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Review

Quaternary Evolution of Ischia: A Review of Volcanology and Geology

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Abstract: Ischia shows intriguing and complex geology, which has been deeply investigated. In this paper, a reappraisal of the Quaternary geologic evolution of Ischia based on literature data is advised, concentrating on the volcanology of the island, based on field data and geochemistry, due to the happening of active fumarolic systems on the island and the marine geology and geophysics, which are intensively studied in the frame of the CARG Project. The literature studies have been incorporated with the geological interpretation of high-resolution seismic profiles, partly previously published and herein reorganized with the aim to highlight the geologic evolution of the different sectors of the island (northern Ischia, southern Ischia). The outcrop data have shown the deposits of ten explosive eruptions: among them, we focused on the S. Angelo Tephra. The laccolith model has been described in order to explain the resurgence of Ischia starting from 55 ky B.P. Geochemical information has been synthesized to reconstruct the volcano-tectonic development of Ischia during the last 55 ky B.P. Different models of block resurgence of Ischia have been discussed, based on literature studies. These aspects have supplemented the Quaternary geologic evolution of Ischia. While the northern Ischia offshore shows complex stratigraphic relationships between buried volcanic edifices, the southern Ischia offshore has been mainly commanded by erosional activities, progressive next to a dense system of submarine channels, and by the volcano-tectonic activities, which have triggered off the location of the Ischia Debris Avalanche.

Keywords: quaternary geologic evolution; ischia island; Gulf of Naples; volcanology; geochemistry; marine geology; marine geophysics

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1. Introduction

In this thesis, a review of the literature data on Ischia Island is presented, discussing volcanological, geochemical, structural and marine data. The purpose of this paper is to match previous knowledge with key interpreted seismic sections of Ischia, respectively, in the northern and southern offshore of the island aimed at retracing the Quaternary geological development of the island.

The Phlegrean Islands, reckoning Ischia, stand for a physiographic and geographic region stationed between the Gulf of Gaeta in the north and the Gulf of Naples south (Figure 1). The Ischia-Procida-Phlegrean Fields volcanic complex is sited in agreement to an influential structural element, ENE-WSW trending, which has controlled the arrangement of the main eruptive centers. This regional tendency is corroborated by the direction of the submarine topography, shown in Figure 1. This physiographic and geographic region has also created a morphological threshold between the Gulf of Gaeta and the Gulf of Naples (Figure 1).

At Ischia Island, sited in the Gulf of Naples (eastern Tyrrhenian margin, Italy) authoritative volcanological and geochemical works have been held [1–32]. At the same time, structural surveys went on, talking about the relations between the tectonic environment, both at a regional and a local scale, and the caldera resurgence, one natural physical process observed at Ischia [33–53]. Moreover, marine geological studies have used the data collected in the frame of the scientific and technical activities of the CARG Project [54–64]. The sketch geologic map of Ischia displays the main geological units and that the stable sector of the caldera is located between the caldera faults and the normal faults of the margins of Epomeo Mt. [27] (Figure 2).

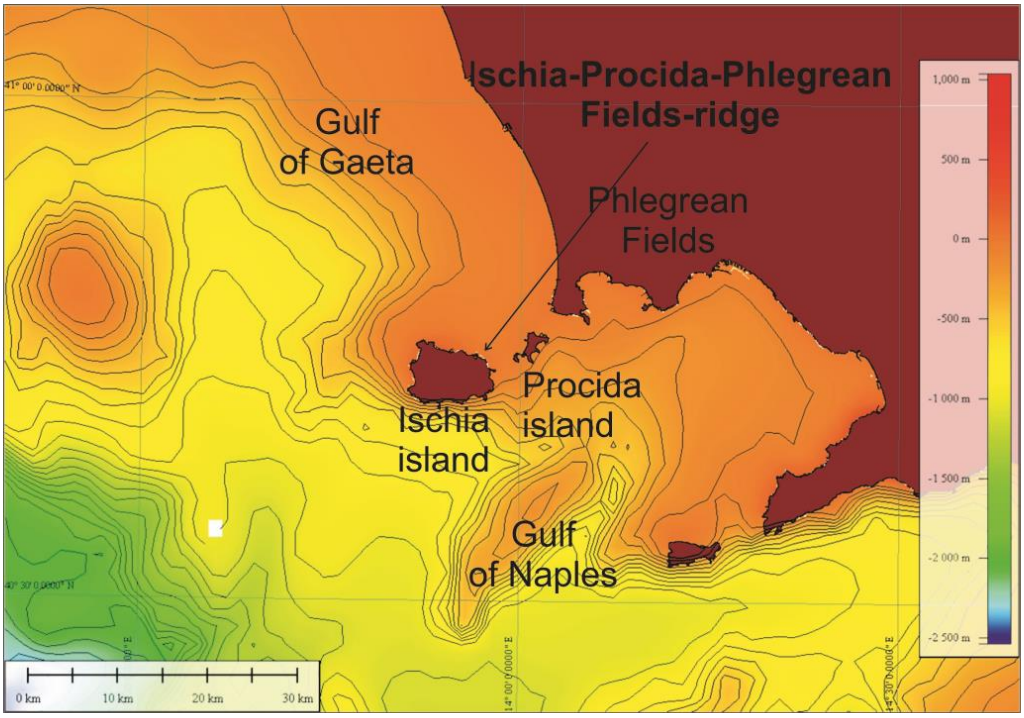

Figure 1. Sketch bathymetric map showing the Ischia-Procida-Phlegrean Fields volcanic complex, which is located over an important ENE-WSW regional structural alignment.

The composite chrono-stratigraphic sequence of Ischia is shown in Figure 2 [27]. From the oldest to the youngest, the main geological units are represented by the Ancient Ischia (Punta Imperatore lavas, marine sands and Punta Imperatore breccias), by the S. Nicola synthem (Parata lavas, Pignatiello pyroclastics, Cava Celario epiclastics, Pizzone tuffs, Frassitelli tuffs, M.te Epomeo Green Tuff, Secca d'Ischia pyroclastics), by the Buceto synthem (Campomanno epiclastics, Cava Leccie marine clays) [27] (Figure 2). These three synthems are overlain by the Ischia Island synthem, which is composed of four sub-synthems (Fontana-Fasano sub-synthem, Campotese sub-synthem, La-Rita Caccaviello sub-synthem including the Debris Avalanches and Ischia Porto sub-synthem) [27] (Figure 2). The Fontana-Fasano sub-synthem is mainly composed of the Citara tuffs. The Campotese sub-synthem is composed of the Scarrupo di Panza welded scoriae, by the Russo pyroclastics, by the S. Angelo Tuffs and by the Faro-Punta Imperatore pyroclastics. The La Rita-Caccaviello sub-synthem is composed of the Trippodi and Costa Sparaina domes, by the Cava del Puzzillo Tuffs and by the Zaro lavas. This sub-synthem is overlain by the Debris Avalanches, representing an important stratigraphic unit of Ischia. Finally, the Ischia Porto sub-synthem is the youngest one and is composed of the Piano Liguori pyroclastics, of the Rotaro pyroclastics and lavas, of the Vateliero pyroclastics, of the Cretaio pyroclastics, of the Montagnone dome, of the Rotaro and Punta della Scrofa lavas and of the Arso lavas and scoriae [27] (Figure 2).

The key volcanological and geochemical papers on Ischia have been analyzed, starting from the paper of Brown et al. [23], which has given a new pyroclastic stratigraphy on Ischia from 75 to 50 ky B.P. and has reviewed the previous stratigraphic studies on Ischia [3,4,7,8]. The first study, which has established the stratigraphic setting of Ischia, has been performed by Vezzoli [8]. The stratigraphy shown in the work of Vezzoli [8] has taken into account stratigraphic studies on south-western and south-eastern sectors of Ischia (Figure 1), including Procida [3,4,7].

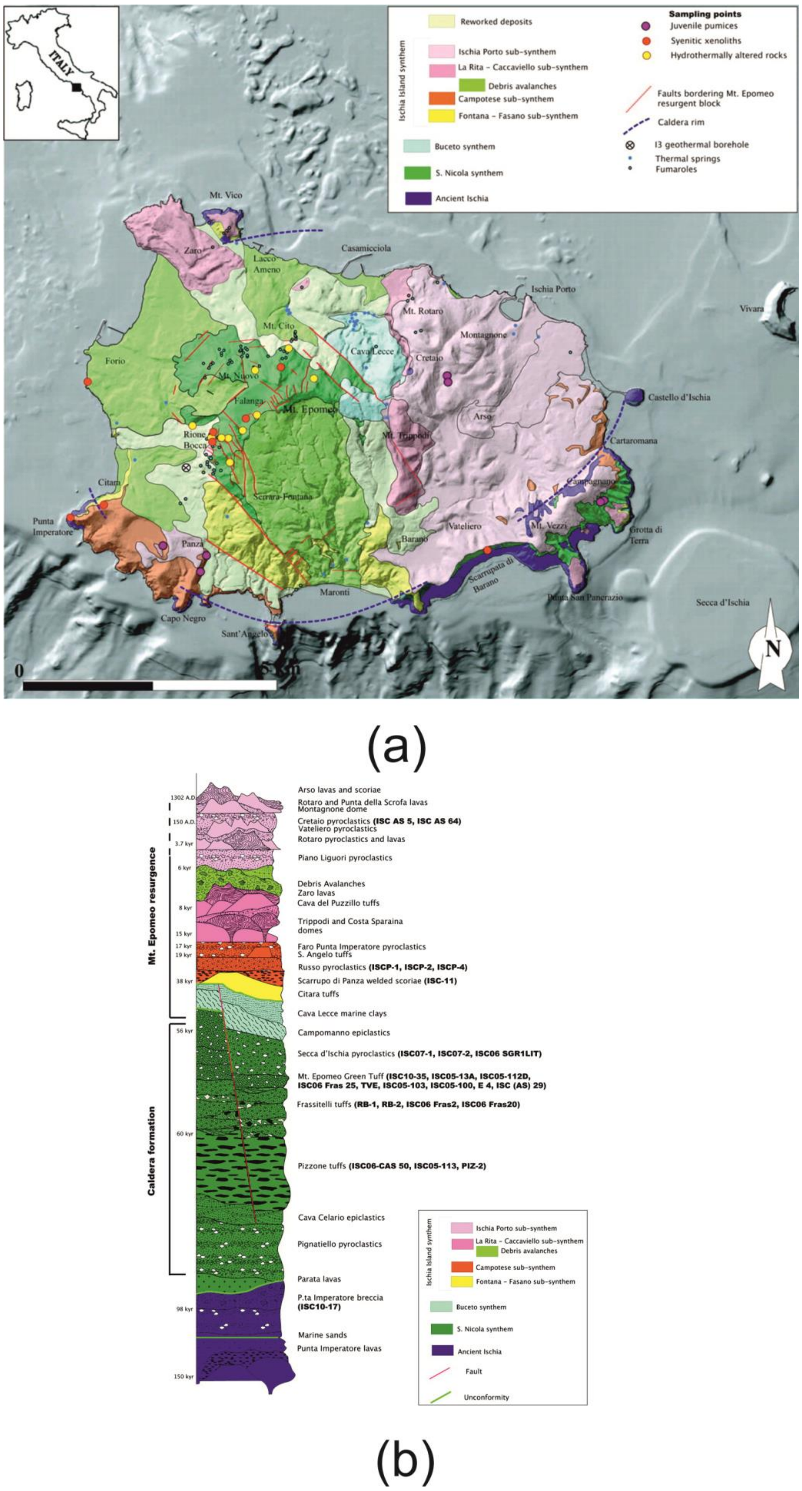

Figure 2. (**a**) Geologic map of Ischia Island; (**b**) composite chrono-stratigraphic sequence of Ischia (modified after [27]).

The S. Angelo Tephra, as defined by Brown et al. [23], correlates with the pumices and the ignimbrites of the M.te S. Angelo volcanic center [8] and with the explosive breccias of the MEGT (UMSA of Rosi et al.) [7]. The Mago, Olummo, Tisichiello and Porticello Tephra fit with the Pignatiello Formation [8]. The Porticello Tephra matches with the "Pomici Pliniane C" [7]. The Chiummano Tephra is an unprecedented pyroclastic unit, antecedently saw as an alluvial deposit [8]. The Schiappone Tephra represents a younger deposit, not directly related to the MEGT. While K/Ar dates of the first tephra are not still available, only K/Ar dates of the Schiappone Tephra have been established and vary between 55,800 +/− 1800 years and 49,000 +/− 1100 years in the southern sectors of the island ("Scarrupata di Barano") [23].

A laccolith model has been proposed in order to explain the process of resurgence during the past 55 ky B.P. [30]. Starting from 55 ky B.P., the stress exerted on the lower crust of Ischia during the resurgence has brought forth an addition of fracturing, coupled with a decrement of the Young modulus of the rocks, which has commanded the magma upheaval [30]. The laccolith bulk increases from 21 km^3 (33 ky B.P.) to the present-day mass, which is larger than 80 km^3. The high intensity (MSC degrees) of historical seismicity may be genetically related to the episodic variations of pressure in the laccolith.

The key geochemical papers on Ischia geochemistry which allow us to recognize different volcanological phases that characterize the volcanic evolution of Ischia Island include Civetta et al. [10], Poli et al. [6] and Crisci et al. [9]. According to Civetta et al. [10], three main volcanological cycles occurred in this volcanic complex during the last 55 ky. The first cycle (55 ky–33 ky, was characterized by trachytes to alkali-trachytes put in place by explosive eruptions. The second cycle (28 ky–18 ky) was characterized by trachy-basalts to alkali-trachytes, when the basaltic magma in the magmatic system transformed it into an open system. The third interval (10 ky–1302 AD) was qualified by latites to alkali-trachytes and by the occurrence of an isotopically-zoned magmatic chamber [10].

Poli et al. [6] have rendered evidence of successive magmatic cycles established on major and trace elements and mineralogical data. The 1st rhythm (prior to 150 ky B.P.) is qualified by alkali-trachyte pyroclastic deposits. The 2nd rhythm (150–75 ky B.P.) establishes alkali-trachyte to phonolite lava domes and secondary pyroclastic deposits. The 3rd round (55–20 ky) is marked by pyroclastic deposits, trachyte and alkali-trachyte in composition. The 4th interval, ranging in age from 10 ky B.P. and 1302 A.D., shows lava flows.

Crisci et al. [9] have distinguished two main volcanic series at Ischia, characterized by the occurrence of strongly evolved rocks, including trachy-basalts and latites. Mixing magma and crystal fractionation processes have been suggested. Two cycles (PRES and POES; Pre-Epomeo series and Post-Epomeo series) and three main magmatic sequences (A, B, C) have been distinguished in the volcanic history of Ischia, separated by the eruption of the Epomeo Mt. Green Tuff (MEGT; 55 ky B.P.).

The structural studies on Ischia have mainly analyzed the tectonic problems related with the caldera resurgence [33–53]. Acocella and Funiciello [48] have drawn the structural attributes of the island in the regional environment, the lower structure of the resurgent block and the fundamental interaction between the regional and the local strengths and the power of the preexisting regional faults during the resurgence.

The north-western body of the island is qualified by structures having a N320° and NE-SW direction. The N320° faults co-occur with the gravimetric anomalies [33,38]. The N-S faults on the eastern slope of the dome coexist with the arrangement of the volcanoes of Costa Sparaina and Trippodi, qualified by gravimetric, magnetic and geochemical anomalies [33,38,53]. NE-SW normal faults concur with the placement of the Zaro vents, while the strike-slip faults on the Zaro lava flow may be caused by the different viscosity of the lava during the flux.

The marine geological studies on Ischia have been mainly performed in the frame of the scientific and technical activities of the CARG Project [54–64]. These surveys mainly centered on the seismo-stratigraphic environs of the Ischia offshore based on the geological reading of high-resolution seismic sections [59,60,64] on the stratigraphic building of the Quaternary marine sediments of Ischia [61] and on the bioclastic deposits of Ischia, including the rhodolith deposits [63]. Sbrana et al. [56] have proposed a preliminary seismo-stratigraphic framework of the Ischia offshore in the explanatory notes to the geological map "Isola di Ischia" at the 1:10.000 scale. This framework has been integrated in the next seismo-stratigraphic papers [59–61,64]. In this paper, the seismo-stratigraphic representation of some seismic sections, recorded in the northern and southern Ischia offshore and previously unpublished, is presented, adding to former geological knowledge.

2. Materials and Methods

The used methods are seismic stratigraphy [65,66], volcano seismic stratigraphy [64,67–69] and the revision of literature. During the last years, seismo-stratigraphic concepts and techniques have been profoundly reorganized [70,71]. The high-resolution sequence stratigraphy of siliciclastic shelves has been retooled [72], allowing for obtaining new results on the control factors of the sequence development, including allocyclic factors (glacio-eustasy, tectonics, climate) and autocyclic factors, which are internal to the depositional systems. The volcano seismic stratigraphy has applied seismo-stratigraphic concepts and methods to the volcanic sequences [67–69].

The Sparker seismic profiles analyzed in this paper have been acquired in the frame of the scientific and technical activities of the CARG project at the 1:10.000 scale of Ischia Island [56] (Figure 3). During the corresponding oceanographic cruise, the Sparker lines have been recorded perpendicularly to the coastline, with some lines oriented parallel to the coast, according to the navigation plan shown in Figure 3. The seismic acquisition has been carried out by using a single-channel system (D-seismic), composed of an EG&G Trigger Capacitor Bank mod. 231 and PSU mod. 232, and of a seismic source SAM96 Sparker, which is more than a receiver. The range of frequencies included in the signal range between 100 and 3000 Hz. The D-seismic gives the spectrum frequencies of the signals in real time with different time windows, both during the acquisition and playback. The navigation fix as reported on the seismic sections has a distance of 550 m. The depths are reported in msec (twt; two-way travel times).

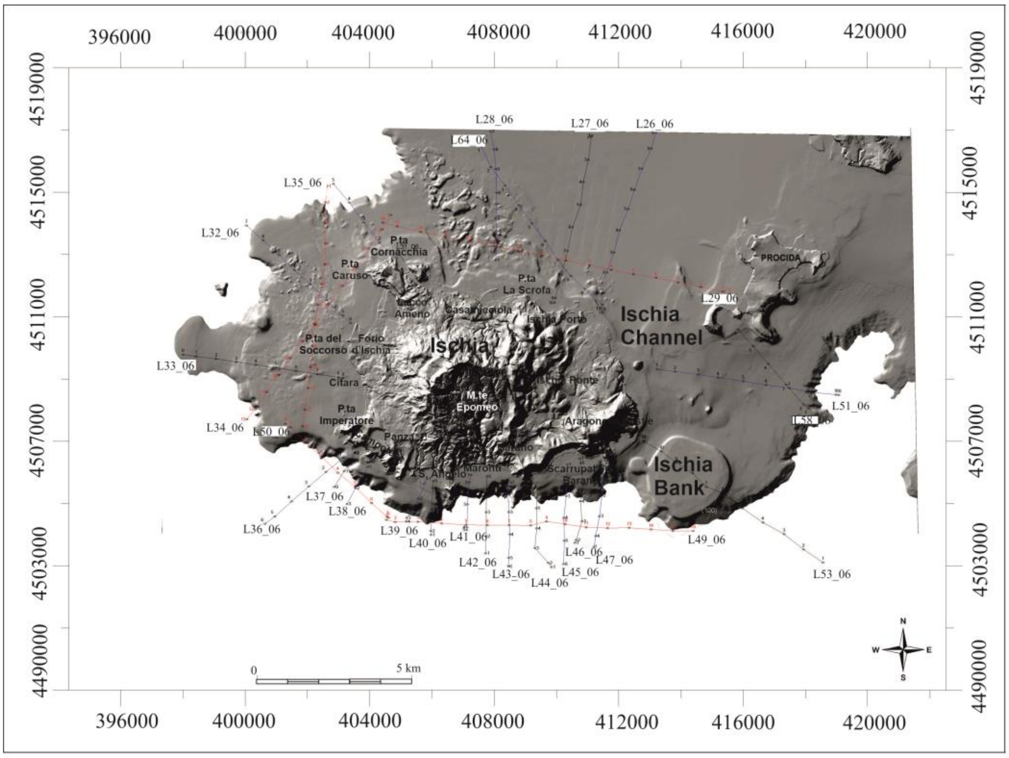

Figure 3. Ischia Digital Elevation Model with the location of the Sparker seismic profiles (modified after Sbrana et al. [56]).

3. Results

The most important literature studies on Ischia have been reviewed, focusing on the different disciplines in the field of earth sciences, and reassessed in the subsections. Moreover, we reconsider and construct interpreted seismic sections, concentrating on the contrasting sectors of the Ischia offshore (northern Ischia seaward, southern Ischia seaward). These data, coupled with literature studies, have allowed delineating the geologic evolution of Ischia during the Quaternary.

3.1. Review of the Volcanology and Geochemistry of Ischia

The volcanology and the geochemistry of Ischia have been deeply studied and are herein reviewed. One of the most important volcanological papers on Ischia is the paper by Brown et al. [23]. These authors have mainly analyzed the outcrops located in the southern sector of the island (Figure 4). The outcrop data have shown that the most crucial eruptions occurred and numerous volcanic edifices were active here. The deposits of ten explosive eruptions, from phonolitic to basaltic and trachyandesitic compositions, have been described and interpreted, recognizing at the same time the pyroclastic deposits of previously unknown eruptions. The discharge of the Monte Epomeo Green Tuff (MEGT) is the most valuable volcanic case, which has controlled the caldera collapse of Ischia Island.

The stratigraphic units foregoing the MEGT activity mainly go on at southern Ischia [23] and regard the S. Angelo Tephra, appearing in the S. Angelo promontory (Figure 4), the Mago Tephra, appearing at the Grotta del Mago (south-eastern Ischia), the Olummo Tephra, unconformably lying the paleosol sited at the top of the Mago Tephra, the Tisichiello Tephra, overlying an unconformity and a paleosol in the Olummo Tephra ad appearing eastwards of the Monte di Vezzi structure, and the Porticello Tephra, at the Procida island ("Pomici pliniane") [7]. The Olummo, Mago, Tisichiello and Porticello units add a portion of the Pignatiello Formation [8].

During the resurgence, Ischia held a flexural uplift, and an advanced fracturing and break with faults of the lower crust (thickness 2 km), with an addition in the volume of the laccolith of at least 80 km^3 [30] (Figure 5). Assorted elastic and viscoelastic performances have allowed us to measure the release modes of the stresses due to the pressurization state of this laccolith. Stress release goes on during tectonic uplift and seismic crises. Great eruptions take place as commanded by the long-term uplift of Epomeo Mt., while small explosive and effusive discharges occurred at the peripheral regions of the resurgent block [30].

Beginning from 55 ky B.P., Ischia experienced a resurgence in a caldera taking shape after an ignimbrite eruption (Epomeo Mt. Green Tuff, MEGT, 55 ky B.P.). The total tectonic uplift, as inferred by the contemporary elevation of marine terraces constituted of Quaternary marine deposits, is about 710 m in the southern sector and about 920–970 m in the northern sector, with a rate of tectonic uplift ranging between 2.3 and 3.3 cm/y [13,17,19].

The resurgence, which has affected the central body of the island, is assorted with the alimentation of new magma at low depths, which, from 28 to 18 ky B.P., has brought forth volcanic deposits with a changeable composition. The most progressive area involved in the resurgence is the Epomeo Mt. block, placed in the central sector of the island. The margins of the block correspond with a system of sub-vertical faults, which are NW-SE, NE-SW and N-S trending. During the last uplift phase, from 8.6 and 5.7 ky B.P., avalanches have been fed by the Epomeo top, as shown by the horseshoe shape of the slide scar with the hummocky deposits stationed to the south of Ischia [20].

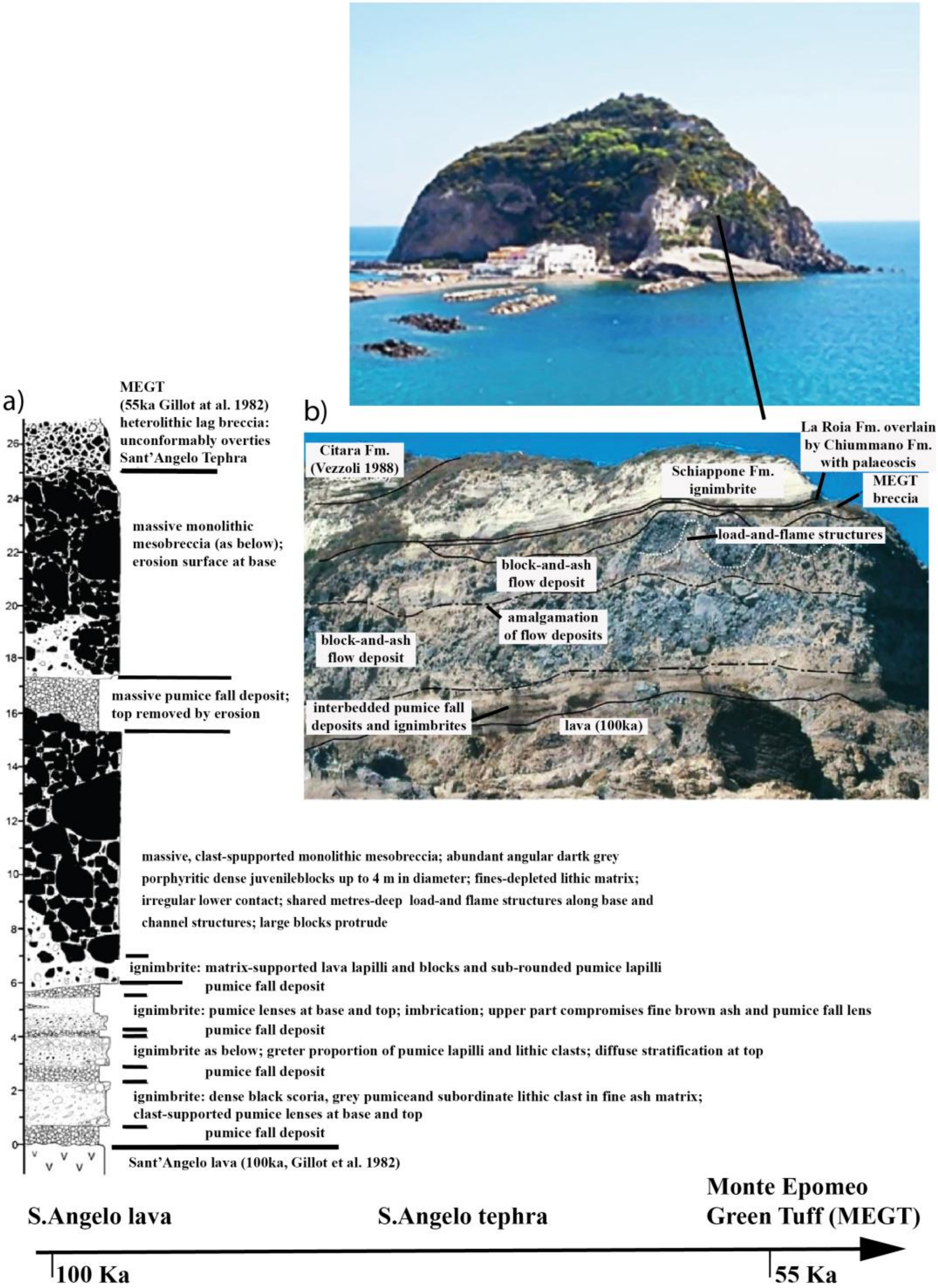

Figure 4. The S. Angelo tephra of Ischia (modified after Brown et al. [23]) (**a**) stratigraphic column of the S. Angelo tephra. (**b**) Interpreted outcrop data showing the stratigraphic relantionships of the tephra and adjacent formations.

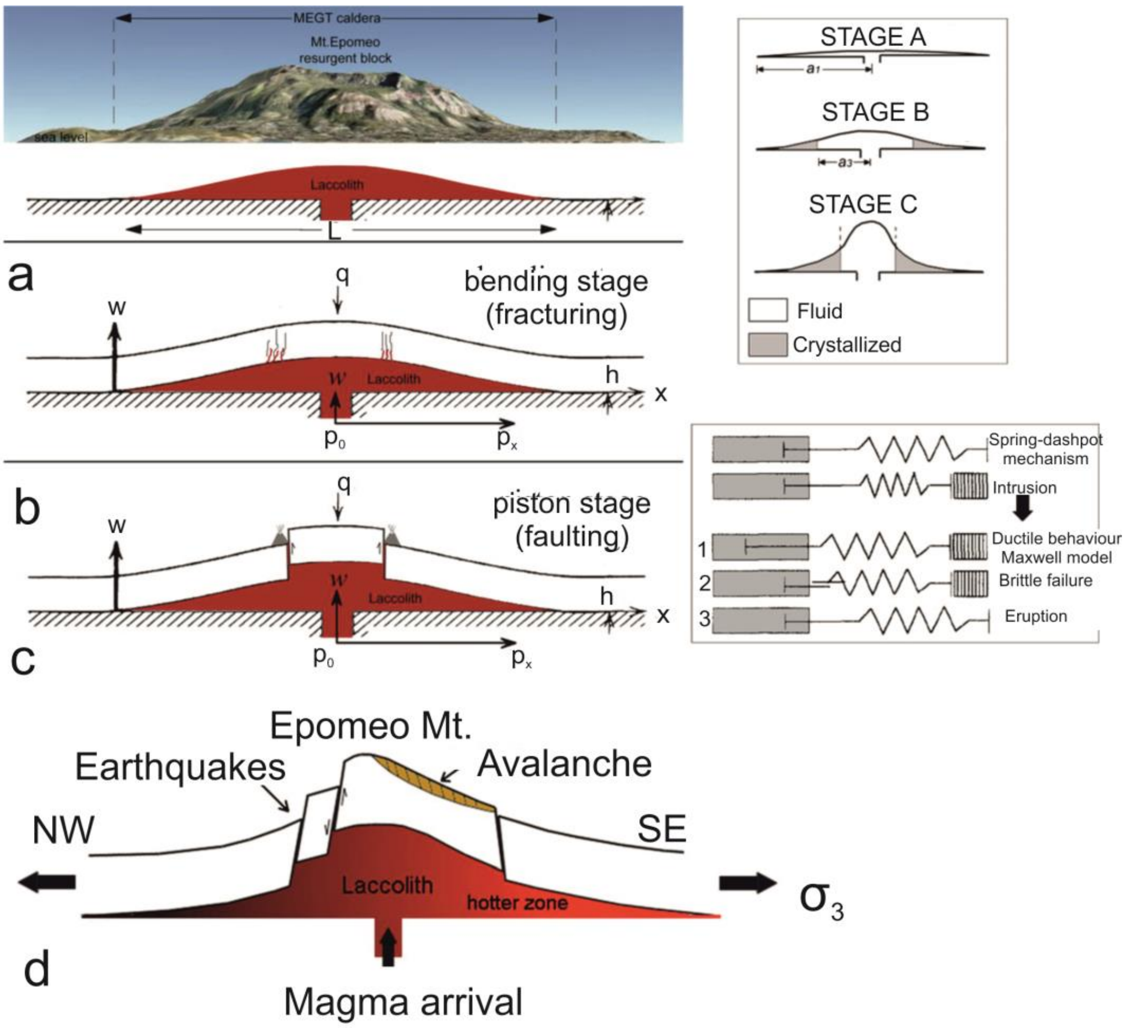

Figure 5. The laccolith model of Ischia constructed by Carlino [30] (**a**,**b**,**c**) and Carlino et al. [19] (**d**). w: plate uplift; p_0: laccolith pressure; p_x. laccolith pressure at phase x; q: average magma influx; L: length of the elastic plate; h: thickness of the elastic plate; σ3: minimum principal stress [30].

The laccolith model yields a good enough agreement between the geologic, tectonic and volcanologic constraints during the resurgence initiating from 55 ky B.P. (Figure 5). This theoretical account has supplied only the dimensions and the pressure essential to display the tectonic uplift and the deformation shapes. A criticism of the compressional and longitudinal strengths and the pressure physical process during the laccolith growing sets the time and the flux rate of magma for the pressurization of the laccolith. The geological constraints in the laccolith model are the rate of tectonic uplift of Epomeo Mt, the bulk of the erupted products, the period of quiescence between the different volcanic phases, the frequency of the eruptions in geological time and the geochemical data relative to the erupted magma [30].

The laccolith hypothesis [30] initiates with the premise that the low crustal layer of Ischia (two kilometers in depth), which has experienced tectonic uplift and fracturing during the last 55 ky B.P., reposes above a laccolith (Figure 5). The increment in pressure of this magmatic body, which has displayed resurgence, was achieved with the placement of a resurgent block wide 4 × 4 km (Epomeo Mt), then further uplifted (piston phase, about 33 ky B.P. up to 10 ky B.P). The resurgence during the last two stages of quiescence (33–29 ky B.P. and 18–10 ky B.P.) and the ensuing eruptions are genetically related to the action of new magma [10]. During the resurgence, the island has been affected by gravitational instabilities in the southern sector (large debris avalanches) and by seismic activity in the northern sector.

The issues on the laccolith model have been reassessed by Carlino et al. [73], focusing on the volcano-tectonics of the northern portion of Ischia and with the relationships with the resurgence, the subsidence and the earthquakes. In particular, the seismogenic fault genetically related with the historical and recent destructive earthquakes of Ischia (Casamicciola 2017 earthquake) has been identified, and interpreted as formed in the northern portion of the island during the later phases of the caldera resurgence. A volcano-tectonic model of northern Ischia has been constructed [73], showing the down throwing of the fault zones offshore and the processes of stress loading and release onshore, which have been triggered by the subsidence of the Mt. Epomeo block.

The geochemical information has proved the divergences in the magmatic development and has unveiled the value of the magma mixing [10]. Three chief rounds have been differentiated in the magmatic past times of the last 55 ky. The first round (55–33 ky; trachyte and alkali-trachyte) is marked by explosive eruptions, and by minor contamination. During the second round (28–18 ky B.P.), initiating with the arrival of trachy-basaltic magma in the system of rules, the magmatic chamber transformed to an open system and was marked by mixing processes between the new magma participating the magmatic chamber and the resident magma and by processes of contamination with the fluids. The volcanic deposits of the third round (10 ky–1302 AD) vary in composition from latite to alkali-trachyte and exhibit a negative correlation between the rate of differentiation and the Sr isotopic ratios. The isotopic changes are evidence for a magmatic chamber, chemically zoned, and mixing procedures, before or during the eruption [6,10].

Table 1 summarizes the geological data on the volcanic deposits, on the tectonic activity and on the volcano-tectonic evolution of Ischia during the last 55 ky B.P. [10]. The periods from 10 to 18 ky B.P. and from 28 to 33 ky B.P. correspond with hiatuses of the volcanic activity and of the volcanic products.

Ischia's volcanic history displays two cycles of activity (PRES and POES, Pre-Epomeo and Post-Epomeo lavas), separated by an important explosive phase, producing the Monte Epomeo Green Tuffs [9]. The geochemical data has specified three main magmatic sequences (A, B, C). The first sequence (sequence C) is in the PRES and is constituted of lava fluxes, domes and other pyroclastic products, which together make the volcanic basement of the island. The composition of these products varies between the trachyte and the phonolite, with a marked predominance of the last products. The other two sequences are effusive and pyroclastic sequences, which erupted after the Epomeo Green Tuffs. Their constitution varies between latite-trachyte-phonolite (sequence B) and trachy-basalt-latite (sequence A).

The caldera resurgence goes on in the central sector of the island in compatibility with fault systems N40–50W e N50–60E, highlighting the main regional tectonic structures [11,18] (Figure 6). The uplift occurred through the reactivation and the individuation of faults, resulting in the formation of down thrown blocks. Towards the NE, the bound of the resurgent area is not unsubtle, as well as along the shoreline, where beach deposits form marine terraces uplifted at several heights by faults having an E-W and a NW-SE trend. The westerly sector of the most uplifted block, corresponding to Epomeo Mt, is limited by high-angle reverse faults (Figure 6). The north-eastern and the south-western flanks of the resurgent area are confined by normal faults. The resulting lowland, which is the area in which the volcanism has been mainly concentrated during the last 10 ky, is connected westwards to Epomeo Mt. through uplifted blocks.

The kinetics of the resurgence of the Epomeo block can be stated by several proposals. All of them adopt as a trigger-off performance the entrance of a magmatic body at low depths [1,2,12,14,26]. Orsi et al. [12] have advised a performance of block resurgence, ruled by simple shear strengths, considering both the geological and volcanological constraints, as the arrangement of the volcanic edifices genetically concerned to the resurgence (Figure 6). This mechanism preserves the status of the magma uprising only in the sector of the resurgent area held in by an extensional regime, as detected in the calderas of Pantelleria and Campi Flegrei [12,14].

Table 1. Sketch table showing the geological data on the volcanic deposits, tectonic setting and volcano-tectonic evolution of Ischia during the last 55 ky (modified after Civetta et al. [10]; Crisci et al. [9]); Poli et al. [6]).

Volcanic Deposits	Location	Tectonic Setting	Type of Rocks
Civetta et al. [10]. Fallout tephra, lava domes, lava flows and pyroclastic surge deposits (Selva del Napolitano; Rio Corbore; Zaro; Piano Liguori; Costa Sparaina; Montagnone; Monte Vico; Trippodi; Vateliero; Arso; Maisto; Cannavale; Marecoppo; Cava Bianca (0–10 ky B.P.)	Eastern side of the Epomeo Mt. block. North-western and south-western corners of the block.	Volcano-tectonic faults bordering the Epomeo block; NE-SW trending fault systems.	Latite, trachyte, alkali-trachyte.
Civetta et al. [10]. Lava flows; magmatic and hydromagmatic pyroclastic deposits (Grotta di Terra dyke; Grotta del Mavone lava flow; S. Angelo tuff; 18–28 ky B.P.)	South-eastern and south-western corners of the present-day island	NW-SE and NE-SW fault systems. Beginning of resurgence of the Epomeo Mt. block.	Trachybasalts, trachyte, alkali-trachyte
Civetta et al. [10]. Magmatic and hydromagmatic pyroclastic deposits (Pietre Rosse Tuff; Agnone Tuff; Sammontano Tuff; Ciglio Tuff; 33–50 ky B.P.)	South-western and north-western corners of the present-day island	NW-SE and NE.-SW fault systems downthrowing the central part of the island	Trachyte, alkali-trachyte
Civetta et al. [10]. Large pyroclastic flows. MEGT (Monte Epomeo Green Tuff)	Southwards of the present-day island	NW-SE and NE-SW fault systems	Trachyte, alkali-trachyte
Crisci et al. [9]. Sequence C. Lava flows, domes and other pyroclastic products.	Punta della Signora, S. Angelo, S. Pancrazio, Scarrupata di Barano	Not specified	Trachyte to phonolite (predominant)
Crisci et al. [9]. Sequence B. Effusive and pyroclastic products erupted after the Epomeo Green Tuffs (55 ky B.P.).	Ischia harbor	Not specified	Latite-trachyte--phonolite
Crisci et al. [9]. Sequence A. Effusive and pyroclastic products erupted after the Epomeo Green Tuffs (55 ky B.P.)	Zaro, Arso		Trachybasalt latite
Poli et al. [6]. Pyroclastic products older than 150 ky B.P.	South-eastern Ischia	Extensional phase at the end of the period, controlling the emplacement of the lava domes of the next phase	Alkali-trachyte
Poli et al. [6]. Lava domes and minor pyroclastic deposits (75 ky B.P.–150 ky B.P.)	South-eastern Ischia		Alkali-trachyte to phonolite
Poli et al. [6]. Great pyroclastic emissions (20–55 ky B.P.)	Epomeo Green Tuffs	Reactivation of the structural trends of the first phase	Trachyte to alkali-trachyte
Poli et al. [6]. Lava flows (10 ky B.P.–1302 A.D.)	Arso, Zaro	Tectonic uplift of the Epomeo block. Individuation of the Ischia graben.	Alkali-trachyte, basalt, latite

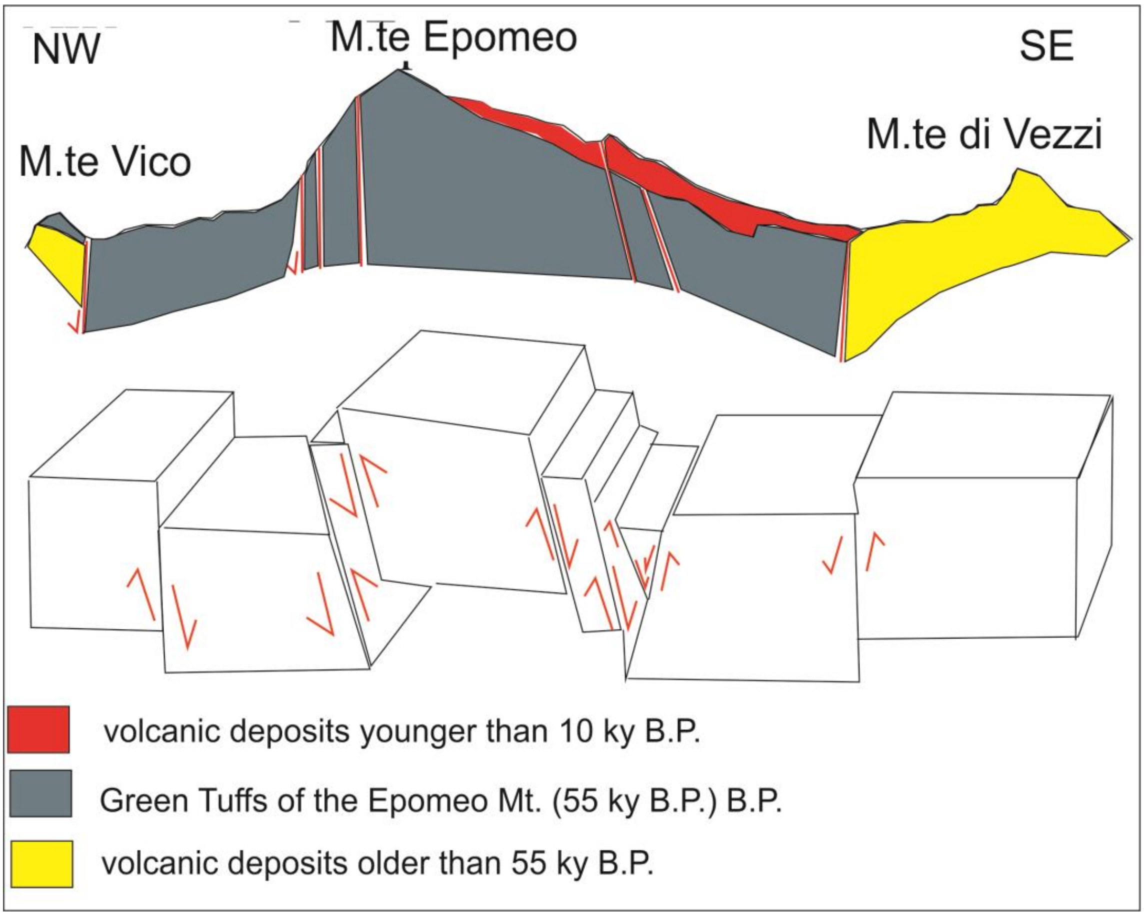

Figure 6. The model of block resurgence of Ischia proposed by Orsi et al. [11].

3.2. Review of the Structural Geology of Ischia

One basic piece of research in the field of structural geology is the paper of Acocella and Funiciello [48], who have analyzed the interactions between regional and local tectonics. Ischia Island is mainly characterized by NW-SE and NE-SW trending normal faults and shows a resurgent dome, uplifted by about 800 m during the last 33 ky B.P. [48]. These faults are genetically related to the regional extensional structures.

The reactivation of the antecedent regional groups during the resurgence has limited the extension of the uplifted area. N-S and E-W trend faults hold in the margins of the dome, as restrained by the resurgence. About 90% of the products synchronous with the resurgence have erupted outside, showing that the process of resurgence has locally replaced the volcanism during the last 33 ky. In the volcanic areas, the deformation patterns lead from the strengths applied to a regional scale or to a local scale. The regional strengths regulate the formation of fractures, which may represent ways of preferential uprising of magma, while the local ones by the emplacement of magma or by gravity [34,35,41]. The arrangement of a resurgent dome consists of an uplift of a component portion of a volcanic complex. This process is a common passage in the rejuvenation of the last stage of the calderas and is connected with the pressure or with the variations of volume of the magmatic chamber. The active processes of resurgence may induce newly formed magma or reactivated structures, genetically associated to a regional or local stress field [48].

Two frameworks have been suggested to delimit the structure of a resurgent dome. The first one is the model of the volcano-tectonic horst, where the resurgent block is enclosed by faults plunging seawards [37,40,53], while the second one is the simple shear model, where the resurgent block, rooted around a horizontal axis, is restrained by faults immersing landwards.

The faults plunging landwards and enchained by the dome are agreeable with the model advised by Orsi et al. [11]. Based on this model, the simple shear mechanism has brought forth the rotation of the block around an N-S horizontal axis, which makes normal faults and high angle reverse faults on the opposite parts of the block. The model of Acocella and Funiciello [48] is slightly different from the model of Orsi et al. [11], both in the field data (top of the Epomeo Green Tuffs) and in the geometry, suggesting that the block rotation must happen close to a NE-SW axis located in the Maronti area. The width (w) of the resurgent block of Ischia is about 4 km and its uplift (H) approximately 1 kilometer. This aspect ratio (H/w) proposes that the antecedent regional faults, located at the edges of the block, have commanded the dimension of the uplifted area during the resurgence [48].

Molin et al. [52] have dealt with the structural, seismic and hydrothermal features of Ischia, examining the states with the resurgence (Figure 7). The resurgent blocks are the uplifted sectors of the volcanoes, where most of the uplift is accommodated along fringy faults. Aerial photograph reading, coupled with geological survey and structural analysis, links to a rescript of the seismic and hydrothermal activity at Ischia.

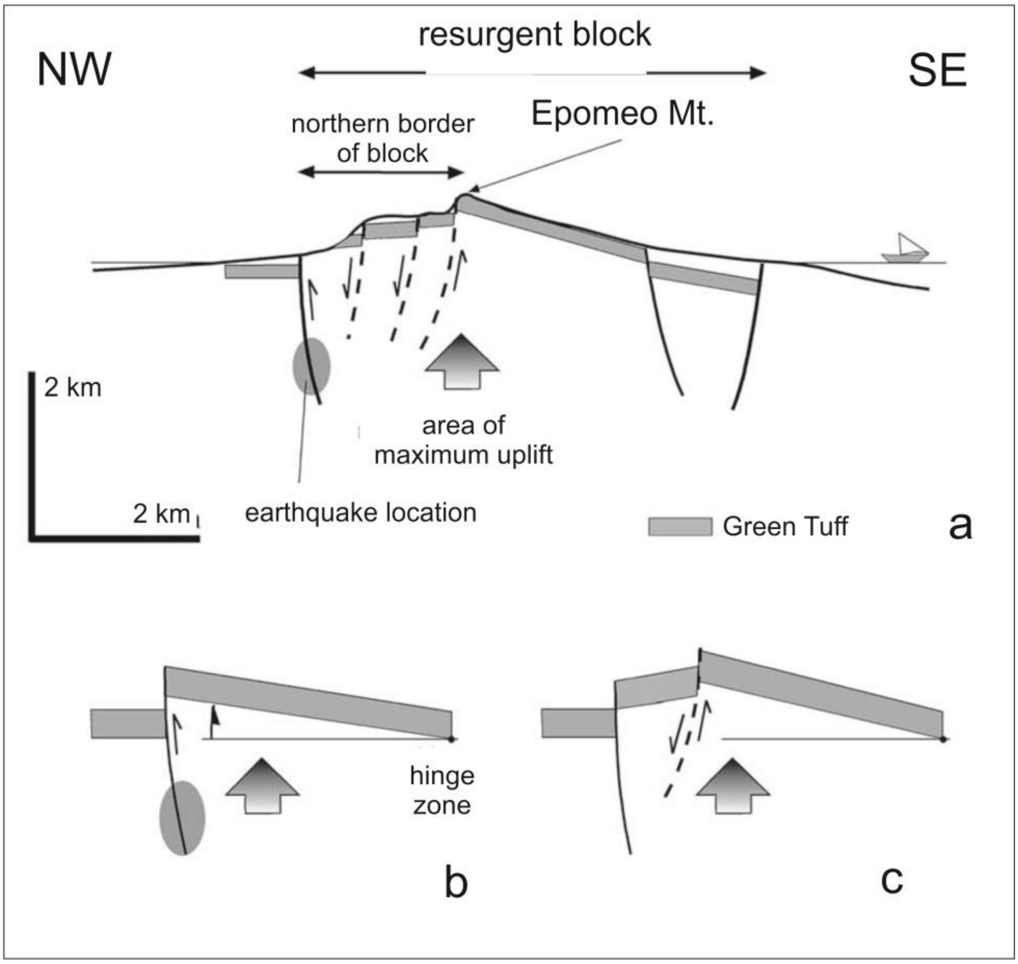

Figure 7. Model for the uplift of the Ischia resurgence (modified after Molin et al. [52]) (**a**) Sketch diagram showing the actual tectonic setting, with the asymmetric block bordered by high-angle inward-dipping reverse faults, and outward-dipping normal faults in the innermost part. (**b**) Sketch diagram showing the model of the intermittent trapdoor uplift, with the seismic activity controlled by the reverse faults on the most strained side of the block. (**c**) Sketch diagram showing the model of the intermittent trapdoor uplift, with the activity of the reverse fault controlling the collapse of the periphery of the block and forming the outward-dipping normal faults.

The resurgent block is qualified by a northerly portion, more uplifted, leapt by normal faults holding an E-W and a NE-SW trend, set up in parallel segments on an area broad of 1.5 km. Skin-deep earthquakes happen in agreement of the outer group of faults. A model of tectonic uplift of a block holding the shaping of faults, accountable for the seismicity and the hydrothermal changes along the most uplifted part, is planned [52].

The asymmetric uplift of the block is mainly held in by the state of the high angle reverse faults, disposed landwards, in the outermost part of the fault zone that are turned up at the northern periphery of the block (Figure 7). The seismic activity happens along the faults, actuating the observed variations of the hydrothermal activity.

Normal faults inclined seawards develop in the innermost part of the northern periphery of the block. Their formation was triggered by the gravitational slide of the periphery of the volumes bounded by the reverse faults. In this setting, the normal faults accommodate the uplift along the periphery of the block. Using analogue models, the answers suggest that the outermost faults bordering the resurgent blocks are high-angle inward-dipping reverse faults. They are the outcome of the modification in the path of the stress trajectories in a different uplift and are agreeable with former hypotheses for the resurgent block at Ischia [11,48]. The analogue models also prove that high-angle outward-dipping normal faults are created, as controlled by the gravitational collapse related to the state of the reverse faults, in an inner part of the block.

A further reactivation of the outer reverse faults triggers a new cycle, and the process is continuous during geological time. In this setting, the combined activity of the reverse and normal faults along the periphery of the block accommodates the space created by the resurgence. A similar mechanism of uplift of the resurgent block of Ischia may be interpreted as an effect of a filling of the magmatic system, as suggested by the evolution of the volcanic activity in the eastern sector of the island during the last 5 ky [14].

The structural setting of Ischia has also been discussed based on integrated geophysical and geochemical data [74]. The magnetic and gravimetric maps have been constructed integrating newly acquired datasets and old datasets published by the authors. The pole-reduced magnetic data have shown the main magnetic anomaly fields occurring in the island, with the main magnetic maxima located in correspondence with the volcanic lavas younger than 10 ky B.P. (Zaro, M.te Rotaro, M.te Trippodi) and older than the Epomeo Green Tuffs on the southern sector of the island (Punta Imperatore, Capo Negro) [74].

3.3. Review of the Marine Geology of Ischia

Numerous are the studies performed on the marine geological setting of Ischia. Most of them are based on the data recorded during the scientific and technical activities carried out in the frame of the realization of the sheet n. 464 "Isola di Ischia" of the CARG project, both at the 1:50.000, 1:25.000 and 1:10.000 scales [55,56].

Aiello [60] has built the seismo-stratigraphic setting of the Late Quaternary to Holocene volcanic and sedimentary units and their correlation with the coastal units. New data have been exhibited on the Late Quaternary geologic development of the Ischia offshore through the interpretation of seismic profiles matched with the coastal geology of the comparable sectors. An elaborated geological work has been held out, centering on some aspects of the Ischia coastal part, seeing both high tuff sea cliffs (Succhivo, Punta dello Schiavo) and low sandy beaches (Spiaggia degli Inglesi, Cava dell'Isola). The first region is drafted by the Succhivo coastal cliff land, sited on the southern Ischia coastal belt westward of the S. Angelo headland; the second area is sited between the Ischia harbor and the beach of Spiaggia degli Inglesi; the third area is stationed in the western Ischia offshore towards the beach of Cava dell'Isola; the fourth sector is depicted by the tuff coastal cliff of Punta dello Schiavo, placed in the south-western Ischia offshore.

The Quaternary deposits of Ischia have been addressed based on marine geological and sedimentological collection [61]. Marine geological maps at the 1:10.000 scale have been drawn, exhibiting that the sands are prevailing in the eastern Ischia offshore and the bioclastic sands happen at the top of relict volcanic edifices (Forio Bank, Ischia Bank) [61].

Rhodolith deposits go on at the Ischia Bank and the genetically related parasitic vent and in the Ischia Channel, located between the Ischia and Procida islands [61].

The bioclastic deposits of Ischia are represented by detritus facies derived by processes of in situ reworking of organogenetic materials on hard sea bottoms and are composed of coarse-to-middle-grained sands and gravels in a scarce pelitic matrix [61,63]. Significant outcrops are on the inner shelf from 20 to 50 m, on the morphological saddles (Ischia Channel) and at the top of relict volcanic edifices, at both Ischia (Ischia and Forio Banks) and Procida (La Catena, Il Pertuso, Formiche di Vivara banks).

Milia et al. [64] have discussed the stratigraphic relationships between the volcanic and sedimentary units of the northern Ischia volcanic field, both onshore and offshore. The volcano-stratigraphic interpretation has allowed us to recognize the seismo-stratigraphic units of the northern Ischia offshore, showing acoustically transparent and chaotic seismic facies. The volcanic units, limited in extent, are inter-layered with eight seismic units, having continuous reflectors and corresponding with clastic units, which have been deposited during the inter-eruptive phases. During the Holocene, the eruptive activity of Ischia has been recorded in the area between the Ischia Castle, the Ischia harbor and Punta della Scrofa.

The seismo-stratigraphic setting has also been reconstructed and is characterized by the occurrence of the volcanic basement, which is shallow over the whole area [54]. The acoustic basement is unconformably overlain by the volcaniclastic deposits and by the hemipelagic marine sediments [54]. The magnetic anomaly map has shown a complex pattern and a good correlation with the regional aeromagnetic data. In the western Ischia offshore, the magnetic anomaly has an amplitude of 1500 nT. This value is in agreement with the values observed in the volcanic edifices of the Campania region (Somma-Vesuvius, Roccamonfina, Ventotene).

3.4. Ischia Seismo-Stratigraphic Setting

The stratigraphic building of Ischia is herein addressed through the interpretation of seismic sections read in several sectors of the island (Figure 3). In particular, Figure 8 exhibits the interpretation of line L28 (northern Ischia). The seismo-stratigraphic units have been represented with different color blocks (Figure 8). Five seismo-stratigraphic units have been acknowledged, seeing the volcanic unit of Casamicciola, the three basin filling units of the northern Ischia offshore, and the hummocky deposits. The volcanic unit of Casamicciola is an unexplained unit, similar to a volcanic acoustic substratum, scoured at its top by an erosional unconformity (1 in Figure 8). Units 2, 3 and 4 are the basin-filling units of the northern Ischia offshore: unit 2 is qualified by parallel to sub-parallel seismic reflectors, and locally, by prograding clinoforms; unit 3 is separated from parallel to sub-parallel seismic reflectors; unit 4 is defined by parallel seismic reflectors (Figure 8). The hummocky deposits (H1 and H2 in Figure 8) are the deposits of volcanic gravity flows, having a dome-shaped external geometry and a hummocky facies.

The environs of Southern Ischia are talked about through the geological interpretation of the seismic profile L47 (Barano Bay; Figure 9). The section tracks the "Scarrupata di Barano", a steep coastal cliff and corresponding slope facing from the Barano sector of Ischia towards the Tyrrhenian Sea.

The volcanic products outcropping in the Scarrupata di Barano have been discussed by Vezzoli et al. [53], and consist, respectively, of the La Guardiola lava, of the upper and lower Scarrupata di Barano Formation, and of the domes and lava flows of Monte di Vezzi.

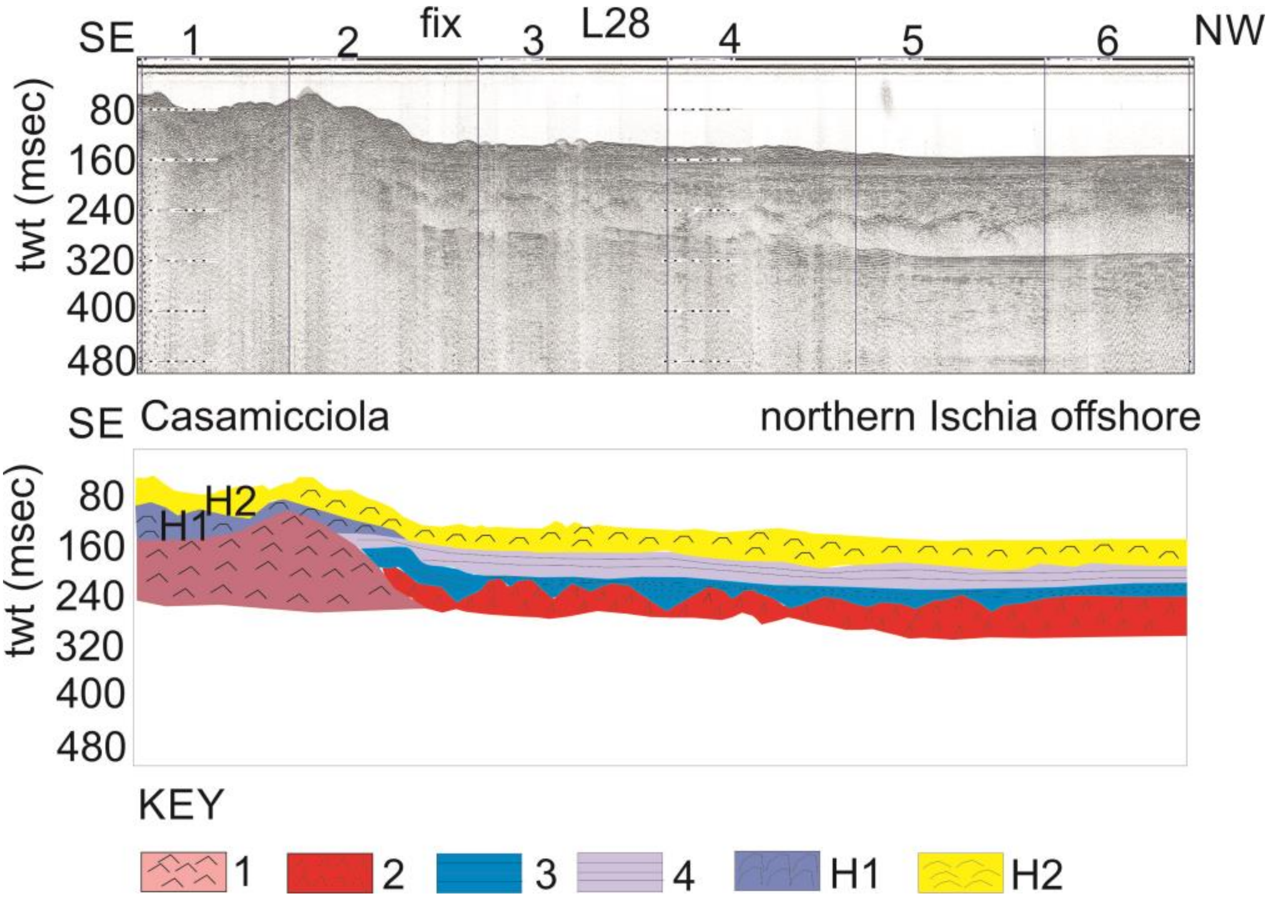

Figure 8. Seismic profile L28 (northern Ischia) and corresponding geologic interpretation.

During the eruptive phases following the eruption of the Epomeo Green Tuffs (55 ky B.P.), the La Guardiola lava has been overlain by the Monte di Vezzi Formation, composed of not welded pumice flows erupted from the Epomeo Green Tuff, by the S. Costanzo Formation, composed of white tuffs, well stratified, with pumice, by the Monte di Vezzi Formation, composed of well-bedded pumice fall breccias and brown scoria layers and by the Piano Liguori Formation, composed of inter-layered white ashes and pumice layers.

Four units have been recognized ("Barano 1" and "Barano 2" volcanic acoustic basement, pyroclastic sequence and marine sequence). The Barano 1 and Barano 2 units have been, respectively, correlated with the Upper Scarrupata di Barano Formation and with the Lower Scarrupata di Barano Formation, which are both composed of tuffs and breccia. These two thick sequences are overlain by a sequence, probably pyroclastic in nature, characterized by parallel horizons. These sequences are overlain by the youngest unit, interpreted as a marine sequence.

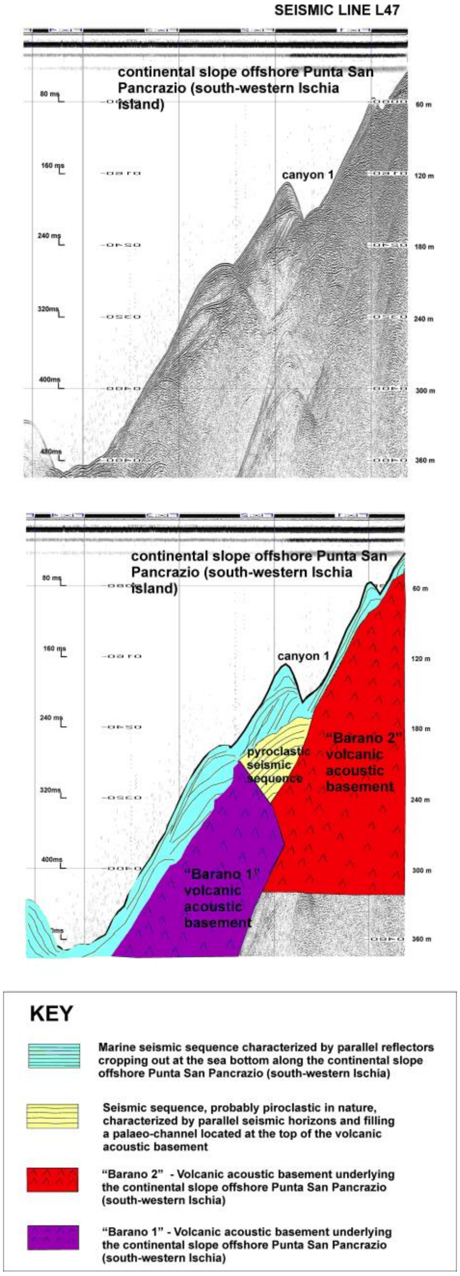

Figure 9. Seismic profile L47 (southern Ischia, Punta S. Pancrazio) and corresponding geologic interpretation.

4. Discussion and Conclusions

A reassessment of the volcanological and geological data of Ischia is herein advised, centering on several aspects, which, respectively, affect the volcanology, the geochemistry, the structural geology, and the marine geology and geophysics of Ischia. This reappraisal, coupled with the seismo-stratigraphic data available in previous papers and resumed in this paper, allows discoursing on the Quaternary geologic development of Ischia.

It is not easy to give an answer to most of the open questions existing on Ischia. Some open questions are: What genetic model better explains the origin and the evolution of volcanism at Ischia? Which is the relation between tectonics and volcanism? How does mixing phenomena originate? What are the regional implications? etc. We have tried to do it, in this section and in the whole paper, by examining different models existing in literature and with the presentation of data and argumentation in previous sections.

Linking the addressed models with the Quaternary geologic evolution of Ischia represents a main issue and novelty of this paper.

The information of Brown et al. [23] is in contrast with the earlier ideas of volcanologists on a long phase of quiescence of the eruptive activity of Ischia between 75 and 50 ky B.P. [8,30]. The alluvial deposits, previously mentioned to foreground an extended pause in the volcanic activity and in related input, have been re-interpreted as pyroclastic deposits.

A new volcanological evolution of Ischia during the Late Pleistocene has been declared [23]. The outcropping products include trachyte and phonolite lava domes, lava and pyroclastic deposits ensuing from a period of time of magmas, discrimination and volcanic eruption. The happening of some scattered volcanic centers fed by magma advises a differentiated magmatic chamber below the region, preceding the MEGT eruption [8].

The S. Angelo tephra and the Tisichiello tephra have upheld cinerite deposits and block deposits of pyroclastic flux, proposing the intermittent growth and the destruction of the lava domes in the volcanic centers in the southern sector of the island. The volcanic activity, in correspondence with these centers, has created eruptive columns, which have aroused the dispersion of pumices on the whole territory of the island. The paleogeography of that period was unusual compared to the present-day one. The volcaniclastic and marine deposits occurring below the LMEGT (Rione Bocca) have indicated the occurrence of a depression, older than 55 ky B.P. and located in the central sector of the island.

This depression was probably encircled by discrete centers (lava domes and pyroclastic fluxes of Carta Romana-Monte Cotto, S. Angelo, M.te Vico and Punta Imperatore). The geophysical data in the western offshore of Ischia [54] have sustained the remnants of a wide complex, which could be the source of some of these eruptions. Ischia could be connected to the mainland by an isthmus that added part of the present-day island of Procida, given the average sea levels were 50–80 m lower than the actual ones. This eruptive phase probably continued up to the eruption of the MEGT (55 ky B.P.), which controlled the caldera subsidence on the whole island and has partially destroyed the magmatic chamber. This eruption had two phases of emplacement of ignimbrite deposits, having a thickness higher than 200 m, in the down throwing caldera. The volcaniclastic deposits occurring between the two ignimbrites show that the subsided caldera was open to the sea during the eruption.

The most recent eruptive activity of the MEGT (55 ky B.P.) regards a distinct number of phreato-magmatic and magmatic eruptions, which have brought forth eruptive columns and density pyroclastic currents (Capo Grosso, Chiummano and Schiappone eruptions). Thick ignimbrite deposits along the south-eastern coast of the island have indicated an inclined topography, now lacking, southwards of the Scarrupata di Barano. The large-scale collapse of the southern flank of the island destroyed this topography [20].

The post-MEGT volcanism is different from the pre-MEGT volcanism [23]. The divergences show a shifting towards phreato-magmatic eruptions (Capo Grosso, Chiummano and Schiappone tephra). This shifting has probably been held in by the subsidence during the caldera collapse, which has aided the entry of the seawater into the magma in eruption. Moreover, the magma composition varies from phonolite and trachyte-trachyandesite and basalt-trachyandesite, as an outcome of the MEGT eruption.

Comparisons with the present-day volcanic state of the island have been performed [23]. The most harmful eruptions have occurred during the Holocene. Some of these eruptions have potentially overpowered the whole island, and have produced two major pyroclastic currents. The MEGT has held in the subsidence of the caldera on the entire island. The type and the magnitude of the volcanic activity are strongly in contrast with the most recent one, ranging in age from 10 ky B.P. and 1302 A.D., seeing numerous explosive and effusive eruptions, having little volume. These eruptions had an impact only on Ischia or on parts of Ischia. The deviations in scale and impact of the volcanism during the last 75 ky are the outcome of main variations of the magmatic system and of the volcano-tectonic structure of the island. From 75 to 50 ky B.P. a highly differentiated magmatic chamber influenced the volcanism. The consequent caldera collapse, the partial destruction of the magmatic chamber and the time distribution of the volcanism have been governed by the caldera resurgence: the volcanism has been mainly concentrated along the margins of the resurgent block [11] and the distribution during the geological time of the volcanic eruptions is strongly controlled by the periods of tectonic uplift [22].

The volcanic activity of Ischia has been classed by Carlino [30] in five main stages, identifying an old cycle and a recent cycle, divided by the eruption of the MEGT (55 ky B.P.). Starting out from 55 ky B.P., Ischia island is qualified by the resurgence of its central sector and by the occurrence of effusive and explosive eruptions. The time period of volcanic activity between 55 and 33 ky B.P. originated with the eruption of the MEGT and was predominated by explosive eruptions, which have showed, based on the geochemical composition of the rocks, a magmatic chamber, chemically zoned and in evolution.

The caldera natural depression has been filled up, both in subaerial and submarine states, by the deposits of the MEGT, by the tuffs of the Citara Formation and by the Colle Jetto Formation. The outset of the two main volcanic periods, pursuing the eruption of the MEGT (29–18 ky B.P. and 10 ky–1302 D.C.) has been tagged by a lessening of the isotopic ratios of the Sr and of the Nd [10]. These two states are marked by the happening of small explosive and lava eruptions. During the following volcanic phases, up to 0.4 km^3 of volcanic deposits were erupted [22] with an increasing number of eruptions and a general decrease in their energy. The last eruption of 1302 A.D. produced a lava flow in the eastern sector (Arso lava flow).

The laccolith model advised by Carlino [30] shows the resurgence of Ischia, sustained up to 55 ky B.P., and its volcanic activity and seismicity. The happening of this magmatic body at shallow depths is implied by gravimetric, aeromagnetic and self-potential data [26,38,74]. On the surface, an evolved stage of the laccolith has been known by the presence of peripheral faults and steep slopes along the resurgent block. In this framework, the organization and the growth of the laccolith are ensuant to the eruption of the MEGT. When the tectonic uplift originates, it produces flexure and fracturing of the root (stage of folding). This has been post-dated by the individuality of faults, the uplift of blocks and then the volcanic activity placed along the fractures conjugating this block.

According to the data, seismo-stratigraphy and Ischia's geologic evolution are addressed. The Ischia offshore is characterized by alkali-trachytic rocks, adding trachyte, latite and alkali-basalt and belongs to a volcanic complex constructed during the last 55 ky B.P. The geological interpretation of marine DEMs [24,55,56,58] and of high-resolution seismic profiles [55,56,59–64] (Figures 8 and 9) has implied submarine instability processes, adding catastrophic processes qualified by debris avalanche deposits and continuous processes defined by creep and accelerated erosion along submarine canyons. In the northern, western and southern flanks of the volcanic complex, debris avalanche deposits appear. The presence of these deposits has been commanded by the volcano-tectonic uplift of Epomeo Mt., genetically related to the caldera resurgence that happened during the last 30 ky B.P. The most influential among these deposits are the deposits of the Ischia Debris Avalanche (IDA) [20], which have been circularized southwards up to 40–50 km. As an important divergence with the IDA, the debris avalanche deposits in both the western and northern sides of the island are not directly related with evident slide scars occurring onshore.

5. Conclusions

A review of the volcanology and geology of Ischia has been carried out, focusing on the volcanological and geochemical data and integrating the literature knowledge with the interpreted seismic sections recorded in the frame of the CARG project.

Field geological and volcanological data have displayed the volcanic deposits of ten explosive eruptions, coupled with pyroclastic deposits of previously unknown eruptions. Among them, the S. Angelo Tephra has a particular relevance and its stratigraphic relationships with the other volcanic tephra of Ischia have been discussed.

The laccolith model has integrated geological and geophysical constraints, showing that the flexural uplift was coeval with the resurgence and that it was followed by fracturing and faulting of the shallow crust, increasing the laccolith volume of about 80 km^3.

The integrated geochemical models have outlined the magmatic evolution of the volcanic complex, characterized by at least three phases of magmatic activity, reaching four phases in the time interval ranging between prior than 150 ky B.P. and historical times.

Different modes of resurgence of the volcanic complex have been proposed and are herein discussed, basically a model of block resurgence, controlled by simple shear strengths, and a model of asymmetric uplift of the block, controlled by high angle reverse faults, interacting with gravitational movements.

The Ischia seismo-stratigraphic setting has been shown, focusing on northern and southern sectors of the island, highlighting the complexity of the volcaniclastic and sedimentary seismic sequences and the strong control of mass movements on the emplacement of debris avalanche deposits.

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