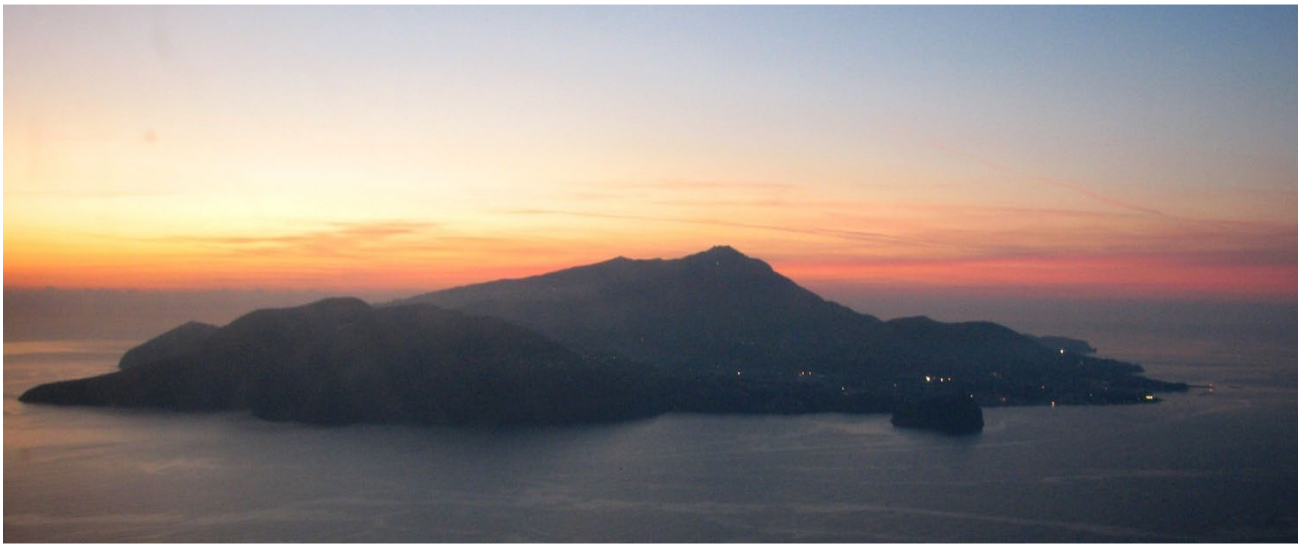
Field trip to the Ischia resurgent caldera, a journey across an active volcano in the Gulf of Naples[1]

IASPEI/IAVCEI Inter-Association Commission on "Volcano Seismology & Acoustics"

October 1st-6th 2023 - Lacco Ameno, Ischia Island (Italy)

October 2nd 2023 Field Trip Guide



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Preface

Ischia is one of the most impressive examples of post-caldera resurgence in the world, with its almost 1,000 m of uplift in less than 30 ka. This three-days field trip will lead the participants through the geological and volcanological history of the island, illustrating the volcanic and related hazardous phenomena threatening about 50,000 inhabitants. Effusive and explosive eruptions, catastrophic earthquakes and huge debris-avalanches struck the island that, since Neolithic times, experienced a complex history of alternating human colonization and natural disasters.

The field trip consists of the circumnavigation of the island, aimed to outline its main volcanological, geomorphological and tectonic features and to observe the oldest volcanic rocks exposed, stimulating discussions about coastal evolution and the relationships between volcanism, volcano-tectonism and slope instability.

[1] This Guide is extracted from: Sansivero, Fabio, et al. "Field trip to the Ischia resurgent caldera, a journey across an active volcano in the Gulf of Naples." Geological field trips and maps (2018).

Geological setting

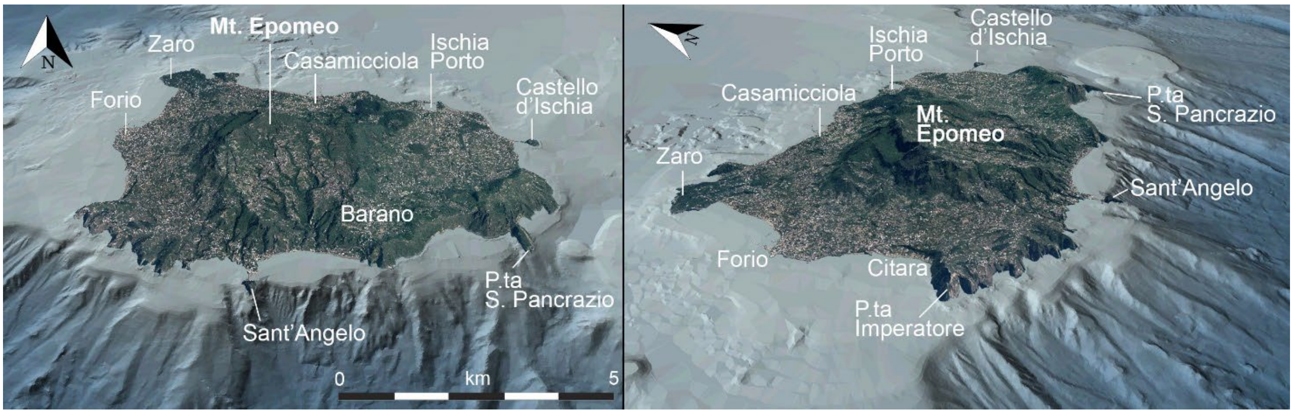

Fig. 1 - 3D view of Ischia island with bathymetry (modified after Della Seta et al., 2012).

The island of Ischia, located at the north-western border of the Gulf of Naples, hosts an active volcanic field, which is included in the framework of the Tyrrhenian volcanism. This volcanism is connected to the Plio-Quaternary evolution of the western Mediterranean area, which is characterized by the anticlockwise rotation of the Italian peninsula, occurred during the interaction between the African and the European plates (Ippolito et al., 1973; D'Argenio et al., 1973; Finetti and Morelli, 1974; Bartole, 1984; Piochi et al., 2005). The activation of NW-SE normal faults and NE-SW normal to strike-slip transfer faults during this process, allowed the magmas to reach the surface, feeding the volcanism that is still active also in the other Neapolitan volcanoes (Somma-Vesuvius and Campi Flegrei caldera).

Ischia is only the emerging part of a much wider complex that rises about 1,000 m above the sea bottom (Fig. 1; Orsi et al., 1999; Bruno et al., 2002). It covers an area of 46.4 km^2 and reaches the maximum elevation of 787 m a.s.l. at Mt. Epomeo, which is located in the central part of the island. A minor alignment of peaks characterizes the south-eastern part of the island. The coast morphology alternates steep cliffs and promontories with sandy beaches and slopes that gently dip to the sea.

The rocks exposed on the island are mainly volcanic or landslide deposits and subordinate terrigenous sedimentary rocks that testify the alternation of constructive and destructive phases of morphogenesis, due to the interplay among volcanism, volcano-tectonism and diffuse episodes of slope instability (de Vita et al., 2006; 2010; Della Seta et al., 2012).

Volcanological evolution

The beginning of volcanic activity at Ischia is not well defined, as the oldest dated rocks are not the lowermost exposed on the island. They have an age of about 150 ka and volcanism continued until the last eruption, occurred in 1302 AD, with intercalated centuries to millennia of quiescence (Vezzoli, 1988). The oldest exposed rocks (Scarrupata di Barano Formation; Vezzoli, 1988; Ancient Ischia Synthem; Sbrana and Toccaceli, 2011; Fig. 2) range in age between 150 and 74 ka and are lavas and pyroclastic deposits, representing the remnant of a partially eroded volcanic complex, exposed in the south-eastern part of the island, and small lava domes, exposed along the coasts. Between 74 and 55 ka a very intense period of explosive volcanism followed, likely producing the highest magnitude eruptions occurred on the island from vents mainly located along the southern coasts of Ischia (Brown et al., 2008; Rifugio di San Nicola Synthem; Sbrana and Toccaceli, 2011). This long lasting period of activity culminated between 60 and 55 ka with the caldera-forming eruptions that generated at least two or three ignimbritic deposits, known in the literature as the Mt. Epomeo Green Tuff (Brown et al., 2008 and references therein; Pizzone, Frassitelli and Mt. Epomeo Green Tuff of Sbrana and Toccaceli, 2011). The caldera collapse caused the submersion of the central part of the island, and these tuffs mainly constitute the caldera filling deposits, which were emplaced partially in a submarine environment and partially on land, outside the caldera margins. Since its formation the caldera depression became a basin of sedimentation, in which a sequence of volcanoclastic and terrigenous deposits formed by the reworking of the tuffs and sedimentary supply from the mainland (Sbrana and Toccaceli, 2011). After these caldera-forming eruptions, volcanism continued up to 33 ka with the activation of vents in the south-western and north-western offshore of the island, from which originated a series of high-energy hydromagmatic eruptions, whose deposits are presently exposed to the west of Mt. Epomeo. The intrusion of the magmas that fed these eruptions, very likely started the uplift of the caldera floor, causing the emersion of the Mt. Epomeo resurgent block.

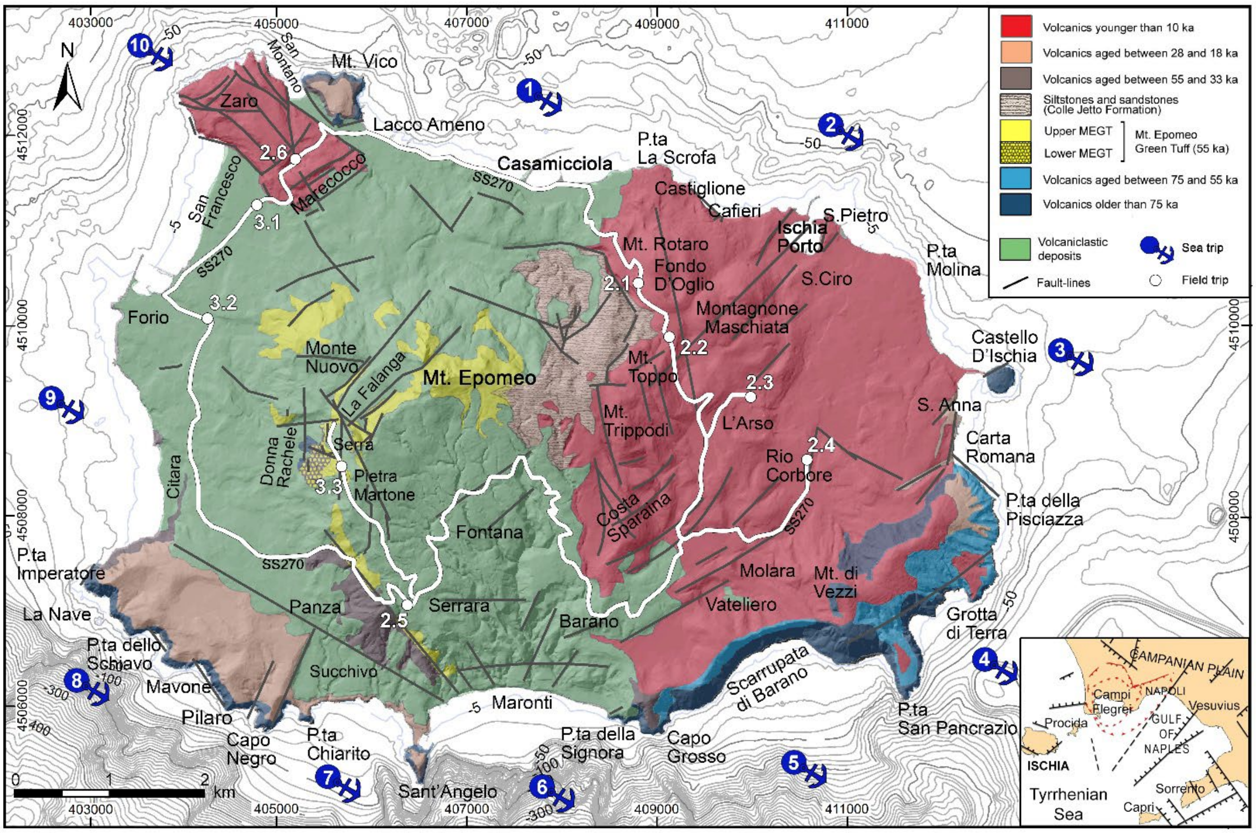

Fig. 2 - Geologic sketch map of Ischia with sea and field trips (modified after de Vita et al., 2010).

After a repose interval that lasted about 5 ka, volcanism resumed at 28 ka with a series of effusive and both phreatomagmatic and magmatic, low-energy explosive eruptions, which occurred sporadically until 18 ka. These eruptions produced lava flows, Strombolian fallout deposits and the building of small tuff-cones and scoria cones, currently exposed along the south-eastern and south-western coasts of the island (Campotese Subsynthem; Sbrana and Toccaceli, 2011).

The following time interval is of controversial interpretation in the literature, based on different radiometric datings of the outcropping volcanics. Vezzoli (1988) defines this period as a repose interval that lasted between 18 and 10 ka. More recent studies suggest that some eruptions occurred during this time span (Sbrana and Toccaceli, 2011). However, despite this discrepancy, almost all the authors agree in considering this time interval as a period of very reduced volcanic activity. On the contrary, the following period, started at 10 ka, was characterized by a very intense volcanic activity, mainly concentrated at around 5.5 ka and in the last 2.9 ka (de Vita et al., 2010). Almost all the eruption vents of this period are localized in the eastern part of the island. Only a few of these were activated outside this area, along regional faults or at the margins of the resurgent block. The last 2.9 ka of activity were characterized by at least 34 effusive and explosive eruptions Effusive eruptions generated lava domes and usually high-aspect ratio lava-flows. Only the last eruption, occurred in 1302 AD produced a lava flow which had the mobility to travel as far as about 3 km. Explosive eruptions produced variably dispersed pyroclastic-fall and –current deposits with variable impact on human settlements and the environment, and built small tuff-cones and tuff-rings (de Vita et al., 2010 and references therein; Sbrana and Toccaceli, 2011; de Vita et al., 2013).

In the past 10 ka volcanism was characterized by the alternation of periods of very intense activity and long lasting intervals of quiescence (Fig. 3). Therefore, it has been hypothesized that episodes of magma intrusion and resurgence occurred intermittently (Tibaldi and Vezzoli, 2004; de Vita et al., 2006; Vezzoli et al., 2009; de Vita et al., 2010).

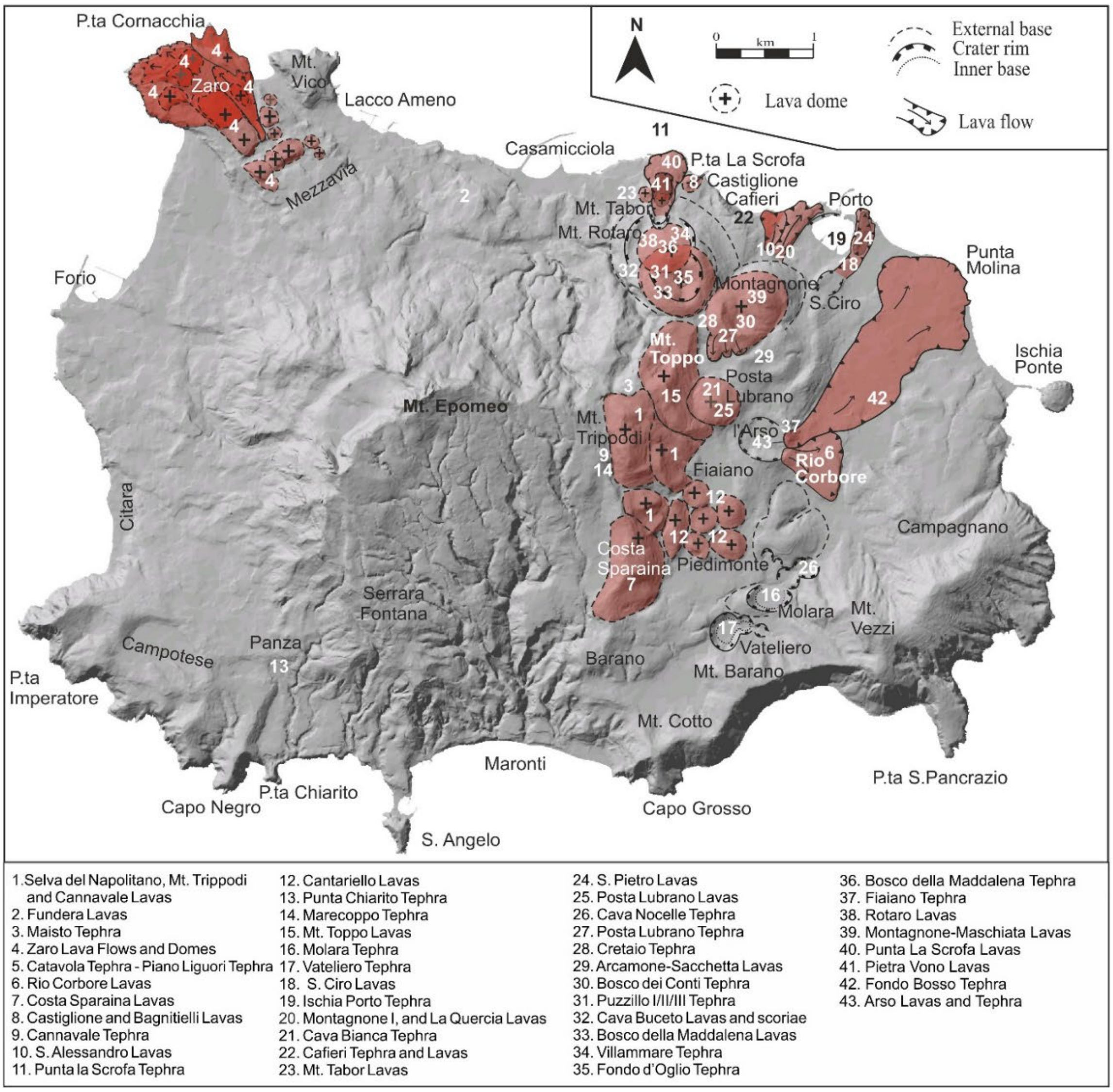

Fig. 2 - Geologic sketch map of Ischia with sea and field trips (modified after de Vita et al., 2010)

In particular, during the past 5.5 ka the deposits related to surface gravitational movements preceded and followed the emplacement of the eruptions products, testifying that vertical movements related to resurgence that caused slope instability, occurred through the activation of the same faults that fed volcanism. According to de Vita et al. (2006) the emplacement of both large debris avalanche and minor landslide deposits occurred in four main phases of gravitational instability and volcanic activity, dated between 5.5 and 2.9 ka, around 2.9 ka, between 2.6 and 2.3 ka, and between 2.3 and 1.9 ka, respectively. Also the last eruption, occurred on the island in 1302 AD, was preceded by the activation of large mass movements, leading Della Seta et al. (2012) to hypothesize the occurrence of a possible fifth phase of slope instability.

Since the last eruption, no evidence of renewal of uplift have been recorded. Del Gaudio et al. (2010) based on radar interferometric data and levelling surveys, suggest that in very recent times only a low rate of subsidence is recordable at Ischia, likely due to the depressurization of the hydrothermal system and crack-closure processes (Manzo et al., 2006; Sepe et al., 2007). However, the historical time intense volcanism (de Vita et al., 2010), the presence of widespread fumaroles and thermal springs (Di Napoli et al., 2011) and seismic activity (Cubellis and Luongo, 1998) testify that at the present the Ischia magmatic system has to be considered still active.

Resurgence

Ischia is one of the most impressive case of intracaldera resurgence in the world, with an about 1,000 m of uplift of its central part. The resurgent area is composed of a series of differentially displaced blocks, and is characterized by a polygonal shape, defined by the intersection of newly formed, volcano-tectonic faults, and regional faults reactivated during resurgence (Orsi et al., 1991; Acocella and Funiciello, 1999). The uplifted blocks are variably raised and inclined, with a general tilting of the entire area around a NE-SW oriented horizontal axis, located in the southeastern part of the resurgent area. The result is an asymmetric block structure, in which the most uplifted part is located in the northwestern sector of the resurgent area (Fig. 2; Rittmann and Gottini, 1980; Vezzoli, 1988; Orsi et al., 1991; Acocella and Funiciello, 1999; de Vita et al., 2006; de Vita et al., 2010; Della Seta et al., 2012). The western part of the resurgent area is bordered by N-S and NE-SW trending structures. To the east N-S, NE-SW and NW-SE trending faults define a series of blocks differentially lowered toward east. Toward north-northeast the limit of the resurgent area is not well defined, as still along the shoreline there are beach deposits displaced at different elevations above sea-level by E-W and NW-SE trending faults.

The beginning of resurgence, as well, is not precisely defined, although it is commonly accepted that it was related to the intrusion of new magma into the system (Rittmann, 1930; Rittmann and Gottini, 1980; Orsi and Chiesa, 1988; Orsi et al., 1991; Luongo et al., 1995; Tibaldi and Vezzoli, 1997; Tibaldi and Vezzoli, 1998; Acocella and Funiciello, 1999; Moli et al., 2003; Carlino et al., 2006; 2012), very likely occurred before the eruptions dated at 33 ka.

As already stated, geodetic data show a generalized subsidence of the uplifted block. This suggests that currently the resurgent phenomenon is at rest (de Vita et al., 2006; Manzo et al., 2006; Sepe et al., 2007; De Novellis et al., 2018).

Magmatic system

The exposed volcanic rocks of Ischia belong to the low-K series of the Roman Comagmatic Province and range in composition from shoshonite to phonolite. The most abundant rocks are alkali-trachyte (Fig. 4a; Angiulli et al., 1985; Poli et al., 1987; Poli et al., 1989; Crisci et al., 1989; Civetta et al., 1991; Sbrana and Toccaceli, 2011; D’Antonio et al., 2013; Moretti et al., 2013; Casalini et al., 2017).

According to Sbrana and Toccaceli (2011) the oldest outcropping rocks (150-75 ka) are trachytic in composition, with an alkali content and a Na_2O/K_2O ratio that decrease over time. The highest magnitude explosive eruptions of this period had a phonolitic composition with higher Na_2O/K_2O ratio and higher peralkalinity index.

The period of activity included between 75 and 50 ka has been deepen inside by Brown et al. (2014). These authors evidenced that significant changes occurred in the magmatic system before and after the caldera-forming eruptions, and that it was periodically refilled by magmas of deep origin, characterized by different isotopic compositions. Before the Mt. Epomeo Green Tuff eruption, magmas were trachytic and phonolitic in composition, poorly enriched in radiogenic Sr and progressively less radiogenic with time. The eruptions that immediately preceded the Green Tuff were fed by an isotopically distinct magma and, as the Green Tuff itself, had a phonolitic-to-trachytic composition. Brown et al. (2004) estimate that an amount of about 5-10 km^3 of magma accumulated at a depth of 4-6 km in a 20 ka long time-span. Following the Green Tuff eruptions, volcanism was fed by a new and less differentiated magma, whose geochemical and Sr and Nd isotope variations bear witness to the ascent of distinct magma bodies, variably contaminated by a crystalline metamorphic basement. These magmas directly reached the surface or stagnate and differentiate at shallower depths, erupting during explosive eruptions (Brown et al., 2014).

During the past 50 ka the magmatic system behaved in a complex way, being characterized by phases of evolution in closed-system conditions that alternate with phases in which new and isotopically distinct magmas entered the system, recording evidence of contamination and mixing processes with resident magmas. Magma composition and eruptive dynamics of the post-Green Tuff activity, are significantly different from the previous periods. The erupted magmas were shoshonitic and latitic in composition (Civetta et al., 1991; Brown et al., 2008; 2014), and the eruptions show a progressively increasing water/magma interaction that culminated with the eruptions of the Citara Formation (Rittmann, 1930; Rittmann and Gottini, 1980; Vezzoli, 1988; Tufi di Citara in Sbrana and Toccaceli, 2011).

The magmas that fed the eruptions included between 28 and 18 ka vary in composition with time from shoshonite to alkali-trachyte, with increasing incompatible elements content and Sr isotopic ratio. This variability has been interpreted as the evidence of the arrival of a new basic magma into the volcanic system and its progressive differentiation and mixing with the resident magma (Civetta et al., 1991).

Civetta et al. (1991) evidenced that the last period of volcanic activity at Ischia (10 ka BP – 1302 AD) was characterized by a well evident decrease in the value of Sr isotopic composition, and interpreted it as reflecting the arrival of a geochemically distinct magma into the system. The erupted products are mostly trachytic and subordinately latitic, with a negative correlation between chemical and isotopic composition. Piochi et al. (1999) stated that chemical and isotopic variations of all the rocks of this period, and mineralogical disequilibria of the less evolved products are evidence of mixing among different magmas either in the deepest part of the magmatic system or during the ascent of melts. At the present, according to the available geological and petrological data (Civetta et al., 1991; Orsi et al., 1996; Piochi et al., 1999), the magmatic system of Ischia seems to be composed of a deep and poorly-evolved magma reservoir, interconnected with shallower, smaller and more-evolved magma batches (also evidenced by the modelling of magnetic data; Orsi et al., 1999).

Starting from the geochemical and isotopic analysis of a set of samples representative of almost all the outcropping Ischia products, Casalini et al. (2017), showed that long period of permanence in magma chambers are required to justify the anomalous Sr isotopic ratios of some products. They also demonstrated, reconstructing the isochrones on the basis of Rb and Sr contents, that the time of residence of magmas before eruptions, range from a few tens to hundreds and thousands of years (Fig. 4b).

The studies conducted on the more mafic products of the pas 10 ka by D'Antonio et al. (2013) and Moretti et al., (2013) converge to the hypothesis of generation of magmas mainly dominated by gas-fluxing of CO_2 in a mantle modified by crustal assimilation. This process should be demonstrated by typically mantellic δO^{18} values and a Sr isotopic ratio that increases towards crustal values.

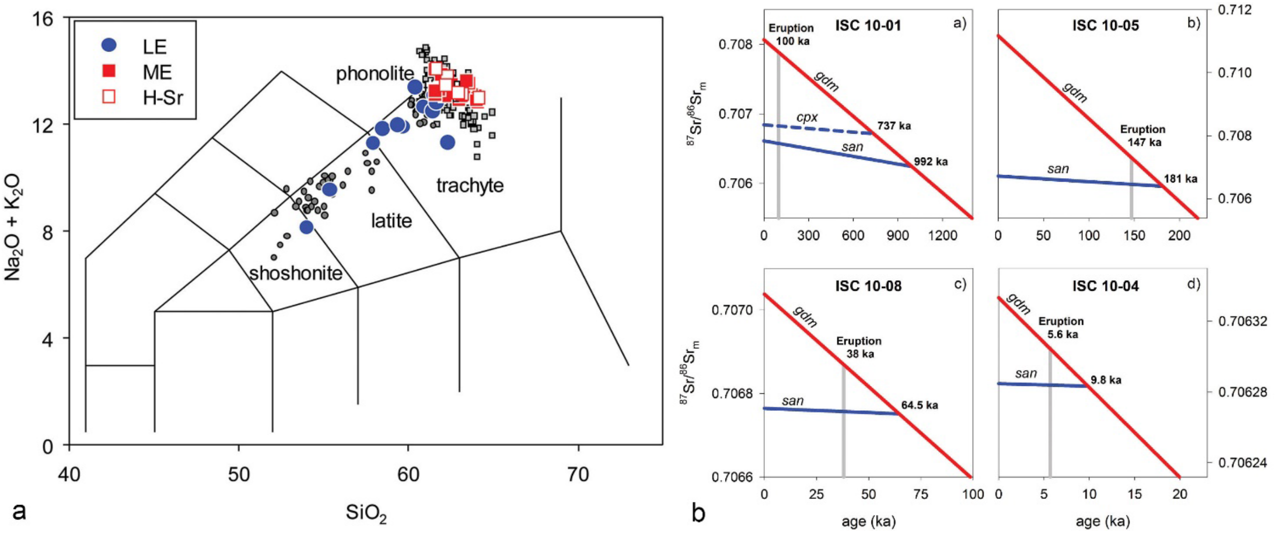

Fig. 4 – a) TAS diagram of the Ischia volcanics. Solid circles are referred to less-evolved samples (LE), solid squares to more-evolved samples (ME) and open squares represent a sub-group of more evolved samples (H-Sr) with anomalous radiogenic 87Sr/86Sr (modified after Casalini et al., 2017). Gray circles and squares are literature data. b) isochrones reconstruction in 87Sr/86Srm vs. age plots of selected samples with both anomalous (a and b), and normal (c and d) whole-rock 87Sr/86Sr (modified after Casalini et al., 2017). Straight lines represent groundmass (gdm) and minerals (san = sanidine, cpx = clinopyroxene) backward evolution of 87Sr/86Sr based upon their respective 87Rb/86Sr. The intersection yields the mineral crystallization age and the mineral residence time is calculated by subtracting the K-Ar eruption age.

Slope instability

Volcanism and volcano-tectonism at Ischia were strictly linked with slope instability at least in the past 10 ka. Deposits related to the gravitational instability of both coastal and resurgent block slopes involved very variable volumes of rocks and debris, remobilized by different landslide mechanisms.

These characteristics allowed to classify slope instability phenomena in two categories: i) large rock and debris landslides and ii) impulsive shallow landslides.

The first category includes rock avalanches, due to the collapse of entire portions of slopes that deform over a long-time scale (104-105 years; Mass Rock Creep; Chigira, 1992), or debris avalanches related to impulsive triggers. The second one includes smaller landslides, such as rock failure, roto/translational slides and earth/debris flows and lahars (volcanoclastic debris flows), triggered by volcanic eruptions, phreatic explosions and earthquakes, or by meteo-climatic events (Catenacci, 1992; Del Prete and Mele, 1999; 2006; Tibaldi and Vezzoli, 2004; de Vita et al., 2006; Della Seta et al., 2012

In fig. 5 are reported the chronostratigraphic relationships between large rock and debris avalanches, impulsive shallow landslides and volcanic deposits (Della Seta et al., 2012).

Landslide deposits intercalated with volcanic deposits younger than 10 ka (Tibaldi and Vezzoli, 2004; de Vita et al., 2006) are concentrated in the eastern and southern sectors of the island. The northern and western sectors are characterized by the outcrop of huge landslide deposits, likely emplaced as rock avalanches generated by MRC (Fig. 6), that are mainly part of the historical record (Della Seta et al., 2012; and references therein). The most intense phenomenon recorded on the island is a rock avalanche detached from the western side of Mount Epomeo (Della Seta et al., 2012; Sbrana and Toccaceli, 2011), with a volume estimated at 125 million m^3. A deep seated gravitational slope deformation (DSGSD), likely related to MRC process is also reported as affecting the Monte Nuovo, on the western slope of Monte Epomeo (Fig. 6) in historical reports (Del Prete and Mele, 2006; and references therein).

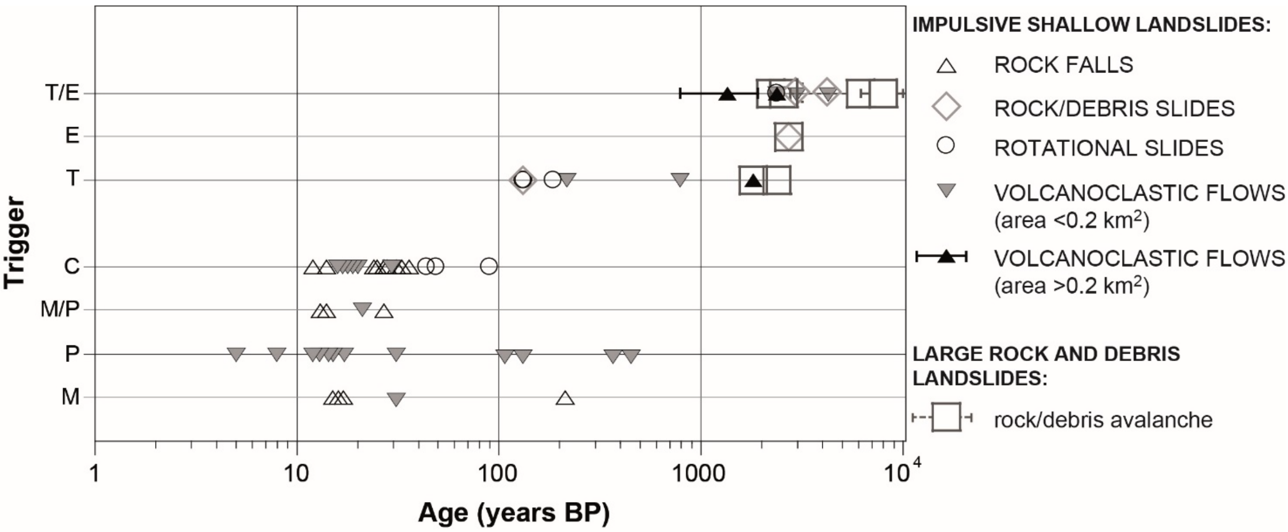

Fig. 5 - Time distribution of the slope gravitational events for Ischia, in relation to primary volcanic deposits (dotted lines) and grouped according to the impact area (modified after Della Seta et al., 2012).

Geological and historical evidence of impulsive shallow landslides are reported by Di Martire et al. (2012), which collected the historical record, consisting in 288 individual landslide events, of which 23 occurred between the fourth century B.C. and 1924 and 255 between 1970 and 2010, with a temporal registration gap between 1924 and 1970 (Del Prete and Mele, 2006). The most recurrent typologies are represented by rock falls/topples, slides, flows and complex landslides (Figure 7). Most of them are represented by flows (debris- or mud flow), which are concentrated within gullies, and by rock falls/topples, which affect the steepest slopes of Mount Epomeo and, above all, the sea cliffs (Catenacci 1992, Del Prete and Mele, 1999).

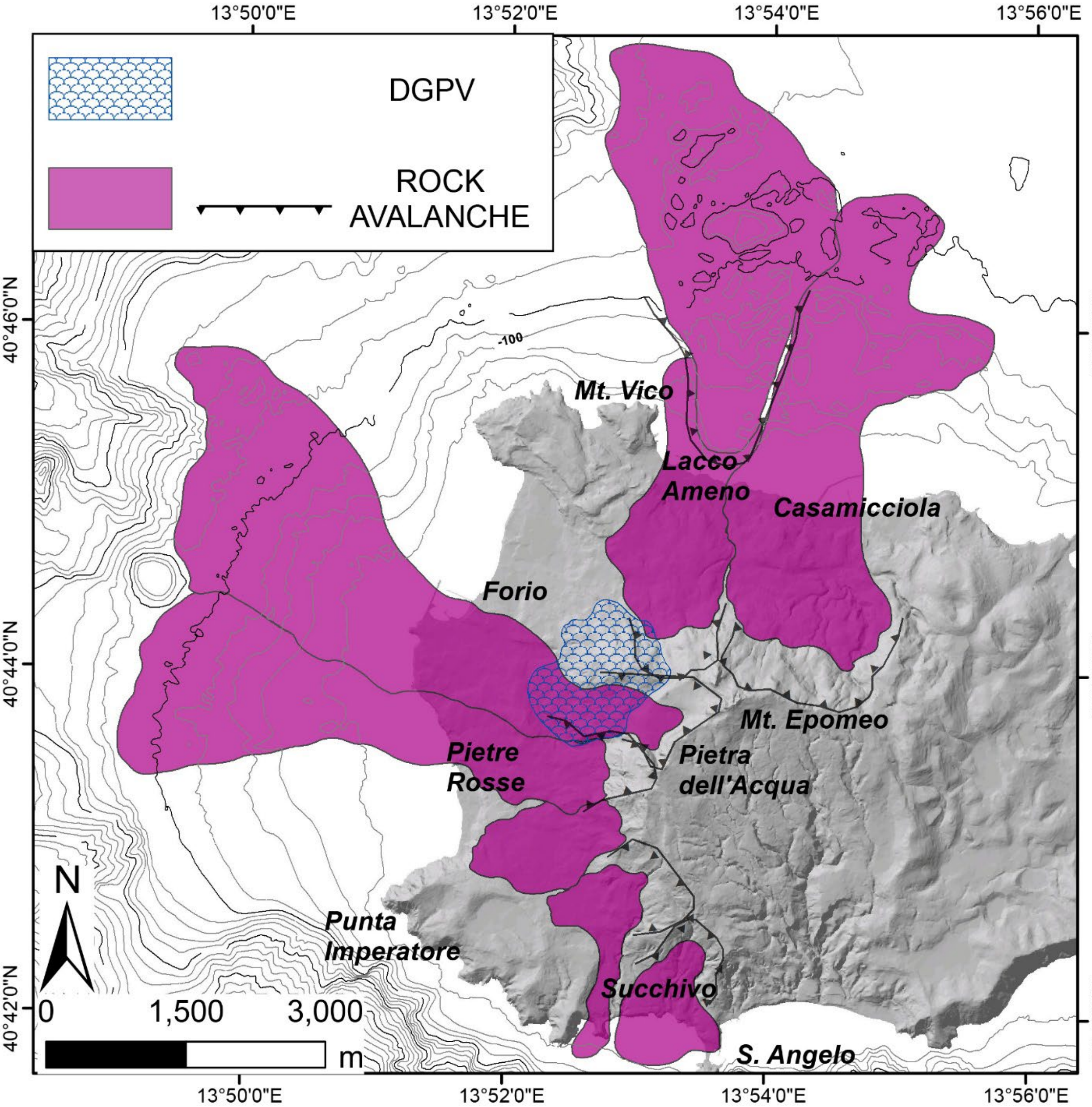

Fig. 6 - Spatial distribution of the rock avalanche deposits and of the ongoing MRC in the western sector of Mount Epomeo (modified after Della Seta et al., 2012).

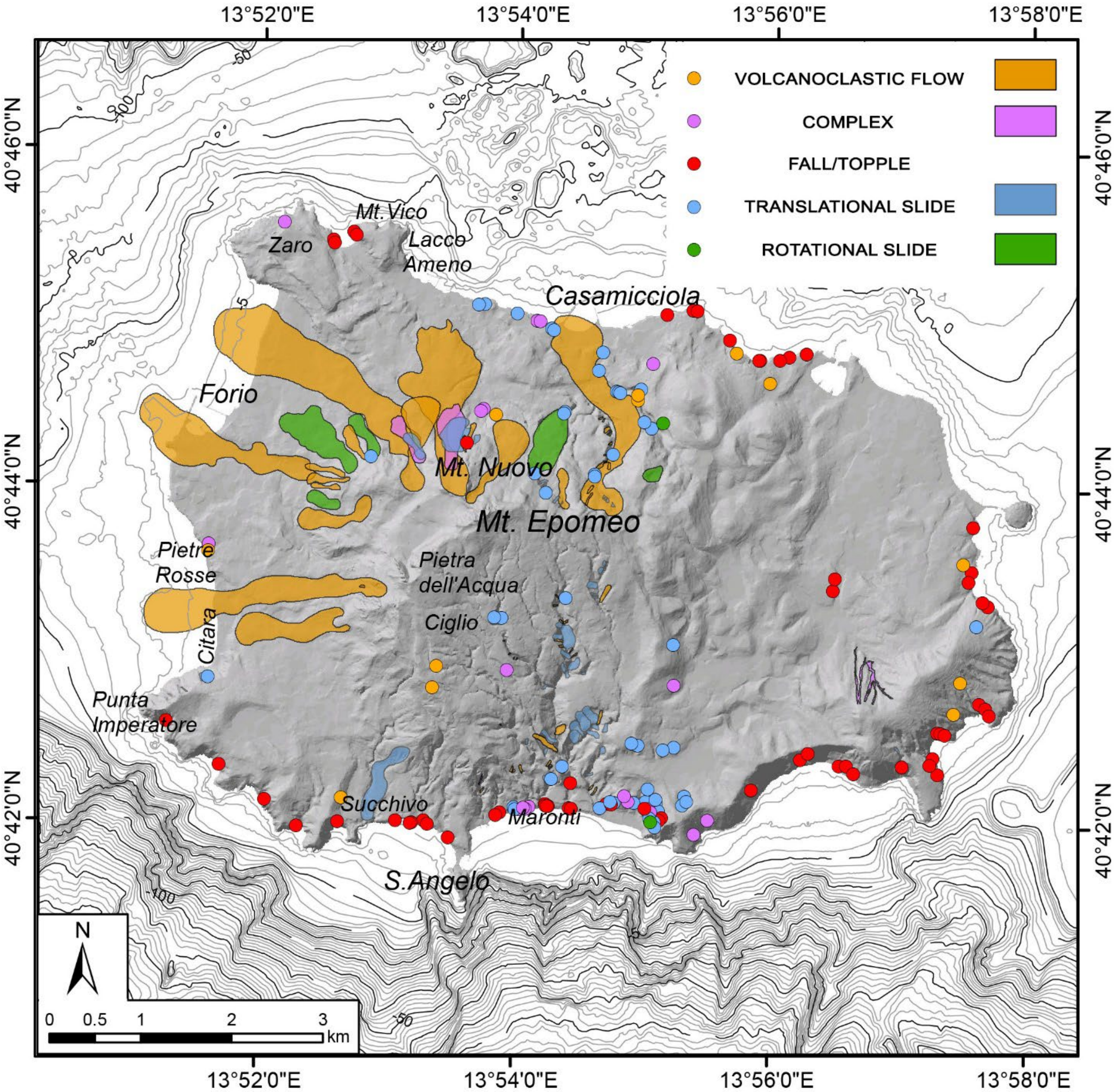

Fig. 7 - Spatial distribution of the impulsive landslides, including the debris avalanche IDA, at Ischia (modified after Di Martire et al., 2012).

Some events were chronologically constrained by stratigraphic relations with other landslide deposits and/or pyroclastic deposits (de Vita et al., 2006), while others were associated with the earthquakes of 1228, 1797, 1828, 1881, 1883 (Della Seta et al., 2012; and references therein).

ITINERARY

Circumnavigation of the island

Sailing around the Ischia island is undoubtedly the best way to view the deposits related to the ancient volcanic activity (150-18 ka), exposed along marine cliffs. It also gives the opportunity to identify some volcanic edifices and slope-instability deposits, produced during the last period of activity (10 ka – 1302 AD). All stop points are reported in figure 2.

Stop 1.1 – Northern sector of Mt. Epomeo and Casamicciola area

The coast between Lacco Ameno and Casamicciola is mainly characterized by deposits correlated to at least two large episodes of rock-avalanche from the northern slope of Mt. Epomeo (Della Seta et al., 2012; Sbrana and Toccaceli, 2011). The famous mushroom-shaped rock of Lacco Ameno, is a Green Tuff hummock, modelled by sea erosion, that was carried and deposited by a rock-avalanche older than 6 ka (Fig. 8). Several historical debris-flow and mud-flow deposits, triggered by earthquakes and heavy rain episodes, overlie the rock-avalanche deposits. Historical chronicles reported more than 15 episodes of rock fall, debris slide and flash flood in the area of Casamicciola, with loss of life in the last ten decades (Santo et al., 2012). The last flood episode occurred in 2009 and caused one victim and twenty injured.

Fig. 8 - Mushroom-shaped Green Tuff rock of Lacco Ameno (a); view of the northern slope of Mt. Epomeo from the sea at Lacco Ameno (b).

Casamicciola is the area of Ischia mostly affected by historical seismicity. More than 13 major earthquakes occurred in this area since 1228, with two catastrophic events in 1881 and 1883 (Cubellis and Luongo, 1998). These events were followed by a period of low seismic activity, which culminated on August 21, 2017 with a new earthquake of Md = 4.0 (De Novellis et al.,.2018; Nappi et al., 2018). The seismicity is typically characterized by shallow hypocentres, moderate energy and high macroseismic intensity in a very limited area.

Stop 1.2 – From Punta La Scrofa to Ischia Porto

East of Casamicciola Harbour the coast is made of deposits related to the more recent period of volcanic activity (last 10 ka), which are overlain by mud-flow and debris-flow deposits. At Punta La Scrofa promontory, layered pyroclastic currents and subordinate fallout deposits are clearly visible (Punta La Scrofa Tephra; de Vita et al., 2010). They are dated 8th century BC as pottery fragments of this age were found at the base and inside the deposits. The geometry of the layers, bomb sags and sedimentological evidence suggest they are part of a tuff-cone likely located in the offshore, a few hundreds of meters north of Punta La Scrofa.

These deposits are overlain by two lava-flow units which are the last products of the Rotaro composite volcano, one of the two examples of polygenic volcanic edifice of the last 10 ka at Ischia.

To the east of Punta la Scrofa, at Castiglione locality, highly fractured and foliated dark-grey lavas are exposed along the coast. These lavas are part of a lava-dome, which is coeval with a dyke, exposed at sea level at Bagnitielli locality. On the top of the lava dome a Bronze Age village (14th century BC) was found, partially buried by the previous mentioned pyroclastic deposits.

The coast between Bagnitielli and Ischia Porto shows a complex sequence (Fig. 9; de Vita et al, 2010) of volcanic and sedimentary deposits. To the west, the Castiglione Lavas and Bagnitielli Dyke (A, Fig. 9) are the oldest exposed deposits. Towards east the base of the sequence is composed of fossiliferous siltstones (SF, Fig. 9) overlain by a beach deposit (Sp, Fig. 9) that contains pottery dated at the 8th century BC. In the middle part of the sequence, the products of the local eruptive vent of Cafieri are exposed. They are composed of fine-ash and pumice-lapilli pyroclastic-current layers (C_1, Fig. 9), and a thin lava-flow and scoriae bed (C_2, Fig. 9), which represent the latest episodes of activity of this vent, whose neck (N, Fig. 9) is still partially visible. Pyroclastic fallout deposit with subordinate pyroclastic-currents beds, related to Posta Lubrano Tephra (D, Fig. 9), Bosco della Maddalena Tephra (F, Fig. 9) and Cretaio Pyroclastics (E, Fig. 9) are exposed at the top of the sequence. The first two deposits originated from the Posta Lubrano and Rotaro volcanic vents, respectively. The Cretaio Pyroclastics (dated between the 1st century b.C and the 1st century A.D.) is the product of the highest magnitude eruption in the past 10 ka. Toward the east the Cafieri pyroclastic- current beds overly a paleosoil dated 6th-5th century BC (P, Fig. 9), which develops above the S. Alessandro Lavas. These lavas are the lowermost unit of the volcanic succession exposed up to Ischia Porto. The top of this sequence is composed of a pyroclastic deposit, the Bosco dei Conti Tephra (G, Fig. 9), originated by the Montagnone volcanic complex (de Vita et al., 2010).

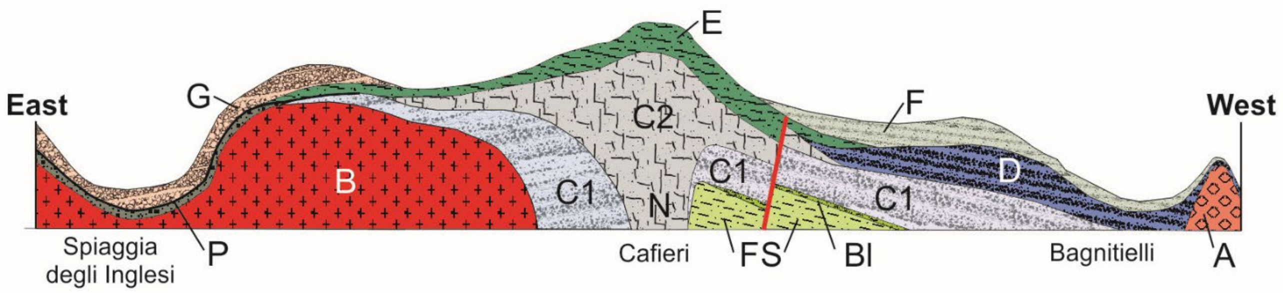

Fig. 9 - Sketch of the coast between Bagnitielli and Spiaggia degli Inglesi (modified after de Vita et al., 2010). A = Castiglione Lavas and Bagnitielli Dyke, B = San Alessandro Lavas, C1-C2 = Cafieri eruptive centre, D = Posta Lubrano Tephra, E = Cretaio Pyroclastics, F = Bosco della Maddalena Tephra, G = Bosco dei Conti Tephra, P = Paleosol dated 6th-5th century b.C., FS = Fossiliferous Siltstones, Bl = Beach deposit dated 8th century b.C.

The harbour of Ischia is a volcanic crater (Fig. 10b, c), formed during an explosive eruption occurred in the 5th century BC (the Ischia Porto eruption; de Vita et al., 2013). Originally it was a crater lake, separated from the sea by an isthmus of land, which was removed in 1854 by order of the king of the Two Sicilies Ferdinand II, to create the currently active harbour structure. The eruption was very low energetic and fed by a small volume of magma. It was characterized by the alternation of phreatomagmatic and magmatic phases, which produced dilute and turbulent pyroclastic density currents, and Strombolian scoria fallout deposits (Fig. 10a), dispersed in a radius of a few hundred meters around the crater.

To the west of the harbour entrance, welded scoria layers (SCP, Fig. 10b), belonging to the Ischia Porto eruption, overly the La Quercia lava flow (LQ; Fig. 10b), erupted during the early stages of formation of the Montagnone volcanic complex. To the east of the harbour entrance the small hill of S. Pietro is made of two superimposed lava flows, older than the Ischia Porto eruption: the S. Ciro Lavas (SC, Fig. 10b) at the base and the S. Pietro Lavas (SP, Fig. 10b) at the top. The first lava flow was emitted by a vent morphologically recognizable to the South of the harbour, the second one was likely a viscous lava body extruded locally. At the top of the S. Pietro hill, the remnants of building materials, related to the construction of a temple, were found. As reported by the Strabo's historical chronicles, the construction was abandoned between 474 and 466 BC by the Greek garrison of Syracuse due to the violent earthquakes that preceded the Ischia Porto eruption (Buchner, 1986; de Vita et al., 2013).

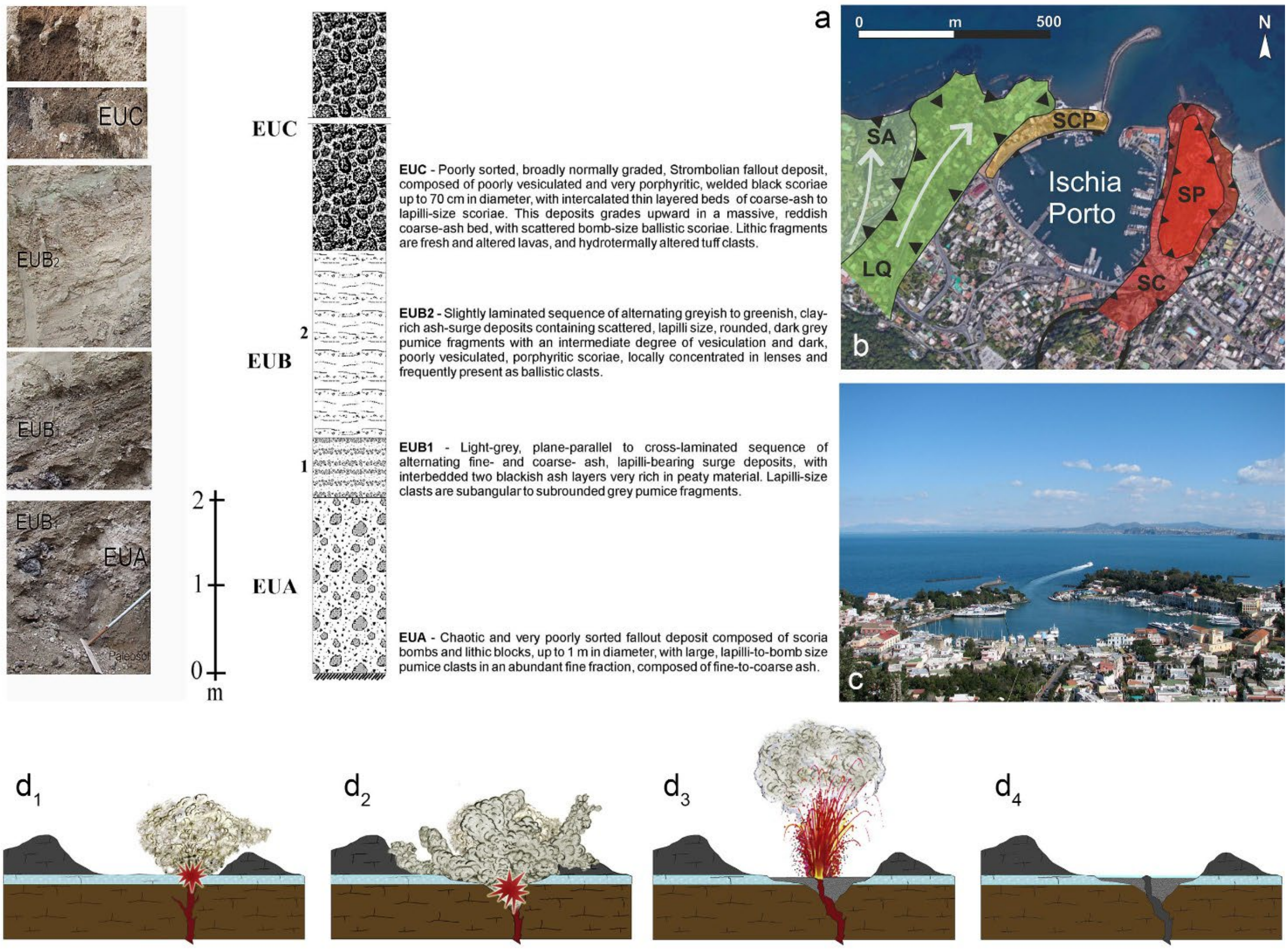

Fig. 10 - Ischia Porto eruption (5th century BC; modified after de Vita et al., 2013). a) Description and pictures of type section; b) area morphology sketch map: SA = S. Alessandro Lavas, LQ = La Quercia Lavas, SCP = Ischia Porto welded Scoriae, SC = S. Ciro Lavas, SP = S. Pietro Lavas; c) view of the harbour from Montagnone hill. Eruption history: d1) opening phase; d2) main phreatomagmatic phase; d3) strombolian phase; d4) emplacement of the lava plug within the crater.

The volcanic edifice at SW of Ischia Porto, well visible when approaching the harbour by sea, is the Montagnone-Maschiata volcanic complex.

Stop 1.3 – From Punta Molina to Carta Romana

Sailing toward East, at Punta Molina the flow-front of the Arso Lavas is exposed along the shoreline. These lavas are the product of the last eruption occurred on the island in 1302 A.D. (fig. 11).

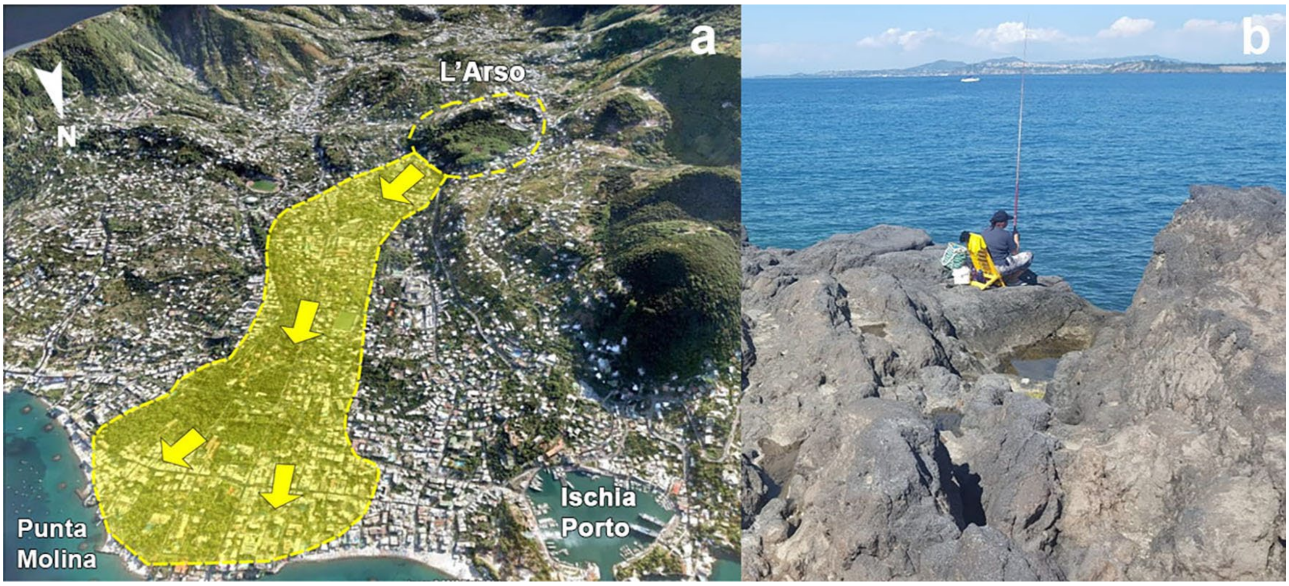

Fig. 11 - Limits and flow directions (a) of the lava flow emitted during the L'Arso eruption (1302 A.D). Arso Lavas outcrops at Punta Molina (b) with Procida island and Campi Flegrei in the background.

Rounded Punta Molina the view is caught by the Castello d'Ischia lava dome, place of a suggestive Aragonese castle (fig. 12). This lava dome is one of the older volcanic products of the island (dated ~ 130 ka). The interpretation of this edifice is controversial, as some authors classified it as a welded-scoriae cone (Rittmann and Gottini, 1980; Sbrana and Toccaceli, 2011). A NE-SW trending fault exposes the inner structure of the edifice, characterized by flow foliation or strata of welded scoriae, depending on the given interpretation. The lava body is overlain by several pyroclastic deposits, belonging to explosive activity occurred between 73 and 59 ka (Sbrana and Toccaceli, 2011. At least three paleosols are well visible.

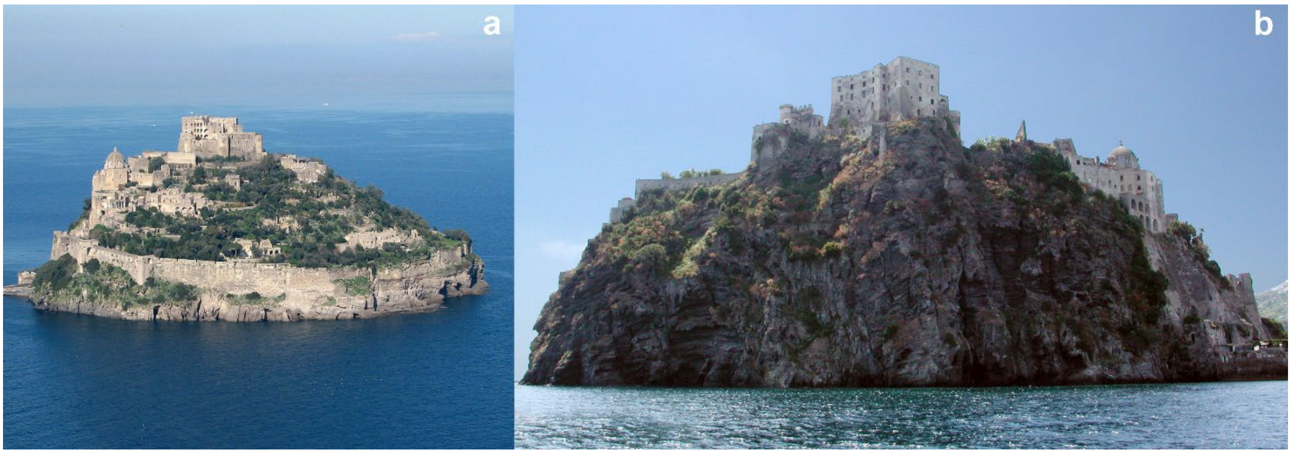

Fig. 12 - Views from South (a) and North (b) of Ischia Castle Lava Dome (~ 130 ka).

The coast of S. Anna, to the weast and south-west of Castello d'Ischia, is composed of a sequence of scoriaceous lava flows (S. Anna Lavas, 23 ka) likely erupted on land. At Carta Romana these lavas cover a sequence of pyroclastic-fallout and -current deposits (Carta Romana Pyroclastics), alternated with several paleosols, belonging to the Ancient Ischia Synthem (~ 100 ka; Sbrana and

Toccaceli, 2011). The S. Anna Lavas are overlain by the Piano Liguori Pyroclastics (5.5 ka; Orsi et al., 1996), which are a sequence of fine ash and pumice lapilli pyroclastic surges, produced by a phreatomagmatic eruption in Neolithic times. In all the Carta Romana area numerous submarine thermal springs are present. These springs were well known also to Romans which founded in this area the settlement of Aenaria, with villas, thermal pools and industrial activities. Nowadays the rests of this settlement are located at 5-7 metres below the sea level.

Stop 1.4 – From Grotta del Mago to Punta San Pancrazio

The coast from Carta Romana to Punta della Pisciazza shows a complex pyroclastic sequence with interbedded lava flows which is composed of Carta Romana Pyroclastics at the base and Casa Mormile and Piano Liguori Pyroclastics at the top. Doubled Punta della Pisciazza, the base of the exposed sequence is composed of lavas dated at 73 ka (Lave di Parata, Vezzoli, 1988).

At Grotta del Mago, a deep natural cave consisting of several chambers of various size, the following sequence is shown (fig. 13): Lave di Parata (A, fig. 13) at the base, mantled by the plinian pyroclastic fallout and flow complex sequence of Formazione di Pignatiello (B, fig. 13) which is an important regional theprostratigrapich marker. The sequence continues with the Plinian pyroclastic-fallout and -surge deposit of Secca d'Ischia (C, 61 ka; fig. 13), which likely was emitted by a vent now located into the sea between Ischia and Procida island. At the top the Piano Liguori Pyroclastics (E, fig. 13) close the sequence. In correspondence of the cave the darkish deposits of Grotta del Mago scoria cone (D, 28 ka; fig. 13) are well visible, as well as its feeding dyke that lies along a NW-SE trending eruptive fracture.

Fig. 13 - Grotta del Mago succession (dotted lines = limits between volcanic units). A = Lave di Parata (73 ka), B = Formazione di Pignatiello, C = Secca d'Ischia Pyroclastics (61 ka), D = Grotta del Mago Scoria (28 ka), E = Piano Liguori Pyroclastics (5.5 ka).

At Punta San Pancrazio the homonymous greyish-black lavas are exposed, likely representing a portion of an eroded lava dome, originated a little further to the south (Sbrana and Toccaceli, 2011).

Stop 1.5 – From Punta San Pancrazio to Punta della Signora

From the western edge of Punta San Pancrazio towards west, the scene is morphologically dominated by Mt. Vezzi (Fig. 14) and, in correspondence of the San Pancrazio Beach, the sequence of the exposed deposits is characterized, at the base, by the yellowish, highly fractured, pyroclastic-current deposits of the Upper Member of Scarrupata di Barano Tuffs (A, Fig. 14). These tuffs are the remnants of a series of old (>150 ka) volcanic edifices (tuff-cones) that form the backbone of the south-eastern part of the island, built during an intense early magmatic and hydromagmatic activity. They are covered by the greyish-black scoria spatters of Mt. Vezzi (B, 126 ka; Fig. 14) representing the product of lava fountaining along eruptive fractures in the south-eastern sector of Ischia.

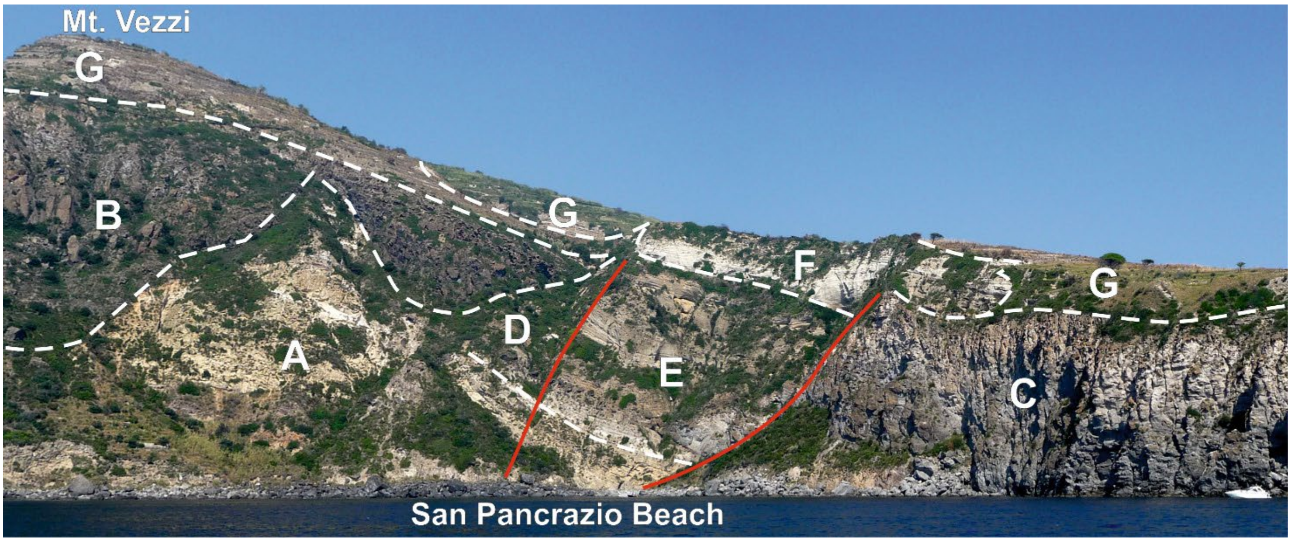

Fig. 14 - The San Pancrazio beach succession (dotted white lines = limits between volcanic units; red lines = faults). A = Upper Member of Scarrupata di Barano Tuffs (>150 ka), B = Mt. Vezzi welded scoria (126 ka), C = Punta San Pancrazio Lavas, D = Lower Member of Formazione di Pignatiello, E = San Pancrazio Beach Tuffs, F = Lower Member of Secca d'Ischia Pyroclastics (61 ka), G = Piano Liguori Pyroclastics (5.5 ka).

The high cliff of Scarrupata di Barano shows at base the complete sequence of the Scarrupata di Barano Tuffs, which reaches a thickness of more than 100 m. At the western edge of the bay, the 220 m thick deposit of La Guardiola Lavas is made of darkish lavas and scoria beds, produced by low-energy Strombolian explosions and lava fountaining activity. It is mantled by the Piano Liguori Pyroclastics (5.5 ka).

Towards west the Scarrupata di Barano is separated from the Maronti beach by the Punta della Signora and Capo Grosso promontories. At Punta della Signora, a 50 m thick sequence of welded spatters (Fig. 15, A; Punta della Signora Spatters, 147 ka) crops out at the base. The spatters are overlain by the deposits of the Scarrupata di Barano Tuffs and the Lower Member of Secca d'Ischia Pyroclastics (C, Fig. 15). Monte Cotto Tuffs (D, 38 ka; Fig. 15) and Piano Liguori Pyroclastics (E, Fig. 15) close the sequence at the top. Between Punta della Signora and Capo Grosso a N-S trending vertical fault defines the contact between the oldest dated deposits of Punta della Signora Spatters (A; 147 ka, Fig. 15; Vezzoli, 1988) and the Capo Grosso welded Scoriae (B, Fig. 15).

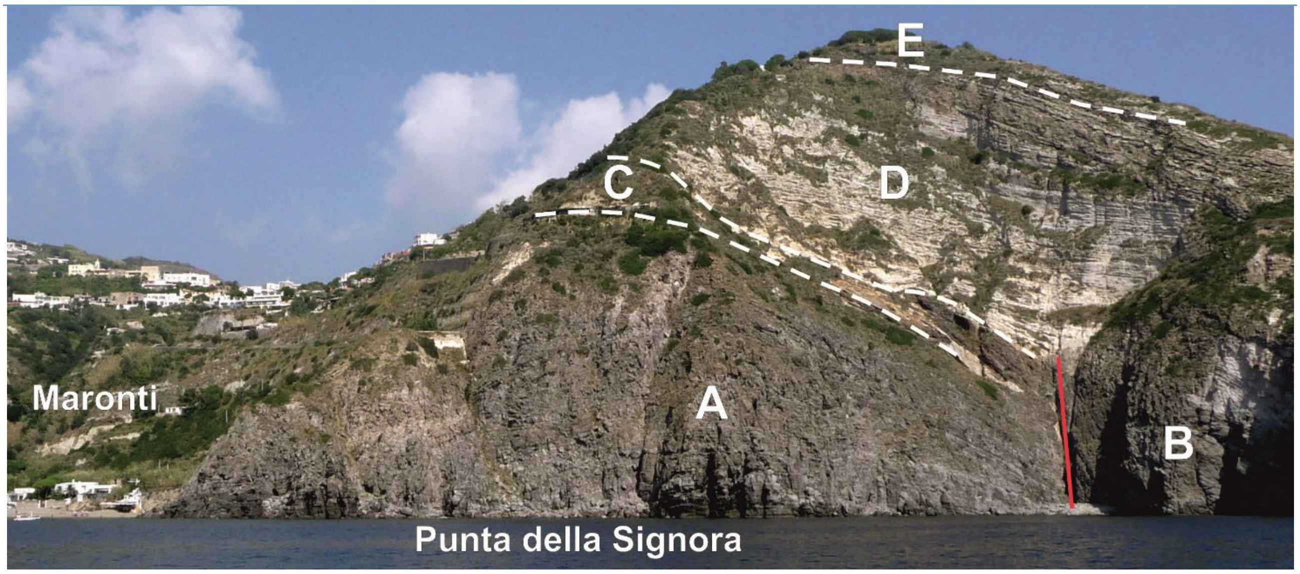

Fig. 15 - Punta della Signora sequence (dotted white lines = limits between volcanic units; red line = fault). A = Punta della Signora Spatters (147 ka), B = Capo Grosso welded Scoria, C = Scarrupata di Barano Tuffs + Lower Member of Secca d'Ischia Pyroclastics (61 ka), D = Monte Cotto Tuffs (38 ka), E = Piano Liguori Pyroclastics (5.5 ka).

Stop 1.6 Maronti beach and Mt. Epomeo southern slope

The Maronti beach was the widest beach of the Ischia island in the past. Nowadays, due to the shore erosion and the anthropic activity, its extents are strongly reduced. Along the beach numerous thermal springs are noticeable, whereas in the western side, close to S. Angelo, some high temperature fumaroles (~100°C) are known. The deposits outcropping at the base of Mt. Epomeo southern slope are mainly debris-avalanche deposits containing heterometric greenish to light-grey blocks of hydrotermalized tuffs and epiclastic deposits due to the reworking of intra-calderic deposits during the uplift of Mt. Epomeo block. Subordinate debris-flow deposits, produced by the remobilization of the aforesaid deposits, outcrop in the same area. Along the slope of Mt. Epomeo at least three orders of marine terraces can be viewed. They represent different phases of uplift of the resurgent Mt. Epomeo block.

In the submerged counterpart of this basin, an extensive long-range side scan sonar survey, evidenced the presence of a huge debris avalanche deposit. The so-called "Ischia Debris Avalanche - IDA" has been recognized as the largest event of this type described at Ischia (Chiocci and de Alteriis, 2006; de Alteriis and Violante, 2009; Fig. 16), covering an area of 250-300 km^2, extending from the foot of the submarine escarpment (-550 m to -1100 m and with a runout of 50 km). Tibaldi and Vezzoli (1998, 2004) associated the avalanche events to the recurrent collapse of the southern flank of Mount Epomeo, due to phases of acceleration of the resurgence (uplift rates up to 3 cm/yr), and identified three main mechanisms that may have contributed to an intermittent increase of the shear stress along the slopes in the last 33 ka: i) the uplift driven by the rising of magma which produces an increase in the static load; ii) the fault-associated tilting; iii) the earthquake shaking.

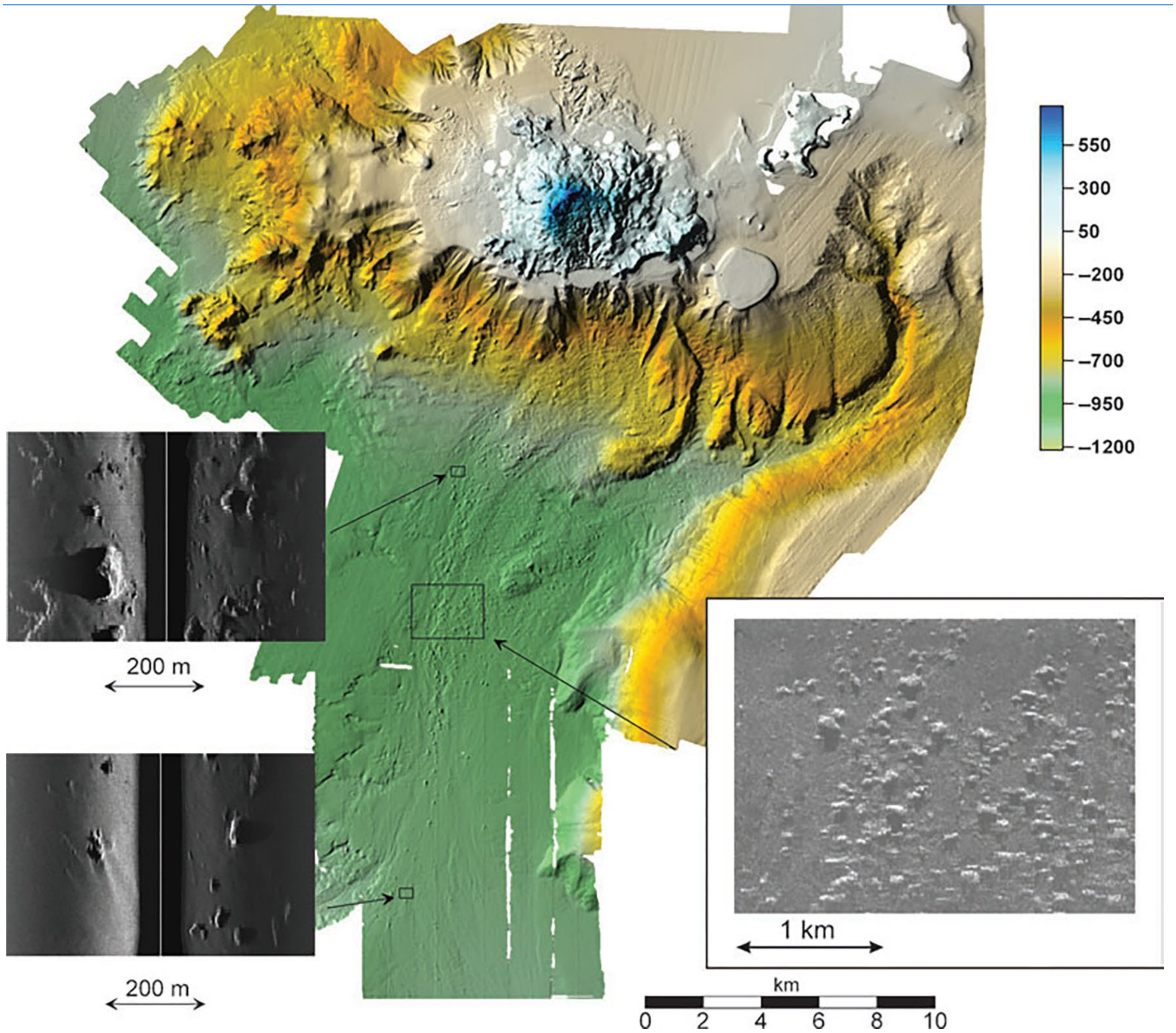

Fig. 16 – Digital Terrain Model of Ischia offshore. The multibeam surveys denoted the presence of hundred metres large blocks at about 18 km from the source area (low frequency side scan sonar image in the box) and at 950 m depth (modified after De Alteris et al., 2009).

Due to contrasting stratigraphic evidence and age determinations, the volume, timing and dynamics of emplacement of IDA (single event or multi-event) are still uncertain.

Stop 1.7 - Sant'Angelo and Sorgeto

The western end of the Maronti beach is defined by the small promontory of Sant'Angelo. It is connected to the coast through a narrow isthmus and hosts the ruins of an Aragonese tower at its top. The Sant'Angelo promontory is the remnant of a lava dome, which was truncated by an E-W trending fault that lowered the northern side of the dome. This is in turn mantled by a pyroclastic sequence (Fig. 17). At the base of the sequence the Mt. Sant'Angelo scoriaceous grey lavas (A, ~100 ka, Fig. 17; Vezzoli, 1988) are exposed. They are overlain by the Elephant Pyroclastics (~97 ka; Sbrana and Toccaceli, 2011) that lies above a marine erosional surface. The Elephant Pyroclastics are a succession of pumice-fallout beds and fine-graded pyroclastic-current layers (B, Fig. 17). The sequence continues to the top with a lithic-rich breccia deposit (C, Punta Sant'Angelo Breccia; Fig. 17), which has been considered in the past the basal breccia of the Mt. Epomeo Green Tuff eruption.

The San Michele Tuffs, a hydromagmatic deposit likely originated from a tuff cone located in the offshore south of Maronti, and the overlying Sant'Angelo Tuffs (E, ~20 ka; Fig. 17) close the sequence. The Sant'Angelo Tuffs are a thinly stratified succession composed of a basal yellowish tuff breccia, overlain by pyroclastic surge beds with bomb-sags, ash and pumice lapilli fallout layers, massive coarse pyroclastic density current deposits and an upper pumice- and scoria-bomb fallout deposit at the top. These tuffs outcrop along the coast between Sant'Angelo and Punta Chiarito and represent the product of a tuff-cone forming eruption, whose vent was likely located originated from a tuff cone located in the near offshore to the south-east of Punta Chiarito in the sea, as also evidenced by bathymetric data (Sbrana and Toccaceli, 2011).

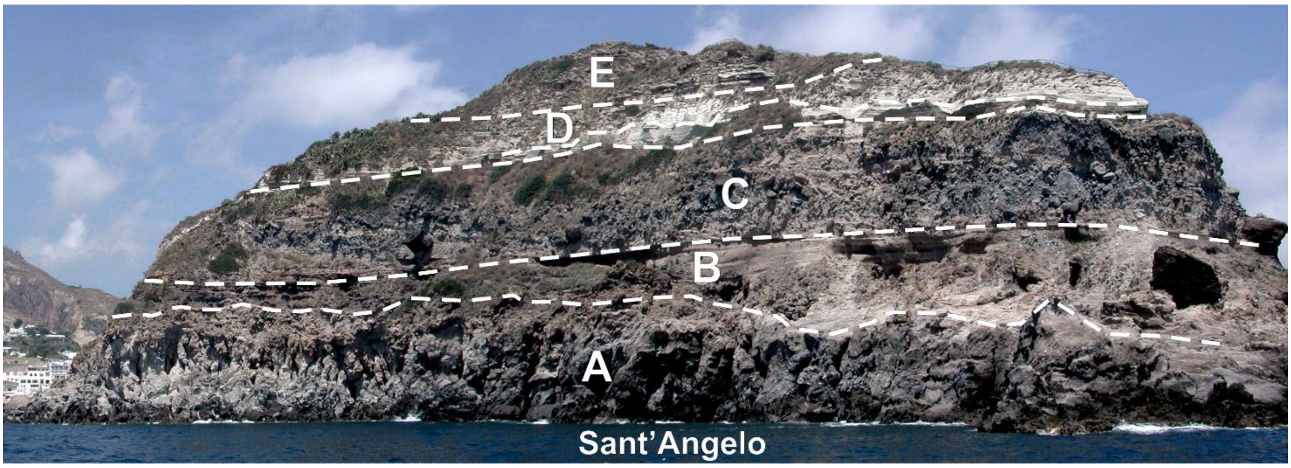

Fig. 17 – S-E view of Sant'Angelo promontory (dotted lines = limits between volcanic units). A = Mt. Sant'Angelo Lavas (~100 ka), B = Elephant Pyroclastics (~ 97 ka), C = Punta Sant'Angelo Breccia, D = San Michele Tuffs, E = Sant'Angelo Tuffs (~20 ka).

The coast from Sant'Angelo to Punta Chiarito is characterized by a 50 m high cliffs with hanging valleys, cut within the Sant'Angelo Tuffs deposits.

A picture of Baia di Sorgeto, whose hydrothermal springs (80-90°C) at sea level give the opportunity to swim also in winter time, is reported in Fig. 18. In the eastern part of the bay, the highly fractured Punta Chiarito Lavas (A, Fig. 18) are part of a lava dome cut by a fault, which lowered its northern side. The lavas are overlain by the Sant'Angelo Tuffs (G, Fig. 18) and by patches of a mud-flow deposit (H, Fig. 18), widely distributed in the Succhivo area. This mud-flow deposit also overlies the pyroclastic deposit of Punta Chiarito Thepra, which buried a Greek settlement of the 8^{th}-7th century B.C., as it was evidenced in the archaeological excavations on the top of Punta Chiarito promontory (Gialanella, 1998; de Vita et al., 2006).

In the middle of the bay, a normal fault (red line, Fig. 18) displaces towards south the Sorgeto Tuffs (C, Fig. 18), putting them in contact with the Sant'Angelo Tuffs (G, Fig. 18). The Sorgeto Tuffs are a succession of hydromagmatic pyroclastic-fall and -flow deposits, belonging to the Ancient Ischia Synthem (Sbrana and Toccaceli, 2011). Along this fault the hyperthermal spring of Sorgeto emerges with its chlorinated-alkaline waters.

In the western part of the Sorgeto bay the altered and highly fractured lavas of Capo Negro (B, Fig. 18) are at the base of the succession. The lavas are overlain by the Sorgeto Tuffs (C, Fig. 18) and by the Cava Pelara Pyroclastics (D, Fig. 18), a succession of spatter- and breccia- fallout deposit, capped by yellowish stratified tuffs at the top.

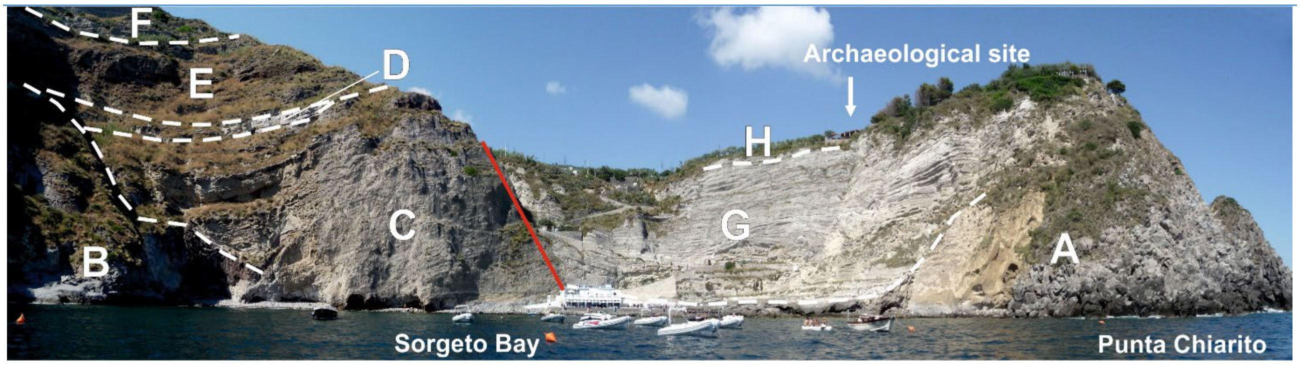

Fig. 18 - Sorgeto Bay (dotted white lines = limits between volcanic units; red line = fault). A = Punta Chiarito Lavas, B = Capo Negro Lavas, C = Sorgeto Tuffs, D = Cava Pelara Pyroclastics, E = Scarrupo di Panza Pyroclastics, F = Russo Pyroclastics, G = Sant'Angelo Tuffs (~20 ka), H = mud Flow. The archaeological site hosts the rests of a Greek settlement dated VIII-VII century BC which was buried by the deposits of Punta Chiarito eruption.

The sequence continues towards the top with the Scarrupo di Panza Pyroclastics (E, Fig. 18), consisting of reddish to dark-grey scoriaceous lapilli-fallout deposit, which likely originated from a vent located in the sea close to La Nave rock. The Russo Pyroclastics (F, Fig. 18) closes the sequence. This deposit consists of a succession of grey pumice-fallout beds, related to three Plinian eruptions, produced by vents located in the offshore of Punta Imperatore (Sbrana and Toccaceli, 2011).

Stop 1.8 – From Capo Negro to Punta Imperatore

Towards west the coast beyond Capo Negro is dominated by the units belonging to the Campotese Subsynthem (Sbrana and Toccaceli, 2011), with the darkish scoriaceous lavas of Pilaro, whose thickness reaches about 100 m, outcropping at the base of the exposed sequence. These lavas are overlain by the Scarrupo di Panza and Russo Pyroclastics, up to Grotta del Mavone, where a normal fault lowered towards west the Pilaro Lavas and put them in contact with a small lava flow (Rosicariello Lavas). At Grotta del Mavone the highly porphyric homonymous lavas (A, ~29 ka, Fig. 19; Vezzoli, 1988) are at the base of the succession that ends at the top with the Scarrupo di Panza Pyroclastics (B1-2, Fig. 19). This last deposit is widely exposed along the cliff up to Punta Imperatore, and the dark welded-scoria beds of the upper member (B2, Fig. 19) thicken in this direction due to the proximity to the emission vent. At Punta dello Schiavo the light-grey lavas of Pomicione lava-dome (C, Fig. 19) cover the Scarrupo di Panza Pyroclastics at the top of the succession.

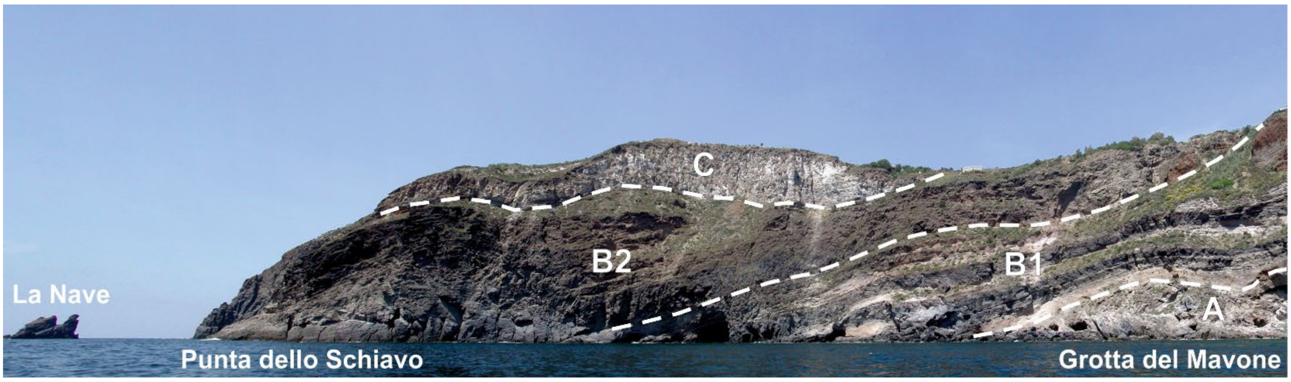

Fig. 19 – Coast between Grotta del Mavone and Punta dello Schiavo (dotted white lines = limits between volcanic units). A = Grotta del Mavone Lavas (~ 29 ka), B (1-2) = Lower Member (1) and Upper Member (2) of Scarrupo di Panza Pyroclastics, C = Pomicione Lavas. La Nave rock represents likely the rests of eruptive centre which originated the Scarrupo di Panza Pyroclastics.

The volcanic sequence at Punta Imperatore is reported in fig. 20. At the base the light-grey Punta Imperatore Lavas (A, ~117 ka; Vezzoli, 1988) are characterized by an erosional marine surface with patches of fossiliferous sands. The sequence continues with different pyroclastic deposits, dated between 98 and 18 ka, separated by paleosols and erosional surfaces. These deposits vary from very proximal breccia and scoria to fine-graded tuffs, and were emitted by local vents and vents located in the Punta Imperatore offshore.

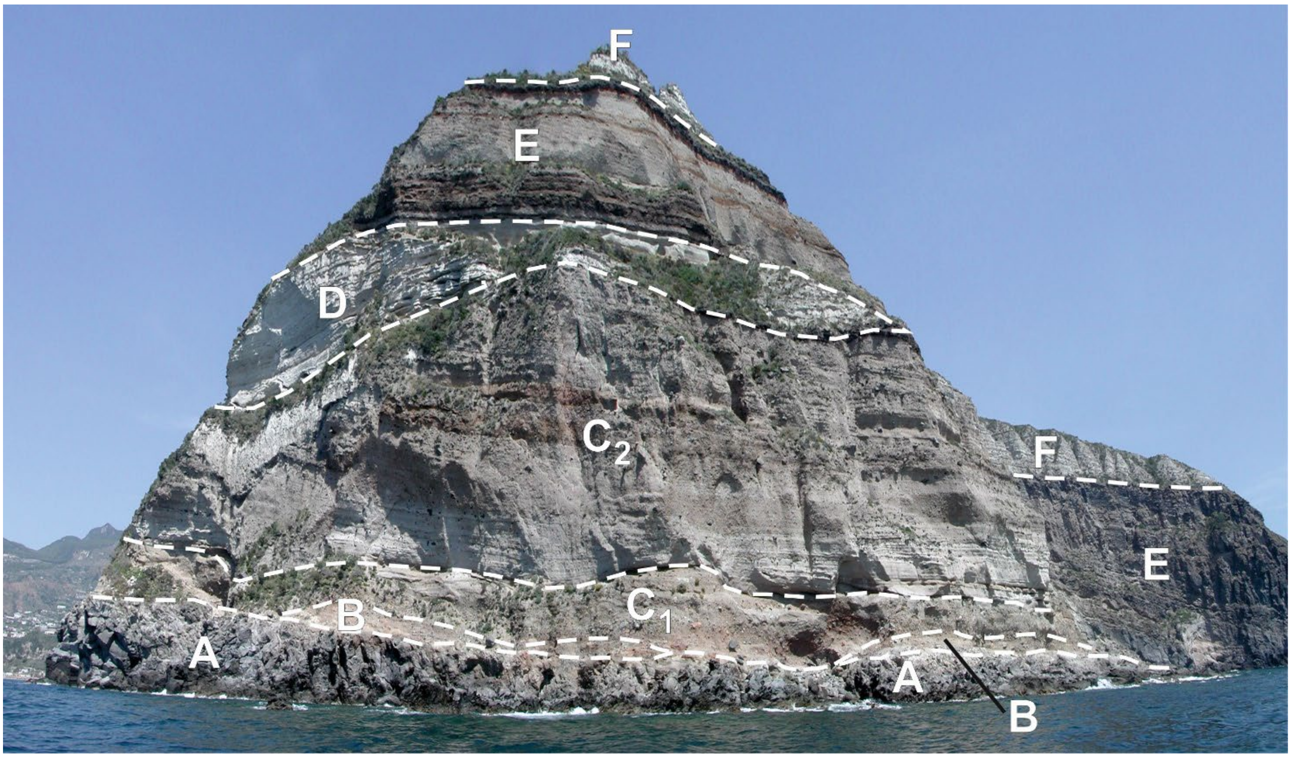

Fig. 20 – Sequence at Punta Imperatore promontory (dotted white lines = limits between volcanic units). A = Punta Imperatore Lavas (~117 ka), B = Elephant Pyroclasts (~97 ka), C = Spiaggia di Agnone Pyroclastics (C1 = lower member, C2 = upper member), D = Citara Tuffs (~45 ka), E = Scarrupo di Panza Pyroclastics, F = Faro Punta Imperatore Pyroclastics (~18 ka).

Stop 1.9 – The Forio area and the western slope of Mt. Epomeo

The coast between Punta Imperatore and Forio is well-known for the Citara beach and its hot-springs, which is the site of one of the most famous thermal park of the island (Fig. 21a). Along the coast, between Punta Imperatore and Pietre Rosse, the Citara Tuffs (~33 ka; Vezzoli, 1988) outcrop, showing high-angle unconformities and paleo-valleys filling, with spectacular slumping structures and soft deformations in the pyroclastic- currents deposits (Fig. 21b).

The Citara Tuffs are a succession of yellowish stratified pyroclastic-current deposits with accretionary lapilli, diffuse cross-bedding structures and bomb sags, which likely were emitted by tuff-cones in the off-shore of Citara. This succession is overlain in the Citara and Forio area by rock-avalanche (4th century B.C.; Della Seta et. al., 2012) and debris-flows deposits (Della Seta et al. 2012; Di Martire et al., 2012) with several hummocks emerging from the sea. Also the coast between Forio and Zaro is dominated by these rock-avalanche deposits with numerous hummocks distributed in the near off-shore of Forio, up to the San Francesco beach.

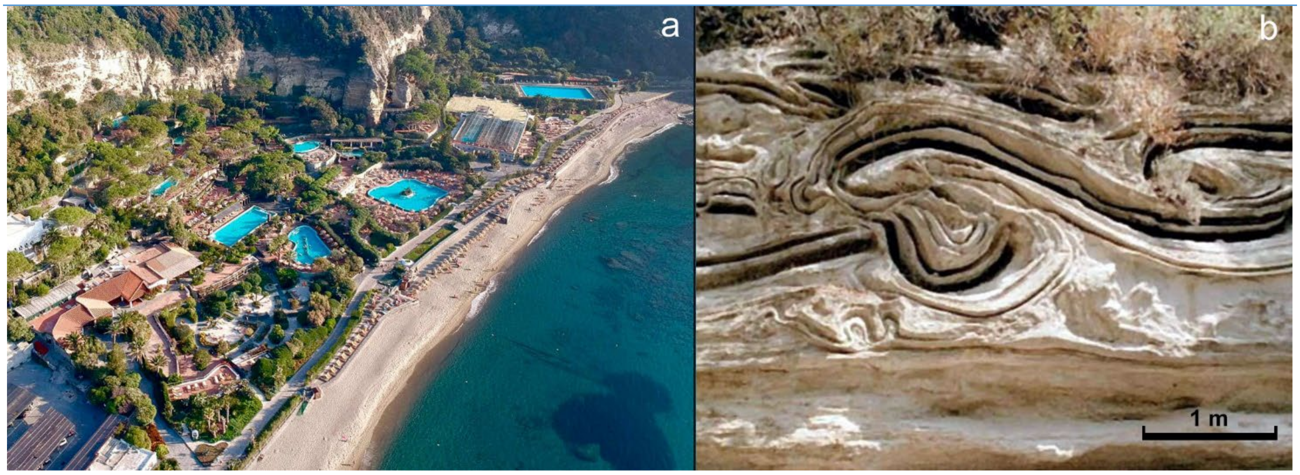

Fig. 21 – Citara beach with Citara Tuffs deposits (~ 33 ka) at the back of the thermal park (a) and spectacular slumping and soft deformation structures in Citara Tuffs pyroclastic currents (b).

The western flank of Mt. Epomeo is clearly visible from this part of the coast, with its steep slopes, generated by high-angle vertical-to-reverse faults related to the resurgence, and the slope-instability related deposits. The Mt. Nuovo DSGSD block is well evident as well in the western part of the landscape, at the foot of the Falanga hanging wall. The morphological evolution of these slopes and the characteristics of the related deposits, will be outlined during the second day of this field trip.

Stop 1.10 – From Zaro promontory to Mt. Vico

The Zaro promontory is a lava field, formed by the products of several effusive and low-energy explosive eruptions that generated lava domes, lava flows and scoria-fallout deposits at around 6 ka (Vezzoli, 1988; Fig. 3). These products were erupted from a fissure-vent area, along NE-SW trending fractures that likely reactivated regional faults, also active during the formation of the caldera and the following resurgence. These faults also mark the limit of the resurgent area in the north-western corner of the caldera (de Vita et al., 2010).

Fig. 22 – Zaro Lavas outcrop (basal flow, ~ 6 ka) at San Francesco beach.

Between Zaro and Mt. Vico the bay of San Montano was the site of the first landing in southern Italy of Greek colonies from Eubea in the 8th century BC. The Greek colony of Pithekoussai included an *acropolis*, on top of Mt. Vico, a *necropolis* with more than 2,000 graves in the San Montano valley, and a *chora* that likely extended from Mezzavia (between Lacco Ameno and Forio) to the southern coast of the island.

The Mt. Vico promontory, east of San Montano Bay, is a lava dome (A, 75 ka, Fig. 23; Vezzoli, 1988) displaced by NW-SE and NE-SW trending faults, which are the site of fumarole activity and several hot thermal springs. The lava dome is overlain by a sequence of pyroclastic deposits composed of pumice lapilli beds (Pignatiello Formation; B, Fig. 23), a breccia belonging to the Porticello formation (C, Fig. 23), a stratified succession of whitish fine ash and pumice beds belonging to the Secca d'Ischia Pyroclastics (D, Fig. 23) (Sbrana and Toccaceli, 2011). At the top of the sequence a stratified ash- and pumice lapilli-deposit has been correlated to the Cretaio Tephra (E, Fig. 23), which is the deposit of the highest-magnitude eruption occurred during the past 10 ka, from a vent located in the eastern part of the island (1st century BC – 1st century AD; Orsi et al., 1992).

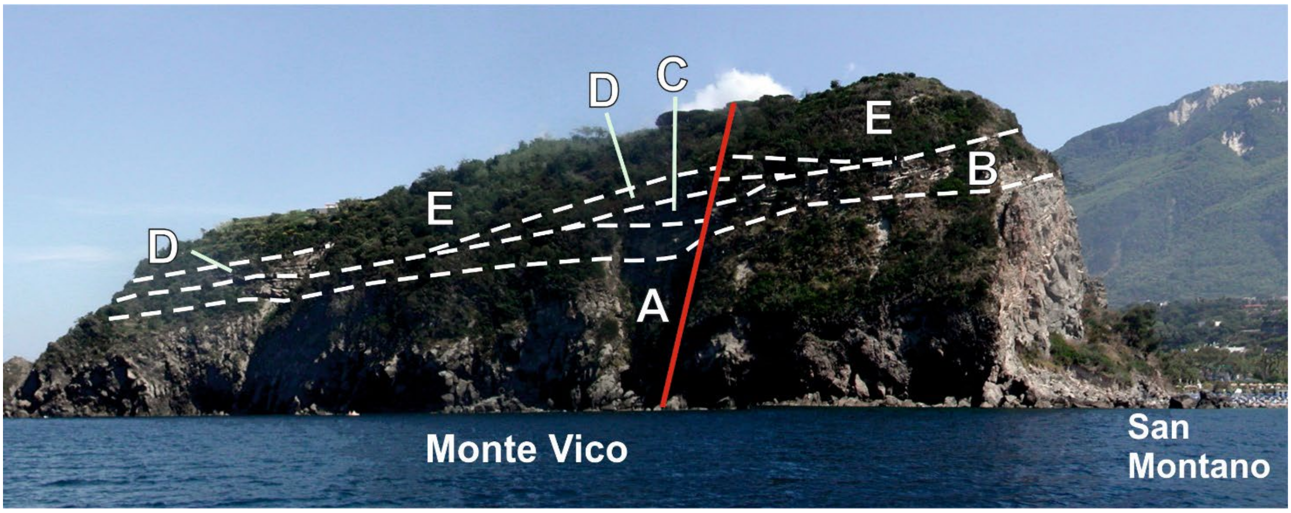

Fig. 23 – Northern slope of Mt. Vico (dotted white lines = limits between volcanic units; red line = fault). From base to top: A = Mt. Vico Lavas (75 ka), B = Pignatiello Formation, C = Il Porticello Breccia, D = Secca d'Ischia Pyroclastics, E = Cretaio Tephra (1st century BC – 1st century AD).

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