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Cretaceous Palaeokarst and Cenozoic Erosion of the North Sporades (Greece): Results from Geomorphological Studies and Fission-Track Analysis

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Content

Der kreidezeitliche Paläokarst und die känozoische Reliefgeschichte der Nordsporaden (Griechenland): Geomorphologische Befunde und Spaltspurenanalysen

Zusammenfassung

Die Reliefentwicklung der Magnesischen Inseln (Nordsporaden) wurde anhand geomorphologischer Geländebeobachtungen auf Skopelos und mittels Spaltspurdatierungen an Gesteinen von Skiathos, Skopelos und Alonnisos untersucht. Die gemessenen Spaltspuralter und modellierten Abkühlpfade weisen auf regionale und zeitliche Schwankungen der posteozänen Abtragungsgeschwindigkeiten hin.

Zwei präeozäne Generationen von Paläokarst sind auf Skopelos zu beobachten. Die erste entwickelte sich während der Unterkreide auf triadischen Dolomiten des alten pelagonischen Schelfs. Die Bauxite und Laterite, mit denen dieser Palaeokarst versiegelt ist, sind aus verschwemmtem Material der Eohellenischen Decke hervorgegangen. Eine zweite Generation von Paläokarst entwickelte sich auf oberkretazischen Rudistenkalken und wurde unter palaeogenem Flysch begraben.

Drei Generationen neogener Verflachungen treten auf Skopelos oberhalb von 300 m Seehöhe auf. Die modellierten Abkühlpfade und tektonische Beobachtungen implizieren, daß diese Formengemeinschaften vor ungefähr vor 5 bis 10 Ma, d. h. im späten Miozän (Tortonium bis Messinium) entstanden sein müssen.

Im Gegensatz zu Skopelos kann die Erhaltung präpliozäner Reliefreste auf Skiathos und im Südwestteil von Alonnisos weitgehend ausgeschlossen werden. Auf Skiathos war starke neogene Bruchtektonik wirksam.

Abstract

The relief history of the Magnesian Islands (North Sporades) has been studied by geomorphological field observations on Skopelos and by apatite fission track analysis on Skiathos, Skopelos and Alonnisos. The measured fission-track ages as well as modeled cooling paths reveal regional variations in post-Eocene erosion.

Two generations of pre-Eocene palaeokarst can be observed on Skopelos Island. The older one developed during the Early Cretaceous on Triassic dolomites of the ancient Pelagonian shelf. This palaeokarst is sealed by bauxites and laterites which were derived from parent rocks of

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the Eohellenic nappe. A second palaeokarst generation developed on Upper Cretaceous rudist limestones and was buried under Palaeogene flysch deposits.

Three generations of Neogene planation surfaces occur on Skopelos Island above 300 m altitude. Modeled cooling paths and tectonic observations imply that these planation levels must have been formed between approximately 10 and 5 Ma ago, i.e. during the Late Miocene (Tortonian and Messinian).

In contrast to Skopelos, the preservation of pre-Pliocene relief elements can be mostly excluded for Skiathos and southwestern Alonnisos. Neogene horst-graben tectonics were distinctly active on Skiathos.

1. Introduction

Geomorphological research concerning the aspects of Neogene to Quaternary relief development in Greece (a.e. RIEDL, 1984, 1998; WEINGARTNER, 1994) has revealed the presence of widespread relief remnants that originally have developed under climate conditions that were completely different from present. Such different climate has been demonstrated by palaeosoils and related relief features, which are characteristic of semihumid tropical regions. Furthermore, a steplike arrangement of the palaeo-planation surfaces indicates the influence of tectonic activity on the surface development.

Up to now, the stratigraphic position of the palaeo-relief has been mostly estimated through correlation of sediment data. Meanwhile, apatite fission-track dating (a.e. BISCHOFF, 1993; WEINGARTNER & HEJL, 1994) is an alternative tool for the age determination of palaeo-landscapes. In the North Sporades, the method has been applied in order to determine post-Eocene erosion rates as well as to elucidate tectonic influence on the major relief development.

2. Geological setting

The alpidic orogen of the Hellenides results from Jurassic until Cenozoic cycles of subduction, folding and nappe thrusting. Orogenic activity migrated mainly from the internal to the external Hellenides, i.e. from NE towards SW, as can be deduced from the age of contemporaneous flysch sediments (JACOBSHAGEN, 1986) and from the position of palaeovolcanic arcs (PAPANIKOLAOU, 1993).

The islands of Skiathos, Skopelos, Alonnisos and Peristera belong to the Pelagonian zone of the Central Hellenides (JACOBSHAGEN, 1986) which also include the Parnassos and Pindos zone (cf. Fig. 1). The Pelagonian zone is built up by carbonate shelf sediments on an underlying crystalline basement. The Pelagonian shelf developed from the late Palaeozoic until the Jurassic, with deposition of mostly neritic carbonates and minor quantities of pelagic basin sediments, such as cherty limestones. From Triassic until Early Cretaceous, the Axios-Vardar ocean separated Rhodope and adjacent areas to the N from the Pelagonian zone and the External Hellenides to the S (PAPANIKOLAOU, 1993).

By the end of the Jurassic, the water depth of the Pelagonian shelf increased and subsequently it was overthrust by the Eohellenic nappe, obviously originating from the Innerhellenic Axios-Vardar zone (THORBECKE, 1987, p. 12). The Eohellenic nappe comprises ophiolitic sequences with a thin cover of oceanic sediments. Nappe emplacement has occurred after the Kimmeridgian but before the Cenomanian (JACOBSHAGEN & WALLBRECHER, 1985, p. 594).

After a period of erosion, the former Pelagonian shelf and the Eohellenic nappe submerged again and were covered by transgressive Upper Cretaceous limestones and by Palaeogene flysch sediments. The pre-Cretaceous Pelagonian shelf and the Eohellenic nappe together with their Mesoautochthonous sedimentary cover (Upper Cretaceous – Palaeogene) have been categorized as "Pelagonian zone sensu lato" (THORBECKE, 1987, p. 12), while the "Pelagonian zone sensu strictu" is restricted to the pre-alpidic basement and the pre-Cretaceous carbonate platform (late Palaeozoic – Jurassic). Nappe thrusting within the Pelagonian zone s. l. lasted until the Late Eocene.

In our study area (Fig. 2), the Pelagonian zone s. str. is represented by the Skiathos Formation and by Upper Triassic dolomites. The Skiathos Formation occurs in the western part of Skiathos and forms a small belt to the S of Glossa peninsula which belongs to Skopelos Island (Fig. 3). This complex formation is composed of various metasediments, including phyllites, micaschists and gneisses. A Late Palaeozoic age of the formation has been postulated on the base of few questionable fossils and a presumed molasse facies (JACOBSHAGEN & SKALA, 1977, p. 237-238). The Skiathos Formation of Skopelos Island is conformably overlain by Norian-Rhaetian dolomites – their age is well documented by fossil occurrences (MATARANGAS, 1992). Therefore, the underlying Skiathos Fm. may have been deposited from Late Palaeozoic until Carnian times.

Eastern Skiathos and the Glossa peninsula (northwestern Skopelos) belong to the Eohellenic nappe. It comprises slices of serpentinite, metabasalts, micaschists and phyllites with small intercalations of marble. The Eohellenic nappe of Skiathos and Skopelos rests unconformably on the Skiathos formation.

The Upper Cretaceous transgression commenced after a long period of erosion that is documented by lateritic palaeosoils and bauxites at the base of the transgressive sequence. These lateritic formations fill cavities on a karstified palaeosurface that had developed on the Pelagonian dolomites. Cretaceous sedimentation began with dolomitic breccias and conglomerates, which were overlain by limestones up to 200 m in thickness. *Rudistae, Echinodermata* and *Miliolidae* are frequent in the thick-bedded and massive limestone successions. Palaeogene flysch sediments reach a maximum thickness of approximately 150 m.

The Palouki Formation comprises an alternation of thin-bedded limestones, sandstones and dark phyllitic schists. It occurs on southeastern Skopelos, on Alonnisos and Peristera. An Early Cretaceous age is proven by fossils (MATARANGAS, 1992, p. 99). Thus, we conclude that this zone remained continuously below sea-level during the Cretaceous. The Palouki Formation of Skopelos was overthrusted onto the Mesoautochthonous flysch succession – probably at the end of the Eocene (Mesohellenic orogeny). According to JACOBSHAGEN & SKALA (1977), an Eocene age is also assumed for the greenschist metamorphism of the Eohellenic nappe.

Afterwards, the main compressional activities, i.e. nappe thrusting and subduction, migrated southwards into the area of External Hellenides (Gavrovo, Ionian and Paxos zone).

A molassic back-arc basin was formed in the area of the Southern Cyclades and in Western Thessaly during the Early Miocene (Mesohellenic Molasse in Fig. 1). At this time, mainland Greece was connected with Minor Asia through a land-

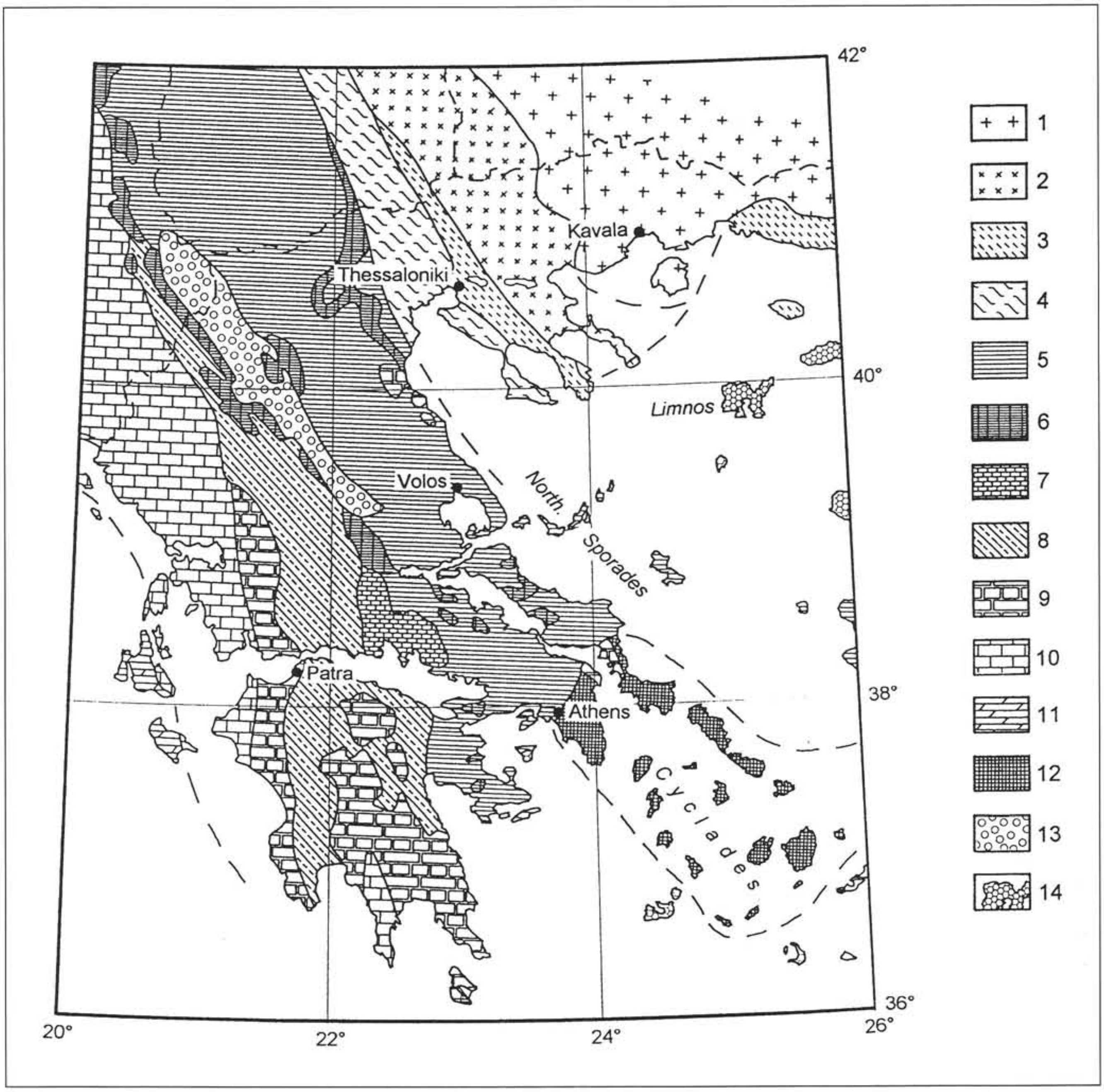


Fig. 1
Simplified geotectonic map of mainland Greece and the northwestern Aegean islands. 1 = Rila-Rhodope zone, 2 = Serbomacedonian zone, 3 = Circum Rhodope belt, 4 = Axios-Vardar zone, 5 = Pelagonian zone, 6 = Ophiolites in general (except Axios-Vardar oph.), 7 = Parnassos zone, 8 = Pindos zone, 9 = Gavrovo zone, 10 = Ionian zone, 11 = Paxos zone, 12 = Cycladic crystalline, 13 = Mesohellenic molasse, 14 = Cenozoic volcanics.

bridge including Attica, Southern Evia, Northern Cyclades, Ikaria and Samos (PAPANIKOLAOU, 1993). This configuration was essentially maintained until Late Miocene.

Present-day subduction occurs along the outer rim of the Hellenic arc (Peloponnesos-Crete-Rhodos). Precise geodetic measurements with a global positioning system (LE PICHON et al., 1995) have shown that, with respect to Europe, the southern Aegean plate moves towards southwest at a velocity of 30 mm/a. Marine molasse sedimentation still continues in the back-arc position of the Cretan Basin, whereas the Aegean land-bridge to the N has been destroid by extension and subsidence. The Cyclades Islands represent the summits of the former land area. During the last 15 Ma, sediments up to 6 km thick, accumulated in the subsiding North Aegean trough (LYBÉRIS, 1984). The Sporades basin E of the Pelion Mountains (Eastern Thessaly, Greek mainland) is the westernmost part of the North Aegean trough. It has a present-day water depth of more than 1000 m.

3. Palaeokarst features

3.1 Bauxite karst and laterite karst

On Skopelos Island, the oldest generation of landforms is represented by palaeokarst troughs which are sealed by bauxites and laterites (PANAGOS & LIATI, 1996) and which must have developed during the first emersion of the Pelagonian zone, i.e. after the Eohellenic upthrust and before the Late

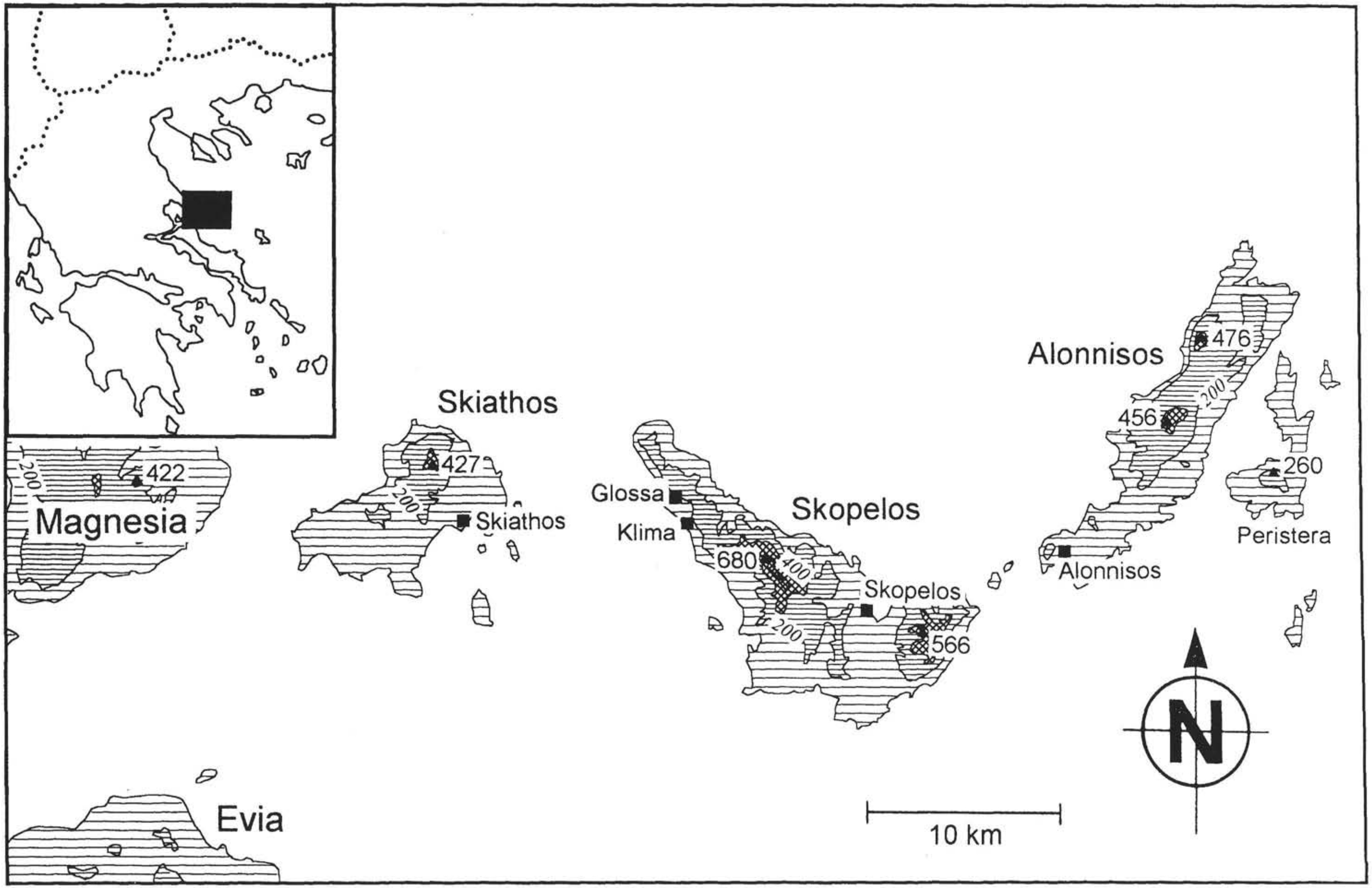


Fig. 2
Topographic sketch map of the Magnesian Islands (North Sporades). The position of the area is indicated in black on the contour map of Greece.

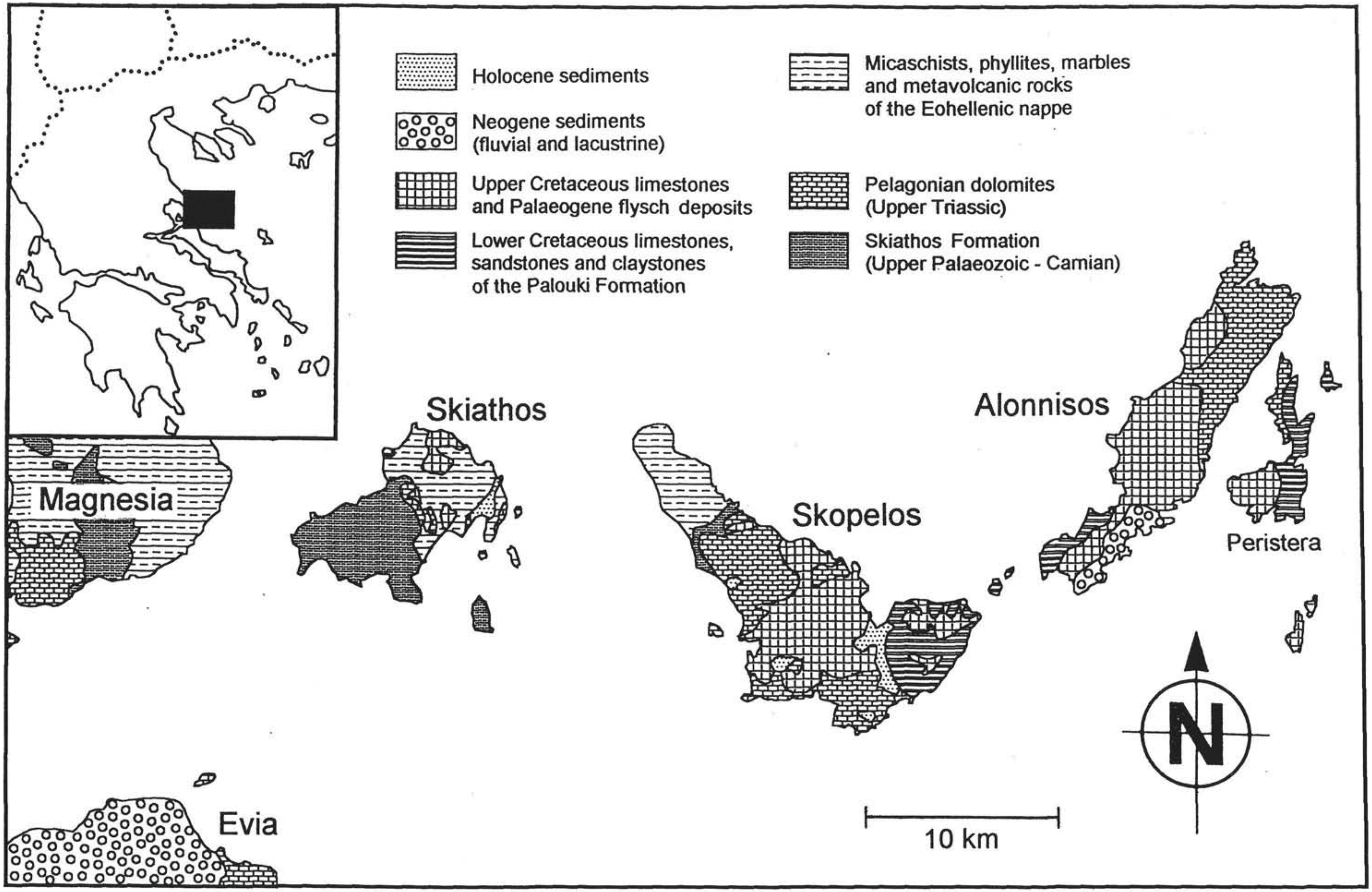


Fig. 3
Simplified geological map of the Magnesian Islands (sources: JACOBSHAGEN & SKALA, 1977; JACOBSHAGEN & WALLBRECHER, 1985; MATARANGAS, 1992; VIDAKIS, 1995).

Cretaceous transgression. Hence, we may assume an Early Cretaceous age for this palaeokarst. It was subjected to deformation during the Mesohellenic phase. Palaeokarst in similar stratigraphic positions has also been observed on Skiathos Island (Heinitz & Richter-Heinitz, 1983, p. 45).

The Lower Cretaceous palaeokarst of Skopelos consists of round karren and "hohlkarren" and 10 m wide karst troughs. They developed on Triassic dolomites and are filled with lateritic, violet to greenish or kaolinitic matadero (Kubiena, 1955), i.e. material of tropical soil. Metabasalts, serpentinites and schists of Eohellenic nappe remnants served as source rocks for the development of the laterites and bauxites, as has been deduced from light and heavy mineral analysis, as well as from lithic fragments in the lateritic matrix (Matarangas, 1992). Other noteworthy features are the crumbling walls of the karren and karst troughs as well as the subcutaneous, sawtooth-like disintegration of the Pelagonian dolomites. In some parts collapsed hummocky karren can ce observed, which are completely mantled by decomposed matadero. Upper Cretaceous conglomerates unconformably overlie all these forms of palaeokarst.

The bauxite and laterite karst of Skopelos and Skiathos displays a great similarity with the buried fossil karst at the Amvlema Pass in Central Greece (Riedl, 1984), and also with the pre-Gosauian bauxite karst of the Northern Calcareous Alps (Austria; Riedl, 1973).

3.2 Preflysch karst

The next generation of landforms developed at the end of the Cretaceous and/or in the lowermost Palaeogene. These landforms appear in the Upper Cretaceous rudist limestones and are mostly buried under Palaeogene flysch successions. Partly exhumed karst cones and cockpit dolines can be observed in the Palouki Massif and in the Karya (cf. Fig. 4). Evidence of similar karst landforms has been documented for the Gavrovo-Tripolitza zone on the Peloponnese by Richter (1978) and Richter & Mariolakos (1973). Analogous observations have been made on Kythira Island by Theodoropoulos (1973) and in upper Arcadia by Riedl (1978). Such kind of landforms are also found in the Parnassos-Giona zone (Richter & Mariolakos, 1973).

Dercourt & Fleury (1977) deny the existence of this generation of landforms on the grounds that there are "couches de passage" (marine intercalations) between limestones and flysch in the Western and Central Hellenides. The apparent contradiction between such marine "transitional series" (Richter, 1978) and simultaneous subaerial karst development can be easily eliminated by the following consideration: In the less uplifted areas, marine conditions may have continued for longer time and transitional series between rudist limestones and flysch may have been deposited. Conformable transitions from Upper Cretaceous limestones to Palaeogene flysch sediments have been observed occasionally on Skopelos and Alonnisos (Matarangas, 1992). Therefore, we suggest that areas with persistent marine conditions could have alternated on a fairly small scale with areas subjected to subaerial denudation.

4. Neogene-Quaternary planation surfaces of Skopelos Island

4.1 Planation system A

The oldest planation system A, situated at an altitude of 550 m, dominates the Palouki Massif and the southwestern Delphi ridge (Fig. 4) and is formed in Pelagonian dolomites. In parts, it rises above 600 m altitude, but in areas where uplift was less, it covers the karst blocks of Mt. Plakes and Mt. Glyphada at an average elevation of 200 m. It may be described as an association of forms comprising solution plains, small domes, micropoljes, uvalas and bowl-shaped dolines. Thick covers of residual red soil are another characteristic feature. These soils are loamy clays with a colour value of 10 R 4/6. The results of heavy-mineral analysis reveal that the substratum of the red soils cannot have derived from Triassic dolomites, but only from formerly wide-spread rocks of the Eohellenic Glossa nappe (serpentinites, metabasalts, mica schists, phyllites). Erosion of the non-carbonate cover together with simultaneous red soil weathering, filling of the karst clefts with soil and the development of karst plains on the Triassic dolomites constitute a contemporary system. The high content of kaolinite in the palaeosoils (15%), together with haematite and goethite (10%) as well as diaspore (5%) indicate that a semi-humid to tropical climate produced this denudation surface with palaeoplastosols.

The whole association of forms is very similar to those reported at elevations of 1450 m in the Olonos Limestones of Arcadia (Riedl, 1978), to the peneplains of Mt. Parnassos (Maull, 1921), to the top levels on Ikaria and Samos (Riedl, 1989) as well as to the Eastern Thessalian mountain swell (Riedl, 1981).

4.2 Planation system B

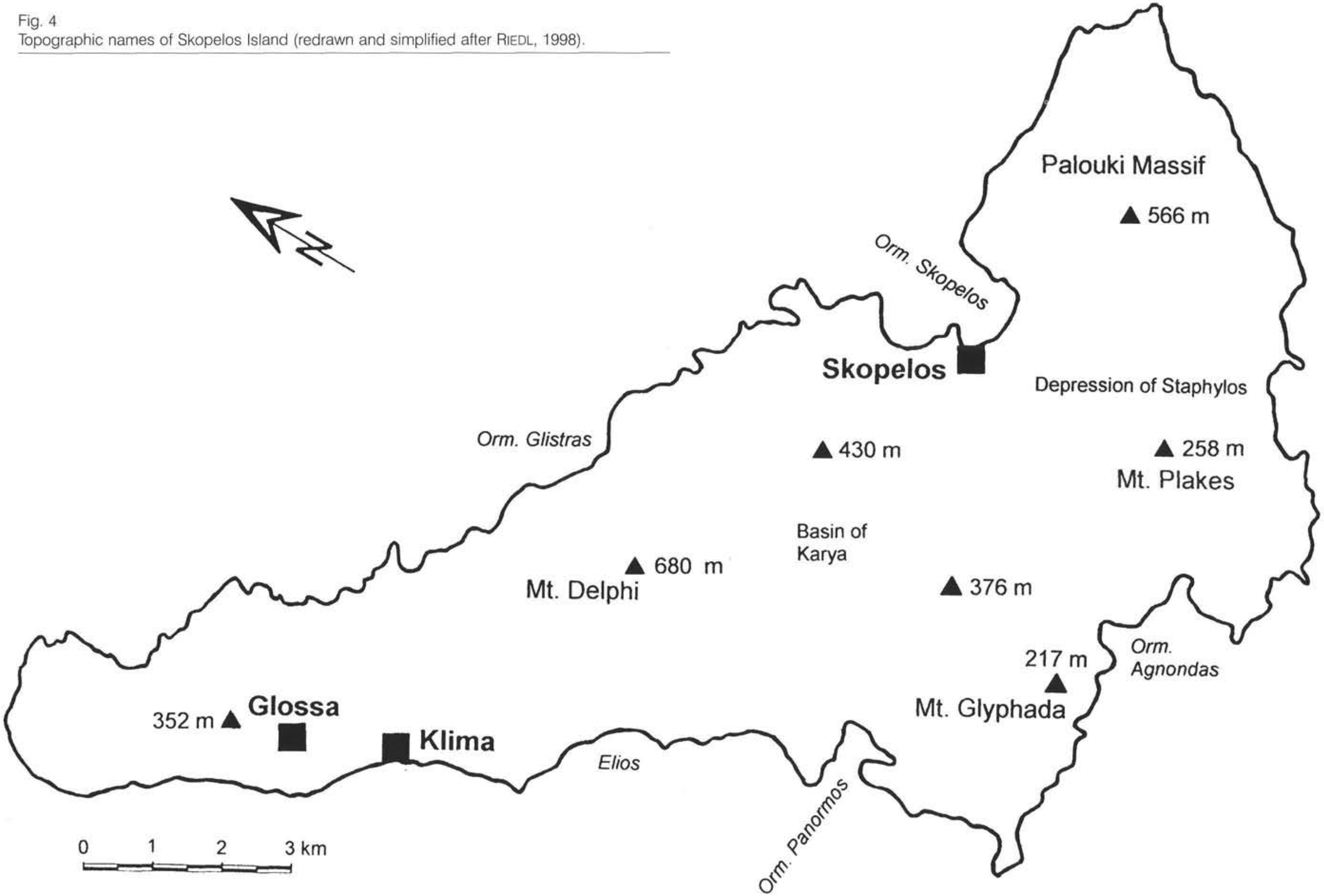
Level B occupies an average height of 450 m. It is located on Mt. Palouki and, in the form of a broad bench, it extends to the southeastern foot of Mt. Delphi. Furthermore, it appears as a flat surface disrupted into several spurs on the northeastern slope of Mt. Delphi. It extends onto its western slope and onto the Glossa Peninsula. Summing up, level B encircles nearly all sides of Mt. Palouki and Mt. Delphi. Between both mountains, a flat valley with a width of 7 km was formed. Such wide open valleys with sides flaring out are typically generated by sheetwash under semihumid-tropical conditions. The areal extent of level B as well as the development of extensive valley floors striking out into the air gives clear evidence for a landscape evolution that occurred in a larger continental environment with orographic conditions that were entirely different from the present-day island configuration.

4.3 Planation system C

Level C is located at an average height of 350 m. Similar to both older systems, it extends widely, straddling present-day watersheds. It is a dominant feature on the Glossa Peninsula, where it has been warped over a vertical distance of 50 m. Level B was also affected by these neotectonic warpings. In both cases, the axes of flexuring strike from ENE to WSW, in good correspondence with the lineations mapped by Matarangas (1992). These neotectonic deformations do not affect morphological levels below 350 m.

Level C is characterized by broad embayments and passes as well as by relict surfaces of intramontane basins. The embayments are about 2 km wide because of the ancient predominance of deep weathering and sheet processes. Level C displays a strong morphological affinity to the planation surfaces of Mt. Ossa on Greek mainland (Riedl, 1981), where the planation level at 1000 m altitude extends far 2 km into the older and higher systems of landforms. To the S of the Mt. Ossa summit, the flat passes are 6 km wide, while on Skopelos they have a width of 6.5 km between Karya and Mt. Palouki.

Fig. 4
Topographic names of Skopelos Island (redrawn and simplified after RIEDL, 1998).



4.4 Pediment system D

Level D occurs at an average altitude of 200 m. Compared to the older systems we note a remarkable break in the morphological features. This level is characterized by pediments and basin-shaped valley heads. The entire slope of Mt. Palouki has been modified by pedimentation, which extended down to the depression of Staphylos. Relatively fast uplift *en bloc* must have occurred after the formation of level D, as is indicated by triangular-shaped slopes on the east side of Mt. Palouki.

4.5 Coastal marginal pediment system E

Pediments occur along the coast at an average elevation of 120 m. They occur on the smoother northern slope of the Glossa Peninsula and they constitute the initial surface for the present-day outline of the bays (Elios, Panormos). The pediments are associated with a regular pattern of landforms. In the depression of Staphylos, they are covered by angular scree mixed with loam and they merge into glacis. At the counter discharge margin, these glacis are connected with karst blind valleys. After this synchronous development of forms, the blind valleys were transformed into poljes or uvalas.

5. Apatite fission-track analysis

Thirteen samples with a minimum mass of 3 kg each were collected on Skiathos, Skopelos and Alonnisos islands during a field trip in April 1996. They were taken from surface outcrops of the Skiathos Formation, the Eohellenic metasediments, the Lower Cretaceous sandstones and the Palaeogene flysch. Localities and lithologies of seven successfully dated samples are listed in Table 1.

After rock crushing and dry sieving, the sand fraction with a grain size between 100 and 250 μm was suspended in distilled water and treated with flotation chemicals according to the procedure described by HEJL & NEY (1994). Hydrophobic apatite tends to concentrate in a foam on the water surface and is easily separated from the remaining suspension. Afterwards, the dried apatite concentrates were purified with a Frantz magnetic separator and heavy liquids. Two gneiss samples from western Skiathos, two phyllitic samples from the Eohellenic nappe (eastern Skiathos and Glossa peninsula), one flysch sample from Skopelos and one from Alonnisos did not yield enough apatite. The remaining seven samples could be successfully dated.

Fission-track dating was performed by the grain population method (cf. WAGNER & VAN DEN HAUTE, 1992). One fraction of each apatite concentrate was heated in a furnace for 24 hours at 500°C. The heated fractions were irradiated in the thermal column of the ASTRA reactor (Forschungszentrum Seibersdorf, Austria) which has a flux of thermal neutrons in the order of 5×10^{10} cm^{-2} s^{-1} with a relative amount of epithermal neutrons of less than 0.1%. Thermal neutron fluence was determined by γ-spectrometry of simultaneously irradiated Co monitors (cf. VAN DEN HAUTE et al., 1988).

Natural and irradiated grain populations of each sample were embedded in epoxy resin, ground, polished and etched for 60 s in 5% HNO_3 at 20°C. Fission tracks were counted in transmitted light at a total magnification of 1250x (oil immersion).

The fission-track ages were calculated with the ^{238}U spontaneous fission constant $\lambda_f = 8.46 \times 10^{-17}$ a^{-1}. System calibration was tested with two age standards: Durango apatite and apatite from the Mt. Dromedary banatite in New South Wales (cf. JONCKHEERE et al., 1993, and GREEN, 1985, respectively). Within the error limits, the measured fission-track ages of the standards coincide to their reference ages (HEJL, 1997).

Dating results are reported in Table 2 and Fig. 5. Sample GR 25 is a greywacke from the Palaeogene flysch of eastern Skiathos, GR 28, 29 and 30 are gneisses from the Skiathos Formation, GR 32 is a Palaeogene flysch sandstone, GR 34 and 36 are Lower Cretaceous sandstones of Palouki unit. As it must be taken into account that apatites from sedimentary and metasedimentary rocks might be inhomogeneous in composition (U-content, Cl/F ratio), we have compared the poisson and standard errors of each sample. For the samples GR 25, 28, 29 and 30 (all from Skiathos) poisson and standard errors are in the same order of manitude (the poisson error is always more than 50% of the standard error), thus suggesting that the compositional spread is rather low. The samples from Skopelos and Alonnisos (GR 32, 34 and 36) obviously have a wider compositional variation because the standard errors are approximately three times higher than the poisson errors. An additional check of the frequency of track densities (tracks per counting grid) yielded no evidence for bimodal distributions within individual samples. Therefore, the calculated standard errors seem to be valid.

Lengths of confined spontaneous tracks were measured in overetched samples (20 s in 25% HNO_3 at 20°C) by use of a

Tab. 1
List of dated samples. Sample GR 25 is a greywacke from the Palaeogene flysch of eastern Skiathos, GR 28, 29 and 30 are gneisses from the Skiathos formation, GR 32 is a Palaeogene flysch sandstone, GR 34 and 36 are Lower Cretaceous sandstones of the Palouki unit.

Sample code	Date	Rock type	Locality	Altitude (m)
GR 25/SASP 94	16-Apr-96	Greywacke	Skiathos, NE of Ag. Georgios	110
GR 28/SASP 97	17-Apr-96	Augengneiss	Skiathos, Kap Gournes	10
GR 29/SASP 98	17-Apr-96	Gneiss	Skiathos, N of Platania	130
GR 30/SASP 99	17-Apr-96	Augengneiss	Skiathos, between Kechrias and Platania	110
GR 32/SASP 101	18-Apr-96	Sandstone	Skopelos, saddle Karya	340
GR 34/SASP 103	19-Apr-96	Sandstone	Skopelos, Ag. Polyxenis	350
GR 36/SASP 105	22-Apr-96	Sandstone	Alonnisos, 500 m NW of the ancient village	190

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

Sample code	Number of grains	Spontaneous tracks		Induced tracks		Error 1σ	Neutron	Fission-track
	n_s/n_i	N_s	ρ_s (10^5 cm^{-2})	N_i	ρ_i (10^5 cm^{-2})	of ρ_s/ρ_i (%)	fluence (10^{14} cm^{-2})	age ± 1σ (Ma)
GR 25 / SASP 94	250/200	228	0.570	561	1.753	14.6	7.78	12.6 ± 1.9
GR 28 / SASP 97	300/150	1436	8.310	1653	19.132	4.6	10.00	21.6 ± 1.1
GR 29 / SASP 98	300/150	600	3.472	731	8.461	7.5	10.00	20.4 ± 1.6
GR 30 / SASP 99	400/200	240	0.783	836	5.457	8.4	10.00	7.1 ± 0.6
GR 32 / SASP 101	200/200	858	2.681	1207	3.772	13.6	7.78	27.5 ± 3.8
GR 34 / SASP 103	200/200	535	1.672	726	2.269	15.4	7.78	28.5 ± 4.4
GR 36 / SASP 105	200/200	171	0.534	841	2.628	26.8	7.78	7.9 ± 2.1

drawing tube attachment to the microscope and a digitizing tablet. A statistically significant number of at least 30 confined tracks could be found only in four samples (GR 28, 29, 32 and 34). Histograms showing the frequency distributions of their track lengths are presented in Fig. 5.

An inverse modeling routine was performed with the program AFTSolve (version 0.7.1, © 1996, Donelick analytical, Inc. and Richard A. Ketcham) by friendly permission of Raymond A. Donelick. This program calculates the range of thermal histories (temperature versus time) that are potentially consistent with the measured age and the measured frequency distribution of confined track lengths. 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 program maps out the 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. We have estimated the apatite's resistance to track annealing by measuring the diameters of etch pits parallel to the crystallographic c-axis (dpar). The arith-metic mean of dpar was used as kinetic variable in the program (U.S. Patent Number 5,267,274 and Australian Patent Number 658,800). Generation of random cooling paths can be constrained to thermal histories within a narrowed range of possibilities. On a time-temperature diagram, these additional specifications are vertical bars which must be crossed by the cooling paths. In course of the fitting procedure, the field of interest can be narrowed progressively by elimination of "hopeless" time-temperature areas. Modeling results are shown in Figs. 6, 7, 8 and 9.

6. Discussion of thermochronological data

The measured apatite fission-track ages range from 28.5 to 7.1 Ma, i.e. from middle Oligocene until late Miocene (according to RÖGL, 1996). Track length distributions were obtained for the samples from western Skiathos (GR 28 and 29) and from Skopelos (GR 32 and 34). The other samples (from eastern Skiathos and from Alonnisos) did not fulfill the minimum requirement of 30 measurable confined tracks because their spontaneous track densities were too low. The four measured frequency distributions of confined spontaneous tracks (cf. histograms in Fig. 5) are characterized by very similar mean lengths ranging between 13.0 and 13.5 μm. Standard deviations range from 1.3 to 2.2 μm. These values are potentially consistent with the assumption of slow steady cooling but complex thermal histories, for example stepwise cooling, can not be excluded (cf. GLEADOW et al., 1986, p. 410 f.).

In a first interpretation step, the measured ages were considered as cooling ages to a rock temperature of approximately 100°C. With a present-day surface temperature of 10°C (annual mean) we obtained the following mean cooling rates: Values around 4.3°C/Ma for both samples from western Skiathos (GR 28 and 29), 12.7 and 7.1°C/Ma for central and eastern Skiathos (GR 30 and 25, respectively); values around 3.2°C/Ma for both samples from Skopelos (GR 32 and 34) and 11.4°C/Ma for southwestern Alonnisos (GR 36). Dividing these cooling rates by an assumed thermogradient of 30°C/km yields the following mean erosion rates: 0.14, 0.42 and 0.24 mm/a for western, central and eastern Skiathos, respectively; 0,11 mm/a for Skopelos; 0,38 mm/a for southwestern Alonnisos. For the Oligocene and Early Miocene we do not expect thermogradients of much more than 30°C/km, because the thinning of the Aegean crust obviously began not earlier than 10 Ma ago. Anyhow, the calculated mean

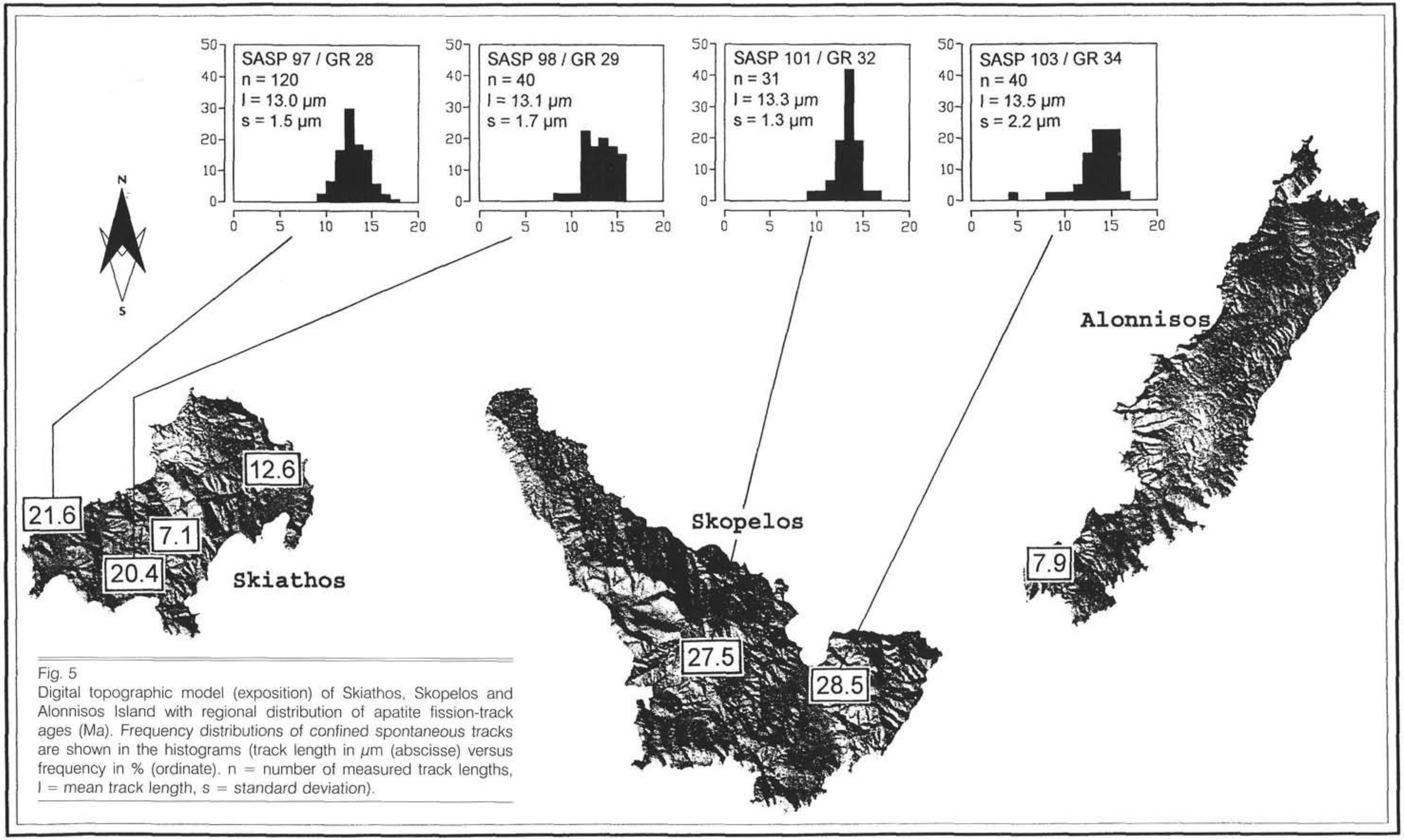
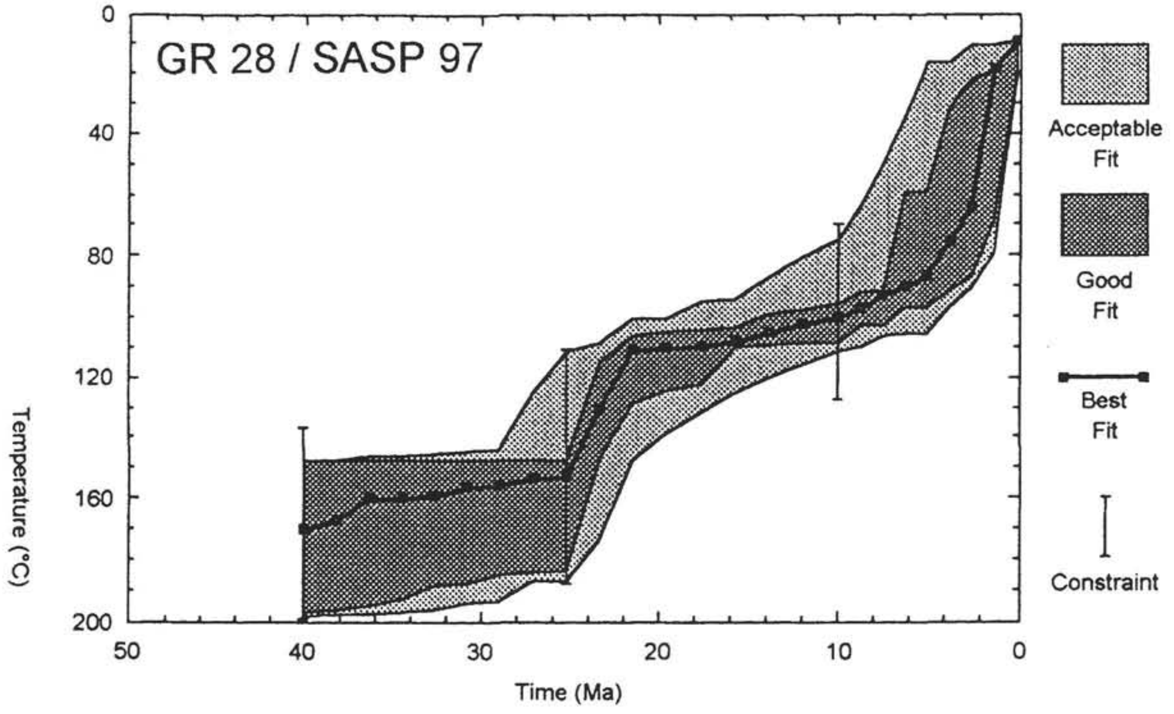


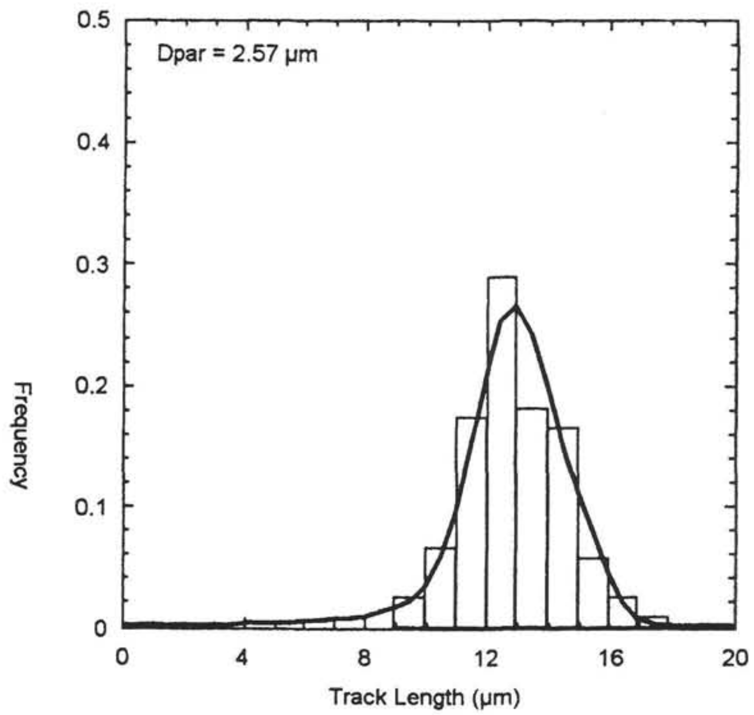
Fig. 5
Digital topographic model (exposition) of Skiathos, Skopelos and Alonnisos Island with regional distribution of apatite fission-track ages (Ma). Frequency distributions of confined spontaneous tracks are shown in the histograms (track length in μm (abscisse) versus frequency in % (ordinate). n = number of measured track lengths, l = mean track length, s = standard deviation).

SCALE 1:130000
2000 0 2000 4000 6000 8000 10000
METERS

* Data base: 10x10 meter Digital Elevation Model

Project: Neogene and Quarternary Relief Development - Sporadic Islands
Project Members: H.Riedl, H.Weingartner
Cartography: T.Gaisecker
Date: April 1995





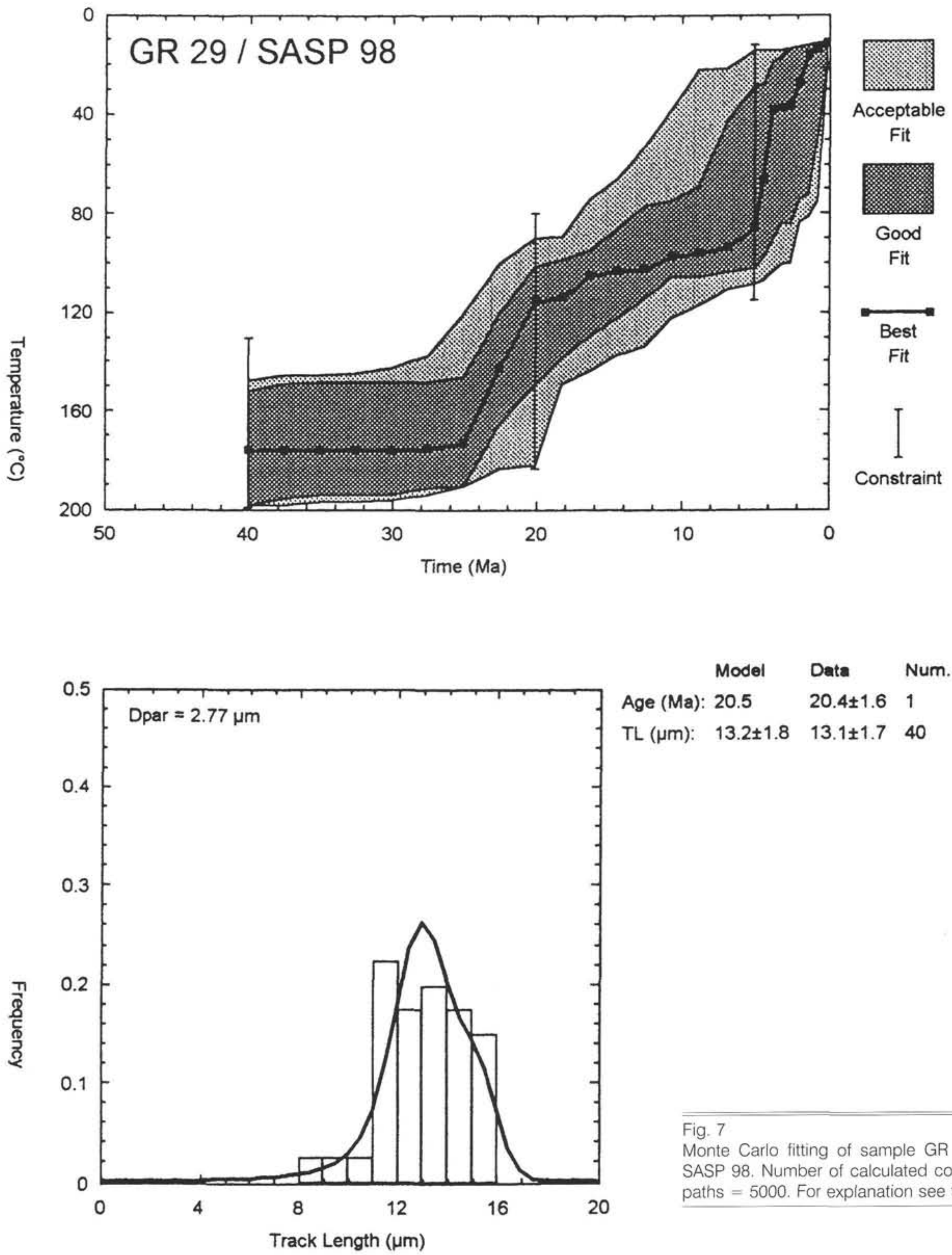
	Model	Data	Num.	G.O.F.
Age (Ma):	21.6	21.6±1.1	1	0.96
TL (µm):	12.9±1.8	13.0±1.6	120	0.84

Fig. 6
Monte Carlo fitting of sample GR 28 / SASP 97. Number of calculated cooling paths = 20000. For explanation see text.

erosion rates might be considered as maximum values for the samples with ages under 10 Ma.

The fission-track ages from western, central and eastern Skiathos are different at 2-sigma and even higher levels of significance. All four samples were taken at altitudes below 150 m (cf. Table 1). Such variation in altitude is rather small and cannot be the reason for the pronounced difference in fission-track ages. GR 25 and 30, for example, were taken at the same elevation of 110 m, but have very different ages of 12.6 and 7.1 Ma, respectively. In order to explain these age differences, we must assume that horst-graben tectonics have been active during the last 22 Ma. Central Skiathos had the strongest uplift and erosion rate. Therefore, it behaved as a horst with respect to western and eastern Skiathos.

In contrast to Skiathos, both samples from Skopelos yielded similar ages within the limits of error. They were taken nearly at the same altitude between 340 and 350 m. Similar

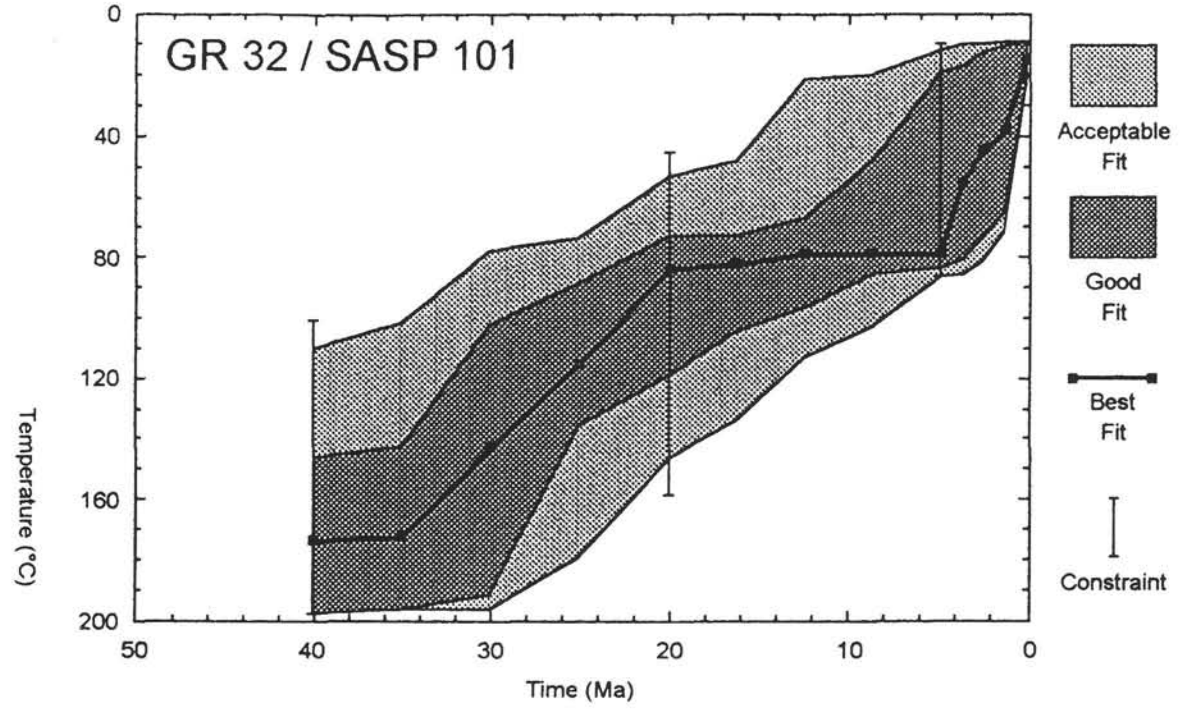


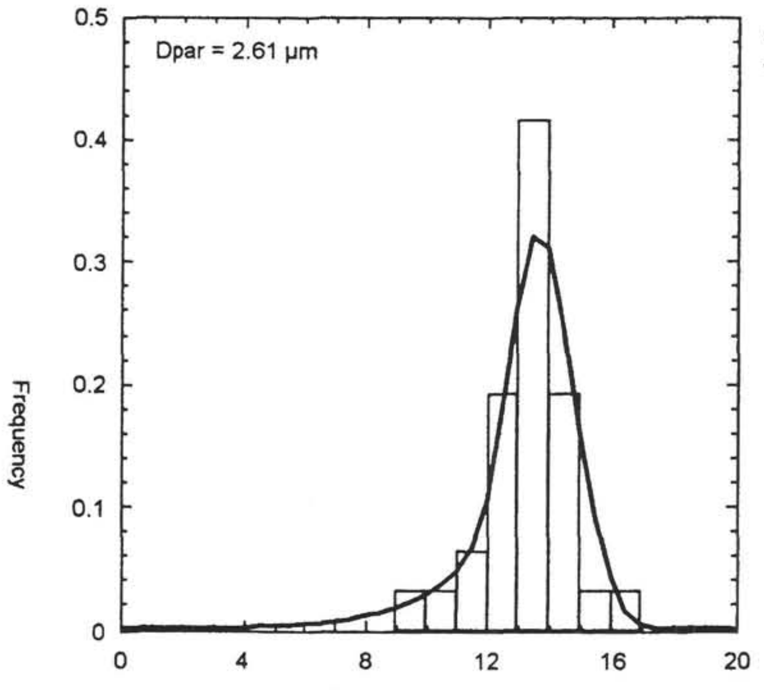
	Model	Data	Num.	G.O.F.
Age (Ma):	20.5	20.4±1.6	1	0.92
TL (µm):	13.2±1.8	13.1±1.7	40	0.99

Fig. 7
Monte Carlo fitting of sample GR 29 / SASP 98. Number of calculated cooling paths = 5000. For explanation see text.

cooling and erosion histories of central Skopelos and the Palouki peninsula since the middle Oligocene confirm a pre-Neogene thrusting of the Palouki unit onto the Mesoautochthonous rocks of central Skopelos. Afterwards, no important displacement has taken place, allowing the preservation of the generations of Neogene relief features at roughly similar altitudes on both sides of the thrust.

Temporal variations of cooling and denudation can be evaluated by modeling the measured age and the track length distribution of a sample. The range of thermal histories (temperature versus time) that are potentially consistent with the data of GR 28, 29, 32 and 34 are shown in Figs. 6, 7, 8 and 9, respectively. These models were obtained by a stepwise procedure. First runs were made with only few specifications and with a small number of calculated paths (< 2000). From run to run, we eliminated "hopeless" time-temperature areas by setting narrower constraints and we increased the number of calculated paths. By trial and error, we acquired final model





	Model	Data	Num.	G.O.F.
Age (Ma):	27.4	27.5±3.8	1	0.98
TL (µm):	13.3±1.8	13.3±1.3	31	0.95

Fig. 8
Monte Carlo fitting of sample GR 32 / SASP 101. Number of calculated cooling paths = 5000. For explanation see text.

specifications, which then were tested with a high number of calculated paths (5000 at least).

Model calculations for both samples from western Skiathos (GR 28 and 29) yielded broadly similar results (Figs. 6 and 7). They indicate stepwise cooling during the Neogene. After a cooling event at the Oligocene-Miocene boundary (i.e. between 25 and 20 Ma), the samples resided within a narrow temperature interval around 100°C until the late Miocene. At the Miocene-Pliocene boundary (i.e. around 5 Ma ago), cooling was accelerated again. This second phase of erosion seems to correlate with the subsiding North Aegean trough (Lybéris, 1984) and could be due to the emerging island configuration at its southern rift-shoulder. The small cooling step around 40°C (best fit of GR 29) could be an artifact of the model. Anyhow, western Skiathos must have experienced a total depth of erosion in the order of 3000 m during the last 20 Ma, and the present-day outcrop level was not close to the surface before the end of the Miocene. This statement seems

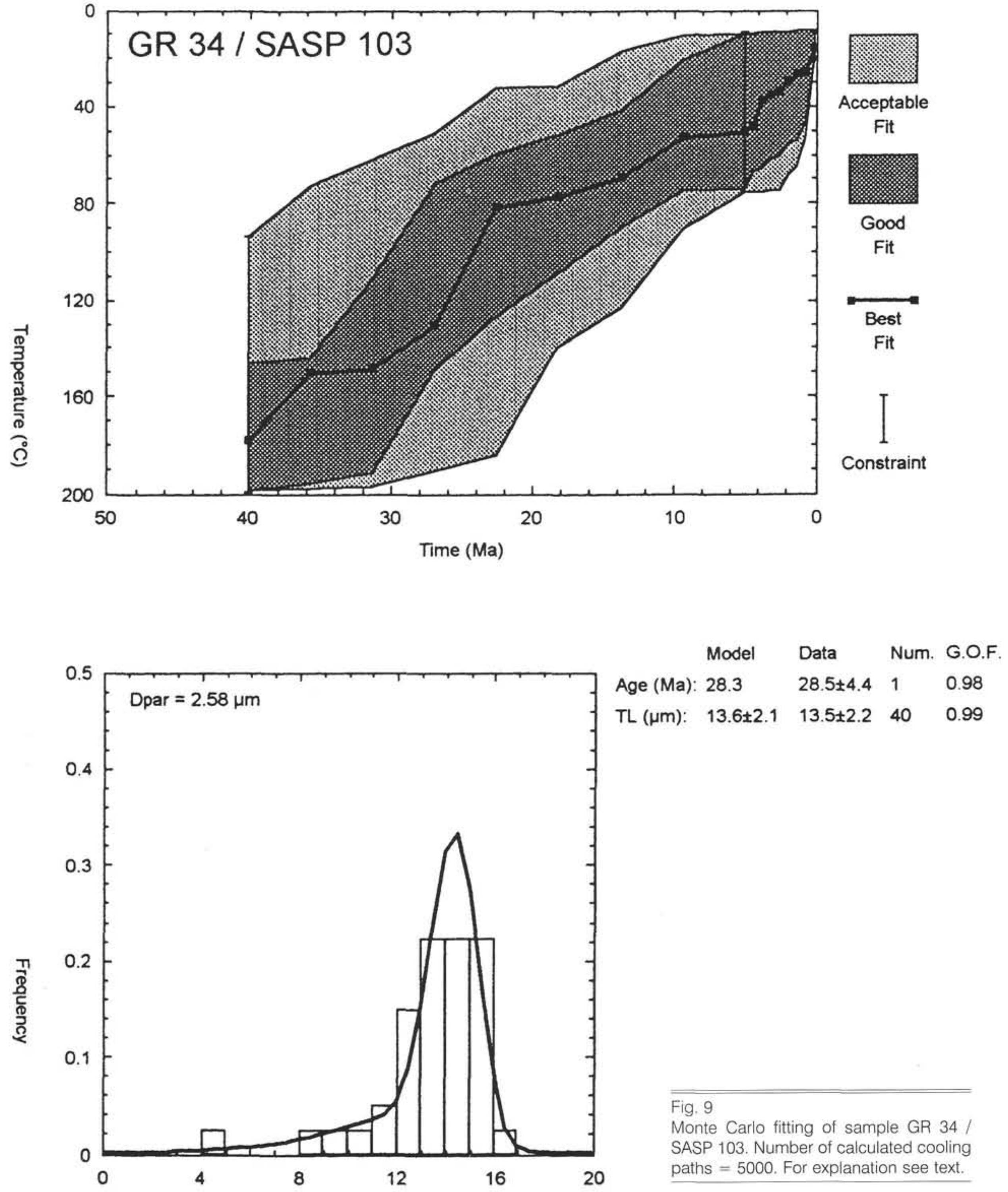


Fig. 9
Monte Carlo fitting of sample GR 34 / SASP 103. Number of calculated cooling paths = 5000. For explanation see text.

to be valid also for central and eastern Skiathos where even younger fission-track ages were measured. Therefore, we conclude that any remnants of pre-Pliocene relief generations should not be preserved on Skiathos (cf. WEINGARTNER, 1998).

Model calculations for the samples from Skopelos (GR 32 and 34) indicate rather steady cooling during the Neogene (Figs. 8 and 9). Accelerated post-Miocene erosion can not be excluded (best fit) but was probably less pronounced than on Skiathos. We do not emphasize the best fit below of 60°C because fission-track analysis is not very diagnostic in that temperature area. The present-day outcrop level could have been close to the surface around 10 Ma ago, i.e. in the middle Miocene. Thus, we may speculate that there can be preservation of pre-Pliocene relief generations.

GR 32 and 34 were taken at an altitude corresponding to planation system C, which displays a great morphological affinity with the flat surfaces of Mt. Ossa on Greek mainland (RIEDL, 1984). Level A, B and C were affected by neotectonic warping. The flexures strike from ENE to WSW and represent the youngest deformations on Skopelos (MATARANGAS, 1992). They were probably caused by dextral movements of the Aegean microplate with respect to the Eurasian plate (PAPANIKOLAOU, 1993). Such dextral strike-slip movements led to the formation of the North Aegean system of troughs, which are up to 6 km deep. The Miocene-Pliocene boundary marks a decisive period of tectonic fracturing in the evolution of the Sporades trough, which is closest to Skopelos (DEWEY & ŞENGÖR, 1979). This implies that levels A, B and C must have developed in pre-Pliocene times, whereas systems D and E turn out to be of Pliocene or Quaternary origin. Taking into account the thermochronological results, the age of planation system C can be narrowed to the time-span between approximately 10 and 5 Ma ago, i.e. to the Late Miocene (Tortonian and Messinian; cf. RÖGL, 1996). Planation system A and B are 200 and 100 m above level C, respectively. Such differences in altitude corresponds only to a small shift in the cooling path of the rocks. Assuming a normal geothermal gradient of 30°C/km, the cooling paths of level A and B would be shifted by 6 and 3°C with respect to the cooling path of level C. Thus, planation systems A and B can not be much older than 10 Ma (cf. Figs. 6 and 7).

7. Conclusions

The geomorphological evolution of North Sporades has been derived from field observations on palaeosoils and erosion surfaces, from stratigraphy and from the results of apatite fission-track analysis. The main characteristics of the relief history can be outlined as follows:

* *A Lower Cretaceous palaeokarst* developed on Triassic dolomites of the Pelagonian shelf and was sealed by bauxites and laterites which were derived from Eohellenic parent rocks (metabasalts, serpentinites and schists).
* *A second palaeokarst generation* developed on Upper Cretaceous rudist limestones and was buried under Palaeogene flysch deposits.
* *Three generations of Neogene planation surfaces* form the top levels of Skopelos Island at 550, 450 and 350 m altitude. At the Miocene-Pliocene boundary, they were partially affected by tectonic warping connected to increased subsidence of the Sporades trough. The age of these planation surfaces can be narrowed to the time span between approximately 10 and 5 Ma ago, i.e. to the late Miocene (Tortonian and Messinian).
* *Two pediment systems* occur on Skopelos at average altitudes of 200 and 120 m, respectively. They must be Pliocene or Quaternary in age.
* Any remnants of pre-Pliocene relief can be excluded for Skiathos and probably also for south-western Alonnisos. Skiathos was affected by Neogene *horst-graben tectonics*.

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