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RESEARCH ARTICLE

F. Lucchi · C. A. Tranne · N. Calanchi · P. L. Rossi

Late Quaternary deformation history of the volcanic edifice of Panarea, Aeolian Arc, Italy

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Abstract A series of raised palaeoshorelines is documented along the emergent coastal slopes of Panarea and surrounding islets at elevations of 115 (palaeoshoreline Ia) and 100 m a.s.l. (Ib), 62.5 m (II), 35 m (III), 12 m (IV), 10–12 (Va) and 5 m (Vb). According to stratigraphic constraints and cross-cutting relationships, these palaeoshorelines are correlated with discrete high sea-level stillstands during marine oxygen-isotope stages (MIS) 5e, 5c, 5a and 3. Coastal elevation changes suggest the occurrence of a long-term, sustained uplift trend of the volcanic edifice since the last interglacial (last 124 ka). The uplift rates are not constant but display a progressive deceleration from maximum values of 1.5–1.58 m/ka, in the period between 124 and 100 ka, down to the lowest values of 0.66–0.69 m/ka, which tend to be constant starting from 81 ka BP. The long-term deformation pattern of Panarea suggests that a transitory, volcano-related component of uplift interplayed with the regional tectonic component affecting the sub-volcanic basement, which has undergone a persistent and widespread uplift since the mid-Pleistocene. The volcano-related component of uplift, prevailing between 124 and 100–81 ka, is interpreted as the result of visco-elastic deformation mechanisms which characterize the progressive re-equilibration of the shallow magmatic system following the incoming quiescence of the volcanic edifice. The long-term uplift values at Panarea are higher than in the main portion of the western-central Aeolian Arc, where a mean uplift rate of 0.34 m/ka was estimated since the last interglacial (last 124 ka). Such a pattern of deformation on a regional scale may be a response to active deformation processes connected with the southeastward rollback of the subducting Ionian slab which is still active only in correspondence with the eastern sector of the Aeolian Arc (including Panarea). In the short-term, a localized submergence trend has been documented at the nearby islet of Basiluzzo for the last 2,000 years, likely connected to neo-tectonic movements along main NE–SW trending faults.

Keywords Panarea · Aeolian arc · Palaeoshorelines · Coastal elevation changes · Uplift · Volcano-related deformation · Late quaternary

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F. Lucchi (✉) · C. A. Tranne · N. Calanchi · P. L. Rossi
Dipartimento di Scienze della Terra e Geologico-Ambientali,
Università degli Studi di Bologna,
Piazza Porta S. Donato 1,
40126 Bologna, Italy
e-mail: lucchi@geomin.unibo.it
Tel.: +39-51-2094936
Fax: +39-51-2094904

Introduction

The volcanic edifice of Panarea belongs to the Aeolian Arc, a late Quaternary volcanic structure located along the northwestern side of the Calabrian Arc, Southern Tyrrhenian Sea, in one of the most active coastal regions of the whole Mediterranean Basin. Our aim is to reconstruct the long-term deformation history of Panarea and make a comparison with its eruptive history for the purpose of investigating the relative role played by volcano-related deformation on a local scale and sustained tectonic deformation along active plate boundaries on a regional scale. Because of its critical location between the western-central sector of the Aeolian Arc and the active volcano of Stromboli, the definition of the deformation pattern of Panarea may provide a contribution to the understanding of the still controversial geodynamic significance of the Aeolian volcanism.

Crustal vertical movements at Panarea since the last interglacial are here reconstructed by evaluating coastal elevation changes recorded by marine palaeoshorelines which are documented along the emergent coastal slopes. Raised marine palaeoshorelines are valuable palaeosea-level indicators and are frequently adopted as reference markers for detecting deformation by isolating the tectonic contribution to relative sea-level changes (Lajoie 1986, and references therein; Bosi et al. 1996; Bordoni and Valensise 1998). This approach is not usual in volcanic settings which may be characterized by marked vertical instability and

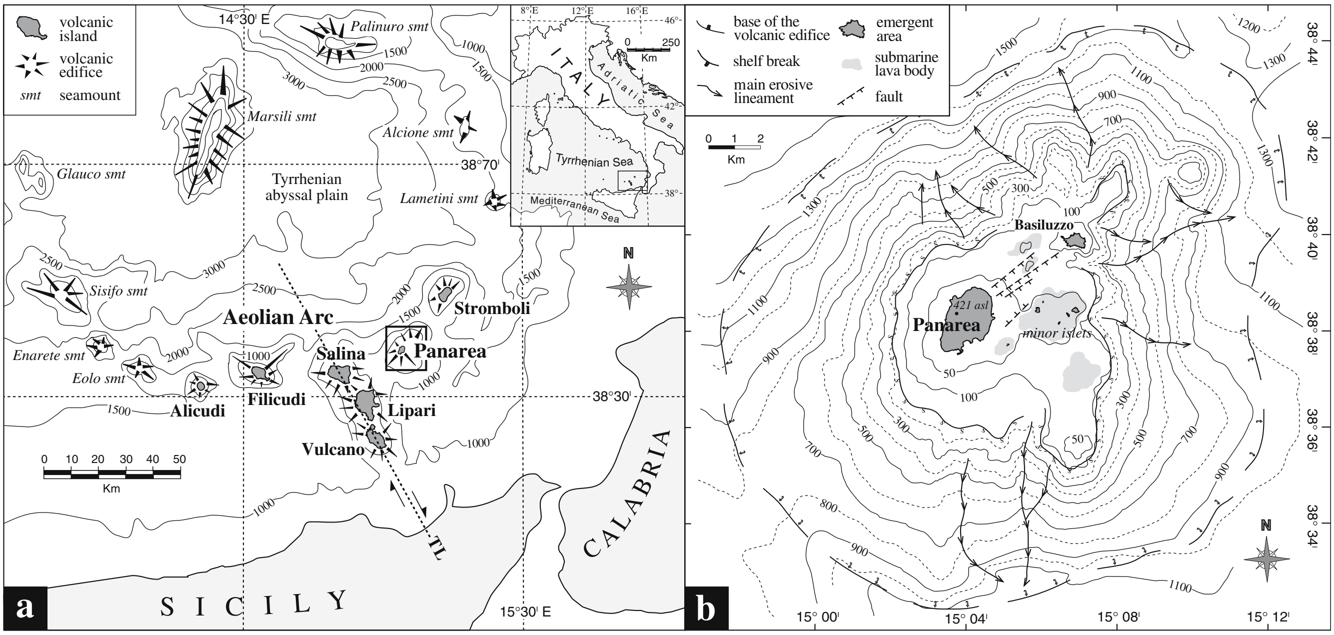


Fig. 1 **a** Bathymetry of the Southern Tyrrhenian Basin and location of the Aeolian Arc (modified from Beccaluva et al. 1985); the trace of the Tindari Letojanni (*TL*) litospheric structural line is shown (from Neri et al. 2003, and references therein). **b** Morphostructural sketch map of the submarine portion of the volcanic edifice of Panarea and minor islets (modified from Gabbianelli et al. 1993). Coordinates conform to the Gauss-Boaga System (IGM). Depth *contour lines* in m b.s.l.

frequent inversions from positive to negative vertical displacements that can make the evaluation of the deformational behaviour difficult (Bartolini and Carobene 1996). Nevertheless, the use of palaeoshorelines is applied to the volcanic edifice of Panarea for its uncommon, well-preserved succession of datable marine terraces and notches located above the present sea level, as well as for the detailed knowledge of stratigraphic relationships between palaeoshorelines and volcanic products (Calanchi et al. 1999; Lucchi et al. 2003). The reconstruction of the long-term deformation history of Panarea by means of analysis of coastal elevation changes represents a further contribution to the understanding of the geological evolution of the volcanic edifice, in addition to more typical geophysical, volcanological, structural and petrochemical studies.

Geological and structural setting

Panarea (3.5 km^2, together with surrounding islets) is the smallest island of the Aeolian Arc (Fig. 1a), a Quaternary volcanic structure located along the northwestern side of the Calabro-Peloritan block in the Southern Tyrrhenian Sea (Barberi et al. 1973, 1974; Barone et al. 1982; Beccaluva et al. 1982, 1985; Gasparini et al. 1982; Gillot 1987; Ellam et al. 1988). The Aeolian Arc is made up of seven volcanic islands whose distribution is strongly controlled by regional fault systems (De Astis et al. 2003, and references therein). Panarea is located, together with Stromboli, in the eastern sector of the Aeolian Arc, which is bounded by the NNW–SSE Tindari-Letojanni lithospheric structural line, striking from the central portion of the Aeolian Arc to Mt. Etna (Lanzafame and Bousquet 1997; Falsaperla et al. 1999; De Astis et al. 2003; Neri et al. 2003). The volcanic edifices of Panarea and Stromboli form a broad volcanic belt extending for more than 45 km along a NE–SW direction (Gabbianelli et al. 1993). In particular, the mainly submarine volcanic edifice of Panarea rises from a depth of 1,300 m below sea level (b.s.l.) up to 421 m above sea level (a.s.l.; Fig. 1b). The island of Panarea and the surrounding islets (Basiluzzo to the NE, the small rocks of Le Formiche and the islets of Dattilo, Panarelli, Lisca Bianca, Bottaro and Lisca Nera, hereafter termed minor islets, to the E) are the emergent tips of this volcanic edifice. They rise from its submarine, almost flat summit, which is marked by a clear shelf break (at an average depth of 130 m b.sl.; Fig. 1b) likely formed by marine erosion during the last glacial lowstand (Chiocci and Romagnoli 2004).

Both submarine and subaerial portions of the volcanic edifice of Panarea are conditioned by a main NE–SW and a minor NNW–SSE tectonic trend which are outlined by faults, the orientation of dykes, and by the alignment of volcanic structures (Calanchi et al. 1999, and references therein). The main NE–SW tectonic trend is in response to an extensional stress field in a NW–SE direction, whereas the minor NNW–SSE tectonic trend is likely the surficial expression of the Tindari-Letojanni structural line (Falsaperla et al. 1999; De Astis et al. 2003). Main events of tectonic instability occur along the NE–SW structural system; in particular, some NE–SW normal faults are combined in a complex horst-and-graben structure that affects the top portion of the island of Panarea (Fig. 2), causing the entire western flank to be unstable and slump seaward.

Volcanic activity at Panarea and minor islets, starting at 150 ka BP (Calanchi et al. 1999), is mainly characterized by the emplacement of lava domes, plugs, coulees and lava flows (Fig. 2), which are high-K calcalkaline andesite to dacite and rhyolite in composition (Calanchi et al. 1999, 2002b); pyroclastic deposits are subordinate. According to the recently revised stratigraphy (Lucchi et al. 2003), the eruptive history is divided into six successive eruptive epochs (*sensu* Fisher and Schminke 1984; Fig. 3) that are periods of volcanic activity separated by quiescence stages when reworking processes in subaerial and marine environment were prevalent. The main island of Panarea, and likely the minor islets, were almost entirely built up during the first five eruptive epochs, developing in a relatively short time span between about 150 and 105 ka (Figs. 2 and 3). During the last 100 ka, volcanic activity at Panarea and minor islets is characterized by the emplacement of the endogenous dome of Basiluzzo and of two pumiceous pyroclastic layers (l1 and l2–3 layers; Fig. 3). Widespread pyroclastic deposits of external provenance, well known in the area of the Aeolian Arc as Brown Tuffs (Crisci et al. 1981, 1983; Losito 1989; Lucchi 2000; Tranne et al. 2002a,b), were emplaced at Panarea and surrounding islets during several discrete eruptive events that occurred between about 70 and 8 ka (Fig. 2). Some other tephras of external provenance are intercalated within the Brown Tuffs succession and provide significant chronologic and stratigraphic constraints (Fig. 3). There is no evidence of volcanic activity at Panarea and minor islets during the last 8 ka.

Methodology

The field evidence of palaeoshorelines is mainly represented by well-exposed terraced surfaces and, subordinately, by marine notches (Fig. 4). Commonly, shallow-water conglomerate overlies the terraced surfaces and, in places, beach gravels and sands occur. Fossiliferous sediments consisting of fragments of *Briozoi*, several mollusc shells, encrusting calcareous algae and algal nodules occur SW of Piano Milazzese (Pichler 1968; Corselli and Travaini 1989) along the slope which links the flat area of Piano Milazzese with the present seashore.

Relict features are related to former sea levels (palaeoshorelines) mainly by evaluating the elevation of significant geomorphologic markers, e.g. the inner margins and marine notches, which are usually assumed to indicate the elevation of the palaeoshorelines at a relative sea-level highstand (Lajoie 1986). The fossiliferous sediments are related to a palaeoshoreline by defining their depositional environment.

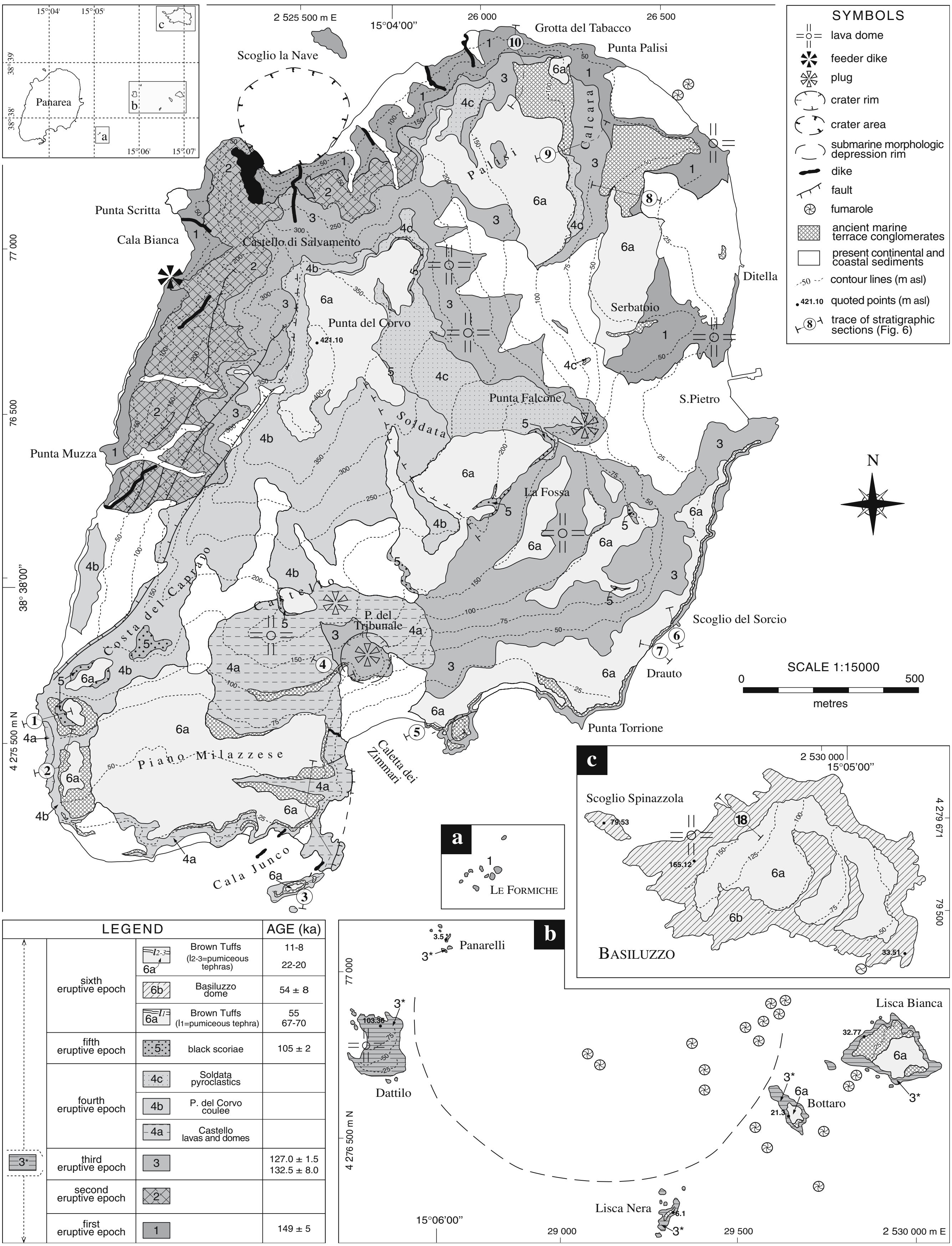
Elevations were always estimated in reference to the present mean sea level by averaging readings on a pocket altimeter; the measures were positioned (and so checked) on topographic maps at 1:10,000 and 1:5,000 scale, so that the analytical error is less than ±2.5 m. Moreover, different degrees of accuracy must be taken into account owing to the precise identification and measurement of the markers.

Marine notches are in general the best morphological indicators of former sea levels notably in the restricted tidal range (less than 0.5 m) environment of the Mediterranean Sea (Carobene and Pasini 1982; Pirazzoli 1986; Firth et al. 1996; Rust and Kershaw 2000). On the other hand, at Panarea their direct measurement sometimes is complicated owing to their outcropping conditions on steep coastal cliffs. Therefore, in this work, the most significant geomorphic feature is the inner margin of a marine terrace, which is an accurate datum for establishing former sea level because it developed within the tidal range (Orme 1998; Trenhaile 2002). The measurement of the elevation of the inner margin is in general much more complicated, owing to the uncertainty in the assessment of its correct position, because of the cover of recent deposits and of local erosional reshaping of the terraces. In the case of Panarea, however, the inner margins usually show clear morphological field evidence (Fig. 5) and good lateral continuity (Fig. 4), so that the error in the estimation of their elevation can be generally controlled within ±2.5 m.

Palaeoshorelines

By correlation of the elevation of inner margins and marine notches and by means of detailed stratigraphic and cross-cutting relationships, a set of several raised palaeoshorelines is reconstructed along the eastern slopes of the island of Panarea and on the islets of Lisca Nera, Bottaro and Lisca Bianca (Fig. 4). The palaeoshorelines are arranged in order starting with those occurring at the highest elevation and according to their relative chronology: palaeoshoreline I at 115 (±2.5) m (Ia) and 100 (±5) m a.s.l. (Ib), palaeoshoreline II at 62.5 (±2.5) m, palaeoshoreline III at 35 (±2.5) m, palaeoshoreline IV at 12 (±3) m and palaeoshoreline V at 10–12 (±2.5) m (Va) and 5 (±2.5) m (Vb). Ranges of elevation are provided for assessing the analytical error and the possible error deriving from the uncertain evaluation of position and elevation of inner margins and notches. Palaeoshorelines Ia, II and III show the best morphological evidence and provide the most clear elevation and spatial identification (Fig. 5). A continuous and complete staircase of palaeoshorelines either did not form or is not preserved in any part of the island of Panarea (Fig. 4) because the palaeoshorelines may be missing or laterally discontinuous owing to subaerial reworking processes, marine erosion during the formation of younger palaeoshorelines, or local tectonic instability along NE–SW-oriented tectonic structures.

Palaeoshorelines are assigned a relative age through accurate definition of the stratigraphic relationships between volcanic products and marine deposits related to each palaeoshoreline (Fig. 6). Moreover, the cross-cutting relationships between distinct successive palaeoshorelines are taken into account. Then, according to the general assumption that their formation corresponds to interglacial stillstands (Lajoie 1986, and references therein; Trenhaile 2002), the palaeoshorelines are attributed (and so dated) to discrete high sea level stillstands corresponding to marine



SYMBOLS
lava dome
feeder dike
plug
crater rim
crater area
submarine morphologic depression rim
dike
fault
fumarole
ancient marine terrace conglomerates
present continental and coastal sediments
contour lines (m asl)
quoted points (m asl)
trace of stratigraphic sections (Fig. 6)
Panarea
2 525 500 m E
15°04'00"
26 000
26 500
Grotta del Tabacco
Punta Palisi
Scoglio la Nave
Palisi
Calcara
Punta Scritta
Cala Bianca
Castello di Salvamento
77 000
Ditella
Serbatoio
Punta del Corvo
421.10
Punta Falcone
S.Pietro
76 500
Soldata
Punta Muzza
La Fossa
N
38° 38'00"
Costa del Capraro
Castello
P. del Tribunale
Scoglio del Sorcio
Drauto
SCALE 1:15000
0
500
metres
4 275 500 m N
Piano Milazzese
Punta Torrione
Caletta dei Zimmari
Cala Junco
LE FORMICHE
Scoglio Spinazzola
79.53
165.12
2 530 000
15°05'00"
4 279 671
79 500
33.51
BASILUZZO
LEGEND
AGE (ka)
sixth eruptive epoch
Brown Tuffs (l2-3=pumiceous tephras)
11-8
22-20
Basiluzzo dome
54 ± 8
Brown Tuffs (l1=pumiceous tephra)
55
67-70
fifth eruptive epoch
black scoriae
105 ± 2
fourth eruptive epoch
Soldata pyroclastics
P. del Corvo coulee
Castello lavas and domes
third eruptive epoch
127.0 ± 1.5
132.5 ± 8.0
second eruptive epoch
first eruptive epoch
149 ± 5
Panarelli
3.5
77 000
103.36
Dattilo
4 276 500 m N
Lisca Bianca
32.77
Bottaro
21.3
Lisca Nera
6.1
15°06'00"
29 000
29 500
2 530 000 m E

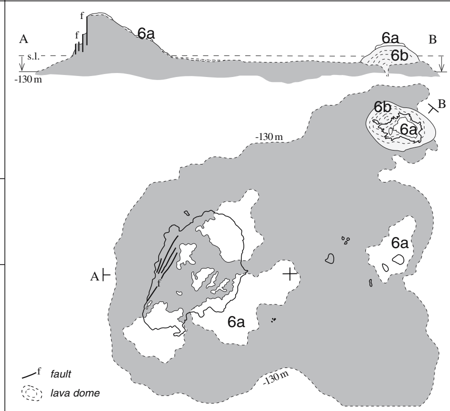
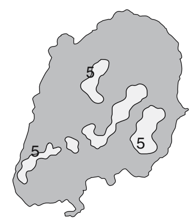
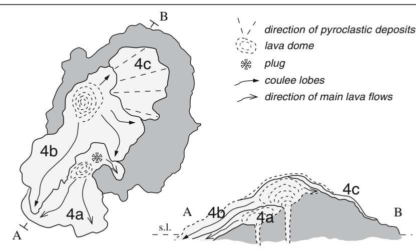
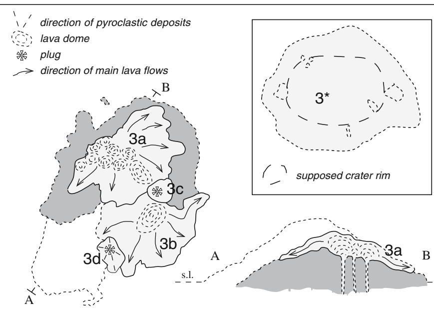
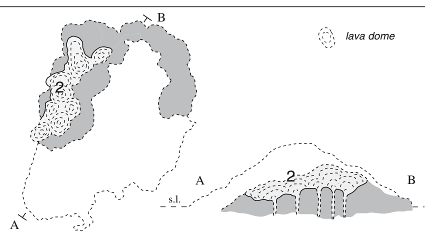
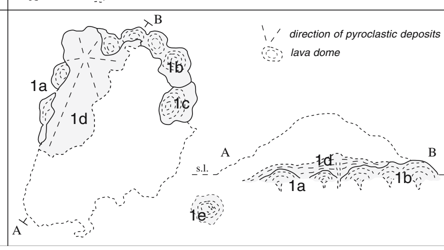
◀**Fig. 2** Geological sketch map of Panarea and surrounding islets: **a** Le Formiche rocks; **b** area of minor islets; **c** Basiluzzo islet. Volcanic products are displayed according to the reconstructed eruptive history (labels relate to the successive eruptive epochs); see Fig. 3 for dating references. The distribution of marine terrace conglomerates is shown. The location of stratigraphic sections of Fig. 6 is also provided. Coordinates conform to the Gauss-Boaga System (IGM)

oxygen-isotope stages (MIS) 5 and 3 (Fig. 7). Even if precise global sea-level curves cannot be determined, the patterns are broadly similar to the eustatic curve of Chappell and Shackleton (1986), which is hereby assumed as a reference for the studied area.

The most elevated palaeoshoreline I developed between about 130 ka, the age of the underlying volcanic products of the third eruptive epoch (Fig. 6, sections 9–10), and about 105 ka, the age of the overlying scoriaceous deposits of the fifth eruptive epoch (Fig. 6, section 1). Within this stratigraphic interval, the shoreline occurs at two distinct elevations: main palaeoshoreline Ia is recorded at Palisi, northern Panarea, as a prominent terraced surface which is bordered by a well-developed inner margin at 115 (±2.5) m a.s.l. (Fig. 5a), whereas minor palaeoshoreline Ib occurs discontinuously in central and southern Panarea at an elevation of 100 (±5) m a.s.l. (Fig. 4). Cross-cutting relationships between the two palaeoshorelines are absent but, according to a general assumption of continuous crustal uplift, the palaeoshorelines are assigned a relative chronology where palaeoshoreline Ia, which occurs at higher elevations, is the oldest and palaeoshoreline Ib is the youngest. This chronology appears to be supported by the fact that palaeoshoreline Ib cuts volcanic products of the fourth eruptive epoch (Fig. 6, sections 1–2 and 4) whereas the pumiceous pyroclastics of Soldata, included in the same eruptive epoch, likely overlie marine deposits related to palaeoshoreline Ia (Fig. 6, sections 8–9). Within the time span stated above (between 130 and 105 ka), palaeoshorelines Ia and Ib can be attributed to two different episodes of sea-level stillstand during MIS 5e (Fig. 7). Indeed, the occurrence of a double high sea-level stillstand during MIS 5e has been known for a long time (Chen et al. 1991; Hearty and Dai Pra 1992; Gallup et al. 1994; Neumann and Hearty 1996; Edwards et al. 1997; Hearty and Kindler 1997; Hearty 1998; White et al. 1998; Hearty and Neumann 2001; Schellmann and Radtke 2004; Schellmann et al. 2004). At Panarea, palaeoshoreline Ia can be attributed to the main high sea-level stillstand of MIS 5e, for which we assume the age of 124 ka from the curve of Chappell and Shackleton (1986), which matches the ranges 128–120 ka BP (Esat et al. 1999; McCulloch and Esat 2000) and 130–118 ka BP (e.g. Chen et al. 1991; Stirling et al. 1998) which are generally indicated for the last interglacial. Palaeoshoreline Ib can be then attributed to a discrete, short-lived high sea-level stillstand at the end of MIS 5e. This episode of sea-level stillstand could correspond to a minor highstand peak dated at about 118 ka in the curve of Chappell and Shackleton (1986). On the other hand, if a model is adopted in which MIS 5e is represented by a single, prolonged sea-level highstand (Stirling et al. 1998; Waelbroeck et al. 2002), palaeoshorelines Ia and Ib may not record real sea-level fluctuations within MIS 5e, but they would document two discrete episodes of temporary sea-level stillstand occurring when the rate of sea-level rise is equal to the crustal uplift rate. In this case, the two episodes of sea-level stillstand could not be dated precisely but only attributed to a range of time spanning between about 130 and 118 ka, which is the total duration of the sea-level highstand corresponding to MIS 5e (Stirling et al. 1998; Waelbroeck et al. 2002).

Palaeoshoreline II is preserved along the whole eastern coast of Panarea and is represented by marine terraces at Calcara (north Panarea; Fig. 5b), Piano Milazzese (south Panarea) and Serbatoio (central Panarea), with the inner margin at an elevation of 62.5 (±2.5) m a.s.l. (Fig. 4). These terraces show the widest surfaces and the most continuous inner margins of the whole set and, therefore, palaeoshoreline II affords an excellent reference datum. Palaeoshoreline II cuts volcanic products of the third and fourth eruptive epochs (Fig. 6, sections 2–3 and 8) and undercuts terraces related to palaeoshorelines Ia and Ib (Fig. 6, sections 2 and 8–9). Therefore, its formation developed in the time span between the end of MIS 5e, which is the relative age of palaeoshorelines Ia and Ib, and about 70 ka, which is the maximum age of the overlying Brown Tuffs pyroclastic succession related to the sixth eruptive epoch (Fig. 6, sections 7–8). According to this time period (Fig. 7), palaeoshoreline II correlates with the high sea-level stillstand corresponding to MIS 5c, dated at 100 ka (Chappell and Shackleton 1986).

The fossiliferous sediments occurring SW of Piano Milazzese appear to be relevant to palaeoshoreline II when considering that the palaeoecological significance of the faunal assemblage indicates a submarine slope environment, with depths varying between −15 and −40 to −50 m, which is coherent with the elevation of that palaeoshoreline (Lucchi et al. 1999). The fossiliferous sediments are assigned a relative age by means of AAG (Amino Acid Geochronology method; Kaufman and Miller 1992) data provided by Belluomini (1985) and Hearty (1986), which have been reinterpreted in the light of our geomorphologic reconstruction. The formation of the fossiliferous sediments is attributed to MIS 5a/5c (Corselli and Travaini 1989; Lucchi et al. 1999), which is a confirmation of the attribution of palaeoshoreline II to the high sea-level stillstand of MIS 5c, based on stratigraphic and cross-cutting relationships. Palaeoshoreline III is preserved in central and southern Panarea (Fig. 4) and is represented by terraced surfaces showing inner margins at elevation of 35 (±2.5) me a.s.l. (Fig. 5c) and by a marine notch at the same elevation. These surfaces clearly undercut older terraces and, therefore, palaeoshoreline III must be considered more recent than palaeoshoreline II. Palaeoshoreline IV is recorded in the same areas of Panarea by scattered terraced surfaces at 12 (±2.5) m a.s.l. which undercut palaeoshoreline III (Fig. 8). As a consequence, palaeoshorelines III and IV developed in a common time span between the end of MIS 5c (100 ka; Chappell and Shackleton 1986), during which the older palaeoshoreline

ERUPTIVE HISTORY			
Eruptive epochs	Main features	Age (ka)	Volcano-stratigraphic sketch maps
sixth eruptive epoch	Upper Brown Tuffs (**6a**) and intercalated tephras of external provenance correlated to the Vallone del Gabellotto pyroclastic deposits from Lipari (dated at 11.4±1.8 and 8.6±1.5 ka; Cortese et al., 1986) and to the Monte Guardia Sequence from Lipari (dated at between 22 and 20 ka; Tranne et al., 2002a). A pumiceous pyroclastic layer (*l2-3*) is intercalated between these two external tephras: its grain size (up to 2.5 cm) and mineral content imply a local but still unknown provenance source.	8.6 ± 1.5 11.4 ± 1.8 22-20	
	Endogenous lava dome of Basiluzzo (**6b**), high-K calcalkaline rhyolitic in composition; it is dated at 54±8 ka (K/ar date; Gabbianelli et al., 1990).	54±8	
	Lower Brown Tuffs (**6a**) and intercalated tephras of external provenance correlated to the Grey Porri Tuffs from Salina (67-70 ka; Keller and Morche, 1993) and to the known Ischia Tephra (55 ka; Morche, 1998). A pumiceous pyroclastic layer (*l1*) is intercalated: its grain size (up to 2.5 cm) implies a local but still unknown provenance source.	55 67-70	
	angular unconformity relations and subaerial erosion		
fifth eruptive epoch	Scattered, black scoriaceous pyroclastics of Punta Falcone (**5**), calcalkaline basaltic to basaltic-andesitic in composition. Their grain size (up to 2 cm) implies a local source even if the corresponding eruptive vent is still poorly known: petrochemical analogies and the westward decrease of the deposit thickness suggest an hyphotetical provenance from the area of minor islets. The scoriae are constrained by the occurrence, at the top of the succession, of an alkaline tephra which correlates with the marine deep-sea X-5 layer, dated at 105±2 ka (Kraml, 1997)	105±2	
	angular unconformity relations and subaerial erosion		
fourth eruptive epoch	Plug, lava dome and lava flows of Castello (**4a**), lobate coulee and subordinate pyroclastic breccias of Punta del Corvo (**4b**), high-K calcalkaline andesite and dacite in composition. The pumiceous pyroclastic deposits of Soldata (**4c**), which are calcalkaline andesites to dacites, derive from a final explosive phase which determined the desctruction of the north-eastern front of the coulee of Punta del Corvo.		
	angular unconformity relations		
third eruptive epoch	Lava domes and lava flows of Palisi (**3a**) and La Fossa (**3b**), plugs of Punta Falcone (**3c**) and Punta del Tribunale (**3d**). The plug of Punta del Tribunale rises into the remnants of a tuff cone. High-K calcalkaline andesite to dacite in composition. The dome of La Fossa is dated at 132.5±8.0 (average K/ar date; Gabbianelli et al., 1990), whereas the plug of Punta del Tribunale at 127.0±1.5 (^{40}Ar / ^{39}Ar; Calanchi et al. 1999). The third eruptive epoch includes phases of volcanic activity also in the area of minor islets (**3***), where remnants of lavas and lava domes occur, as inferred by the age attribution of submarine lavas at 130.0±9.0 (K/ar date; Gabbianelli et al., 1990).	127±1.5 130±9 132.5±8	
	subaerial erosion (paleosol)		
second eruptive epoch	Lava domes, massive lavas and subordinate scoriaceous pyroclastics occurring in the sector of Cala Bianca (**2**). High-K calcalkaline andesite to dacite in composition.		
	subaerial erosion (paleosol)		
first eruptive epoch	Lava domes, lava flows and subordinate pyroclastics, high-K calcalkaline andesite to dacite in composition. Lava domes occur at Punta Scritta (**1a**), Grotta del Tabacco (**1b**) and Ditella (**1c**), whereas pyroclastics are exposed nearby Torricella (**1d**). The small rocks of Le Formiche (**1e**) consist of lavas. The oldest rocks are dated to 149±5 (^{40}Ar / ^{39}Ar; Calanchi et al. 1999).	149±5	

◀ **Fig. 3** Summary of the eruptive history of Panarea and minor islets organized in eruptive epochs (*sensu* Fisher and Schminke 1984) Dating references: Calanchi et al. 1999; Cortese et al. 1986; Gabbianelli et al. 1990; Keller and Morche 1993; Kraml 1997; Morche 1998; Tranne et al. 2002a

II was formed, and about 70 ka, which is the maximum age of the overlying Brown Tuffs pyroclastic succession (Fig. 6, sections 6–7; Fig. 9). This stratigraphic interval fits MIS 5a (Fig. 7) and, therefore, palaeoshorelines III and IV appear to document at Panarea a double high sea-level stillstand within MIS 5a. Indeed, this double occurrence is a possible confirmation of recent proposals on a wider scale (Potter and Lambeck 2003; Schellmann and Radtke 2004; Schellmann et al. 2004; Potter et al. 2004).

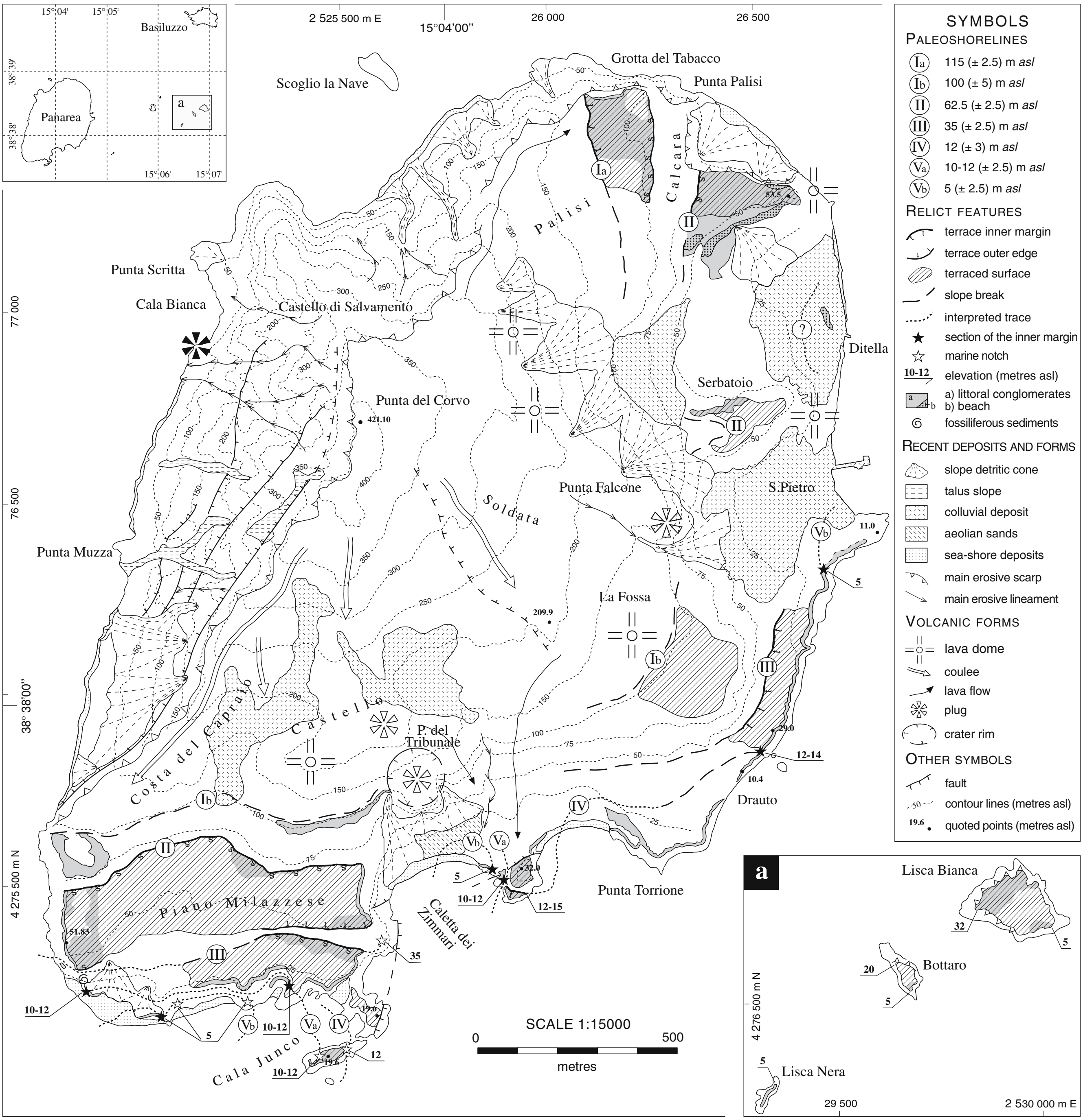


Fig. 4 Morphostructural sketch map of Panarea and of the islets of Lisca Nera, Bottaro and Lisca Bianca (**a**): areal and altimetric distribution of the field evidence of raised palaeoshorelines is highlighted. Main volcanic forms and recent deposits and forms are also shown. Coordinates conform to the Gauss-Boaga System (IGM)

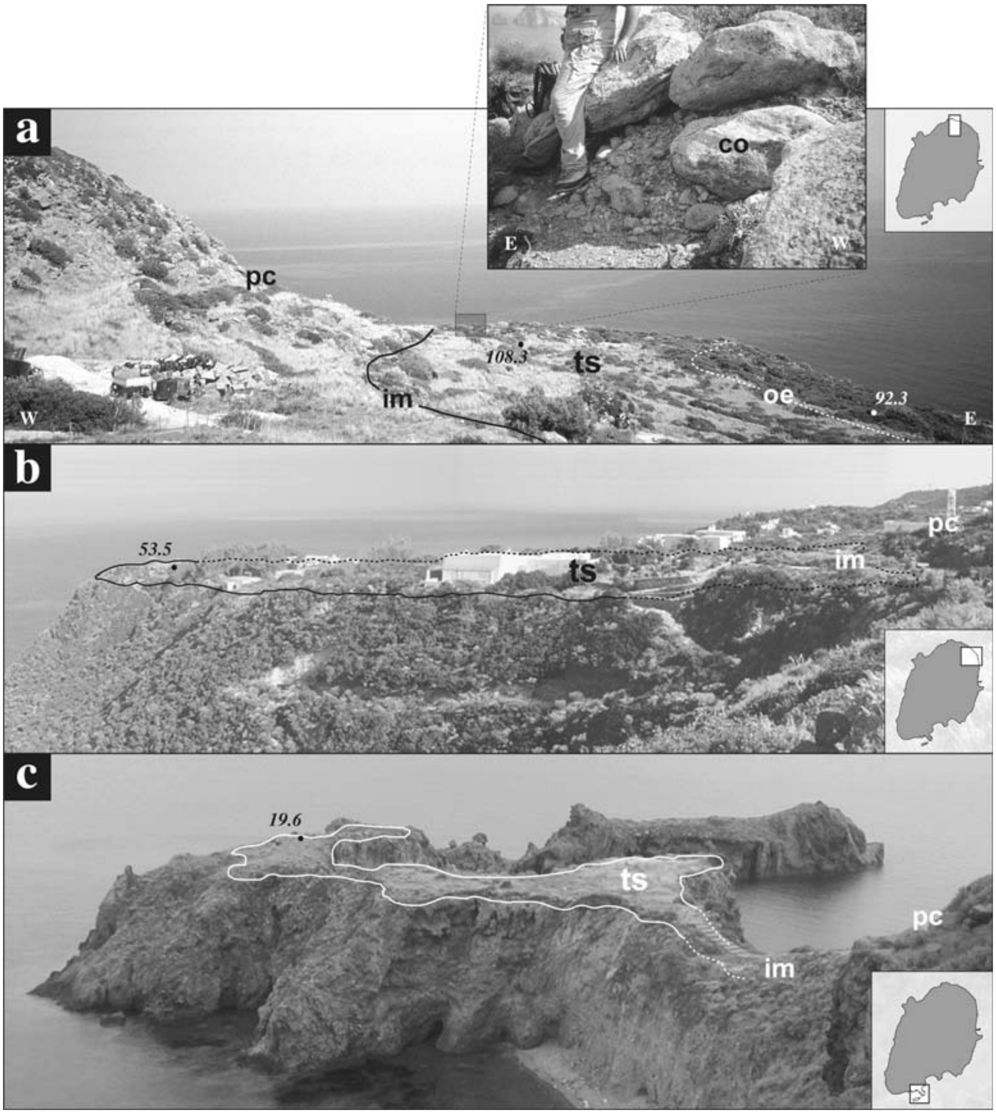


Fig. 5 Field evidence of main palaeoshorelines. Symbols: *im* inner margin; *ts* terraced surface; *oe* outer edge; *pc* palaeocliff. Quoted points are in metres a.s.l. **a** Palaeoshoreline Ia terraced surface at Palisi, north Panarea (inner margin at elevation of 115 m a.s.l.); the enlarged box highlights the occurrence of marine terraced conglomerate (*co*). Truck on the left for scale. **b** Palaeoshoreline II wide terraced surface at Calcara, north Panarea (inner margin at elevation of 60–65 m a.s.l.). **c** Palaeoshoreline III terraced surface occupying the entire top of the Villaggio Preistorico cape, south Panarea (inner margin at 35 m a.s.l.)

At Panarea, palaeoshoreline III is attributed to the main high sea-level stillstand within MIS 5a, which is dated at 81 ka in the curve of Chappell and Shackleton (1986). This is confirmed by the occurrence of pumiceous pyroclastics known as Petrazza tuffs from Stromboli (age of 80 ka; Lucchi et al. 2003), which are intercalated to the corresponding marine conglomerate in some places at Drauto (Fig. 9). Palaeoshoreline IV, which undercuts palaeoshoreline III, would record a short-lived episode of high sea-level stillstand during late MIS 5a, which could correspond to the minor sea-level highstand occurring at age of about 70 ka (Fig. 7) in the curve of Chappell and Shackleton (1986). On the other hand, if we adopt a model in which MIS 5a is represented by a single sea-level highstand (Waelbroeck et al. 2002), palaeoshorelines III and IV may record two different episodes of temporary sea-level stillstand when the rate of sea-level rise is equal to the crustal uplift rate. If so, the two episodes of sea-level stillstand within MIS 5a could not be dated precisely but only attributed to a range of time corresponding to the total duration of the sea-level highstand of MIS 5a (Waelbroeck et al. 2002).

Palaeoshoreline V is the least elevated in the staircase defined at Panarea. It discontinuously occurs at two distinct elevations in the central and southern Panarea (Fig. 4): palaeoshoreline Va is represented by small and scattered terraced surfaces and marine notches at elevations of 10–12 (±2.5) m a.s.l. and palaeoshoreline Vb occurs at 5 (±2.5) m a.s.l. crosscutting the higher palaeoshoreline Va. According to these elevations (and provided errors), palaeoshoreline Va can be partly superposed upon palaeoshoreline IV. On the other hand, the occurrence of two distinct stand-alone features in such a close range of elevations appears to be clearly outlined in one place in the area of Caletta di Zimmari (Fig. 8), where a small terraced surface related to palaeoshoreline IV, which is displaced by a N70E normal fault, is undercut by a narrow terrace occurring at a similar but lower elevation which is not affected by the same tectonic displacement and, therefore, is related to a distinct palaeoshoreline (that is palaeoshore-

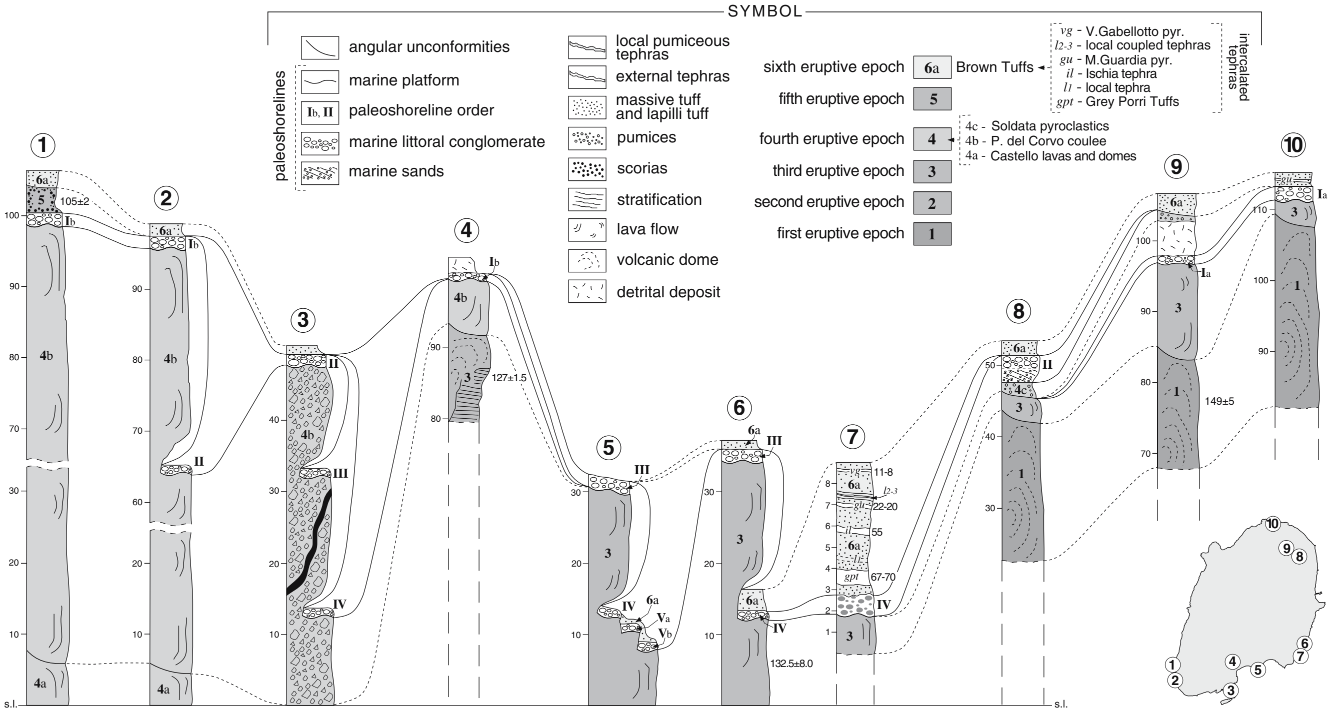


Fig. 6 Correlation of composite, synthetic stratigraphic sections along the eastern coast of Panarea, where the stratigraphic relationships between volcanic products and marine conglomerate related to the raised palaeoshorelines (Ia, Ib, II, III, IV, Va, Vb) are shown. Labels of volcanic products conform to Figs. 2 and 3. Age attribution (in ka) of volcanic products is also provided (see text and Fig. 3 for references). Vertical scale is given in metres a.s.l.

line Va). The formation of palaeoshorelines Va and Vb apparently occurred in a time span starting from the end of MIS 5a (81 ka; Chappell and Shackleton 1986), during which the formation of palaeoshoreline IV was likely to occur, up to 11–8 ka, which is the age of the most recent overlying Brown Tuffs (Fig. 6, section 5). Within this time span (Fig. 7), palaeoshorelines Va and Vb appear to fit MIS 3 and, in particular, they may be attributed to the main high sea-level stillstands of MIS 3, dated at 59 and 53 ka, respectively, in the sea level curve of Chappell and Shackleton (1986).

Remnants of palaeoshorelines also occur in the area of minor islets (Fig. 4a): they are represented by relict terraced surfaces and marine conglomerate at elevations between 5 and 32 m a.s.l. on the islets of Lisca Bianca and Bottaro and by marine conglomerate on the rocks of Lisca Nera. Owing to the lack of significant geomorphologic features (e.g. inner margins and notches), they cannot be precisely related to former sea levels and, therefore, they could not be correlated with any of the palaeoshorelines defined on the island of Panarea. On the other hand, according to stratigraphic relationships, the formation of those marine

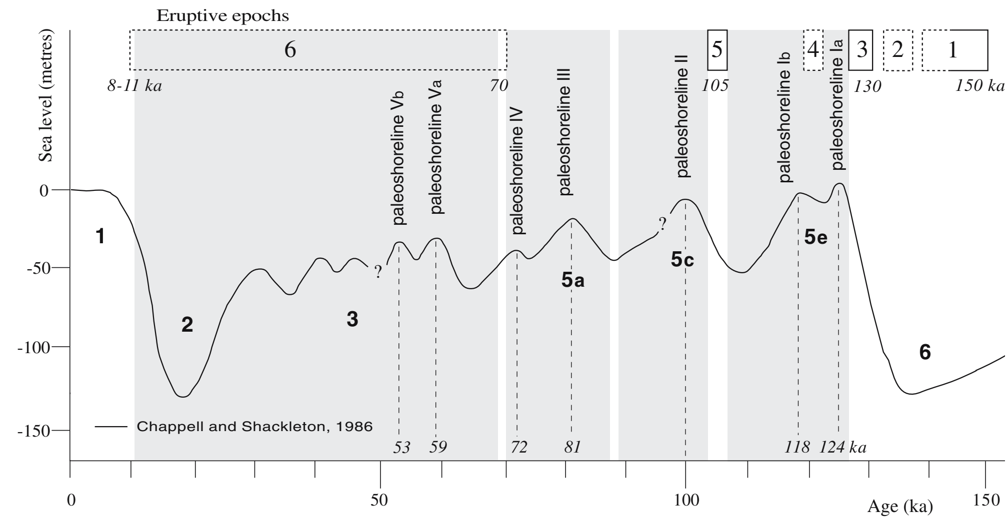


Fig. 7 Chronology of the palaeoshorelines at Panarea. The possible intervals of formation of the palaeoshorelines (in grey) are reconstructed by means of stratigraphic relationships with volcanic products (emplaced during the eruptive epochs) and of cross-cutting relationships. In the light of these intervals of formation, the palaeoshorelines are attributed to high sea-level stillstands of the curve of Chappell and Shackleton (1986), with the resolution of marine oxygen-isotope stages (MIS)

deposits and forms can be constrained to a time interval between about 130 ka, which is the inferred age of the underlying lavas, and about 70 ka, which is the maximum age of the overlying Brown Tuffs. Within this time span, the present elevation of the deposits suggests a questionable correlation with palaeoshorelines III and IV of the staircase derived from Panarea.

Finally, in the light of the provided chronologic attributions, none of the emersed morphological indicators of palaeoshorelines at Panarea appears to be related to the Holocene transgression, even if it cannot be excluded that possible evidence existed and then was eroded. Actually, the absence of Holocene features at Panarea and in the whole Aeolian Arc (Lucchi 2000; Calanchi et al. 2002a) is in contrast with Holocene occurrence in NE Sicily and Calabria (Pirazzoli et al. 1997; Rust and Kershaw 2000; Antonioli et al. 2002, 2003).

Coastal elevation changes

Coastal elevation changes recorded by raised palaeoshorelines within the study area represent the result of the interaction between Late-Quaternary sea-level fluctuations

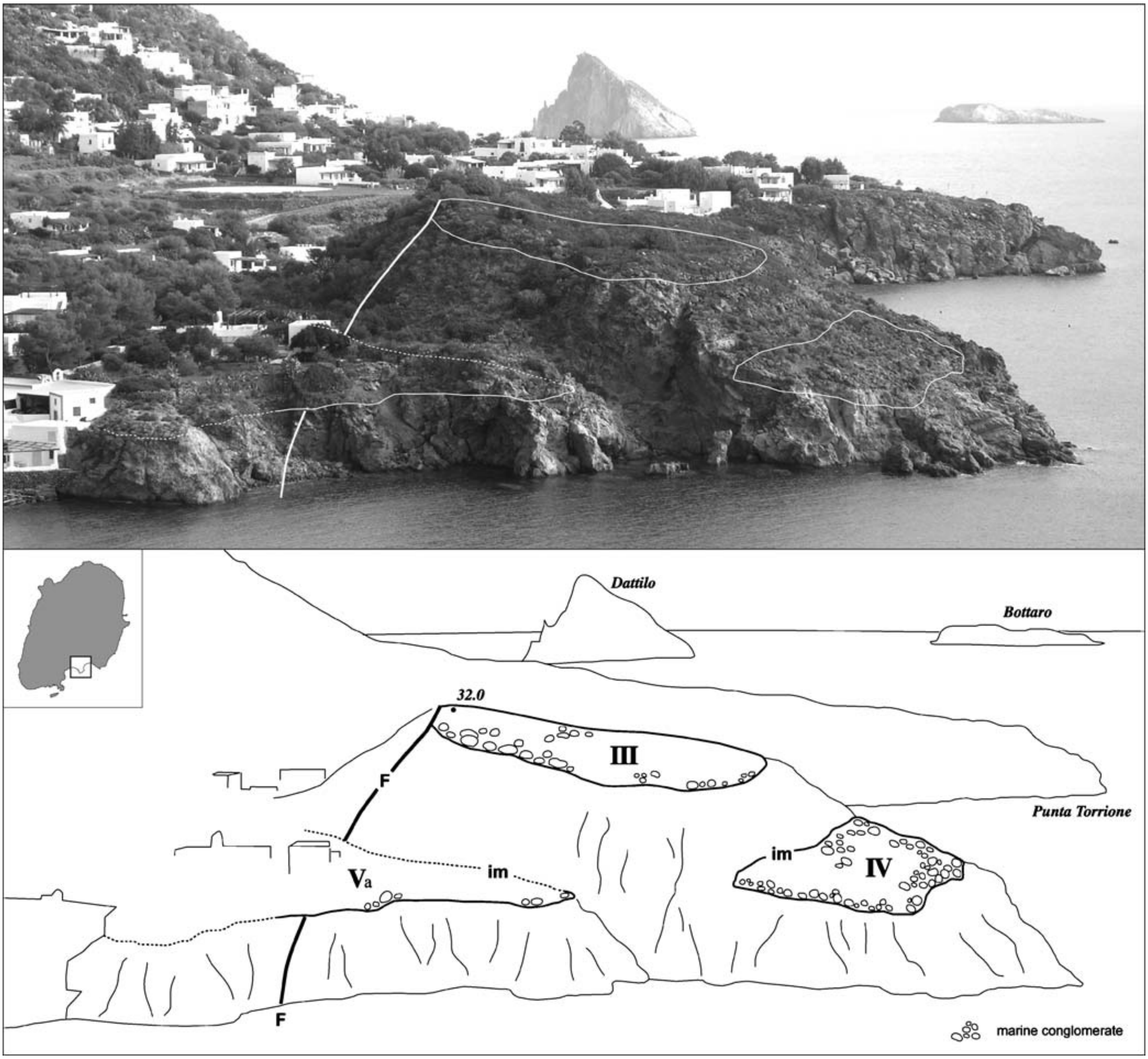


Fig. 8 Cross-cutting relationships. On the cape to the east of Caletta dei Zimmari, a small terraced surface related to palaeoshoreline IV (*im* inner margin, at elevation of 12–15 m a.s.l.) undercuts a palaeoshoreline III small terrace. The two terraces are displaced along a subvertical N70E normal fault (*F*). A narrow terrace related to palaeoshorelines Va (*im* inner margin, at an elevation of about 12 m a.s.l.) undercuts palaeoshoreline IV. These cross-cutting relationships are outlined by the fact that palaeoshoreline Va is not displaced by the fault affecting palaeoshorelines III and IV. Quoted point is in metres a.s.l.

and crustal vertical movements. By measuring the present elevation of the palaeoshorelines and comparing them with the original sea-level elevation, it is possible to determine the pattern and calculate the magnitude and rates of vertical crustal deformation since the time of formation of the palaeoshorelines (Table 1). The estimate must take into account uncertainties inherent in measuring the original position of the sea level during the eustatic peaks starting from MIS 5 (Broecker et al. 1968; Chappell 1974; Ku et al. 1974; Harmon et al. 1983; Chappell and Shackleton 1986; Lajoie 1986, and references therein; Martinson et al. 1987; Bard et al. 1990; Lambeck and Nakada 1992; Gallup et al. 1994; Stirling et al. 1998; Esat et al. 1999; Toscano and Lundberg 1999; McCulloch and Esat 2000; Lambeck et al. 2002; Waelbroeck et al. 2002; Potter et al. 2004; Schellmann et al. 2004). The curve of Chappell and Shackleton (1986), which results from the comparison between a deep Pacific ^{18}O record from marine cores (the so-called SPECMAP curve; Shackleton et al. 1983 and Imbrie et al. 1984) and a high-resolution sea-level record from marine terraces at Huon Peninsula, New Guinea (Chappell 1983), gives an estimation of sea-level elevation over the past 260 ka. The global eustatic sea-levels provided by that curve are hereby assumed as an estimate of local sea levels, even if in theory they can be different owing to the occurrence of glacio-hydro-isostatic readjustments (Lambeck and Johnston 1995; Pirazzoli 1998; Lambeck and Bard 2000; Lambeck et al. 2003, 2004), because the difference appears to be relatively small and negligible for the last interglacial at mid- and low-latitudes (Lambeck and Chappell 2001). As regards the last interglacial maximum, corresponding to MIS 5e, the sea-level elevation of +6 m a.s.l. derived from Chappell and Shackleton (1986) is fully concordant with the value of 6±3 m a.s.l. which was recently estimated as the expected position of the palaeosea-level in southern Sardinia (Lambeck et al. 2004; Ferranti et al. 2005).

Time-averaged rates of uplift of the island of Panarea from the last interglacial are calculated by plotting the uplift of each dated palaeoshoreline as a function of its age. Uplift rates for main palaeoshorelines Ia, II and III (which gave the most clear chronologic and geomorphologic identification) decrease from maximum values of 0.88 (±0.02) m/ka for palaeoshoreline Ia, corresponding to MIS 5e, to lower values of 0.715 (±0.055) m/ka for the palaeoshoreline II, corresponding to MIS 5c, and 0.665 (±0.095) m/ka for the palaeoshoreline III, corresponding to MIS 5a (Fig. 10); time-averaged uplift rates for palaeoshorelines II and III appear to be constant within the provided estimate errors (Table 1). This uplift trend is confirmed if all the palaeoshorelines of Panarea are taken into account: in fact, an homogeneous uplift rate is highlighted for palaeoshorelines Ia (time-averaged value of 0.88±0.02 m/ka) and Ib (time-averaged value of 0.845±0.045 m/ka) and, moreover, the time-averaged uplift rate appears to be fairly constant at values ranging between 0.66 and 0.715 m/ka (within the provided errors) when the estimates are independently performed for palaeoshorelines II, III, IV and V (Table 1; Fig. 10). Palaeoshorelines Ib, IV and V are not well constrained in their elevation signature (the elevation differences are low) and chronological attribution (the corresponding sea-level stillstandings are not precisely fixed in the sea-level curves) and, therefore, the uplift rates have wider limits that are poorly defined.

Time-averaged uplift rates are estimated by assuming, at least initially, a constant movement and a similar trend between the time of formation of each palaeoshoreline and

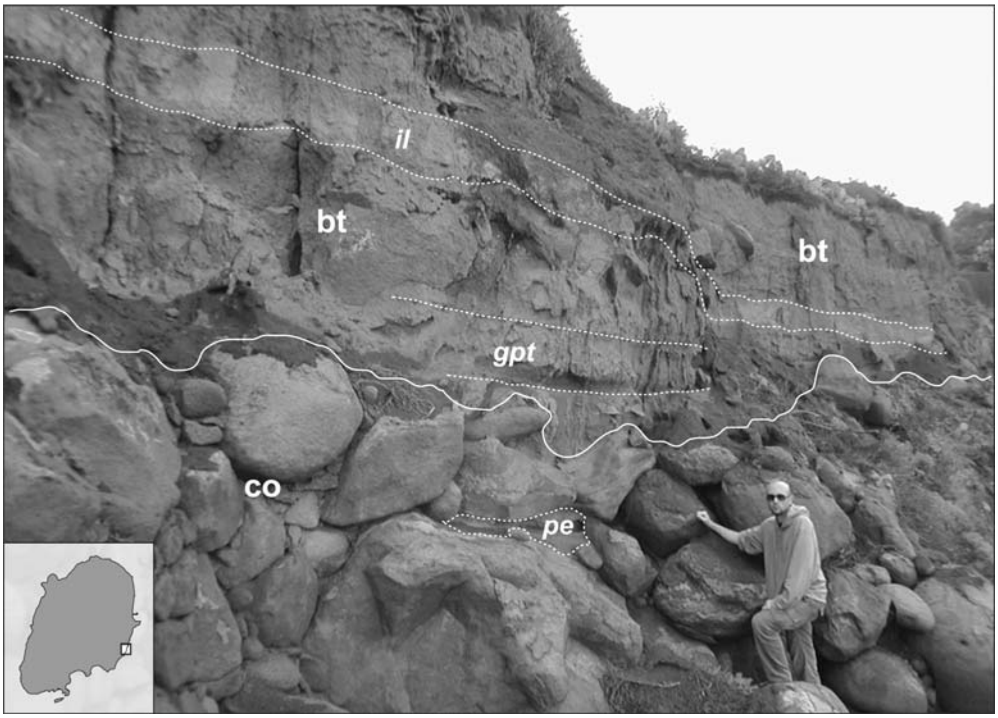


Fig. 9 Stratigraphic section along the coastal cliff at Drauto. Littoral conglomerate related to the palaeoshoreline III (*co*) is overlain by the Brown Tuffs (*bt*) pyroclastic succession (corresponding to the sixth eruptive epoch of Panarea), where Grey Porri Tuffs (*gpt*), dated at 67–70 ka, and Ischia tephra (*il*), dated at 55 ka, are visible. Pyroclastic deposits correlated with the Petrazza Tuffs from Stromboli (*pe*), dated at about 80 ka, are intercalated with the conglomerate

Table 1 Summary table of chronologic and elevation data of the palaeoshorelines in the study area

Marine isotopic stage-MIS		5e		5c	5a		3	
Age, ka[b]		124[a]	118	100[a]	81[a]	72	59	53
Palaeoshorelines		Ia[a]	Ib	II[a]	III[a]	IV	Va	Vb
Present elevation (E), m a.s.l.		115 (±2.5)[a]	100 (±5)	62.5 (±2.5)[a]	35 (±2.5)[a]	12 (±3)	10–12 (±2.5)	5 (±2.5)
Original elevation (e), m a.s.l.[b]		+6[a]	0	−9 (±3)[a]	−19(±5)[a]	−36	−28 (±3)	−30
Uplift (E-e), m	Range	106.5–111.5[a]	95–105	66–77[a]	46.5–61.5[a]	45–51	32.5–45.5	32.5–37.5
	Mean value	109 (±2.5)[a]	100 (±5)	71.5 (±5.5)[a]	54 (±7.5)[a]	48 (±3)	39 (±6.5)	35 (±2.5)
Uplift rate (m/ka=mm/y)	Range	0.86–0.9[a]	0.8–0.89	0.66–0.77[a]	0.57–0.76[a]	0.63–0.71	0.55–0.77	0.61–0.71
	Time-averaged value	0.88 (±0.02)[a]	0.845 (±0.045)	0.715 (±0.055)[a]	0.665 (±0.095)[a]	0.67 (±0.04)	0.66 (±0.11)	0.66 (±0.05)

Uplift amounts and rates are also provided

[a]Refers to the most reliable data related to palaeoshorelines Ia, II and III, which gave the clearest spatial and chronologic identification in the defined staircase

[b]Chappell and Shackleton 1986

present day. This assumption may be faulty and cause underestimation of possible short-term, not linear or alternating vertical crustal movements but it is still a useful statistical approach to the definition of the long-term vertical behaviour of the volcanic edifice of Panarea.

To avoid that problem, a curve of cumulative uplift is reconstructed by plotting the pulses of uplift which result from the difference in uplift affecting two successive palaeoshorelines, as a function of the corresponding time span (Fig. 11); the resulting partial uplift rates, which are obtained for each time interval, allow variations in the amount or rate of vertical crustal movements to be outlined.

The curve of uplift history at Panarea confirms the occurrence of a trend of progressive decrease in time of uplift rates. If we first consider only the main palaeoshorelines Ia, II and III, which are the most reliable in the defined staircase, a maximum uplift rate of 1.56 m/ka is estimated for the period between 124 and 100 ka and a sudden decrease to values of 0.92 m/ka is highlighted for the period between 100 and 81 ka (Fig. 11a). This trend is confirmed if all the palaeoshorelines are taken into account: partial uplift rates reach maximum values of 1.5 and 1.58 m/ka in the 124–118 ka and 118–100 ka time spans, respectively, and display a progressive deceleration through values of 0.92 m/ka between 100 and 81 ka, down to minimum values ranging between 0.66 and 0.69 m/ka which appear to have been fairly constant between 81 and about 50 ka BP (Fig. 11).

Owing to the lack of evidence of Holocene stillstands at Panarea and surrounding islets, no data are available over the time span between about 50 ka and the present. Therefore, the corresponding time-averaged uplift rate (0.66–0.67 m/ka over the last 81 ka BP; Figs. 10 and 11) is simply a calculation based on the assumption that uplift has been constant for the entire last glacial cycle up to the Holocene.

In the short-term, evidence of a submergence trend, which is opposite to the afore-mentioned long-term uplift trend, is identified at Basiluzzo. There, near to Punta di Levante, remnants of a Roman-aged wharf are located at depth of 3–4 m b.s.l. (Kapitaen 1958; Bernabò Brea and Cavalier 1991), corresponding to a total vertical displacement of 4.2 m b.s.l. (Anzidei et al. 2002). If we consider a local sea-level rise in the area of the Aeolian Arc of about 1.5 m over the last 2,000 years BP which is the effect of ongoing glacio-hydro-isostatic adjustments and eustatic sea-level rise (Lambeck et al. 2004), a net crustal vertical displacement of 2.7 m, corresponding to a subsidence rate of 1.35 m/ka during the last 2,000 years, appears to have occurred at Basiluzzo. There is not any evidence that this submergence trend could affect other sectors of Panarea and minor islets.

Discussion

Long-term deformation pattern

All the geomorphologic evidence at Panarea and surrounding islets suggests the occurrence of a long-term, continuous but not constant in time, sustained uplift trend of the volcanic edifice starting from the last interglacial (Figs. 10 and 11). Considering that relative sea-level changes induced by glacio-hydro-isostasy, which are relevant for the Holocene transgression, can be considered negligible for the last interglacial (glacio-hydro-isostastic readjustments may have affected maximum sea transgression elevations of only a few metres; Lambeck and Nakada 1992), such a deformation pattern is interpreted basically as the result of crustal vertical movements.

Crustal vertical movements of a volcanic island are interpreted as reflecting the interaction between regional tectonics and volcano-related deformation. Volcano-related deformation, which is connected to magmatic or volcano-tectonic processes, is usually transitory and active at a local scale. On the contrary, regional tectonic processes which affect the sub-volcanic basement are slower, active on a larger scale and usually of lower magnitude (Lajoie 1986).

The whole inner sector of the Calabrian Arc has undergone continuous, large-scale uplift since the Mid-Pleistocene at mean rates <1.21 m/ka (Hearty et al. 1986; Cosentino and Gliozzi 1988; Valensise and Pantosti 1992; D'Addezio et al. 1993; Westaway 1993; Miyauchi et al. 1994; Catalano and Cinque 1995; Carobene et al. 1997; Bordoni and Valensise 1998; Tortorici et al. 2003). This uplift process on a regional scale is explained as the result of the isostatic rebound of the upper Tyrrhenian plate (including the Calabrian Arc) in response to the gravity-induced southeastward rollback of the subducting Ionian plate (Amato and Montone 1997; Hirn et al. 1997; Negredo

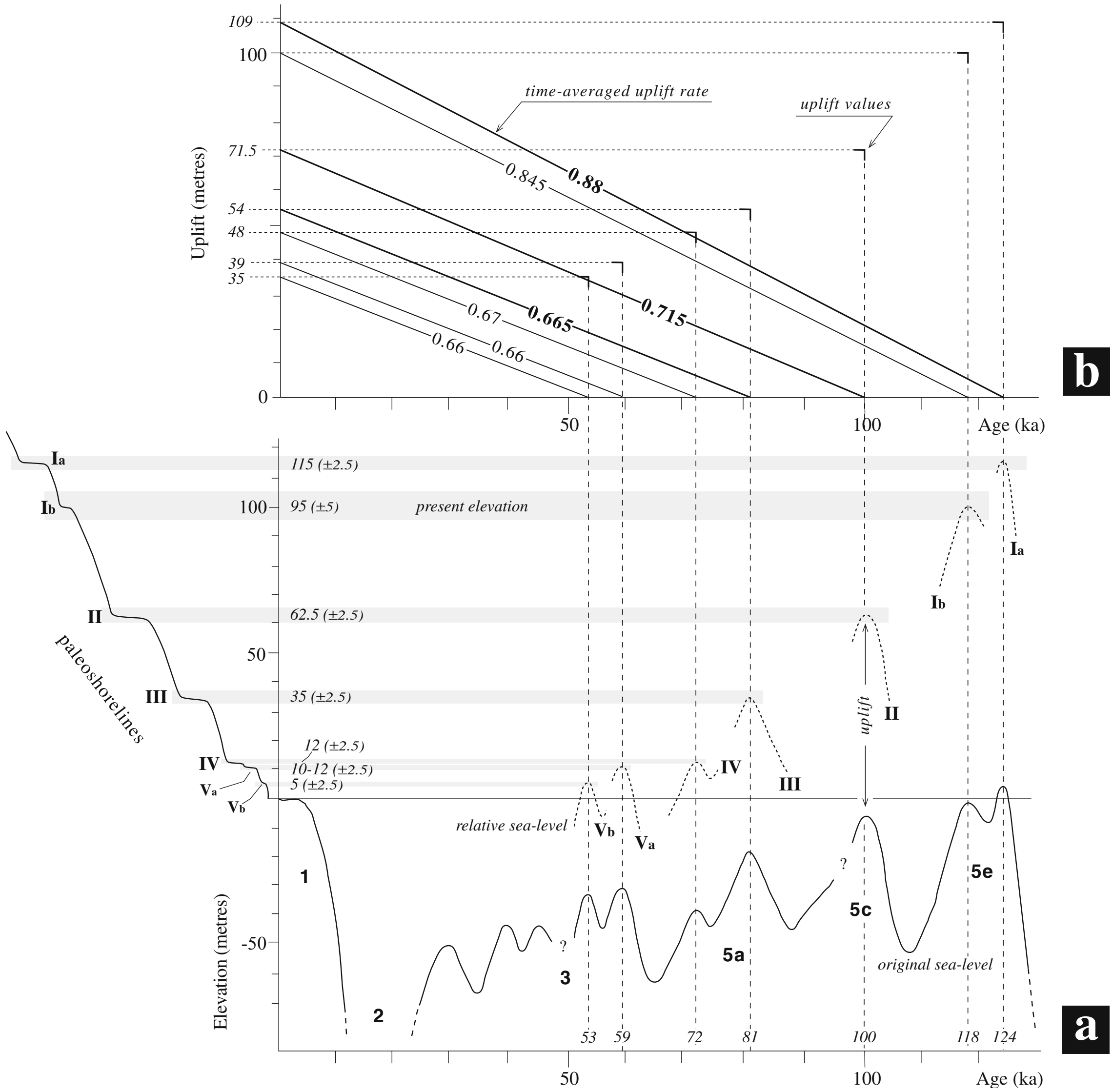


Fig. 10 Coastal elevation changes at Panarea. Amounts and rates of vertical uplift of the volcanic edifice from the last interglacial are evaluated by means of the interpretation of chronologic and elevation data of the palaeoshorelines. **a** The vertical uplift which affected each palaeoshoreline is evaluated by correcting the present elevation of the palaeoshorelines (which is the relative sea-level curve) for the glacio-eustatic sea-level fluctuations (from the curve of Chappell and Shackleton 1986). **b** Time-averaged uplift rates (in m/ka) are estimated by plotting the amounts of uplift as a function of the age of the corresponding palaeoshoreline and by assuming a constant uplift between its time of formation and present times

et al. 1999; Gvirtzman and Nur 1999, 2001; Doglioni et al. 2001; Neri et al. 2003).

According to this geological and structural framework, the deformation pattern of Panarea is that of a volcanic edifice growing and developing upon a sub-volcanic basement, the northwestern margin of the Calabro-Peloritan block, which has undergone a persistent and widespread uplift. In these terms, the decreasing uplift trend that is recorded by the deformation pattern of Panarea from the last interglacial suggests the occurrence of a transient, volcano-related component of uplift which is superimposed on the regional signal, assumed on average constant over the investigated time span, so contributing to the overall amount of uplift. As shown by the uplift history curve (Fig. 11), the volcano-related component is prevailing between 124 and 100/81 ka, whereas the regional component of deformation appears to prevail during the last 80 ka when uplift rates tended to be constant. The comparison of the uplift history with the eruptive history of Panarea (Fig. 12) suggests that the volcano-related component of uplift occurred during a time span which is characterized by a progressive reduction of volcanic activity: in fact, most of the erupted volcanics at Panarea were emplaced between 150 and 118 ka BP (first to fourth eruptive epochs; ep1 to ep4, Fig. 12), whereas volcanic activity during the last 105 ka (fifth and sixth eruptive epochs; ep5 and ep6, Fig. 12) is characterized by episodic eruptions related to eruptive vents which are likely not located on the main island of Panarea. Therefore, the transient volcano-related deformation at Panarea appears to be connected, for the most part, with post-eruptive processes characterizing the progressive quiescence of the volcanic edifice. Considering that it is not possible to appreciate the contribution of single deformative events (because, according to the methodological assumptions stated above, only time-averaged total deformations have been estimated by assuming constant rate and trend over time periods of some thousands of years), the volcano-related uplift component can be interpreted on a longer term as the effect of relative contribution of volcanic output and magma supply to a shallow magmatic system. A quantitative approach would be needed but it cannot be adopted because it requires the knowledge of some physical parameters (e.g. displacement field, nature of the deformation source, position, dimension and depth of the magma chamber) which, at the moment, are not defined in the volcanic area surrounding Panarea (which is mostly submarine), owing to its complex structural setting and to its poorly known crustal structure. Therefore, the long-term volcano-related deformation at Panarea can be investigated only from a qualitative point of view, by invoking the occurrence of syn-eruptive and mainly post-eruptive

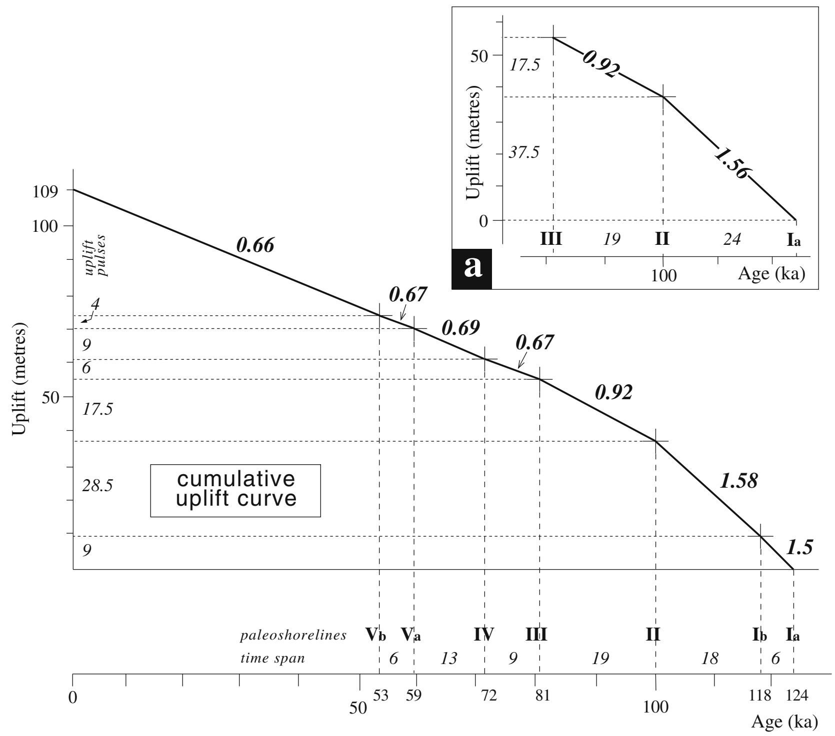


Fig. 11 Cumulative uplift at Panarea. The cumulative uplift curve is obtained by adding the uplift pulses which result from the difference in uplift affecting two successive palaeoshorelines in the staircase defined at Panarea. Partial uplift rates (in m/ka) are estimated by plotting each uplift pulse as a function of the corresponding time span. **a** Cumulative uplift curve if only the main palaeoshorelines Ia, II and III are taken into account

Marine isotopic stage - MIS	5e		5c	5a		3	
Age, ka	124	118	100	81	72	59	53
Paleoshorelines	**Ia**	Ib	**II**	**III**	IV	Va	Vb
Uplift (mean value), m	109	100	71.5	54	48	39	*35*
Time span (Δt), ka	**6**	**18**	**19**	**9**	**13**	**6**	
Uplift pulses (Δu), m	**9**	**28.5**	**17.5**	**6**	**9**	**4**	
Partial uplift rates (Δu/Δt), m/ka	**1.5**	**1.58**	**0.92**	**0.67**	**0.69**	**0.67**	

processes which are connected to elastic (with an effect mainly on the short-term and on cm scales) and, more probably, visco-elastic deformation mechanisms (which can produce ground deformation on the long-term, e.g. tens of thousands years). These mechanisms are:

1. Long-term ground deformation due to the isostatic readjustment of the crustal block comprising the volcanic edifice of Panarea which, at the end of the eruptive activity, may be less dense because of thermal expansion of the heated crust and also greater density of fluid filled fractures; the crust would be forced to reach a new configuration of gravitational equilibrium (post-eruptive deformation)
2. Visco-elastic deformation of the rocks around the magma chamber as a result of the relaxation of deviatoric stresses (post-eruptive deformation)
3. Elastic ground deformation resulting from volume or pressure increase in the shallow magma chamber which is responsible of the volcanic activity at Panarea (syn-eruptive deformation); ground uplift may occur also during the post-eruptive phase as the effect of the inflation of the magma chamber due to the supply of new magma without giving rise to eruptive activity (post-eruptive deformation); in order to assess how much magma was emplaced in the post-eruptive phase, we should know the lateral extent of the uplift area, which is unfortunately unavailable

Recent vertical movements

The lack of Holocene features at Panarea (and in the whole Aeolian Arc) does not permit investigation of the deformation pattern over the last 6,000 years. An apparent contrast with the estimated long-term rates of net emergence is suggested by the fact that the long-term uplift rate of 0.67 m/ka over the last 81 ka, if extrapolated during the last 6,000 years, would predict a crustal displacement at 3–4 m a.s.l. On the other hand, the glacio-hydro-isostatic effects of the last deglaciation in the southern Tyrrhenian caused a continuous relative sea-level rise of about 6–7 m over the last 6,000 years (Lambeck et al. 2003; Lambeck et al. 2004) which can compensate for if not overcome that crustal displacement. So, the lack of Holocene evidence at Panarea does not necessarily suggest a decrease of tectonic uplift rates during the last few thousands years, but it most probably records the absence of prolonged sea-level stillstands during which notch-forming processes can be active.

On the short-term, subsidence at a rate of about 1.35 m/ka over the last 2,000 years is documented at Basiluzzo. That process, which has already been corrected for the glacio-hydro-isostatic and eustatic components, was recently interpreted as the result of volcano-related crustal deformation connected with the cooling of the magma chamber corresponding to the dome of Basiluzzo (Tallarico et al. 2003). On the other hand, we believe that the submergence trend at Basiluzzo could be more likely explained as the result of localized neo-tectonic displacement along main NE–SW-oriented tectonic structures in the submarine area between Panarea and Basiluzzo (Fig. 1b).

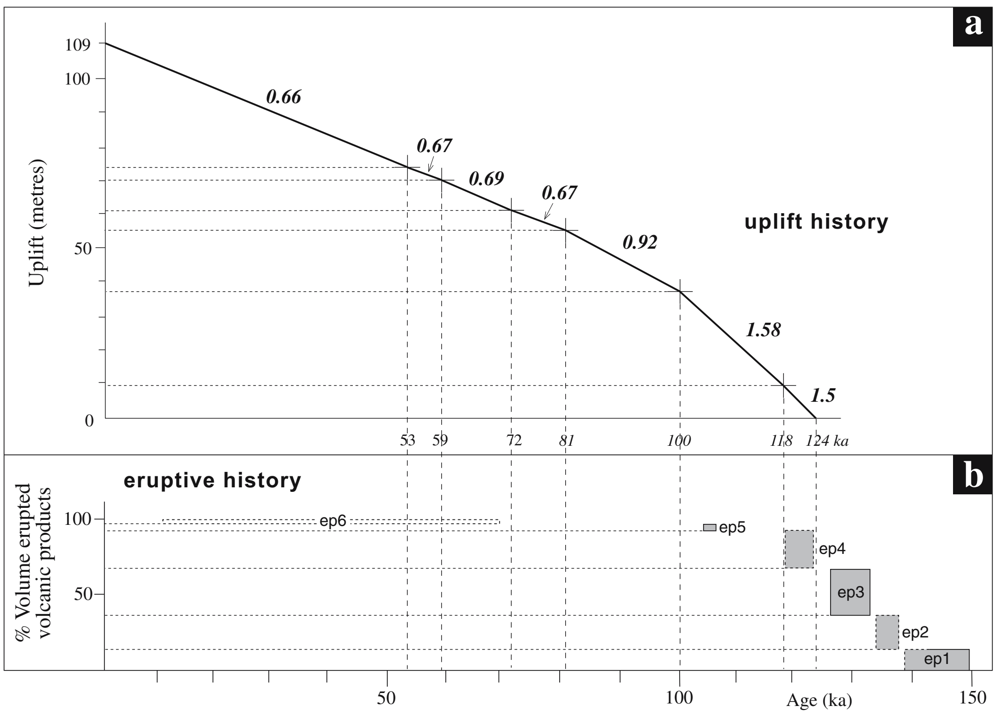


Fig. 12 Comparison between uplift history (**a**) and eruptive history (**b**) of the Panarea volcanic edifice. The uplift history is shown by means of the cumulative uplift curve of Fig. 11, whereas the eruptive history is displayed in terms of percentage in volume of volcanic products deposited during the successive eruptive epochs of the volcanic edifice (*ep1*, *ep2* correspond to first eruptive epoch and second eruptive epoch)

Comparison with the other islands of the Aeolian Arc

According to our reading of data, at Panarea, volcano-related deformation (in superposition on the regional uplift component) has appeared to play a significant role in controlling long-term coastal tectonics over the last 124 ka. This is in contrast with the rest of the Aeolian Arc, considering that the volcanic edifices of Lipari, Filicudi and Salina and, probably, Alicudi (the islands of Stromboli and Vulcano are not counted because remnants of palaeoshorelines are lacking) are affected by a long-term continuous uplift trend characterized by time-averaged rates which have on average been constant at a mean value of ca. 0.34 m/ka since the last interglacial (Lucchi 2000; Calanchi et al. 2002a; Lucchi et al. 2004a,b). The uniform uplift trend of the main portion of the central-western Aeolian Arc is explained by assuming a prevailing regional tectonic component of deformation. This behaviour, which is not expected in volcanic areas where volcano-related deformation is generally supposed to be dominant (Bartolini and Carobene 1996), may be explained by evaluating the specific temporal and spatial scale of volcanic activity. In fact, volcanic activity generally goes along with strong vertical ground deformation which occurs in the short-term and is usually constrained by the closeness of the corresponding eruptive centre. In the case of large polygenic volcanic edifices like the aforementioned Lipari, Filicudi and Salina, volcanic activity in correspondence of single eruptive centres could be joined to independent and localized vertical deformation of discrete sectors which may not be able to affect the vertical mobility of the whole volcanic edifices. On the other hand, those volcanic edifices suffer larger scale deformation such as the one related to regional tectonics which is known to be active in the whole inner sector of the Calabrian Arc.

Moreover, the regional uplift component at Panarea (not less than 0.67–0.69 m/ka) appears to be higher than at Lipari, Filicudi, Salina and Alicudi (constant at 0.34 m/ka). This suggests the occurrence of a different tectonic setting between the eastern (including Panarea) and the main portion of the western-central sector of the Aeolian Arc, even if, unfortunately, a comparison with the volcanic edifice of Stromboli (which is located in the eastern sector of the Aeolian Arc) cannot be performed. However, the deformation pattern on a regional scale appears to be in agreement with the complex pattern of the Aeolian Arc and southern Tyrrhenian kinematics, which is characterized by the occurrence of two structurally distinct domains separated by the NNW–SSE Tindari Letojanni structural line running across the central Aeolian Islands (Selvaggi and Chiarabba 1995; Frepoli et al. 1996; Amato and Montone 1997; Bruno et al. 1999; Falsaperla et al. 1999; Negredo et al. 1999; Frepoli and Amato 2000; Neri et al. 2003; De Astis et al. 2003, and references therein; D'Agostino and Selvaggi 2004; Pondrelli et al. 2004). The western domain (including Salina, Filicudi and Alicudi) is characterized by an evident compressional regime induced by plate convergence, by high crustal thickness and shallow crustal seismicity. On the contrary, the eastern domain (comprising Panarea and Stromboli) is characterized by an NW–SE-oriented extensional regime, reduced crustal thickness and deep-focus earthquakes depicting a NW-dipping Benioff zone (Selvaggi and Chiarabba 1995). According to this evidence, the subduction in the southern Tyrrhenian is still occurring only to the east of the central Aeolian Islands (de Voogd et al. 1992; Bruno et al. 1999; Falsaperla et al. 1999; Argnani 2000; Doglioni et al. 2001; De Astis et al. 2003, and references therein; Neri et al. 2003, and references therein; Faccenna et al. 2004; Pondrelli et al. 2004). Therefore, if regional uplift is attributed to the rollback of the subducting Ionian plate with consequent isostatic rebound, we may speculate that this effect is more rapid and produces higher uplift in the eastern sector of the Aeolian Arc (comprising Panarea), where subduction and rollback should be actively occurring.

Summary

A model of long-term deformation history of the volcanic edifice of Panarea from the last interglacial is suggested in which net and persistent uplift occurs with rates gradually decreasing from maximum values of 1.5–1.58 m/ka in the period between 124 and 100 ka down to the lowest values of 0.66–0.69 m/ka which tend to be constant over the last 81 ka. This deformation pattern is interpreted as the result of a transitory, volcano-related component of uplift, active on a local scale, which is superposed on a tectonic component of uplift, active on a regional scale in the framework of the southern Tyrrhenian geodynamics. The volcano-related component of uplift is explained as the result of visco-elastic deformation during the progressive re-equilibrium of the shallow magmatic system which goes along with the ongoing quiescence of the volcanic edifice. Moreover, as for the regional component of uplift, occurrence of deformation processes induced by active subduction below the eastern sector of the Aeolian Arc is suggested as explaining different tectonic settings between Panarea and the western-central Aeolian Arc. Finally, in the short-term, the subsidence trend affecting Basiluzzo during the last 2,000 years is related to localized neo-tectonic movements.

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