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Young Neogene tectonics and relief development on the Aegean islands of Naxos, Paros and Ios (Cyclades, Greece)

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Abstract

Neogene tectonics and topographic relief of the Attic-Cycladic Composite Unit (ACCU) have evolved in a geotectonic setting behind the Hellenic convergent plate boundary. Post-metamorphic tectonics were dominated by extension at crustal scale, giving rise to metamorphic core complexes. Tilted horsts and half-grabens emerged from listric block rotations during brittle stages of extension. However, remnants of subhorizontal planation systems are still preserved on several islands of the Cyclades.

Apatite fission-track ages of 11 samples from the islands of Naxos, Paros and Ios range between 13.4 and 7.8 Ma, i. e. from Middle to Late Miocene. Thermal history calculations indicate rapid cooling in the Middle/Late Miocene, mainly between 12 and 8 Ma ago. Maximum cooling rates were in the order of 50 to 130 °C/Ma. Afterwards, cooling decelerated and most samples were subjected to low temperatures (<60 °C), i. e. they resided close to the surface until present.

Fast cooling during the Middle/Late Miocene was essentially produced by tectonic exhumation due to strong crustal extension, while the amount of surface erosion was much smaller. Apatite fission-track thermochronology indicates a maximum age of 10 Ma for the uppermost planation level of Ios and a maximum age of 8 Ma for the peneplain remnants of Naxos and Paros. From the climato-geomorphological point of view, such ages would be consistent with the climatic evolution of the Eastern Mediterranean.

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Junge neogene Tektonik und Reliefgestaltung auf den Ägäisinseln Naxos, Paros und Ios (Kykladen, Griechenland)

Zusammenfassung

Die neogene Tektonik und Reliefgestaltung des Attisch-Kykladischen Deckenstapels fanden an der Rückseite der konvergierenden Plattengrenze der hellenischen Subduktionszone statt. Die post-metamorphe Tektonik der Kykladen ist durch großräumige Krustendehnung und die Bildung metamorpher Kernkomplexe geprägt. Durch listrische Abschiebungen entstanden Pultschollen und Halbgräben, bzw. stark asymmetrische Horste und Gräben. Trotz der damit verbundenen Rotationsbewegungen sind mehrere subhorizontale Systeme von Altflächen auf den Kykladen erhalten geblieben.

Die Apatit-Spaltspuralter von 11 Proben von Naxos, Paros und Ios liegen zwischen 13,4 und 7,8 Ma (mittleres bis spätes Miozän). Thermochronologische Modellierungen weisen auf eine schnelle Abkühlung im mittleren und späten Miozän hin, hauptsächlich vor 12 bis 8 Ma. Die maximalen Abkühlraten lagen in der Größenordnung von 50 bis 130 °C/Ma. Danach verlangsamte sich die Abkühlung und die Proben verweilten bis zur Gegenwart bei niedrigen Temperaturen (<60 °C) bzw. in geringer Tiefe.

Die schnelle Abkühlung im mittleren und späten Miozän wurde hauptsächlich durch tektonische Exhumierung infolge starker Krustendehnung verursacht. Die oberflächliche Erosion dürfte einen wesentlich kleineren Einfluß gehabt haben. Thermochronologischen Modellierungen der Apatit-Spaltspurdaten ergeben ein Maximalalter von 10 Ma für die älteste erhalten gebliebene Reliefgeneration von Ios und ein Maximalalter von 8 Ma für die tropischen Rumpfflächen von Naxos und Paros. Diese Alter stehen im Einklang mit der klimatischen Entwicklung des ostmediterranen Raumes.

Tectonique et géomorphologie néogène des îles de Naxos, Paros et Ios (Cyclades, Grèce)

Résumé

Le développement tectonique et geomorphologique du Crystallin d'Attique et des Cyclades pendant le Néogène a eu lieu dans un environnement d'extension à l'arrière de la subduction hellénique. Cette tectonique post-métamorphique est caractérisée par un régime d'extension ductile, qui a produit des dômes metamorphiques semblables à ceux de la région du Basin and Range, mais aussi par des déformations cassantes. Quoiqu'un système de failles normales a produit des rotations tectoniques, certaines surfaces d'érosion anciennes sont preservées en position sub-horizontale sur quelques îles des Cyclades.

Onze échantillons de roche provenant des îles de Naxos, Paros et Ios ont été datés par la méthode des traces de fission en apatite. Leur ages de traces de fission se trouvent entre 13,4 et 7,8 Ma (Miocène moyen et supérieur). Les trajectoires thermochronologiques indiquent un refroidissement rapide pendant le Miocène moyen et supérieur, c'est à dire entre 12 et 8 Ma avant le temps présent. Les vitesses de refroidissement maximales ont été dans un ordre de grandeur entre 50 et 130 °C/Ma. Plus tard le refroidissemnt a été ralenti et les roches examinées ont démeuré à températures basses (<60 °C) et en petite profondeur jusqu'au présent.

Le refroidissement rapide pendant le Miocène moyen et supérieur a été produit essentiellement par une exhumation tectonique en conséquence d'une extension crustale. L'influence de l'érosion superficielle était négligeable. La thermochronologie des traces de fission en apatite indique un age maximal de 10 Ma pour le plus ancien relief de Ios et un age maximal de 8 Ma pour les surfaces de troncature de Naxos et Paros. Ces ages sont compatibles avec le développement climatique de la Méditerranée orientale.

1. Introduction

The Attic-Cycladic Composite Unit (ACCU) is an Alpidic nappe pile, which has developed by thrust faulting, ductile thinning and normal faulting. Crustal extension has occurred in a geotectonic setting to the north of the Hellenic convergent plate boundary (LISTER et al, 1984; JOLIVET et al., 1994; FORSTER & LISTER, 1999).

An Eocene blueschist unit was overthrust upon a parautochthonous unit of low-grade metamorphic rocks. The Oligo-Miocene exhumation of that blueschist unit was mainly a consequence of ductile thinning and low-angle normal faulting (AVIGAD & GARFUNKEL, 1991, 1993; GAUTIER et al., 1993; GAUTIER & BRUN, 1994; VANDENBERG & LISTER, 1996). The extensional decompression interfered with a regional low-P medium-T metamorphism and with granitic plutonism (FAURE et al., 1991; PAPANICOLAOU, 1993). Tectonical slices of ophiolitic material, sedimentary and low-P metamorphic rocks are still preserved on top of the present-day blueschist unit.

Continuous subduction retreat of the Hellenic convergent plate boundary yielded a southward propagation of both high-pressure metamorphism and subsequent exhumation. On the island of Crete, which is situated above the present-day Hellenic subduction zone, Oligo-Miocene high-P low-T metamorphic rocks occur in the lower plate of an extensional detachment, while the upper plate is not affected by Tertiary metamorphism (THOMSON et al., 1999).

The tectonic evolution of the Cyclades is not consistent with the idea of long lasting peneplanation on rigid continental areas, proposed by PHILIPPSON (1959) according to the concept of DAVIS (1899). Miocene intrusion ages of plutonic rocks – being now exposed at the surface – and subsequent tectonic movements imply a landscape development during rather short time under the climatic conditions of the East Mediterranean Neogene (RIEDL, 1979, 1982 a, b, 1984 a, b, 1989, 1991; WEINGARTNER, 1994; LOUIS & FISCHER, 1979). The distribution of palaeo-planation surfaces of the Cyclades exhibits a steplike arrangement, which might be the result of a regional piedmont-staircase development or of local horst-graben tectonics dissecting a former peneplain. Despite the fact of listric block-rotations during Neogene extension, the preserved planation relics are not tilted significantly but are still subhorizontal.

Our investigation deals with apatite fission-track thermochronology of the islands of Paros, Naxos and Ios. The modelled cooling paths below of ~120 °C are discussed in the context of tectonic, stratigraphic and geomorphological findings. Thus, the age of preserved relief features and young tectonic deformations can be better constrained.

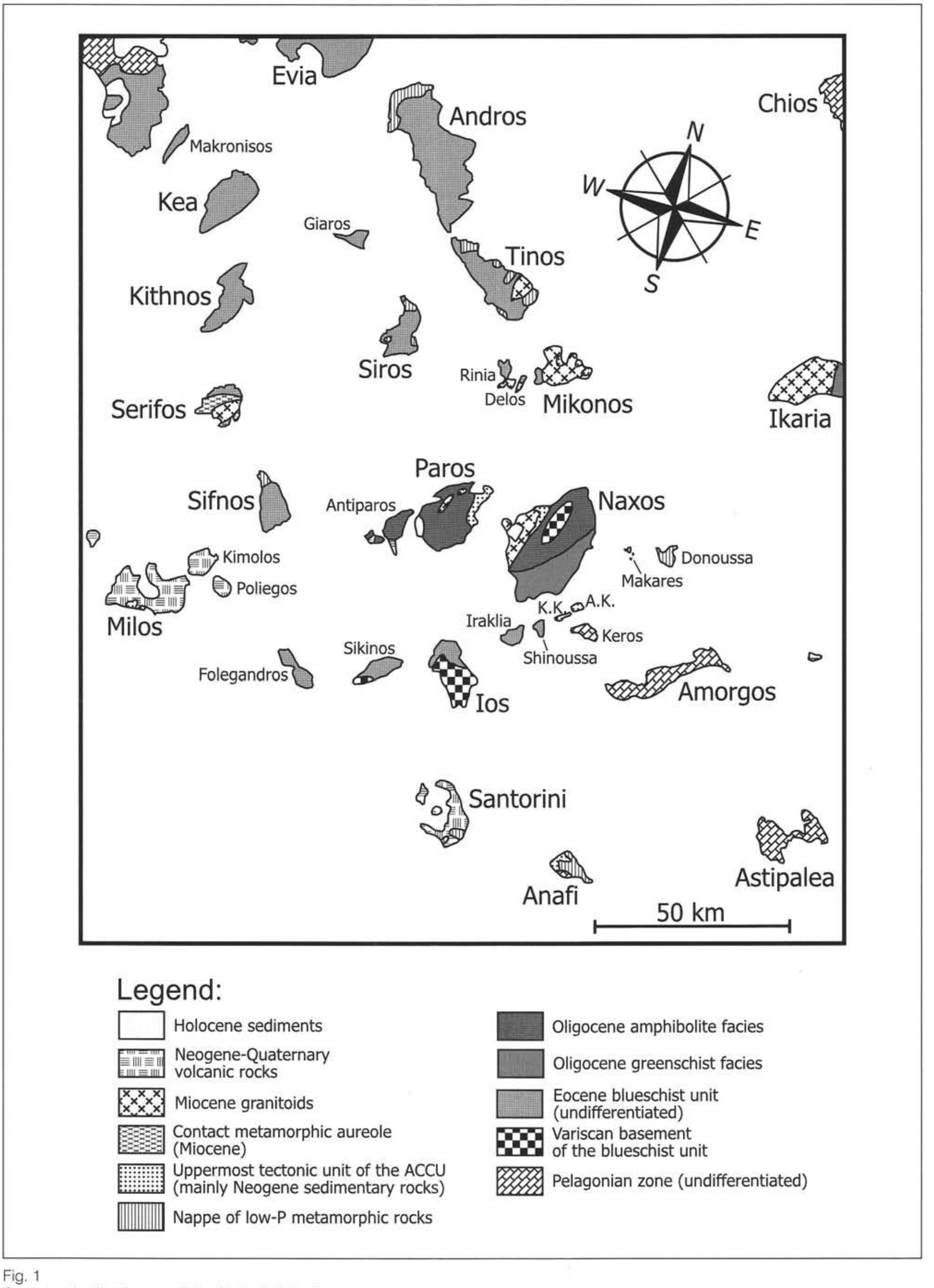


Fig. 1
Geotectonic sketch map of the Cycladic islands.

2. Geological setting and pre-Oligocene development

Attica, southern Evia, most of the islands of the Cyclades, as well as Ikaria and Samos belong to a polyphase complex being mainly composed of metamorphic and plutonic rocks (Fig. 1). These crystalline rocks of the Central Aegean have been summarized under terms like "Median Aegean crystalline belt" (DÜRR et al., 1978), "Attic-Cycladic massif" (ANDRIESSEN et al., 1979, 1987; VANDENBERG & LISTER, 1996), "Central Aegean crystalline complex" (ALTHERR, 1980), "Attic-Cycladic crystalline complex" (ALTHERR et al., 1982), "Cycladic massif" (VAN DER MAAR & JANSEN, 1983; AVIGAD & GARFUNKEL, 1991), "Cyclades-Menderes window" (translation of the German expression "Kykladen-Menderes Fenster", by Thorbecke, 1987), "Cycladic blueschist belt" (LEE & LISTER, 1992; AVIGAD & GARFUNKEL, 1991) and others. These expressions refer to specific geodynamic concepts, have different petrogenetic and regional limitations and therefore, cannot be used as synonyms. Especially the term "massif" should be avoided, because it suggests a rather stable block within a mobile orogenic belt (PHILLIPPSON, 1959). Such a concept is clearly disproved for the area under discussion.

We have chosen the collective name "Attic-Cycladic Composite Unit" (ACCU) for the metamorphic units, Neogene plutons and pre-Pleistocene sedimentary rocks of the whole region. The ACCU can be subdivided into three main units as follows:

1. pre-Miocene metamorphic rocks of a lower tectonic unit,
2. Miocene plutons emplaced within these metamorphic rocks and
3. a hanging wall of Neogene sedimentary rocks with slices of their former basement, i. e. greenschists, Permo-Triassic limestones, ophiolites and Upper Cretaceous neritic limestones.

The metamorphic rocks of the lower tectonic unit form a nappe pile being composed of three structural units: (1) A lowermost par-autochthonous unit of low-grade metamorphic rocks is exposed in southern Evia, Samos and Tinos; (2) an Eocene high-P unit with blueschist, which occupies an intermediate position; (3) an upper unit of low-P metamorphics, including metamorphosed ophiolites, is exposed on the islands of Andros, Tinos and Siros.

The protoliths of the high-P unit comprise a Variscan metamorphic basement and a series of sedimentary and volcanic rocks of presumable Mesozoic age. Variscan basement rocks are exposed in the central part of the Naxos gneiss dome, as well as on the island of Ios and in the souternmost part of Sikinos (ANDRIESSEN et al., 1987; BALDWIN & LISTER, 1998; DÜRR et al., 1978; HENJES-KUNST & KREUZER, 1982; KREUZER et al., 1978; VAN DER MAAR & JANSEN, 1983).

Few Mesozoic fossils have been reported from the post-Variscan series. Rhaetian fossils (*Heteroporella zankli* and *Thecosmilia clathrata*) were found in marbles of Tinos (MELIDONIS, 1980); some questionable late Triassic algae and foraminifera were reported from dolomitic marbles of Naxos (DÜRR et al., 1978; ALTHERR et al., 1982). Also the Sr isotope composition of the marbles of Naxos (ANDRIESSEN et al., 1979) is not in contradiction to a Mesozoic sedimentation age. It is worth to notice that corundum and diaspore bearing marbles of Naxos have been compared with those of the Menderes crystalline complex in Anatolia (cf. DÜRR et al., 1978; JANSEN & SCHUILING, 1976), where they are stratigraphically overlain by rudist limestones. The metabauxites could record Cretaceous periods of subaerial weathering as it is proven for the Parnassos-Ghiona zone and the Pelagonian zone (cf. FAUPL et al., 1998, 1999; HEJL et al., 1999). All these arguments together support the assumption that the high-P unit of the ACCU belongs to the Pelagonian zone which is mainly composed of a Variscan basement and carbonatic shelf sediments. The Pelagonian zone is a member of the Internal Hellenides (BRUNN, 1956), which also comprises the Axios-Vardar zone, the Circum-Rhodope belt, the Serbo-Macedonian zone and the Rila-Rhodope unit.

During the Early Cretaceous, the Pelagonian zone was subjected to subaerial weathering and denudation. The corresponding palaeosurface is characterized by karstification, lateritic palaeosoils and bauxites. Afterwards, this palaeokarst has been buried under a Cenomanian-Turonian transgressive sequence (e. g. FAUPL et al., 1999; HEJL et al., 1999). Rudist limestones were formed in the shallow water of a Late Cretaceous sea. During the Maastrichtian, the carbonate platform began to collapse. Down-faulted regions with persistent pelagic sedimentation and uplifted areas with erosion and karstification alternated on a rather small scale (cf. FAUPL et al., 1999; HEJL et al., 1999). Finally, the Pelagonian zone was covered by terrigeneous flysch deposits of Palaeocene and Eocene age. The onset of the Mesohellenic orogeny in the Late Eocene coincides with the end of Pelagonian sedimentation.

This Mesohellenic orogeny began with the closure of the Pindos ocean and was responsible for the high-P metamorphism (M_1) of the Cycladic blueschist unit (FAUPL et al., 2002). The climax of this high-P metamorphism occurred between 45 and 40 Ma ago (ALTHERR et al, 1979; ANDRIESSEN et al., 1979; KREUZER et al., 1978). Glaucophane schists together with greenschists and marbles occur in the northern part of Ios (Fig. 4) where the peak conditions of the high-P event reached about 13 kbar and 475 °C (VAN DER MAAR & JANSEN, 1983). On the islands of Naxos and Paros, the Eocene blueschist parageneses are almost entirely erased by a younger Barrovian overprint (M_2), which will be described in the next chapter.

3. Oligocene and Neogene metamorphism, plutonism and tectonics

The Mesohellenic high-pressure event of the ACCU was followed by crustal-scale extension, while orogenic compression was shifted south- and westwards into the Gavrovo, Ionian and Paxos zone, forming the External Hellenides. Tectonic stretching created ductile shear zones, low-angle normal faults and gave rise to the formation of metamorphic core complexes (LISTER et al., 1984; LEE & LISTER, 1992; GAUTIER et al., 1993; GAUTIER & BRUN, 1994; VANDENBERG & LISTER, 1996).

At the same time, an Oligo-Miocene Barrovian metamorphism (M2) produced greenschist and amphibolite facies retrogression of the Mesohellenic blueschist facies (M1). According to JANSEN (1973 and 1977) and JANSEN & SCHUILING (1976), the Barrovian metamorphic zonation of Naxos

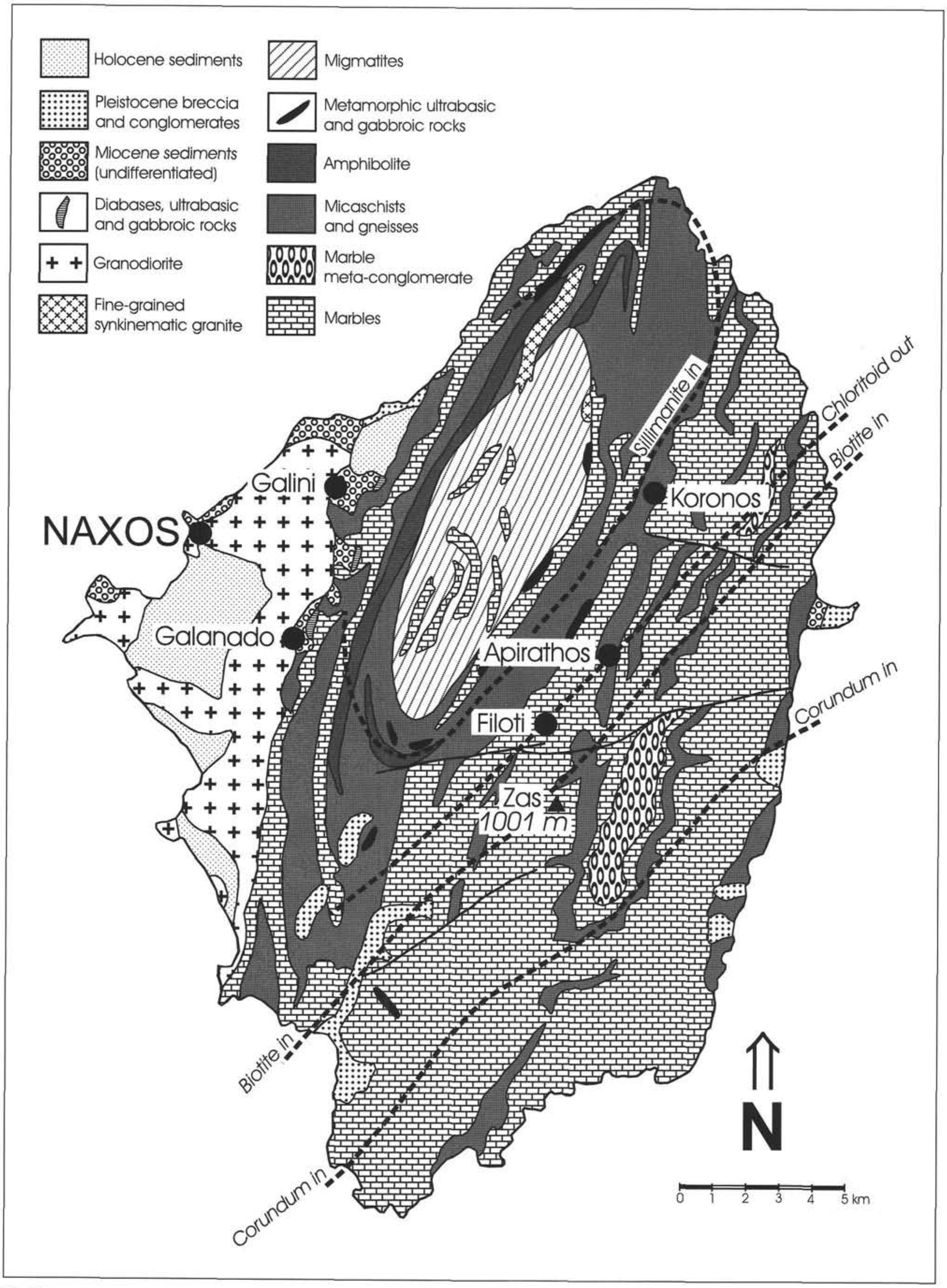


Fig. 2:
Geological map of Naxos, simplified and slightly modified after JANSEN (1973) and ANDRIESSEN et al. (1979).

(Fig. 2) increases from greenschist facies in the SE to partial anatexis in the center of the migmatic gneiss dome. From the biotite-chloritoid zone upwards (i. e. towards northwest), K-Ar ages of hornblende, muscovite and biotite range between 21 and 11 Ma (ANDRIESSEN et al., 1979). These ages seem to reflect postmetamorphic cooling after a temperature peak around 25 Ma. Also the island of Ios comprises a Neogene metamorphic core complex with a lower unit consisting of strongly deformed orthogneisses and garnet-mica schists, and with an upper unit consisting of marbles and schists of the blueschist facies. A domed up top-to-the-south shear zone occurs in the upper part of the footwall (BALDWIN & LISTER, 1998).

After the Barrowian metamorphism, the lower tectonic unit of the ACCU was intruded by I-type and S-type granitoids (ALTHERR et al., 1982). Precise timing of these intrusions is still a matter of debate. Based on K-Ar and Rb-Sr mineral ages, ALTHERR et al. (1982) have argued for an intrusion time span from 22 to 14 Ma ago, shortly after the culmination of the Barrowian metamorphism, despite ANDRIESSEN et al. (1979) had reported a Rb-Sr isochron of 11.1 ±0.7 Ma for the Naxos granodiorite. However, the intrusions must have occurred in Miocene times. Their emplacement was accompanied by ductile extension (FAURE et al., 1991; LEE & LISTER, 1992).

The western part of Naxos consists of an I-type granodiorite, which has caused contact metamorphism of the country rock (JANSEN, 1977; ALTHERR et al., 1982). After consolidation the granodiorite was subjected to mylonitic shearing. As on Mikonos, the Naxos intrusion is overlain by slices of the uppermost tectonic unit of the ACCU. These hanging-wall slices of western Naxos comprise ophiolites (diabases, ultrabasic and gabbroic rocks) and Neogene sediments (Fig. 2).

Northwestern Paros has been intruded by a two-mica S-type granite (Fig. 3). K-Ar dates of biotite and muscovite from this intrusion (12.4 ±0.2 Ma and 11.5 ±0.2 Ma, respectively) have been interpreted as cooling ages (ALTHERR et al., 1982).

Neogene aplite dykes, which intrude basement rocks of Ios (Fig. 4) have been identified by HENJES-KUNST & KREUZER (1982). One of these dykes yielded a phengite Rb-Sr age of 13.2 ±0.4 Ma. Larger Neogene plutonic rocks do not occur on that island.

The structural analysis of ductile and brittle deformations on Naxos and Paros islands have demonstrated that a major normal sense detachment zone dipping to the N separates the Neogene sediments and slices of their former basement (Marmara nappe) from an originally deep-seated unit below (GAUTIER et al., 1993). The latter comprises the Neogene plutons as well as Barrovian metamorphic rocks. Extension seems to be responsible for most ductile deformations within greenschist facies and higher-grade metamorphic rocks. An other north dipping detachment zone has been identified farther N, on the islands of Mikonos, Tinos and Andros (GAUTIER & BRUN, 1994).

Some fission-track ages of both apatite and sphene from central Aegean plutons have been reported by ALTHERR et al. (1982). Their apatite ages from the Cyclades range from 8.0 Ma (Serifos) to 10.8 Ma (Tinos). Frequency distributions of track length have not been reported yet.

4. Comments to the Neogene stratigraphy

The uppermost tectonic unit of the ACCU comprises unmetamorphosed sedimentary rocks of the Neogene (Fig. 1). They are known from Attica, many islands of the Cyclades as well as from Ikaria and Samos. The Neogene of the Cyclades comprise both marine and continental facies. The stratigraphy of fresh-water deposits has been improved by the investigation of limnic gastropods (BÖGER, 1983).

Within the area of Fig. 1, Neogene sediments are preserved on Paros, Naxos, Katokoufo, Anokoufo, Makares Group, Mikonos, Anafi and Milos. Marine Lower Miocene (mainly Burdigalian) occurs on both sides of the straits Paros-Naxos (BÖGER, 1983; ROESLER, 1972; ÖKONOMIDIS, 1935). The marine sequence has a maximum thickness of over 200 m and comprises shales, marls, sandstones and conglomerates. Fossils of gastropoda, lamellibranchiata, anthozoa, bryozoa, echinodermata and foraminifera have been found within this series. The Lower Miocene is unconformably overlain by fresh-water deposits that are composed of conglomerates, sandstones, travertines and cherty beds. This sequence has a total thickness of more than 150 m and contains plant fossils and gastropods. In the older literature (cf. ROESLER, 1972), these younger non-marine deposits have been classified as Pliocene, but a detailed investigation of the gastropod fossils suggested a Middle to Late Miocene age of the traverine beds – strictly speaking Late Serravallian to Early Tortonian (BÖGER, 1983). Fresh-water deposits of fairly similar lithology and age (Serravallian-Tortonian) also occur on Katokoufo, Anokoufo and the Makares Group.

Granite pebbles are common in the fresh water sequence but are absent in the Lower Miocene conglomerates. The first appearance of granite pebbles could coincide with the exhumation of Neogene Cycladic plutons in Middle Miocene times. However, both petrology and provenance of the Neogene pebbles have not been investigated in detail.

Sandstones and conglomerates of Mikonos have a clastic spectrum, which is very similar to that of the marine series of Naxos and Katokoufo: pebbles of Tertiary metamorphics or granitoids are missing. On these grounds, DÜRR & ALTHERR (1978) as well as BÖGER (1983) have argued that the sedimentation age of this so-called "molasse" could range from Oligocene to Middle Miocene, but the statement is not proven by fossils. The quoted sedimentary rocks of Mikonos form the hanging-wall over a low-angle detachment fault and a ductile shear zone in the underlying granodiorite. The sense of motion was top to the NE (LEE & LISTER, 1992).

Marine Pliocene occurs on Milos and marine sedimentation also prevailed after the Messinian in the area of the present-day Sea of Crete.

5. Relief features

5.1 Naxos

Essential aspects of the geomorphology of Naxos have been clarified almost twenty years ago (RIEDL, 1982 a, b). The western region of the island is dominated by a peneplain situated at a mean height of 230 m, between the

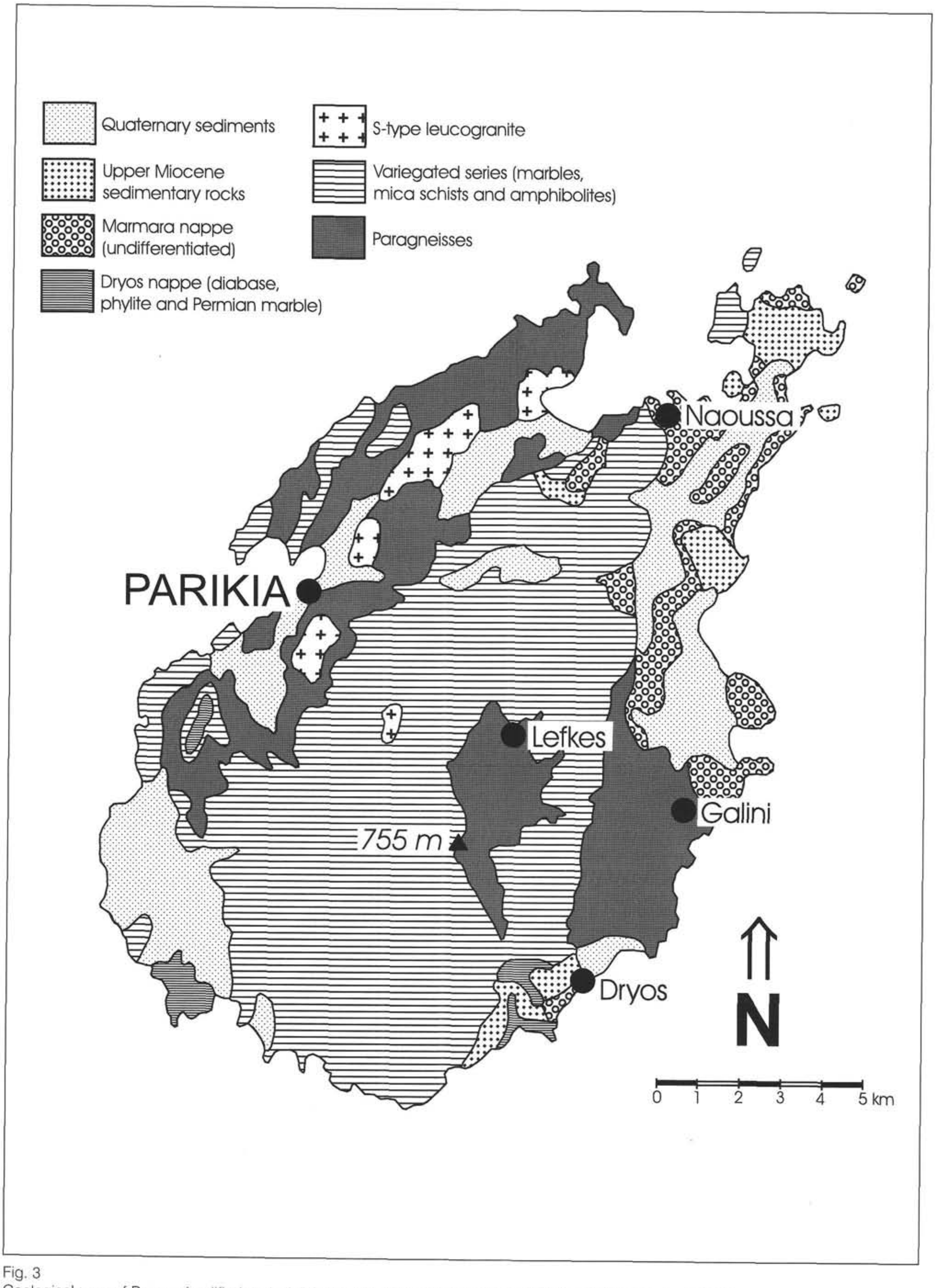


Fig. 3
Geological map of Paros, simplified and slightly modified after PAPANIKOLAOU (1980) and ALTHERR et al. (1982).

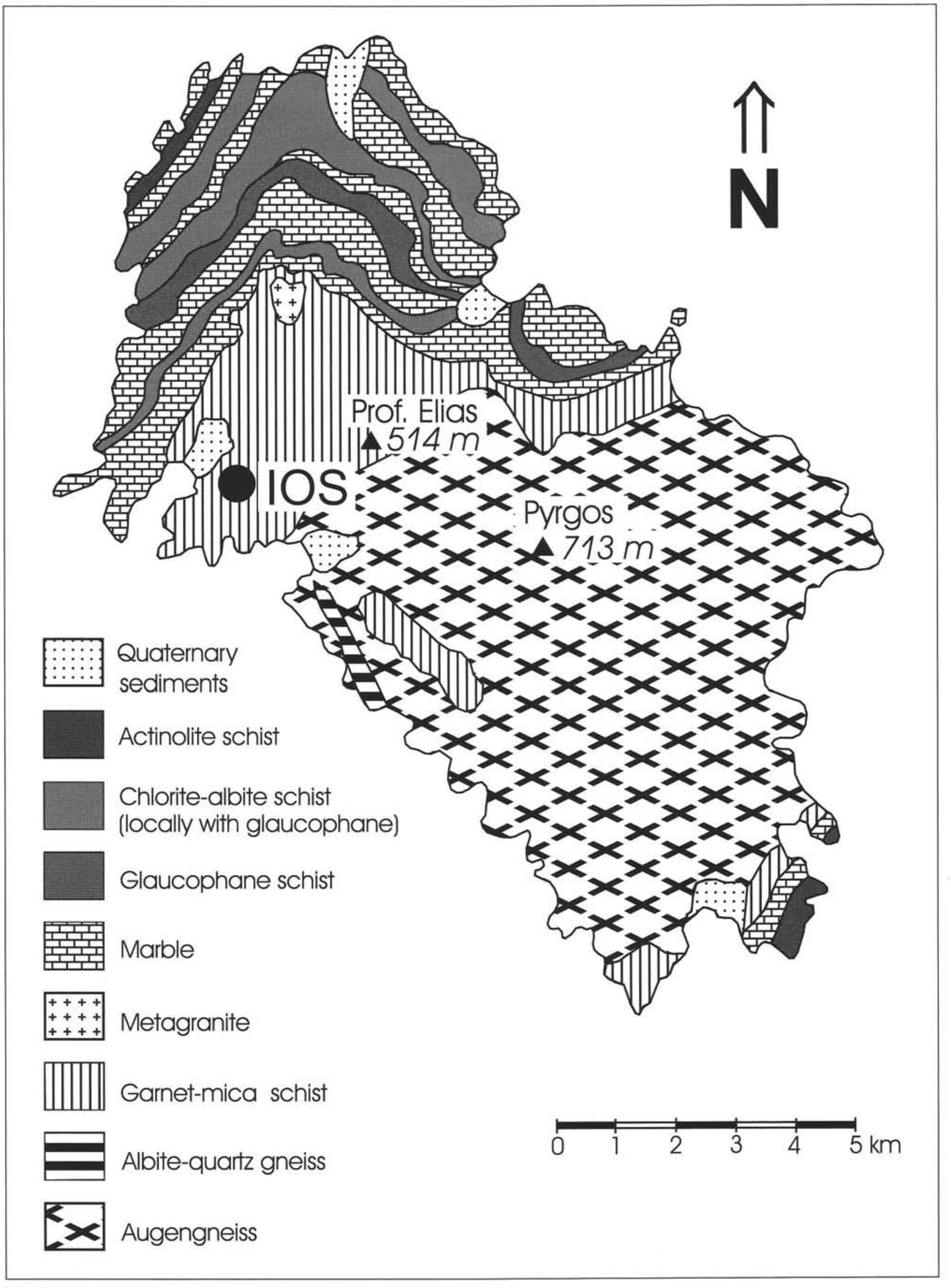


Fig. 4
Geological map of Ios, simplified after VAN DER MAAR and JANSEN (1981).

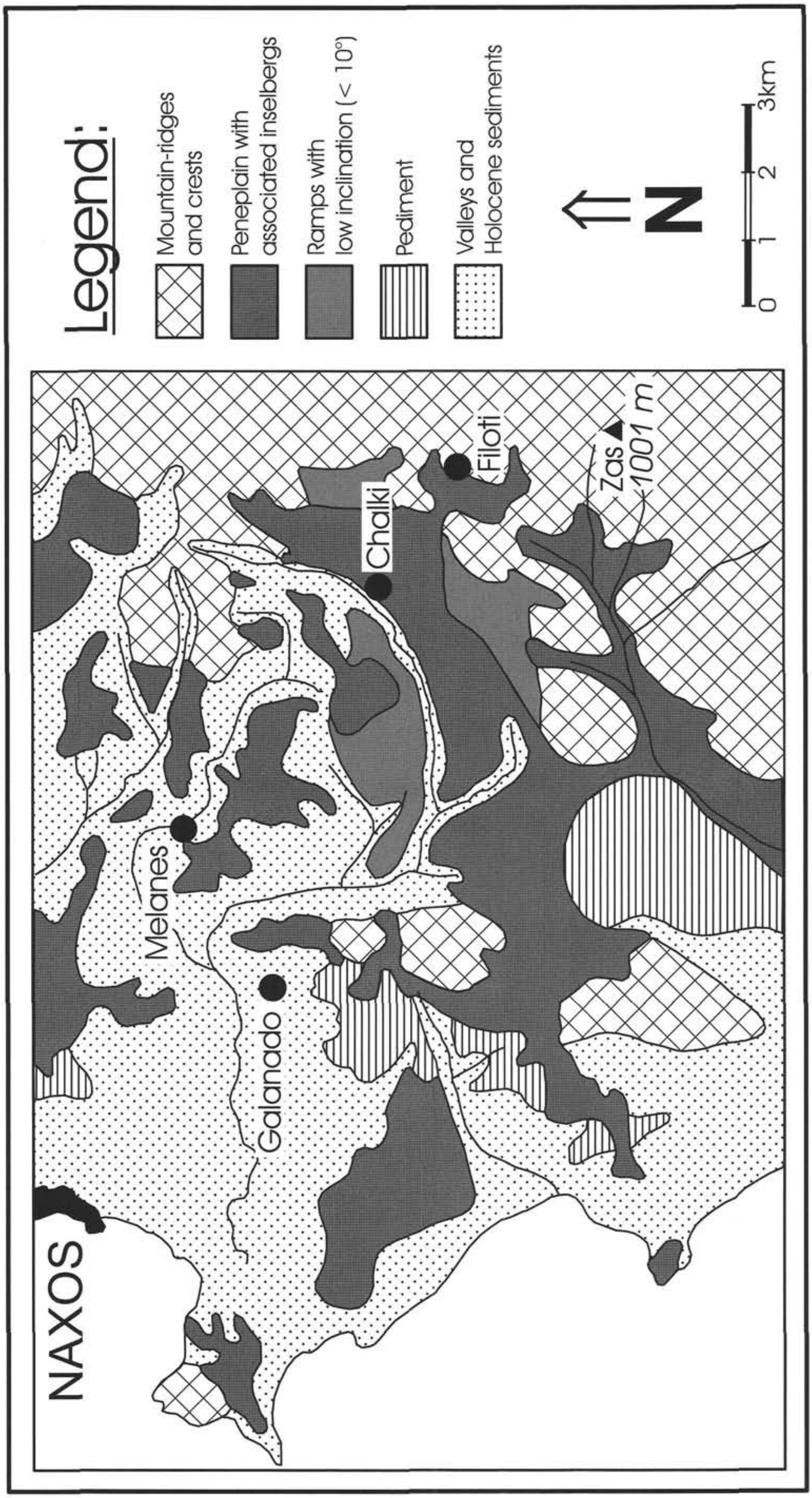


Fig. 5
Geomorphological map of western Naxos, after RIEDL (1982 a).

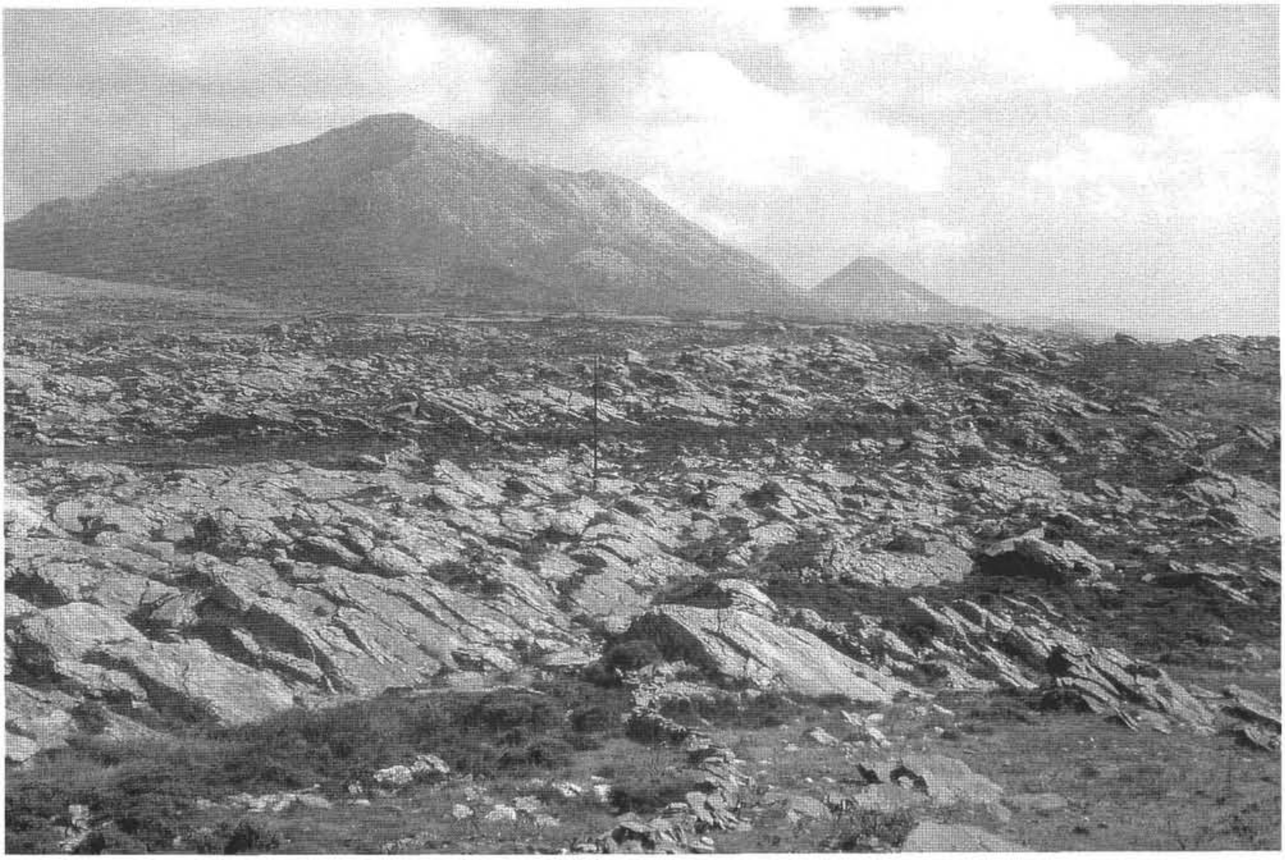


Fig. 6
Tragea peneplain of the island of Naxos viewn from the NW. Mt. Zas (1001 m) is situated in the background on the right-hand side.

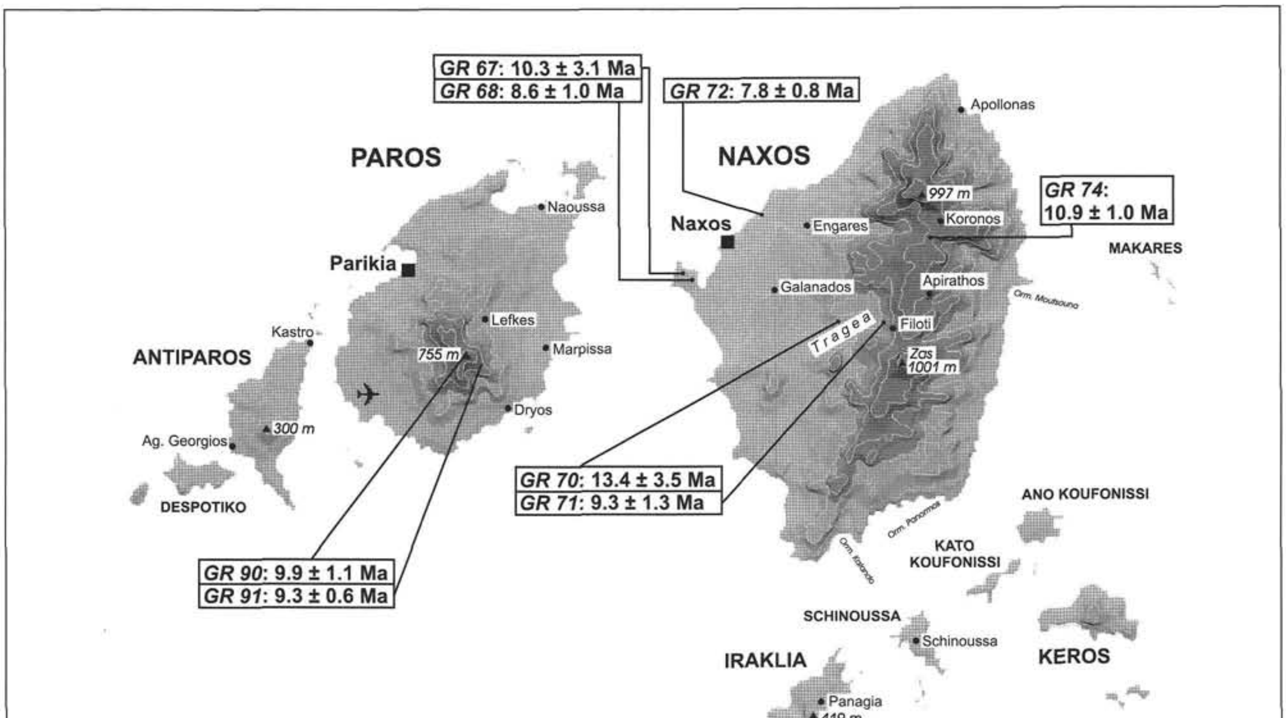


Fig. 7
Digital elevation model of Naxos, Paros and Antiparos, with sample locations and measured fission-track ages of apatite (±1σ).

City of Naxos and the valley of Melanes. In a very similar way, the south-eastern extension of the peneplain also dominates the landscape of "Tragea" (Figs. 5, 6 and 7). At the margin of the coastal plain of the City of Naxos, the same planation system is represented by inselberg swarms, being only some decameters high. Ramp slopes between these inselbergs are adapted to the level of the peneplain (cf. LOUIS & FISCHER, 1979, p. 143). A fundamental attribute of the peneplain torso is given by the fact, that it cuts all pre-Pleistocene structural units in a discordant way, i. e. the metamorphic rocks of the gneiss dome and its schist cover, the Miocene granodiorite and the Neogene sedimentary rocks of the upper allochthonous unit belonging to the so-called "Aegean nappe" according to BÖGER, (1983, p. 806). The planation surface interlocks with mountainous relief, where it forms small embayments, flat passes and ramp slopes. These features are typical for the geomorphic processes of sheet-flood erosion together with deep tropical weathering of the bedrocks. BÜDEL (1965, 1977) and LOUIS (1967) have mentioned that the morphological style of Naxos exhibits a broad similarity to the present-day peneplains in the semihumid tropics. Since the genesis of the Naxos peneplain, its weathering basal relief has been mainly exhumed. Sediments provided by the denudation of tropical weathering material are preserved at the bottom of flat floored valleys. Remnants of a younger coastal pediment are preserved to the S of Galanado.

On the basis of climato-geomorphological arguments, RIEDL (1984 a) has proposed an Upper Miocene or Lower Pliocene age for the Naxos peneplain. The assumption of a marginal tropical climate of that period is supported by palaeo-ecological investigations (THUNNEL, 1979; THUNNEL & WILLIAMS, 1983; VELITZELOS & ZOUROS, 1998; SUC & ZAGWIJN, 1983).

5.2 Paros

The highest erosion level of Paros (Figs. 3 and 7) is situated at a mean altitude of 650 m and is characterized by hogback cupolas and cone mountains, as for example the summit of Profitis Elias (755 m). This relief level is bounded by a fault escarpment towards E, where it slopes to a large peneplain at a mean elevation of 400 m, being dissected by v-shaped valleys. To the N of Prof. Elias this planation level has a length of 3 km and a width of 1.5 km. Farther to the N (3 km to the E of Parikia) a W-E striking polje forms the boundary of this peneplain. Towards W, the transition between the 400 m peneplain and the coastal plain of Parikia seems to be influenced by fault scarps.

5.3 Ios

The topmost planation system of Ios (Figs. 4 and 8) is situated at 700 m altitude, around the summit of Mt. Pyrgos (713 m), and is strongly transformed by Pleistocene mor-

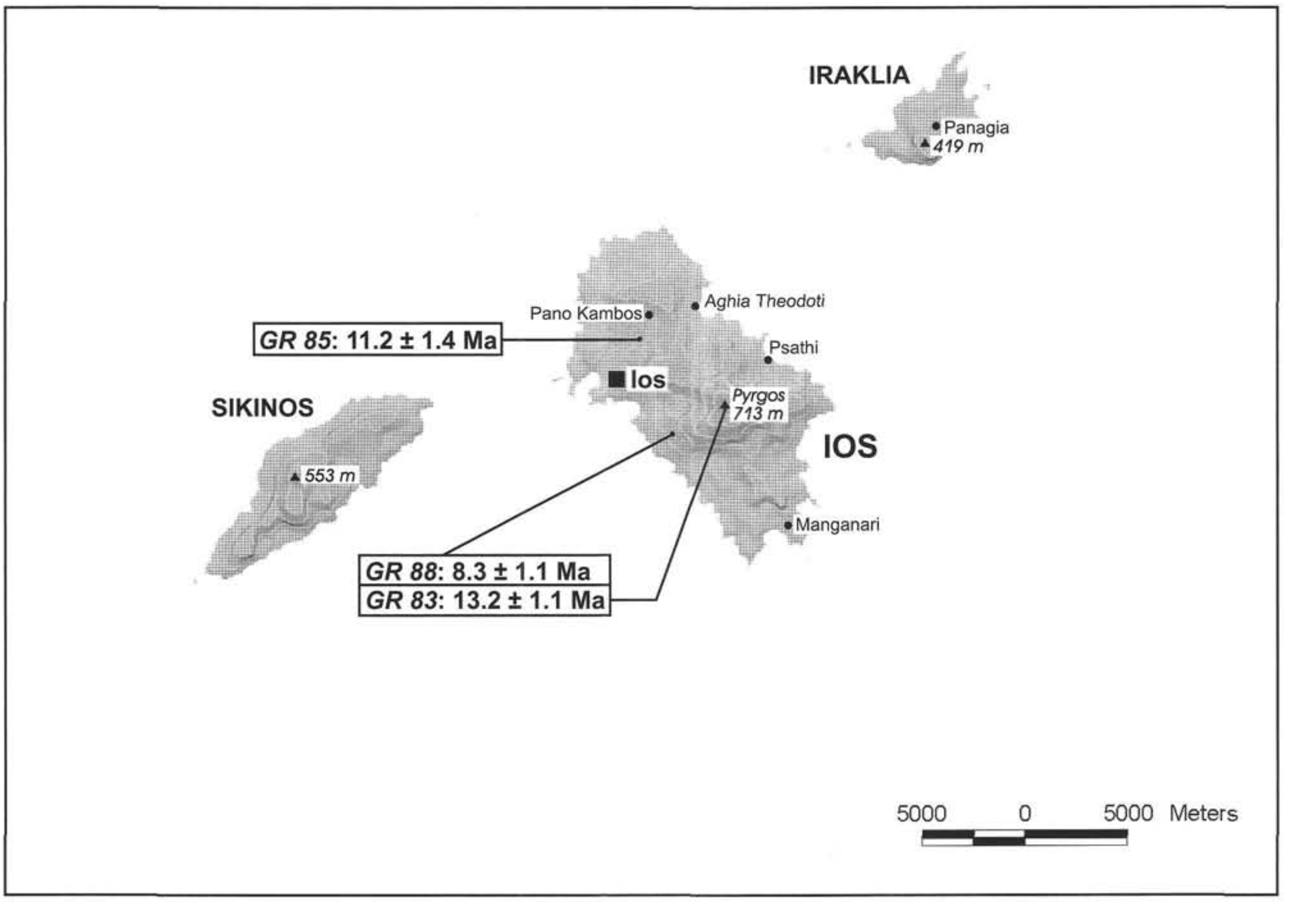


Fig. 8
Digital elevation model of Ios with sample locations and measured fission-track ages of apatite ($\pm 1\sigma$).

phodynamics. It is characterized by asymmetric castle coppies and tafoni that are developed within the augengneisses. Residuals of presumable Neogene soil are preserved in concavities between the castle coppies. This strongly weathered material is locally covered by Pleistocene creeping rubble, which can be observed on the northern slopes of Mt. Pyrgos, near the monastery of Ag. Ioannis Prodromos. The Pleistocene rubble consists of breccias being overprinted by fossil paragleys.

At a mean height of 650 m, the heads of ancient flat valleys are closely related with the topmost planation system. These valleys are accompanied by recent smooth slopes and the valley bottoms are adapted to a lower relic peneplain at 500 m altitude, which surrounds the system of Mt. Pyrgos. Farther to the S, an other peneplain system occurs at elevations between 300 and 400 m. The erosion level of the latter is locally overprinted by strong chemical weathering yielding kaolinized augengneisses with pocket-like red plastosoils. Flat valley heads at a mean altitude of 220 m are developed in deeply weathered augengneisses characterized by extensive production of grit.

The described geomorphological pattern is slightly modified in the region of northern Ios. A small basin is situated within garnet-mica schists 2 km to the N of Profitis Elias (514 m). This basin is bordered by the margin of the 500 m peneplain in the S (Prof. Elias) and by marble hogbacks in the W and N. The basin's bottom lies between 80 and 150 m altitude. It is associated with pediments having an inclination of approximately 2% and forming triangular embayments at the basin's margin. The pediments show close relations to Pleistocene debris, often developed as breccia and having a proven thickness of up to 6 m (RIEDL, 1984 a).

6. Apatite fission-track dating

Sampling was performed in the course of two field trips in 1998: Eight rock specimens from the island of Naxos (GR 67-74) were collected in April, six rock specimens from the island of Ios (GR 83-88) and three rock specimens from the island of Paros (GR 89-91) were collected in November. Besides the granite samples of western Naxos and few micaschists, most samples are orthogneisses. Locations and lithologies of eleven successfully dated samples are listed in Table 1. The locations are also displayed in the Figs. 7 and 8.

After crushing and dry sieving, apatite was extracted by chemical flotation of the grain size fraction between 100 and 250 μm according to the procedure described by HEJL & NEY (1994). Subsequently, the dried apatite concentrates were purified with a Frantz magnetic separator and heavy liquids.

Fission-track dating was performed by the grain population technique (WAGNER, 1968; GLEADOW, 1981; WAGNER & VAN DEN HAUTE, 1992). A subpopulation of each apatite sample was heated in a furnace for 24 hours at 500 °C in order to anneal the natural tracks. These heated grain fractions were irradiated in channel 8 (Cd ratio for Au = 11) of the Thetis nuclear reactor at the University of Ghent (Belgium). The thermal neutron fluences were determined by γ-spectrometric measurements on simultaneously irradiated metal activation monitors, i. e. Co and Cu (cf. VAN DEN HAUTE et al., 1988).

After irradiation, both grain populations of each sample were embedded separately in epoxy resin, ground, polished and etched for 60 s in 5% HNO_3 at 20 °C. The fission tracks were counted in transmitted light with an Olympus BH-2 microscope (total magnification of $\times$ 1250; oil immersion).

The fission-track ages were calculated with the ^{238}U spontaneous fission constant $\lambda_f = 8.46\times10^{-17}$ a^{-1} (GALLIKER et al., 1970). According to the recommendations of the IUGS Subcommission on Geochronology (HURFORD, 1990), the validity of the system calibration has been repeatedly tested with Durango apatite (JONCKHEERE et al., 1993). The dating results of the present investigation are reported in Table 2 as well as in Figs. 7 and 8. The SASP code (acronym from

Table 1
Locations of successfully dated samples.

Sample code	Location	Altitude (m)	Rock type
SASP 189 / GR 67	NAXOS: eastern slope of Strongilo Mt.	70	granite
SASP 190 / GR 68	NAXOS: 1 km SE of Strongilo Mt.	30	protomylonitic granite
SASP 192 / GR 70	NAXOS: Tragea plain, 1.4 km to the W of Khalki	260	migmatic biotite gneiss
SASP 193 / GR 71	NAXOS: Tragea plain, 1.3 km E of Khalki, 1 km NW of Filoti	320	biotite schist
SASP 194 / GR 72	NAXOS: 3 km to the NE of Chora Naxos	80	granite
SASP 196 / GR 74	NAXOS: saddle 1 km SSW of Koronos	730	micaschist
SASP 212 / GR 90	PAROS: 150 m NNW from the summit of Prof. Elias (OTE Station)	680	gneiss
SASP 213 / GR 91	PAROS: 1.2 km ESE from the summit of Prof. Elias (OTE Station)	440	gneiss
SASP 205 / GR 83	IOS: Summit of Pyrgos Mt., 10 m S of OTE Station	710	augengneiss
SASP 207 / GR 85	IOS: 2.2 km NNE of Chora Ios, 1.5 km NW of Prof. Elias	120	muscovite schist
SASP 210 / GR 88	IOS: 2 km SE of Milopotamos, 1.5 km N of Ormos Klima	280	augengneiss

Table 2
Results of apatite fission-track age determinations.
N_s, N_i = total number of counted tracks (spontaneous and induced).
ρ_s, ρ_i = areal track densities (spontaneous and induced).

Sample Code	No. of grains n_s/n_i	Spontaneous Tracks N_s	ρ_s (10^5 x cm^{-2})	Induced Tracks N_i	ρ_i (10^5 x cm^{-2})	ρ_s/ρ_i	Error 1σ of ρ_s/ρ_i (%)	Neutron Fluence (10^{14} x cm^{-2})	Fission-track age ± 1σ (Ma)
NAXOS:									
SASP 189 / GR 67	70/50	60	0.536	206	2.575	0.2080	30.20	9.92	10.26 ± 3.11
SASP 190 / GR 68	300/100	279	0.502	1082	2.756	0.1822	10.41	9.86	8.63 ± 0.96
SASP 192 / GR 70	100/100	161	1.006	565	3.531	0.2850	25.69	9.45	13.38 ± 3.45
SASP 193 / GR 71	500/300	86	0.108	251	0.523	0.2056	13.55	9.14	9.34 ± 1.29
SASP 194 / GR 72	300/150	276	0.575	842	3.508	0.1639	9.35	9.54	7.77 ± 0.75
SASP 196 / GR 74	200/100	268	0.838	588	3.675	0.2279	8.60	9.62	10.90 ± 0.98
PAROS:									
SASP 212 / GR 90	400/200	145	0.629	323	2.804	0.2245	10.26	8.88	9.91 ± 1.05
SASP 213 / GR 91	400/200	677	2.938	1756	15.243	0.1928	6.27	9.72	9.31 ± 0.63
IOS:									
SASP 205 / GR 83	300/150	398	2.303	700	8.102	0.2843	7.80	9.33	13.18 ± 1.08
SASP 207 / GR 85	200/100	122	1.059	245	4.253	0.2490	11.82	9.07	11.22 ± 1.36
SASP 210 / GR 88	400/200	97	0.421	261	2.266	0.1858	13.41	8.94	8.26 ± 1.13

"**Sa**lzburger **S**paltspuren**p**robe") is a running numbering for fission-track samples being dated by the Salzburg laboratory.

The natural apatite mounts with track densities of more than 0.8×10^5 cm^{-2} were overetched for 20 s in an aqueous solution of 5.5 *M* HNO_3 in order to determine the frequency distributions of full confined spontaneous track lengths (GLEADOW et al., 1986). Because of rather low fossil track densities ($<3\times10^5$ cm^{-2}) only few confined tracks could be found. Their lengths were measured by use of a drawing tube attachment to the microscope and a digitizing tablet. Histograms showing the frequency distributions of the spontaneous track lengths are presented in the Figs. 9-13.

Time-temperature paths were modelled with the program AFTSolve (version 0.7.1, © 1996, Donelick analytical, Inc. and Richard A. Ketcham), which was friendly provided by Raymond A. Donelick. This program calculates the range of thermal histories (temperature versus time) being potentially consistent with the measured fission track data, i. e. both age and track length distributions (cf. CARLSON et al.,1999; DONELICK et al., 1999 and KETCHAM et al., 1999). Random paths are created by a Monte Carlo scheme. For each path, the resulting fission-track age and length distribution are calculated and the goodness-of-fit (G.O.F.) between calculated and measured data is evaluated by a Kolmogorov-Smirnov test. The apatite's resistance to track annealing was estimated by measuring the diameters of etch pits parallel to the crystallographic c-axis (= dpar; U.S. Patent Number 5,267,274 and Australian Patent Number 658,800). We used the arithmetic mean of dpar as kinetic variable for our calculations.

For the AFTSolve calculations presented in this article we used the following specifications:

- the measured fission-track age of apatite,
- the frequency distribution of full confined spontaneous tracks,
- the arithmetic mean of dpar (10 measurements at least for each sample),
- the cooling was not allowed to enter the temperature area <200 °C previous to the moment corresponding to published biotite or K-feldspar cooling ages (K-Ar and Ar-Ar, respectively) of the nearest locations (ANDRIESSEN et al., 1979; ALTHERR et al., 1982; BALDWIN & LISTER, 1998).

Time-temperature regions that envelop all thermal histories with "good" and "acceptable" fit, corresponding to G.O.F. values from 0.5 to 1 and from 0.05 to 0.5, respectively, are displayed in the Figs. 9-13.

Our apatite fission-track ages from Naxos, Paros and Ios range between 13.4 ± 3.5 and 7.8 ± 0.8 Ma corresponding to the Middle and Late Miocene (according to RÖGL, 1996). Frequency distributions of confined track lengths are available for two samples from Naxos (GR 70 and 74), one sample from Paros (GR 91) and two samples from Ios (GR 83 and 85). They are characterized by high arithmetic means ranging in the small interval of 14.4 to 14.9 μm (cf. histograms of Figs. 9-13). The corresponding standard deviations vary from 1.3 to 1.9 μm. Such length distributions are typical for thermal histories with decelerated cooling, i. e. fast cooling through the partial annealing zone followed by a long residence time in the temperature zone of quasi full track stability (GLEADOW et al., 1986).

In a first step, we interpreted the measured fission-track ages under the assumption of slow steady cooling. With a temperature of effective track retention of 100 °C and an average surface temperature of 15 °C we calculated the following mean cooling rates: 6.4 to 10.9 °C/Ma for Naxos, 8.6 to 9.1 °C/Ma for Paros and 6.4 to 10.3 °C/Ma for Ios. Even without track-length information, such steady cooling is improbable because of the occurrence of granite pebbles in the fresh-water conglomerates of the Cyclades. This suggests that some of the plutons have been exposed at the surface in Middle or Late Miocene times. Consequently, we should expect early and rapid cooling of the plutons with a subsequent deceleration of cooling.

In a second step, we applied the modelling routine of AFTSolve to those samples where we obtained frequency distributions of confined track lengths. Thus, thermal histories of two samples from Naxos could be modelled (Fig. 9 and 10). Sample GR 70 was taken from a migmatic gneiss

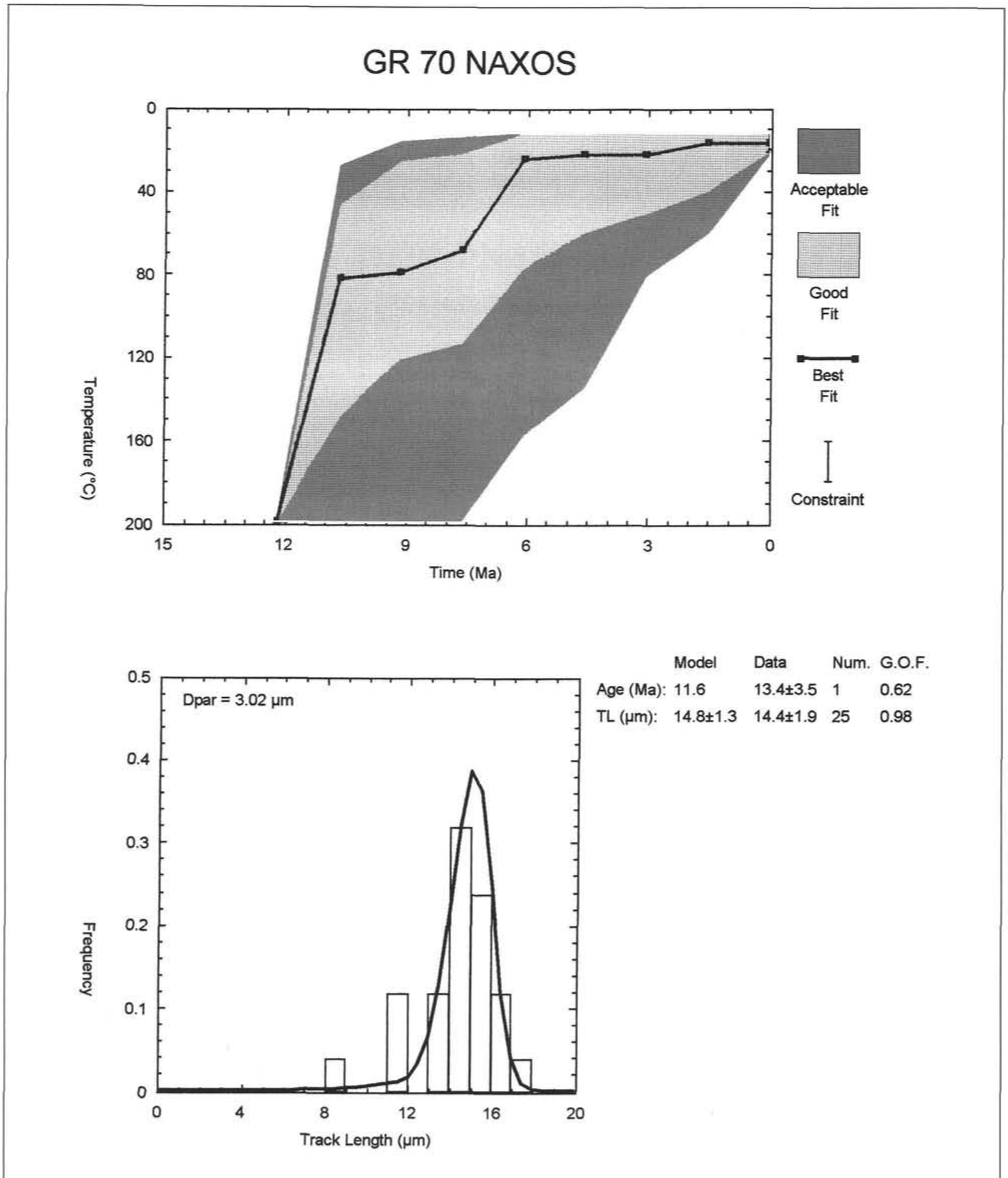


Fig. 9
Monte Carlo fitting of sample GR 70 (Naxos, Tragea peneplain, at 260 m altitude). 10000 calculated cooling paths.

exposed on the Tragea plain to the W of Khalki, at an altitude of 260 m. Its apatite fission-track age of 13.4 ±3.5 Ma has a rather large uncertainty but coincides at the 1σ level with the K-Ar biotite age of a neighbouring location (ANDRIESSEN et al., 1979). Within our model assumptions, cooling was not allowed to enter the temperature range <200 °C previous to 12.2 Ma ago, i. e. the moment corresponding to that K-Ar biotite age. The range of thermal histories being potentially consistent with the data is displayed in Fig. 9. Between 12 and 11 Ma ago, the sample has experienced fast cooling at a rate in the order of 70 °C/Ma. As early as 10 Ma ago, it could have been close to the surface, i. e. at a temperature in the order of 20 °C. Sample GR 74 was collected at an altitude of 730 m and yielded an

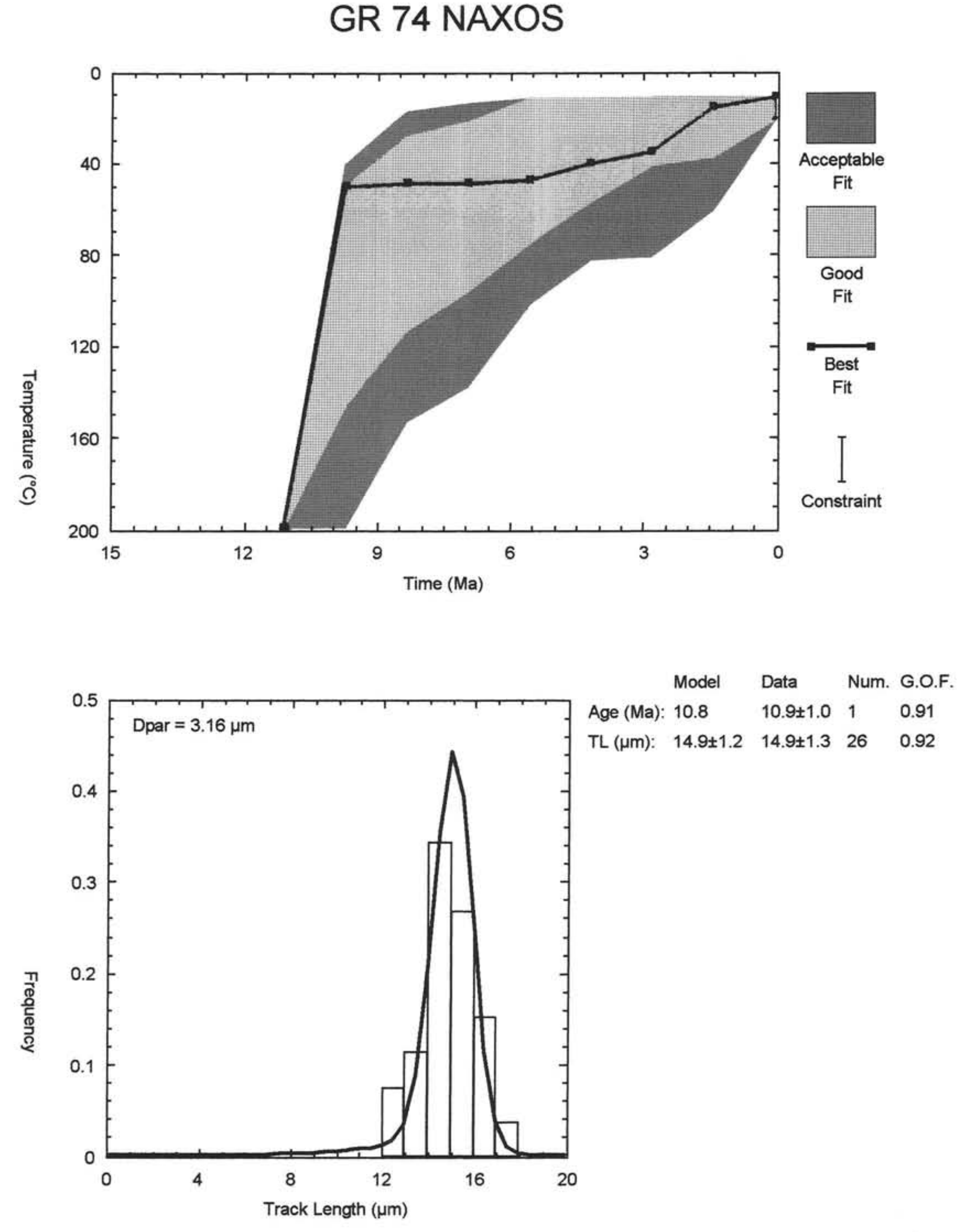
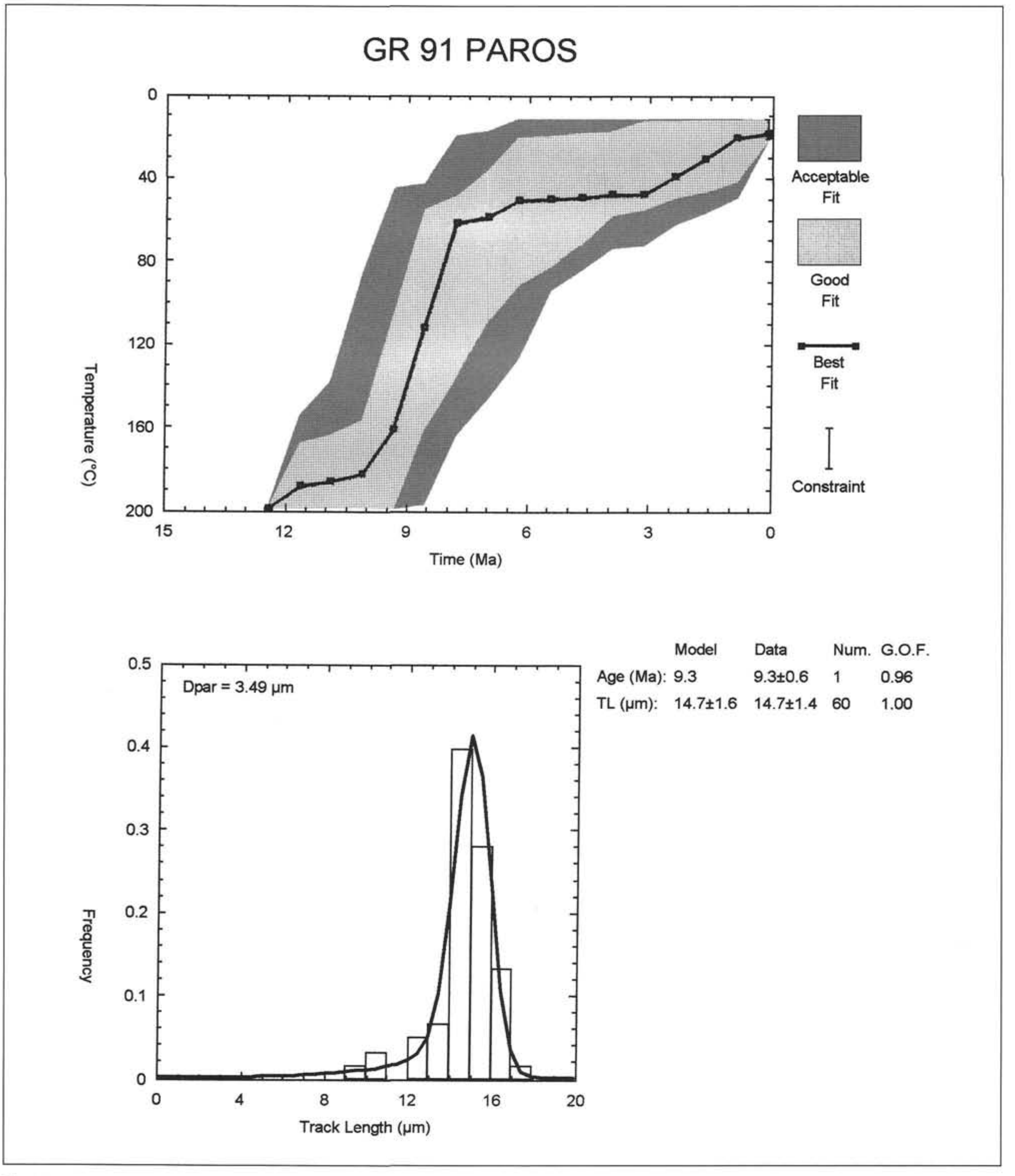


Fig. 10
Monte Carlo fitting of sample GR 74 (Naxos, saddle 1 km SSW of Koronos, at 730 m altitude). 10 000 calculated cooling paths.

apatite fission-track age of 10.9 ±1 Ma, which also coincides at the 1σ level with the K-Ar biotite age of a neighbouring location (11.1 ±0.3 Ma, according to ANDRIESSEN et al., 1979). The result of the model calculations is shown in Fig. 10. Between 11 and 10 Ma ago, the sample was subjected to very fast cooling at a rate about 130 °C/Ma. It could have been close to the surface around 8 Ma ago.

Confined track lengths distributions are available for only one apatite sample from Paros (GR 91). It has a fission-track age of 9.3 ±0.6 Ma. Modelling of Fig. 11 was performed with the fission-track data of GR 91 and a K-Ar biotite age of 12.4 Ma, taken from ALTHERR et al. (1982). Rapid cooling at a rate in the order of 70 °C/Ma took place between 9 and 8 Ma ago. The

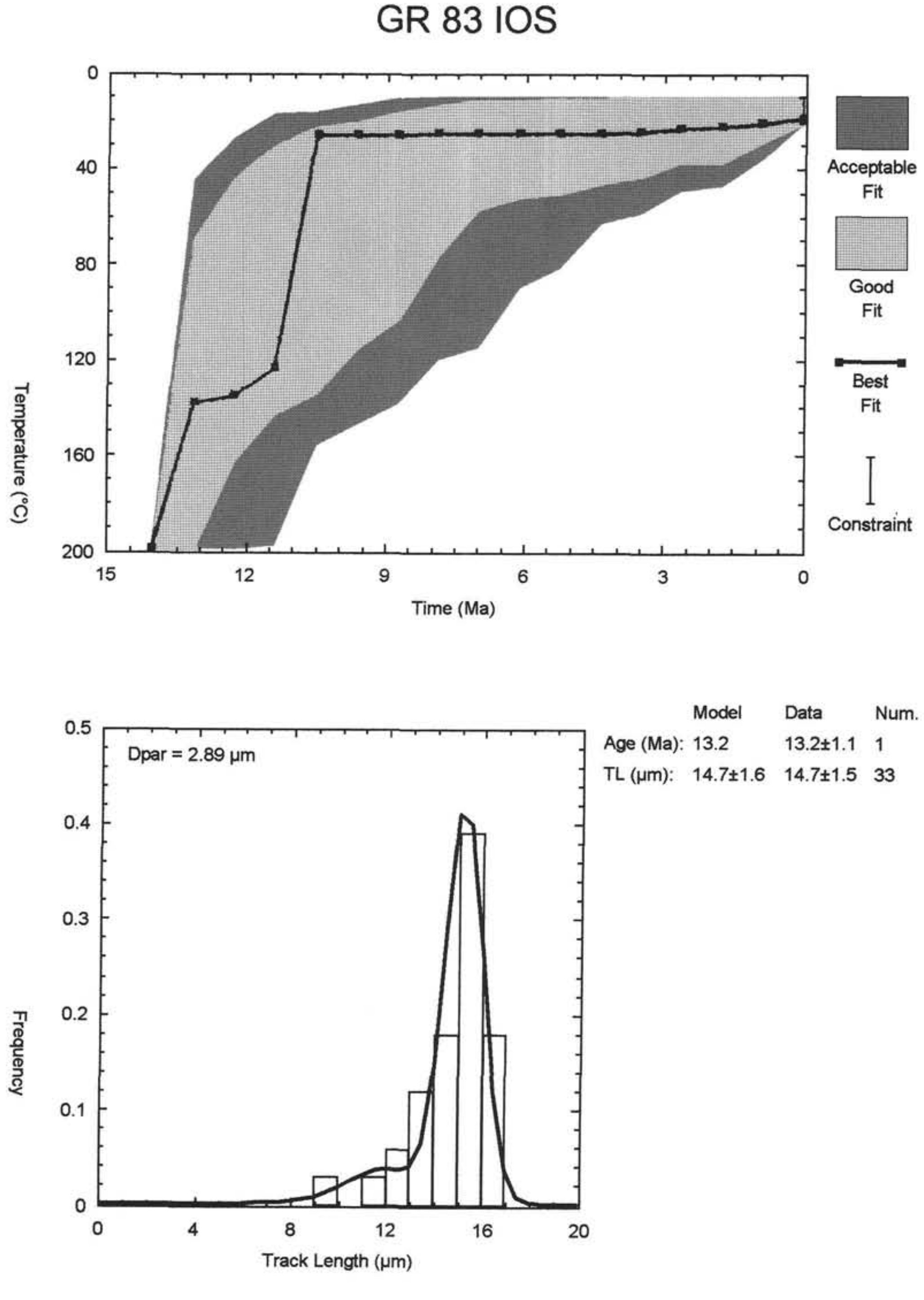


	Model	Data	Num.	G.O.F.
Age (Ma):	9.3	9.3±0.6	1	0.96
TL (µm):	14.7±1.6	14.7±1.4	60	1.00

Fig. 11
Monte Carlo fitting of sample GR 91 (Paros, 1.2 km ESE from the summit of Profitis Elias, at 440 m altitude). 10000 calculated cooling paths.

sample could have been close to the surface about 8 Ma ago.

Two samples from Ios (GR 83 and 85) were chosen for confined track length evaluation. GR 83 was taken from the summit of Mt. Pyrgos (710 m) and has an apatite fission-track age of 13.2 ±1.1 Ma. The location of GR 85 has an altitude of 120 m. This sample yielded an apatite fission-track age of 11.2 ±1.4 Ma. Thermal history calculations of both samples yielded decelerated cooling paths (Figs. 12 and 13). Maximum cooling rates of over 50 °C/Ma occurred about 11 Ma ago. Sample GR 83 (summit Mt. Pyrgos) could have been very close to the surface as early as 10 Ma ago. This would be consistent with a Middle Miocene age of the topmost peneplain system of Ios.



	Model	Data	Num.	G.O.F.
Age (Ma):	13.2	13.2±1.1	1	0.97
TL (µm):	14.7±1.6	14.7±1.5	33	0.99

Fig. 12
Monte Carlo fitting of sample GR 83 (Ios, summit of Pyrgos Mt., 710 m altitude). 10000 calculated cooling paths.

7. Discussion of the tectonic and geomorphic evolution

Miocene cooling rates between 50 and 130 °C/Ma have been inferred for crystalline rocks of Naxos, Paros and Ios by thermochronologic modelling. Afterwards, cooling was decelerated but reheating did not occur.

The uppermost tectonic unit of the ACCU mainly consists of Miocene sedimentary rocks. These deposits are always allochthonous with respect to the Cenozoic blueschist unit, the Barrowian metamorphics and the Miocene plutons. Therefore, BÖGER (1983) suggested that all the Neogene sediments, together with slices of their original basement of ophiolites and pre-Neogene sediments, belong to a so-

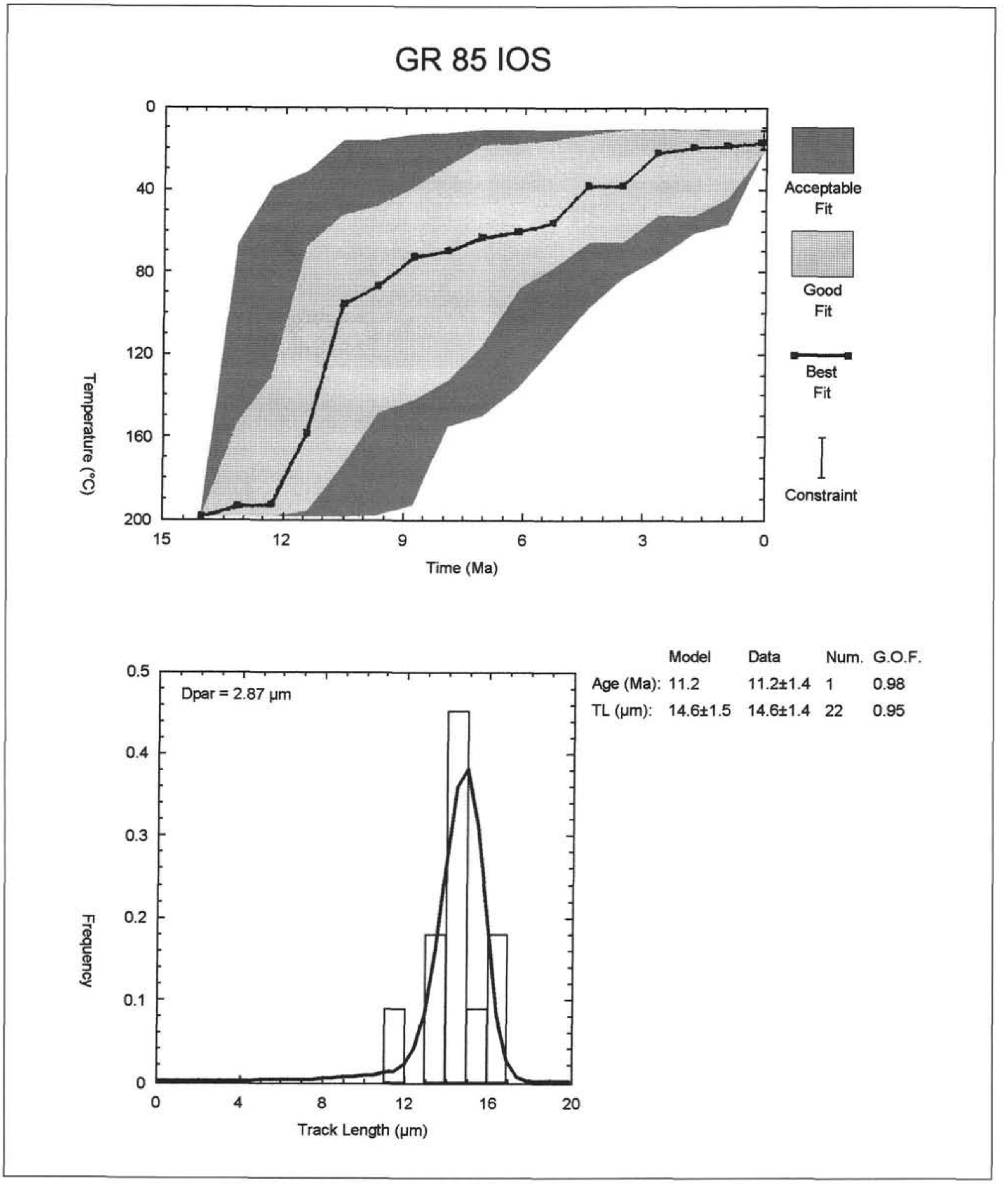


Fig. 13
Monte Carlo fitting of sample GR 85 (Ios, 1.5 km to the NW of Profitis Elias, at 120 m altitude). 10000 calculated cooling paths.

called Aegean nappe ("komplexe Ägäisdecke"), which should have been emplaced in Late Miocene times by gravitational sliding from a crustal rise in the area of the present-day Sea of Crete towards the N. The model also claims an overthrust of the uppermost unit of the ACCU onto a pre-existing Miocene relief. Such model is neither supported by structural observations nor by geochronological data.

In the case of compressive thrusting or gravitational sliding of a single nappe body, we should expect a uniform sense of shear over large distances, but this is not the case. The Neogene of Mikonos, for example, has been sheared top to the NE (LEE & LISTER, 1992), while ductile shear zones of Naxos and Ios exhibit a sense of movement top to the S (LISTER et al., 1984; VANDENBERG & LISTER, 1996). A Middle Miocene or younger overthrust would also imply a noticeable reheating of the lower tectonic unit, i. e. the blueschist unit and its Miocene plutons. The apatite fission-track data clearly demonstrate that this was not the case. In preceding chapters we have also mentioned that Miocene nappe stacking in a convergent setting can be excluded by structural observations. Thus, we are confronted with the seeming paradoxon of fast cooling in the lower tectonic unit (footwall) and simultaneous subsidence in the hanging wall.

When the heat flow towards the surface is close to a steady state, every kind of surface approach of a rock can be the reason for the rock's cooling. Several processes of regional exhumation have been discussed in the tectonic literature. The proposed exhumation models can be grouped as follows:

1. Vertical uplift and regional erosion
2. Oblique extrusion of squeezed orogenic wedges combined with frontal erosion
3. Horizontal extension on a crustal scale

Cooling scenarios by combined uplift and erosion have been extensively discussed in the fission-track literature (WAGNER & REIMER, 1972; WAGNER et al., 1977; HEJL & WAGNER, 1990; WAGNER & VAN DEN HAUTE, 1992). Ideally, when the vertical temperature gradient is constant in time, the velocity of a sample relative to the isotherm of effective track retention is equal to the erosion rate, because the isotherms are at constant depth. Of course, the cooling rate at two or three kilometer depth does not respond immediatly to a sudden change of the erosion rate. Only when a sample has been uplifted at constant speed from the bottom of the partial annealing zone until the surface, the measured fission-track age corresponds precisely to the time when the sample has passed the temperature of effective track retention and the erosion rate can be calculated by the formula *erosion rate = cooling rate / geothermal gradient* (WAGNER & VAN DEN HAUTE, 1992). In fact, such perfect steady state of both erosion and heat flow is seldom realized in nature and there will be always a certain delay between changing erosion rates and the response of heat flow at depth (cf. PARRISH, 1985). Two-dimensional heat flow calculations of MANCKTELOW & GRASEMANN (1997) have shown that the relief influence on the shape of the 100 °C isotherm is negligible as long as the topographic amplitude is less than 3000 m, the horizontal distance between neighbouring valleys is less than 6000 m and the regional denudation rate is less than 1000 m/Ma.

Using the Higher Himalaya Crystalline as an example, GRASEMANN et al. (1999) have developed a kinematic model for the oblique upward extrusion of squeezed orogenic wedges above major thrust zones. In earlier models, HODGES et al. (1993) had assumed that the extruding wedge did act as rigid block between distinct faults and alternatively GRUJIC et al. (1996) had proposed pervasive simple shear of the whole wedge. The improved concept of GRASEMANN et al. (1999) is based on a quantitative kinematic analysis of the Main Central Thrust Zone, which indicates an increasing pure shear component in course of a decelerating strain path. The model suggests that deformation is concentrated on the wedge borders and that the central part mainly extrudes by pure shear. This is in agreement with the observed fact that the highest metamorphic conditions are recorded in the central part of the wedge. Such extrusion process operates only in compressive tectonic settings and therefore cannot have produced the Neogene unroofing of the ACCU.

Horizontal extension at regional scale yields a decompression of rocks because it diminishes the distance between a given point of rock and the surface of the earth. Such pressure response to crustal thinning should be instantaneous but heat flow and temperature respond with a certain delay. However, fast cooling has been reported from many extensional areas, especially from metamorphic core complexes. Fission-track thermochronology in the context of extensional unroofing has been discussed for the island of Crete (THOMSON et al., 1999), for the Basin and Range Province (FOSTER et al., 1991; FOSTER & JOHN, 1999) and for an active metamorphic core complex of Papua New Guinea. From the latter BALDWIN et al. (1993) have reported local cooling rates exceeding 500 °C/Ma. The late cooling pattern of metamorphic domes can be complicated by brittle dip slip tectonics and by listric rotations.

Hypothetic erosion rates for a simple uplift-and-erosion scenario can be calculated from the mean cooling rates that have been obtained by assuming 100 °C closure temperature of the apatite fission-track system and a mean surface temperature of 15 °C (Chapter 6). When we divide these cooling rates by an assumed geothermal gradient of 30 °C/km we obtain the following mean erosion rates: 210-360 m/Ma for the Naxos samples, 290-300 m/Ma for the Paros samples and 210-340 m/Ma for the Ios samples. These hypothetical erosion rates are in the same order of magnitude as the slope of the regression lines that have been calculated for the plot of age versus altitude (Fig. 14). However, the assumption of steady cooling is in contradiction to the results of thermochronological modelling and the fit of the regression lines is rather bad, especially for the Ios samples.

Maximum cooling rates between 50 and 130 °C/Ma, as they have been derived from the AFTSolve t-T modelling, would correspond to erosion rates between 1700 and 4300 m/Ma. Such extreme erosion rates are not compatible with the Neogene extensional tectonics and the sedimentary record of the Cyclades. The quoted mean and maximum erosion rates would be similar to those of collisional mountain belts like the Western Alps or the Himalayas. During the Neogene and Quaternary such topography was certainly not realized in the central Aegean. Sedimentary record in the hanging wall and remnants of former peneplains testify a different morphological situation.

Because of the aforegoing arguments we favour a model of cooling by extension, which could explain the early and fast stages of cooling. The model should be consistent with the following facts:

1. Strong crustal extension during the Neogene is proven by low-angle normal faulting of Miocene sedimentary rocks, by mylonitic shear zones within the granites of Mikonos and western Naxos as well as by the metamorphic core complexes of Naxos and Ios.
2. Apatite fission-track thermochronology indicates very fast cooling in the Middle/Late Miocene, especially between 12 and 8 Ma ago. Afterwards, cooling was decelerated and the samples resided at low temperatures until present.
3. Subsidence of the hanging wall, as it is proven by the Miocene sediments, was fairly simultaneous with cooling of the footwall. Granite pebbles do not occur in Lower Miocene conglomerates but are common in fresh-water conglomerates of Late Serravallian and Early Tortonian age (Middle to Late Miocene).
4. Topographic relief elements of former peneplains are still preserved on several islands of the Cyclades. These planation relics are not tilted significantly – they are still subhorizontal. The well preserved peneplain of Tragea (western Naxos) has a mean inclination of less than 3° and truncates all structures of the Naxos metamorphic core complex.

The chronology of Neogene tectonics and relief development can be outlined as follows: After the climax of the Barrovian metamorphism (around 25 Ma ago) the whole

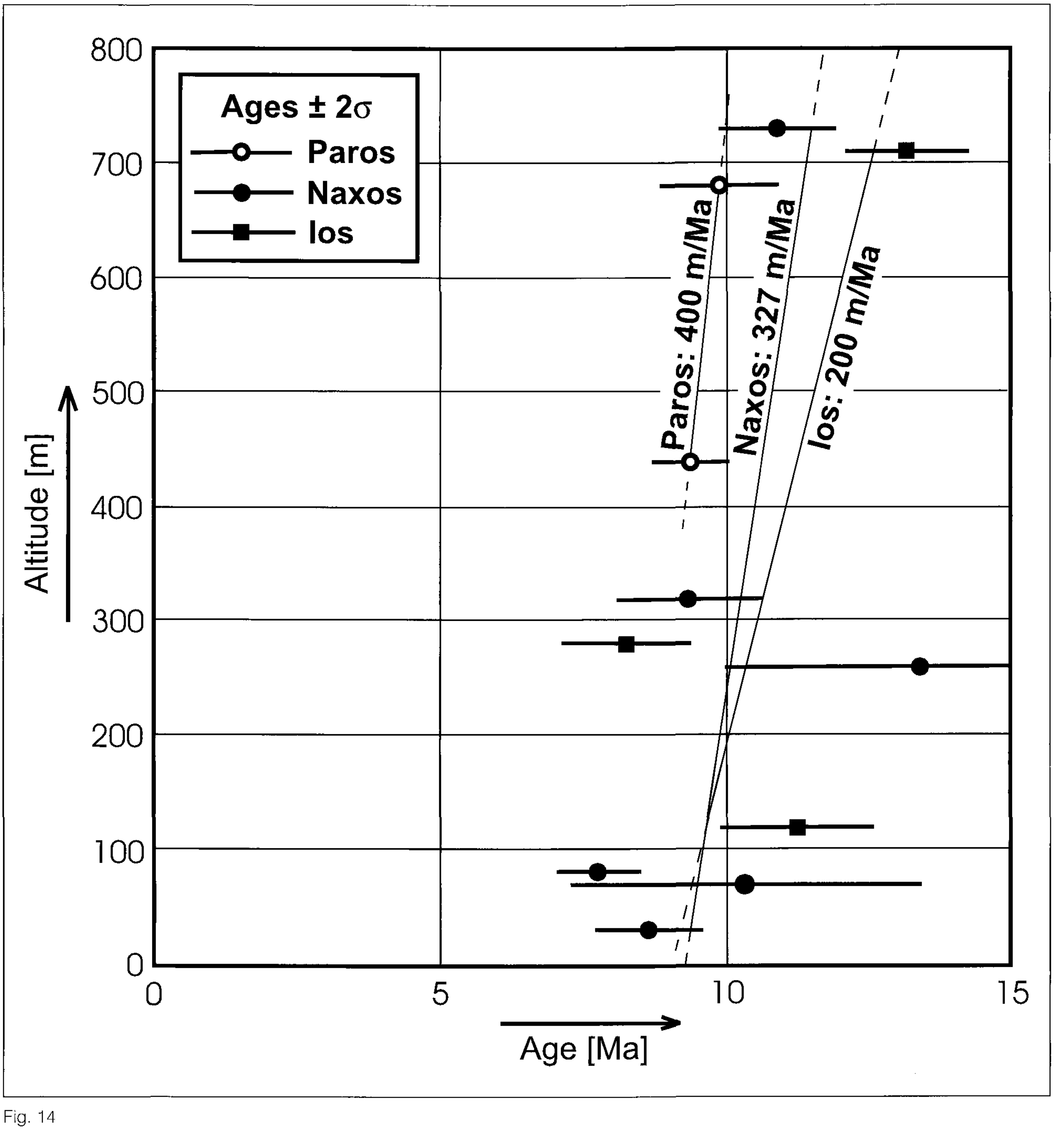


Fig. 14
Measured fission-track ages versus elevation of sampling locations.

ACCU was subjected to crustal extension to the north of the Hellenic convergent plate boundary. Metamorphic core complexes were created by ductile extension and interfered with the emplacement of granitic plutons. Afterwards, these core complexes were tilted by listric dip-slip faulting above crustal detachment zones. GAUTIER & BRUN (1994) have identified two north-dipping detachment zones within the Cyclades and have argued for an Early Miocene tilting of the core complexes. In the Late Serravallian, some Neogene granites were exposed at the surface for the first time and contributed to the gravels of contemporaneous freshwater conglomerates. Afterwards only minor extension and erosion occurred. Preserved peneplain relics of the Cyclades could be as old as Middle Miocene (about 10 Ma). Until the Early Pliocene, the climate of the area was close to tropical conditions with intensive seasonal rain (RIEDL, 1984 a, 1989; BERTOLDI et al, 1989; THUNNELL, 1979). The present-day island configuration was mainly established during the Pleistocene.

8. Conclusions

From the Miocene onwards, the Attic-Cycladic Composite Unit (ACCU) was situated in a geotectonic setting behind the Hellenic convergent plate boundary. With regard to the young tectonic and geomorphic evolution of the Cyclades we conclude that:

1. Crystalline rocks of Naxos, Paros and Ios have experienced rapid cooling between 12 and 8 Ma ago (Middle/ Late Miocene) with maximum cooling rates in the order of 50 to 130 °C/Ma.
2. Fast cooling was mainly produced by strong crustal extension. The formation of metamorphic core complexes was initiated by ductile extension. Afterwards, tilted horsts and half-grabens were created by brittle extension above of major detachment zones.
3. Morphological remnants of former peneplains appear to be not tilted but are still subhorizontal. They must have developed after the main extension of the ACCU. These palaeorelief features could have a maximum age of 10 Ma in the case of Ios and 8 Ma in the case of Naxos and Paros, as is indicated by apatite fission-track thermochronology.
4. The climatic development of the Eastern Mediterranean would have enabled peneplanation until the Early Pliocene.

9. Ackowledgements

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References

ALTHERR, R., 1980: I- and S-type granitoids of the central Aegean crystalline complex (Greece). – EOS Trans. amer. geophys. Union, **61,** 402, Washington.

ALTHERR, R., KREUZER, H., WENDT, I., LENZ, H., WAGNER, G. A., KELLER, J., HARRE, W. & HOHNDORF, A., 1982: A Late Oligocene/ Early Miocene high temperature belt in the Attic-Cycladic crystalline complex (SE Pelagonian, Greece). – Geol. Jb., **E23,** 97-164.

ALTHERR, R., SCHLIESTEDT, M., OKRUSCH, M., SEIDEL, E., KREUZER, H., HARRE, W., LENZ, H., WENDT, I. & WAGNER, G. A., 1979: Geochronology of High-Pressure Rocks of Sifnos (Cyclades, Greece). – Contrib. Mineral. Petrol., **70,** 245-255.

ANDRIESSEN, P., BOELRIJK, N., HEBEBA, E. PRIEM, N., VERDURMEN, E. & VERSHURE, R., 1979: Dating the events of metamorphism and granitic magmatism in the alpine orogen of Naxos (Cyclades, Greece). – Contrib. Mineral. Petrol., **69,** 215-225.

ANDRIESSEN, P. A. M., BANGA, G. & HEBEDA, E. H., 1987: Isotopic age study of pre-alpine rocks in the basal units on Naxos, Sikinos and Ios, Greec Cyclades. – Geologie en Mijnbouw, **66,** 3-14.

AVIGAD, D. & GARFUNKEL, Z., 1991: Uplift and exhumation of high-pressure metamorphic terrains: the example of the Cycladic blueschist belt (Aegean sea). – Tectonophysics, **188,** 357-372.

AVIGAD, D. & GARFUNKEL, Z., 1993: The role of extension in unroofing the Cycladic blueschist belt. – Geol. Soc. Greece, **28 (1),** 57-69.

BALDWIN, S. L. & LISTER, G. S., 1998: Thermochronology of the South Cyclades shear zone, Ios, Greece: Effects of ductile shear in the argon partial retention zone. – J. J. Geophys. Res., **103 (B4),** 7315-7336.

BALDWIN, S. L., LISTER, G. S., HILL, E. J., FOSTER, D. A. & MCDOUGALL, I., 1993: Thermochronologic constraints on the tectonic evolution of active metamorphic core complexes, D'Entrecasteaux Islands, Papua New Guinea. – Tectonics, **12,** 611-628.

BERTOLDI, R., RIO, D. & THUNNELL, R., 1989: Pliocene-Pleistocene vegetational and climatic evolution of the South-Central Mediterranean. – Palaeogeography, Palaeoclim., Palaeoecol., **72,** 263-275.

BÖGER, H., 1983: Stratigraphische und tektonische Verknüpfungen kontinentaler Sedimente des Neogens im Ägäis-Raum. – Geol. Rundschau, **72,** 771-814.

BRUNN, J. H., 1956. Contribution à l'étude géologique du Pinde septentrional et d'une partie de la Macédoine occidentale. – Ann. géol. Pays Hellén., **7,** 1-358.

BÜDEL, J., 1965: Die Relieftypen der Flächenspülzone Süd-Indiens am Ostabfall Dekans gegen Madras. – Colloquium Geographicum, II, 100 p., Bonn.

BÜDEL, J., 1977: Klima-Geomorphologie. Borntraeger, Berlin-Stuttgart.

CARLSON, W. D., DONELICK, R. A. & KETCHAM, R. A., 1999: Variability of apatite fission-track annealing kinetics: I. Experimental results. – Am. Mineralogist, **84,** 1213-1223.

DAVIS, W. M., 1899: The Geographical Cycle. – Geographical Journal, **14,** 481-509.

DONELICK, R. A., KETCHAM, R. A. & CARLSON, W. D., 1999: Variability of fission-track annealing kinetics: II. Crystallographic orientation effects. – Am. Mineralogist, **84,** 1224-1234.

DÜRR, ST. & ALTHERR, R., 1978: Neogene Deckenreste auf Mykonos/Kykladen. – XXVI. Congr.-Ass. plen. C.I.E.S.M., Antalya.

DÜRR, ST., KELLER, J., OKRUSCH, M. & SEIDEL, E., 1978: The Median Aegean cristalline Belt: Stratigraphy, Structure, Metamorphism, Magmatism. – In: Closs et al. (eds.): Alps, Apennines, Hellenides; I.U.C.G. Sc. Rept., **38,** 455-477.

FAUPL, P., PAVLOPOULOS, A. & MIGIROS, G., 1998: On the provenance of flysch deposits in the External Hellenides of mainland Greece: results from heavy mineral studies. – Geol. Mag., **135,** 421-442.

FAUPL, P., PAVLOPOULOS, A. & MIGIROS, G., 1999: The Palaeogene history of the Pelagonian Zone s. l. (Hellenides, Greece): Heavy mineral study from terrigeneous flysch sediments. – Geologica Carpathica, **50,** 449-458.

FAUPL, P., PETRAKAKIS, K., PAVLOPOULOS, A. & MIGIROS, G., 2002: Detrital blue amphiboles from the western Othrys Mountain and their relationship to the the blueschist terrains of the Hellenides (Greece). – Int. J. Earth Sci., **91,** 433-444.

FAURE, M., BONNEAU, M. & PONS, J., 1991: Ductile deformation and syntectonic granite emplacement during the late Miocene extension of the Aegea (Greece). – Bull. Soc. géol. France, **162,** 3-11.

FORSTER, M. A. & LISTER, G. S., 1999: Detachment faults in the Aegean core complex of Ios, Cyclades, Greece. – In: U. Ring, M. T. Brandon, G. S. Lister and S. D. Willett (eds.): Exhumation Processes: Normal Faulting, Ductile Flow and Erosion. Geological Society, London, Special Publications, **154,** pp. 305-323.

FOSTER, D. A. & JOHN, B. E., 1999: Quantifying tectonic exhumation in an extensional orogen with thermochronology: examples from the southern Basin and Range Province. – In: U. Ring, M. T. Brandon, G. S. Lister and S. D. Willett (eds.): Exhumation Processes: Normal Faulting, Ductile Flow and Erosion. Geological Society, London, Special Publications, **154,** pp. 343-364.

FOSTER, D. A., MILLER, D. S. & MILLER, C. F., 1991: Teriary extension in the Old Woman Mountains area, California: evidence from apatite fission track analysis. – Tectonics, **10,** 875-886.

GAUTIER, P., BRUN, J.-P. & JOLIVET, L., 1993: Structure and kinematics of upper Cenozoic extensional detachment on Naxos and Paros (Cyclades islands, Greece). Tectonics, **12,** 1180-1194.

GAUTIER, P. & BRUN, J.-P., 1994: Crustal-scale geometry and kinematics of late-orogenic extension in the central Aegean (Cyclades and Evvia Island). Tectonophysics, **238,** 399-424.

GALLIKER, D., HUGENTOBLER, E. & HAHN, B., 1970: Spontane Kernspaltung von ^{238}U und ^{241}Am. – Helv. Phys. Acta, **43,** 593-606.

GLEADOW, A. J. W., 1981: Fission-track dating methods: What are the real alternatives? – Nucl. Tracks, **5,** 3-14.

GLEADOW, A. J. W., DUDDY, I. R., GREEN, P. F. & LOWERING, J. F., 1986: Confined fission track lengths in apatite: a diagnostic tool for thermal history analysis. – Contrib. Mineral. Petrol., **94,** 405-415.

GRASEMANN, B., FRITZ, H. & VANNEY, J.-C., 1999: Quantitative kinematic flow analysis from the Main Central Thrust Zone (NW-Himalaya, India): implications for a decelerating strain path and the extrusion of orogenic wedges. – J. Struct. Geol., **21,** 837-853.

GRUJIC, D., CASEY, M., DAVIDSON, C., HOLLISTER, L. S., KÜNDIG, R., PAVLIS, T. & SCHMID, S., 1996: Ductile extrusion of the Higher Himalayan Crystalline in Bhutan: evidence from the quartz microfabrics. – Tectonophysics, **260,** 21-43.

HEJL, E. & NEY, P., 1994: Flotationsverfahren zur Abtrennung von Apatit und Zirkon aus silikatischen Paragenesen. – Mitt. Österr. Miner. Ges., **139,** 129-133.

HEJL, E., RIEDL, H. & WEINGARTNER, H., 1999: Cretaceous palaeokarst and Cenozoic erosion of the North Sporades (Greece): Results from geomorphological studies and fission-track analysis. – Mitt. Österr. Geol. Ges., **90,** 67-82.

HEJL, E. & WAGNER, G. A., 1990: Geothermische und tektonische Interpretation von Spaltspuren am Beispiel der Kontinentalen *Tiefbohrung in der Oberpfalz. – Naturwissenschaften,* **77,** *201-*213.

HENJES-KUNST, F. & KREUZER, H., 1982: Isotopic dating of pre-Alpidic rocks from the island of Ios (Cyclades, Greece). – Contrib. Mineral. Petrol., **80,** 245-253.

HODGES, K. V., BURCHFIEL, B. C., ROYDEN, L. H., CHEN, Z. & LIU, Y., 1993: The metamorphic signature of contemporaneous extension and shortening in the central Himalayan orogen: data from Nyalam transect, southern Tibet. – J. Metamorphic Geol., **11,** 721-737.

HURFORD, A. J., 1990: Letter to the editor: Standardization of fission-track dating calibration: recommendation by the fission-track working group of the I.U.G.S. Subcommission on Geochronology. – Chem. Geol., **80,** 171-178.

JANSEN, J. B. H., 1973: Naxos Island. – Geological map of Greece, 1:50.000. Athens (IGME).

JANSEN, J. B. H., 1977: The geology of Naxos. – Geol. Geophys. Res., **19,** 1-100, Athens (IGME).

JANSEN, J. B. H. & SCHUILING, R. D., 1976: Metamorphism of Naxos: Petrology and geothermal gradients. – Am. J. Science, **276,** 1225-1253.

JOLIVET, L., BRUN, J.-P., GAUTIER, P., LALLEMANT, S. & PATRIAT, M., 1994: 3D-kinematics of extension in the Aegean region from the early Miocene to the Present, insights from the ductile crust. – Bull. Soc. géol. France, **165,** 195.

JONCKHEERE, R., MARS, M., VAN DEN HAUTE, P., REBETEZ, M. & CHAMBAUDET, A., 1993: L'Apatite de Durango (Mexique): analyse d'un minéral standard pour la datation par traces de fission. – Chem. Geol., **103,** 141-154.

KETCHAM, R. A., DONELICK, R. A. & CARLSON, W. D., 1999: Variability of apatite fission-track annealing kinetics: III. Extrapolation to geological time scales. – Am. Mineralogist, **84,** 1235-1255.

KREUZER, H., HARRE, W., LENZ, H., WENDT, I., HENJES-KUNST, F. & OKRUSCH, F., 1978: K/Ar- und Rb/Sr-Daten von Mineralen aus dem polymetamorphen Kristallin der Kykladen-Insel Ios (Griechenland). – Fortschr. Mineral., **56 (Bh. 1),** 69-70.

LEE, J. & LISTER, G. S., 1992: Late Miocene ductile extension and detachment faulting, Mykonos, Greece. – Geology, **20,** 121-124.

LISTER, G. S., BANGA, G. & FEENSTRA, A., 1984: Metamorphic core complexes of Cordilleran type in the Cyclades, Aegean Sea, Greece. – Geology, **12,** 221-225.

LOUIS, H., 1967: Reliefumkehr durch Rumpfflächenbildung in Tanganyika. – Geografiska Annales, Ser. A., **49,** 256-267.

LOUIS, H. & FISCHER, K., 1979: Allgemeine Geomorphologie, 4. Aufl. – Lehrbuch der Allgemeinen Geographie, Band 1, 814 p., Berlin – New York.

MANCKTELOW, N. S. & GRASEMANN, B., 1997: Time-dependent effects of heat advection and topography on cooling histories during erosion. – Tectonophysics, **270,** 167-195.

MELIDONIS, N. G., 1980: The geological structure and mineral deposits of Tinos island (Cyclades, Greece). The Geology of Greece, **13,** 80 pp., Athens.

ÖKONOMIDIS, G., 1935: Beiträge zur Kenntnis des Paläogens und Neogens auf der Insel Naxos. – Jb. geol. B.-A., **85,** 333-342.

PAPANICOLAOU, D., 1980: *Contribution to the Geology of the Aegean* Sea: The Island of Paros. – Ann. géol. Pays Hellén., **30,** 65-96, Athens.

PAPANICOLAOU, D., 1993: Geotectonic evolution of the Aegean. – Bull. Geol. Soc. Greece, **28 (1),** 33-48.

PARRISH, R. R., 1985: Some cautions which should be exercised when interpreting fission-track and other dates with regard to uplift calculations. – Nucl. Tracks, **10,** 425.

PHILIPPSON, A., 1959: Die griechischen Landschaften. Band IV: Das ägäische Meer und seine Inseln. 523 pp., Frankfurt/Main.

RIEDL, H., 1979: Climatically controlled fossilized key features of Greece. – Proceedings VI. Colloquium on the Geology of the Aegean Region, Vol. 1, 503-508, Athens.

RIEDL, H., 1982 a: Vergleichende Untersuchungen zur Geomorphologie der Kykladen unter besonderer Berücksichtigung der Insel Naxos. – Salzburger Exkursionsberichte, **8,** 9-54.

RIEDL, H., 1982 b: Die Altflächenentwicklung der Kykladen. – Ann. géol. Pays Hellén., **31,** 33-84, Athens.

RIEDL, H., 1984 a: Paleoclimatic aspects of the geomorphology of the Cyclad archipelago (Greece) with references to methodological problems. – Paléobiologie continentale, **14 (2),** 403-413.

RIEDL, H., 1984 b: Die Reliefgenerationen Griechenlands. – Österr. Osthefte, **26,** 156-177, Wien.

RIEDL, H., 1989: Geomorphological sequences in the Attic-Cycladic region. – Geographica Rhodopica, **2,** 87-94.

RIEDL, H., 1991: Landforms and processes associated with the exhumation of the plutonic basal surface in the area of of the Aegean Archipelago. – Bull. Geol. Soc. Greece, **25,** 67-82.

ROESLER, G., 1972. Das Neogen von Naxos und den benachbarten Inseln. – Zt. deutsch. geol. Ges., **123,** 523-525.

RÖGL, F., 1996. Stratigraphic correlation of the Paratethys Oligocene and Miocene. – Mitt. Ges. Geol. Bergbaustud. Österr., **41,** 65-73.

SUC, J. P. & ZAGWIJN, W., 1983: Plio-Pleistocene correlations between the northwestern Mediterranean region and northwestern Europe according to recent biostratigraphic and palaeoclimatic data. – Boreas, **12/3,** 153-166, Oslo.

THOMSON, S. N., STÖCKHERT, B. & BRIX, M. R., 1999: Miocene high-pressure metamorphic rocks of Crete, Greece: rapid exhumation and buoyant escape. – In: U. Ring, M. T. Brandon, G. S. Lister & S. D. Willtett (eds.): Exhumation Processes: Normal Faulting, Ductile Flow and Erosion. Geological Society, London, Special Publications, **154,** pp. 87-107.

THORBECKE, G., 1987. Zur Zonengliederung der ägäischen Helleniden und westlichen Tauriden. – Mitt. Ges. Geol. Bergbaustud. Österr. Special Issue, **2,** 161 pp.

THUNNELL, R., 1979: Quantitative biostratigraphy and paleoclimatology of the late Neogene deep sea drilled sequences from the Mediterranean. – In: Ann. géol. Pays Hellén., **47,** 1215-1223, Athens.

THUNNELL, R. C. & WILLIAMS, D. F., 1983: The steppic development of Pliocene-Pleistocene palaeoclimatic and palaoceanographic conditions in the Mediterranean oxygen isotope studies of DSDP sites 125 & 132. – Utrecht Micropal. Bull., **30,** 111-127.

VANDENBERG, L. C. & LISTER, G. S., 1996: Structural analysis of basement tectonites from the Aegean metamorphic core complex of Ios, Cyclades, Greece. – J. Struct. Geol., **18,** 1437-1454.

VAN DEN HAUTE, P., JONCKHEERE, R. & DE CORTE, F., 1988: Thermal neutron fluence determination for fission-track dating with metal activation monitors: a re-investigation. – Chem. Geol. (Isotope Geosci. Sect.), **73,** 233-244.

VAN DER MAAR, P. A. & JANSEN, J. B. H., 1981: Island of Ios. – Geological map of Greece, 1:50.000. Athens (IGME).

VAN DER MAAR, P. A. & JANSEN, J. B. H., 1983: The geology of the polymetamorphic complex of Ios, Cyclades, Greece and its significance for the Cycladic massif. – Geol. Rundsch., **72,** 283-299.

VELITZELOS, E. & ZOUROS, N., 1998: New results on the petrified forest of Lesvos. – Proceedings of the 8th Int. Congr. Patras. Bull. Geol. Soc. Greece, **32/2,** 133-142, Athens.

WAGNER, G. A., 1968: Fission-track dating of apatites. – Earth Planet. Sci. Lett., **4,** 411-415.

WAGNER, G. A. & REIMER, M., 1972: Fission track tectonics: the tectonic interpretation of fission track ages. – Earth Planet. Sci. Lett., **14,** 263-268.

WAGNER, G. A., REIMER, M. & JÄGER, E., 1977: Cooling ages derived by apatite fission-track, mica Rb-Sr and K-Ar dating: the uplift and cooling history of the Central Alps. – Memor. Istit. Geolog. e Mineral. Univers. Padova, **30,** 3-28.

WAGNER, G. A. & VAN DEN HAUTE, P., 1992: Fission-Track Dating. xiii + 285 pp., Enke, Stuttgart.

WEINGARTNER, H., 1994: Die Insel Thasos. Eine physisch-geographische Synthese. – Salzburger geogr. Arb., **24,** 166 pp.

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