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GEOLOGICAL CONSTRAINTS FOR A CONCEPTUAL EVOLUTIONARY MODEL OF THE SLOPE DEFORMATIONS AFFECTING MT. NUOVO AT ISCHIA (ITALY)

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EXTENDED ABSTRACT

I vulcani attivi sono strutture ad elevata dinamica morfoevolutiva che, come tali, possono facilmente dare luogo a condizioni di instabilità gravitativa. Tali instabilità possono manifestarsi a diverse scale, da poche centinaia di migliaia di metri cubi fino al collasso di interi settori degli edifici vulcanici (*flank instabilities s.s.*). L'Isola di Ischia non fa eccezione a tali scenari; nel corso dell'Olocene, è stata, infatti, interessata da numerosi eventi di frana, variabili da colate di detrito e scorrimenti superficiali a collassi generalizzati di versanti rocciosi. Questi ultimi sono, in genere, associabili alle dinamiche vulcano-tettoniche connesse al fenomeno di risorgenza calderica che ha interessato la struttura del Monte Epomeo.

Il presente studio si concentra sulla deformazione gravitativa che interessa l'area del Monte Nuovo ubicata lungo il versante occidentale del Monte Epomeo, originatasi a seguito di un catastrofico evento vulcano-tettonico verificatosi durante le ultime fasi di sollevamento . In corrispondenza di questo rilievo affiorano depositi di flusso piroclastico alcali-trachitici messisi in posto 55 ka (Tufo Verde del Monte Epomeo *Auctt.*) e lave trachitiche e fonolitiche costituenti parte del basamento dell'isola datate 133 ka.

Attraverso un approccio multidisciplinare, questo studio propone un modello geologico-tecnico di dettaglio del versante del Monte Nuovo, portando ad un nuovo modello interpretativo della deformazione gravitativa che lo interessa. Attraverso un rilevamento geomorfologico, sono state individuate scarpate di faglia, terrazzi morfologici, trincee e contropendenze, che forniscono dei vincoli cinematici oggettivi al processo di deformazione gravitativa di versante. Un rilievo geomeccanico estensivo è stato finalizzato a derivare proprietà geomeccaniche di ammasso e valutare la loro influenza sul processo in corso. Al fine di vincolare ulteriormente il modello geologico-tecnico del versante, sono state realizzate specifiche campagne geofisiche, consistenti in misure di rumore ambientale distribuite nell'intera area del Monte Nuovo ed interpretate secondo il metodo di Nakamura (1989), ovvero l'approccio dei rapporti spettrali tra componenti orizzontali e verticali (HVSR). I risultati ottenuti hanno messo in luce la complessità della deformazione gravitativa in atto, portando ad identificare la zona di taglio che guida l'instabilità gravitativa e consentendo l'attribuzione al fenomeno franoso di un meccanismo di scorrimento biplanare composito. In particolare, le misure di rumore sismico effettuate hanno apportato un utile contributo alla definizione del modello geologico, evidenziando un picco di risonanza a 0.8 Hz non direzionato e relazionabile alla risonanza di un ammasso a ridotta rigidezza (riferibile alla porzione interessata dall'instabilità gravitativa), con uno spessore pari a circa 250 m, sovrapposto ad un substrato rigido. Il modello proposto ha, inoltre, messo in luce la stretta relazione esistente tra le emissioni idrotermali e l'assetto stratigrafico e strutturale del versante di Monte Nuovo, evidenziando una concentrazione di emissioni fumaroliche in corrispondenza delle brecce basali, dove la circolazione di fluidi ha causato un'intensa alterazione, riconoscibile per la presenza di mineralizzazioni autigeniche secondarie, che rappresentano geotermometri in riferimento all'evento di alterazione idrotermale.

Ai fini del presente studio, è stata, inoltre, prodotta una carta geologica e sono state ricostruite quattro sezioni geologiche, delle quali due normali e due longitudinali alla direzione di deformazione (vedasi Tavola Allegata fuori testo). Tali sezioni mettono in luce l'esistenza di tre distinte zone di taglio, la più profonda delle quali, in accordo con le evidenze morfometriche e con le misure geofisiche, è localizzata ad una profondità di circa 250 m dal piano campagna. Le evidenze geometriche hanno permesso di associare alla deformazione di versante un meccanismo di scorrimento traslazionale di tipo biplanare che inviluppa un volume di circa 190 milioni di m^3. Tale superficie è controllata da sistemi di giunti ad alto angolo, limitatamente alla zona di scarpata. Di contro, la superficie a basso angolo, lungo la quale si esplica uno spostamento a componente prevalentemente orizzontale pari a circa 60 m, non appare controllata da elementi strutturali. In definitiva, il modello evolutivo qui ipotizzato, che giustifica la deformazione gravitativa di versante in atto presso Monte Nuovo, vede un ruolo preponderante delle pressioni interne al sistema idrotermale ad esso soggiacente nello sviluppo e propagazione verso monte della zona di taglio. Le evidenze ottenute rafforzano le analogie geometriche e volumetriche esistenti tra la deformazione in atto e grandi frane di versante verificatesi nel medesimo settore, lasciando aperta la possibilità di una analoga evoluzione verso condizioni di collasso generalizzato.

ABSTRACT

Ischia Island was the scenario of several Holocene slope instability events occurred at different scales, from shallow mass movements, triggered by meteo-climatic forcing, up to massive rock slope failures such as large debris avalanches these last ones related to the volcano-tectonic dynamics of a resurgent caldera. The present study focuses on the gravitational deformation that involves Mt. Nuovo, located in the western portion of Mt. Epomeo resurgent block. A high-resolution engineering-geological model was reconstructed according to a multi-modelling approach supported by field geo-structural evidences and constrained by passive seismic investigations. It revealed a complex morpho-structural setting and led to the identification of a multiple compound mechanism, involving a rock mass volume of about 190 million of cubic meters.

The obtained geological model shows a partial structural control of the pre-existing tectonic pattern on slope deformation mechanisms, highlighting geometric and volumetric similarities between the Mt. Nuovo ongoing deformation and an already occurred rock avalanche. The defined conceptual evolutionary model allows to hypothesize the role of inner pressures constraining the shear zone initiation and propagation and making reliable a future scenario of generalized collapse.

Starting from these new field and laboratory data, numerical models will be reconstructed in order to depict the evolution of the gravitational slope deformation, evaluate its sensitivity and constrain future evolutionary instability scenarios.

Keywords: *Ischia Island, hydrothermal system, slope instability, volcanic hazard*

INTRODUCTION

Active volcanoes can be affected by gravity-induced slope deformations up to generalised failure related to their heterogeneous structures and rapid growth. The development of disequilibrium conditions can evolve through instabilities at different scales, with volumes of a few 10^5 m^3 (e.g., rolling bocks) to some 10^7 m^3 during the collapse of entire sectors of the volcano edifices. Several factors have been described as triggers for volcano flank collapses (Bozzano *et alii*, 2013; McGuire, 2006), including cryptodome emplacements, such as Mount Saint Helens (Voight, 1981), dyke intrusions as described in the Canary islands (Siebert, 1984), seismicity, such as at Bandai San (Sekiya & Kikuchi, 1889) and hydrothermal pressurization (Reid, 2004). These events mostly affect polygenic volcanic edifices where voluminous, weak, and hydrothermally altered rock portions can facilitate collapse events. The hazards associated with lateral collapses are very relevant in the case of volcanic islands due to their potential to generate tsunamis. Ischia Island, an emerged portion of the Phlegraean Volcanic District, is characterized by widespread and recurrent instability processes (De Alteris *et alii*, 2009; Della Seta *et alii*, 2011) due to volcano-tectonic activity and associated to topographic perturbations. The strict interconnection between active volcanism, evolution of the magmatic and hydrothermal systems and widespread slope instabilities at Ischia Island (e.g., De Vita *et alii*, 2006) developed over the last thousands years through cyclical phases of volcanic unrest with associated modifications in the stress-strain conditions acting on the slopes. Specifically, stress changes induced by shallow magma reservoir and/or hydrothermal groundwater dynamics, associated with topographic effects and structural and lithological factors exerted an active and passive control on slope instabilities, as recorded by several landslide deposits overlaid by, and interbedded to, volcanic successions and/or submarine deposits.

Here we investigate the slope deformations active in the western sector of the Mt. Epomeo area which represents one of the most significant gravitational processes active at Ischia. Based on new geological, geomorphological, geomechanical and geophysical data, we propose an high-resolution engineering-geological model of the slope to provide constraints on the ongoing gravitational slope deformations and to depict possible future scenarios associated with volcanic unrest episodes.

GEOLOGICAL SETTING

The densely populated Ischia Island is an emerged portion (about 46 km^2) of the active Phlegraean Volcanic District. The Phlegrean structural setting is related to the Plio-Pleistocene extensional phase, active along the Tyrrhenian margin of the Apennine chain, which led to the formation of the Campanian plain graben (Orsi *et alii*, 2003; De Vita *et alii*, 2006; De Vita *et alii*, 2013). The Phlegrean volcanism developed through multiple large caldera forming events alternating to less intense explosive activity from scattered, mostly monogenetic eruptive centers. On Ischia Island (Fig. 1), the oldest volcanic activity was dominantly effusive with the emplacement of a trachytic and phonolitic lava (TL) plateau (dated at ~150 ka) cropping out in the southeastern sector (Vezzoli, 1988). Later on, between 150 and 74 ka, small lava domes formed the Mt. Vezzi, Mt. Barano and Mt Vico reliefs, along with small eruptive edifices in the coastal area of Sant'Angelo, Punta Chiarito, Capo Negro, Punta Imperatore (Chiesa *et alii*, 1987; De Vita *et alii*, 2013; Fig. 1).

The main Mt. Epomeo Green Tuff (MEGT) caldera forming event opened a new phase of activity after about 20,000 years of quiescence (Orsi *et alii*, 1991; Tibaldi & Vezzoli, 1998). The MEGT unit, alkali-trachytic in composition, is characterized by a greenish colour due to zeolitization in a seawater-rich environment (Altaner *et alii*, 2013), possibly related to an undersea emplacement environment, i.e., the submerged caldera floor.

Based on depositional and componentry features, the MEGT

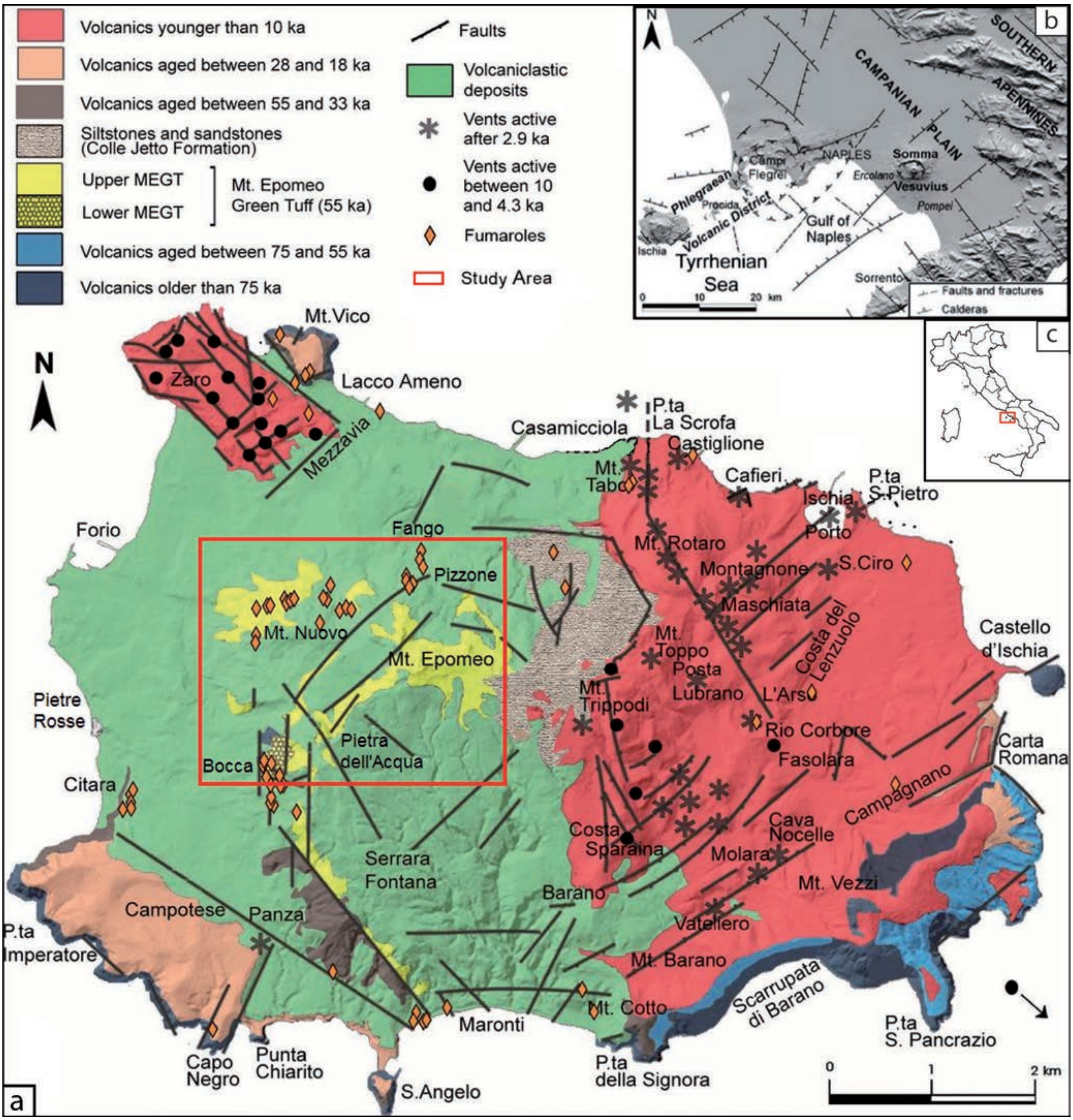

Fig. 1 - a) Geological sketch map of Ischia Island; b) structural sketch map of the Neapolitan volcanic district; c) location of the study area (modified after Della Seta *et alii, 2011)*

has been divided in: a) an intra-caldera member made up of two pyroclastic flow deposits (Upper and Lower) separated by a volcanoclastic deposit; b) an extra-caldera sequence with pumice ash-fall deposits and widespread lag-breccia deposits in a relatively distal setting (Brown *et alii*, 2008). The MEGT intra-caldera succession displays a variable thickness with a maximum of 70 m for the lower pyroclastic flow unit (LMEGT) and 200 m for the upper pyroclastic flow unit (UMEGT). Both units are opened

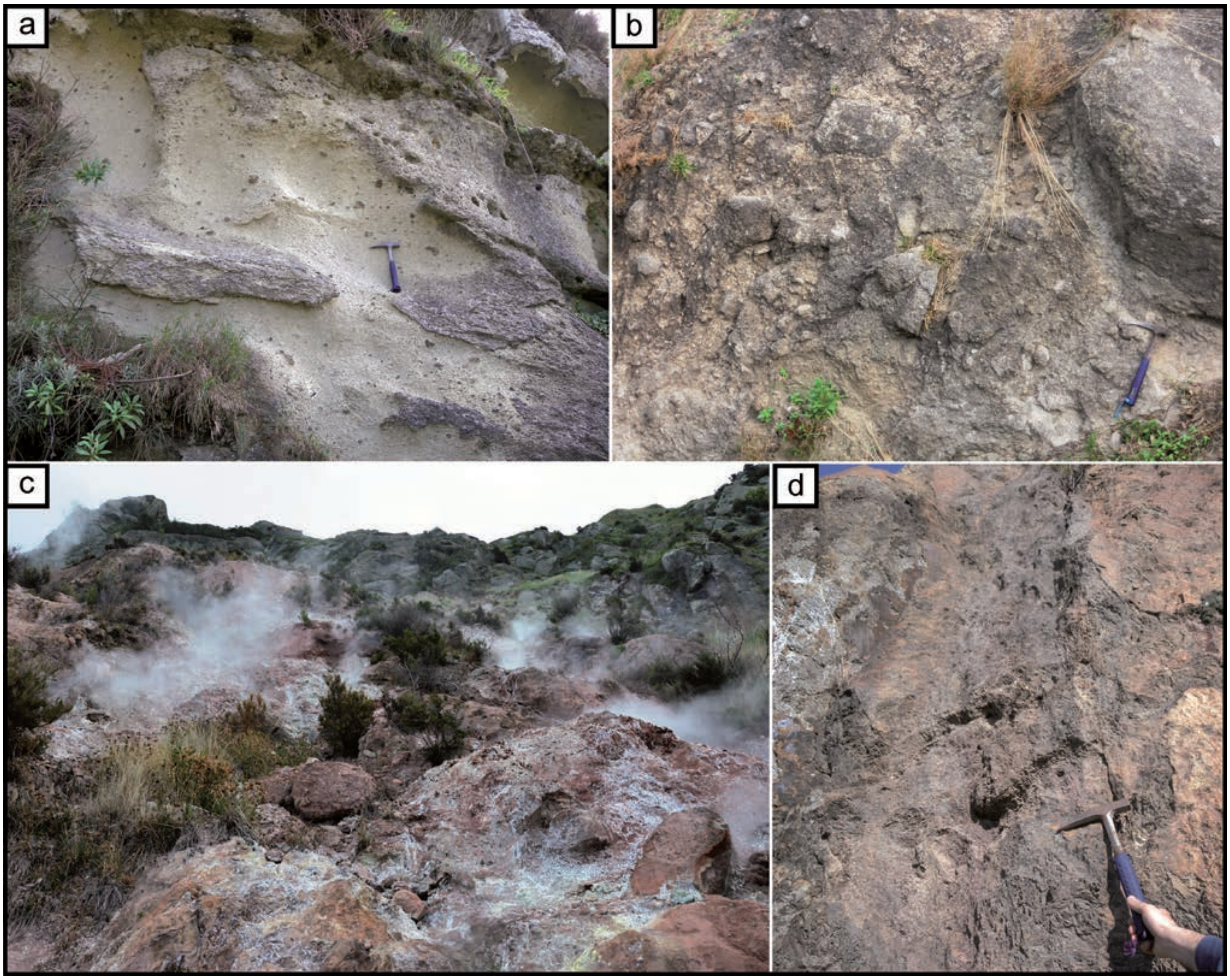

Fig. 2 - Outcrops of (a) MEGT, (b) MEGT lithic breccias, (c) Donna Rachele fumarolic fields, (d) Rione Bocca Trachytic Lavas (TL)

by a basal lithic breccia (Fig. 2) with a thickness varying from 20 to 50 meters. Eluvial-colluvial deposits and debris deposit close the stratigraphic succession hiding the tuff and lava outcrops, as clearly shown in the Mt. Nuovo area, where these deposits are largely distributed (Fig. 1).

The MEGT is a zeolitized trachytic ignimbrite consisting in an altered ash matrix that contains altered pumice and sanidine along with plagioclase, biotite, horneblende, augitic clinopyroxene phenocrysts and lithic ejecta in minor amount; mafic xenocrysts such as olivine rarely occur. The phenocrysts are generally unaltered. No differences in MEGT components have been found between LMEGT and UMEGT. A detailed mineralogical and geochemical study on the MEGT and an associated polymictic breccia (Altaner *et alii*, 2013) showed that the phenocryst assemblage of MEGT consists mainly of K-feldspar crystals of both pyrogenetic (primarly) and authigenetic origin, chabazite and/or phillipsite zeolites and clay minerals associated with minor amounts of analcime and calcite. The clay minerals comprise illite/smectite randomly interstratified, Fe-rich illite and minor smectite. Plagioclase, biotite, horneblende and clinopyroxene phenocrysts are minor component.

After the major MEGT caldera-forming event, a series of explosive eruptions (until ~33 ka ago) took place from vents located in the SE- and NW sectors of the island. Later on, effusive and small volume explosive eruptions took place from scattered vents until the last eruption occurred in AD 1302.

A greenish-yellow tufite, associated with the marine reworking of MEGT (named "Tufite del Mt. Epomeo"; Vezzoli, 1988), records a marine sedimentation phase in the caldera depression. This deposit is unconformably topped by alternate fossiliferous white siltstones, whitish volcanic ashy layers and yellow sandstone (named "Colle Jetto Fm."; Vezzoli, 1988). The resurgence of the caldera produced an asymmetric uplift of the central sector of the Island that generated the Mt. Epomeo relief. This resurgence could have been generated by the emplacement of a shallow laccolith (Rittmann, 1930), or by magma chamber dynamics (Tibaldi & Vezzoli, 1998; Orsi *et alii*, 1991). Acocella *et alii* (1999) and Molin *et alii* (2003), based on analogue models of caldera collapse and resurgence, propose an asymmetric "trapdoor" mechanism, controlled by a network of NW-SE oriented sub-vertical faults. The uplift, between ~700 m and 900 m over the last 30 kyr, corresponding to an average uplift rate of about 3 cm/yr, has been estimated through the present-day elevation of the outcropping marine sediments (Tibaldi & Vezzoli, 1998). The caldera resurgence played a key role in the geological and geomorphological evolution of Ischia Island. In fact, this event strongly controlled the volcano-tectonic activity, the local seismicity and the gravitational processes that involve the edge of the resurgent block. Superimposed to the above mentioned crustal deformation dynamics, a persistent hydrothermal system, with high heat flow (200-400 mW/m^2; Cataldi *et alii*, 1991) and several thermal springs and gas vents (i.e. fumaroles with temperature up to 100°C), is driven by a a relatively shallow magmatic body. The most stable and active fumaroles are localized in the Rione Bocca area (Donna Rachele; see Plate 1). In this area, the shallow circulation of thermal fluids pervades semilithoid pyroclastic rocks (tuffs) and lavas through a dense cracks network; the geometry of thermal fluid circulation consists of multilayered aquifers confined by low-permeability layers with vertical displacements induced by faulting (Carlino *et alii*, 2014). In the Mt. Nuovo sector the hydrothermal system is dominantly fed by rainwater with significant seawater inputs, as clearly evidenced by chemical and isotopic markers (Di Napoli *et alii*, 2011).

GEOMORPHOLOGICAL FEATURES

The resurgence event strongly conditioned the geomorphological evolution of the island, particularly the gravitational processes that involve the edge of the resurgent block. Historical chronicles documented since the 8th century BC and recent geological and geomorphological studies allowed many authors to reconstruct the history of major slope instability events at Ischia Island (Vezzoli, 1988; Del Prete & Mele, 2006; Tibaldi & Vezzoli, 2004; De Vita *et alii*, 2006; Della Seta *et alii*, 2011 and references therein). These events, characterized by different mechanisms, age and triggers are dated from the early Holocene. The oldest recognized events (up to 1000 years BP) are mainly represented by large lahars (> 0.2 km^2), while debris avalanches were triggered exclusively by volcano-tectonic factors (earthquakes and/or eruptions). Nonetheless, it is likely that events triggered by meteo-climatic conditions occurred in this period but were not preserved and/or documented.

Between 1000 and 100 years AD both volcano-tectonically and meteo-climatically triggered events have been documented, but the first ones are represented only by small lahars (<0.2 km^2), slumps and debris/rock-slides. Finally, in the last 100 years slope instability at Ischia was exclusively triggered by meteo-climatic factors, causing mainly shallow landslides, rock falls and slumps , as in the well-documented case of Mt. Vezzi in 2006, on which specific studies have been already published (IJEGE 02/2007).

A detailed stratigraphic study by De Vita *et alii* (2006) evidenced a complex succession of intercalated primary volcanics and slope instability-related volcanoclastic deposits. This study outlined the clustering in space and time of mass movements before, during and after the main periods of volcanism, highlighting, in the last period of activity, between ca. 5.5 and 1.9 ka, a strong interplay among slope instability and volcano-tectonic activity. In particular, the presence of paleosols and tephras in the stratigraphic succession allowed to define four main phases. This cyclicity was interpreted as the evidence that resurgence has occurred through the alternation of periods of uplift and periods of volcano-tectonic quiescence. During quiescence, new magma intrusion triggered resurgence accompanied by seismicity and slope instability, with or without renewal of volcanic eruptions. The most gravitationally unstable slopes of the island are the north-, northwest- and southwest facing steep flanks of Mt. Epomeo and in the Serrara Fontana basin, on the southern flank of the block, as testified by the widespread volcanoclastic deposits they are covered by.

The lowlands between Casamicciola and Forio are, in fact, mostly covered by secondary volcanoclastic deposits emplaced due to slope instability events. Single scars and bodies of slope failure have been identified and mapped in this sectors of the island by Della Seta *et alii* (2011), after geomorphological, stratigraphic and textural analyses. The related events, mostly occurring since 3 ka, include large debris avalanches (basal contact of the main event outcrops in Pietre Rosse), large lahars and minor mass movements such as rock falls, slumps, debris and rock slides, and small lahars (Fig. 3).

Massive rock slope failures affected the strongly fractured and hydrothermally altered rock masses of the most uplifted sectors of the Mt. Epomeo, where often characterized by the intersection of fracture systems and associated fumaroles.

The massive flow of fragmented rocks followed the initial collapse from a rock slope through expanding and shattering mechanisms responsible for spreading and run-out of debris avalanches.

The topography of debris avalanche deposits shows typically natural levees, marginal and distal cliffs, and linear ridges close to the margins of the deposit and a common hummocky topography (Siebert, 1984; Glicken, 1998) due to the hetero-

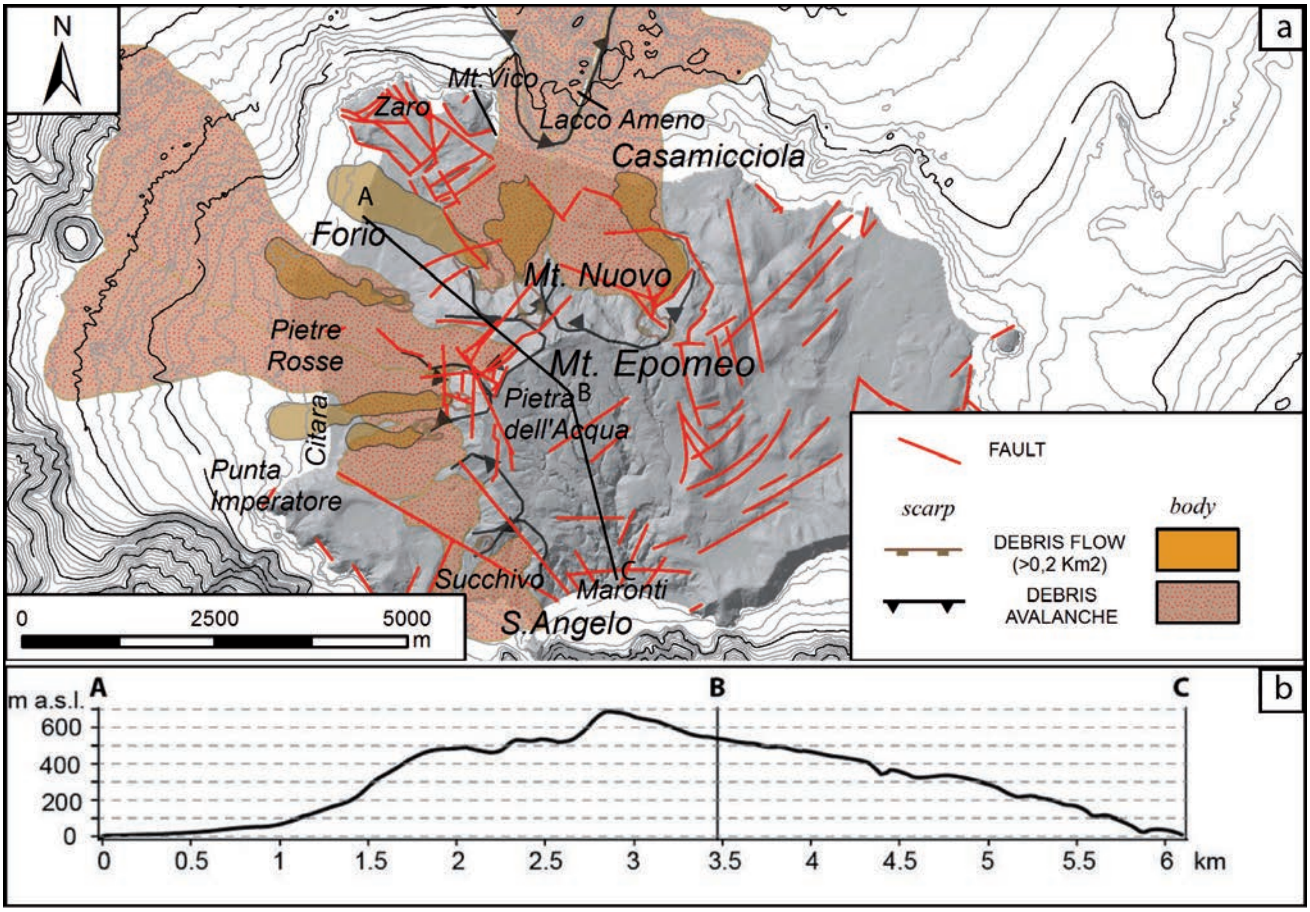

Fig. 3 - Distribution of the major volcano-tectonically triggered slope instability landforms. b). Topographic profile across the Mt. Epomeo resurgent block (modified after Della Seta *et alii, 2011)*

geneity of the deposits, mainly made up of a massive, chaotic, poorly sorted, vesicular matrix, which incorporates megaclasts and large blocks up to hundreds of cubic meters mainly composed of MEGT. The topographic overprint suggests that some lahar events occurred, mostly on top of debris avalanche bodies, producing debris flow depositional bodies, some of which also entered the sea. Bathymetric surveys have highlighted also the existence of extended deposits to the north, northwest and south of the island, the latter interpreted as the products of a single catastrophic event that occurred in historical times from the southern slopes of Mt. Epomeo (Serrara Fontana), named the Ischia Debris Avalanche (IDA; Chiocci & De Alteriis, 2006; De Alteriis *et alii*, 2010), whose estimated volume ranges between tens to hundrends Mm^3. In addition to these large landslides, which represent the major catastrophic mass movements occurred in the island from the Holocene, a still active deep seated gravitational slope deformation (DSGSD) was reported as triggered by a catastrophic volcano-tectonic event that took place around 460÷470 BC.

The slope-scale gravitational deformation affects the northwestern flank of Mt. Epomeo in correspondence of Mt. Nuovo (Della Seta *et alii*, 2011). This deformation involves a steep slope (almost 60°) in the northwestern corner of the Mt. Epomeo resurgent block (Fig. 4) and has a planimetric extent of about 1.6 km^2. The main diagnostic features of such a deformational process consist in counter-slope terraces and opened deep trenches with a direction almost parallel to the slope face (Fig. 4). This block seems presently to be affected by an estimated westward displacement rate of maximum 15 mm/year, on the basis of precision levelling, GPS surveys, and DInSAR data (Manzo *et alii*, 2006).

The morphological evidence of slope deformation and the historical occurrence of large avalanches are diagnostic elements to define the evolutionary style of this area. The deformation affecting the western part of Mt. Epomeo resurgent block, and in particular the Mt. Nuovo gravity-induced slope instability, is the response to a stress field initially connected with the recurrent inflation and deflation phases, these last ones related

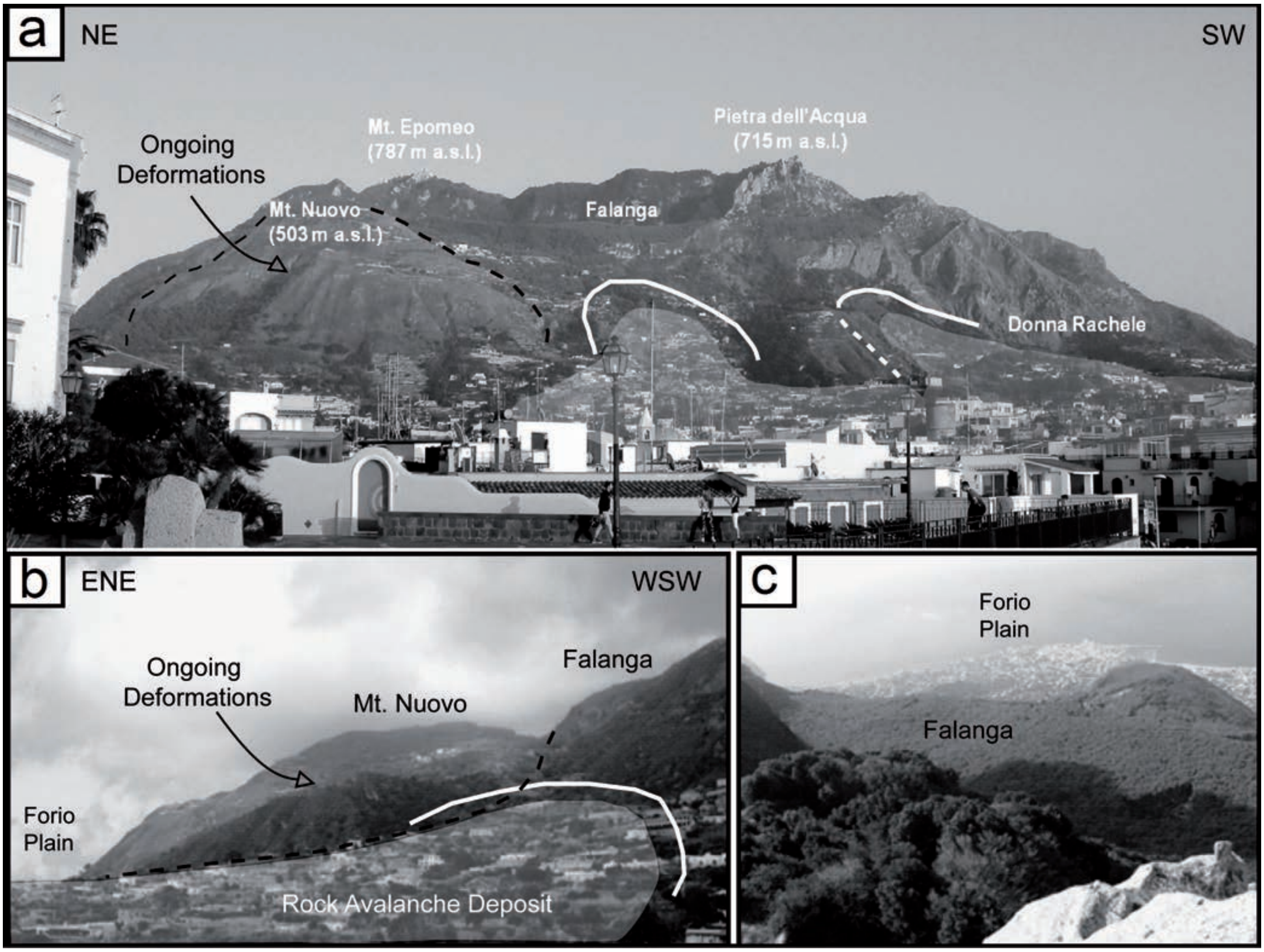

Fig. 4 - a) Panoramic view of the Mt. Epomeo relief from the Forio Plain; the Mt. Nuovo area, involved in the ongoing gravitational deformation is clearly visible on the left side of the picture. b) NW-SE view of the deformed block and of the apical zone of one of the documented rock avalanches. c) View of the Falanga plateau and Mt. Nuovo (downslope) from the top of Mt. Epomeo

to the pressurization/depressurization or intrusion/migration of magmas at shallow depth. In addition destabilizing actions, possibly related to the pressurization of the local hydrothermal system, cannot be neglected.

According to Zaniboni *et alii* (2013), the possible evolution of the active Mt. Nuovo slope deformations toward a generalized collapse, that can be assimilated to the already occurred rock avalanche in the south-western adjacent sector, could produce a tsunami wave able to reach high speeds (30 m/s) and height (more than 5 m) and therefore configuring significant risk conditions for the coasts of both the island and the Campanian region. In order to derive constraints to the geometry and mechanisms of the gravitational slope deformation, as well as to evaluate the possible evolution of this process, an high-resolution geological model has been reconstructed.

ENGINEERING-GEOLOGICAL MODELLING

Methodology

In order to identify the shear zones that presently drive the gravitational slope deformations of Mt. Nuovo and to infer mechanisms and volumes associated with this gravity-induced process, a high-resolution engineering-geological model was reconstructed through a multidisciplinary approach including geological, geomorphological, geomechanical and geophysical investigations.

New field observations, combined with geological data from literature, allowed to identify the geological framework in which the Mt. Nuovo slope deformation is taking place.

The starting point of this modelling was a geological and geomechanical survey focused on the identification and mapping of the two MEGT flow units along with their basal lithic breccias, which allowed to reconstruct the stratigraphic setting and to assess the role of tectonic elements on the gravity-induced slope deformation.

By means of geomorphological surveys and terrain analyses (in GIS environment), fault scarps, terraces, saddles, trenches and morphological counter-slopes were identified, thus providing more details and constraints to the geometry of the slope deformation. At the same time, a geomechanical survey was carried out to derive the properties of the outcropping jointed rock mass and to evaluate their influence on the gravitational process. An inventory of the fumaroles located within the Rione Bocca and the Forio plain areas was also realized (see the annexed Plate 1), based on both available data (Della Seta *et alii*, 2011; Chiodini *et alii*, 2004) and field observations. Several fumaroles were inventoried, among which the most active and persistent are located in the Donna Rachele area. Moreover, a lot of smaller gas vents were recognized along the Mt. Nuovo and Falanga slopes, partly characterized by an intermittent behavior and partly extinct.

Seismic geophysical investigations were carried out to characterize the local seismic response of the Mt. Nuovo slope as well as to derive other constrains to the geological model. At this aim, ambient seismic noise measurements were performed during two distinct field surveys over an area of approximately 1 km^2, from Mt. Epomeo to Mt. Nuovo, along a section that crosses the main surveyed structural and geomorphological features from Mt. Epomeo to Mt. Nuovo (see Plate 1). Each measurement station was equipped with a 3-component seismometer and acquired for at least 1 hour. A LE-3D/5s seismometer by Lennartz Electronic GmbH coupled with a REFTEK 130-01 data-logger, set to a 250 Hz sampling frequency, was used for the first survey; the other measurements were carried out using a 1.4 Hz SL06 acquisition unit by SARA Electronic Instruments, set to a 200 Hz sampling frequency. The seismic noise records were processed by Geopsy software (www.geopsy.org) developed in the frame of the SESAME project (Bard & SESAME Team, 2004). The time histories, were de-trended sampled with a 40 s moving time window, 5% cosine tapered, converted to the frequency domain and smoothed by a Konno-Ohmachi function (Konno-Ohmachi, 1998, b=40) to get average spectra of the three components and average HVSR (Horizontal to Vertical Spectral Ratio) according to Nakamura (1989); the distribution of HVSR values on the horizontal plane (HVSR rotate) was moreover taken into account.

Under specific conditions, i.e. flat topography and horizontal subsurface layers, a peak of significant level (>2 according to Bard & SESAME Team, 2004) in the HVSR curve points out the resonance frequency (f_0) of a softer soil overlaying a bedrock. At the present, nevertheless, this technique is applied also in more complex geo-morphological conditions and can contribute to obtain useful information about subsurface structures. In our case-study, the evidence of a 1D resonance frequency was used to to indirectly assess the depth of the deformed rock mass. Due to these basic assumptions, the presence/absence of seismic resonance was used to derive other constrains to the geological model and to confirm the reconstructed one. This control was performed relating the f_0 value to the thickness of a "soft" layer, to indirectly assess the depth of the landslide rock mass. A Vs value of 900 m/s was assumed for the MEGT (Strollo *et alii*, 2015), based on measures available for similar tuffs in the Phlegraean area (i.e Neapolitan Yellow Tuff) (Nunziata *et alii*, 1999). It is worth noting that Vs values for such a weak-rock range between 500 e 1000 m/s depending on physical conditions (degree of hardening, texture, fractures density) as well as on depth.

The litotechnical features of the MEGT were well treated by several authors which analyzed geotechnical parameters and mechanical behavior respect to weathering and alteration (Pola e*t alii*, 2014). A decay of mechanical properties was clearly highlighted in tests performed on zeolite-rich materials as the MEGT, that showed a marked influence of high temperatures on the compressive and tensile strength (Heap *et alii*, 2009). Such a behaviour can be regarded as significant in the hyper-thermal area of Ischia, as rock mass rheology can be strongly controlled by thermo-baric conditions.

Results

The detailed geological survey allowed to highlight the stratigraphy and the depositional features of the units outcropping in the Mt. Nuovo study area. The oldest unit is represented by the TL of Rione Bocca (133 ka; Vezzoli, 1988), which is intensely jointed and pervasively altered by hydrothermal fluid circulation (Fig. 2).

Over this unit the massive, ashy deposits of the MEGT crop out extensively. Our high-resolution geological map (see Plate 1) distinguishes the two main flow units (Lower MEGT and Upper MEGT) of which it is composed (Brown *et alii*, 2008). It was also possible to identify and map, for both Lower and Upper MEGT, the basal levels of lithic breccia that indicate the initial phase of the Mt. Epomeo eruption activity. These levels are represented by clast-supported deposits composed by TL blocks and heterometric lapilli. Lava blocks from both LMEGT and UMEGT basal breccia are porphyritic (porphyric index, PI between 5 and 25 vol %) with a phenocryst assemblage dominated by sanidine and subordinate plagioclase ± clinopyroxene ± biotite ± oxides. Microlites of alkali-feldspar, occasionally joined to plagioclase and clinopyroxene, are included in the rock groundmass ranging from holocrystalline to hyalopilitic. No clear difference has been found between the LMEGT and UMEGT lava blocks of breccia, except that, in the Lower MEGT, mafic minerals are always present, whereas in the Upper MEGT, if present, clinopyroxene and/or biotite occur as microphenocrysts (Fig. 5). Notably, in correspondence of both the basal breccia levels an intense hydrothermal flow activity is clustered, as highlighted by several fumaroles. Depending on the distance from the fumarole vents, the inner circulation of fluids causes incipient to intense alteration of the breccia levels that, in lava blocks,

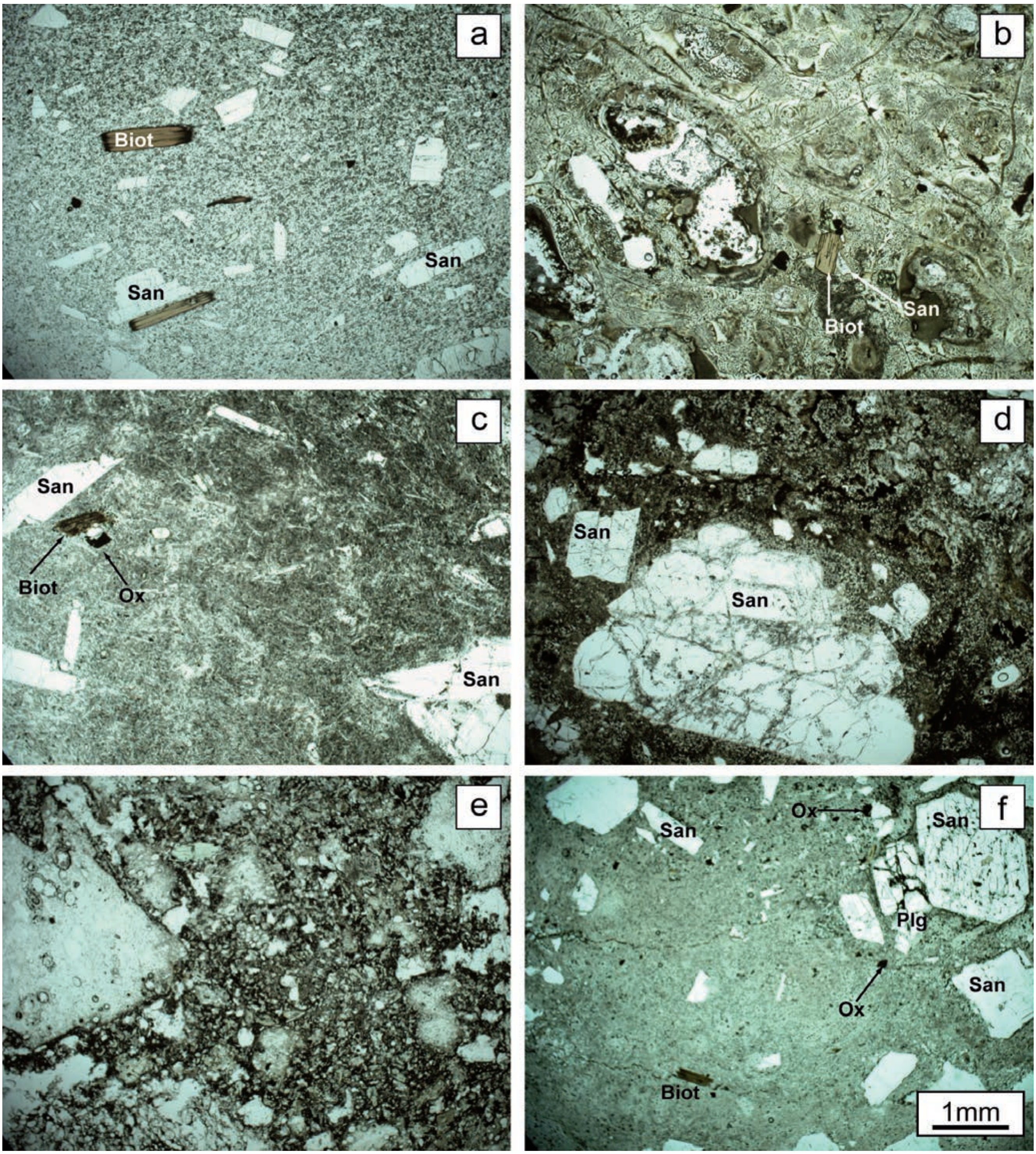

Fig. 5 - Optical photomicrographs (plane polarized light) of samples of Mt. Epomeo Green Tuff. Fresh a) to moderately altered b) porphyric trachytes from LMEGT breccia. Altered samples from this breccia level show a partial to complete replacement of groundmass phases by analcime and clay minerals. Weakly c) to highly altered e) porphyric trachytes of UMEGT breccia. In the samples collected at the fumaroles (e) also phenocrysts are affected by hydrothermal alteration showing a pervasive substitution of them with clay minerals. (f) Mt. Epomeo Green Tuff sample in which fresh sanidine, plagioclase, biotite and oxide phenocrysts are enclosed in the altered ash matrix. San: sanidine; Biot: biotite; Plg: plagioclase; Ox: oxide

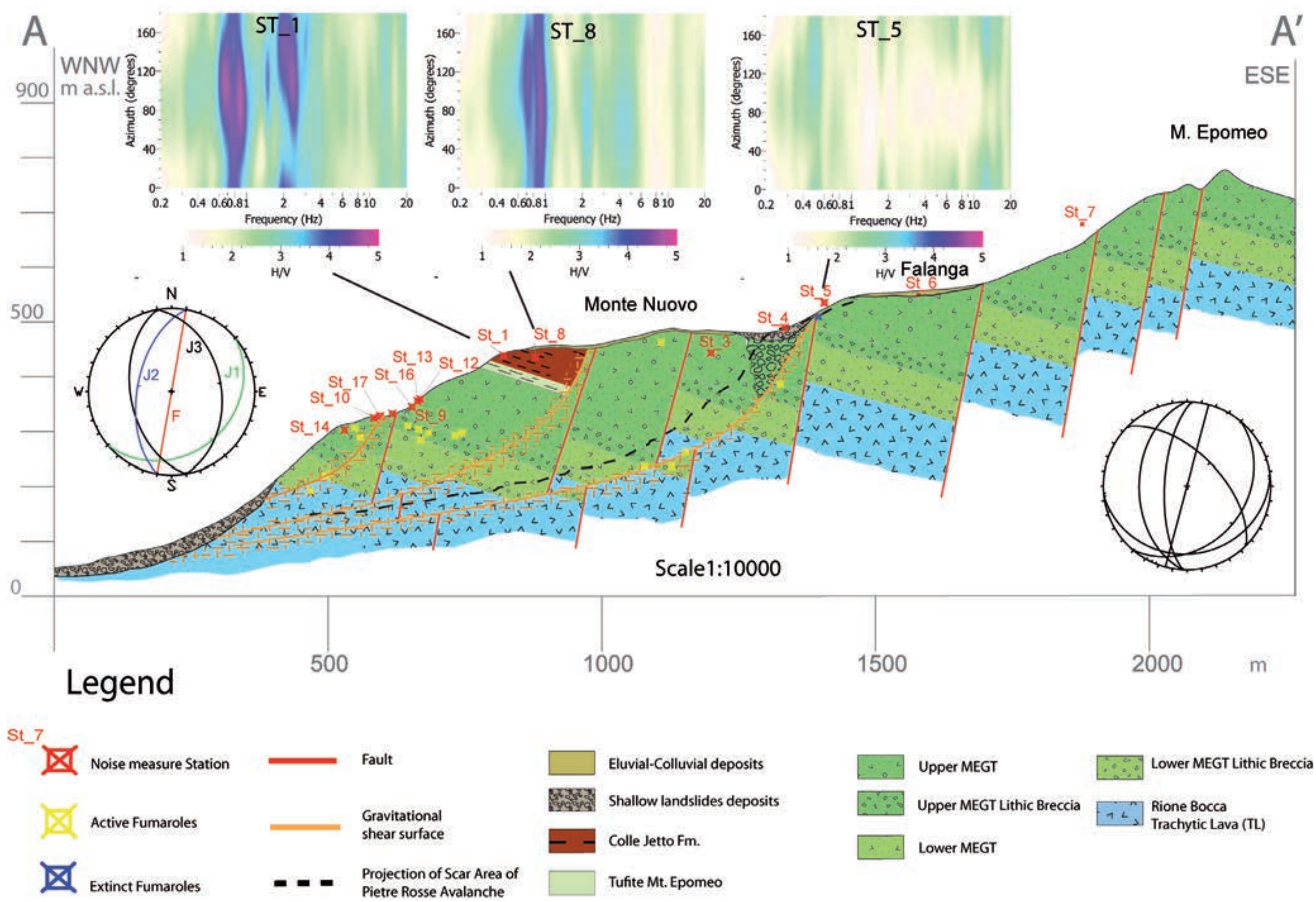

Fig. 6 - Geological section of the gravitational deformation affecting the Mt. Epomeo western slope. Fumaroles as well as seismic noise measurement locations are projected from the surface position to the cross-section. The dashed black line represent the shape of the already detached avalanche of Pietre Rosse scar area, shifted 150 m eastward. The synthetic stereoplot of the main joint sets measured in the Mt. Nuovo area (left) and in the scar area of the Pietre Rosse rock avalanche (right) are also shown

is recognizable by the presence of secondary authigenic mineralizations in the groundmass giving an orange to orange-red colour to the rock. The authigenic mineral assemblage analcime + montmorillonite + kaolinite + hematite recognized by X-ray diffraction analyses on altered samples suggests temperatures of hydrothermal alteration in agreement with the temperature of fumaroles (up to 100°C; Altaner *et alii*, 2013 and references therein). The phenocrysts assemblage recognized in the MEGT samples is the same to that observed by Altaner *et alii* (2013) (sanidine, plagioclase, biotite, clinopyroxene and horneblende). The secondary authigenic mineralizations detected by X-ray diffraction analyses on a sample of MEGT (at Pizzone site - NE of Mt. Nuovo, see Fig. 1) are similar to those reported by Altaner *et alii* (2013) in Green Tuff clasts of polymictic breccia samples (K-feldspar + analcime + clay minerals ± phillipsite ± calcite); in our sample the phillipsite zeolite and calcite are absent. The different types of alteration minerals identified indicate that MEGT experienced several alteration events; in particular, the mineral association of phillipsite ± chabazite, interstratified illite/smectite, Fe-rich illite and low amount of analcime point to an alteration event at low-temperature (<70°C) whereas the association of authigenetic K-feldspar, analcime Fe-rich illite and interstratified illite/smectite suggests a hydrothermal alteration episode at temperature higher than 70°C, possibly up to 100-150°C (Altaner *et alii*, 2013).

The results of geomechanical survey focused on reliable outcrops of MEGT highlighted that the welded cineritic matrix is interested by pervasive high angle conjugated systems and low-angle sets of discontinuities, dipping from 50 to 70° and 25-30° (J2, F; see Fig. 6), respectively. The main joint sets are a NS +/- 10° trending system dipping westward around 50° and a NE-SW oriented set dipping 20-30° to SE (J1; see Fig. 6). The high-angle planes are related to both major regional tectonic systems and local systems responsible for the resurgence of the Mt. Epomeo, while the low-angle ones correspond to gravitational shear planes.

The most pervasive systems also control the widespread landslide process affecting the Mt. Nuovo slope as they are located at the edge of the main escarpments, where discontinuities isolate large unstable blocks, such as those identified in the Falanga plain.

The joint trends have a direct correspondence in the morphological trenches observed upslope from the deformed volume, where they developed parallel to the slope suggesting a gravitational origin.

The alignment of the aforementioned landforms with the main tectonic elements suggests a main tectonic control: pre-existing discontinuities, combined with high slope gradient, led to a slow mass rock creep process that evolved in a shear-zone driven deep landslide.

Based on the collected geological data it was possible to draw four engineering-geological cross-sections of the Mt. Epomeo western slope.

These sections intercept three distinct gravitational shear surfaces: the main one is about 250 m deep, while the two minor ones cut the topographic surface in correspondence of the top of Mt. Nuovo and downslope, respectively.

The geometric evidence allow to classify the slope deformation as a "type E" structurally-defined compound "constrained at toe" slide (Hungr & Evans, 2004) with main rupture surfaces following an high angle joint set at scarp (F, J2 joint set, see Fig. 6) and a basal shear zone cutting the rock mass. The resulting landslide mechanism is a mainly translational one even if a rotational contribution to the sliding can be deduced by retro-deforming the landslide mass starting from its present setting. Geometry of secondary failure surfaces, counter-slope terraces and evidence of back-tilted markers within the outcropping tuffs (i.e. elongated scoria) also indicate a rotational component in the landslide mass movement.

The bi-planar compound setting of the main sliding surface involve a rock mass volume of about 190 Mm^3 with a total horizontal displacement of about 65 m (Fig. 6). More in particular, the flat portion of sliding surfaces seems to be not controlled by structural elements (i.e. strata, joints or faults, see Fig. 6) since they result in a counter slope setting (this is the case of the geological contacts) or in a high-angle down-slope dipping (this is the case of main faults and joint sets). On the other hand, the high-angle portion of the sliding surfaces corresponds to main faults that displace Mt. Nuovo from the top of the Falanga plain, revealing a significant structural control.

The seismic noise measurements provided a useful contribution to the reconstruction of such a geological setting as they pointed out a HVSR resonance peak at 0.8 Hz at stations ST_1, ST_3, ST_8 (see Fig. 6 for their projection along the geological cross-section). As the HVSRs does not show directivity, we could relate this resonance to an impedance contrast between a soft-rock layer and a bedrock, i.e. under almost 1D condition. Taking into account the geological setting of the Mt. Nuovo slope, the observed resonance could be related to an approximately 250 m thick soft layer constituted by the MEGT which is part of the landslide mass and overlay the TL constituting the landslide bedrock (Fig. 6).

Such a seismic resonance is no more evident moving from Mt. Nuovo toward the Falanga plain where the MEGT is not yet involved in the landslide process so justifying a more reduced impedance contrast respect to the TL.

Concerning the sector between the Falanga plain and the top of Mt. Epomeo, the measurement at station ST_4 shows a 7 Hz HVSR peak that is consistent with the presence of a shallow unconsolidated terrain, partially made of a rock slide mass and partially of eluvial-colluvial deposits generated by weathering and hydrothermal alteration. Based on the obtained frequency and taking into account the Vs values typical for such kind of deposits (500-600 m/s) it is possible to estimate a debris thickness of about 15 meters, that is in agreement with the collected evidence. The other noise measurements do not show significant HVSR peaks: this absence of resonance can be ascribed to the presence of major faults or shear zones that increase the rock mass jointing conditions of both the landslide mass and its bedrock, reducing their impedance contrast.

Moreover, many noise measurements show HVSR values higher than 2 within a wide frequency range as the FFT amplitudes of the horizontal components are generally higher than the vertical ones. According to Del Gaudio *et alii* (2007), such an effect can be referred to a topographic amplification due to peculiar landform geometries like steep slopes or sharp ridges, that control the directional distribution of FFT. In addition to the approximation related to the assumed 1D model, further uncertainties derive from lack of stratigraphic or active seismic data, useful for calibrating the seismo-stratigraphic model.

The here proposed engineering-geological model highlights the correspondence between the gas vent location and the basal breccias outcropping at the base of the two MEGT flow units. Such a correspondence is evident in both the Donna Rachele (Rione Bocca) fumarolic field and in the Mt. Nuovo area and could be related to the contrast of permeability between the MEGT breccia levels and the massive lava, which represent the local hydrothermal reservoir. Based on the here reported engineering-geological section (Fig. 6) the fumarolic emergences are justified as they rise from a complex net of faults and fractures, i.e. they are related to the structural setting of the slope and the ongoing gravitational deformation. The presence of extinct fumaroles upslope the main surface seems to confirm that both lithological and structural elements control the emergence of ascent fluids from the deep reservoir. In this framework, structural discontinuities represent preferential escape paths for the ascent of fluids, because of the induced fracturing, while the gravitational surfaces may have interrupted the lateral continuity of the reservoir, preventing the ascent of fluids in the highest areas and leading to the extinction of gas vents.

CONCEPTUAL EVOLUTIONARY MODEL OF THE MT. NUOVO ONGOING DEFORMATION

Based on the high-resolution engineering-geological model of Mt. Nuovo a preliminary conceptual model was derived to justify the ongoing gravity-induced slope deformations. This model relates stress field within the hydrothermal system (due to high-pressure fluids) with crack initiation at the foot of the slope (i.e. where less confining pressures exist) that evolve in fractures concentrated along highly jointed rock mass zones (Fig. 7). These fractures evolve in a proper shear zone propagating upslope until they reach the pre-existing volcano-tectonic elements, i.e. those related to the resurgence mechanism. This shear zone favored the sliding deformation and allowed the opening of deep trenches (Fig. 7). The projection on Mt. Nuovo section (A-A'; Fig. 6) of the scar surface of the already detached rock avalanche in the adjacent south-western slope (Della Seta *et alii*, 2011), outlines an extraordinary similarity in terms of both geometry and shape of the reconstructed sliding surfaces (Fig. 6). Also the geostructural setting of the rock avalanche scar area, reveals very similar features respect to the one obtained at Mt. Nuovo (see Fig. 6). This evidence strengthens the analogy between the evolution of the occurred landslide and the gravitational ongoing-deformation, leading to assume a generalized collapse of the slope as a possible ultimate scenario for the Mt. Nuovo landslide evolution.

CONCLUSIONS

This study proposes a high-resolution engineering-geological model of the Mt. Nuovo (NW of Mt. Epomeo) at Ischia Island, which is involved in a shear-zone-driven gravity-induced slope deformation. The model was constrained by major morpho-structural field evidence of the landslide mechanism and by the results of ambient noise measurements. The here experienced multidisciplinary approach allowed to provide more constraints to the understanding of the gravitational deformation affecting the Mt. Nuovo in terms of structural control, rock mass properties and involved volumes.

Moreover, the here proposed geological model highlights that the hydrothermal emissions are strictly related to both the stratigraphic and structural setting of the area.

This model represents the first step to define the gravitational

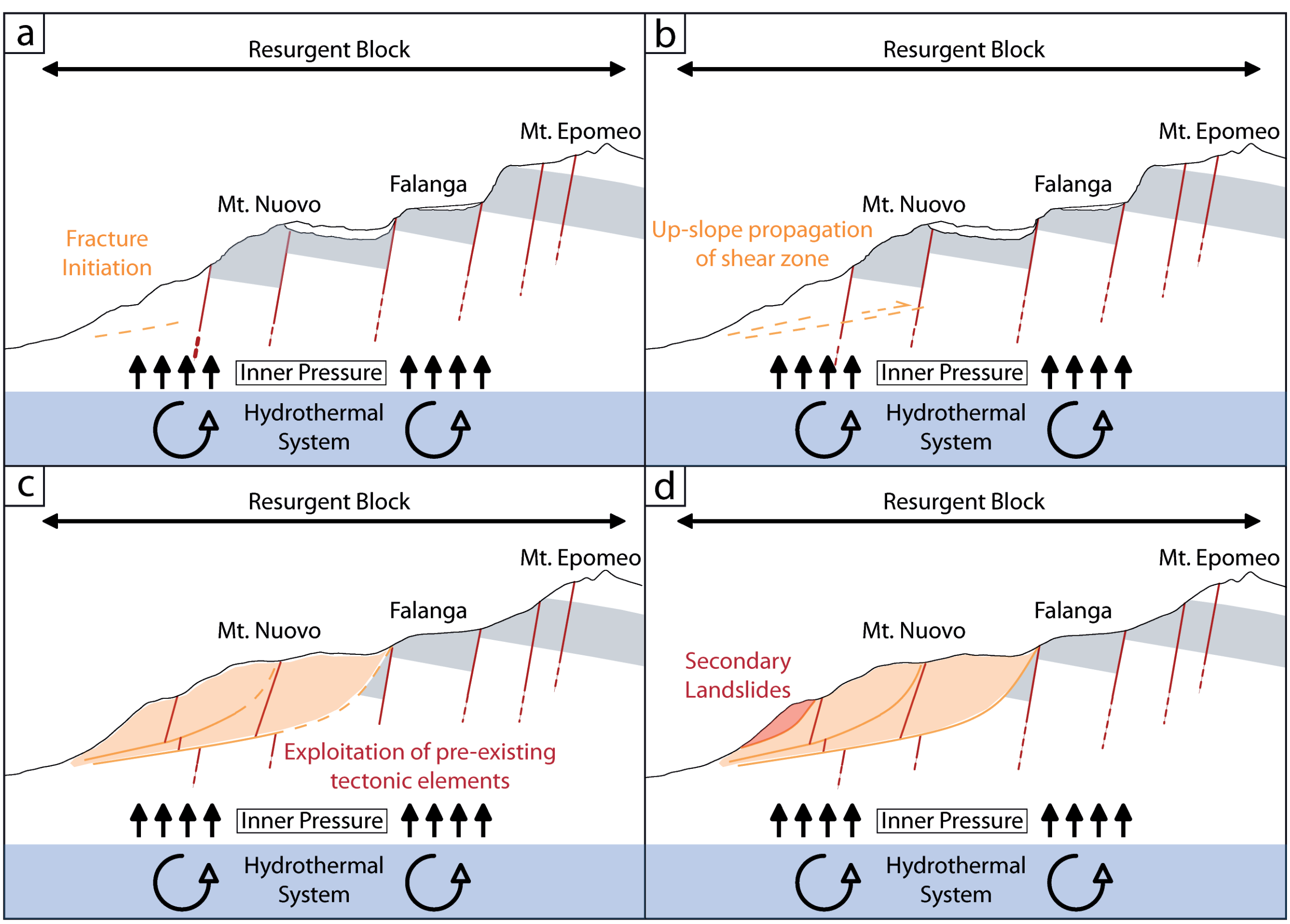

Fig. 7 - Conceptual evolutionary model of the Mt. Nuovo slope deformation

evolution of the Mt. Nuovo relief providing new constrains to the ongoing deformations. The here proposed model also points out a strict relation between geological setting and hydrothermal system, which pervasively permeates the geological succession, and suggests possible role of inner pressures in conditioning the evolution of the ongoing deformations. The highlighted features confirm the complexity of the landslide process by the identification of a multiple compound mechanism with a main rupture surfaces, about 200-250 m deep and involving a volume of about 190 Mm^3.

Future studies will be devoted: i) to better constrain the local seismostratography; ii) to sample and characterize the thermo-mechanical behavior of the MEGT; iii) to quantify the thermo-baric conditions of the hydrothermal system capable to lead the ongoing landslide process toward a general collapse. Moreover, since it is not a-priori negligible, the effect due to transient actions related to earthquakes, teleseismic and/or bradiseismic events will be modelled, as they can interact with the landslide-involved mass (Lenti *et alii*, 2015) and modify the stress-strain field of both the landslide slope and the underlying hydrothermal system. To this aim, a thermodynamic numerical model will be performed by considering a multilayer hydrothermal system and a conductive-convective heat transfer. This model will be coupled with a thermo-mechanical stress-strain model of Mt. Nuovo slope, to infer possible interactions between the thermo-baric field of the hydrothermal system and the ongoing landslide process.

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Geological constraints for a conceptual evolutionary model of the slope deformations affecting Mt. Nuovo at Ischia (Italy)

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Plate 1 - Geological map of Mt. Epomeo western slope (Ischia)

Legend to Map

- Debris Avalanche
- Debris Flow
- Debris Slide
- Slump
- Mud Flow
- Eluvial and Colluvial Deposits
- Marine and MEGT reworking
- Upper MEGT
- Upper MEGT Lithic Breccia
- Lower MEGT
- Lower MEGT Lithic Breccia
- Rione Bocca Trachytic Lava (TL)
- Seismic Noise stations
- Rock Sampling
- Active Fumaroles
- Extinct Fumaroles
- Fault
- Gravitational Shear Surface
- Section Trace
- Trench

Legend to Sections

- Projection of Seismic Noise Station (St_7)
- Projection of Active Fumaroles
- Projection of Extinct Fumaroles
- Projection of Scar Area along profile EE'
- Trench Debris
- Shear Zone