Etna (Del Negro and Napoli, 2002), where the Chiancone unit has been inferred to be extensively
present in the offshore. In this respect, it is interesting to note that a similar study based on potential methods comes to a different conclusion, reducing the offshore extent of the Chiancone unit (La Delfa et al., 2011).

Our results in the offshore region led to reconsider the volume estimates of the Chiancone unit, that is assumed to be indicative of the volume of material evacuated from collapse of the Valle del Bove. Although mass wasting is a widespread process in the area, the related deposits do not record a large unique event (Pareschi et al., 2006).

In this respect it might be interesting to note that late Miocene volcanics have been reported in the subsurface, south of Catania (Longaretti et al., 1991). If the morphologic high observed in the central sector offshore represents the northern prolongation of the Hyblean Plateau, late Miocene volcanics might be present here as well, and can be responsible for the observed magnetic signal.

An attempt to frame our observation in a stratigraphic setting can be made by using the geological constraints. The offshore erosional platform can be taken as due to the last sea level lowstand (about 20 ka). The Chiancone units was deposited following the Valle del Bove collapse (loosely comprised between 15 ka, age of the final activity of Ellittico volcano (Branca, 2003; Del Carlo et al., 2004), and ca. 8 ka, age of the upper part of the Chiancone deposits), likely by fluvial reworking of debris avalanches, as suggested by the facies of the deposits (Calvari and Groppelli, 1996; Calvari et al., 1998). The prograding unit terminates toward the coast, against the erosional surface which represents the base of Chiancone, and can be interpreted as deposited during the last sea level fall. In this scheme, therefore, the Chiancone can be interpreted as a retrogressive deposit during the last sea level rise (Fig. 14).

4.5. Sequence of deformational events

Direct dates of sediments and rocks are lacking in the area, and the age of the sedimentary units identified on seismic profiles is often only loosely constrained by regional correlation.
Nevertheless, from the analysis of the whole seismic data set, some key events can be identified and correlated across the study area, allowing a sequence of deformational events to be worked out (Fig. 15).

Intense erosion represents a remarkable morphological feature of the region offshore of Mount Etna, and is characterized by several incised canyons and slide scars (see also Chiocci et al., 2011). Recent assessment of Holocene uplifted coastlines in the Peloritani and Southern Calabria indicates an increase, of about 0.5 mm/yr, in the uplift rates since late Holocene (ca. 6 ka) (Antonioli et al., 2009). Seismic data show that the remarkable erosion has been a fairly recent event (e.g., Fig. 8), and we take the intense erosion as related to the late Holocene increase in regional uplift. It is worth noting that the intense erosion and mass wasting operating along the submarine slope have masked the morphologic expression of deeper structures, making it difficult to detect them (e.g., Chiocci et al., 2011).

The geological evolution of Mount Etna suggests that the initiation of the Pernicana Fault is not older than 15 ka, the age of the present day volcanic edifice (Mongibello) that grows above a previous edifice (Ellittico) partly dismantled by the Valle del Bove collapse (Branca et al., 2004, 2008).

The erosional platform that is present, at about 100 m water depth, near the coast adjacent to Mount Etna (Fig. 12) can be related to the last sea level lowstand, dated at ca. 20 ka. This erosional surface can be followed from offshore of the Chiancone northward, to the Riposto Ridge area.

The onset of Mount Etna magmatism, leading to the intrusion of the large magmatic body, started at about 120 ka (Branca et al., 2004), and we infer that the intrusion-related deformation could be responsible for the initiation of shortening at the bulge frontal thrust. In fact, this frontal thrust is kind of outlining the large-scale intrusion located below Mount Etna (Fig. 2).

The main structural features which have been identified offshore of Mount Etna are summarized in Fig. 5. The thrust fault defining the boundary of the offshore bulge merges to the north into a region of NE-trending folds, at the prolongation of the Pernicana fault. The morphologic high is composed by a northern part, where a thick package of sedimentary strata has been thrust and folded (see Figs. 8 and 10), and by a less deformed southern part, which is interpreted as the northern prolongation of the Hyblean Plateau (Fig. 10).

Folding in the northern part promoted the gravitational instability that originated the large-scale submarine landslide (Figs. 5 and 9). As previously mentioned, the onset of thrusting preceded the activity of the Pernicana fault, and was therefore occurring before the main building stage of the present volcanic edifice.

Pleistocene NNE-trending thrust faults are also present in this northern area (Fig. 4). The strata involved in this deformation have been subsequently affected by the previously described folding.
These thrust faults are therefore the oldest features recognized in the area; they are interpreted as the northern prolongation of the Gela thrust front, that likely continues underneath the Etna edifice (Fig. 1). If this interpretation is correct, thrusting can be as old as middle Pleistocene (Argnani, 1987; Patacca and Scandone, 2004).

4.6. Flank instability: Comments on triggering mechanisms

Three actors are playing a role in the deformation that affected the eastern flank of Mount Etna: i) tectonics, as Mount Etna is located in a position where several tectonic structures are currently active, ii) gravitational instability, promoted by the Ionian depressed topography, and iii) magmatic intrusion, which gave rise to the volcanic edifice (Fig. 1).

Some of the tectonic features observed in the study area formed before the onset of the magmatic system that led to the Etna central edifice (ca. 120 ka), and can be attributed to the regional tectonics. In the offshore area, the shallow thrust faults observed in the western part of the Riposto Ridge are an example. The Timpe faults, onshore, also formed before the development of the Etna edifice, as testified by the associated magmatic activity (220–130 ka; e.g., Branca et al., 2008). The link with magmatism and the current seismicity, recorded down to 10 km or more, indicates that the Timpe faults are crustal-scale tectonic features. Altogether, the contribution of these tectonic structures in shaping the bulge offshore of Mount Etna appears rather limited.

Gravity played an important role, particularly in the late stages of evolution, but it was not enough by itself to drive the whole of the deformation. It certainly promoted the marked asymmetry that caused the preferential dismantling of the eastern flank of the volcano, but it seems that gravity was superimposed to tectonic and volcano/tectonic processes.

It has been recently proposed that the gravitational instability of the eastern flank of Mount Etna, that is facing the deep Ionian basin, is the main controlling factor for the volcano evolution (Chiocci et al., 2011). It has been inferred that instability was triggered along the margin because abundant magma intrusion (starting at ca.120 ka) caused a lateral bulging toward the deep Ionian basin. Large-scale mass wasting originated from the base of the unstable slope and propagated upslope, to the present configuration, with faults in a semicircular pattern that dissect the coastal area. The Timpe fault system is considered as part of this large-scale retrogressive sliding. In spite of the relatively superficial nature of the sliding, two WNW–ESE crustal lineaments, bounding the bulge to the north (Fiumefreddo lineament) and to the south (Catania Canyon lineament), are thought to be critical in assisting the large-scale mass wasting. A relationship certainly exists between the offshore bulge and Mount Etna; nevertheless, some of the inferences that Chiocci et al. (2011) have made are not supported by our data. For instance, the Riposto Ridge has been considered as made up by relatively strong tectonic units (Chiocci et al., 2011); however our seismic profiles (Fig. 10) show that it is composed by folded strata deposited on the margin, and it is actually weaker than the structural high located to the south. Although extensional faults affect the uppermost sediments, they appear to be related to the combined contribution of folding and gravity. Extensional faults, therefore, are mostly superficial features, and are not reflecting regional extension; in fact, folds and thrust faults are observed in several localities within the bulge. In the same line, the eastern slope is affected by intense mass wasting, but this process is the most recent occurring in the area, being preceded, and sometimes promoted, by tectonic deformation. The northern branch of the semicircular pattern of faults is partly visible near the Riposto Ridge, but it is likely overemphasized in the southern branch, where faults are mainly visible near the coast and may be interpreted as the southern extent of the Timpe fault system. The magmatism and relatively deep seismicity associated to the Timpe faults suggest an origin different from gravitational sliding, and their age (onset at ca. 220 ka) contrasts with the upslope progression of the sliding. Finally, the Catania Canyon and the Fiumefreddo lineaments are only morphologic features that have no
expression at depth. The tectonic structures that bound the offshore bulge (Fig. 5) are not crustal features that extend further east; they only contributed to the development of the bulge.

Magmatism is a specific feature of the Etnean area, which is superimposed to the complex tectonic setting of the region. Seismic tomography has revealed the occurrence of a large intrusive body below the volcanic edifice. The estimated volume of the upper part of the intruded body, between 3 and 9 km, is over 650 km$^3$. It has often been assumed that the intrusion of the large magmatic body is responsible for the origin of the offshore bulge, irrespective of the deformation mechanism (cfr. Borgia et al., 1992; Chiocci et al., 2011). We also believe that the deep magmatic intrusion can account for part of the observed large-scale deformation, with the topographically depressed Ionian area being responsible for the eastern structural asymmetry. From the interpretation of our data we propose that the frontal thrusting followed the large intrusion below Mount Etna, but its inception preceded the development of the Pernicana Fault, which developed much later (Fig. 15).

We consider the sliding of the eastern flank, that is currently measured by GPS velocities (e.g., Bonforte et al., 2011), as a minor contributor to the observed shortening at the front of the offshore bulge.

On the other hand, shallow magma emplacement within the volcanic edifice can amplify the deformation near the central craters, and can trigger favorably oriented faults, such as the Pernicana Fault and the north-eastern Rift (e.g., Currenti et al., 2008). The instability of the eastern flank of Mount Etna has likely affected the magmatic evolution of the upper part of the volcano, and it seems that the interplay between magmatic intrusion/eruption, and the sliding of the eastern flank, guided by the Pernicana Fault, characterized the most recent history (last 15 ka) of the volcanic edifice.

5. Conclusions

Seismic data show a remarkable degree of structural complexity offshore Mount Etna (Fig. 5). The Pernicana Fault, for instance, is not continuing offshore as a sharp feature; rather, the deformation is expressed as a set of ENE–WSW folds located very close to the coastline. Seismic data indicate that these tectonic structures have affected the offshore of Mount Etna before the Pernicana Fault system was developed, less than 15 ka ago. The southern guideline of the collapsing eastern flank of the volcano is poorly expressed onshore, and does not show up offshore; in fact, seismic data indicate that the Catania canyon, a remarkable E–W-trending feature, does not reflect a tectonic control. In a similar way, no structural guideline has been observed offshore, at the prolongation of the Pernicana Fault. Moreover, the Timpe Fault system does not continue toward the Malta Escarpment.

Seismic interpretation also shows the occurrence of a structural high located just offshore the edifice of Mount Etna. Whereas a complex deformation affects the boundary of this tectonic element, it shows only limited internal deformation. Preliminary results led to interpret this structural high as the northernmost extent of the Hyblean foreland. The role of this element in the volcanic-tectonic evolution of the region appears rather complex and requires further investigations.

We consider that part of the topography of the offshore bulge pre-existed the constructional phase of Mount Etna, being an extension of the Hyblean Plateau. Only in the northern part, the bulge is a recent tectonic feature, being composed by Plio-Quaternary strata that were folded before and during the building of Mount Etna. The offshore bulge is bounded by a thrust fault that can be related to the intrusion of the large-scale magmatic body below Mount Etna. Borgia et al. (1992) and followers present a model which links the currently observed sliding of the eastern flank of the volcano to the offshore thrust faults. Our seismic data indicate that the sliding of the eastern flank is younger than the frontal thrusting initiation, and its contribution to overall shortening is only minor. Therefore, the driving mechanism for the origin of the offshore bulge is the magmatic intrusion, rather than the gravitational collapse of the volcanic edifice.

The interpretation of seismic data indicate that part of the offshore bulge pre-existed the construction of Mount Etna, unlike what was proposed by Chiocci et al. (2011); part of the offshore bulge was build up by thrusting, rather than simply being an inflation response to magmatic intrusion. Moreover, we did not find any evidence for the occurrence of crustal-scale E–W-trending faults bounding the bulge on its northern and southern sides. The extensional faults observed in the Riposto Ridge result from a combination of large-scale folding and downslope gravity. Although gravity contributed significantly to the recent dismantling of the offshore slope of Mount Etna, there is more than just gravity in shaping the offshore bulge.

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Appendix A. Details of seismic acquisition and processing

A1. Acquisition

The TAORMINA multichannel seismic survey, carried out in September 2006 onboard of the R/V Urania of the National Council of Researches (CNR), has led to the acquisition of ca. 700 km of seismic profiles. Together with seismic data, Sub Bottom Profiles were acquired by a 16 transducers hull-mounted DATASONICS CHIRP-II profiler, with operating frequencies ranging between 2 and 7 kHz, in order to investigate the near bottom sediments.

The seismic survey has been carried out with two different systems, according to the operation conditions encountered during the survey:

1) 48-channel Teledyne seismic streamer with 600 m of active section and 12.5 m group interval. The streamer was kept at an operation depth of ca. 10 m. Shot interval was 18.75 m to get a 16-fold coverage. A seismograph StrataVisor (Geometrics) was used for acquisition, with 1 ms sampling and 5 s of record length.

2) 24-channel Teledyne seismic streamer with 120 m of active section and 5 m group interval was used in the narrower part of the Messina Straits. The streamer was kept at an operation depth of ca. 1 m. Shot interval varied between 12.5 and 20 m to give a coverage from 3 to 4.8. A seismograph DMQ Link II (Seismic Source) was used for acquisition, with 1 to 2 ms sampling and 3 to 4 s record length. In both cases the energy source was a G.I. Gun Sodera in Harmonic mode (105 + 105 c1), fed by a 35001 electrically-driven compressor Bauer, and operating with a pressure of 140 bars. The Sure Shot system (Real Time Micro Systems) was used to control the shots. The depth of the energy source was ca. 8 m.

The seismic survey Malta Escarpment (MESC) 2001 was carried out in July–August 2001, on board the R/V Urania and has led to the acquisition of 2500 km of seismic profiles. Data acquisition has been carried out using a 48-channel Teledyne streamer and a Sodera generator-injector gun in harmonic mode (105 + 105 in3). The group interval of the acquisition streamer was of 12.5 m for a total active length of 600 m. Shot interval was 50 m giving a coverage of 600%. Seismic data were collected by a Teledyne 48-channel streamer and digitized and recorded by a Geometric’s Stratavisor seismograph, with sampling rate of 1 ms and record length varying from 8 to 12 s. The streamer was kept at an operation depth of ca. 10 m, whereas the depth of the energy source was about 6 m.
In May 2005, about 480 km of high resolution MCS profiles were collected offshore Catania, in front of Mount Etna, by FUGRO OCEAN-SISIMICA S.p.A., operating on the M/V Pehlivan II. The survey was carried out for INGV using a 1200 m long Litton Industries quick coupler streamer, with 96 traces and a group interval of 12.5 m. The streamer was connected to a TTS-II digital data recording system with a sampling interval of 1 ms and a record length of 3 s. The seismic source was an airgun array of total size of 120 in³ operated at a pressure of 2000 psi. The shooting interval was 12.5 m. The source and streamer were towed approximately 2.5 m below sea level.

A2. Processing

The MESC-2001 and TAORMINA 2006 seismic data have been processed using the software Disco/Focus by Paradigm, following a standard sequence (Yilmaz, 1987) up to time migration. The main processing steps are:

1) Resampling every 2 ms of the original record, 
2) Spherical divergence gain to recover signal amplitude, 
3) Editing and CDP sorting, 
4) Velocity analysis every 200 CDP, 
5) Normal Move Out correction, 
6) Stack, 
7) Muting to remove noise in the water column, and 
8) Finite-Difference Time Migration.

The processing of ca. 360 km of INGV seismic lines was completed using the Fugro Seismic Imaging Unisese package. The major steps of the processing sequence were: trace editing, gain recovery, sorting in the CDP domain, velocity analysis, pre-stack time migration, NMO correction and CDP stacking. Muting in the CDP domain was done to remove NMO stretch. The mute was applied with 2 traces remaining at the seabed for shallow areas (WB~1000 ms) or 4 traces remaining for deeper areas. Full-fold data (no traces muted) was used after WB ~ 800 ms. A post-stack time variant filter was applied near the end of the processing sequence.

Appendix B. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.jvolgeores.2012.04.016.

References


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