Z. Geomorph. N. F.	51	2	165–190	Berlin · Stuttgart	June 2007

Geomorphological evolution of Phlegrean volcanic islands near Naples, southern Italy[1]

by

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with 9 figures and 5 tables

Summary. Using volcanological, morphological, palaeoecological and geoarchaeological data we reconstructed the complex evolution of the island volcanic system of Procida-Vivara, situated west of Naples between the Island of Ischia and the Phlegrean Fields, for the last 75 ky.

Late Pleistocene morphological evolution was chiefly controlled by a series of pyroclastic eruptions that resulted in at least eight volcanic edifices, mainly under water. Probably the eruptive centres shifted progressively clockwise until about 18 ky BP when volcanic development on the islands ceased.

The presence of stretches of marine terraces and traces of wave cut notches, both below and above current sea levels, the finding of exposed infralittoral microfossils, and the identification of three palaeo-surfaces buried by palaeosoils indicates at least three differential uplift phases. These phases interacted with postglacial eustatic fluctuations, and were separated by at least two periods of general stability in vertical movements. A final phase of ground stability, characterised by the deposition of Phlegrean and Ischia pyroclastics, started in the middle Holocene. Finally, flattened surfaces and a sandy tombolo developed up to the present-day.

Recent archaeological surveys and soil-borings at Procida confirm the presence of a lagoon followed by marshland at the back of a sandy tombolo that were formed after the last uplift between the Graeco-Roman period and the 15th–16th century. These areas were gradually filled with marine and continental sediments up to the 20th century.

Finally, our investigation showed that the volcanic sector of Procida-Vivara in the late Pleistocene-Holocene was affected by vertical displacements which were independent of and less marked than the concurrent movement in the adjacent sectors of Ischia and of the Phlegrean Fields. The displacements were probably controlled by volcano-tectonic phenomena rather than bradyseism (slow pseudo-elastic deformation of soil due to underground magma intrusion and/or gas and steam pressure).

Zusammenfassung. *Die geomorphologische Entwicklung der phlegreischen Vulkaninseln bei Neapel.* – Mit vulkanologischen, morphologischen, paläökologischen und geoarchäologischen Daten wurde die Entwicklung der vulkanischen Inseln Procida-Vivara für die letzten 75.000 Jahre rekonstruiert.

[1] This work is the result of a research carried out by all the authors. Particularly, T. De Pippo, C. Donadio and C. Petrosino carried out the geological and geomorphological description of the island volcanic system of Procida-Vivara; G. Aiello and D. Barra took care of palaeoecological analysis; finally, geomorphological interpretation and reconstruction of complex evolution of the island volcanic system as well as conclusions are the result of all authors collaboration.

DOI: 10.1127/0372-8854/2007/0051-0165 0372-8854/07/0165 $ 6.50

Die spätpleistozäne Entwicklung wurde durch mindestens acht submarine pyroclastische Ausbrüche gesteuert, deren Zentren sich dextral verschoben und 18.000 BP endeten. Marine Terrassen, Wellenkerben, infralittorale Mikrofossilien sowie drei Paläooberflächen mit Böden dokumentieren drei Hebungsphasen. Diese überlappen mit den holozänen Meeresspiegelschwankungen und bewirken zwei Perioden an Höhenkonstanz. Eine letzte Phase, belegt durch Ablagerungen von pyroclastischen Sedimenten aus Ischia und den Phlegreischen Feldern, beginnt im mittleren Holozän und es entwickelte sich ein flaches Relief und ein Tombolo.

Archäologische Studien und Bohrungen belegen eine Lagune und Marschland hinter einem sandigen Tombolo. Diese bildeten sich nach einer Hebungsphase zwischen der griechisch-römischen Periode und dem 15–16. Jahrhundert und wurden bis ins 20. Jahrhundert mit marinen und kontinentalen Sedimenten aufgefüllt.

Letztlich zeigen die Untersuchungen, dass Procida-Vivara im Untersuchungszeitraum durch vertikale vulkanotektonische Bewegungen beeinflusst wurde, die unabhängig von den angrenzenden Sektoren von Ischia und den Phlegreischen Feldern abliefen.

Résumé. En employant les données volcanologiques, morphologiques, palaeoecologiques et geoarcheologiques nous avons reconstruit l'évolution complexe, dans les derniers 75 ky, du système volcanique de l'île de Procida-Vivara, situé à l'ouest de Naples entre l'île d'Ischia et des Champs Flégréens.

L'évolution morphologique du Pléistocène terminal a été principalement commandée par une série d'éruptions pyroclastiques qui ont originè au moins huit édifices volcaniques, principalement sousmarines. Probablement les centres éruptifs ont décalé progressivement dans le sens des aiguilles d'une montre jusqu'à environ 18 ky BP, quand le développement volcanique sur les îles a cessé.

La présence des bords des terrasses et des traces marines des sillions de battant emergè et submergè, la découverte des microfossils infralittoral exposés et de trois palaeo-surfaces évidentes enterrées par des palaeosoils a accordé l'identification d'au moins trois phases différentielles de soulèvement. Ces phases ont agi l'un sur l'autre avec des fluctuations eustatiques postglaciales et ont été séparées par au moins deux périodes de stabilité générale dans les mouvements verticaux; une phase finale de stabilité, commençant dans l'Holocène moyen et caractérisée par le dépôt des pyroclastites des Champs Flégréens et d'Ischia, le développement des surfaces aplaties et un tombolo arénacé, continue à l'actuel.

Les aperçus archéologiques récents et les investigations geognostic chez Procida confirment la présence d'une lagune suivie du marais au fond d'un tombolo arénacé, formée après que la dernière phase de soulèvement du sol, entre les périodes Graeco-Romaines et les 15ème–16ème siècles, et graduellement comblée de sédiments marins et continentaux jusqu'au 20ème siècle.

En conclusion, notre recherche a prouvé que le secteur volcanique de Procida-Vivara pendent le Pléistocène terminal-Holocène a été affecté par le mouvement vertical du sol ce qui était indépendant et moins marqué que le mouvement concourant dans les secteurs contigus d'Ischia et des Champs Flégréens, très probablement commandé par des phénomènes volcanotectoniques plutôt que le bradyseism.

1 *Introduction*

The islands of Procida and Vivara (fig. 1), situated in the northwestern part of the Bay of Naples, are located at the edge of the large multi-crater volcanic area known as the Phlegrean Fields (Rosi & Sbrana 1987). The geological history, physiography and active volcanism of this area have led to research towards the volcanological elements, especially in sight of the bradyseismic crises in the 1970s and 1980s. Our studies, however, aim to enhance the understanding of the evolutionary dynamics of regional morphology, highlighting the mutual, complex interaction between eruptive mor-

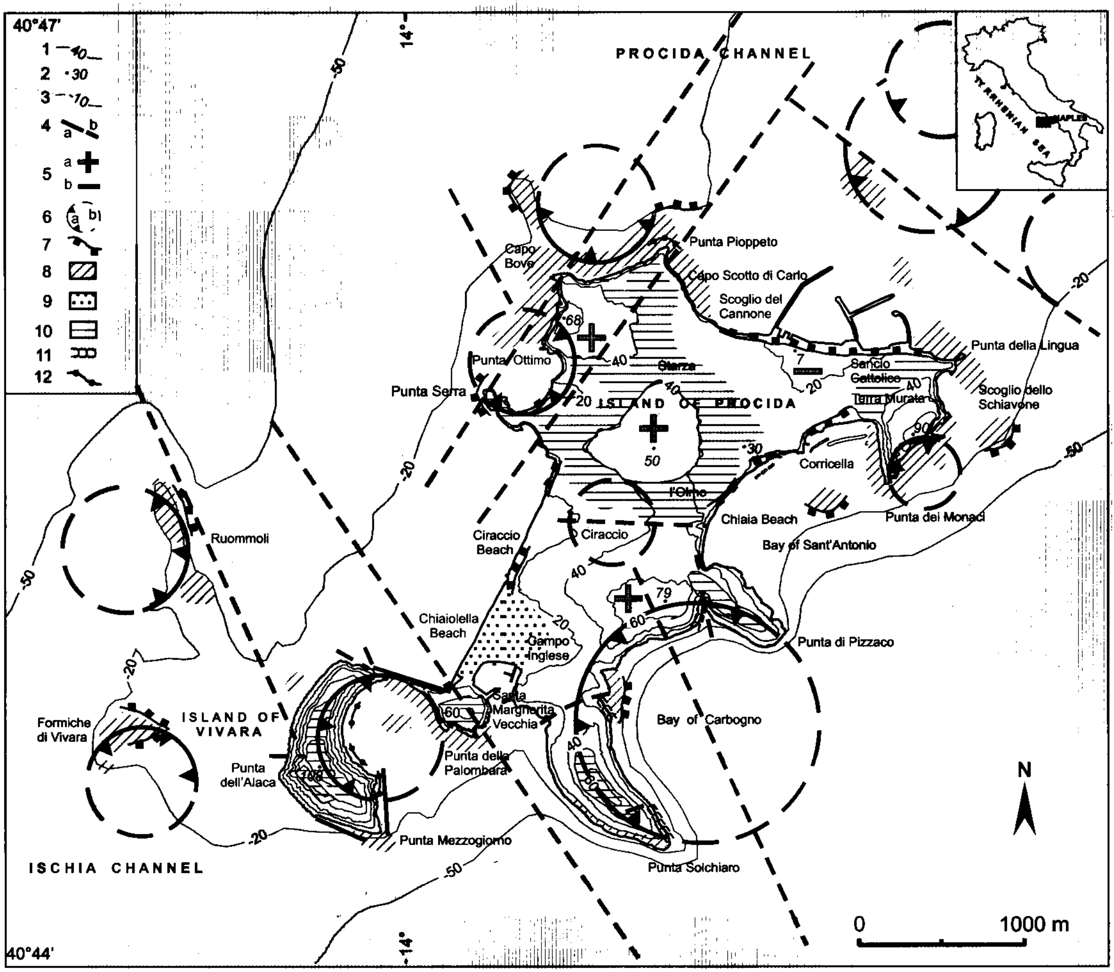

Fig. 1. Geomorphologic map of the island volcanic system of Procida-Vivara; 1) contour line (m); 2) altitude (m); 3) isobath (-m); 4) fault: a) certain; b) buried or presumed; 5) morphostructural relief: a) high; b) low; 6) crater rim: a) relic, b); reconstructed or buried; 7) palaeo-cliff; 8) sea terrace; 9) sandy tombolo; 10) flattened surface of complex genesis; 11); exposed palaeo wave cut notch 12) ancient coastline.

phologies, volcano-tectonic phenomena and eustatic oscillations in the late Pleistocene-Holocene. These are documented by several forms above and below current sea level, palaeo-environmental analysis and geoarchaeological data.

2 *Volcanological and structural context*

The Phlegrean Fields lie within the Campanian Plain, which is a Pliocene-Quaternary broad structural depression in the southern sector of the Tyrrhenian basin, delimited by NW-SE faults (Apenninic trend) along the northeastern border and E-W faults (anti-Apenninic trend) along the northern and southern edges (BRANCACCIO et al. 1991). The current conformation of Procida and Vivara is the result of complex geological events: uplift dynamics of the southern Apennine Chain, late Quaternary sea level fluctuations, the Phlegrean Pleistocene-Holocene volcanic eruptions (SCANDONE et al. 1991), and changes wrought by human impact over the last 25 centuries. The Phlegrean Fields – together with the islands of Ischia, Procida and Vivara – are a complex volcanic area (DI GIROLAMO et al. 1984, ROSI & SBRANA 1987, VEZZOLI 1988, FEDELE et al. 2006), formed by many monogenic pyroclastic edifices. They include active though quiescent structures (Solfatara) characterized both by explosive events (pyroclastic products) and, to a lesser extent, effusive products (lavas, lava domes). Volcanic activity started in the upper Pleistocene and continued up to 1538 AD. One or more pyroclastic eruptions gave rise to the formation of Campanian Ignimbrite (*Campanian Grey Tuff*), frequently found in outcrops and in the subsoil of the region (ORTOLANI & APRILE 1985). This ignimbrite outcrops locally on the islands of Capri and Procida, with a radiometric age of 37–39.2 ky BP (DEINO et al. 1992 and 1994, DE VIVO et al. 2001).

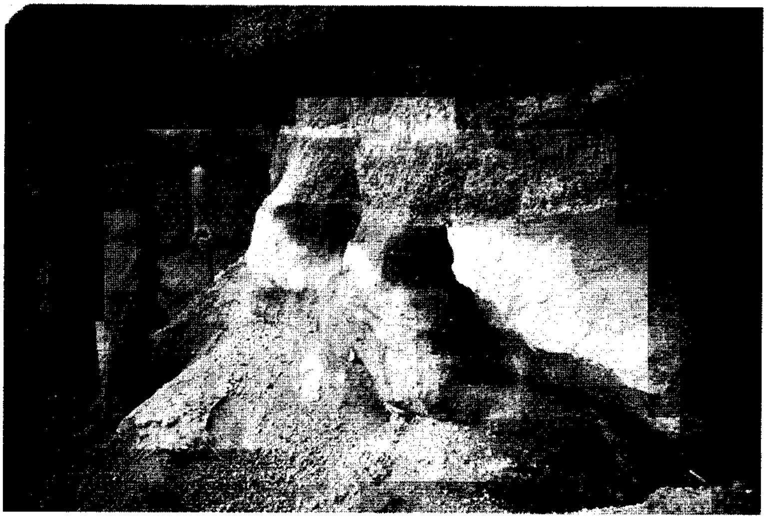

Fig. 2. Pyroclastics of Ischia (pumice fall unit), outcropping along the southwestern sector of Procida (Ciraccio).

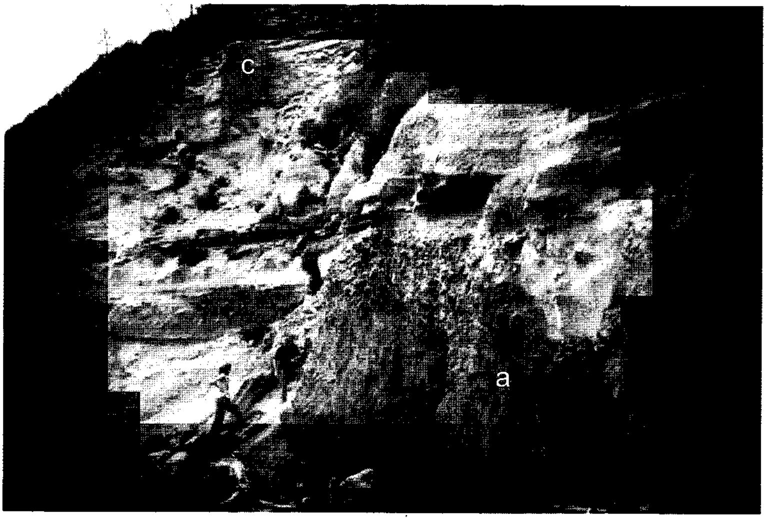

Fig. 3. The sea cliff of Pozzo Vecchio bay with rock piles at the foot, to the northwest of Procida: a) trachytic breccias; b) undefined pyroclastics; c) Solchiaro formation.

The islands of Procida and Vivara (fig. 1), formed by local eruptive centers, covered by pyroclastics from more recent Phlegrean and of Ischia (fig. 2) fallouts, represent a transitional element between the edifices on Ischia (towards SW) and those on the mainland (towards NE) (PARASCANDOLA 1924, 1926, 1928a and 1953, RITTMANN 1951, DI GIROLAMO & STANZIONE 1973). The eruptive centres are arranged around the continuation of a deep tectonic line that crosses Ischia and the middle of Procida, in a SW-NE direction (IMBÒ et al. 1964, PESCATORE & ROLANDI 1981). Their genesis is chiefly attributed to basaltic and trachytic explosive activity in shallow sea waters (CRISTOFOLINI et al. 1973, DI GIROLAMO & STANZIONE 1973, DI GIROLAMO & ROLANDI 1975 and 1979) and to the emplacement of trachytic and lava flows. The most ancient products are found outcropping on Vivara (> 55 ky BP), while the most recent are those of the eruptive centre of Solchiaro on Procida (~ 18 ky BP). The lava dome of Punta Ottimo, the volcanoes of Punta Serra, Terra Murata, Fiumicello (FEDELE et al. 2006) and the trachytic breccias (fig. 3) of Capo Scotto di Carlo and Punta della Lingua were formed before and/or in the interval between these two episodes (table 1; DI GIROLAMO et al. 1984, LIRER et al. 1991, DE ASTIS et al. 2004).

A recent review of the volcanoclastics on Procida and Vivara based on published reports, morphostratigraphic and radiometric data, and location of the deposits in relation to those on the Island of Ischia carried out by DE ASTIS et al. (2004) suggests new dates for the volcanic edifices (table 1). The dates are ~ 74 (Pozzo Vecchio) and ~ 18 ky BP (Solchiaro). The same authors, in accordance with DEINO et al. (1992 and 1994) and DE VIVO et al. (2001), dated the breccias (Breccia Museo trachytic formation) to 37–39 ky BP and related them to the proximal *facies* of the ignimbrite formation (ROSI & SBRANA 1987, PERROTTA & SCARPATI 1994, MELLUSO et al. 1995, ORSI et al. 1996).

Table 1 Absolute dating from various sources of some volcanic products outcropping in Procida and Vivara, conducted on underlying palaeosoils or on the roof of volcanic formations.

site	radiometric dating (ky BP)				
	Di Girolamo et al. 1984			Lirer et al. 1991	De Astis et al. 2004
	cycle	^{14}C	K/Ar	^{14}C	K/Ar and ^{14}C
Pozzo Vecchio					> 74–37
	I	40		> 37 (> 48)	
Vivara				34.05 ± 0.80	≥ 55–39.8
P. Ottimo and C. Bove (NW of Procida)	II		34 ± 0.80		
Vivara				31.46 ± 0.51	
Terra Murata (NE of Procida)	II–III	29 ± 0.80			
Fiumicello (NW of Procida)	II–III	26.7			> 55–29.8 ± 0.80
Vivara				22.14 ± 0.27	
Scotto di Carlo (N of Procida)	III			18.53 ± 0.14	
	III	19.62 ± 0.27		17.26 ± 0.14	
Solchiaro (SE of Procida)		14.1			< 18

On the mainland some violent explosive eruptions at about 15 ky BP generated *Neapolitan Yellow Tuff* (Deino et al. 2004), that outcrops locally on the Island of Procida as ashfall distal *facies* on top of the Breccia Museo trachytic formation (Lirer et al. 1991). Eruptions occurred in the western area of Naples and in Pozzuoli, generating many monogenic volcanic edifices in the Holocene, subsequent to the volcano-tectonic sinking of the Phlegrean caldera. These may be correlated to the volcano-tectonic events dated between about 9 and 5 ky BP. The Phlegrean eruptive cycle ended with the pyroclastic eruption of Monte Nuovo in 1538. The relic structures of volcanic edifices found in the Channels of Ischia and Procida may be correlated to ancient phases of volcanism on Ischia and in the Phlegrean Fields. Probably some are older than Vivara and have forms generated by both submarine and continental processes (de Alteriis et al. 1996, De Astis et al. 2004). On the islands there are exposed and submerged traces of old sea levels, roughly between +20 and −20 m, consisting of marine terraces with rock pools and gullies (Parascandola 1928b and 1947), caves, and fossil cliffs with wave cut notches. These features, at least those currently at major depths, were formed in a coastal environment during the sea-level stand preceding the last glacial peak and were subsequently remodelled (de Alteriis et al. 1996).

Metal objects found at the ancient settlement at Punta Mezzogiorno and the more recent structure at Punta dell'Alaca on Vivara have been attributed to the Aegean-Mycenaean period (Middle Bronze Age 1 and 2; Giardino 1998). Vivara Island has submerged anthropogenic structures that include a stairway with its base at about −9.5 m, cut into the pyroclastics at Punta Mezzogiorno, within the southern limit of the relic crater (Mocchegiani Carpano 2001). Since Roman times, the Phlegraean zones have been known for their thermal and bradyseismic phenomena (Günther 1903a and 1903b, Guerra et al. 1973, Scherillo 1973). The latter, occurring along the coastal strip between Monte di Cuma and Castel dell'Ovo in Naples (De Pippo et al. 1996a, 1996c and 1999), resulted in vertical oscillations of the soil that during the bradyseismic crises of 1970–1972 and 1982–1984 (Luongo et al. 1988, Dvorak & Mastrolorenzo 1991) led to an overall uplift of about 3 m, with its epicentre in Pozzuoli. Ruins of the Graeco-Roman period and Middle Ages up to about −10 and −5 m, together with morphostratigraphic evidences (Cocco et al. 1988, Cinque et al. 1991), show the magnitude of Phlegraean bradysismic movements in the last 2.5 ky. However, geomorphological or geoarchaeological evidence for bradyseismic phenomena has yet to be recorded for the islands of Procida and Vivara as well along the Vesuvian coast (De Pippo et al. 1996b).

3 *Geomorphological features*

According to Pliny and Servius, Procida (in the local dialect called *Pròcita*) owes its name of Greek origin *(Προκύτη, stretched out or lying down)* to its flattish form as seen from the sea. By contrast, Vivara (in the local dialect called *Bivàra*), is thought to have come from the Latin word *vereor* or *vivarium* indicating the presence of springs or a fish-farm in the Roman age according to Neumann (De Lorenzo & Riva 1900). It may well be derived from the root *(k)var* meaning *to curve*, preceded by *bi(s)*, *twice* (Pianigiani 1993), with reference to its double bow shape, typical of a relic marine volcano; or from the Akkadic *barum*, meaning *preserve* (Semerano

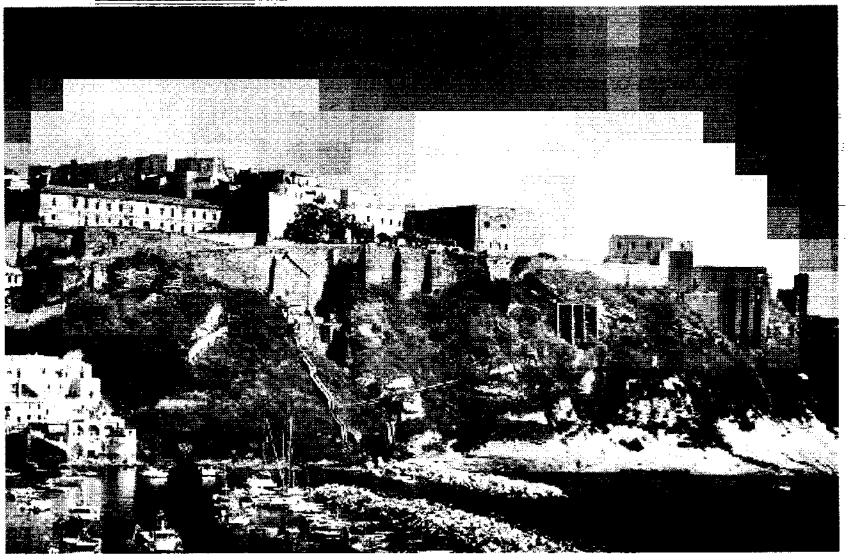

Fig. 4. Steep pyroclastic cliff with gullies of the relic volcano flank of Terra Murata, to the northeast of Procida.

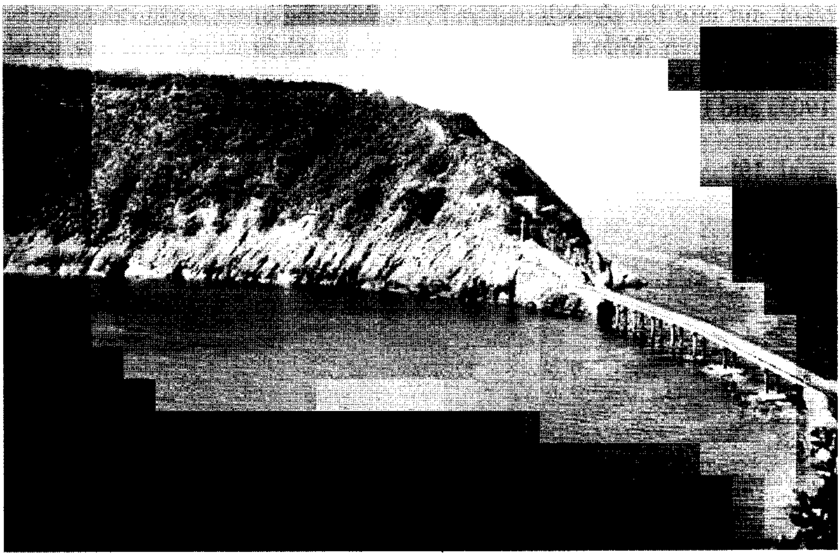

Fig. 5. The island of Vivara, with the level surface on the summit, and the bridge that joins the parts of its relic crater (Punta Capitello at Vivara, and Santa Margherita Vecchia at Procida); from the base to the top, the succession consists of Vivara formation, Formiche di Vivara ancient deposits, Ischia pumice fall unit and Formiche di Vivara recent deposits.

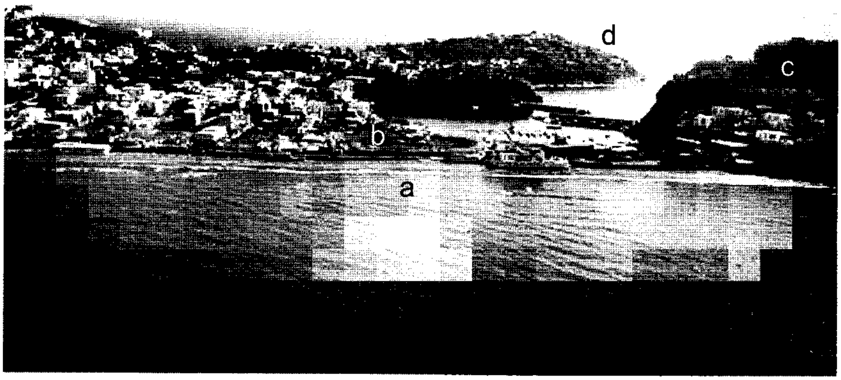

Fig. 6. The southern sector of Procida: a) sand beach of Ciraccio-Chiaiolella; b) sand tombolo of Chiaiolella-Campo Inglese; c) promontory of Santa Margherita Vecchia; d) promontory of Punta Solchiaro, SE part of the relic volcano of Solchiaro.

1984), from which the word *Bewahrer* has been derived. Neumann indicated that from the Greek period the island had been a natural haven for ships from high seas. The island of Procida stretches for about 3 km in a SW-NE direction. It is about 2 km wide and flattish, with a mean height of 50 m and a maximum altitude of 91 m a. s. l. (Terra Murata; fig. 4). Vivara is situated to the southwest (fig. 5), close to Procida. It extends N-S for about 900 m and has a maximum height of 108 m. Access is gained from Procida over a bridge that joins the parts of its relic crater (Punta Capitello – Santa Margherita Vecchia). The central part of both islands are level, bounded by near-vertical coastal cliffs (fig. 1). The coast is marked by alternating semicircular bays, near-triangular coves and bow-shaped promontories resulting from the dismantling of craters of various ages, craters that are often concentric or overlain. The only areas with straight coastlines are those on Procida (Spiaggia di Ciraccio; fig. 6), to the west, and the northern strip (Sancio Cattolico) and that to the south on Vivara (Scola Frusta). Morphological highs occur at the centre of Procida (Starza), and also towards the northwest (Ottimo), northeast (Terra Murata) and southeast (Centane).

The most salient geomorphological aspects of the Phlegrean islands are related to the evolution of volcanic forms, consisting of the many relic craters, and of erosional forms modelled on the products of their eruptive activity. Moreover, subsidence and uplift of the Phlegrean area due to volcano-tectonic and bradyseismic events, together with late Würmian (MIS 2) sea level fluctuations, have played a major role in the physical layout of the landscape. Evidence for such episodes includes both submarine geoarchaeological elements and the presence of straight, deep and sloping gullies cut into the steep cliffs in the pyroclastics. The gullies are sometimes truncated, at other times they continue below the sea level with a narrow cross section. The hydrographic network is almost totally absent, but locally shows a centrifugal radial pattern, and only in places a centripetal one, strongly related to relic volcanic mor-

Table 2 New classification of volcanic edifices exposed and submerged at Procida and Vivara based on morphography (HEIKEN 1971) and main lithology (DI VITO et al. 1985); H/L indicates the ratio between the measured height and base diameter of the volcanoes.

volcano	lithology	shape (HEIKEN 1971)	morphography (H/L)	morphological classification (DI VITO et al. 1985)
Pozzo Vecchio	ash	ring-shaped	1/21	*ash ring*
Vivara	tuff	ring-shaped	1/12	*tuff ring*
Formiche di Vivara	tuff	ring-shaped	1/10	*tuff cone*
Fiumicello	tuff	(truncated) conical – ring-shaped	1/10–1/20	*tuff cone – tuff ring*
Terra Murata	tuff	(truncated) conical	1/10–1/20	*tuff cone – tuff ring*
Solchiaro	tuff	ring-shaped	1/20	*tuff ring*

phology. There are marine terraces which occur (between +6 and +20 m), and others are submerged at various depths (between −4 and −20 m). A summital levelled erosion surface of complex genesis occur. Well-preserved traces of palaeo-sea levels (wave cut notches, rock pools) are recorded in the exposed areas above (+2 m), and sometimes below (−4/−5 m), the sea level.

The volcanic edifices consist of relics left by volcano-tectonic collapses and both marine and continental erosion. Often less than 50 % is preserved of the original edifice with its subcircular or subelliptical base. The diameter of bases, rims, crater bases and heights of the volcanoes cannot always be correctly measured. Thus it was not possible to use the relationships between some of the indicators, such as the ratio of the diameter of the crater base to the height of the volcano, for structural classification (TAZIEFF 1969a and 1969b). However, the morphography of tuffaceous volcanoes was inferred from the ratio between height and diameter at the base (HEIKEN 1971), extrapolated from newest form measurements indicating that most of the edifices were originally annular or of truncated cone to ring shape (table 2). These volcanoes may be classified on a strictly lithological basis (DI VITO et al. 1985) as tuff rings (Vivara, Solchiaro) or tuff cones (Formiche di Vivara) or where the original shape cannot be discerned as falling between the two types (Fiumicello, Terra Murata). The ash volcano of Fiumicello, with its conical ring-shape, may be classified as an ash ring (table 2). Currently, these islands are also shaped by waves and sea currents, surface run-off, weathering of the rocks, and gravity processes. The effects of their mutual interaction (pocket beaches, gullies, sea cliffs, rock piles, wave cut notches, marine terraces) are observable, especially along the coastal strip and in the underwater environment immediately offshore, where they tend to accelerate coastal retreat.

The perimeter of Procida mostly consists of eroding near-vertical cliffs as high as 40 m and only in some zones are there narrow strips of sand and pebbles (beaches of Ciracciello and Ciraccio to the west, Cimitero to the northwest, Sancio Cattolico to the north and Chiaia to the southeast). The beach of Cimitero is a pebbly pocket beach, delimited by the promontories of Punta Serra and Punta Ottimo, which has the well-preserved concave shape of a relic volcanic crater. The shoreline of the Ciracciello-Ciraccio complex, between Punta Capitello and Punta Serra, is the one most extensive (about 1,400 m). Unlike others it lies on a roughly straight NE-SW line. It consists of a beach about 15 m wide (Ciraccio) at the foot of a cliff, which at the Ciraccio stack joins up with a sandy tombolo (Chiaiolella-Campo Inglese). The tombolo, partly modified by human activities, has developed towards the once isolated relic northeastern slope of the Vivara edifice (Santa Margherita Vecchia), and partly towards the northwestern flank of the volcano of Solchiaro. There are also some stacks (fig. 7) generated by selective erosion processes (Ciraccio, Scoglio del Cannone, Scoglio dello Schiavone) and sometimes by rockfall (Punta dei Monaci) of pyroclastic products. Spits of sea terraces and traces of old sea levels are found in various zones on the islands. We observed no submerged marine terraces at depths exceeding −20 m, depths recorded only along the southeastern side of Procida and southwestern side of Vivara where the processes of demolition of the volcanic edifices and tuffaceous coastal cliffs have been intense and rapid. An exposed sea terrace, stretching for about 600 m and up to about 15 m wide, was noted along the southern side of the Bay of Solchiaro, as far as Punta Solchiaro. Along the cliffs and inside the relic craters (Solchiaro, Pozzo Vecchio) there are more or less deep (from about 1 up to 10 m) grooves with a V-shaped channel. Those that flow into the sea has created equilateral triangular-shaped coves (Carbogno), at times continuing below sea level down to about −20 m. Others dissect the cliffs on the flanks up to their bases (Ciraccio, Cimitero, Chiaia, Sancio Cattolico), are often truncated, and display the shape of an isosceles triangle.

Flatter summits of the islands of Procida and Vivara display a 7 to about 15 m thick covering with few or no channels made by water courses, unlike the island flanks in tuff. The cover material is unindurated pyroclastics, with interbedded palaeosoils dating from < 40 to ~ 4 ky BP as results from K/Ar and ^{14}C ages of the soils, of the upper or lower volcanic deposits (table 1; Di Girolamo et al. 1984, Lirer et al. 1991, De Astis et al. 2004), and from geoarchaeological data (Giardino 1998, Mocchegiani Carpano 2001). The origin of this morphology is complex. The forms may be attributed to erosive processes occurring in exposed environments which originated on flat surfaces both of islands. The summit of Procida slopes very gently (< 0.4°) towards north, while that of Vivara slopes northwest and southeast (< 3°). These surfaces are found on Procida at the margins of a central rise (Starza) and in a restricted depressed area towards northeast. On Vivara, by contrast, these occur along the crater and within a small flattish zone towards the southwest. The surfaces occur at different heights and cannot be correlated between islands. Below the strips of flat summital surfaces, outcrops of alternating ash and pumice occur along the pyroclastic cliffs at Punta dell'Alaca on Vivara, north of Santa Margherita Vecchia, at the beach of Ciraccio, and east of Pozzo Vecchio on Procida. Three interbedded palaeosoils that mark three continental palaeo-surfaces are now buried within such layers. These deposits at Santa Margherita Vecchia lie between the Fiumicello and the Breccia Museo formations.

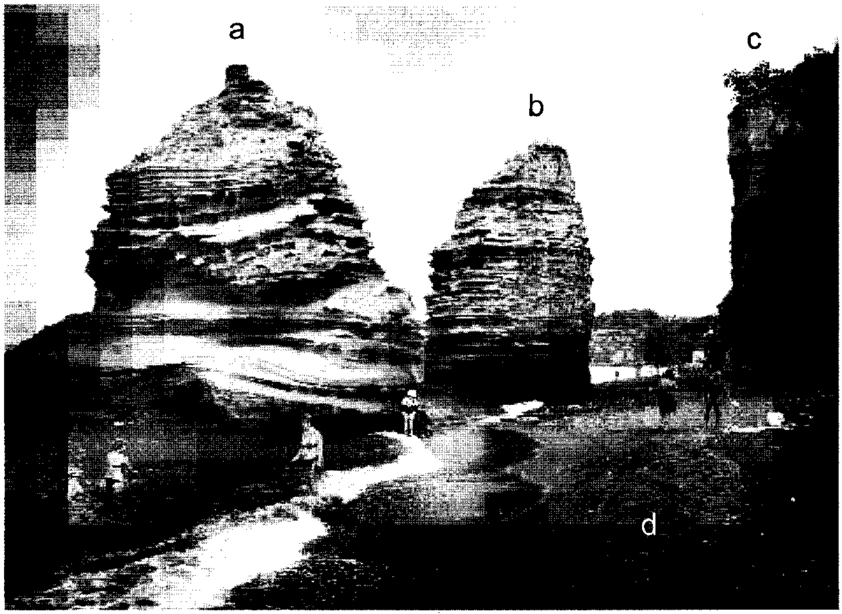

Fig. 7. The pyroclastic stacks of Ciraccio (a and b), close to the retreated sea cliff (c) back to the Ciraccio sand beach (d), to the southwest of Procida; in the past one stack was joined to the coast by a natural arch subsequently collapsed.

4 *Palaeoecology*

During the geomorphological investigation of the area we observed two sand levels, showing backshore and shoreface sedimentological features. Two sand samples (P1, +2.5 m and P2, +3 m) were collected from the Cimitero beach (fig. 8), in the NW of Procida. The deposition of these sand layers took place between the Breccia Museo and the Solchiaro formations, at the base of the third cycle (DI GIROLAMO et al. 1984). The aim of the paleoecological study of these sediments was to verify the presence of marine sediments between the first and the last cycle. Paleobathymetry estimation allow to quantify for the first time the extent and rate of the vertical movements in the study area. The present section is a synthesis of a detailed microfaunal study (AIELLO et al., in progress). Sample P2 is devoid of fossil remains. Sample P1 yielded bivalve fragments, gastropods, echinoderm spines, siliceous sponge spicules, rare specimens of planktonic foraminifers, ostracods and benthic foraminifers.

The benthic foraminifer and ostracod assemblages include 33 and 19 species respectively, listed in tables 3 and 4. Species percent frequencies are reported in the same tables. Both benthic foraminifers and ostracods are poorly preserved. Consequently, some taxa have been left in open nomenclature. The poor state of preservation is very probably related to a depositional environment with waters undersaturated in calcium carbonate. The assemblages are dimensionally heterogeneous and the valves of the ostracods are mainly unbroken. These features show that the assemblages are partly or entirely autochthonous. Most of the species found in P1 sample are marine and presently living in the Mediterranean Sea. The structure of the foraminiferal assemblage, dominated by *Ammonia beccarii* and *Elphidium crispum* but characterized also by taxa such as Anomalinidae, Bolivinidae, Buliminidae and *Cassidulina carinata*, fit well with the description of the biocoenoses recorded by Blanc-Vernet (1969) on coastal detritic bottoms.

Pontocythere turbida, *Cytheridea neapolitana* and *Semicytherura incongruens* dominate the ostracod assemblage; this dominance, together with the presence of taxa such as *Costa edwardsi*, *Cytherella vulgatella*, *Buntonia sublatissima* and *Microcytherura (Tetracytherura) angulosa*, suggests a shallow neritic palaeo-environment. It cannot be excluded that some specimens were displaced from shallower waters, hence the not-dominant "deeper" taxa (present or more abundant below −20/−30 m depth) are highly significant for a paleobathymetric reconstruction. On comparing the available ecological data for the Mediterranean Sea, the ostracod number of species/number of specimens ratio (= 0.165) and the very low planktonic/benthic foraminifer ratio (= 1/303), suggest a palaeodepth estimation of −30/−60 m (most probably about −40 m depth) on a muddy sand substrate.

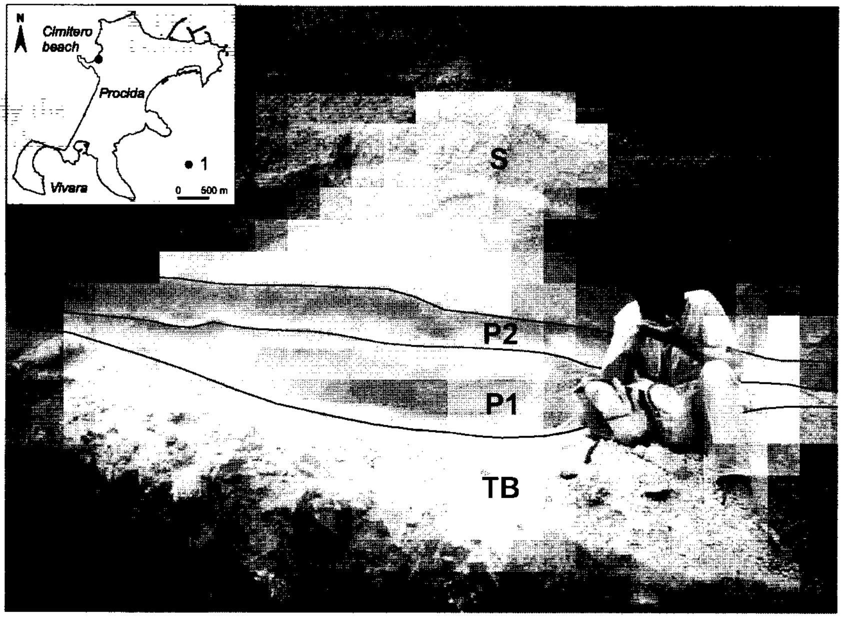

Fig. 8. Marine (P1) and continental (P2) deposits sampled respectively at +2.5 and +3 m along the beach exposed at Cimitero, to the northwest of Procida Island, on which palaeoecological analyses were conducted. 1: sampling area; TB: trachytic breccia of Pozzo Vecchio; P1: infralittoral marine sediments with microfossils; P2: aeolian reddish sediments; S: Ischia tephra.

Table 3 List of benthic foraminifers, number of specimens (n. s.), and species percent frequencies in P1 sample (see text for details).

SPECIES	n. s.	%
FORAMINIFERIDA		
Nodosariidae		
Lenticulina gibba (D'ORBIGNY 1839)	1	0,11
Fissurina aff. *F. orbignyana* SEGUENZA 1862	1	0.11
Bolivinitidae		
Bolivina aenariensis (COSTA 1856)	1	0.11
Bolivina catanensis SEGUENZA 1862	1	0.11
Buliminidae		
Bulimina aculeata D'ORBIGNY 1826	6	0.66
Bulimina elongata D'ORBIGNY 1846	11	1.21
Bulimina marginata D'ORBIGNY 1826	5	0.55
Reussella spinulosa (REUSS 1850)	1	0.11
Uvigerinidae		
Uvigerina mediterranea HOFKER 1932	4	0.44
Discorbidae		
Buccella granulata (DI NAPOLI ALLIATA 1952)	18	1.98
Neoconorbina terquemi (RZEHAK 1888)	6	0.66
Rosalina sp.	2	0.22
Valvulineria bradyana (FORNASINI 1900)	1	0.11
Asterigerinidae		
Asterigerinata mamilla (WILLIAMSON 1858)	45	4.95
Spirillinidae		
Spirillina vivipara EHRENBERG 1843	1	0.11
Rotaliidae		
Ammonia beccarii (LINNEO 1758)	420	46.2
Ammonia perlucida (HERON-ALLEN & EARLAND 1913)	4	0.44
Elphidiidae		
Elphidium complanatum (D'ORBIGNY 1839)	3	0.33
Elphidium crispum (LINNEO 1758)	286	31.46
Elphidium cuvilleri LÉVY 1966	4	0.44
Elphidium granosum (D'ORBIGNY 1846)	3	0.33
Elphidium macellum (FICHTEL & MOLL 1798)	2	0.22
Elphidium maioricense COLOM 1942	1	0.11
Elphidium punctatum (TERQUEM 1878)	6	0.66
Elphidium sp. A SGARRELLA & MONCHARMONT ZEI 1993	8	0.88
Elphidium sp.	2	0.22
Cibicididae		
Planulina ariminensis D'ORBIGNY 1826	2	0.22
Hyalinea baltica (SCHROETER 1783)	2	0.22

Table 3 continued.

SPECIES	n. s.	%
Cibicides lobatulus (WALKER & JACOB 1798)	30	3.3
Cassidulinidae		
Cassidulina carinata SILVESTRI 1896	7	0.77
Nonionidae		
Pullenia bulloides (D'ORBIGNY 1846)	1	0.11
Anomalinidae		
Cibicidoides pachyderma (RZEHAK 1886)	18	1.98
Melonis barleanum (WILLIAMSON 1858)	6	0.66

5 *Morphoevolutionary reconstruction*

On the basis of the morphological features of the volcanic edifices, the reciprocal morphostratigraphic ratios and radiometric age of the eruptive products indicated by the literature, palaeo-environmental analyses, geoarchaeological data and soil-borings, we propose the probable reconstruction of the main morphoevolutionary phases of the island system (fig. 9, table 5).

The Pozzo Vecchio volcano was formed during the first phase (75–40 ky BP), followed by the formation of the island of Vivara volcano, of the lava dome or pyroclastics to the southwest of Vivara and of the Formiche di Vivara and Ruommoli banks volcanoes in the Ischia Channel. The deposition of infralittoral marine sediments along the Cimitero beach followed. The genesis of the Fiumicello volcano, the deposition of pyroclastic products of Ischia (VEZZOLI 1988), as well as the genesis of the buried palaeo-surfaces both at Procida and Vivara up to subsequent stable period in vertical movements, the formation of the Punta Serra volcanites, of the lava dome of Punta Ottimo, of the Terra Murata volcano and of the presumed or currently buried Montaùto volcano or lava dome (IMBÒ et al. 1964, SEGRE 1967), marked by a high morphostructural relief, followed.

During the second phase (40–30 ky BP), there was volcano-tectonic activity along the northwestern sector of Procida. There was the deposition of Phlegrean trachytic breccias (Breccia Museo) at Vivara and Procida. Initial subsidence of this area was followed by an uplift with displacement of these marine deposits, and deposition of aeolian reddish sediments of the Cimitero beach.

During the third phase (30–18 ky BP), an eruptive stasis and a general stability in vertical movements of both the islands were registered.

The Solchiaro volcano was formed during the fourth phase (18–15 ky BP), and finally volcanic activities ended at about 15 ky BP. Probably the eruptive centres shifted progressively clockwise until about 18 ky BP when volcanic development on the islands ceased.

Table 4 List of ostracods, number of specimens (n. s.), and species percent frequencies in P1 sample (see text for details); j: presence of juvanile specimens.

SPECIES	n. s.	%
OSTRACODA		
Platycopida		
Cytherellidae		
Cytherella vulgatella AIELLO et al. 1996	j	
Podocopida		
Cytherideidae		
Cyprideis torosa (JONES 1850)	4 j	3.48
Cytheridea neapolitana KOLLMANN 1860	34 j	29.57
Cushmanidae		
Pontocythere turbida (G. W. MÜLLER 1894)	39 j	33.91
Trachyleberididae		
Bosquetina sp.	1	0.87
Buntonia sublatissima (NEVIANI 1906)	1	0.87
Carinocythereis sp.	j	
Cistacythereis (H.) turbida (G. W. MÜLLER 1894)	3	2.61
Costa edwardsi (ROEMER 1838)	2	1.74
Pterygocythereis sp.	j	
Hemicytheridae		
Urocythereis flexicauda BONADUCE et al. 1976	2	1.74
Urocythereis sp. 1 Barra 1997	3	2.61
Loxoconchidae		
Loxoconcha ovulata (O. G. COSTA 1853)	2	1.74
Lococoncha sp.	1	0.87
Paracytherideidae		
Paracytheridea sp.	1 j	0.87
Cytheruridae		
Microcytherura (T.) angulosa (SEGUENZA 1880)	1	0.87
Semicytherura incongruens (G. W. MÜLLER 1894)	18	15.65
Semicytherura sulcata (G. W. MÜLLER 1894)	2	1.74
Semicytherura tergestina MASOLI 1968	1	0.87

Vertical ground movements occurred during the fifth phase (15–5 ky BP). General subsidence was followed by an uplift with partial displacement of sea terraces that are currently present between +6 and +20 m on Procida. The subsequent stable conditions were marked by the deposition of the pyroclastic products of Phlegrean continental volcanoes Fondi di Baia on Procida and probably on Vivara.

During the sixth and final phase (5 ky BP – present-day), a new uplift displaced the wave cut notch of Punta Solchiaro at +2 m as well as the sea terraces present on Procida. The deposition on Procida and Vivara of the most recent pyroclastics of Phlegrean continental volcanoes Fondi di Baia and of the fallout from the northeastern sector of Ischia followed (Rosi et al. 1988a and 1988b; Vezzoli 1988). As we highlighted for the first time, the complex origin of flat surfaces (~4.3–3.8 ky BP) on the top of Procida and Vivara occurred almost contemporaneously, followed by a marked subsidence at Vivara until Middle Ages (XV century). Subsequently, the sandy tombolo and a lagoon environment evolved, followed by a marshland that has disappeared. Finally, since medieval times, the complex morphodynamics has been characterised by general vertical stability.

Briefly, the present-day formation and morphological evolution have been controlled by differential vertical ground movements that have interacted with the glacial eustatic sea level fluctuations in the last 40 ky. Along broad sectors of the islands, at least three uplift phases due to volcano-tectonics, are characterized by considerable displacement (+50/+90 m) and time interval (up to 4 ky). These uplifts alternated with at least three subsidence phases of lesser magnitude (up to –20 m) and of similar time interval. These phases are separated by at least two periods of general vertical stability and by a third period which is still continuing. Each explosive eruptive phase was followed by volcano-tectonic collapse and progressive crater dismantling, at times with submarine collapse of older volcanic edifices (Formiche di Vivara, Ruommoli), connected with a general subsidence.

The multi-cyclical late-Würmian (MIS 2) sea terraces of order I (–18/–20 m) found in the Channel of Ischia, on Procida and Vivara were first lowered and then remodelled by the sea during the postglacial eustatic rise, while new terraces of order II (–12/–15 m), III (–10/–12 m), IV (–6/–8 m) and V (–4 m) were incised both along the flanks (II–IV) and on the summit of the same pyroclastic structures, due to levelling of the crater rim (IV–V), in the Channel of Ischia, on Procida, Vivara and in the Channel of Procida. In the last case, the sea terraces assumed the shape of a sickle, which may still be observed in places (banks of Formiche di Vivara, Ruommoli and Capo Bove), inherited by the slightly lowered remnants of the crater rim. By contrast, the late Quaternary sea terraces found between +6 and +20 m were disturbed by at least two phases of volcano-tectonic uplift at about 9 and 5.5 ky BP, with a period of general stability in between, as in the Phlegrean coastal area of La Starza (Cinque et al. 1985).

The formation of the sandy tombolo of Chiaiolella-Campo Inglese, southeast of Procida, is likely to have occurred after this last uplift which affected part of the sea bed and may well be related to the subsequent deposition of pyroclastic ejecta, accumulated since the most recent Holocene climatic *optimum* (Cotecchia et al. 1996). The tombolo led to the development of a lagoon followed by marshland behind it, northeast of the promontory of Santa Margherita Vecchia, gradually filled in with marine and continental sediments. These transitional environments are recognised in recent archaeological surveys and soil-borings (Comune di Procida 2002) due to

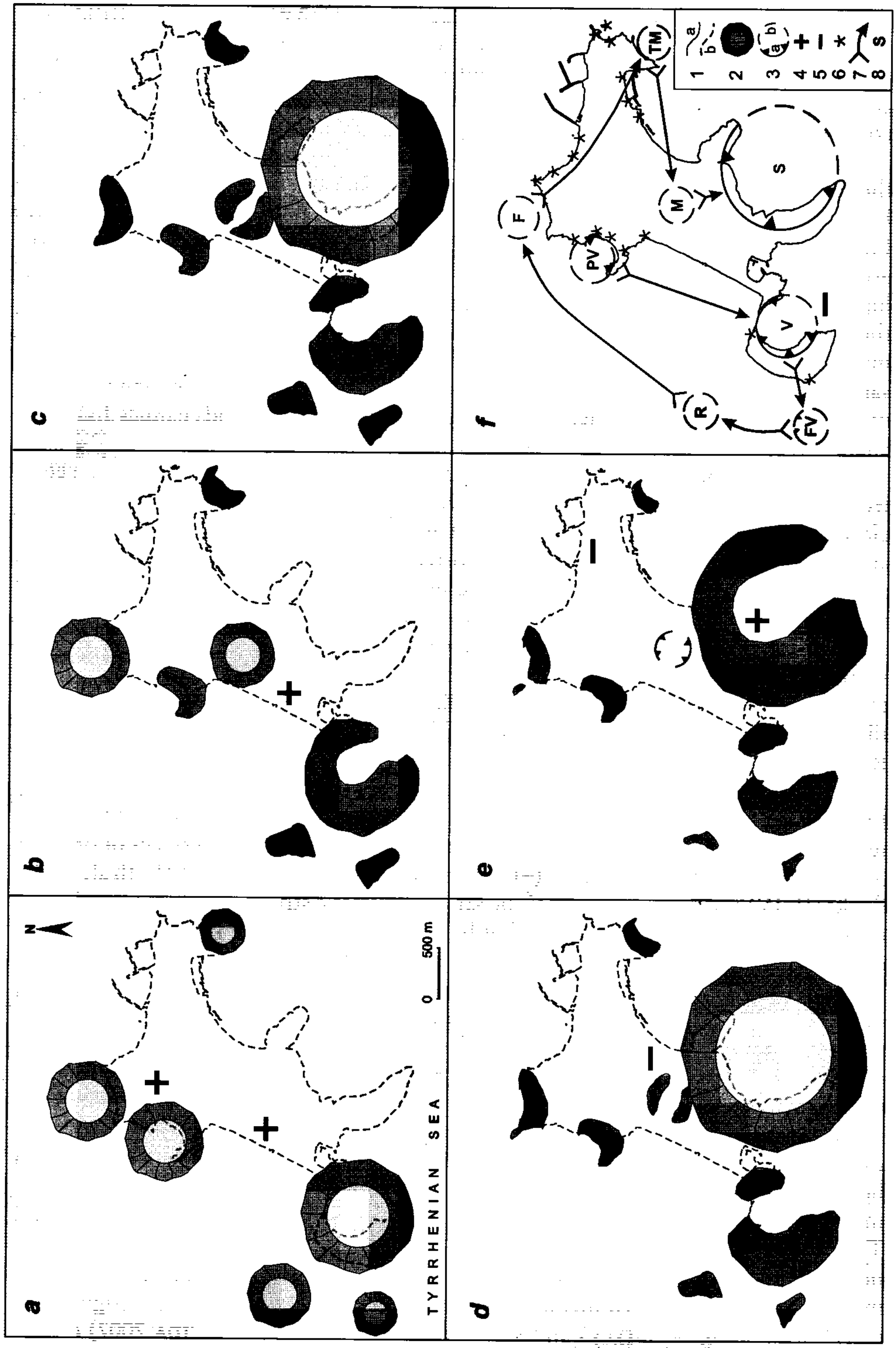
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Fig. 9. Reconstruction of the probable geomorphologic evolution of the island volcanic system of Procida-Vivara; a) 75–40 ky BP: genesis of the Pozzo Vecchio, of the island of Vivara and of the Fiumicello volcanoes; formation of the structure to the southwest of Vivara Island, of the volcanic edifices of the Formiche di Vivara and Ruommoli in the Ischia Channel; deposition of infralittoral marine sediments of the Cimitero beach; deposition of the pyroclastics of Ischia; formation of the Punta Serra volcanites, of the lava dome at Punta Ottimo, of the Terra Murata volcano and of the presumed or currently buried Montaùto volcano or lava dome; genesis of the palaeo-surfaces buried on Procida and Vivara; b) 40–30 ky BP: deposition of trachytic breccias (Breccia Museo) on Vivara and Procida; subsidence phase of the northwestern sector of Procida uplift phase of the northwestern sector of Procida with displacement of infralittoral marine deposits along the Cimitero beach; deposition of aeolian reddish sediments of the Cimitero beach; c) 30–18 ky BP: eruptive stasis and general stability in vertical movements; d) 18–15 ky BP: genesis of the Solchiaro volcano; deposition on Procida of the *Neapolitan Yellow Tuff* formation; end of the volcanic activities; e) 15–5 ky BP: general subsidence, followed by an uplift with partial displacement of the sea terraces currently present between +6 and +20 m on Procida; general vertical stability, with deposition on Procida and Vivara of the oldest pyroclastic products of Phlegrean continental volcanoes; f) 5 ky BP – present-day: uplift with displacement at +2 m of the wave cut notch of Punta Solchiaro and of the sea terraces present between +6 and +20 m on Procida; deposition on Procida and Vivara of the most recent pyroclastics of Phlegrean continental volcanoes, and of the pyroclastics from the northeastern sector of Ischia; formation of the level summital surfaces of complex origin on Procida and Vivara; marked subsidence at Vivara; development of the sandy tombolo and of the marsh to the southwest of Procida; gradual in-fill of the marsh; recent phase of general stability of vertical soil movements and demolition of the volcanic edifices due to erosional processes. 1) current coastline (a) and reference trace (b); 2) volcanic edifice; 3) crater rim: a) relic; b) reconstructed or buried; 4) uplifting area; 5) subsiding area; 6) trachytic breccias outcropping; 7) probable migration of main eruptive centres; 8) abbreviation of volcano name: PV, Pozzo Vecchio; V, Vivara; FV, Formiche di Vivara; R, Ruommoli; F, Fiumicello; TM, Terra Murata; M, Montaùto; S, Solchiaro.

Table 5 Scheme of the main morphoevolutionary phases in the last 75 ky of the island volcanic system of Procida-Vivara, based on volcanological, morphostratigrafic, palaeoecological and geoarchaeological data.

phase		volcanic, morphological or geoarchaeological data		tectonics
n°	age range (ky BP)	site	product/indicator	
I	75–40	Pozzo Vecchio Vivara Fiumicello	pyroclastics	
		Cimitero beach	foraminifer and ostracods analysis	
		Vivara and Procida	palaeo-surfaces	
		SW of Vivara, Formiche di Vivara, Ruommoli	pyroclastics	alternation of uplift, volcano-tectonic collapse and subsidence
		Vivara and Procida	pyroclastics of Ischia	
		Punta Serra, Punta Ottimo, Terra Murata, (Montaùto)	pyroclastics and/ or lava domes	
II	40–30	Vivara and Procida	Breccia Museo	subsidence
III	30–18		marine terraces	uplift
IV	18–15	Solchiaro Procida	pyroclastics *Neapolitan Yellow Tuff*	 stable
		end of volcanic activities		
V	15–5	Vivara and Procida	marine terraces pyroclastics of Phlegrean Fields	subsidence uplift
		Vivara and Procida	wave cut notches, marine terraces pyroclastics of Phlegrean Fields pyroclastics from the NE of Ischia	stable uplift stable
VI	5 – present day	Vivara Punta Mezzogiorno	palaeo-surface Aegean-Mycenaean submerged ruins	
		Campo Inglese	brakish water fish and mollusc fossils, Graeco-Roman fish hooks, peat levels in soil borings	subsidence
		Vivara and Procida	wave cut notches, marine terraces	stable

the presence of brackish water fish and mollusc fossil species, Graeco-Roman fish hooks, and peat levels. Finally, from the Graeco-Roman period to medieval times subsidence caused buildings from the Aegean-Mycenaean age to be submerged up to about –9.5 m (Punta Mezzogiorno on Vivara), followed by a more recent phase of general vertical stability.

6 *Discussion and conclusions*

The morphogenetic processes that contributed to modelling the landscape and the current physiography of the islands are connected to endogenous processes and to the interaction between the passive morphostructure and the exogenous processes since 75 ky BP, the period of the earliest volcanic outcrops (Ischia, Vivara and submerged relic volcanoes in the Channel of Ischia). The processes of degradation and dismantling of the volcanic slopes were intense during the last glacial (MIS 2) and the post-glacial phase of sea level rise. Coastal terraces submerged between –4 and –20 m, are thought to have been formed both before and after the Last Glacial Maximum (~ 18 ky BP). In particular, the deeper ones (> 15 m) are the result of polycyclic evolution during the post-glacial sea level rise along with vertical ground oscillations of volcano-tectonic origin.

For the first time palaeo-environmental reconstruction of the beach of Cimitero on Procida, based on palaeobathymetric data (–30/–60 m) regarding microfossil associations, and their present-day location (+ 2.5 m) have been carried out. The chronological attribution between the periods of volcanic formations of the trachytic breccia of Pozzo Vecchio and the Ischia tephra between which the marine sediments analysed were deposited, as well as the corresponding eustatic levels for the Tyrrhenian Sea (– 18 and – 25 m; Alessio et al. 1996, Waelbroeck et al. 2002), would indicate an overall uplift of 50 to 90 m due to volcano-tectonic causes. The corresponding mean rates are between + 0.7 and + 1.2 mm/year, most probably around + 0.9 mm/year given that the most likely palaeodepth of – 40 m estimated for the microfossil associations.

The magnitude of the differential uplift in this area of Procida, albeit considerable, is well below that calculated with eustatic correction for the fossiliferous marine sediments on Ischia, distributed at varying heights due to volcanic and tectonic disturbances. Indeed, the late Pleistocene sediments of Cava di Leccie (Mt. Epomeo), in the northwest of Ischia, deposited at ~ 55 ky BP (Vezzoli 1988) at – 70/– 120 m and uplifted to + 350 m (Barra et al. 1992a), display an average rate of 8.7 mm/year. The Holocene sediments at Cafieri, in the northeast of Ischia, deposited at – 50/– 80 m about 9.8 ky BP and raised to + 4 m (Barra et al. 1992b), also show very high average rates (10–13 mm/year). In contrast, sediments at Le Querce on Ischia, formed at – 40/– 50 m about 6.4 ky BP and raised to + 1.8 m (Barra et al. 1992b), have average rates comparable with those to the northwest of Procida (0.9–2.2 mm/year). Moreover, the magnitude of the uplift of Holocene fossiliferous marine sediments of the La Starza terrace at Pozzuoli is not comparable with that of Procida, but it is similar to that of Cafieri on Ischia. Such sediments, deposited between – 10 and – 50 m and uplifted to + 30 m after intense volcano-tectonic events and bradyseism (Zamparelli et al. 1983, Cinque et al. 1985, Amore et al. 1988a and 1988b, Barra 1991), display an overall uplift between 40 and 80 m in two phases between 9 and 5 ky BP, corresponding to higher average rates (8–16 mm/year) than on Procida. Thus, the southern sector of Procida in the late Pleistocene would appear to have undergone independent vertical movement of lesser magnitude than those on the adjacent sectors of Ischia and the Phlegrean Fields, probably controlled by volcano-tectonic phenomena rather than bradyseism.

As regards the age of the stairway cut into the pyroclastics at Punta Mezzogiorno on Vivara, it is attributed to the Bronze Age (4.1–3.8 ky BP). Hence the current position of its base at –9.5 m depth is an important indicator of the overall subsidence occurring between the Aegean-Mycenean period (~3.8 ky BP) and the present. This may be estimated at about 2.5 mm/year, with a brief sea level stand in medieval times perhaps attested by a weak, but more or less continuous, coastal terrace with rock-pools at about –6 m. The depth of such submerged palaeo-coastlines may be correlated with those found in the Bay of Pozzuoli (DE PIPPO et al. 1984, COCCO et al. 1988, CINQUE et al. 1991, DONADIO et al. 1994) and along the Naples coastline (GUNTHER 1903a, 1903b and 1913, DE PIPPO et al. 1996a and 1996c), related to the Graeco-Roman (–10/–12 m) and medieval coastlines (–5 m) and connected to bradyseismic phenomena. Calculation of the mean rates of vertical movement in these areas, in the period between 3.7–1.8 ky BP and the present-day (DE PIPPO et al. 1999), results in values between 0.2 and 0.8 mm/year, lower than those on Vivara.

The buried surfaces marked by three palaeosoils, found at sites on Procida and Vivara, are positioned between the Fiumicello volcanites and the Breccia Museo trachytic formation. Hence, on the basis of the age of these formations their genesis may be attributed probably to the time range > 55–39 ky BP during a phase of stability in vertical movements.

The level surfaces on the summits of both islands are of different heights. Thus three surfaces may be distinguished, at decreasing heights from southwest to northeast (+82/+108, +35/+61, +26/+30 m) on beds of pyroclastic ejecta, characterised by the presence of three interbedded palaeosoils. The oldest pyroclastics may probably be ascribed to the products of several eruptions occurred on Ischia (VEZZOLI 1988), lying below that of Solchiaro, while the most recent are attributed to the Phlegrean eruptions and to that of the northeastern sector of Ischia. In volcanological terms these pyroclastics are syngenetic and polyphasic, while their summital surfaces are coeval morphologies, in that they probably originated on inherited palaeo-morphologies (relics of crater rims, intracrater depressions) on which the above volcanites were later deposited. Apparently such substantial subsidence on Procida and/or uplift on Vivara of a volcano-tectonic nature does not justify the displacement of a single level surface, with a gap between the nearest strips of about 50 m, after the formation of more recent pyroclastics. For the same reason, even considering the subsidence of about 10 m in historical times, supported by geoarchaeological data, the level surfaces along the relic of the crater rim of Vivara were most probably generated after the collapse and dismantling of this volcanic edifice. Such surfaces represent palaeomorphologies. However, it cannot be ruled out that there was a general subsidence of the ground between approximately 28 and 20 ky BP, that is, after the formation of more ancient pyroclastics of Ischia, but before more recent ones of Phlegrean Fields and of the northeastern sector of Ischia. This subsidence appears to coincide with a phase of stasis in the eruptive activity on the islands recorded also in the Phlegrean area (DI GIROLAMO et al. 1984), followed lastly by the formation of products of the last and most extensive eruption of Solchiaro on Procida. In this case, the palaeo-surfaces which are now buried and delimited by three palaeosoils, would be polycyclic in origin. Dating of the most recent pyroclastic products from Phlegrean Fields and Ischia and the discovery of Aegean-Mycenean metal artefacts on Vivara (GIARDINO 1998) also allows us to attribute the genesis of the surfaces on the summit to the time interval between 4–3.5 ky BP. Finally, the development of the sandy tombolo of Chiaiolella-Campo Inglese probably occurred during the Graeco-Roman period and was completed in the 15^{th}–16^{th} century. Subsequently the sandbar stabilised, entailing – probably in the 20^{th} century – the loss due to gradual in-fill of a marshland that formed in medieval times. This area was subject to considerable human impact in the past 50 years.

The data analysed appear to show that ground movements, from the late Pleistocene until historical times, have affected a more extensive area westwards and are not only confined to the gulfs of Pozzuoli and Naples but also appear to have controlled the complex structure of the volcanic island system of Procida-Vivara.

Achnowledgements

The authors are most grateful to Prof. Vincenzo Morra, Earth Science Department – University of Naples Federico II (Italy), and to Prof. Alessandro Sbrana, Earth Science Department – University of Pisa (Italy), for invaluable informations respectively about local pyroclastics of Procida-Vivara volcanic system and about pyroclastic products of Island of Ischia also outcropping at Procida and Vivara.

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