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Stratigraphy of the Caldera walls of Nisyros volcano, Greece

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Key words: Tephrostratigraphy, Quaternary volcanism, caldera, Nisyros, tectonics, Aegean Arc.
Mots clés: Tephrostratigraphie, volcanisme quaternaire, caldeira, Nisyros, tectonique, Arc Egéen.

ABSTRACT

The active Nisyros volcano, at the eastern end of the Aegean volcanic arc, is topped by a recent caldera, on average 4 km in diameter and 200 m in depth. It is thought to result from the so called Lower Pumice (LP) and Upper Pumice (UP) eruptions, with a poorly constrained age (from 110 ka to 24 ka). In a detailed study of the exposed walls of the caldera, we defined 25 different stratigraphic units (lava flows, tephra and lacustrine deposits). The lava flow unit 3, an early event in the stratigraphic succession, dips *inward*, in the direction of the present caldera; two lacustrine units (with an extension of ~500 m) have also been found in the north-eastern part of the caldera cliff, suggesting the presence of a previous, small caldera. Furthermore, three major tectonic trends (oriented at N40, N70 and N170) have influenced the emplacement of dykes, the faulting and the fracturing of the island, as well as the topography of the eastern flank of the caldera, where redoubling of the stratigraphy occurs. On this basis, we hypothesize that a first, relatively small caldera was present in the earliest period of activity of Nisyros, and that today's caldera is the result of multiple caldera-forming events, in great part controlled by major tectonic trends.

RESUME

Le volcan actif de Nisyros, à l'extrémité orientale de l'arc volcanique égéen, est surplombé par une caldeira récente d'un diamètre moyen de 4 km et 200 m de profondeur, supposée résulter des éruptions des Ponces Inférieures (Lower Pumice-LP) et Ponces Supérieures (Upper Pumice-UP), d'âges mal connus (de 110 ka à 24 ka). Lors d'une étude détaillée des parois exposées de la caldeira, nous avons défini 25 unités stratigraphiques différentes (coulées de lave, tephra et dépôts lacustres). L'unité de lave 3, un épisode précoce dans la succession stratigraphique, s'est écoulée vers l'intérieur de la caldeira actuelle; deux unités lacustres (500 m environ d'extension latérale) ont également été trouvées dans le secteur nord-est de la caldeira, suggérant l'existence d'une caldeira antérieure plus petite. De plus, trois tendances tectoniques majeurs (d'orientation N40, N70 et N170) ont influencé la mise en place des filons, des failles et la fracturation de l'île, ainsi que la topographie du flanc est de la caldeira, où apparaît un redoublement de la stratigraphie. Sur cette base, nous émettons l'hypothèse qu'une première caldeira, relativement petite, était présente dans les premiers moments de l'activité de Nisyros, et que la caldeira actuelle est le résultat de multiples événements, contrôlés en grande partie par d'importantes orientations tectoniques.

Introduction

The isle of Nisyros is a Quaternary volcano located at the easternmost end of the Aegean volcanic arc, in the Dodecanese archipelago, South of Kos (Fig. 1) (Mercator 36°35' N, 27°10' E; UTM 514900 E, 4048600 N, zone 35 S). The island is almost circular, with an average diameter of 8 km, covering an area of about 42 km^2. It lies above a basement of Mesozoic limestone (Varekamp 1993) and a thinned crust, with the Moho located at a depth of about 27 km (Makris & Stobbe 1984).

Gorceix (1873), Martelli (1917), Davis (1967), Di Paola (1974), Vougioukalakis (1984), Bohla & Keller (1987), St. Seymour & Vlassopoulos (1989), Limburg & Varekamp (1991), Papanikolaou et al. (1991) and Francalanci et al. (1995) described the geology and volcanology of the island; in summary, Nisyros displays a succession of calc-alkaline lavas and pyroclastic deposits, with a summit caldera of a 4 km average diameter. Most authors divide the history of the volcano in 4 major stages: (1) an underwater volcano, erupting mafic to intermediate pillow lavas; (2) an andesitic complex which in the end grew to become a large stratovolcano; (3) a stage characterized by two major rhyodacitic plinian eruptions which deposited the Lower Pumice (LP) and Upper Pumice (UP) units, separated by the effusion of large volumes of magma in the eastern part of the island (the Nikià lavas); (4) a caldera collapse follows the pumice eruptions. Today, two-thirds of the caldera are filled with dacitic domes, which likely constitute the last magmatic event on Nisyros. The remaining third is occupied in the most part by the Lakkì plain, and to

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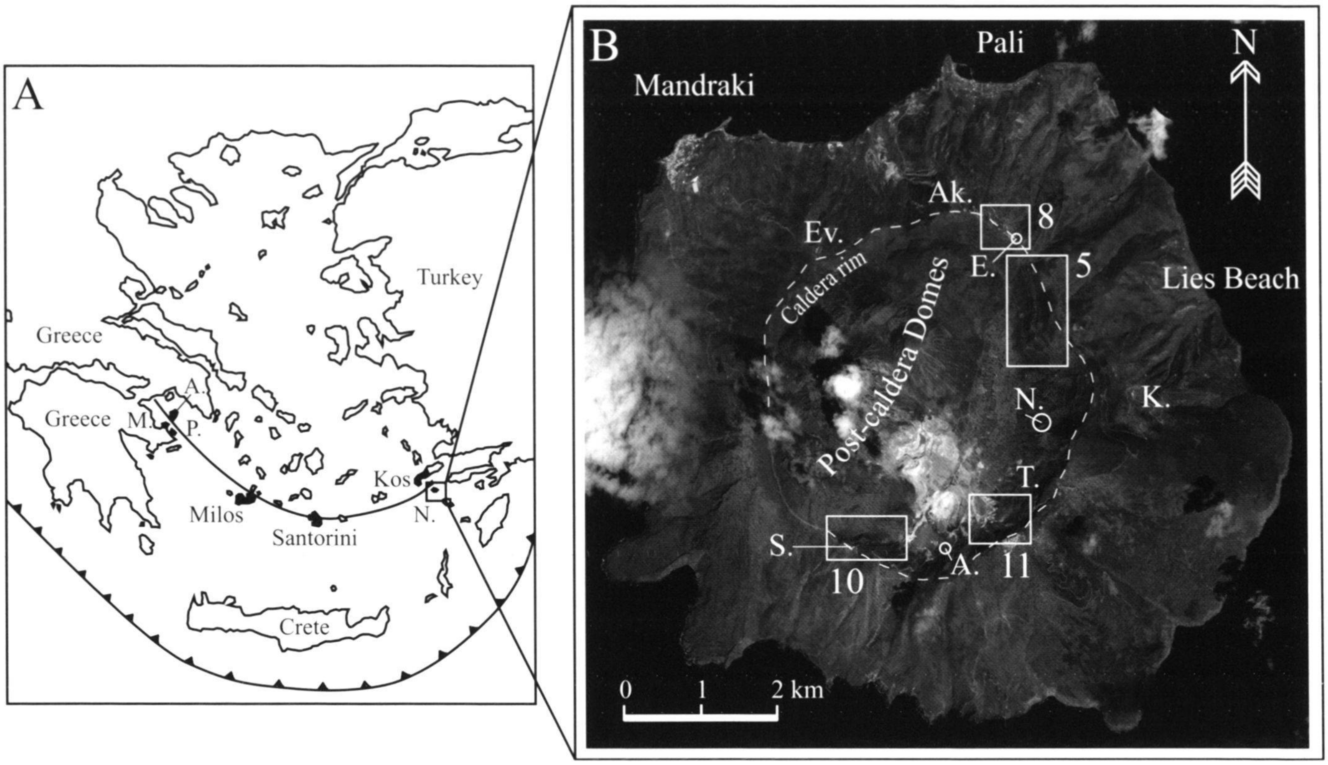

Fig. 1. (A) Location map of the isle of Nisyros inside the Greek archipelagos. [A.] Aegina, [M.] Methana, [N.] Nisyros and [P.] Poros. In black: Quaternary volcanic centres. (B) IKONOS image of the isle of Nisyros. Rectangle numbers refer to the figure numbers. [A.] neck of the Argos lavas (lava flow 14), [Ak.] dome of Akimaronas, [E.] town of Emboriò, [Ev.] Monastery of Evengelistra, [K.] Monastery of Panaghia Kyra, [N.] neck of the Nikià lava flow (lava flow 21), [S.] Monastery of Stàvros, and [T.] Monastery of Aghios Ioannis Theologos.

the south by the Rammos area, where about a dozen of phreatic craters are related to recent eruptions, some of which having occurred in historical times: at Alexandros (1871), Polyvotis (1871), and at Polyvotis Mikros (1887) (Gorceix 1873; Martelli 1917). This area is also the site of a rather intense hydrothermal activity, which has been drilled and studied for potential geothermal exploitation (Geotermica Italiana 1983; 1984; Dawes & Lagios 1991; Lagios & Apostolopulos 1995; Kavouridis et al. 1999) and investigated for an assessment of volcanic hazards related to hydrothermal explosions (Chiodini et al. 1993; Marini et al. 1993; Brombach et al. 2001).

The aim of this study was to refine the stratigraphy currently available in the literature by an in-depth examination of the volcanic sequence of Nisyros, especially in the caldera walls, where the oldest part is best exposed. In particular, we wanted to improve our knowledge of the explosive events, which occurred prior to the LP eruption and their relation to a possible caldera collapse predating the existing caldera. To this end, we will present a preliminary set of four representative sections and maps along the cliffs of the caldera (Vanderkluysen & Volentik 2001); a full mapping project of the island at the 1:5.000 scale is currently in progress.

Table 1. Summary of radiometric ages available for Nisyros in the literature

Stratigraphy	Age	Reference
Yàli obsidian	24 ka	Wagner 1976
Yàli pumice fall	< 10 ka	Vougioukalakis 1998
	31 ka	Federman & Carey 1980
Upper Pumice	> 44 ka	Limburg & Varekamp 1991
	110 ka	Barberi et al. 1988
	24 ka	Vinci 1983; 1985
Lower Pumice	24 ka	Rehren 1988
Kyra formation	38 ka	Rehren 1988
Argos lava flow	200 ± 50 ka	Di Paola 1974
	66 ka	Keller at al. 1990

Ages

The duration of the volcanic activity on Nisyros is poorly constrained by few numerical ages (Table 1). Since the Yàli pumice fall has been found remobilized on the talus deposits inside the caldera walls, but not on the dome surfaces or interbedded within the dome-related detritus cones, the domes

Table 2. Mineralogy of the lava flows and juvenile fraction of selected samples from Nisyros. Unit numbers refer to the stratigraphy developed in text. Pl = plagioclase, cpx = clinopyroxene, opx = orthopyroxene, ol = olivine, bt = biotite, amp = amphibole, oxi = oxides, ap = apatite, zr = zircon. Abundance of phenocryst phase: ≤5% ◇, 6–10% ⟐, 11–15% ◈, 16–20% ◆. Mineral presents in groundmass: ×. Ghosts, remnants: ✳

	pl		cpx		opx		ol	bt	amp	oxi		ap	zr
Unit 21	◈	×	◇	×	◇	×			◇	◇	×	◇	◇
Unit 19	⟐	×	◇	×	◇	×		×	◇ or ✳	◇	×	◇	◇
Unit 18	◇ to ◆	×	◇	×			◇ or ✳			◇	×		
Unit 17	◇ to ⟐	×	◇	×			◇			◇	×		
Unit 16	◈ to ◆	×	◇	×			◇			◇	×		
Unit 15	◇		◇							◇			
Unit 14	⟐	×	◇	×	◇	×			◇	◇	×	◇	◇
Unit 13	⟐		◇				✳			◇			
Unit 12	◇	×	◇	×			◇			◇	×		
Unit 11	◈	×	◇	×			◇	◇		◇	×		
Unit 10	◇ to ◈	×	◇	×			◇ or ✳			◇	×		
Unit 8	⟐		◇				◇ or ✳			◇			
Unit 7	◈	×	◆	×			✳			◇	×		
Unit 5	⟐	×	◇	×						◇	×		
Unit 3	◇	×	◇	×							×		
Unit 2	◇	×	◇	×			◇			◇	×		
Unit 1	◆	×	⟐	×			◇			◇	×		

are considered to be the youngest (but undated) units. Ages on the Yàli pumice vary in the literature from <10 ka (Vougioukalakis 1998) to 31 ka (Federman & Carey 1980). In addition, an age of 24 ka (by fission tracks; Wagner et al. 1976) for the Yàli obsidian lava flow has to be considered as the lower limit for the Yàli pumice (Allen & McPhie 2000).

Aside from the Yàli pumice fall, the youngest deposit dated on Nisyros is the Upper Pumice unit (>44 ka, Limburg & Varekamp 1991; ^{14}C). For the same deposits, Barberi et al. (1988) obtained an age of 110 ka by the fission tracks method, whereas Vinci (1983, 1985) obtained 24 ka on a tephra distal layer he attributed to the same unit. An age of 24 ka was also found by Rehren (1988; ^{14}C), but for the Lower Pumice unit. The Upper Pumice unit does not outcrop inside the caldera cliff, and neither do the hyaloclastitic lavas that are considered in the literature as the oldest (but undated) deposits of the volcanic activity on Nisyros (Di Paola 1974). Two other ages have been performed on the Nisyros deposits: the base of the Kyra unit has been dated by K-Ar at 38 ka by Rehren (1988), and the Argos lava flow, on

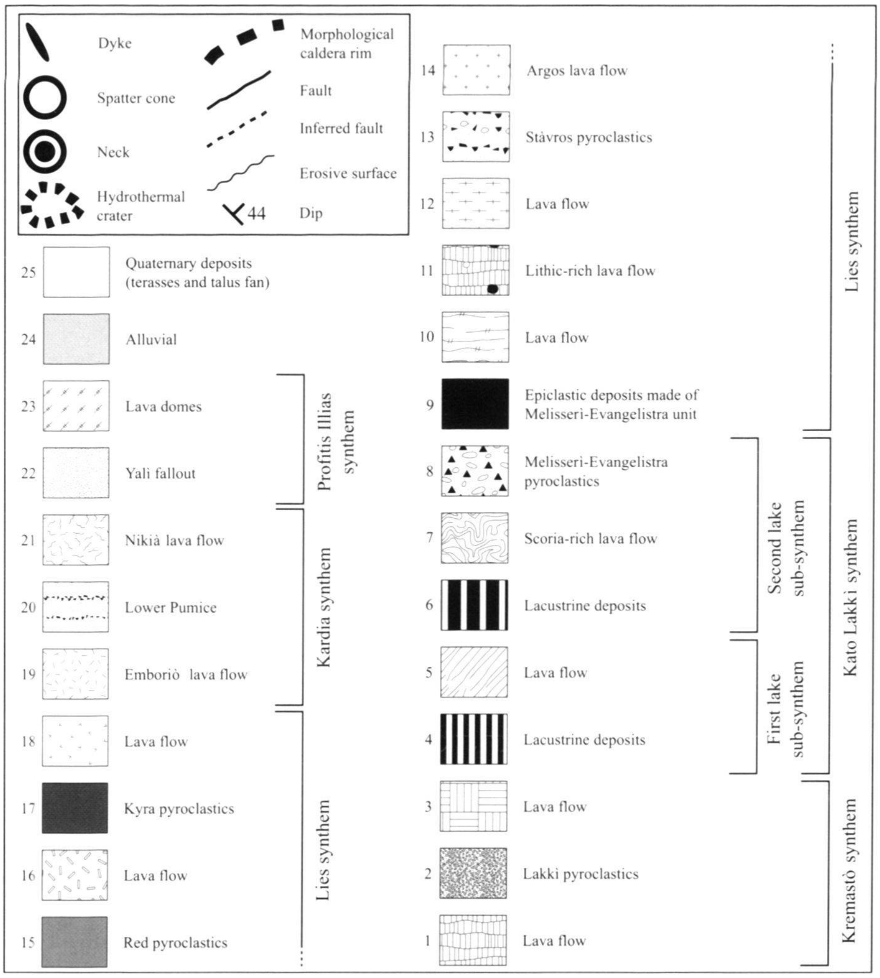

Fig. 2. Legend and symbols used within this paper.

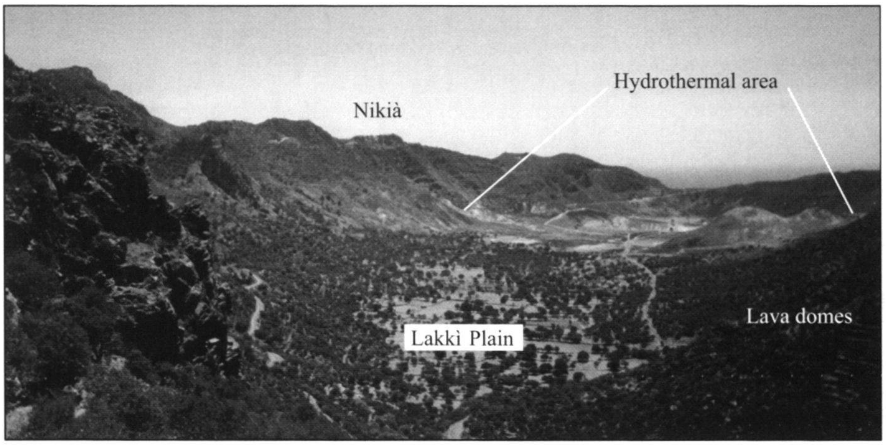

Fig. 3. General view of the Nisyros caldera from the North. On the right side the lava domes that partially filled the caldera depression. A number of young hydrothermal craters occupy the southernmost portion of the caldera plain.

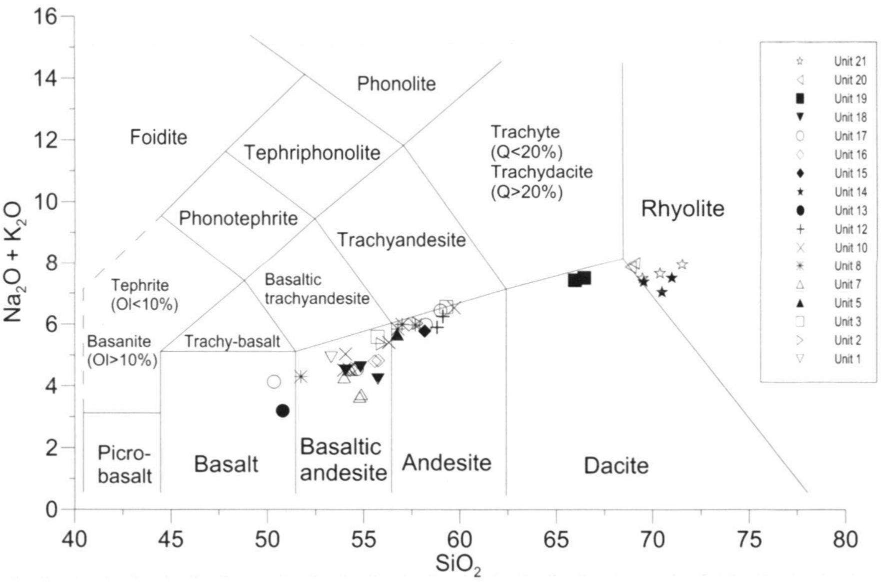

Fig. 4. Total alkali silica (TAS) classification diagram (Le Maitre 1989).

the other hand, yielded an age of 200 ± 50 ka (Di Paola 1974; K-Ar on bulk rock), and more recently 66 ka (Keller et al. 1990).

Stratigraphy

We defined a total of 25 stratigraphic units on the caldera cliffs on the basis of their physical characters (see table 2 for their mineralogy), their stratigraphic position and the presence of discontinuities, erosional surfaces, palaeosoils and epiclastites inside the reconstructed stratigraphic sequence. A classification in synthems and sub-synthems has been adopted based on International Subcommission on Stratigraphic Classification (1987) and outcrops located outside of the caldera (Fig. 2). The best stratigraphic exposures are located on the eastern portion of the caldera, because in the western sector the lava domes partially filled the caldera (Fig.1). On the eastern sector of the caldera cliff, a number of man-made terraces are present, due to the intense farming of the island at the end of the first half of the XX[th] century. The frequent earthquakes, due to the strong tectonic activity (see below), have contributed, in very brief periods of time, to the formation of major talus fans, most of which still being active and often interrupting the stratigraphic continuity of the various individual units along the caldera walls. We used the major tephra units as stratigraphic markers along the caldera cliff. In the vicinity of the hydrothermal explosion craters, the caldera wall (Fig. 3) is at times strongly hydrothermally altered, which tends to hide the lithological differences between a unit and another.

Rock names used in the text for the lavas and for the magmatic fraction of pyroclastic deposits are derived from new analyses (Vanderkluysen & Volentik, work in progress) plotted in a total alkali silica (TAS) classification (Le Maitre 1989) (Fig. 4).

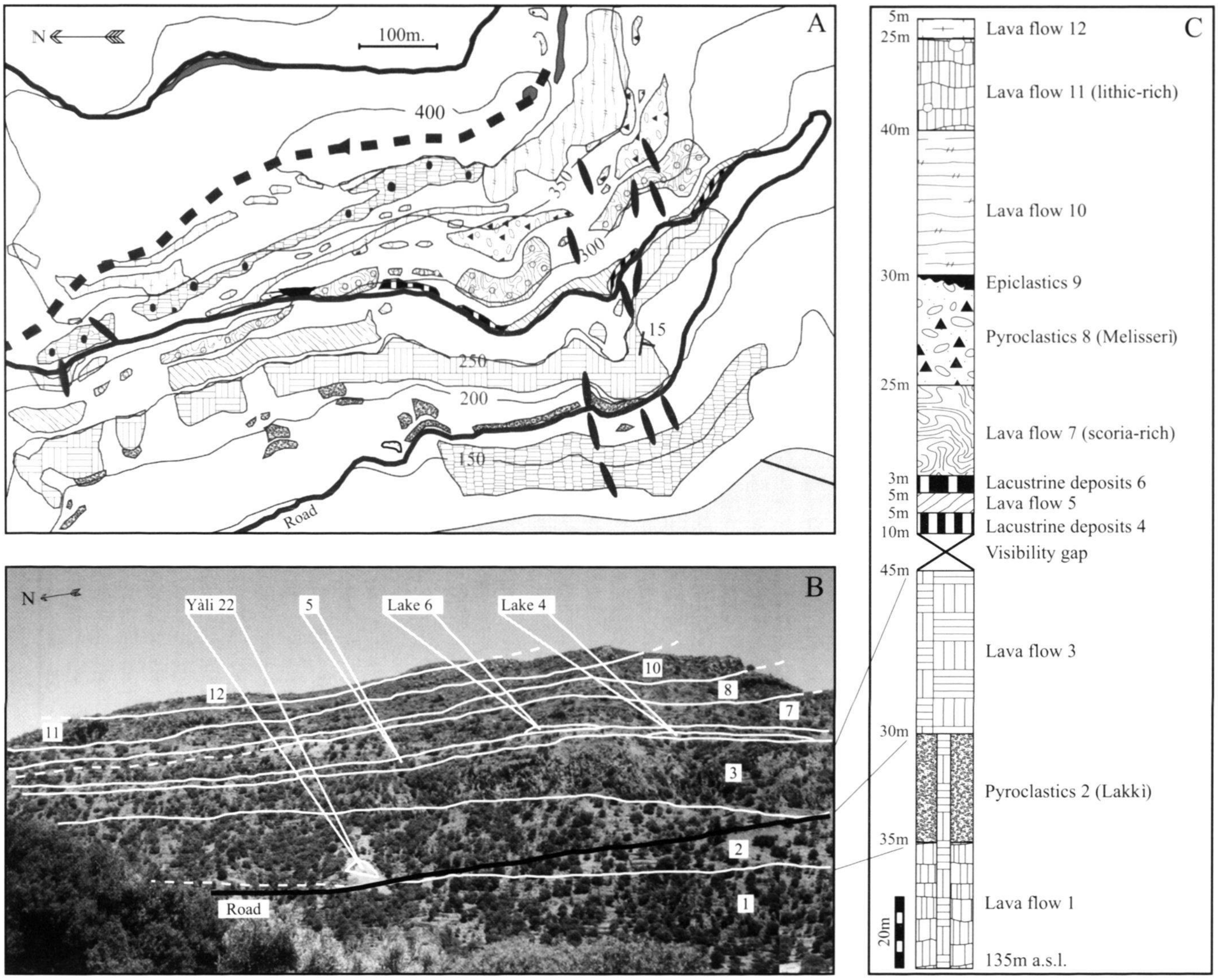

Fig. 5. Geological map (A) and photograph (B) of the caldera wall cut by the road from Mandraki. (C) General stratigraphy of the cliff. See legend in Fig. 2.

Unit 1

This basaltic-andesitic lava flow represents the lowest observable stratigraphic unit in the caldera walls. The only outcrops are found below the road on the north-eastern side of the caldera (Fig. 5). The flow is strongly tectonized and cut by a dyke feeding one of the overlying lava flows (unit 3). Papanikolaou et al. (1991) attributed arbitrarily this lava flow to the hyaloclastitic and pillow lava outcrops near Mandraki.

Unit 2 (Lakkì pyroclastics)

This unit marks the first explosive aerial event recorded on the island. The base comprises a 3.5 m thick fall deposit, followed by flow and surge units, overlaid by a final fallout (Fig. 6-A). The magmatic fraction of this unit is black and light brown when weathered, poorly vesiculated and poorly porphyric with few plagioclase and clinopyroxene crystals. Lithics consist of fresh and argilified andesite fragments only. This unit outcrops on the northern part of the caldera cliff (Fig. 5).

Unit 3

This andesitic lava flow reaches a maximum of 40 m in thickness, but its extension is limited to the north-eastern part of the caldera (Fig. 5).

Lacustrine deposits Unit 4

Those lacustrine beds represent the sedimentation of dominantly volcanic input within an aqueous system, resulting in varved deposits of different granulometry. A detailed stratig-

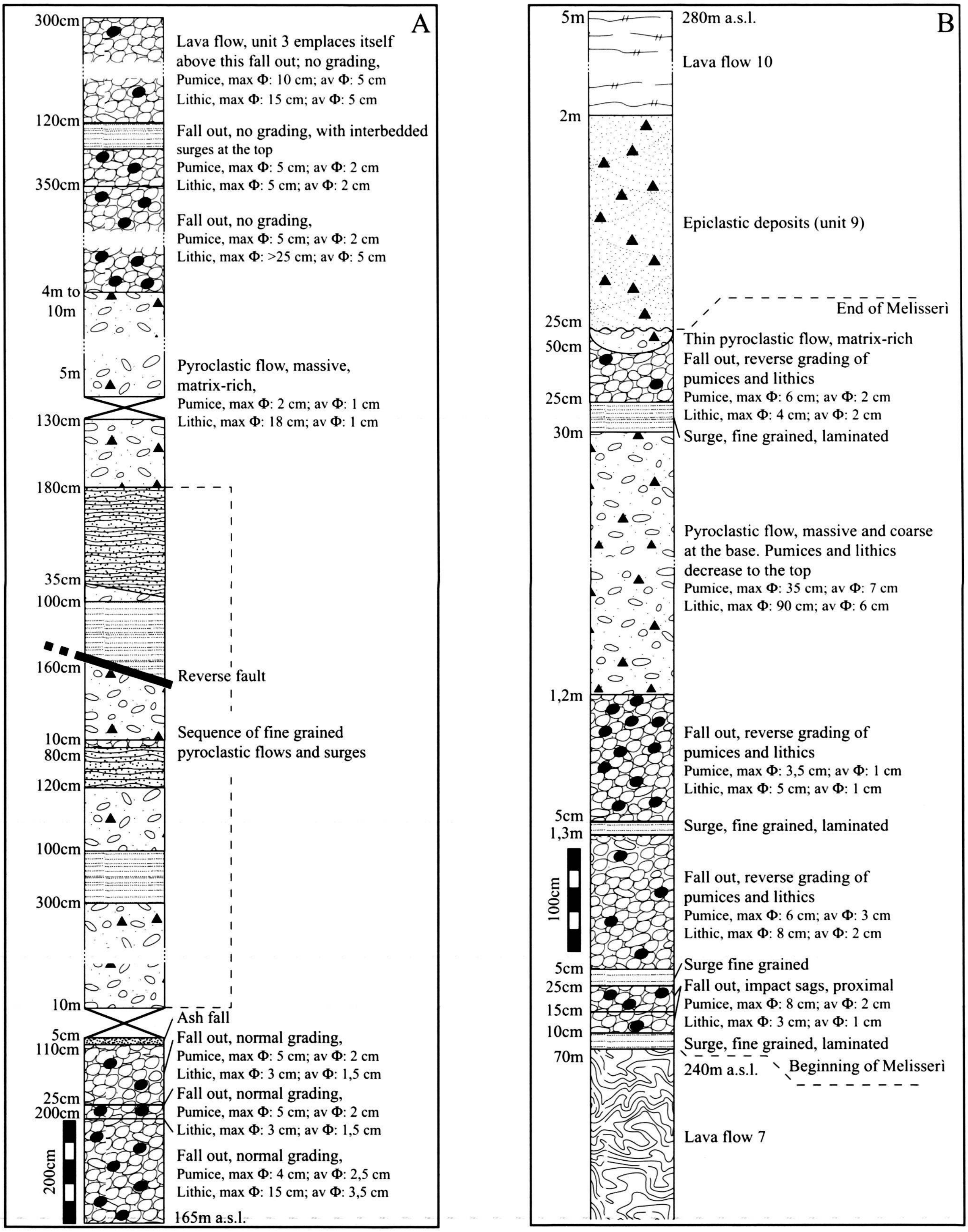

Fig. 6. Detailed stratigraphic sequence of (A) the Lakkì unit, and (B) the Melisserì unit.

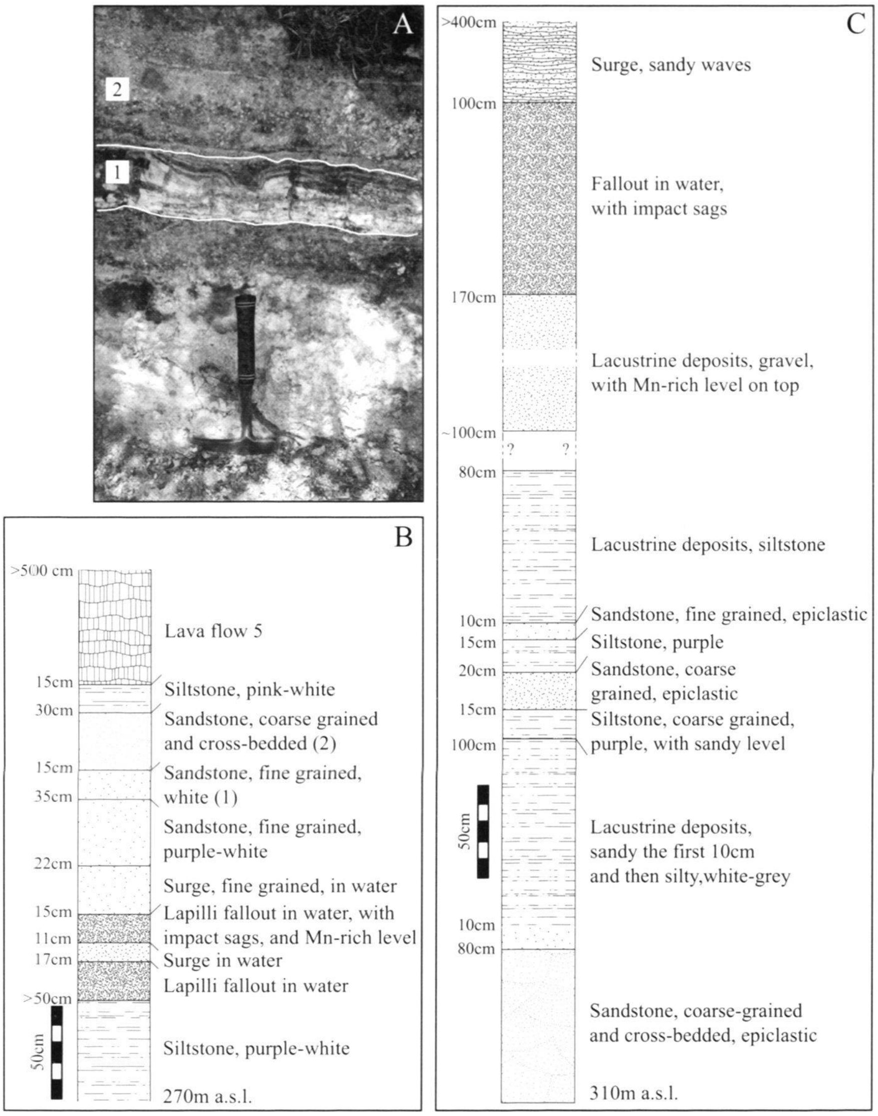

Fig. 7. (A): Photograph of the first lacustrine deposits (Unit 4). (B & C): Detailed stratigraphy of the two lacustrine episodes outcropping on the northern caldera cliff.

raphy is given in Fig. 7-B. This unit is limited in its lateral extension to some outcrops near and on the road-cut on the north-eastern side of the caldera (Fig. 5).

Unit 5

Those basaltic-andesitic lavas are located on top of the lacustrine beds, resulting in load cast structures within the water-saturated sediment. They can only be found on the north-eastern part of the caldera walls (Fig. 5).

Lacustrine deposits Unit 6

Those beds do not substantially differ from the previous lacustrine unit (Fig. 7-C), but the lava flow 5 divides the two. The second lacustrine episode ends with a deposit of lapilli fallout topped with fine sand-waved surges. Like the previous lacustrine deposits, their lateral extent is limited to the north-eastern caldera cliff (Fig. 5). Both lacustrine units dip at 126/22 and both contain black, manganese-rich layers a few centimeters thick.

Unit 7 (scoria-rich lava)

This basaltic-andesitic unit is made of multiple lava flows with thick scoria base and top, which represents a particularity among the Nisyros lava flows. Its thickest section (70 m) is found at the base of the northern wall below Emborìò (Fig. 8), but the same unit can be found all the way around the caldera.

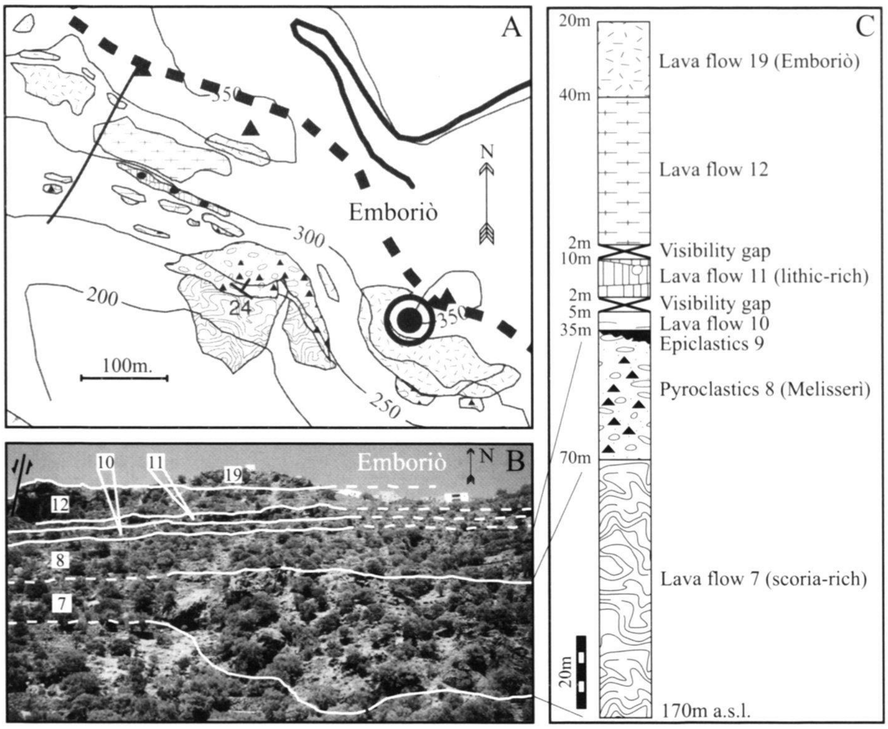

Fig. 8. Geological map (A) and photograph (B) of the sector of the caldera cliff under Emboriò. (C) General stratigraphy of the cliff. See legend in Fig. 3.

Fig. 9. Photographs:
(A) Fallout at the base of the Melisserì unit.
(B) Pyroclastic flow of the Melisserì unit.
(C) Lithic-rich lava flow (unit 11), Remo Chiesa for scale.
(D) The Yàli pumice fall, remobilized within a talus fan, Alain Volentik for scale.

Unit 8 (Melisserì and Evangelistra pyroclastics) and 9 (epiclastics)

The andesitic pyroclastic unit of Melisserì, characterized by pinkish red pumices and scoriae, displays a fallout level at its base (Fig. 6-B), followed in the most proximal section by a 30 m thick pyroclastic flow deposit, and finally a 3.5 m succession of fall, surges, and pyroclastic flows (Fig. 9-A and 9-B). This unit is ubiquitous around the caldera, but the most proximal, and most typical facies are found in its northern part (Fig. 8), whereas the thinnest and most distal outcrops

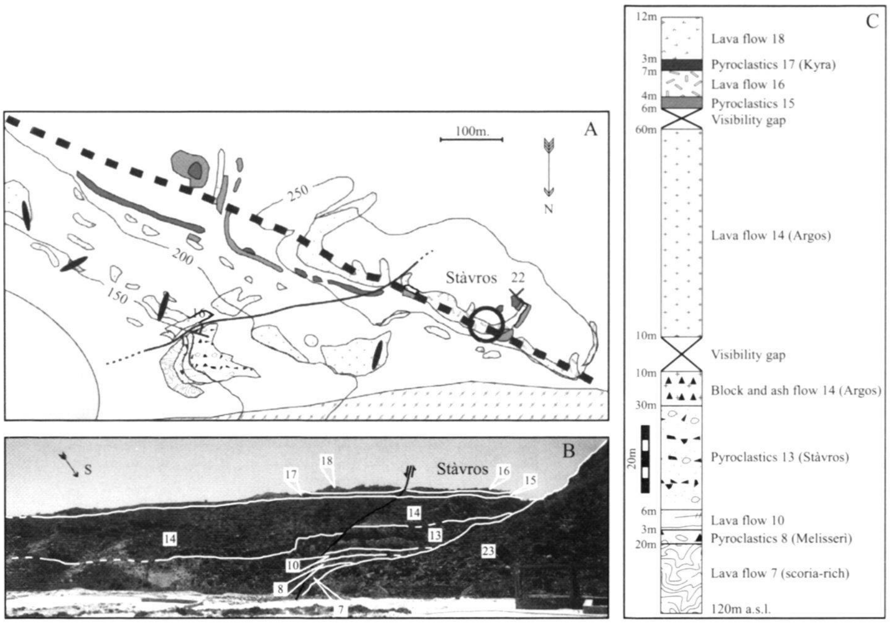

Fig. 10. Geological map (A) and photograph (B) of the Stàvros sector of the caldera. (C) General stratigraphy of the cliff. See legend in Fig. 2.

are located in the opposite wall (Fig. 10). Lithic fragments are made of fresh andesites within the fall deposit, and mainly of fresh sub-intrusive diorites in the pyroclastic flows, suggesting a drastical change of the fragmentation level during the eruption.

Very similar flow units (the Evangelistra sub-unit) with distinctive features of the magmatic fraction (such as lower vesicularity, larger size of cavities and higher porphyric index in respect to Melisserì) can be found below Melisserì. Those units are probably related to the same eruptive event, yet with different eruptive processes.

This unit is overlain by an epiclastic sequence (unit 9) which reworks Melisserì and Evangelistra pyroclastics.

Unit 10

This andesitic lava flow (which presents no specific peculiarity, except for its stratigraphic position) extends all the way around the caldera, almost in a complete stratigraphic continuity. Representative outcrops are located near the road on the north-eastern side of the caldera (Fig. 5).

Unit 11 (lithic-rich lava)

This lava flow has the peculiarity of incorporating up to 30% of xenolithic material (mainly andesitic fragments of various colours, ranging from red to dark grey, which appear in relief compared to the erosion surface), which makes it an excellent stratigraphic marker. It is found throughout the northern portion of the caldera cliffs, from Emboriò up to the neighbourhood of Nikià. Its most illustrative outcrop (Fig. 9-C) is located just above the road upon entering the caldera from Mandraki (Fig. 5).

Unit 12

An andesitic lava flow, with a thick sole of red scoriae. It is found mainly in the northern part of the caldera (Fig. 5 and 8).

Unit 13 (Stàvros pyroclastics)

The main characteristic of this basaltic unit is its base of surge beds of grey lapilli. It is followed by pyroclastic flows and surges, with a substantial dominance of the latter. Fresh andesitic fragments are found as lithics, in particular in the flow deposits. Its thickest section (30 m, Fig. 10) is exposed below the Monastery of Stàvros, on the southern wall of the caldera, becoming substantially less thick northward, until it totally disappears North of Nikià.

Unit 14 (Argos lava)

This is a dark-grey rhyolitic lava, which sometimes presents reddish banding and perlitic textures. This unit can be found in the form of lava flows, domes and subsequent block and ash flows. It includes rare plagioclase phenocrysts within an aphyric matrix. The thickest sections can be found in the southern segment of the caldera, where a neck of Argos lava flow crops out (Fig. 10).

Unit 15

This pyroclastic unit is made up of red, andesitic spatter cones located around the edges of the caldera and are restricted to this particular stratigraphic horizon. No lithics were found in this deposit. A very well exposed scoria cone can be found

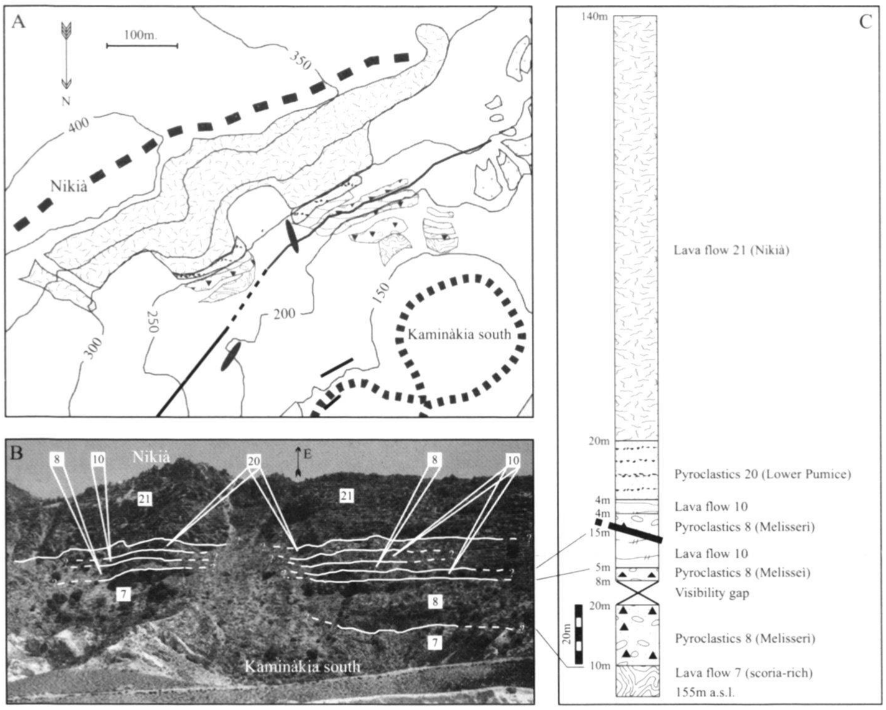

Fig. 11. Geological map (A) and photograph (B) of the sector of the caldera cliff between Nikià and Kaminàkia. (C) General stratigraphy of this sector of the caldera cliff. See legend in Fig. 2.

right under the Monastery of Stàvros, on the southern flank of the caldera (Fig. 10).

Unit 16

This southward flowing basaltic-andesitic lava unit is limited to the southern side of the caldera (Fig. 10), and does not exceed 7 m in thickness. Plagioclase and pyroxene phenocrysts can be observed in hand specimen.

Unit 17 (Kyra unit)

This pyroclastic unit is formed by multiple magmatic and phreatomagmatic eruptive phases (Rehren (1988) has recognized 12 of them, six of which having reached the neighbouring island of Tilos, at about 15 km from Nisyros), ranging in composition from andesite to dacite and divided by a total of five palaeosoils (Rehren 1988). The phenocryst assemblage includes plagioclase, pyroxene and amphibole. A wide variety of lithic fragments were observed in the deposit of this unit: mafic lavas, sub-intrusive rocks, cumulates, limestones and marbles. Its thickest section within the caldera is a 3 m deposit in its southern border (Fig. 10). Deposits that can be related to this unit are also found on the summit of the section above the road in the northern slopes of the caldera walls (Fig. 5).

Unit 18

This appears to be the last basaltic-andesitic effusive event found within the walls of the caldera of Nisyros. Stratigraphically higher than the Kyra unit (unit 17), it is otherwise similar to the lava unit 16, with the same plagioclase and pyroxene crystal assemblage. It does not exceed 10 m in thickness, and its lateral extension is limited to the area near the Monastery of Stàvros (Fig. 10).

Unit 19 (Emboriò lava)

The dominant facies of this unit is a typically light grey dacite with plagioclase phenocrysts within an aphyric matrix, which includes 1-2% of andesitic enclaves. This unit forms characteristic lava domes and associated dome collapse pyroclastic deposits (block and ash flows, cropping out under the Emboriò lava dome). The best exposed of these domes is the 150 m high hill of Akimaronas, which dominates the village of Emboriò (Fig. 8).

Unit 20 (Lower Pumice pyroclastic unit)

This unit, studied in detail by Limburg & Varekamp (1991) and Hardiman (1999), includes a basal pumice fall, followed by pyroclastic flows. A palaeosoil covers the summit of the sequence. Fragments of andesites, skarns and sub-intrusive rocks, some bearing neoformed epidote, are found in the lithic fraction of the pyroclastic flows. Up to 20 m of this deposit can be found in the caldera cliff in the Nikià sector (Fig. 11).

Unit 21 (Nikià lava)

Those thick rhyolitic lavas cover the whole eastern flank of the island, all the way from the rim of the caldera to the sea. Large amphibole-bearing enclaves reaching 1.5 m in size are widespread within the flow. Typical outcrops are found near the Monastery of Aghios Ioannis Theologos and near the village of Nikià , where its thickness can reach 150 m (Fig. 11). A neck that fed this massive lava flow is exposed along the caldera wall (Fig. 1).

Yàli fallout (Unit 22)

The Yàli fallout layer (Allen & McPhie 2000) is found remobilized within the talus fans on the flanks of the caldera (Fig. 9-D). Its pumices are typically aphyric and extremely finely vesiculated.

Post-caldera lava domes (Unit 23)

Those domes, up to 600 m in height (Mt Profitis Illias), fill two-thirds of the caldera on its western side. Typical outcrops are found along the trail that leads from the Monastery of Evangelistra to the active hydrothermal area.

Tectonics

Tectonic data have been collected within the caldera of Nisyros, namely by mapping faults and measuring dip and strike of faults, fractures, extrusions and dykes.

The orientation of fractures and dykes are grouped in 3 well-defined trends, with little to no scattering of the data: a trend at N70°, another at N30° and a last one at N170°. A fact of note is that some dykes along the N70° trend (north-eastern part of the caldera, Fig. 5) feed the lava flow 3, while some others cross the stratigraphy through the Melisserì unit (unit 8) to reach the lava flow 10; this denotes that this trend has been active early in the history of the volcano and has lasted at least until now (as seen from N70°-trending faults on Fig. 10). The same reasoning can be applied to the N170°-trending dyke in the south-eastern part of the caldera (Fig. 11), which appears to be feeding the lava flow unit 10.

Those three main tectonic trends are in good agreement with work previously done by Di Paola (1974), Papanikolaou et al. (1991) and Simaiakis (1992), and can be explained in the overall geodynamical context by the roll-back of the Oriental Mediterranean (Nakamura & Uyeda 1980; Meijer & Wortel 1997). No sign of radial faulting or fracturing (as proposed by Stiros 2000) was witnessed on the cliffs of the caldera.

Furthermore, we noted normal faults with orientations of N30° and N70° leading to the slumping of blocks, step-like morphology and redoubling of the stratigraphy in the south-eastern wall of the caldera, below the village of Nikià (Fig. 11). Those two trends wholly control the morphology of the edge of the caldera in the entirety of its south-eastern segment. The alignment of the necks of the Argos lavas (unit 14) and Nikià lavas (unit 21; Fig. 1), which fall on a N30°-trending line, also outlines this feature. Finally, while most of the caldera margin's elevation is controlled by the thickness of some lava flows, the southern sector (Fig. 10) has, on the other hand, dropped by about 100 m, due to a set of normal faults following the same N30° trend.

Data Discussion

The caldera of Nisyros appears as a near perfect round structure (Fig. 1). This morphological characteristic and the striking appearance of Lower and Upper pumices, spawned the idea into the previous literature that the caldera depression was related to these two explosive events (Hardiman 1999; Vougioukalakis 1998; Papanikolaou et al. 1991; Keller et al. 1990; Di Paola 1974) or even to the last of these pumice eruptions (Limburg & Varekamp 1991). The stratigraphic reconstruction made in the present work points out that on the modern caldera walls can be found the deposits of at least two other explosive events capable of inducing calderic collapse: i.e. the pyroclastic unit 2 (Lakkì) and the pyroclastic unit 8 (Melisserì and Evangelistra).

Despite the fact that the Lakkì deposits outcrop only in one section, they show a thick, typical plinian sequence of fallout, surges and pyroclastic flow deposits (Cas & Wright 1987; Fig. 6-A). The dipping of the first lava flow emplaced after the Lakkì eruption (lava flow 3) in the direction of the present caldera depression, suggests the presence of a morphological depression; this is further demonstrated by the existence of the two lacustrine units inside the north-eastern caldera cliff. Those lacustrine deposits do not continue on the eastern sector of the cliff, but they are confined to the curved sector of the caldera wall illustrated on sketch 5. On the basis of these evidences, we advance the hypothesis that a first relatively small caldera has been formed in the early periods of volcanic activity on the northern sector of Nisyros as a consequence of the Lakkì eruption.

A second important explosive sequence (about 30 m thick) outcrops on the caldera walls, related to the Melisserì/Evangelistra eruption. The stratigraphic sequence of this eruption includes pumice fallout and huge pyroclastic flow units that outcrop all along the caldera wall. Fig. 5, 8, 10 and 11 show that the thickness of the Melisserì flow is declining southward. This decrease corresponds to a reduction of the juvenile scoriae dimension, indicating that the source region of the flow has to be placed on the Northwest sector of the present calderic depression. Epiclastic deposits top the Melisserì sequence, marking the reorganization of the morphology after the eruption. This eruptive sequence and the volume of the deposits outcropping on the caldera walls suggest a second caldera collapse at the end of this eruption.

The eastern sector of the present caldera depression shows evidences of a tectonic instead of volcanic origin. The tectonic trend N70° and N30° controlled the superficial magma feeding system, starting from the very early stages of the volcanic activity.

Dykes feeding the first lava flows of the eastern slopes of the caldera, strombolian edifices and volcanic necks of the major lava flows are all positioned on N30° directions. Faults with this direction caused the downthrowing of the Stàvros sector of the caldera and the formation of the huge morphological step that doubles the stratigraphic succession on the eastern cliff. Other pyroclastic units have been found on the caldera walls, but the scarcity of the outcrops prevents us from defining their importance in the framework of the evolution of the volcanism on Nisyros. Further studies need to integrate the stratigraphy of the caldera walls inside the general stratigraphy of Nisyros.

The problem of the Kyra unit

The Kyra unit (pyroclastics 17), as it was observed and defined just below the Monastery of Panaghia Kyra and on the north-eastern flanks of the volcano above the beach of Lies (Vougioukalakis 1984; Rehren 1988), is not observed in the section available within the caldera. The available outcrops only displayed black lapilli fall deposits. At this stage of knowledge of the Nisyros stratigraphy, we attribute these deposits to the more mafic part (strombolian and violent strombolian activity) of the Kyra eruptive event, according to previous authors (Vougioukalakis 1984; 1998; Rehren 1988; Papanikolaou et al. 1991).

Lacking better exposure that would allow us to clarify the spatial relationships between the unit 15-unit 16-unit 17-unit 18 succession and the Kyra formation, we decided to keep them separated in the stratigraphic sequence and assimilated Kyra to unit 17, until further work is done to extend the present stratigraphy outside of the caldera and until the role of these eruptive events is better understood.

Conclusions

The new stratigraphy on the caldera walls of Nisyros reveals that:

- As a consequence of the explosive eruption of Lakkì, a first caldera has been formed in the north-western sector of the island.
- The Melisserì explosive eruption produced a thick pyroclastic flow layer that is widespread on all Nisyros caldera sectors with an origin in the northern-central sector of Nisyros. It is possible that a second caldera collapse occurred after this eruption.
- Three tectonic trends operate on the island starting from the first stages of volcanic activity and affected the caldera formation and morphology, with orientations of N70°, N30° and N170°.
- The eastern sector of the caldera has been controlled by the N30° trend that caused the redoubling of the stratigraphic succession. Without the activity of this trend, the caldera would be substantially smaller.

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