SUBMERGED HUMMOCKY TOPOGRAPHIES AND RELATIONS WITH LANDSLIDES. NORTHWESTERN FLANK OF ISCHIA ISLAND, SOUTHERN ITALY

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ABSTRACT: High resolution *sidescan sonar* and *multibeam* surveys carried out offshore northwestern sector of the Ischia volcanic island revealed a complex seafloor topography controlled by hummocky features. This peculiar morphology results from irregular mounds and ridges, often organized as composite structures, characterizing landslide deposits of catastrophic events. In the study area submerged hummocky topography well correlate with the extensive slope instability affecting the northwestern border of the Mt. Epomeo, the main volcanic structure of the island, corresponding to a resurgent dome uplifted at least of 800 m in the last 33 Ka. Mostly of these landslide accumulations are related to historical events, but their stratigraphic positions within the post-resurgence volcanic units testify an older slope instability, probably coeval and recurrent with respect to resurgence.
Erosional scarps and sedimentary structures characterizing the northern offshore suggest the occurrence of recent depositional events, while in the western offshore hummocky deposits result partially covered by prograding depositional prism. In both cases the morphologic features point to a recurrence of significant landslide events with catastrophic implications.
Historical seismicity has been recognized as a main triggering factor for slope instabilities along the northern border of Mt. Epomeo. Macroseismic analyses suggest a restricted epicentral area coincident with such a border and controlled by a principal seismo-tectonic structure ENE-WSW oriented. This situation well conforms with the recent individuation of the submerged hummocky topography found offshore Lacco Ameno village, hypothesized on the base of bathy-morphologic analysis.

Keywords: Hummocky Topography, Landslides, Historical Seismicity, Ischia Island, Continental Shelf, Southern Italy.

1 INTRODUCTION

Ischia island is one of the most interesting active volcanic area since the occurrence of historical eruption, earthquake, and landslide events often with catastrophic implications. A modern approach to the study of these phenomena on the island date back to the first part of the XIX[th] century (Lyell, 1837; Fonseca, 1847 Fuchs, 1873). Further investigation were carried out after the destructive seismic event occurred in 1883 (Baldacci, 1883; Mercalli, 1884; De Rossi, 1884; Guiscardi, 1885). Since then a great number of geologic and volcanologic researches have been produced, and at present the area is one of the most studied and monitored. Nevertheless, besides pioneer works (Walter, 1886) and large scale seismostratigraphic studies concerning the entire bay of Naples (Fusi et al., 1991; Milia et al., 1998), less is known about the Ischia submerged areas, and only the recent development in seafloor mapping enabled their extensive investigation (De Lauro et al., 2000; de Alteriis et al., 2001; Marsella et al., 2001; Bruno et al. 2002; Budillon et al., 2003a; 2003b).

The complex volcanological and geological evolution of the Ischia island (fig. 1) has been reconstructed by several authors (Rittman and Gottini, 1980; Gillot et al., 1982; Chiesa et al., 1987; Vezzoli, 1988; Orsi et al., 1991; Alessio et al., 1996; Tibaldi and Vezzoli, 1998; Acocella and Funciello, 1999; Del Prete and Mele, 1999). In particular, analysis of the oldest volcanic deposits occurring along the coastline, allowed to infer the remnants of an ancient caldera resulting from a major collapse between 150 and 75 ka (Vezzoli, 1988). As suggested by stratigraphic evidence, following marine ingressions, a significant ignimbritic eruption dated 55 ka produced another caldera collapse, with the emplacement of the Green Tuff, the best known volcanic deposit occurring on the island (Gillot et al., 1982; Orsi et al., 1991; Tibaldi and Vezzoli, 1998). After this eruptive event, the morphodynamic and geologic evolution of the Ischia island was mainly controlled by a volcano-tectonic activity, which uplifted the Mt. Epomeo block inside the preexisting caldera depression over the past 33 ka.

Hummocky topography has been referred to catastrophic volcaniclastic gravity flows (*debris avalanche*) developed both in subaerial (Siebert, 1984; Orton, 1996; Ui et al., 2000) and subaqueous (Masson et al., 1993; Gardner et al., 1999; Lee et al., 1999; Milia et al., 2003) environments. In the frame of a multidisciplinary study (IAMC–CNR and Stazione Zoologica, Napoli) preliminary to the establishment of marine protected area in the Phlegrean islands, seafloor acoustic investigations including *multibeam* e *sidescan sonar* surveys, revealed complex morphologies related to hummocky features along the northern and

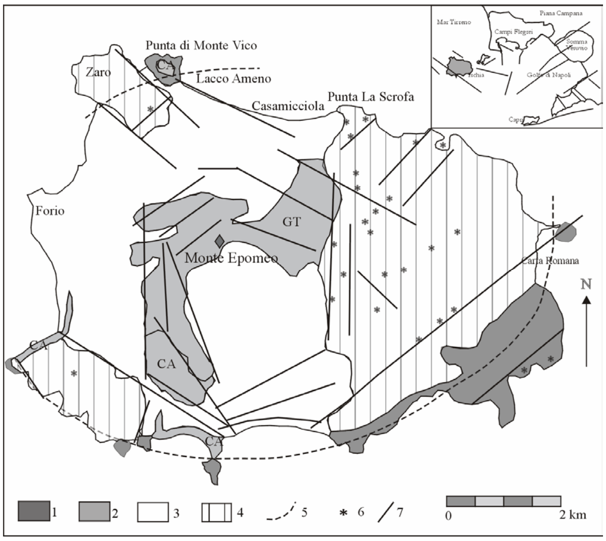

Figure 1. Simplified gelogical map of Ischia island. 1) Pre-caldera volcanic units and circum-caldera lava domes (147 - 75 ka); 2) Monte Epomeo Green Tuff (GT) and Colle Jetto Formation (55 ka); Citara Tuff (33-44 ka); 3) landslide deposits; 4) recent lava flows and pyroclastic deposits (< 20 ka); 5) hypothesized caldera rim; 6) Holocene eruptive vents; 7) faults (from Gillot et al., 1982, Tibaldi and Vezzoli 1998, Del Prete and Mele, 1999, modified).

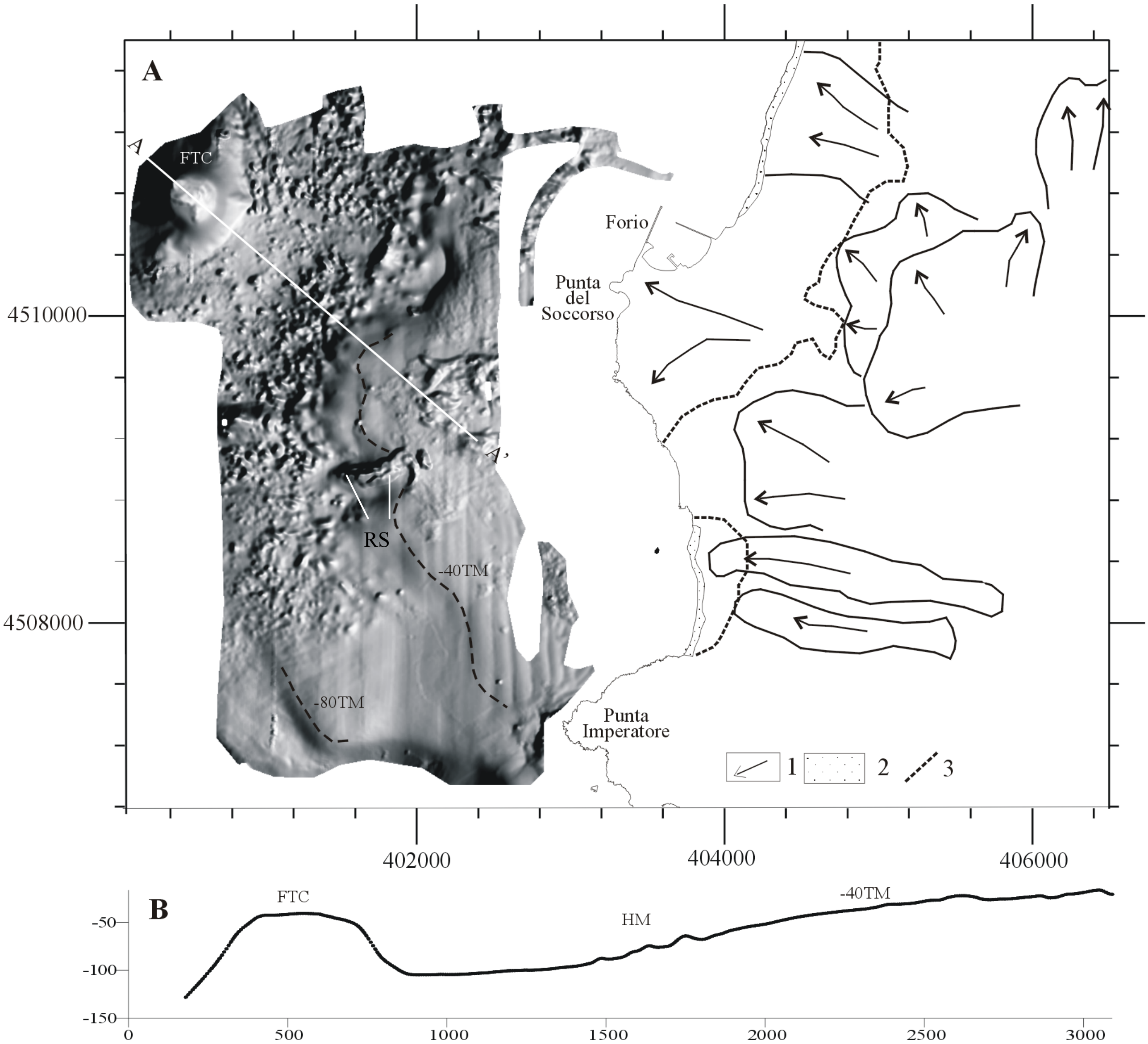

Figure 2. Shaded relief map and morphologic features of the Ischia western offshore and main onland morphologies. A. 1) landslide deposits; 2) present-day beach deposits; 3) ancient coastal cliff; (-40TM) marine terrace rim at -40 m; (-80) marine terrace rim at -80 m; (FTC) Forio tuff cone; (RS) rocky substrate; (A-A') trace of topographic section. B. Topographic section. (HM) hummocky topography. Onland morphology is from Tibaldi and Vezzoli, 1998 and Del Prete and Mele, 1999 (modified).

western offshore of the island (De Lauro et al., 2000; Budillon et al., 2003). The reported surveys do not include the whole seafloor areas interested by hummocks, their extension and features being assessed by new investigations still in progress (D'Argenio et al., in press). Hummocky features, extending over a wide area, have been reported in the southern Ischia offshore (Chiocci et al., 1998; de Alteriis et al., 2001; 2003; Chiocci et al., 2002) where amphitheatre failure scarps developed on land and at sea, allow to establish firm associations with catastrophic landslides.

The aim of this study is to accomplish a morphologic characterization of hummocky topographies in the northwestern offshore of Ischia island, and to establish correlations with the extensive slope instability affecting the northwestern border of the Mt. Epomeo. Moreover, a triggering mechanism for the induced hummocky features offshore Lacco Ameno village (northern Ischia) is inferred by the analysis of the historical seismicity since the XIIIth century, which allowed to recognize a seismogenic area along the northern slope of the Mt. Epomeo resurgent block.

2 MATERIALS AND METHODS

Sidescan imagery and multibeam bathymetric data were collected in the summer 2000 in the northwestern offshore of Ischia island at depths ranging from –15 to – 115 meters, from aboard the RV Thetis (cruises GMS00_4 and GMS00_5).
The multibeam system was a Reason SeaBat 8101, the track being positioned so as to insonify 100 % of the seafloor with at least 20 % overlap. The data were edited for spurious bathymetric and navigation points and processed using the software PDS 1000. Subsequently, the processed data were used to generate maps and digital terrain models (DTM) with accuracy corresponding to the International Hydrographic Organization (IHO, 1997).

Sidescan sonar imagery was acquired with a EdgeTech Df 1000 and range of 150 meters, the tracks being positioned at 250 meter with respect to each others. This allowed a 30 % overlap with a 100 % coverage of the seafloor. The data were edited for navigational and slant range corrections, and processed with ISIS-TEI software package. The processed acoustic imageries were mosaicked to generate map depicting backscatter features of the study area. Navigation was via wide area differential GPS using satellite corrections from Racal sky Spot system, integrated with HYDRO Trimble Navigation software package.

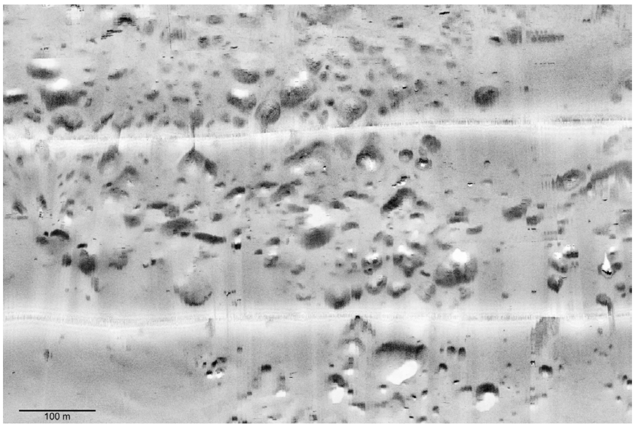

Figure 3. Forio offshore. Sidescan sonar mosaiked image from a seafloor area characterized by hummocky topography. Conical mounds (blocks) very different in size are covered and surrounded by pelitic and minor organogenic sediments. Light tones represent low backscatter.

3 SUBMERGED HUMMOCKY TOPOGRAPHY

Shaded relief and backscatter maps compiled from multibeam and side-scan data, led to recognize a different morphologic organization of the reported hummocky topographies. In the western offshore (*Forio offshore*; fig. 2) extremely etherometric blocks (*conical mounds*; fig. 3), often organized as composite ridges, occur partially covered by a sedimentary prism. In this sector progradation of marine sediments from the shore hide the relations between hummocky deposits and landslide accumulations on land.

In the northern offshore (*Lacco Ameno and Casmicciola offshores*) transverse ridges and troughs with no consistent overall trend have been observed. Moreover, erosional features and *fresh* sedimentary structures suggest a recent morphodynamics. Both in northern and western offshore mounds and ridges are partially covered by pelagic and sandy deposits (fig. 3), with their tops often formed by rocky outcrops (fig. 4).

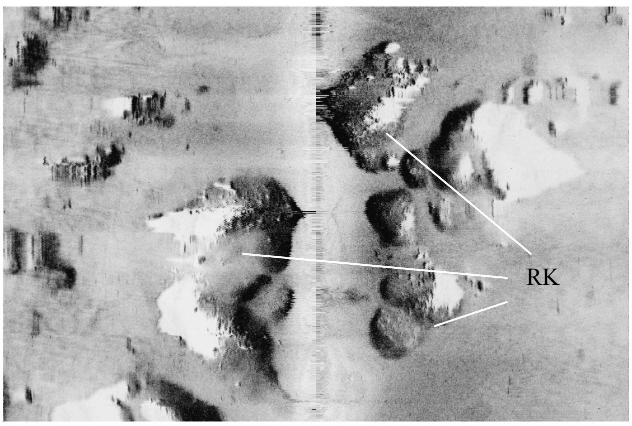

Figure 4. Northern offshore. Unprocessed (slant range corrected) sidescan image showing rocky outcrops (RK) topping large boulders. Light tones represent low backscatter. The insonified seafloor area is 320 x 190 meters.

3.1 *Western offshore*

About 10 Km^2 of seafloor west of Forio village have been investigated and mapped. Of these, about 4.5 Km^2 are characterized by hummocky topography developing at depths ranging from –30 to –130 meters. Other morphologic features interpreted from bathymetric data include two depositional terraces with edges at –40 and –80 meters, a flat-topped volcanic edifice with a circular base (*Secca di Forio*), located 3 Km west of Forio village and a rocky substrate occurring 2 Km west of Cava dell'Isola beach (fig. 2).

The hummocky topography is here formed by countless closely-scattered conical mounds, often bonded each others as larger ridges with different orientation. Individual mounds are extremely various in size (fig. 3), ranging from few meters to 30 meters in diameter and from few meters to about 20 meters in height. Composite ridges may form larger elongated structures, extending up to 150 meters in length and about 30 meters in height. Besides their extreme variability, it may be observed an overall decrease in hummocks concentration with greater water depth.

The morphologic relations between terraced features, volcanic edifice and hummocky topography inferred from bathymetric analyses, help to establish a relative event chronology occurred in the Forio offshore. In this context the emplacement of hummocky deposits locates between two stages of sediment progradation, as they truncate northwards the lower depositional terrace and are sealed by the upper ones (fig. 2). This latter is in turn covered by scattered blocks deposited from historical landslide affecting the western slope of Mt. Epomeo. Hummocky deposits are also older of the Secca di Forio volcanic edifice, as they seem underplaced to its southeastern slope.

3.2 *Northen offshore*

Almost the whole seafloor investigated in the northern offshore is characterized by hummocky topography (fig. 5). The surveys were conducted over a shelf area of about 11 Km^2, ranging in depth from -30 to –120 meters, and only a small sector of about 2.3 km^2 offshore Punta di Monte Vico was lacking of hummocky features. Here a regular surface with a mean inclination of 4% form a terraced structure with a break at – 80 meters. Another slightly defined sedimentary prism, with the edge at –45 meters, is recognizable offshore Casamicciola village (fig. 5).

In the northern offshore hummocky features are mainly controlled by small conical hills and ridges up to 500 meters in length and 45 meters in height separated by shallow depressions. Individual mounds (*blocks*) similar in size and shape to those found in the western offshore also occur.

The most striking morphological features occurring in this sector are related to a depressed, levee-constrained hummocks area, fan shaped in plan view, offshore Lacco Ameno locality (fig. 5). The lateral levees cut into the Mt. Vico sedimentary prism to the west and into previous deposited hummocky deposits to the east (fig. 5B). In particular, the western levee is characterized by a hooked end, with a downhill elongated sedimentary lineations. A second hooked levee, equal in shape and orientation, but less elevated, develops within the depressed area.

Erosional levees and fan-shaped organization point to a rapid emplacement of the displaced materials. The transport-induced erosion produced excavation, departing the run-out direction towards N-W, and leaving a hook at the end of the western levee. These reconstructions are also suggested by the change in orientation of the hummocky ridges close to the western levee and by sedimentary lineations located downhill to the hooked feature (fig. 5).

The reported morphological features suggest a recent age for the levee-constrained hummocks with respect to the deposits occurring in the Forio offshore. This hypothesis is also supported by erosional relations occurring between the eastern levee and the sedimentary prism recognized offshore Casamicciola village.

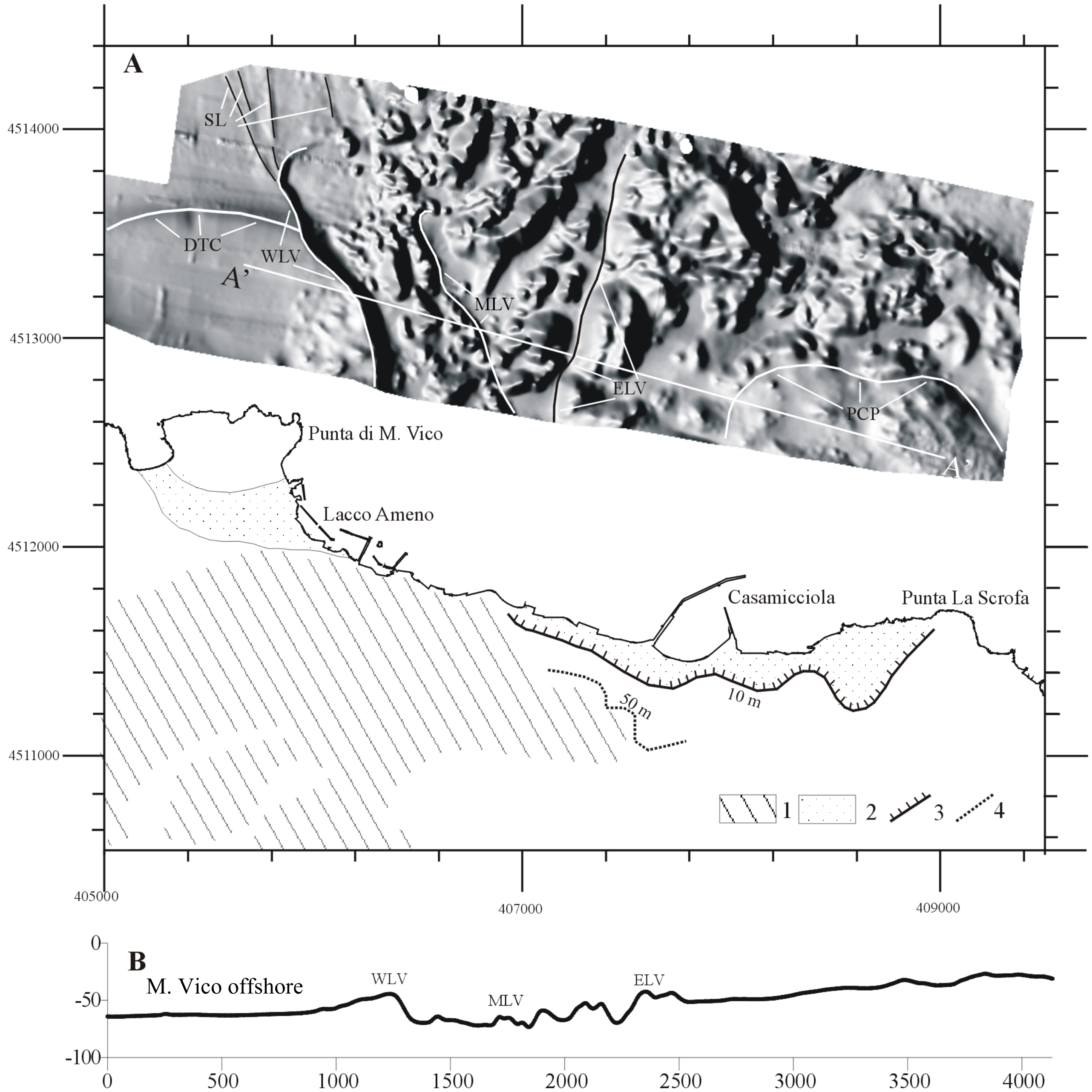

Figure 5. Shaded relief map and morphologic features of the Ischia northern offshore and main onland morphologies. A. 1) landslide deposits; 2) present-day beach deposits; 3) Onland marine terrace and its elevation; 4) ancient coastal cliff; (DTC) marine depositional terrace rim; (WLV) western levee; (ELV) eastern levee; (MLV) minor levee; (SL) sedimentary lineation; (PCP) present day coastal prism; (A-A') trace of topographic section. B. Topographic section from Punta di Monte Vico to Punta la Scrofa offshore. Onland morphology is from Tibaldi and Vezzoli, 1998 and Del Prete and Mele, 1999 (modified).

Finally, the occurrence of a minor hooked-shaped erosional edge within the depressed hummocky area, suggest another depositional event, younger then the previous one, with a main displacement located in the Lacco Ameno offshore.

4 SEISMICITY AND LANDSLIDE EVENTS

The natural history of the Island is characterized by strong catastrophes induced by eruptions and earthquakes since Prehistorical times (Monti, 1980; Rittmann & Gottini, 1980; Buchner, 1986). Nevertheless, numerous destructive earthquakes are well documented only since XIII century (Bonito, 1691, Mercalli 1883, Baratta 1901, Cubellis, 1987).

The historical reconstruction of the Ischia seismicity (XIII-XIX centuries) shows a concentration of seismic events along a narrow band stretching east-west in the northern margin of Mt. Epomeo (Casamicciola and Lacco Ameno territory). Minor and less frequent seismicity (intensity $I \leq$ VI MCS) is localized all over the island, both along the coast and in the inner areas (Alessio et al, 1996). Using macroseismic model Cubellis and Luongo (1998) established the focal parameters related to the 28 July 1883 event, the most destructive earthquake occurred in historical time (I_{max} = XI MCS and M_m = 5.2). In particular, using the Shebalin model (1972), they hypothesized two normal fault-planes with N-S and ENE-WSW strikes, their lengths being 1,7 km and 2 km respectively.

New data based on macroseismic fields reconstruction of five main seismic events, and of epicentral distribution of about 80 minor events, led to recognize the geometry and size a main seismogenic source. This latter develops for about 2 km with a

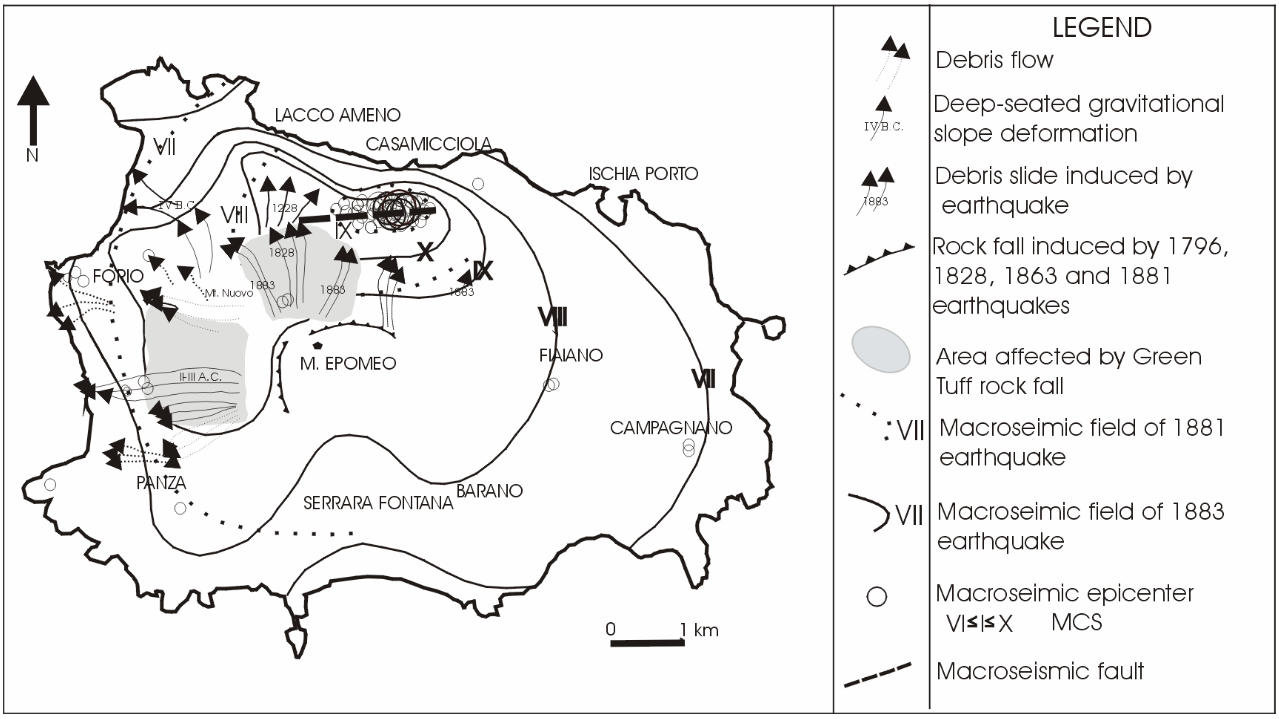

Figure 6. Distribution of earthquake-induced landslides in the North-Western sector of Ischia island since IV Century B.C. (Modified after Guadagno & Mele, 1995). For comparison are reported the macroseismic field of the 1881 and 1883 events (Modified after Alessio et al., 1996; Cubellis & Luongo 1998). Note the similar shape, localization, intensity attenuation of epicentral areas. Location of macroseismic fault segment is also reported.

ESE-WNW orientation along the northern slope of Mt. Epomeo (fig. 6). In particular, the major five earthquakes (1767, 1796, 1828, 1881 and 1883; VIII ≤ I ≤ X MCS) and other 80 minor shocks (I ≤ VII MCS) recur in an area of about 2 km^2, including Fango, Majo, Bagni, Gran Sentinella and La Rita localities (north slope of Mt. Epomeo). The general pattern of the macroseismic fields related to these events shows the following common features: east-west elongation of isoseismal lines, strong north-south gradient and strong decay of intensity to the north and to the east (up to three MCS intensity degrees in one kilometer). Moreover, even stronger earthquakes were weakly felt in the eastern sector of the island.

The analysis of the ground effects induced by historical earthquakes provides evidence that rock falls and debris flows are the most common types of slope failures (Bonito, 1691; Covelli, 1828; Palmieri, 1881; De Rossi, 1884; Guiscardi, 1885; Mercalli 1883; Mercalli,1884; Johnston-Lavis, 1885). These phenomena are also controlled by strong superficial degradation (case-hardening, eolian erosion, fumarolic alteration and fractures; Mele & Del Prete, 1998) affecting the north-western faulted slopes of Mt. Epomeo. As mater of fact, this sector is characterized by “continuous” sliding phenomena (debris flow) mobilizing new mass of soil and old body landslides, with a progressive remolding of soil (debris slide). In particular, earthquake-induced landslides (debris flows evolving into debris slides) occurred over a 600 y. time span (1228 –1883) in a narrow area located along the northern flank of M. Epomeo, with a main landslides deposits reactivation towards Lacco Ameno locality (fig. 6). In the plain of Forio even larger debris flows are present, related to recurring events mostly occurred in Greek and Roman time (Covelli, 1828; Palmieri, 1881; Mercalli 1883; Jonston-Lavis, 1885; Rittmann & Gottini, 1980; Buchner, 1986; Guadagno & Mele, 1995; Mele & Del Prete, 1998). Finally, numerous slideings and topplings triggered by seismic historical events, affected the Green Tuff in the western sector of the island (Monti, 1980; Guadagno & Mele, 1995; Alessio et al., 1996; Cubellis and Luongo, 1998; Mele & Del Prete, 1998). All the reported phenomena are summarized in table 1, which connect landslide events with mocroseismic epicentre and earthquake intensity.

5 DISCUSSION

The correlations between landslide deposits occurring on land and levee-constrained hummocky topography found offshore Lacco Ameno village, lack of a well defined failure scarp in the northwester border of Mt. Epomeo. In this context the attitude and structural features of the resurgent block, provide a clue to characterize the induced slope instability within the uplifted area.

The resurgence of Mt. Epomeo block has been referred to a monocline structure resulting from a tilt around a NE-SW trending horizontal axis, with the southeastern part of the dome acting as a hinge zone (Acocella and Funiciello, 1999). An alternative explanation provide a monocline fold that gradually turns into two main vertical faults along the southern flank of the Epomeo resurgent horst (Tibaldi e Vezzoli, 2000). In both cases it is here relevant to report a resurgence mechanism involving a southwest dipping monocline structure bordered by volcano-tectonic faults, with a main elevation in its northwestern corner (Gillot et al., 1982; Orsi et al., 1991; Tibaldi and Vezzoli, 1998; Acocella and Funiciello, 1999).

Such a resurgence pattern put the northwestern Epomeo flanks under a significant volcano-tectonic stress, with the associate fracturing and hydrothermal activity inducing a strong superficial degradation. New slope is recurrently formed and a remodeling and relocation of previous morphology and landslides deposits, ultimately controlled by local seismicity, likely removed the evidence of a significant hummocky-related failure scarp in the northern sector. On the other hand the progressive uplift produced an increasing dip of the monocline structure towards southwest, triggering a catastrophic landslide occurred as a critical slope angle was reached. This event removed mostly of the available material, delivering it into the sea (Chiocci et al, 1998; de Alteriis et al. 2001; de Alteriis and Toscano; 2003), and

Table 1. Main sliding phenomena triggered by earthquakes in the northern of Ischia Island, since IV century B.C.

Date	Observed phenomena	Affected area	Macroseismic Epicenter	Earthquake Intensity *MCS*
470-460 B.C.	Volcano-tectonic events **Deep-seated gravitational slope deformation,** the sliding phenomenon affected an area of about 3.5 km ^{2} lying between Mount Epomeo and Forio Plane.	Western sector		
II –III A.C.	**Debris slides**, starting from the top of Mount Epomeo towards the Spiaggia di Citara-Cava dell'Isola.	Western sector		
1228	**Rock fall**, starting from steep slope of Mount Epomeo towards Casamicciola-Lacco Ameno. **Debris avalances**	Northern sector	Casamicciola	IX-X
1767	**Rock fall**	Northern sector	Casamicciola	VII-VIII
1796	**Rock fall**, starting from the top of Mount Epomeo, in the norhtern flank.	Northern sector		VIII
1828	**Rock fall**, starting from the top of Mount Epomeo. **Debris avalances,** starting from the northern flank of Mount Epomeo towards Casamicciola and Lacco Ameno.	Northern sector	Casamicciola	VIII-IX
1863	**Rock fall**, starting from steep slope of Mount Epomeo.	Northern sector	Casamicciola	VII
1881	**Rock fall**, starting from the top of Mount Epomeo. **Debris slides**, starting from the northern flank of Mount Epomeo towards Casamicciola and Lacco Ameno, the total area affected by sliding phenomena is about 3,5 Kmq including also the slides occurred in 1828.	Northern sector	Casamicciola	IX
1883	**Rock fall**, starting from northern slope of Mount Epomeo towards Fango and along the slopes of Mount Nuovo and Mount Bastia. **Debris slides**, occurred on the northern flank of Mount Epomeo towards Lacco Ameno, and towards Mount Rotaro.	Northern sector	Casamicciola	X
References: Alessio et al., 1996; Baratta 1901; Bonito, 1691; Covelli, 1828; Cubellis, 1987; Cubellis & Luongo, 1998; De Rossi, 1884; Guadagno & Mele, 1995; Guiscardi, 1885; Johnston-Lavis, 1885; Mele & Del Prete, 1998; Mercalli,1884; Monti, 1980; Ortolani et al., 1991; Palmieri, 1881; Rittmann & Gottini, 1980.				

leaving a well defined amphitheatre failure scarp still preserved along the southern flank of Mt. Epomeo resurgent block.

6 CONCLUSIONS

First result from high resolution acoustic investigations offshore northwestern sectors of Ischia island led to reconstruct seafloor morphological features at a very detailed scale. Hummocky topography with a different organization were found both along the western and northern offshore. Western offshore is characterized by countless closely-scattered conical mounds, often bonded each others as larger ridges with different orientation. Besides their extreme variability, it may be observed an overall decrease in hummocks concentration with greater water depth. In the northern offshore hummocky features are mainly controlled by small conical hills and ridges separated by shallow depressions. Here erosional levees cutting into previous deposited hummocks suggest repeated landslide events.

Marine depositional prisms occurring at different depths characterize both northern and western offshore, and their morphologic relations with hummocky topographies allowed to reconstruct a relative event chronology. The emplacement of the western offshore hummocky deposits locate between two stages of sediment progradation, the northern ones being partially successive. Offshore Lacco Ameno locality a depressed, levee-constrained hummocks area, fan shaped in plan view, cut into a depositional terraces and into previous deposited hummocks, inducing excavation and sedimentary lineations. These features point to a rapid emplacement of the displaced materials with a main delivery area into subacqueous environment. Even if a correct evaluation of the mobilized volumes is not possible, it is likely to infer a landslide-induced tsunami-wave as the displaced material entered into the sea.

A recent age for Lacco Ameno levee-constrained hummocks is also suggested by a well correlation with the onland landslide deposits. These latter reach the coastline only in correspondence of Lacco Ameno locality, breaking the continuity of present-day beach deposits and of an older marine terrace (fig. 5).

Finally, a triggering mechanism for the induced hummocky features offshore Lacco Ameno village (northern Ischia) is inferred by the analysis of the historical seismicity, which allowed to recognize a seismogenic area developing for about 2 km with a ESE-WNW orientation along the northern slope of the Mt. Epomeo resurgent block.

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