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Tectonometamorphic evolution of SE Tinos, Cyclades, Greece

by *Jano Stolz*[1], *Martin Engi*[1] and *Mathias Rickli*[1]

Abstract

The two main tectonic units of Tinos Island differ in their lithological contents and their metamorphic history. The present study investigates in some detail the tectono-metamorphic evolution and juxtaposition of these two main units on SE Tinos.

The upper unit is dominated by ophiolite members which show evidence of an early low-pressure (oceanic?) overprint. No high pressure relics are found in the upper unit, by contrast to the lower unit. The low-angle fault separating them, a normal fault in the interpretation of AVIGAD and GARFUNKEL (1991), remains difficult to interpret on the basis of our field data. However, the two main units show identical mesoscopic structural features (coaxial folds, parallel axial planar schistosities), and their regional medium-pressure greenschist facies overprint is very similar. Based on this evidence, we suggest a joint evolution of the two tectonic units since the mid-Tertiary (Oligocene?). Hence, the two units appear to have acted as a coherent stack during the subsequent thrusting event that emplaced them on top of the low-grade metacarbonates exposed in the Panormos window of northern Tinos. The timing of this emplacement remains unclear but it is likely to predate the intrusion (at a depth of 7 ± 2 km) of Miocene monzogranites in southern Tinos. Their contact aureole affects both the lower and upper unit rocks. During the final stages of uplift the contact at the base of the upper unit was reactivated, displacing the hanging wall to the N by some 500 m.

Greenschists of the lower unit (LU) and the upper unit (UU) are petrographically very similar. In the contact zone between the two units, mylonitic types prevail, and the precise location of the tectonic boundary is difficult to map. Geochemical data provide a means to distinguish greenschists of the LU from those of the UU. Furthermore, these data point to a range of source materials for the UU metabasic rocks: Besides the common MORB-affinity, more evolved ferro-gabbroid dikes occur, and a minor gabbro suite of boninitic character was identified, the significance of which is presently not understood.

Keywords: Cyclades, Tinos Island, metamorphic evolution, exhumation tectonics, ophiolite nappe.

1. Introduction

A large part of Greece is made up by the Hellenides, an Alpine orogen with nappe structure. In its central part lies the Median Crystalline Belt of Greece (DÜRR, 1986), which mainly consists of the Attic Crystalline Complex (ACC). The ACC represents a large-scale dome of crystalline basement surrounded by unmetamorphic nappes. The ACC extends over southern Attica, Evvia and the Cycladic Islands and is subdivided into a lower and upper main unit, each comprising several smaller nappes. The lower main unit consists of continental margin rocks (volcano-sedimentary schist, marble and minor meta-ultrabasite and meta-bauxite) that underwent at least two metamorphic cycles during the Tertiary (DÜRR, 1986). Subduction of the Apulian microplate led to blueschist and eclogite facies metamorphism in the Eocene, prior to greenschist facies (and locally higher grade, e.g. on Naxos) overprint at the turning of Oligocene to Miocene (ALTHERR et al., 1979 and 1982; SCHLIESTEDT et al., 1987). The upper main unit consists of Permo-Mesozoic sediments, Cretaceous ophiolite fragments and Eocene molasse deposits; these did not experience any Tertiary metamorphism. They lie as erosional remnants on top of the lower main unit (DÜRR, 1986; PATZAK et al., 1994). Several granitoid stocks intruded the ACC in the Miocene (ALTHERR et al., 1982).

Tinos Island is surrounded by Andros, Myko-

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nos and Syros Islands (Fig. 1). MELIDONIS (1980) distinguishes two tectonic units on Tinos Island; a lower unit (LU) that belongs to the lower main unit of the ACC, and an upper unit (UU) comprising ophiolite members. The LU consists of continental margin rocks (volcano-sedimentary schist, minor marble). These rocks underwent Eocene subduction with metamorphism at > 40 km depth, prior to pervasive, fluid-driven retrogression associated with emplacement into higher crustal levels. Locally, this lower unit (LU) is overlain by an ophiolite unit (serpentinized harzburgite, metagabbro, greenschist, ophicarbonate) lacking high pressure relics. The earliest metamorphic relics of the upper unit (UU) in southeastern Tinos are of low-pressure greenschist facies, likely of oceanic origin; no high-pressure event is recorded (KATZIR et al., 1996). AVIGAD and GARFUNKEL (1989) propose a third, basal unit of weakly metamorphosed sediments exposed only in the Panormos window of northwestern Tinos (Fig. 2). In eastern Tinos, this nappe structure was intruded by a monzogranite stock of Miocene age (ALTHERR et al., 1982). At its western border, a tungsten occurrence (scheelite) was prospected (PAPASTAVROU and PARITSIS, 1990).

Owing to the overall situation of Tinos Island, the structural and metamorphic evolution of its main tectonic unit (LU), containing notable high-pressure relics, has received much attention (AVIGAD, 1990; BRÖCKER, 1990 a, b). Specifically, the eclogites and blueschists, as well as the blueschist-to-greenschist transition that affected most of the rocks of the lower unit, have been investigated petrologically and geochemically by BRÖCKER (1990 a, b and 1991) and BRÖCKER et al. (1987 and 1993). Until recently (PATZAK et al., 1994; KATZIR et al., 1996), few details were known on the upper nappe (UU), and its relations to the LU remain obscure. Whereas PATZAK et al. (1994) studied only an isolated exposure of the UU (Akrotiri, near Tinos Chora, Fig. 2), KATZIR et al. (1996) in-

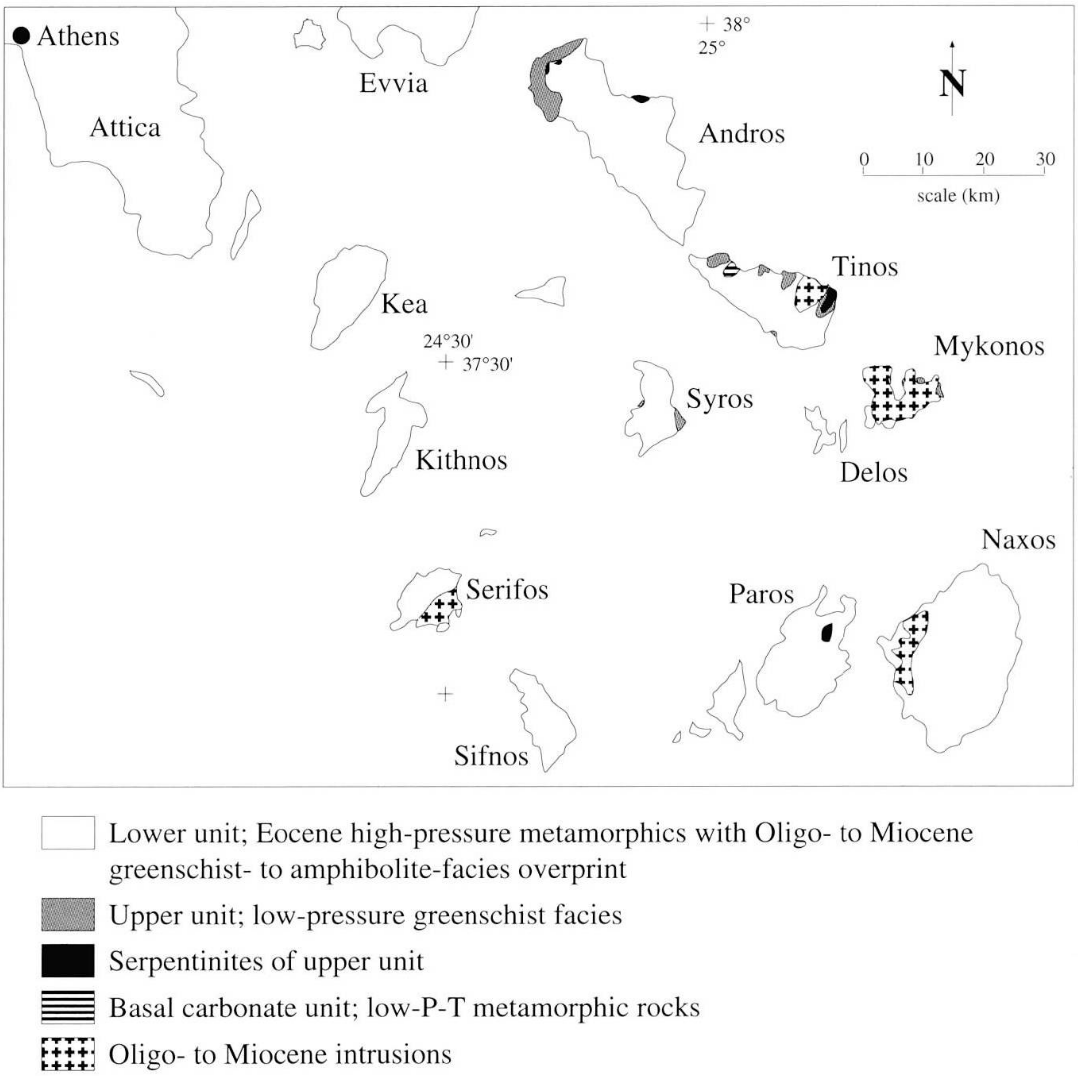

Fig. 1 Regional view of the central Aegean Islands; only major units are shown.

vestigated samples from several erosional klippen of the UU on Tinos. The former study established a minimum age of 77 Ma for the mafic ophiolite members, the latter worked out an evolutionary history of the UU from the early oceanic stage through the emplacement on top of the LU. Finally, recent work by GAUTIER and BRUN (1994 a, b) has concentrated on the tectonic exhumation of several Aegean Islands, including Tinos.

The present investigation focuses on southeastern Tinos, where the UU is dominant, and where its relations to the LU can be studied. Particular emphasis is given to the nature and (relative) timing of the juxtaposition between LU and UU, and to the succession of their tectono-metamorphic evolution.

2. Scope and Methods of Study

In the area around the Tsiknias ridge, detailed field work was undertaken, including geological mapping (1:10'000) of some 20 km^2 (Fig. 4), structural analysis, and extensive sampling (Fig. 3). Subsequent petrological work included the study of some 164 thin sections, some 533 analyses on 11 samples by electron microprobe (EMP), and geochemical analysis of 60 samples by XRF methods. Analytical details follow:

- EMP
  Cameca SX-50, University of Berne.
  15 kV, 20 mA, beam diameter ~1–2 µm,
  10 sec. integration on peaks, 5 sec. on background.
  Natural and synthetic mineral standards were used.
  Full ZAF correction was applied.

- XRF
  Philips X-ray spectrometer, University of Lausanne.
  Major elements:
  Fused pellets 1:5 = sample : Li-tetraborate

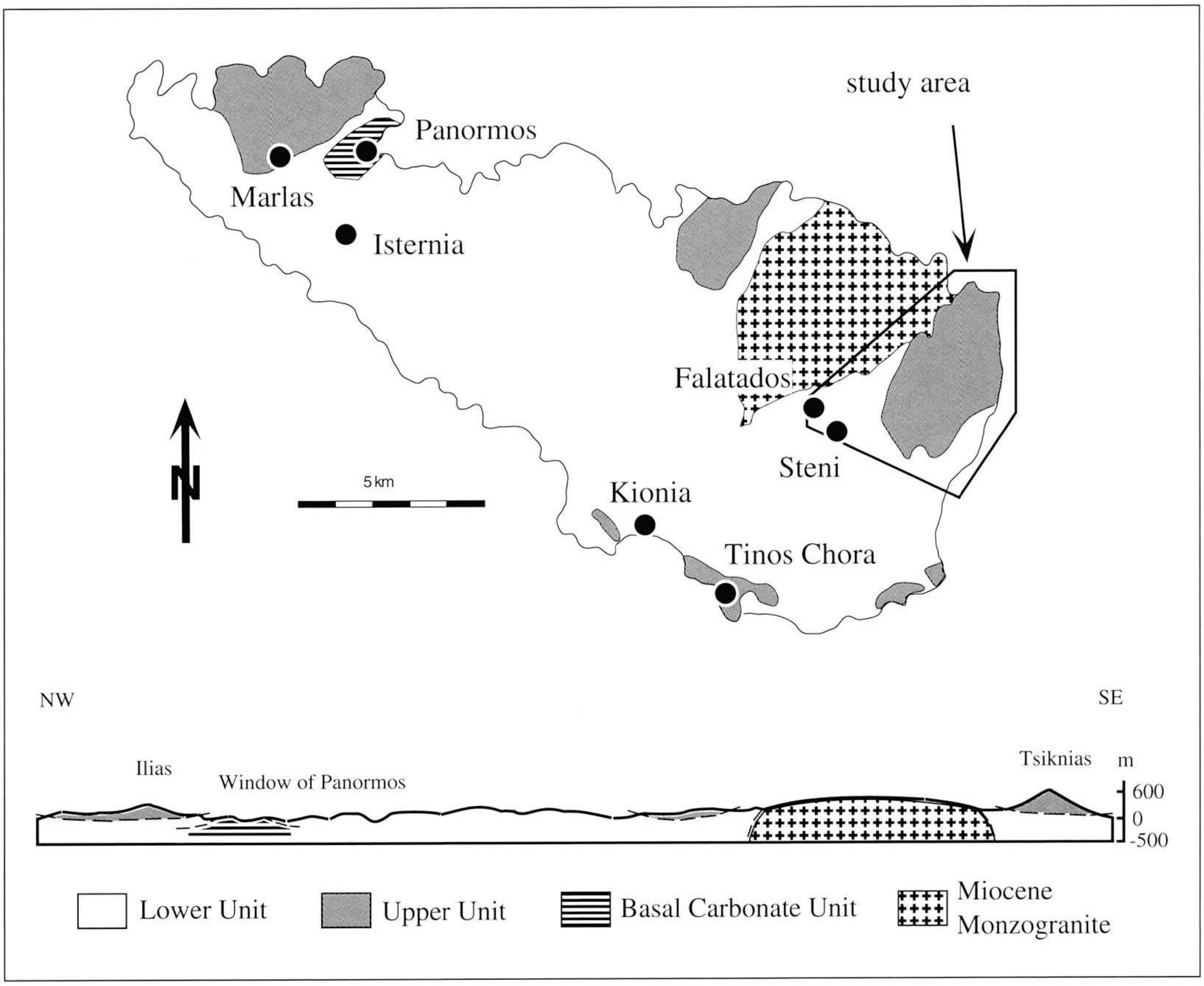

Fig. 2 Geological sketch map and profile of Tinos Island, simplified after AVIGAD (1990).

Trace elements:
Pressed powder pellets.

Table 1 shows representative geochemical data of the metabasites. A complete list of mineral (EMP) and bulk chemical (XRF) analyses is available from the second author upon request. A machine-readable repository is retrievable under http://www.earthsci.unibe.ch/

3. Tectonic units in SE Tinos

The investigated area is characterized by the weakly inclined (normal?) fault that separates the lower unit in the southwest from the upper, ophiolite unit in the northeast (Fig. 4). Both metamorphic nappe units were penetrated by a monzogranite stock as well as associated dikes, the thermal overprint of which caused a contact aureole.

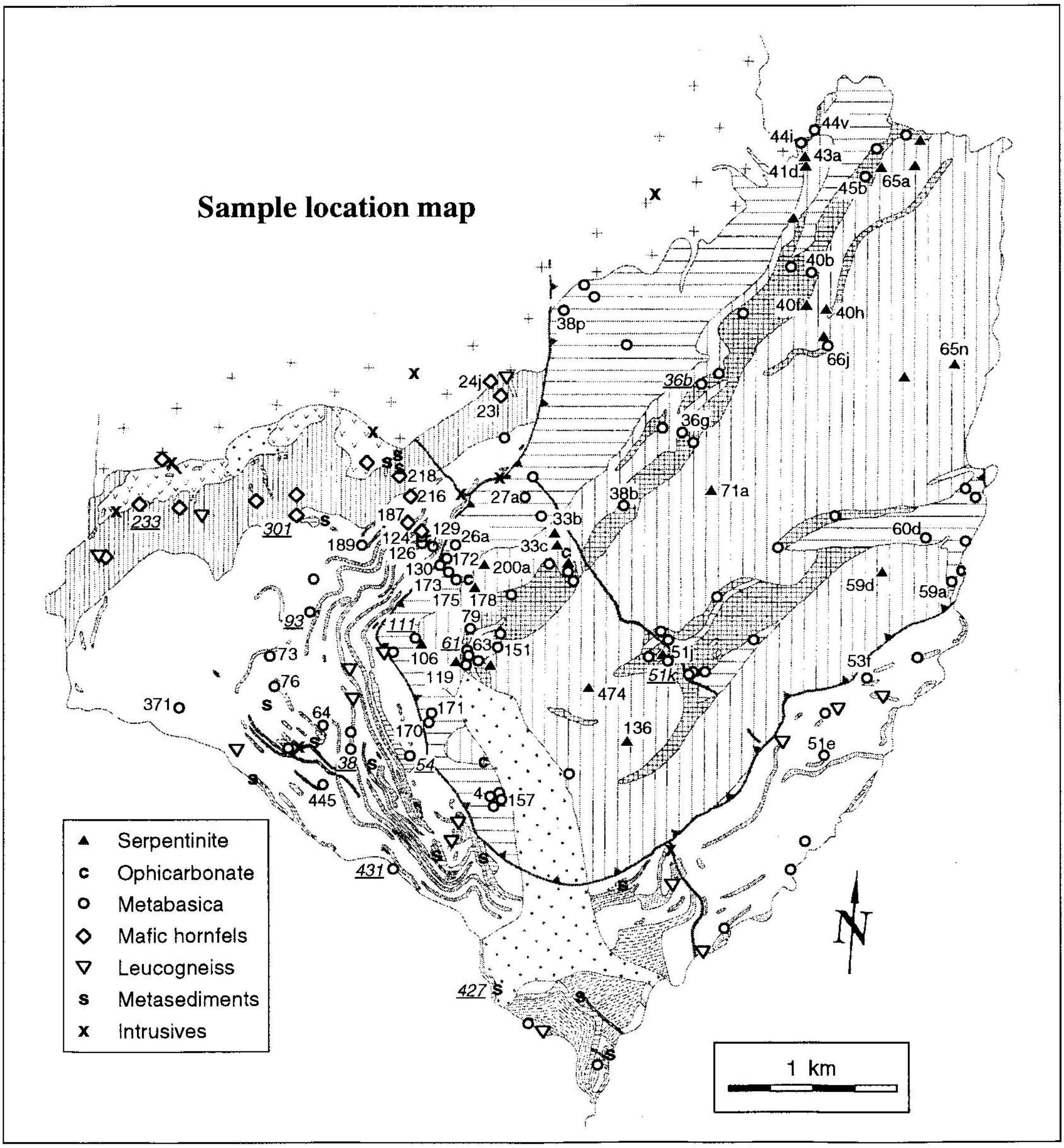

Fig. 3 Sample location map. Numbers indicate samples selected for XRF and <u>microprobe</u> study.

Tab. 1 Representative geochemical data of metabasites.

	Greenschist (LU)			Greenschist (UU)				Metagabbro		
Samples	431	371	24j	4	171	172	38p	151	51k	66j
SiO_2	48.71	51.73	48.66	47.05	49.22	49.80	49.25	48.95	52.54	42.87
TiO_2	0.96	1.00	0.98	1.44	1.76	2.23	1.07	1.28	0.45	1.40
Al_2O_3	16.55	18.63	15.52	14.05	16.11	14.51	17.45	17.00	6.14	15.98
Fe_2O_3	10.02	9.44	9.73	9.16	9.97	11.22	7.89	8.87	8.70	11.78
MnO	0.15	0.12	0.18	0.16	0.16	0.18	0.13	0.13	0.15	0.20
MgO	8.57	5.60	4.11	9.13	6.04	7.23	8.00	8.18	17.05	7.85
CaO	8.39	5.54	15.94	10.03	11.05	10.15	10.53	9.17	11.09	17.29
Na_2O	3.06	4.02	2.90	2.53	3.02	3.22	4.10	3.03	1.29	0.08
K_2O	0.12	2.76	0.28	0.01	0.14	0.07	0.16	0.18	0.07	0.10
P_2O_5	0.15	0.12	0.11	0.18	0.19	0.24	0.09	0.10	0.03	0.36
Cr_2O_3	0.05	0.02	0.06	0.03	0.03	0.03	0.05	0.06	0.23	0.03
NiO	0.02	0.01	0.02	0.03	0.01	0.01	0.02	0.02	0.03	0.02
L.o.I.	3.10	0.99	0.78	5.88	2.23	0.93	0.81	2.83	2.15	1.97
Sum	99.85	99.98	99.27	99.68	99.93	99.82	99.55	99.80	99.92	99.93
Nb	0	0	0	0	0	0	0	0	0	18
Zr	61	81	52	113	133	188	54	84	0	89
Y	19	19	18	25	38	48	20	26	11	27
Sr	178	161	329	153	310	146	248	218	60	531
U	0	0	0	0	0	0	0	0	0	3
Rb	4	57	5	0	6	0	0	10	0	4
Th	0	4	0	0	0	0	0	0	0	2
Pb	0	0	0	0	0	0	0	0	0	0
Ga	14	18	15	13	18	19	16	14	6	21
Zn	60	94	91	81	78	104	66	73	55	141
Cu	63	104	60	37	41	35	23	53	0	0
Ni	123	56	114	199	89	100	123	118	245	108
Co	44	28	44	45	39	46	37	40	48	54
Cr	308	143	388	218	218	212	321	373	1665	239
V	246	179	164	190	258	307	184	200	250	243
Ce	21	34	13	24	0	23	0	0	0	28
Nd	10	14	9	10	7	21	8	10	2	14
Ba	0	179	19	0	0	0	0	0	0	7
La	5	8	0	0	0	3	0	0	0	7
S	110	66	109	70	88	76	77	65	164	150
Hf	0	0	0	0	0	0	0	0	0	0

Oxides in weight-%; trace elements in ppm. Total Fe shown as Fe_2O_3.
L.o.I. = weight loss on ignition

Description of samples
Greenschist (LU): 431: no overprint / 371: weak contact metamorphic overprint / 24j: hornfels
Greenschist (UU): 4 + 171: no overprint / 172: weak contact metamorphic overprint / 38p: hornfels / 4 + 38p: low TiO_2-type / 171: medium TiO_2-type / 172: high TiO_2-type
Metagabbro: 151: MORB-type / 51k: boninitic type / 66j: ferro-gabbroid dike

3.1. THE LOWER UNIT (LU)

The lower unit consists of volcano-sedimentary schists, including mappable members of greenschist (identified here with the label "LU" to distinguish them from strikingly similar rocks of the UU), silver-grey calcareous mica schist and leucogneiss (meta-acidite according to BRÖCKER, 1991), as well as minor marble. In these members, textures can be rather similar, and gradational changes (e.g. in their calcite contents) occur in the mineral assemblages among these lithologic types. Their identification and separation in mapping is further complicated because they are commonly repeated at a scale from decimeters to tens of meters, with laterally variable thickness owing to primary sedimentary and/or tectonic processes. Table 2 gives a short description of the LU litholo-

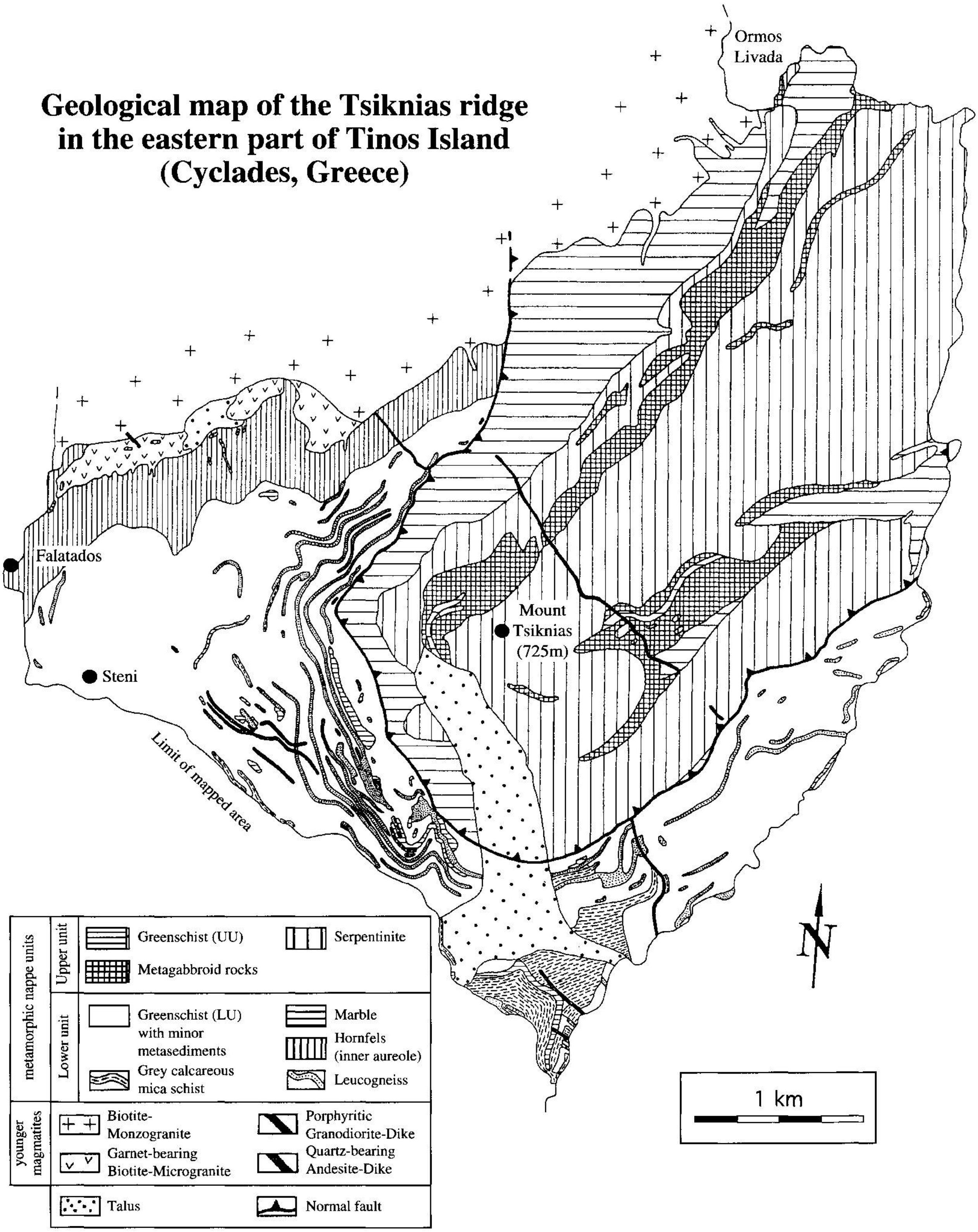

Fig. 4 Detailed geological map of Tsiknias ridge in the eastern part of Tinos Island. Simplified after RICKLI (1994) and STOLZ (1994).

Tab. 2 Lithologic members of the Lower Unit (LU). Abbreviations according to KRETZ (1983).

Lower Unit (LU)	Greenschist (LU)	Chl-Bt-Ep-Act-Ab schists and gneisses; accessories: Qtz, Ms, Ttn, Tur, Mag, Ilm, Py and Hem; medium grained; Ep-Ms as well as Cal-rich layers and lenses are frequent; nemato- to fibroblastic texture; Chl, Bt and Act parallel to schistosity, Ep- and Ab-porphyroblasts may overgrow other minerals; dark to brownish green color; High pressure relics: Grt (often Chl pseudom. after Grt) and rare crossite
	Grey calcareous mica schist	Graphite-bearing Chl-Bt-Cal-Ms-Qtz-Ab phyllites and schists; accessories: Ttn, Tur, Ap, Ep, Hem, Ilm and Py; silver to bluish grey, often crenulated, Cal-rich layers and lenses are frequent; lepidoblastic texture with Ab-porphyroblasts; High pressure relics: Grt (often Chl pseudom. after Grt) and rare crossite
	Leucogneiss	Chl-, Bt- and Ep/Czo-bearing Ms-Ab-Qtz gneisses; accessories: Ap, Ttn, Cal, Py, Hem and Mag; schistosity defined by micas; texture dominated by elongated Qtz- and Ab-grains; creamy to brownish grey color; High pressure relics: Garnet (Chl pseudomorph after Grt less frequent)
	Marble	Qtz- and Ms-bearing dolomite and calcite marbles; accessories: Py, Hem, Bt, Chl, Ttn, Ab, Ep/Czo and Tur; coarse-grained, crystalloblastic texture, twin lamellae are frequent; white to grey, dolomites creamy color; no high pressure relics observed
	Hornfelses of inner aureole	Bt-Hbl-Pl (dark to blackgreen) and Cpx-Qtz-Pl hornfelses (applegreen); Ep-Pl-Cpx-Grt skarn veins new minerals in basic rocks: Pl, Hbl, Cpx, Bt, Mag; Grt and Ep in skarns disappearing minerals: Ms, Chl, Ab, Act; Ep in hornfels chaotic, heteroblastic and parallel textures; mostly static recrystallisation

gies. Whereas in southern and northwestern Tinos blueschist and eclogite assemblages occur in a few locations, high pressure relics in the area studied here are restricted to sporadic and isolated mineral grains or subgrains (e.g. crossite cores).

3.2. THE UPPER UNIT (UU)

Metabasites and ultrabasites make up the UU. The base of the unit consists of greenschist (UU), in part phyllitic, with a thickness of up to 200 m. In all likelihood, all of these mafic schists derive from gabbroid precursors, the coarse grained fabric of which is, in this lower part of the section, preserved only in local lenses (labelled "amphibolite" by KATZIR et al., 1996, p. 240). A lower serpentinite layer, up to 100 m thick, and a 50 m thick sequence of metagabbro follow, the base of which shows again intense plastic deformation ("pyllonite" in the simplified section of KATZIR et al., op.cit.). Ophicarbonates, as tectonic breccias, and rare talc lenses are intercalated between the greenschists (UU) and the lower serpentinite member. Overlying the metagabbro band and forming the entire crest of the Tsiknias ridge is a second serpentinite member.

Table 3 gives an overview of the lithologic types of the UU. Though strongly deformed, it is tempting to see in this section members of a (gabbro + peridotite) base of an ophiolithic sequence, partially dismembered and inverted by thrusting, that underwent greenschist facies metamorphism (see also KATZIR et al., 1996). On the east side of Tsiknias ridge, where the greenschists (UU) are largely missing, the simplified sequence described above appears imbricated and repeated by duplex-like internal tectonics.

Tab. 3 Lithologic members of the Upper Unit (UU).

Upper Unit (UU)	Serpentinite	Main min.: Atg, Ol; access.: Cpx, Mag/Chr, Tlc, Mg-Chl, Hem + rare Opx; magmatic relics: Cpx (often altered to Tr or Chl), Atg and Tr pseudomorph after Ol and/or Opx; diablastic and/or mesh texture; contactmetamorphic overprint: Ath, Tr, Di, Ol and Ctl and metasomatic Mgs, Ank and Tlc; black to dark bluegreen color, reddish brown when Fe-rich; rare chromite cumulates and talc lenses
	Ophicarbonate	Main min.: Atg, Mgs or Cal and Dol; access.: Tlc, Chl, Mag/Chr, Hem and rare Cpx; Mgs pseudomorph after Cpx or Ol; diablastic texture; white and dark bluegreen to black spotted appearence; tectonic breccias mainly between serpentinites and greenschists (UU)
	Metagabbroid rocks	Heterogeneous rock assemblage; Cpx often as Act ±Chl-pseudomorphs; Metagabbro: Act with Hbl-cores, Ab and Oligoclase; access.: Ep, Chl, Ttn, Mag, Hem and very rare Cpx-relicts; granoblastic texture; Cataclasite: chaotic texture with broken Cpx-relicts and Act, Ab, Chl + Ep; scaly fracture; white and green-black spotted appearence; occasionally gneissic to mylonitic, leucocratic lenses with high Ab-, Qtz- and sometimes high Ms-content occur; contactmetam. overprint: Act with Hbl-rim + Oligoclase; diablastic texture; continuous transition to greenschists (UU) when strongly deformed
	Greenschist (UU)	Chl-Ep-Act-Ab schist; accessories: Qtz, Bt, Ms, Ttn, Mag and rare Cal, but no Grt; magmatic relics: rare cores of light green Hbl in Act; olivegreen to dark green color; fine grained with well developed schistosity; sometimes mylonitic; fibro- to nematoblastic texture with stringy aggregates of recryst. Ab and Qtz; contactmetam. overprint: recryst. green Hbl and oligoclase, Ep-Pl-Cpx-Grt skarn veins

3.3. INTRUSIVE ROCKS

The granite stock of SE Tinos Island has a diameter of about 5 km and largely consists of a biotite monzogranite. In the area mapped, a finer grained and locally garnet-bearing border facies developed within 200–300 m of the intrusive contact. Where dominant, this garnet-bearing biotite microgranite has been distinguished on the map (Fig. 4). ALTHERR et al. (1982) and HENJES-KUNST et al. (1988) describe the biotite granite as I-type granite with an intrusion age of 17–19 Ma and the microgranite as S-type granite with an age of 14 Ma. In the field, the transition between the two granite types appears to be more or less continuous; sharp contacts are only rarely visible. Extensive exfoliation and block formation along joints is typical of both these granites. Within the microgranite, hornfels blocks up to 30 m in size occur; these may in part be roof pendents of the intrusion. Subvertical, dark green andesite dikes show sharp, discordant contacts to the rocks they intruded; the dikes are prominent owing to their resistance to erosion. They have been found only in the LU. Their relative age compared to the granites is unknown, since they have never been observed in contact with the granite or in the UU. However, as the dike rocks show no sign of metamorphism, they are likely to be younger than the granites yet. A granodiorite porphyry dike, up to 5 m wide and with a grey appearance, intruded the LU and UU as well as the granite stock; it appears to be the youngest member of the intrusive suite, although direct crosscutting relations with the andesitic dikes could not be observed. The granodiorite dike shows brittle to weakly ductile deformation only along the contact of the LU and UU, indicating a reactivation of the main fault (see below). Table 4 gives an overview of the intrusive rocks.

Tab. 4 Intrusive rocks of the Tsiknias area.

Intrusive rocks	Biotite Monzogranite	Main minerals: Qtz, Pl, Kfs and Bt; accessories: Hbl, Ttn, Ms, Mag, Ap and Aln; medium to coarse grained, locally weakly deformed; darker appearence than microgranite due to higher Bt- and Hbl-content; Qtz weakly deformed, feldspars occasionally broken; Kfs shows perthitic dissolution and microcline twinning; Ab to Olig. myrmekitic; Hbl alters to Bt
	Microgranite	Main minerals: Qtz, Pl, Kfs and Bt; accessories: Grt, Ms, Mag and Zrn; fine to medium grained, close to hornfelses often gneissic; brighter appearence than Bt-granite; contains red Grt but no Hbl; Qtz is often elongated and the feldspars are broken; myrmekitic Pl and microperthitic dissolution in Kfs is occasionally observed
	Andesite Dike	Magmatic minerals: Pl, 2 Hbl generations, Qtz and Kfs; secondary alteration: Chl, Ep, Cal and Hem; fine grained, olivegreen matrix with small Pl-, Qtz- and Hbl-porphyroblasts; intersertal texture defined by Pl and Hbl; dm to 4 m wide; never observed within granite or Upper Unit
	Granodiorite Dike	Magmatic minerals: Qtz, Pl, Kfs, Hbl, Bt, Mag, Ttn and Zrn; secondary alteration: Chl and Ep; medium grained, grey matrix with white Pl-porphyroblasts and black Hbl; zoned plagioclase crystals, some with myrmekitic textures; 1 to 5 m wide; dissects Lower and Upper Unit as well as both granites

3.4. STRUCTURAL FEATURES AND TECTONIC CONTACTS

The intercalation of greenschist, calcareous mica schist, quartzofeldspathic leucogneiss, and marble in the deci- to decameter range is characteristic for the lithologic members of the LU. All of these show a more or less strong foliation and folding.

The penetrative, bedding-parallel schistosity is axial planar to a first phase of isoclinal folding, with associated local boudinage (meters to decameters in scale), notably of some calcite marble members. A second phase of folding, coaxial to the first, produced larger scale open folds and an associated crenulation schistosity; the latter is especially well developed in calcareous mica schist. (The second stage of deformation under greenschist facies conditions is followed by a post-kinematic, static recrystallization, especially of albite.)

In the LU, AVIGAD (1990) and BRÖCKER (1990b) attribute both of these deformation phases to the Eocene high-pressure event. However, two observations indicate that at least some of this deformation should be attributed to an early phase of the greenschist facies regional event: First, fold axes and schistosities in the LU greenschist and leucogneiss are oriented identically to those in the UU (Fig. 5), for which there is no sign of a high-pressure overprint. Second, in comparable rock types, notably metabasites, all structural features visible in the LU and UU are strikingly similar. We will show below that these deformations and the greenschist facies overprint were likely associated with the formation of the nappe stack during exhumation. Whereas OKRUSCH and BRÖCKER (1990, p. 455) state that "there is no conclusive evidence for an extensive penetrative deformation during the overprint which was characterized predominantly by static recrystallization", we do find it difficult to explain the identical meso- and micro-structural features of LU and UU greenschist as well as their strikingly similar metamorphic assemblages in any other way than by a penetrative deformation / reequilibration event they experienced jointly. The mutually enhancing effects of plastic deformation, local fluid mobility, and retrograde chemical reactions all appear to have worked together to produce the observed strong overprint.

The different lithologic members of the UU responded in different ways to the strain they experienced. The serpentinites behaved as massive, rigid blocks separated by a net of randomly orientated joints and shear zones. These presumably accomodated most of the deformation and are now filled by secondary serpentine. Pervasive early serpentinization has obscured nearly all primary magmatic structures. The gabbroid rocks vary from undeformed, even-grained to foliated to mylonitic or cataclastic. Greenschists (UU) show a well developed schistosity and are often strongly folded. The axes of the mostly isoclinal folds are parallel to the NW–SE striking foliation and show the same orientation as the fold axes within the LU. Larger, open folds (up to 100 m-scale) are observed especially in the SE. Mineral strain lineations are interpreted to originate from the emplacement of the UU above the LU and are parallel to the fold axes. This may result from the rotation of the fold axes into the shear direction as suggested by URAI et al. (1990) on Naxos.

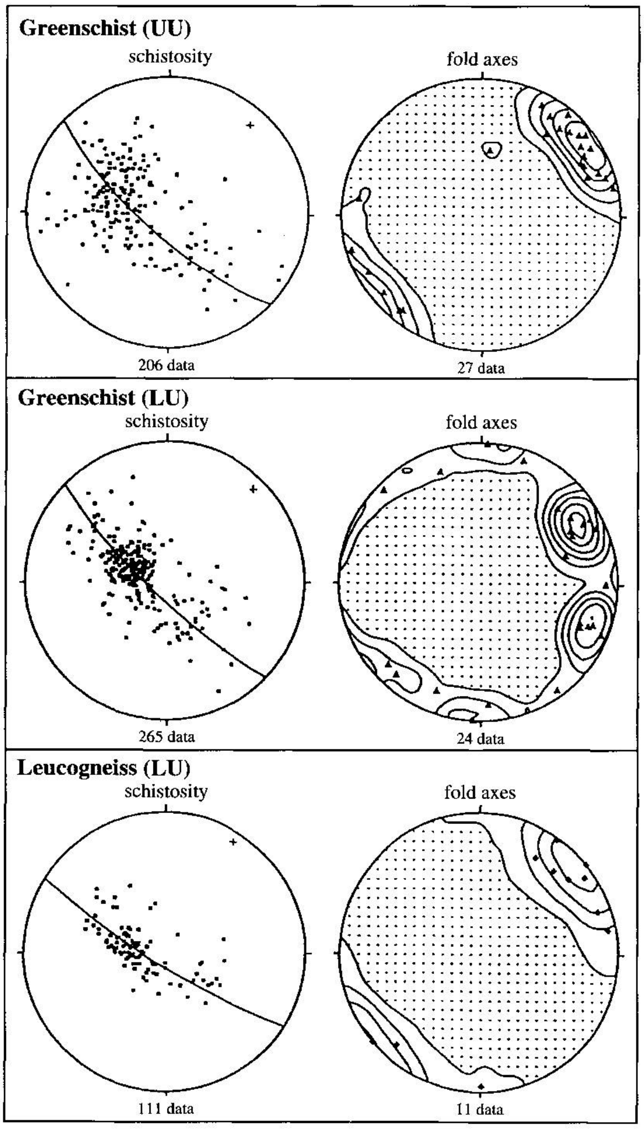

Fig. 5 Stereographic projections of foliation poles and fold axes of greenschists UU and LU and leucogneiss (LU). Corresponding structures in the two units are oriented identically.

Though in the area covered by the present study, high-pressure mineral relics have only been rarely found in thin sections, evidence elsewhere in the LU of Tinos shows that the LU was subducted to depths > 40 km. The overlaying ophiolite body reached greenschist facies conditions only. Because of this jump in the grade of metamorphism and the flat lying tectonic contact between the two units, AVIGAD and GARFUNKEL (1989) interpret this contact to represent a low-angle normal fault. However, on the basis of our field data, the nature of this tectonic contact and its kinematic role remain difficult to interpret. In general agreement to data presented by GAUTIER and BRUN (1994 a, b), the shear (postdating the granite intrusion) established by the displacement of a granodiorite dike indicates a NE-vergent reactivation of the fault zone separating LU and UU. In the contact zone between the two units, mylonites prevail, and the precise location of the tectonic boundary is often difficult to map, especially where the two greenschist (LU and UU) members meet. AVIGAD and GARFUNKEL (1989) attributed the uppermost leucogneiss horizons to the UU, because they observed magmatic zoning in plagioclase which should have been obliterated during high-pressure metamorphism. (This reasoning assumes that the rocks had reached eclogite grade, i.e. passed an omphacite transition.) However, we could neither locate a major shear or fault zone below the leucogneiss unit nor did we find any relic igneous plagioclase zoning within it. On the other hand, there is a striking shear zone between greenschists of the LU and those of the UU, and samples from these two metabasic units are petrographically and geochemically distinct (see chapter 5.1). Talc lenses occur commonly intercalated at the tectonic contacts of the two greenschist units and between UU greenschist and serpentinite. The latter contacts as well as the shear zone with ophicarbonates at the base of the serpentinites demonstrate internal imbrication of the UU. A profile of the contact zone is given in figure 7.

4. Metamorphic evolution

4.1. THE LOWER UNIT (LU)

The rocks of the LU, as part of the lower main unit of the Attic-Cycladic crystalline complex (ACC), underwent Eocene subduction, when pressures of at least 10–12 kbar were reached (BRÖCKER, 1990b). As mentioned above, neither blueschist nor eclogite facies assemblages are found within the study area, since these rocks have been subjected to pervasive, fluid-driven retrogression, so that only Na-Ca-amphiboles and garnet can be observed as relics. Thin sections show rare, millimeter long amphiboles, the optical properties of which identify crossite. They are commonly engulfed by calcite and albite; where in contact with epidote they disintegrate to chlorite. Microprobe data yield mostly barroisitic compositions (Fig. 6). These blue-green amphiboles are interpreted to represent a transition stage of the blueschist-greenschist transformation, where among others the following reactions have occurred (BRÖCKER, 1990b):

Glaucophane + H_2O -> Albite + Chlorite ± iron oxide

Glaucophane + Epidote -> Albite + Ca-Amphibole + Chlorite + iron oxide + H_2O

Crossite + Epidote -> Chlorite + Calcite

Garnet, commonly transformed in part to chlorite and/or biotite, has an almandine- and grossular-rich composition, as it is observed in garnets of the blueschists and eclogites on southern Tinos Island (BRÖCKER, 1990b). Phengite of the calcareous mica schists shows 6.7 to 7.2 Si per formula unit. These and other observations made by BRÖCKER et al. (1993) point to incomplete equilibration of white mica during greenschist facies metamorphism.

At the turning of Oligocene to Miocene (ALTHERR et al., 1982), uplift into higher crustal levels led to the extensive greenschist facies retrogression of the rocks of the LU. Bedding-parallel, continuous transition of blueschists to greenschists, as observed on southern and northwestern Tinos Island, point to a channelled infiltration of a syn-

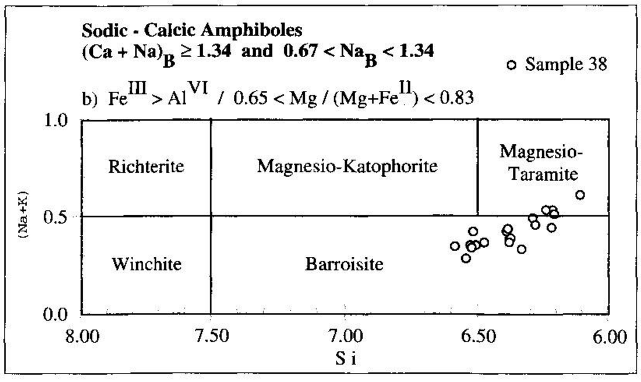

Fig. 6 Amphibole classification scheme after LEAKE (1978) for blue-green amphibole relics in greenschist (LU).

metamorphic fluid that controlled the transformations to greenschist facies (BRÖCKER, 1990a, BRÖCKER et al., 1993; GANOR et al., 1989, 1991, 1996). Within the Tsiknias area, the following greenschist facies assemblages are observed:

greenschist (LU):
Albite-Actinolite-Chlorite-Epidote
± Quartz ± Calcite ± Titanite ± Biotite ± Phengite

calcareous mica schist:
Albite-Quartz-Phengite-Biotite-Chlorite
± Epidote/Clinozoisite ± Calcite

leucogneiss:
Quartz-Albite-Phengite
± Biotite ± Epidote

Microprobe data confirm the mineral compositions of the amphibole and plagioclase, as actinolite and pure albite, respectively. A determination of the greenschist facies P-T-conditions is difficult, not least because of the incomplete re-equilibration of the assemblages. However, adjacent garnet-chlorite pairs in a calcareous mica schist sample give consistent K_D(Fe–Mg) and indicate temperatures ~ 450 °C for an assumed pressure of 3 kbar (see chapter 4.2.), in good agreement with oxygen isotope thermometry of quartz-magnetite (440–470 °C, BRÖCKER et al., 1993).

– *Contact metamorphism*

The intrusion of granitoid stocks in the Miocene produced a contact metamorphic overprint of the rocks in the Tsiknias area. BRÖCKER and FRANZ (1994) investigated the aureole in detail and were able to delineate several mineral zones. In the present study, the thermal effects have been studied less systematically and only in parts of the aureole. Our results are portrayed in a synthetic profile of some 1200 m width (Fig. 7) across the aureole; six zones were recognized in metasediments (notably of variable composition) and basic rocks. While the innermost four of these zones could not be mapped out, suitable mafic samples investigated from what is here labelled the "outer aureole" (Fig. 7) consistently show the phenomena typical of zone 1 (desintegration of epidote, white mica, and chlorite, and finally disappearance of the latter) and zone 2 (hornblende rims around actinolite, recrystallization of biotite). Discrete Grt-Cpx skarns have been repeatedly observed in the inner parts of the aureole, as have hornfels assemblages of Bt-Hbl-Pl, Cpx-Qtz-Pl and, in calcsilicates, again Grt-Cpx. As reported by BRÖCKER (1990b), epidote disappears within hornfels close to the granite, according to the reaction Ep + Chl + Qtz -> Pl + Hbl + Mag + H_2O;

only epidote pseudomorphs remain. In discrete skarn veins, however, new epidote is formed. This points to an infiltration of very CO_2-poor fluids, presumably from the granite, preventing the "epidote out" reaction Czo + CO_2 -> An + Cal + H_2O. Clinopyroxene is salitic, with an average composition $di_{68}hed_{32}$. Besides the common reaction Cal + Qtz + Tr/Act -> Di/Hed + H_2O + CO_2, clinopyroxene formation due to the reaction Tr + Czo -> Di + An + Mg-Chl may be inferred from the observation of clinopyroxene and plagioclase clusters in a amphibole-rich matrix. Based on the calculated T-X_{CO_2}-stability relations for the low CO_2-activity of an infiltrated fluid, clinopyroxene formed already at temperatures < 500 °C. Epidote decomposition and clinopyroxene formation also increased the anorthite contents in plagioclase which varies from an_{26} to an_{53}. Increasing temperatures and the reactions above also affected the composition of the amphiboles. As one approaches the granite, they get poorer in Si and richer in Na, K, Ti and Al (Fig. 8). Green hornblende and recrystallized biotite often form decussate textures. Newly formed garnet is observed only within skarn veins, where its composition is gro_{70} $and_{25}alm_5$. Because of the gradual transition from contact metamorphic to the greenschist facies rocks, the extent of the outer aureole can only be observed in thin section. Characteristic are the desintegration of white mica, chlorite and epidote, and the formation of thin, green hornblende seams around actinolite. The reaction

$$Ms + Qtz + Cal -> Kfs + An + H_2O + CO_2$$

allows a maximum temperature (at X_{CO_2} = 0.5) of 465 °C for the assemblage Ms + Qtz + Cal, calculated (using the thermodynamic data of BERMAN, 1988) on the basis of microprobe data from a Cpx-Qtz-Pl hornfels (sample 301), collected 500 m from the granite. BRÖCKER (1990b) gives an estimate of 540 °C for the inner aureole but no supporting details; an oxygen isotope temperature of 555 °C is indicated by a Qtz-Mag pair from the contact skarn (BRÖCKER et al., 1993). Further details are given by BRÖCKER et al. (1994).

4.2. THE UPPER UNIT (UU)

Contrary to the rocks of the LU, the lithologies of the UU show no sign of the Eocene high-pressure metamorphism, neither in the area studied here

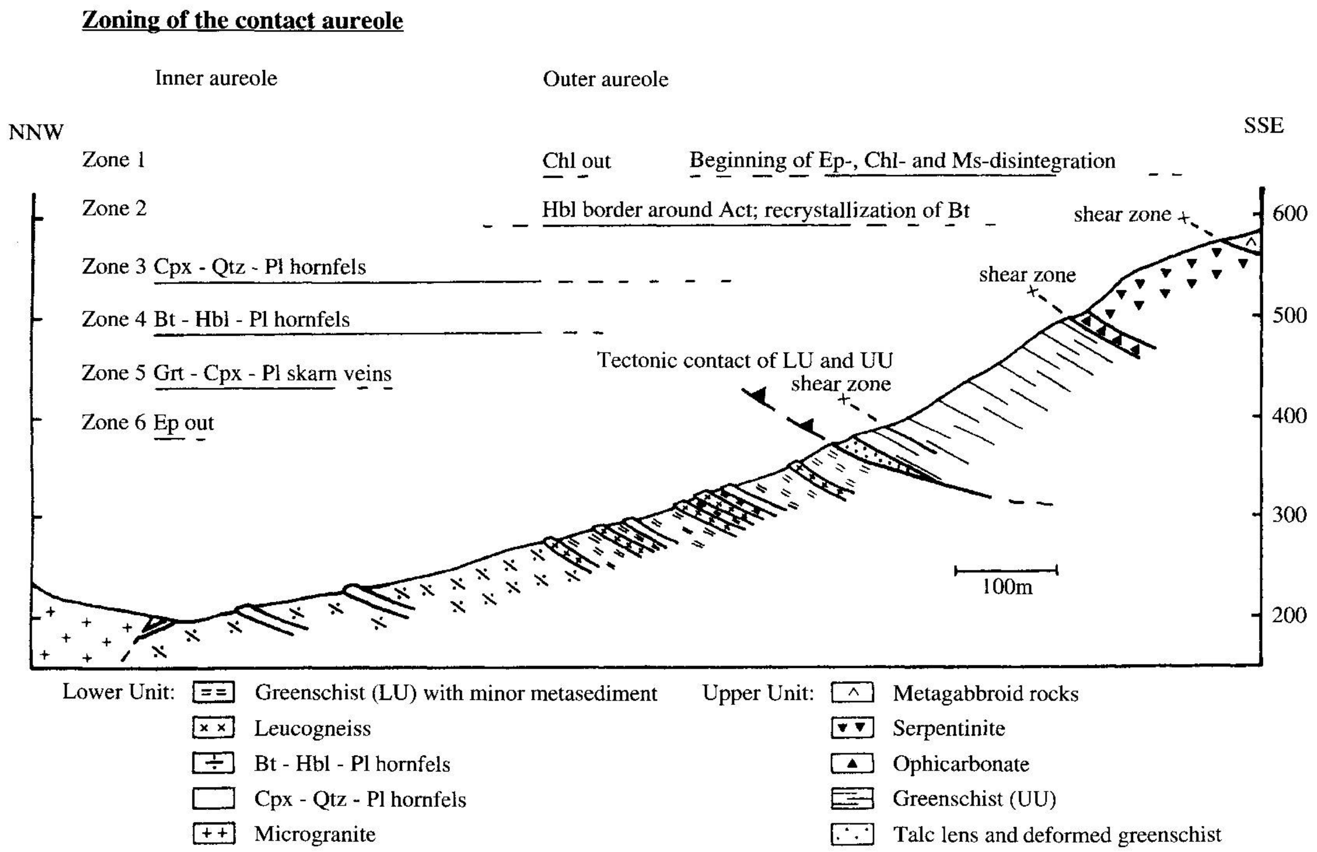

Fig. 7 Synthetic profile of the contact aureole with six metamorphic zones of the lower unit. Trace from NNW (19.67/17.68) to SSE (92.27/18.61), compare figure 11.

nor elsewhere on Tinos (KATZIR et al., 1996). Within the ophiolitic sequence at Mount Tsiknias, we recognize three phases of metamorphism. The earliest phase is documented by cores of brown hornblende in zoned amphibole of the metagabbroid rocks (Fig. 9). These magnesio-hornblende cores (Fig. 10) in some cases contain tiny relics of plagioclase (too small to analyze by EMP), representing the oldest relic assemblage. Whether these cores are of primary magmatic orgin, e.g. from a hornblende gabbro, or were formed by either oceanic or regional low-pressure metamorphism, cannot be decided on the basis of observed fabrics. However, such magnesio-hornblendes typically form under low pressures at temperatures of the greenschist facies (LAIRD and ALBEE, 1981; HYNES, 1982), and these cores may thus be products of an early oceanic metamorphism. We suggest, based on our petrographic and textural observations, that the ultrabasic rocks were initially serpentinized during this same period as well. According to KATZIR et al. (1996) this early phase may have produced primarily low-temperature varieties of serpentine, i.e. lizardite and chrysotile. By contrast, these same authors found indications of an early sea-water interaction at high temperatures within some gabbroid rocks.

The second phase is manifested by the typical greenschist assemblages Ab-Act-Ep-Chl ± Tit ± Mag ± Ilm/Hem in the metabasic rocks and by Atg-Mag ± Chl ± Cpx in serpentinite. Actinolite forms fine needles and thin, white rims around the hornblende cores in the metagabbroid rocks (Fig. 9a). Plagioclase is almost pure albite (< 0.5% An). These assemblages and the increased actinolite contents of amphibole point to somewhat higher pressures compared to the magnesio-hornblende formation (RAASE, 1974). Whether the replacement of lizardite and chrysotile by antigorite, as observed by KATZIR et al. (1996), belongs to this phase or entirely to the subsequent one, is not clear.

– *Contact metamorphism*

The third phase is due to the contact metamorphism following the intrusion of the biotite monzogranite. In the UU, serpentinite locally contains sprays of anthophyllite close to the granite; needles of tremolite are found up to 500 m away from the contact. In thin section, five contact metamorphic zones have been distinguished. These are defined by characteristic mineral assemblages observed as one approaches the intrusive contact (Fig. 11):

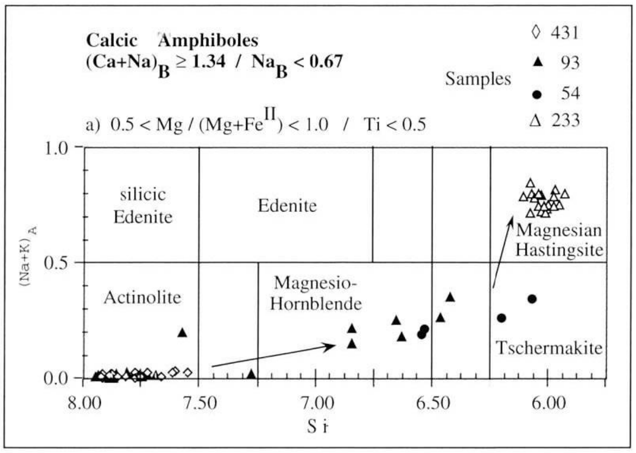

Fig. 8 Evolution of amphibole composition in greenschist (LU) with increasing contact metamorphic overprint. Diagram after LEAKE (1978).

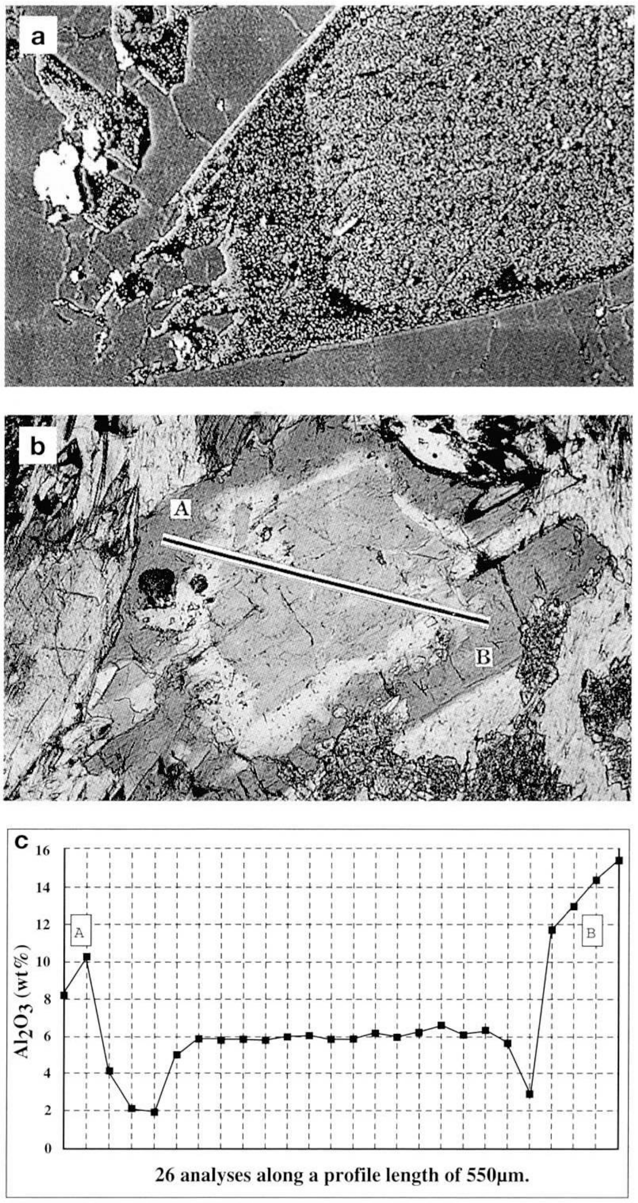

Fig. 9 Microphotograph and Al_2O_3-profile of zoned amphiboles in metagabbro (UU). (a) Sample 51 k (BSE). (b, c) Sample 61. Profile length = 550 µm.

(1) antigorite ->
(2) olivine + antigorite ->
(3) diopside + tremolite + olivine + antigorite ->
(4) tremolite + talc + olivine ->
(5) anthophyllite + talc + olivine

Olivine, tremolite and anthophyllite mostly show retrogression to antigorite and minor talc in samples containing assemblages (4) or (5). The characteristic reactions corresponding to the five isograd assemblages are shown in figure 12. Enstatite has not been observed; this sets an upper temperature limit of < 700 °C, but the maximum temperatures reached probably were substantially lower. Magnesite is not uncommon, especially in samples containing anthophyllite. Hence, the H_2O-activity in these assemblages was lowered by CO_2 in the fluid, and the two high-temperature reactions (4) and (5) shown in figure 12 must have been displaced to lower temperatures. Reducing the H_2O-activity to 0.5 lowers reaction temperatures by some 100 °C (Fig. 13). Local effects of a CO_2-bearing fluid and/or the irregular shape of the granite contact may also be responsible for the observed local discrepancies in the sequence of the isograd reactions.

Within the contact aureole, extending some 1200 m, actinolite in metabasic rocks of both the UU and the LU shows a rim of green, edenitic to pargasitic hornblende. Within the inner aureole, the anorthite content of plagioclase rises abruptly to An_{24-37}, across the peristerite gap. Thin section observations and microprobe analyses reveal disequilibrium textures in many of the rocks of the UU, making most of them unsuitable for thermobarometric calculations (compare BRÖCKER and FRANZ, 1994). Only some of the fine grained, well recrystallized greenschists (UU) seem to give reliable results for the contact metamorphic overprint: Thermobarometry on a sample (36 b) collected 750 m from the granite with the assemblage Olig-Hbl-Qtz-Mag-Chl-Hem indicates pressures of 2.5 ± 0.7 kbar at temperatures of 480 ± 40 °C. These conditions correlate well with the "olivine-talc in" isograd limiting the serpentinites, located also at some 750 m from the granite. Similar problems in obtaining meaningful P-T values have been documented by BRÖCKER and FRANZ (1994), but their final temperature and pressure estimates (P_{max} ~ 2–3 kbar), based on extensive work within the entire aureole, are similar to ours. These authors also point out that the two intrusive pulses, separated in time by some 4 Ma, are likely to have occurred at somewhat different depths, with Δ P~1 kbar due to uplift. However, the thermal overprint due to the later intrusion of the small S-type granite stock cannot be separated from the main contact metamorphic effects of the larger biotite monzogranite pluton.

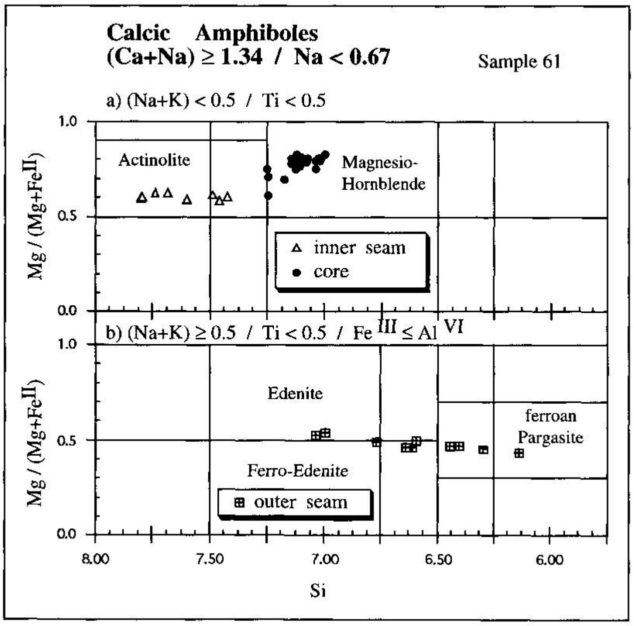

Fig. 10 Amphibole classification scheme after LEAKE (1978) used for zoned amphibole in metagabbro. 44 spot analyses of single, zoned amphibole grain in sample 61. Formula calculations according to ROBINSON et al. (1982, p. 6–9). Total cations exclusive of Na, K and Ca were normalized to 13, Fe_2O_3 was then computed to obtain 23 oxygen / formula unit.

4.3. THE TECTONOMETAMORPHIC EVOLUTION

The exhumation of the high-pressure blueschists and eclogites of the Cyclades continues to be a controversial and highly debated topic (e.g. LISTER et al., 1984; DIXON et al., 1984; AVIGAD, 1990; URAI et al. 1990; GAUTIER and BRUN, 1994 a, b). Furthermore, the question whether the UU belongs to the lower or upper main unit of the Attic-Cycladic crystalline complex (ACC) cannot be answered definitively. If the greenschist facies overprint of the UU were Cretaceous or older, i.e. if Tertiary metamorphism were lacking, the UU would be part of the upper main unit. On the basis of age data by PATZAK (1988) for the Akrotiri unit, AVIGAD (1990) associates the isoclinal folding within the UU with a late Cretaceous, low pressure metamorphic event. Until recently (e.g. KATZIR et al., 1996) the age of the ophiolite was assumed to be Cretaceous. However, new isotopic data by BRÖCKER and FRANZ (1997) indicate that it may well represent older oceanic crust, the metamorphic evolution of which (KATZIR et al., 1996) involved an oceanic stage and subsequent regional metamorphism associated with the tectonic emplacement of the UU. In view of the complex zoning of amphibole documented (Fig. 9) in the present study, as well as the results of KATZIR et al. (1996), we hesitate to associate the Rb–Sr and K–Ar-data of PATZAK et al. (1994) with a specific metamorphic event. Rather, we interpret the fairly large range in the dates obtained by PATZAK et al. (1994) as due to partial resetting of the Rb-Sr and Ar-systems, yielding 77–66 Ma for the former, and 60–53 Ma for the latter. This view is in line with the most recent geochronological data by BRÖCKER and FRANZ (1997).

Based on his early work, MELIDONIS (1980) had suggested that the emplacement of the UU on top of the LU occurred before the Eocene high-pressure metamorphism, and that the two units subsequently experienced the same metamorphic history. The absence of high-pressure mineral relics within the UU would seem to contradict this

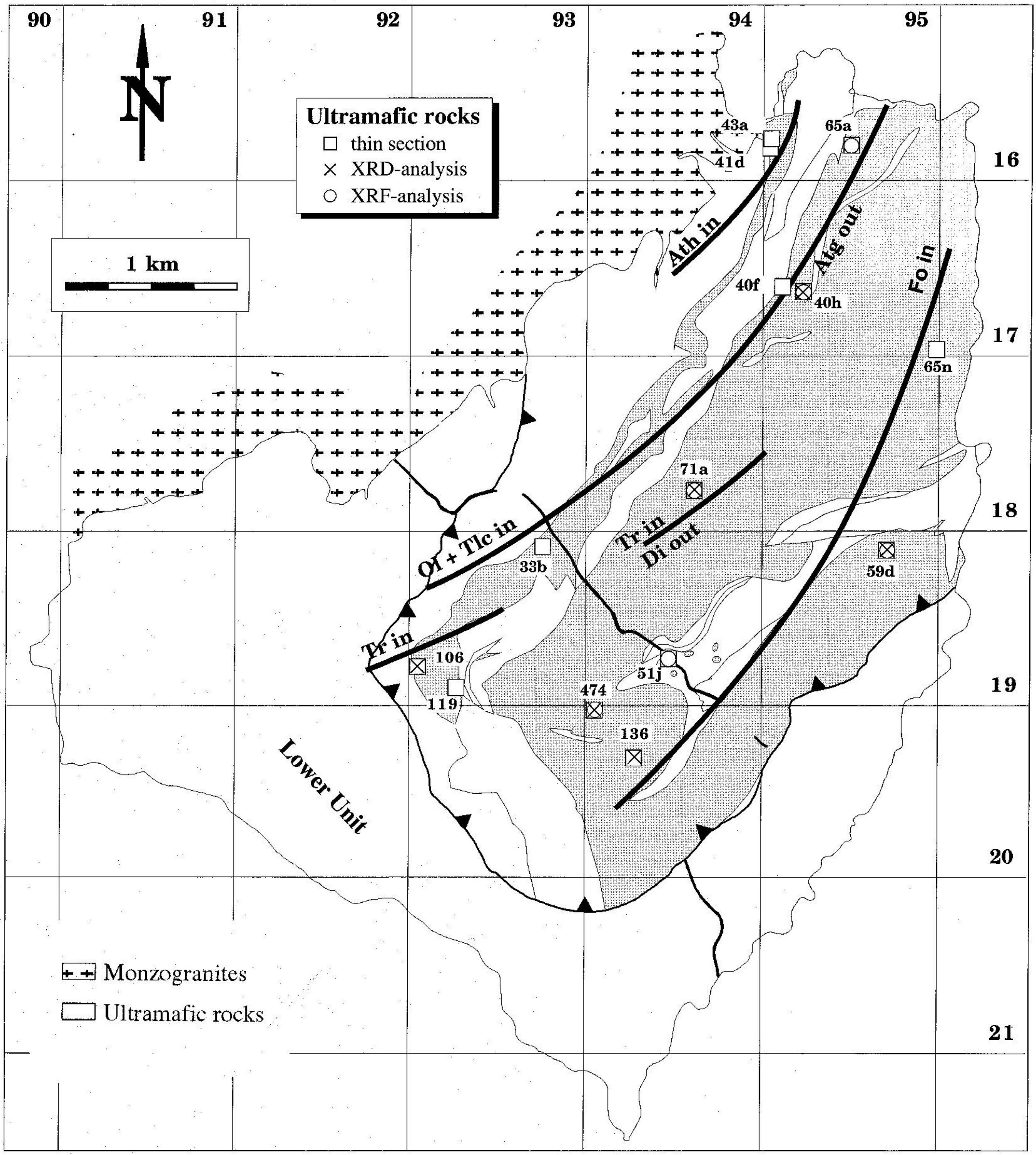

Fig. 11 Map of contact metamorphic isograds in ultramafic rocks.

scheme: The two units must have been at different levels during the early Tertiary. However, the identical orientation of coaxial folds and the parallel axial planar schistosities within the LU and UU as well as their indistinguishable (later) metamorphic grade strongly indicate that the emplacement of the UU above the LU and the subsequent collective deformation happened during the medium-pressure greenschist facies regional metamorphic event, dated by BRÖCKER et al. (1993) at 21–23 Ma. Again, our interpretation is supported by new age data of BRÖCKER and FRANZ (1997).

For the entire evolution, we postulate the following scenario: The ophiolitic sequence of the Tsiknias area was formed in the Jurassic during the opening of the Tethys. During Eocene collision, when the Apulian microplate was subducted below the Eurasian continent (e.g. SCHLIESTEDT et al., 1987), the ophiolite sequence was imbricated within an accretionary wedge, where internal thrusting repeated some of its members (duplex-style). The metamorphic grade in the UU did not exceed greenschist facies, while large parts of the subducted lower main unit of the ACC reached blueschist to eclogite facies conditions. Following rapid, near-isothermal decompression, the deeply subducted high-pressure rocks of the LU reached upper crustal levels by the Oligocene-Miocene boundary and underwent pervasive recrystallization jointly with the higher ophiolithic nappe units. Only locally did a few members of the LU escape the greenschist facies overprint, due to low supply of fluids or a lack of infiltration paths (e.g. GANOR et al., 1989; BRÖCKER, 1990a).

Whereas AVIGAD and GARFUNKEL (1989, 1991) proposed an exhumation of the lower unit by synorogenic extension, along low-angle normal faults, we advocate a model that integrates rapid extension along listric faults above an accretionary wedge; the collapse followed underplating and overthickening (PLATT, 1986). During a late exhumation stage, the nappe stack (LU and UU) was thrusted on top of weakly metamorphosed

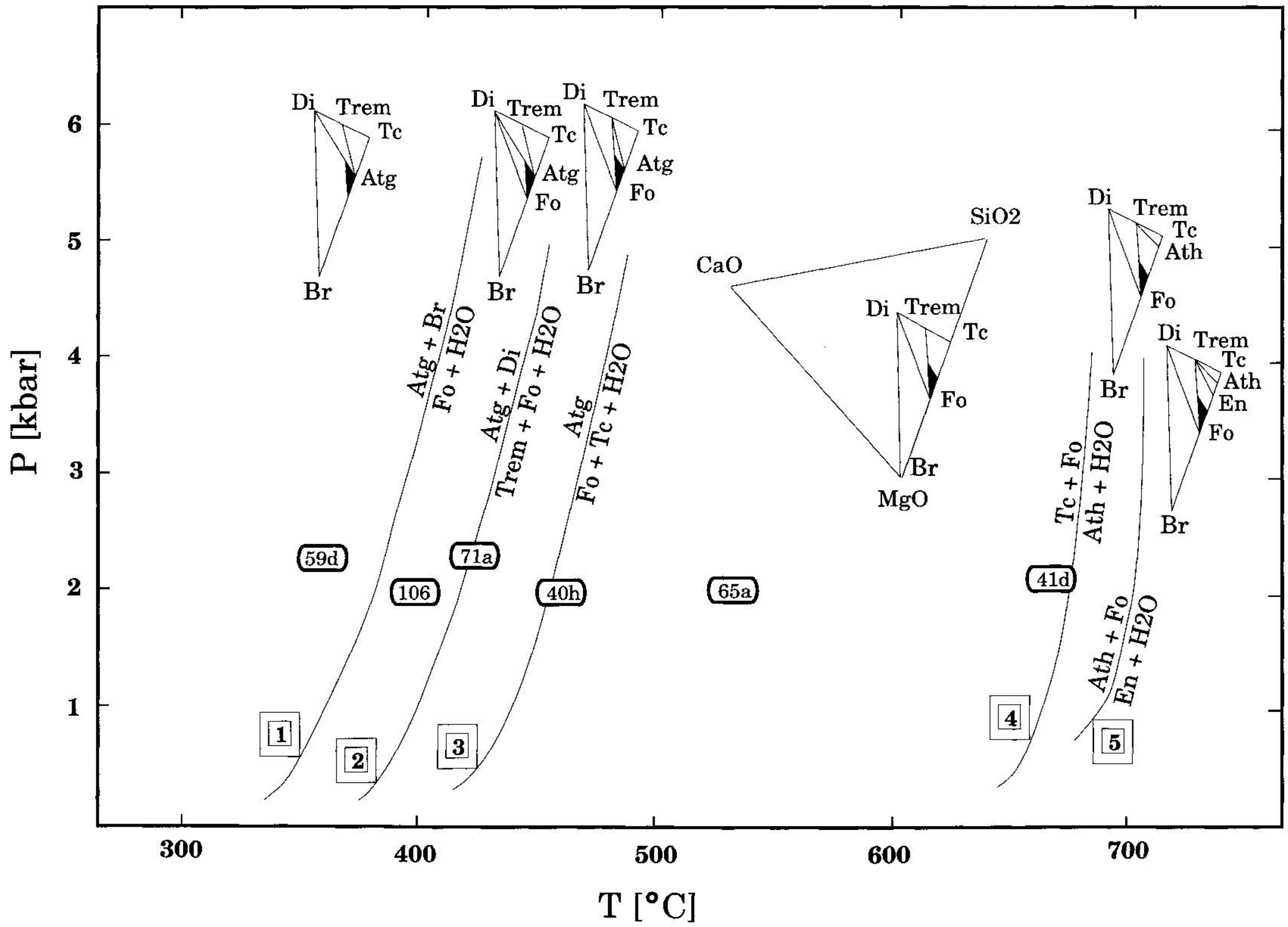

Fig. 12 P-T-diagram for reactions in the ultrabasic system, after TROMMSDORFF and EVANS (1972). Thermobarometry on metabasites indicates 2.5 ± 0.7 kbar for the contact metamorphism. Black fields in triangles show compositional range of serpentinite in the Tsiknias area. Numbers in the rounded boxes refer to samples, localities are shown in figure 11, with corresponding assemblages.

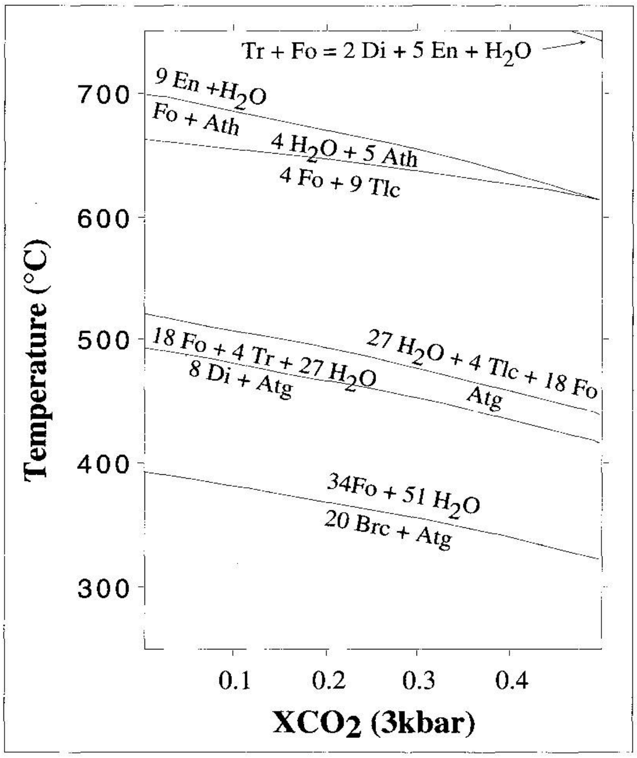

Fig. 13 T-X_{CO_2}-diagram of the system CaO–MgO–SiO_2–H_2O, calculated with MacPTAX (LIEBERMAN, 1991) for phases in figure 12.

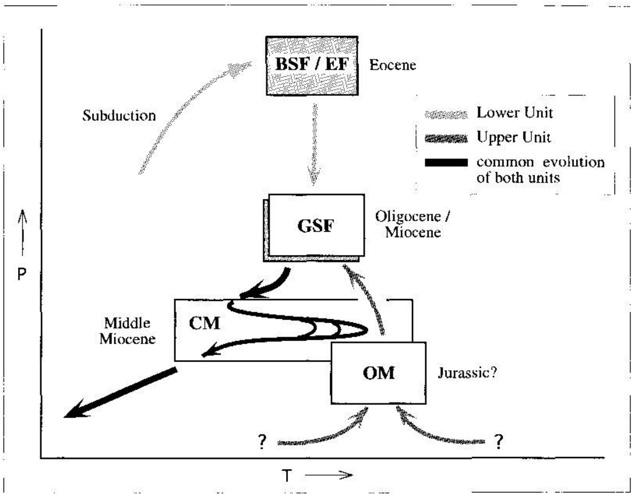

Fig. 14 Schematic P-T-t-path for tectonometamorphic evolution of lower and upper unit. (Metamorphic events: BSF = blueschist facies, EF = eclogite facies, GSF = greenschist facies, CM = contact metamorphism and OM = oceanic metamorphism.)

sediments exposed in the Panormos window of northern Tinos (AVIGAD and GARFUNKEL, 1989). Most likely this happened prior to the intrusion of the two Miocene granite stocks (18 and 14 Ma), the contact aureole of which affected both LU and UU rocks. The low-angle fault at the contact of LU and UU was reactivated during these late stages of uplift, displacing the hanging wall to the NE. This is demonstrated by the granodiorite dike that was sheared and displaced by some 330 m along the contact in the NW and by 760 m in the SE, indicating that the motion involved a slight rotation. A net of joints developed also during the final uplift, visible especially within the granites and the serpentinites. We note that this sense of shear is consistent to the observations in minor shear bands (GAUTIER and BRUN, 1994 a, b). The P-T-t-path in figure 14 summarizes the tectonometamorphic evolution of the LU and UU.

5. Character of the ophiolites

5.1. PROTOLITHS AND GEOCHEMISTRY

The serpentinites, gabbroid rocks and greenschists of the UU roughly correspond to a simplified ophiolitic suite, consisting of an ultrabasic mantle sequence and gabbroid rocks. Mantle sequences tend to be either of harzburgitic or lherzolitic ophiolite type, of which the first occur in the west (Pyrenees-Alps-Carpathian Mountains) and the latter in the east (Arabian Peninsula-Himalayas), whereas in the eastern Mediterranean seams to be a transition zone (NICOLAS, 1989). In the Tsiknias area the interpretation of geochemical data requires caution since the ultrabasic rocks have been serpentinized completly. One pyroxene-rich and eight antigorite-olivine-rich serpentinites were analysed by X-ray fluorescence. CIPW-normalization would identify the serpentinites as meta-harzburgites and meta-lherzolithes (Fig. 15), though Ca-depletion or -enrichment during (oceanic) metamorphism may affect this classification strongly. To minimize such effects, we used discrimination diagrams (Fig. 16 and 17), in which the elements selected tend to stay fairly immobile during metamorphism. Compared to harzburgite, Mg-values in most of our samples are low, but the enrichment in Ni, the depletion in V, as well as low TiO_2 and Al_2O_3 contents, are typical of harzburgite. Similar trends were found by KATZIR et al. (1996). The occurrence of chromite lenses, as observed in the Tsiknias area, is also typical of harzburgitic ophiolites. However, metasomatic processes did affect the geochemistry of the serpentinites and contributed heterogenity to the data (e.g. Na enrichment). Serpentinites appear to have a stronger affinity to harzburgite, but a definite determination of the protolith seems impossible.

The crustal sequence consists of gabbroid rocks and greenschists (UU); these are interpret-

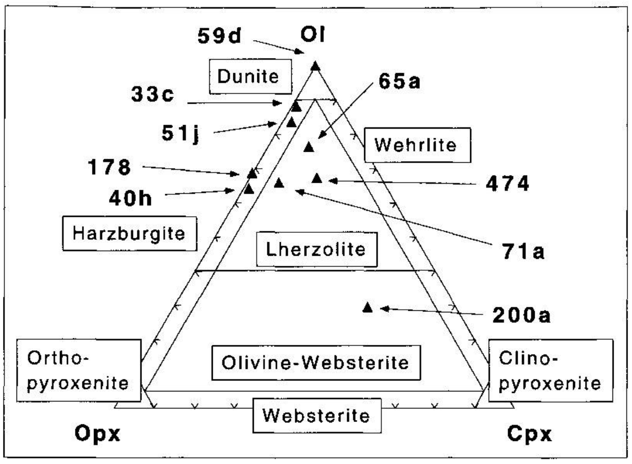

Fig. 15 CIPW-normalized XRF analyses of nine serpentinites.

ed as a variably overprinted sequence of lower oceanic crust, possibly including sheeted dikes; we were unable to discern volcanic (pillow lava) remnants. Greenschists of the UU and the LU are quite similar in their petrography, and both series display MORB-affinity (Fig. 16), but they do show geochemically different characteristics. As in the ultrabasic suite, evidence of element mobilization during polymetamorphism in the mafic sequence, as well as the possibility of tectonic admixing of sedimentary material, are effects that demand caution in interpreting the geochemistry of metabasic rocks in the area studied. Nevertheless, our geochemical data indicate the following: (a) UU greenschists show higher TiO_2-contents (Fig. 17a); these are manifested primarily by Ti-rich cores of their magnesio-hornblende, whereas both types of greenschist possess similar amounts of accessory titanite and Ti-oxides. (b) LU greenschists show higher K_2O-contents (Fig. 18 a and b). The potassium depletion of UU greenschists, compared to average MORB (Fig. 18d), may be a result of high temperature oceanic metamorphism (BEDNARZ and SCHMINCKE, 1990) and/or of a later regional metamorphic event. (c) The correlations of Zr to TiO_2 and Zr + Y to Ni + Cr (Fig. 17 b and c) points to magmatic differentiation of UU greenschists, while those of the LU have constant Zr- and Y-values over a relatively wide variation of Ni + Cr. Inasmuch as the mafic rocks represent a fairly heterogeneous group, figures 18 c and 18 e show that, in the samples investigated here, *no* significant effect due to the contact metamorphic overprint is discernable in the geochemical signature of either type of greenschist (metasomatic effects on the mineralogy and geochemistry are visible, however, e.g. in discrete skarn veins). By contrast to our data, BRÖCKER (1991) found de-

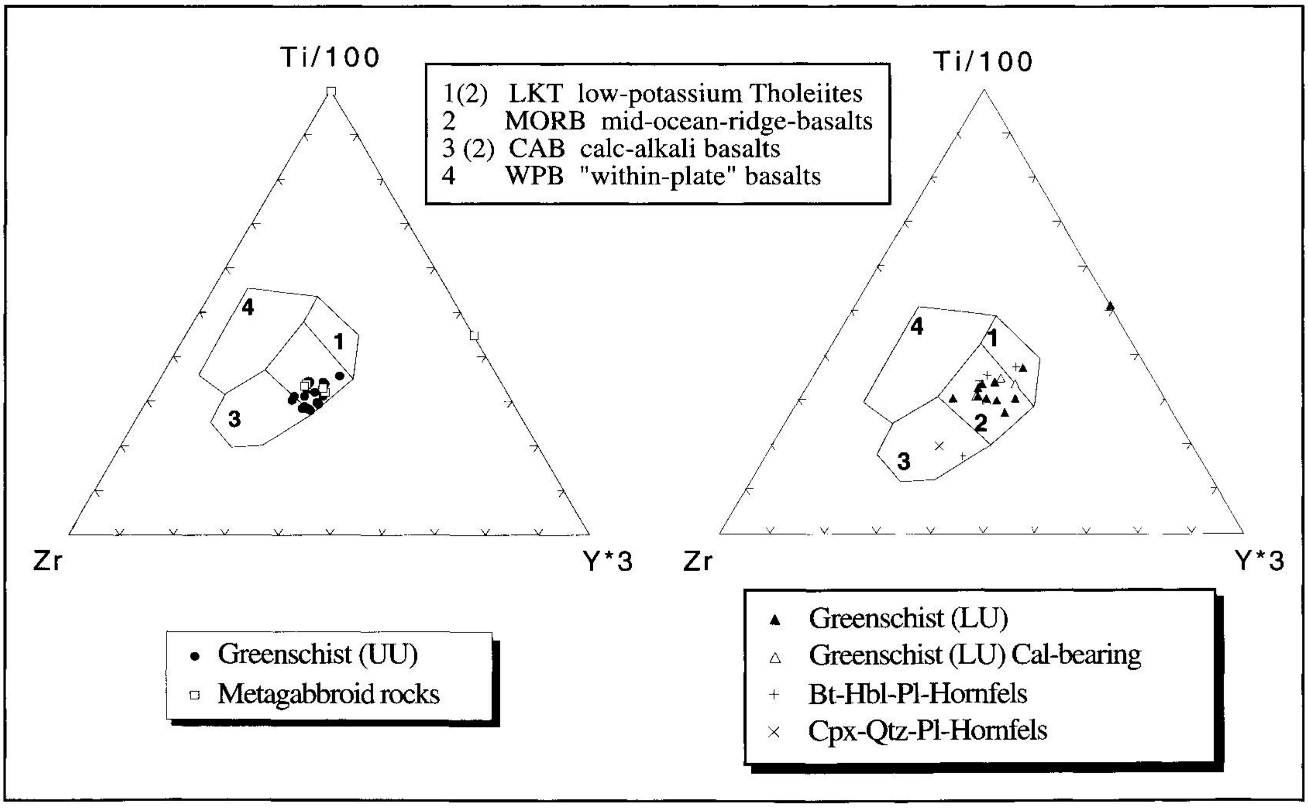

Fig. 16 Ti-Zr-Y-diagrams with composition fields of several basalt types after PEARCE and CANN (1973) document that greenschist (LU) and (UU) and some metagabbroid rocks retain strong MORB affinity.

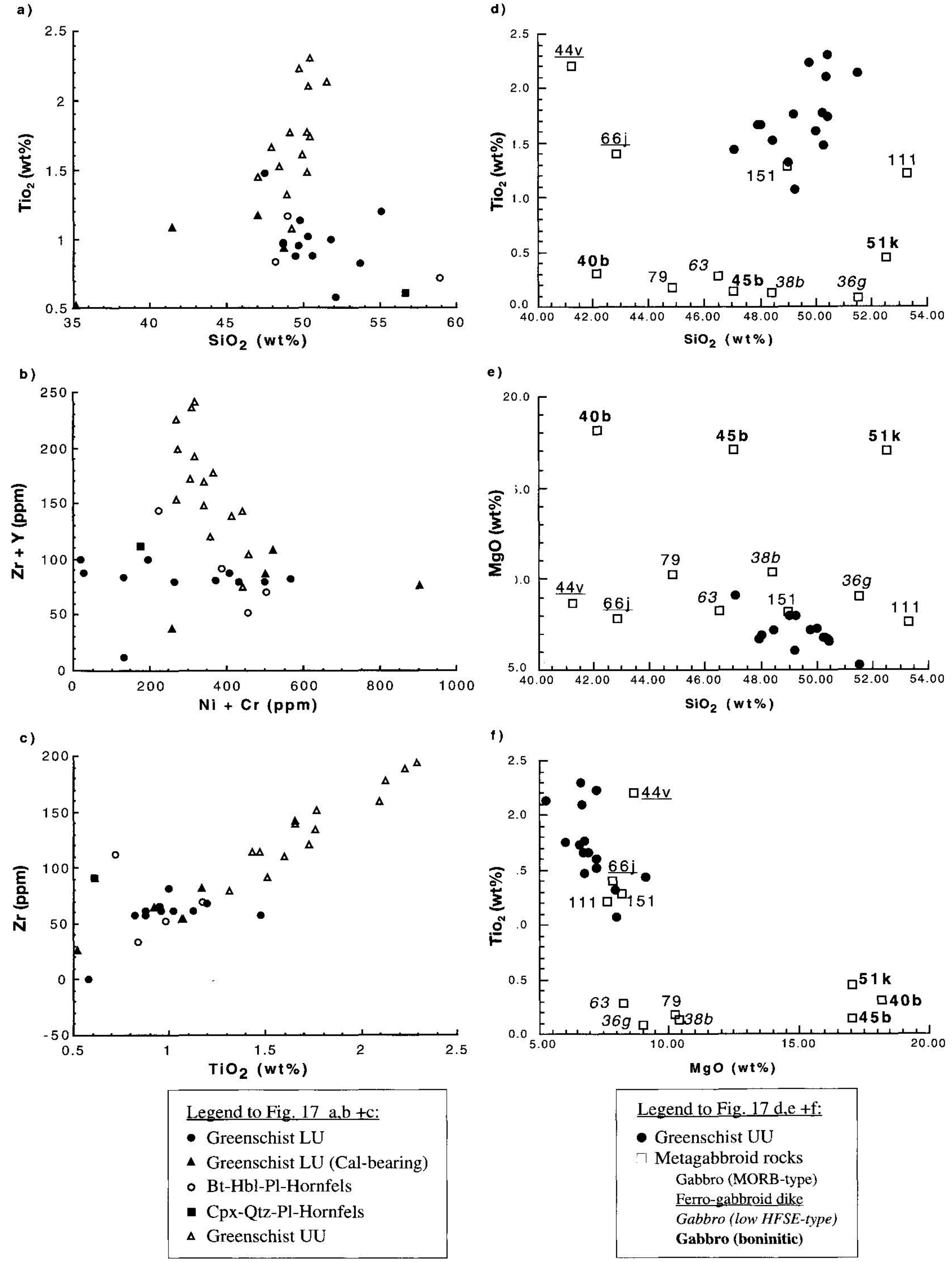

Fig. 17 Element discrimination diagrams: comparison of greenschist and hornfels from the LU, with greenschist and metagabbroid rocks from the UU (see text for explanation).

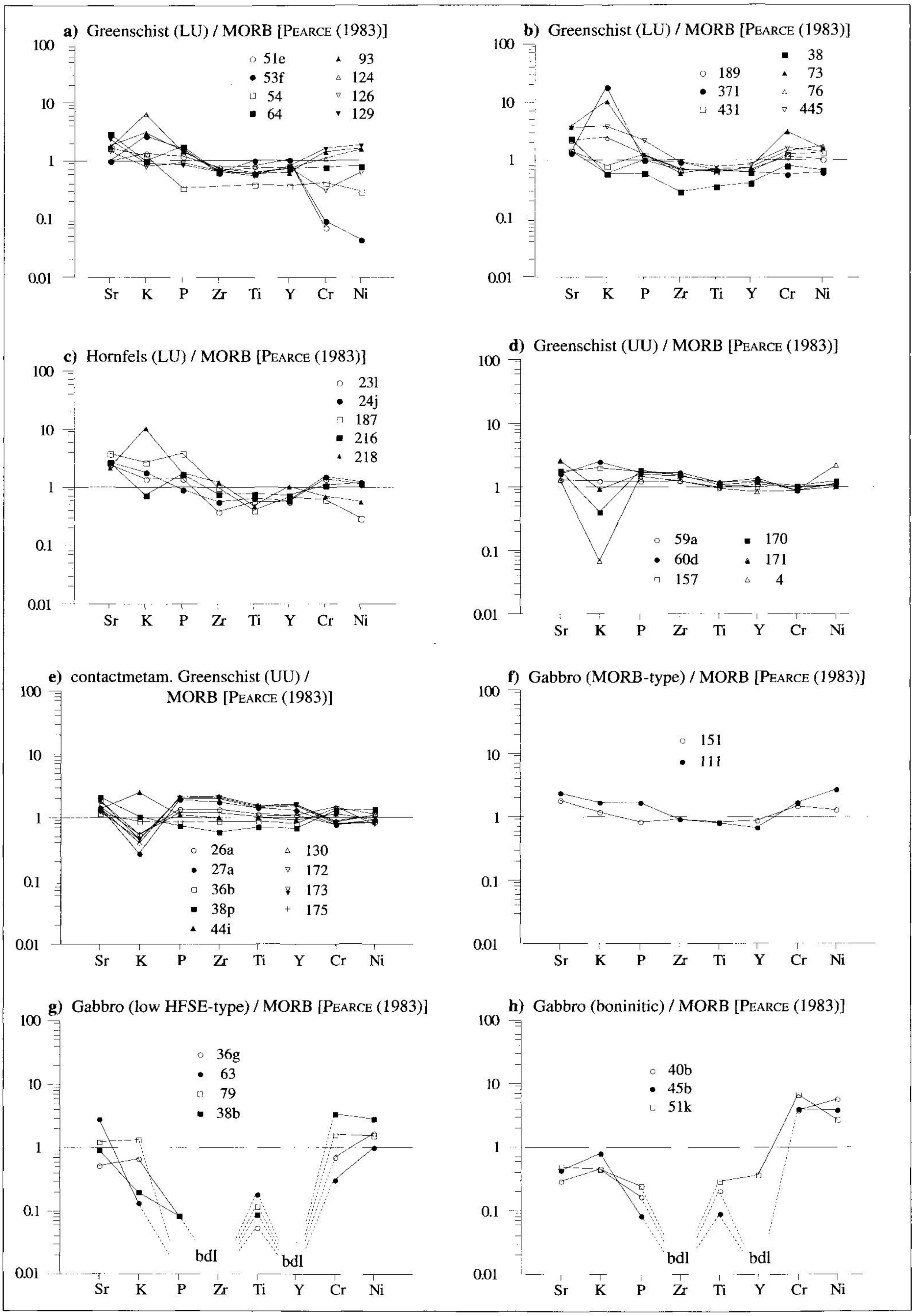

Fig. 18 MORB-normalized diagrams (PEARCE, 1983) of greenschist (LU and UU) and metagabbroid rocks (UU). Concentrations below detection limit (bdl) are indicated by dashed lines.

creased concentrations of Cr and Ni in mafic rocks from within the aureole, compared to samples outside. Finally, we note that although the trace element systematics of metabasaltic hornfels samples are very similar to those of the western edge of the granite, no signs of the scheelite mineralization (PAPASTAVROU and PARITSIS, 1990) were observed along the eastern border of the granite.

The geochemical data of the metabasic gabbroid rocks point to a range of different source materials. Besides the common MORB-affinity (Fig. 18f), more evolved ferro-gabbroid dikes occur, with lower Na_2O and higher CaO, TiO_2 and P_2O_5 contents. Mineralogically, this is manifested by the accessories titanite and apatite. Striking is a gabbro suite that is depleted in the high field strength elements (HFSE) Zr, Y and Ti as well as in P (Fig. 18 g and h). Since all these elements are highly incompatible, these gabbros were evidently dominated by early crystallized phases. For various reasons, notably including relatively high Al-contents, these gabbros do not appear to belong to the ultrabasic suite. Discrimination diagrams (Fig. 17 d, e and f) show that some of these HFSE-depleted gabbros have unusually high contents of MgO and commonly also are rich in SiO_2. This geochemical signature is typical of boninites, found as effusive rocks along transform faults in oceanic crust (CRAWFORD, 1989). Boninites have been interpreted to be products of partial anatexis of a residual mantle within a suprasubduction zone, where H_2O could infiltrate and SiO_2, among other elements, may be added (MURTON, 1990). At Tsiknias, there is neither field nor thin section evidence of a volcanic origin of these HFSE-depleted rocks. At present, their significance is not clear.

5.2 REGIONAL DISTRIBUTION

According to most authors (e.g. MELIDONIS, 1980; AVIGAD and GARFUNKEL, 1989, 1991; KATZIR et al., 1996), the upper unit occurs in the form of nappe fragments on top of the LU at the four locations Tsiknias area, Marlas area in the NW, surroundings of Tinos city and to the west of the granite intrusion. (PAPASTAVROU and PARITSIS (1990) do not include the greenschists west of the granite in the UU.) Ultrabasic rocks are found at the first two locations only, greenschists (UU) dominate elsewhere. It is not certain, whether these nappe fragments did once form a single tectonic unit or whether they may have different histories. As mentioned above (chapter 4.3.), up to now it has been impossible to determine definitely whether the UU belongs to the lower or upper main unit of the Attic-Cycladic crystalline complex (ACC). PATZAK et al. (1994), in a broad regional comparison, point out similarities of the Akrotiri unit (near Tinos Chora, see Fig. 2) to ophiolite mélange members on Crete and elsewhere in the basal parts of the ACC. In our opinion, further detailed structural and geochemical investigations are necessary to document to what extent these "witnesses to a lost terrane" (PATZAK et al., 1994) constitute a coherent paleogeographic unit. Especially the boninitic character of some of the rocks may provide a means to correlate and/or distinguish possibly very different ophiolithic fragments of the ACC. Boninitic lava has been reported from the eastern Peloponnese (PHOTIADES et al., 1993) and from Aegina Island (DIETRICH et al., 1987), but both of these belong to the ophiolitic mélange of the Pindus–Sub-Pelagonian Zone.

6. Conclusions

– Within the volcano-sedimentary schists of the lower unit (LU) neither complete blueschist nor eclogite assemblages are preserved in the Tsiknias area. Due to pervasive, fluid-driven greenschist facies retrogression, only isolated mineral relics remain of the Eocene high-pressure stage.
– Serpentinites, metagabbroid rocks and greenschists of the upper unit (UU) at Tsiknias may constitute a simplified (inverted?) ophiolite suite, metamorphosed under greenschist facies conditions, and imbricated and repeated by duplex-like tectonics.
– LU and UU are separated by a low-angle fault, the character of which is not clear from field evidence.
– The identical orientations of coaxial folds and parallel axial planar schistosities, as well as the equivalent metamorphic grade of the rocks within the LU and UU, indicate that the emplacement of the UU above the LU and the subsequent collective deformation happened during the medium-pressure greenschist facies regional metamorphic event, dated at 25 Ma by ALTHERR et al. (1982), and at 21 Ma by BRÖCKER et al. (1993) and BRÖCKER and FRANZ (1997).
– The low-angle fault at the contact of LU and UU was reactivated, as demonstrated by a sheared granodiorite dike, during a late stage of uplift, displacing the hanging wall by a few hundred meters to the NE.
– Serpentinites occur only in the UU and retain a strong affinity to harzburgite, although metasomatic processes affected their geochemical character during (oceanic?) metamorphism.
– Greenschists occur in the LU and UU; they show dominantly MORB-affinity in both units,

but with lower TiO_2 and higher K_2O contents in the LU. Greenschists of the LU contain garnet and crossite as relics of Eocene high-pressure metamorphism; such relics are missing in the UU.
– Besides the common MORB-affinity, some of the gabbroid rocks of the UU are depleted in Zr, Y, Ti and P and show high Si- and Mg-contents, i.e. a signature typical of boninite. Their significance is presently not understood; no evidence of an effusive formation of these rocks has been found at Tsiknias.
– The intrusion of a monzogranite pluton 17–19 Ma ago and a minor granitic stock some 4 Ma later created a contact aureole of about 1200 m width. Both the lower and the upper unit were thermally affected. Within a synthetic profile, six zones of contact metamorphism are recognized in the LU, five zones in the UU.
– Thermobarometry in a contact metamorphic greenschist (UU), collected 750 m from the granite, yields pressures of 2.5 ± 0.7 kbar at temperatures of 480 ± 40 °C; the stable assemblage is Olig-Hbl-Qtz-Mag-Chl-Hem.
– Whereas epidote desintegrates in Bt-Hbl-Pl hornfels, new epidote is formed in Grt-Cpx skarns due to infiltration of H_2O-rich fluid.
– Zoned amphiboles in metagabbroid rocks document the metamorphic sequence well: Magnesio-hornblende cores correspond to a magmatic or an early, low-pressure (oceanic?) metamorphic event. An inner actinolite seam and an outer edenitic to pargasitic hornblende rim document, respectively, the regional Oligocene-Miocene medium pressure greenschist overprint and the Miocene contact metamorphism.

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