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Burial diagenesis in Tertiary "flysch" of the external zones of the Hellenides in central Greece and the Olympos region, and its tectonic significance

By HANAN J. KISCH[1])

ABSTRACT

Samples of Tertiary "flysch" throughout the external zones of the central Greek Hellenides commonly contain smectite and/or illite-smectite mixed-layers. Burial diagenesis has not exceeded the stage of middle "diagenesis" (sensu KUBLER); the variation in clay mineralogy is considered to reflect mainly clastic clay-mineral distribution and constitution of the illite, rather than a gradient in burial diagenesis or incipient metamorphism. Coal ranks are low: 0.44 to 0.65% $R_{m\ oil}$. The low degree of burial diagenesis indicates that these zones are unlikely to have been covered by major thrust sheets.

In the central Othris area, similarly low degrees of burial diagenesis both in the Triassic-Jurassic (Othris Group) and in the disordantly overlying Upper Cretaceous-Paleocene (Dinai Group) indicate that neither the early Tertiary nor the late Jurassic-Middle Cretaceous deformation were associated with noticeable incipient metamorphism, and thus lend support to an eastward emplacement direction of the Othris ophiolite complex (associated with the latter deformation phase).

In contrast, appreciable anchimetamorphism was found along the western margin of the Olympos window in Thessaly: both the probably partly Paleocene "flyschoid series of Spilia" (the youngest member of the Ossa unit of the Pelagonian allochthon), and the uppermost "flysch" of the Olympos sequence (Middle Eocene) show anchimetamorphic illite crystallinities and partly ordered mica-chlorite and corrensite-like chlorite-vermiculite mixed-layers. It is suggested that this anchimetamorphism is possibly contemporaneous with the last phase of high-pressure metamorphism in the Pelagonian thrust (DERYCKE & GODFRIAUX 1976), and that it could well be related to the probably late Eocene emplacement of the Pelagonian allochthon upon the Olympos sequence.

ZUSAMMENFASSUNG

Schiefer des tertiären «Flysch» in den externen Zonen der Helleniden Zentralgriechenlands enthalten meistens Smektit und/oder Illit-Smektit mixed-layers. Die Überdeckungs-Diagenese hat das Stadium der mittleren «Diagenese» (im Sinne KUBLERS) nicht überschritten: das tonmineralogische Spektrum stellt hauptsächlich die klastische Verteilung der Tonmineralien und der Illit-Zusammensetzung dar. Die Inkohlungsgrade sind niedrig: 0,44 bis 0,65% $R_{m\ Öl}$. Der niedrige Grad der Überdeckungs-Diagenese deutet die Unwahrscheinlichkeit von Bedeckung dieser Zonen durch mächtige Überschiebungsdecken an.

Vergleichbare niedrige Grade der Überdeckungs-Diagenese im zentralen Othris-Gebiet, sowohl in der Othris-Gruppe (Trias-Jura) als auch in der diskordant darüberliegenden Dinai-Gruppe (Oberkreide-Paläozän), zeigen, dass weder frühtertiäre noch spätjurassisch-mittelkretazische Deformationen mit merkbarer Metamorphose verbunden waren, und unterstützen eine ostwärts gerichtete Platznahme des Othris-Ophiolithkomplexes (vergesellschaftet mit der früheren Deformationsphase).

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Dagegen ist beträchtliche Anchimetamorphose dem Westrand des Olymposfensters (Thessalien) entlang festgestellt worden: sowohl die wahrscheinlich teilweise paläozäne «flyschoide Serie von Spilia» (das jüngste Glied der Ossa-Einheit des Pelagonischen Allochthons) als auch der oberste «Flysch» der Olympos-Folge (mittleres Eozän) weisen anchimetamorphe Illit-Kristallinitäten sowie teilweise geordnete Glimmer-Chlorit und Corrensit-ähnliche Chlorit-Vermikulit mixed-layers auf.

Diese Anchimetamorphose könnte möglicherweise mit der letzten Phase der Hochdruckmetamorphose in der Pelagonischen Überschiebungsdecke korreliert werden und könnte wohl mit der wahrscheinlich späteozänen Platznahme des Pelagonischen Allochthons auf die Olympos-Folge verbunden sein.

Introduction

Using the illite-"crystallinity" method, incipient metamorphism has been detected in the last few years in the external zones of a number of orogenic belts, both of Alpine age, e.g. in the sub-Pyrenean and north-Pyrenean zones (KUBLER 1967), the subalpine zone of the French Alps (DUNOYER et al. 1966; DUNOYER 1969, p. 157–160; BARLIER 1974), and the Helvetic zone of the Swiss Alps (FREY 1969, 1970; KISCH 1980b), and in older orogens, e.g. the Rheinische Schiefergebirge (WEBER 1972), and the "Eastern Complex" of the Scandinavian Caledonides (KISCH 1978, 1980a).

The present study is a first attempt to assess the incipient-metamorphic effects of the main Tertiary deformation phase in the Hellenides of central Greece and the Olympos region of Thessaly, and to what extent such effects could be related to cover by thrust sheets. Secondarily, one might use discontinuities in burial-diagenetic grade to detect the effects of earlier folding and thrusting phases, for instance the late Jurassic to early Cretaceous phase, which has affected wide tracts of the more internal parts of the Hellenides.

Geological setting

External zones

The external zones of the Hellenides in AUBOUIN's synthesis consist of nappes or zones representing various paleogeographic realms ("isopic zones") of Mesozoic and Lower Tertiary sedimentation, that were thrust from northeast to southwest (cf. AUBOUIN et al. 1963; AUBOUIN 1965; DERCOURT et al. 1977). In southern continental Greece these zones are from southwest (external) to northeast (internal): the partly allochthonous Ionian and Gavrovo-Tripolitza zones, and the allochthonous Pindos and Parnassos zones (see Fig. 1 and 2). Each of these zones has a "flysch" as the terminal sedimentary member, deposited before emplacement of the overlying thrust sheets; the age of these "flysches" is late Eocene to early Miocene in the Ionian and Gavrovo-Tripolitza zones and Maastrichtian to late Eocene in the more internal Pindos and Parnassos zones. In the Pindos zone there is an earlier period of red marly sedimentation associated with radiolarites and graywacke during the Cenomanian-Turonian, referred to as the "premier flysch".

On the boundary between the external and internal zones, and locally thrust upon the Parnassos zone, lie discontinuous occurrences of the uppermost Jurassic-lower Cretaceous Beotian "flysch", rich in ophiolitic detritus; its deposition could be

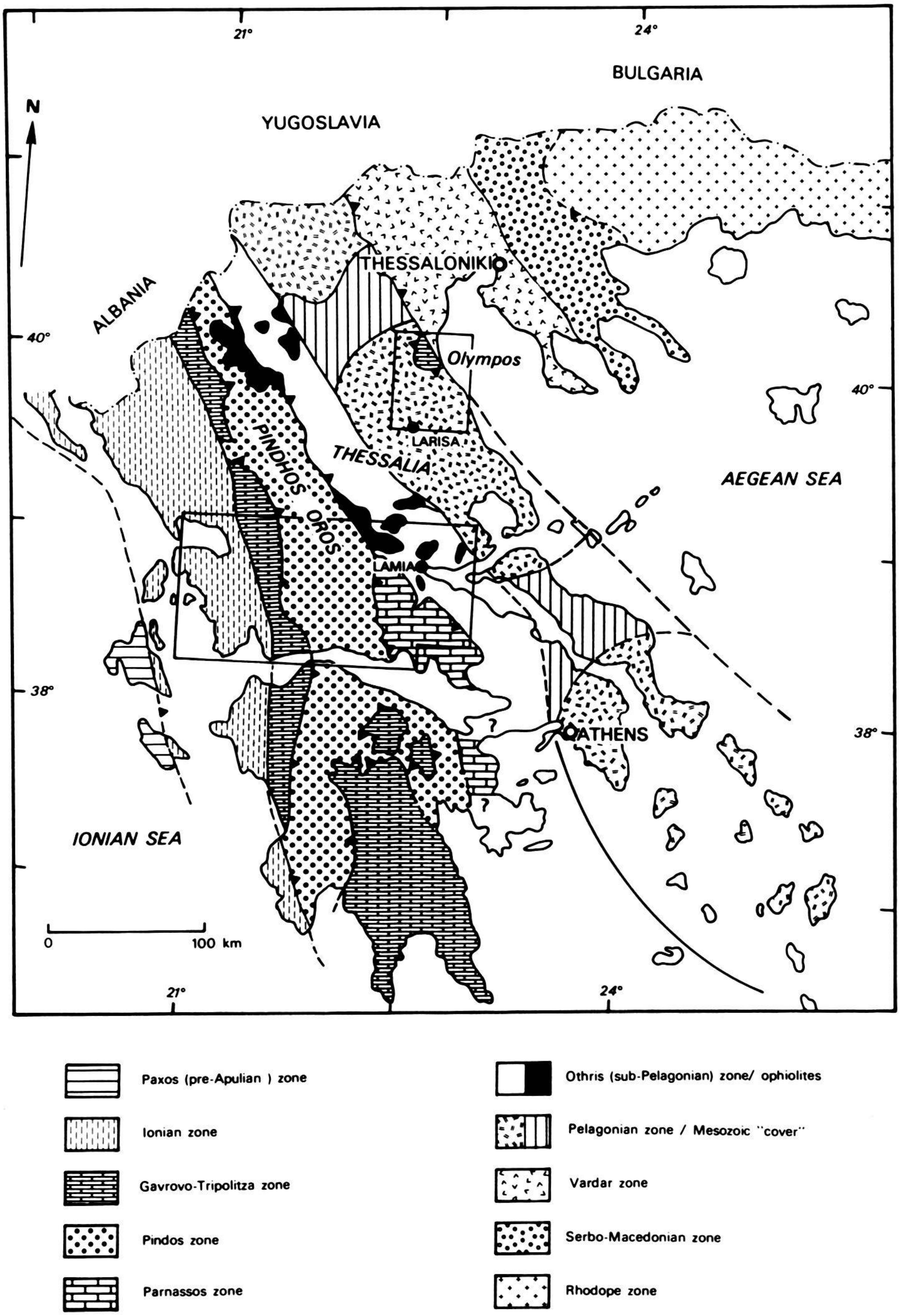

Fig. 1. Isopic zones and major structural units of the Hellenides of AUBOUIN et al. (1963) with modifications after GODFRIAUX (1968), HYNES et al. (1972, and SMITH & MOORES (1974), simplified from BARTON (1975, Fig. 1). The Beotian "flysch" is not shown. The areas of Figures 2 and 3 are outlined.

related to the tectonic emplacement of ophiolites in the internal zones to the east (Celet et al. 1976).

These external zones have been affected only by the Tertiary phase of deformation, and not by the earlier late Jurassic to early Cretaceous deformation phases of the internal zones; they are therefore particularly suitable for a study of the diagenetic or incipient-metamorphic effects of the later deformational phase.

Internal zones

In the more easterly, internal sub-Pelagonian or Othris zone (Smith & Moores 1974), Triassic to Jurassic platform (in northeast) to pelagic (in southwest) sediments (Othris Group of Smith et al. 1975; Maliaque zone of Ferrière 1976) regarded as a continental margin sequence were overthrust by the western Othris ophiolite complex and deformed in late Jurassic to Middle Cretaceous time (no rocks of Kimmeridgian to Albian age are present); these are discordantly overlain by Upper Cretaceous carbonate rocks and Maastrichtian-Paleocene "flysch" (Dinai Group of Smith et al. 1975).

Bernoulli & Laubscher (1972; see also Celet et al. 1976) have argued that the Othris ophiolite was emplaced from the east across the Pelagonian-sub-Pelagonian platform-continental margin sequence. However, careful studies of the variation in sedimentary facies (Hynes et al. 1972; Ferrière 1974, 1976; Smith et al. 1975) and of the vergence of structures in the Triassic-Jurassic Othris Group (Smith & Woodcock 1976; Smith et al. 1979) suggest that the ophiolite complex was thrust upon the platform sequence from the southwest to the northeast. This view has subsequently been incorporated by Ferrière & Vergely (1976) and Vergely (1976) in their "hypothesis of multiple origins" of the Hellenide ophiolites, ascribing the eastward thrusting of the Othris ophiolite ("antithetic orogenic system") to the lower-Cretaceous tectonic phase JE 2.

The Olympos window

In 1962 Godfriaux discovered that Mesozoic carbonate rocks and Middle Eocene "flysch" of the external zones - variously equated with the Parnassos (Godfriaux 1968), Gavrovo-Tripolitza (Aubouin 1973), or Maliaque (Celet et al. 1976) zones - are exposed in the Mt. Olympos window of northern Thessaly under a higher-grade metamorphic thrust unit, the greenschist-facies Flambouron unit of the Pelagonian allochthon (see Fig. 3).

If the Olympos sequence belongs to the Gavrovo-Tripolitza zone, the Olympos thrust must be at the base of the more internal Pindos zone, which may be squeezed out below it. However, if it is equated with the Parnassos sequence, Aubouin's scheme - in which the Parnassos zone is interposed between the Pindos and Othris zone in the south - would require that the Olympos thrust is at the base of the composite Othris-Pelagonian thrust sheet, whereas the Pindos zone was always to the southwest of Olympos (cf. section in Aubouin 1973).

Smith & Moores (1974) conclude that the correlation of the Olympos sequence with the Parnassos zone requires some modifications of Aubouin's paleogeographic

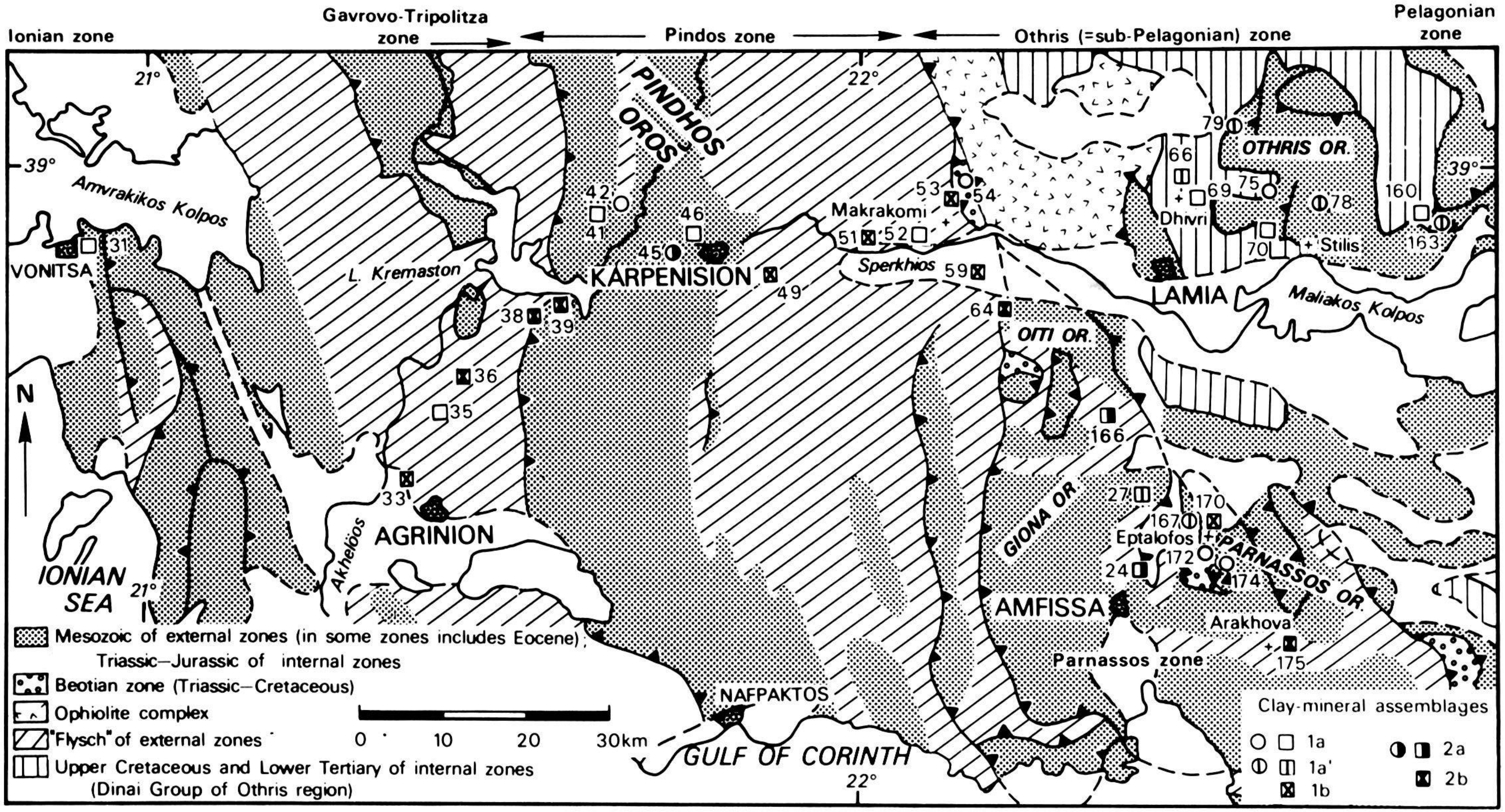

Fig. 2. Schematic structural map of central Greece, showing the numbered sample localities and clay-mineral assemblages. Square symbols: samples from "flysch" (external zones) or Upper Cretaceous–Lower Tertiary (Othris zone); round symbols: samples from the Middle Cretaceous "premier flysch" (Pindos zone), Beotian "flysch", or Triassic–Jurassic (Othris zone). Geology simplified after FANTINET (1977, Fig. 1). The Mouzakion area (province of Kardhitsa) – from which samples no. 90–94 were collected – is about 30 km north of the northern edge of the map.

synthesis; they suggest (p. 170; Fig. 5) that the Parnassos zone sensu stricto, further south, might merely be a large window of the Gavrovo-Tripolitza zone exposed through the Pindos and Othris (sub-Pelagonian) thrusts.

In all the above views, the thrusting of the Pelagonian allochthon across the Olympos is westwards; this requires southwestward transport of the sheet in the early Tertiary. However, BARTON (1975, 1976) has attributed *all* the deformation in the Olympos platform to the Tertiary emplacement of the Pelagonian allochthon *towards the northeast*, no earlier phase of deformation being in evidence; he concludes that the Pelagonian basement always lay to the west of the Olympos.

The Olympos unit is separated from the Flambouron unit on the western and southwestern side by a mylonitized zone ("zone broyée de Kokkinoplos" of GODFRIAUX 1968), which since has been recognized as a separate lower tectonic unit within the Pelagonian allochthon (DERYCKE 1976), correlated with the Ossa unit of the Lower Olympos and Ossa Mountains (GODFRIAUX in DERCOURT et al. 1977, p. 46-47) (see Fig. 3).

The Ossa unit shows widespread occurrence of lawsonite-albite and lawsonite-glaucophane-jadeite facies assemblages (DERYCKE et al. 1974; DERYCKE & GODFRIAUX 1976). The former assemblage (without glaucophane) occurs in the Paleogene (DERYCKE & GODFRIAUX 1977) "flyschoid series of Spilia", the highest stratigraphic member of the Ossa series, and in its equivalents in the mylonitized zones along the western and southwestern margin of the Olympos window. In the latter area lawsonite overgrows folds of the CT2 phase of Maastrichtian to pre-Middle Eocene age (DERYCKE & GODFRIAUX 1977), but is supposed to be older than the post-Middle Eocene thrusting of the Pelagonian allochthon upon the Olympos sequence (cf. MOORES & SMITH 1974, p. 77).

Along this western and southwestern margin of the Olympos window the difference in degree of metamorphism between the clastic rocks of the mylonitized Ossa unit and the tectonically underlying Eocene flysch of the Olympos window can be studied.

Purpose of the investigation

1. Comparisons of the degree of incipient metamorphism in the external zones of the Hellenides with that in the external zones of other orogenic belts, e.g. the Helvetides of the Swiss Alps (FREY 1969, 1970; KISCH 1980b), and the "Eastern Complex" of the central-Scandinavian Caledonides (KISCH 1978, 1980a).

2. Detection of any eastward increase in degree of incipient metamorphism from the more external to the more internal tectonic units; in this way, it might be attempted - among other things - to test SMITH & MOORES' (1974) theory that the Parnassos zone is only a large tectonic window of the Gavrovo-Tripolitza zone, exposed through the overlying Pindos and Othris thrusts (if the metamorphism of the Pindos nappe *preceded* the thrusting, it should show higher degree of metamorphism than the Parnassos zone, despite its presently more external position).

3. Comparison of the illite crystallinity in the "flysch" of the Upper Cretaceous-Paleocene Dinai Group in the Othris region to that in Triassic-Jurassic sedimentary units of the Othris Group, in order to detect possible metamorphic effects of the

Upper Jurassic to Lower Cretaceous phase of deformation and of an associated westward emplacement of the Othris ophiolite complex on the Othris Group sequence.

4. Establish the differences between the degrees of incipient metamorphism of the tectonic units within and around the Olympos window, i.e. between the Tertiary "flysch" of the Olympos sequence, and phyllites of the Ossa and Flambouron units thrust over them.

The methods used for the establishment of the degree of incipient metamorphism are mainly clay mineralogical and measurement of the crystallinity of illite, with some supplementary coal-rank (vitrinite reflectance) data.

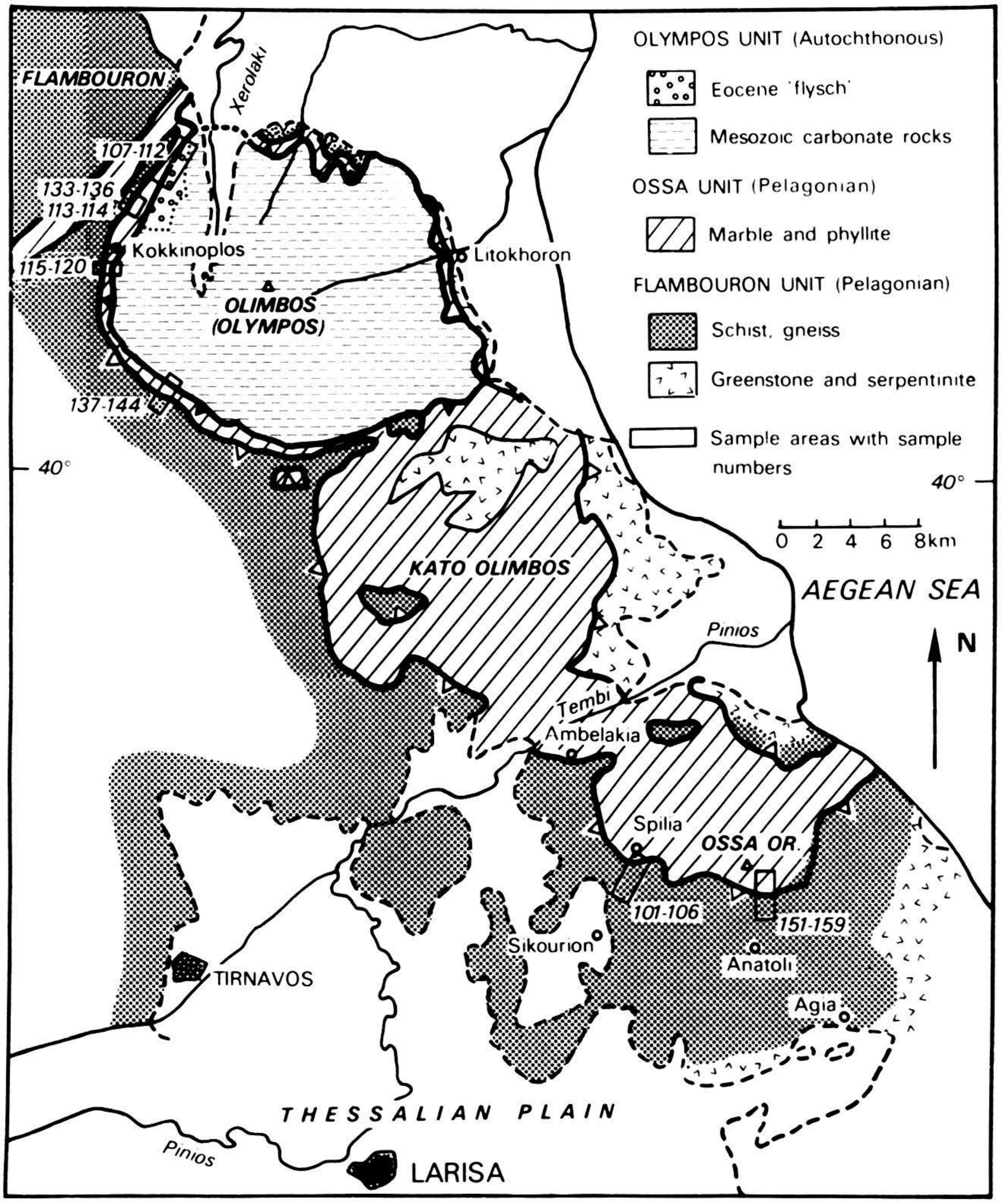

Fig. 3. Schematic structural map of the Ossa and Olympos areas (northern Thessaly, Greece), showing the sampled profiles. Geology after GODFRIAUX (1968; and in DERCOURT et al. 1977, Fig. 54).

Material studied

Sample localities in the external zones and the Othris zone of central Greece are shown on Figure 2. In the external zones, the main profile from Ionian through Gavrovo and Pindos flysch to Parnassos flysch was sampled along and off the west-east road Agrinion-Lake Kremaston-Karpenision-Sperkhios Valley-Lamia-Stilis (provinces of Akarnania, Evritania and Fthiotis). Since the Parnassos zone does not extend north of the Sperkhios Valley, the Parnassos flysch was collected further to the south, in the northern and southeastern Oiti Mountains; some further samples were collected even further to the south, in the Parnassos-Giona area (northeastern Fokis province). A total of 20 Tertiary flysch symples were analyzed.

For purposes of comparison, three samples were studied of the Middle Cretaceous "premier flysch" of the Pindos zone between Lake Kremaston and Karpenision, and west of Mouzakion (northern Pindhos, province of Kardhitsa, north of the area shown on Figure 2), and six of the Beotian flysch of late Jurassic to earliest Cretaceous ("Eocretaceous") age (cf. CELET et al. 1976) along the eastern margin of the Pindos zone in the Sperkhios Valley; west of Mouzakion (JÄGER & CHOTIN 1978); and near Eptalofos in the central Parnassos (CELET et al. 1974).

In the sub-Pelagonian or Othris zone most of the eight samples studied were collected in the central and southern Othris area, west of the "western limit of Tertiary deformation" of HYNES et al. (1972, Fig. 2). They were taken largely from the Triassic to Jurassic Othris Group, and from the Tertiary "flysch" (Dhivri Formation) of the discordantly overlying Dinai Group. A few samples were collected from the Triassic rocks of the Othris Group, and from the Upper Cretaceous rocks (Miloi Formation) of the Dinai Group in the Pelasghia-Miloi area in eastern Othris, close to the "western limit of Tertiary deformation".

Further north, in northern Thessaly, samples were collected of the Olympos "flysch" close to the thrust of the Pelagonian allochthon, from the overlying Ossa-unit ("mylonitized zone"), and of Flambouron-unit phyllites of the western and southwestern margin of the Olympos window (northeast of Kokkinoplos; Ritsos area), and of the Ossa unit in the Ossa Mountains proper. 23 samples were analyzed in detail. For sample localities see Figure 3.

Experimental methods and identification of clay-mineral phases

Methods of sample preparation and of conditions of X-ray diffraction analysis have been more fully described elsewhere (KISCH 1980a).

Identification of 14/7 Å phases

The development of an X-ray reflection at 11.9 to 12.8 Å upon K-saturation, with concomitant attenuation of the 14–15 Å reflection, was taken as indicative of smectite or vermiculite; in order to distinguish between these two minerals ethylene-glycol (EG)-saturation was applied (several hours at about 70 °C in EG vapour in a desiccator).

However, preliminary conclusions about the nature of the 14/7 Å phases could already be drawn from the intensity ratios of the 14–15 Å and the 7 Å reflections.

$I_{7Å} > I_{14Å}$ virtually always indicated chlorite (virtual absence of effects upon either K-saturation or EG).

Whenever $I_{14\text{-}15Å} >> I_{7Å}$, a 11.9–12.8 Å peak developed upon K-saturation, and 16.1–16.8 and 7.6–8.4 Å peaks upon EG-saturation, indicating a smectite mineral; residual peaks remaining at 14 and 7 Å after these treatments usually were in the ratio $I_{7Å} > I_{14Å}$ or $I_{7Å} \approx I_{14Å}$ indicating them to be due to minor chlorite. It is noteworthy that no 8.0 to 8.4 Å peak developed in the K-saturated fractions of these smectites: this distinguishes them from the regular mixed-layers discussed below.

Whenever $I_{7Å} \approx I_{14Å}$ or $I_{7Å} \gtrsim I_{14Å}$, this was invariably due to chlorite-smectite or chlorite-vermiculite mixtures, 14 Å always being weakened by K-saturation. Chlorite-smectite mixtures are distinguished by weakening of the 14 Å peak on EG-saturation (leaving a residual $I_{7Å} > I_{14Å}$) and development of a low-angle "tail" to this peak; chlorite-vermiculite mixtures by comparatively unchanged pattern upon EG.

Effect of mixed-layers on the half-height width of the 10 Å peak

The variable relationships between the 10 Å peak widths (B) of the K- and Mg-saturated fractions has been discussed elsewhere (Kisch 1980a, 1980b), and have mainly been ascribed to the differences in degree of resolution of peaks of mixed-layers (with low amounts of expandable layers) from the illite 10 Å peak.

Table: *Spacings and relative intensities of X-ray diffraction peaks of the mixed-layer phases in the − 2 μm fractions of representative chlorite-poor Ossa-unit phyllites of the western and southwestern margin of the Olympos window after various chemical and heat treatments. All intensities are with reference to the mica 10 Å peak (I = 10).*

Sample	Mixed-layer	unsat.	K-sat.	Mg-sat.	EG-Mg-sat.	EG-unsat.	550°C
137A	c-v	29.5(½)		30(1)			23(w)
	c-v	14.2(4▼)		14.3(2	14.3(2▲	14.0(2▲	11.6(vs)
	m-c		12.1(2△)	12.4(2	12.4(2	13.1(2▽	
	m-c	□(3/4	8.3(2▽	8.2(1□	8.2(1½	8.1(1bb	8.0(w□)
	c-v	7.14(1	7.4(½	7.2(1	7.2(1	7.16(3/4	
	c-v	4.82(½)	vw	vw	vw	4.72(vw)	
	c-v	3.56(1)				3.52(1¼	3.55(vw)
	m-c		3.45(1)	n.d.	3.51(3)	3.44(3/4	
119A	c-v	29.5(3)		30(2½)			22.3(mod)
	c-v	14.0(8◇)		14.3(7◇)	14.3(4½▲		11.7(vs)
	m-c		12.8(3½▲)		13.3(4▽	12.6(2▲)	
	m-c	9.1(3□	8.2(4½◆)	□(1½	8.0(3△	8.2(3bb▼)	7.9(w)
	c-v	7.0(2		7.2(2½	7.2(2		
	c-v	vw	vw	4.85(1½)	4.87(2)	vw	
	c-v	3.55(1½bb)		3.56(2½)		3.52(3	
	m-c		3.49(2▽)		3.52(4)	3.44(1	
141	c-v	31 (1)	30	31		31.5(½)	
	c-v	14.5(24)	14.3(17)	14.5(vs)	15.4(40)	15.5(40)	11.8(3)
	m-c?			11.6(1bb)			
	m-c?					8.6(1)	
	c-v	7.25(7)	7.3(5)	n.d.	7.62(9b▼)	7.7(12▼)	
	c-v	4.85(4)	4.87(3½)	4.80(b)	4.97(3)	4.91(3)	
	c-v	3.60(4▼)	3.64(3▼)	n.d.			
	m-c?				3.56Å	3.57(vw)	

△ low angle tail
▲ do, extending more than 1½°2θ from the peak position
▽ high-angle tail
▼ do, extending more than 1½°2θ from the peak position
◇ both high- and low-angle tail
◆ do, extending more than 1½°2θ from the peak position
bb very broad peak (>1½° 2θ at half height)
□ 7-10 Å plateau
} broad peaks, partly resolved (unresolved at half height)

In this regard it is of interest to note that the 10 Å peaks of the samples from the external zones almost invariably show *high-angle* tails after EG-saturation, indicating presence of expandable, smectitic interlayers in the illite.

In samples from these zones, the peak widths upon EG-saturation are generally narrower than those of either or both of the cation-saturated -2 µm fractions, and range 0.30 to 0.49° $\Delta 2\theta$ (with the exception of two illite-rich samples that show even lower $B_{EG\text{-sat}}$ values of around 0.24° $\Delta 2\theta$). In the samples with large values for $B_{Mg\text{-sat}}$ ($\gtrsim$0.50° $\Delta 2\theta$), $B_{K\text{-sat}}$ is with few exceptions smaller than $B_{Mg\text{-sat}}$, and $B_{EG\text{-sat}}$ is smaller than both due to the resolution of the mixed-layer plateau or high-angle tail from the main illite 10 Å peak. On the other hand, when $B_{Mg\text{-sat}}$ is small (about 0.30 to 0.40° $\Delta 2\theta$), $B_{EG\text{-sat}}$ is not very different in value, and both are similar to or smaller than $B_{K\text{-sat}}$, indicating that the Mg-saturation already sufficed for the resolution of the mixed-layer contribution from the 10 Å illite peak.

Regular mixed-layers

The "flysches" in and around the Olympos window are characterized by the widespread occurrence of 14/7 Å phyllosilicates resembling smectite in that $I_{14Å} >> I_{7Å} \approx I_{3.55Å}$ in the saturated and the Mg-saturated fractions. However, they differ from these minerals in that distinctive broad 12.2–12.9 Å and 8.0–8.4 Å peaks - possible submultiples of a 24–25.5 Å superlattice - become apparent in both the K- and EG-saturated fractions through the strong attenuation of the 14 Å and 7 Å peaks, as well as emergence of a 3.44–3.49 Å peak; in the Mg-saturated samples these peaks are usually insufficiently resolved from the adjoining strong 14 Å and 7 Å peaks.

Several of the chlorite-poor and chlorite-free samples moreover show a high-angle peak at 29–30 Å in the unsaturated and Mg-saturated fractions, which usually disappears upon K- and EG-treatment. Upon heating to 550 °C this feature shifts to 22.5–23 Å, while a very strong peak appears at 11.6–11.8 Å, submultiple of the 23.2–24 Å superlattice of a regular 9.8 $Å_{\text{collapsed smectite or vermiculite}}$/ 13.8 $Å_{\text{chlorite}}$ mixed layer. The position of major peaks of the -2 µm fractions of representative samples upon various treatments are given in the table; X-ray diffraction traces are given as Figure 4.

The presence of the 12.2–12.9 and 8.0–8.4 Å peaks in the K-saturated and EG-saturated (and to a lesser extent in the Mg-saturated and Mg-EG-saturated) fractions indicates presence of a 1:1 possibly partly ordered mica-chlorite mixed-layer. On the other hand, the 29, 14 and 7 Å peaks of the untreated and Mg-saturated fractions, which disappear (29 Å; often 14 Å) or are attenuated upon K- an EG-saturation (with a low-angle tail to 17 Å in the case of EG-saturation), must represent an ordered chlorite-vermiculite mixed-layer with various amounts of swelling chlorite or smectite layers (explaining the behaviour upon glycolation) similar to corrensite.

The presence of chlorite in addition to this mineral can be assessed from 14 Å and 7 Å peaks remaining after K- and EG-saturation, and from the retention of a 13.8 Å reflection after heating to 550 °C.

Results - external zones and Othris zone in central Greece

In view of the variability of the clay mineralogy and the comparatively few data available (38 samples analyzed in full), the data from the Ionic, Gavrovo, Pindos, Parnassos, Beotian and Othris zones will be discussed together. Sample localities and clay mineral assemblages are shown on Figure 2.

Clay-mineral assemblages and their distribution

Two main groups of assemblages may be distinguished: smectite-rich and smectite poor. The distinction between these assemblages are important since smectite and smectite-rich irregular mixed-layers tend to disappear in the course of burial diagenesis, and are absent in the anchizone.

1. Smectite-rich assemblages

1a. Major smectite, with very subordinate illite and illite-smectite mixed-layer "plateau" (between 10 and 14 Å); little or no chlorite ($I_{14Å} >> I_{10Å}$; $I_{14Å} >> I_{7Å}$).

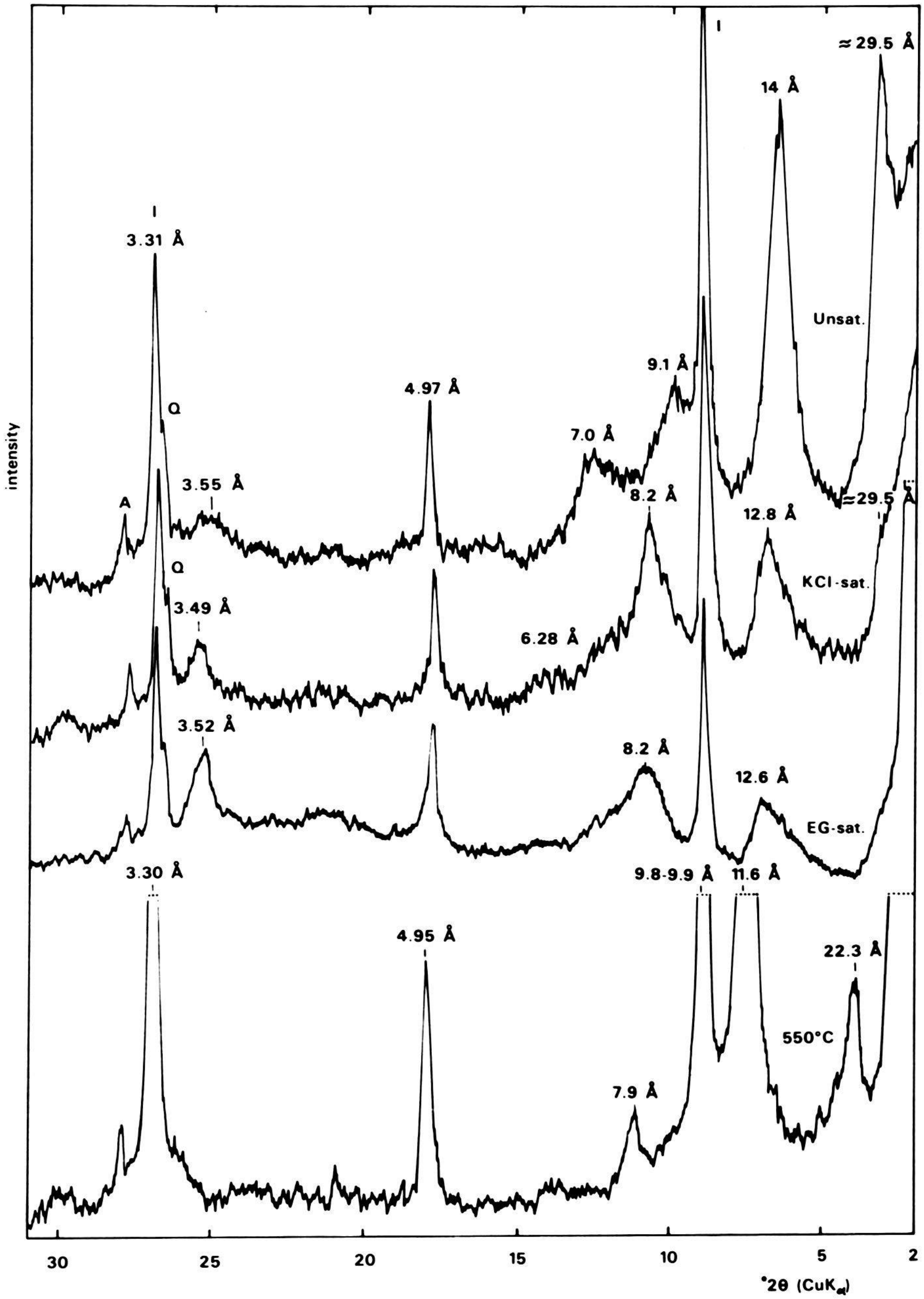

Fig. 4. X-ray diffraction traces of unsaturated, KCl-saturated, ethylene-glycol (EG) saturated (during 48 hours), and 550 °C heated (2 hours) oriented -2 µm fractions of sample containing partly ordered mica-chlorite and chlorite-vermiculite mixed-layers. Sample No. 119A from the "mylonitized zone' on the western margin of the Olympos window, south of Kokkinoplos (Stalamata section of GODFRIAUX in DERCOURT et al. 1977, p. 49). I = illite or muscovite; Q = quartz; A = albite or plagioclase.

This assemblage is common in the Ionian and Gavrovo flysch, and in both the Tertiary and the "premier flysch" of the external Pindos zone between Lake Kremaston and Karpenision, with major illite–smectite mixed-layer (No. 31A, 35A, 41A, 42A, 46A); it predominates in the red marls of the Beotian "flysch" (No. 54A, 90A, 172A, 174A), and in the Dinai Group of the Othris area (No. 69B, 70A, 160A). Locally it occurs in the internal part of the Pindos zone, e.g. west of Makrakomi (No. 52B), the "premier flysch" west of Mouzakion (No. 92B), and in the red radiolarian chert member of the Othris Group (No. 75A).

With major illite ($I_{10Å} \gtrapprox I_{14Å}$) a modification of this clay mineral assemblage (1a′) also occurs in red marls of the Parnassos zone (No. 27A, 167), in the Beotian "flysch" (No. 94A), and in both the Dhivri Formation (Dinai Group) (No. 66A) and the radiolarian chert and shale of the Othris Group (No. 78A, 79A, 163A) of the Othris area.

Chert and shale samples from the Othris Group in central Othris (No. 75A, 78A, 163A), and one Upper Cretaceous sample from the Dinai Group of eastern Othris (No. 160A) also contain a regular smectite–vermiculite mixed-layer with a diffraction peak at approximately 30 Å.

1b. Approximately equal amounts of chlorite, illite and smectite ($I_{7Å} > I_{10Å} > I_{14Å}$).

This clay-mineral assemblage is mainly restricted to flysch of the internal part of the Pindos zone east of Karpenision (No. 49A, 51A, 53A, 93A) and the Parnassos zone (No. 59A, 170A), with relatively little illite–smectite mixed-layer. It was found once in the Gavrovo "flysch" (No. 33A), with an appreciable illite–smectite mixed-layer "plateau".

2. Smectite-poor and smectite-free assemblages

2a. Major illite and minor smectite; little or no chlorite ($I_{10Å} >> I_{14Å}$; $I_{14Å} >$ or $>> I_{7Å}$). Found in the "premier flysch" of the Pindos zone (45 A), and in the Parnassos zone (166 A).

2b. Major chlorite and illite; very minor or no smectite ($I_{7Å} > I_{10Å}$; $I_{7Å} > I_{14Å}$).

This assemblage was found only in samples from the Gavrovo zone (No. 36A, 38A, 39A), from the Parnassos zone (No. 24A, 64A, 175A), and from the Beotian "flysch" (No. 90B).

It may be noted that the chlorite-rich samples are invariably rich in illite, with or without smectite.

Distribution of the smectite-bearing and smectite-poor clay-mineral assemblages in the external zones

Although the smectite-dominant chlorite-poor assemblage (1a) seems to be common among the more external samples studied, it locally occurs also in the internal part of the Pindos zone and in the red marls of the Parnassos zone (although with little illite–smectite mixed-layer), and predominates in the Beotian "flysch". Moreover, the smectite-bearing chlorite–illite assemblage (1b) seems to be widespread in the internal part of the Pindos zone, and to occur also in the Parnassos zone (with relatively little illite–smectite mixed-layer).

Smectite-rich and smectite-poor assemblages have been found in vicinity to each other in all zones: in the Gavrovo zone (No. 35A, 36A); west of Karpenision in the external Pindos zone (No. 45A, 46A); near Makrakomi (No. 52B, 53A) and west of Mouzakion (No. 92B, 93A) in the internal Pindos; west of the Parnassos (No. 24A, 27A), and in the Beotian "flysch" west of Mouzakion (No. 90A, 90B).

It seems, therefore, that there is no distinct tendency for smectite to disappear eastwards.

Illite 10 Å peak width

In most of the group (1a) assemblages, the presence of an illite-smectite mixed-layer plateau between the 10 Å and 14 Å peaks precludes measurement of the width of the 10 Å illite peak in the cation-saturated fractions. However, this plateau is largely removed to lower diffraction angles upon saturation with ethylene-glycol (EG), thus allowing measurement of the 10 Å peak, which then ranges between 0.32 and 0.49° $\Delta 2\theta$.

In the other, illite-rich clay-mineral assemblages the illite 10 Å peak widths can generally be measured in the cation-saturated samples, reflecting the lower content of illite-smectite mixed-layers than in the (1a) assemblages: they usually range from 0.31 to 0.95° $\Delta 2\theta$ in the K-saturated and up to 1.46° $\Delta 2\theta$ in the Mg-saturated fractions. However, upon EG-saturation all these peaks show appreciable narrowing, and usually development of high-angle tails; they then range from 0.23 to 0.46° $\Delta 2\theta$ (in all except two samples between 0.30 and 0.46° $\Delta 2\theta$).

Two samples from the internal Pindos (No. 53A and 93A, both with assemblage [1b]) show «anchizonal» peak widths, 0.26 to 0.35° $\Delta 2\theta$, in both the K-and Mg-saturated -2 µm fractions. However, their appreciable smectite content, and the presence of the smectite-rich (1a) assemblage in the close vicinity, seems to rule out an advanced degree of incipient metamorphism as suggested by the narrow 10 Å peak widths.

It was initially expected that the variations in clay mineralogy (particularly the smectite and illite-smectite mixed-layer content, and the illite crystallinity) might indicate a progressive incipient metamorphism eastwards. However, this expectation is hardly borne out by the following observations:

a) As set out earlier, smectite-bearing assemblages persist throughout the external zones, often in close vicinity to smectite-poor assemblages or in association with ostensibly high illite crystallinities (narrow 10 Å peaks).

b) The similarity of the 10 Å half peak width values of illites from all zones upon EG saturation.

All this is at variance with advanced diagenesis, let alone anchimetamorphism.

It is concluded, therefore, that these differences, both in illite crystallinity and nature of the 14 Å phases, mainly reflect variations in primary clastic clay composition and constitution of the illite and in extent of early-diagenetic alteration, rather than a progressive eastward advance in degree of burial-diagenetic or incipient-metamorphic modification, and that neither the internal Pindos "flysch" nor the Parnassos "flysch" has been "metamorphosed" beyond the stage of middle "diagenesis" (sensu KUBLER 1967): anchimetamorphism is not believed to have been attained anywhere in these zones.

Othris zone

The few samples investigated from the Othris region (8) are distributed over several formations, so that no far-reaching conclusions may be drawn; however, in view of the uniformity of the clay-mineral assemblages found, some general inferences are justified.

The smectitic clay-mineral assemblages (1a) and (1a′) were found in all the investigated samples - commonly with appreciable illite-smectite mixed-layer "plateaus" -, both from the Upper Cretaceous to Paleocene Dinai Group and in the Neraida Chert Member and the overlying Neochorion Formation (both Triassic) of the Othris Group, and both from the Dhivri, Neochorion and Stilis areas in central Othris and the Pelasghia-Miloi area in eastern Othris.

This overall degree of burial diagenesis is as low or lower than in the external zones and precludes appreciable incipient metamorphism as a result of either the late Jurassic-Middle Cretaceous or the Tertiary deformation phases.

Coal rank

Vitrinite reflectance was measured on grain mounts of 13 samples from the external zones of central Greece and the Othris area. For preparation and measurement procedures see references in Kisch (1980a).

Between 2 and 19 reflectance readings were obtained on 10 of these samples - 9 of Tertiary "flysch" (1 from the Ionian zone, 2 from the Gavrovo-Tripolitza zone, 2 from the Pindos zone, 3 from the Parnassos zone and 12 from the Othris zone), and 1 from the Othris Group. The mean sample reflectances in these 10 samples range from 0.44 to 0.65% $R_{m\ oil}$, corresponding to subbituminous B to high-volatile B bituminous coal ranks.

These ranks are markedly lower than the 0.85-1.3% R_{max} measured on shales associated with laumontite-bearing Taveyannaz Greywackes in the Helvetic zone of western Switzerland (Kisch 1980b), and in the lower part of the rank range of 0.44-1.4% R_m found associated with the zeolite facies in the Triassic sequences of the North Range and the Hokonui Hills of Southland, New Zealand (Kisch, in press). This low degree of diagenesis explains the abundance of smectite and high-smectite illite-smectite layers compared with their absence in association with the Taveyannaz Greywacke.

More importantly, it corroborates the very low degree of burial diagenesis in the external zones and the Othris zone of the central Greek Hellenides, and the absence of a distinct metamorphic gradient from west to east.

Results - western and southwestern margin of the Olympos window and the Ossa region

All rocks investigated from these areas showed appreciably narrower illite 10 Å peaks than the more external zones, the half-peak heights ranging from 0.18 to 0.30° $\Delta 2\theta$.

Differences can however be detected between the Olympos "flysch" on one hand, and the Ossa unit of the margins of the Olympos window and the Ossa area itself on the other: the cation-saturated peak widths in the Olympos flysch - with the exception of one weathered specimen - are 0.24-0.29° $\Delta 2\theta$ (e.g. samples 107A to 112A; 132A), whereas all the K-saturated and most of the Mg-saturated -2 µm fractions from the Ossa unit of the "mylonitized zone" (e.g. samples 113A-X to 120; 133; 135A to 141) and of the Ossa itself show narrower peak widths of $\leq 0.24° \Delta 2\theta$. However, these differences are much smaller than was expected from the assumption of thrusting of an already metamorphosed thrust sheet (the Ossa unit) over nonmetamorphic Olympos "flysch".

Common between the two units is the widespread occurrence of 14/7 Å phyllosilicates showing marked 12.2-13.0 Å and 8.0-8.4 Å peaks upon K-saturation, and 12.4-12.7 Å and 7.7-8.3 Å peaks upon EG-saturation, earlier concluded to be partly ordered mica-chlorite and corrensite-like regular chlorite-vermiculite mixed-layers with various amounts of swelling chlorite and smectite layers.

Two assemblages containing these minerals can be distinguished:

a) With $I_{14Å} >> I_{7Å}$, usually showing the low-angle peak or shoulder at 29-31 Å. The strong 14 Å and the weak 7 Å peak almost disappear upon K-saturation and upon heating to 550 °C, indicating the virtual absence of chlorite (samples 113A-X, 117, 119A, 132A, 137A and 141 - i.e. mainly in the Ossa-unit phyllites). X-ray diffraction traces are shown on Figure 4.

b) $I_{14Å} >$ to $\approx I_{7Å}$; these reflections (particularly 14 Å) are attenuated but do not disappear upon appearance of the 12.6-13.0 and 8.0-8.4 Å reflections due to K-saturation, but their relative intensities have invariably become $I_{7Å} > I_{14Å}$, indicating them to represent "residual" chlorite. Presence of chlorite in these assemblages is also apparent from the retention of the 13.8 Å reflection in some of the samples heated to 550 °C (in contrast to the chlorite-free assemblages), in addition to the marked 12.3 Å peak representing the "collapsed" regular mixed-layer (samples 107A, 109A, 110A, 112A and 115 - mainly in the Olympos "flysch").

The significance of these mixed-layers is not clear at this stage. Partly ordered biotite-chlorite mixed-layer reported by EROSHCHEV-SHAK (1970) is thought to have formed during epigenesis from hydrobiotitic weathering products of biotite in a gneiss, whereas partly ordered di-octahedral mica (sericite) - chlorite (sudoite) with small amounts of interlayered expandable layers - and somewhat similar properties to the mixed-layers found around the Olympos window - has been described from the hydrothermal alteration zone of a Kuroko deposit by SHIROZU et al. (1971).

The corrensite-like ordered chlorite-vermiculite mixed-layer with various amounts of swelling chlorite or smectite layers is probably a progressively-metamorphic mineral; corrensite has been reported as an anchimetamorphic formation (KUBLER 1973); alternatively, it might possibly constitute a "hydrobiotite-like" breakdown product of biotite.

The samples from the southern summit region of Ossa appear to be somewhat more crystalline than those from the margin of the Olympos window, and from the southwestern Ossa (Spilia area): the peak widths are less than 0.21° $\Delta 2\theta$ in all four samples investigated, $I_{14Å} < I_{7Å}$ (indicating chlorite), and expanding minerals are absent. The sample with the broadest peak (No. 154A) contains distinct paragonite, which may account for the peak broadening; if this sample is disregarded, the 10 Å peak widths are less than 0.19° $\Delta 2\theta$ in the cation-saturated fractions of the three remaining samples – "epizonal" in KUBLER's scale.

A few samples of the Flambouron schists were studied for comparison. The three samples X-rayed (one each from the Kokkonoplos, Ritsos and Spilia-Sikourion areas) were distinguished by the total absence of *any* 14–7 Å phase, and in two cases – No. 135A from Kokkinoplos and No. 143 from Ritsos – by the presence of stilpnomelane, with its characteristic reflection at 12.4–12.5 Å.

Conclusions and tectonic implications

The main result of the present investigation is the recognition of the low degree of burial metamorphism and the absence of a distinct burial-metamorphic zoning in the Lower Tertiary flysch of the external zones and the Othris zone of central Greece, in contrast to an appreciable degree of incipient metamorphism in the Tertiary of the Olympos and Ossa regions.

External zones

The low degree of burial metamorphism in the external zones is in contrast also to that found in the external zones of some other orogenic belts. The anchimetamorphism in some of these belts has been related by this writer to the former presence of higher tectonic nappes or thrust sheets, e.g. of the Seve-Köli nappe complex on the Cambro-Silurian Jämtland Supergroup of the Scandinavian Caledonides (KISCH 1978, 1980a), and of Pennine nappes on the Helvetic nappes of eastern Switzerland (KISCH 1980b).

Insofar as this tectonic interpretation is correct, the very low degree of burial metamorphism in the external zones of the central Greek Hellenides indicates that no such overlying nappe was ever present, i.e. that the thrust sheets of the Pelagonian zone never extended over the external zones in central Greece.

Othris area

The equally low degree of burial metamorphism, and the absence of a clear discontinuity in degree of incipient metamorphism between the Othris Group sequence and the discordantly overlying Dinai Group indicates that the intervening late Jurassic to early Cretaceous deformation phase – which is related to the emplacement of the Othris ophiolite complex (the Mirna Group of SMITH et al. 1975) onto the Othris Group – did not cause appreciable regional incipient metamorphism. This makes an emplacement of the Othris ophiolite complex from east to west across the Othris zone (BERNOULLI & LAUBSCHER 1972) unlikely, and seems to corroborate emplacement from the west (e.g. HYNES et al. 1972; SMITH & WOODCOCK 1976).

The degree of early Tertiary incipient metamorphism is negligible throughout: there is no evidence for an eastward increase in intensity towards the "western limit of Tertiary deformation" of HYNES et al. (1972, Fig. 2) in eastern Othris.

Olympos region

We have noted the similarity in the illite crystallinity and other clay-mineralogic features of the Olympos "flysch" within the window, and the overlying Ossa-unit phyllites at the western and southwestern margin of the Olympos window: the anchimetamorphic illites and the common occurrence of regular chlorite-vermiculite or chlorite-smectite (or possibly vermiculite-swelling chlorite) mixed-layers.

The lawsonite-albite facies metamorphism in the "flyschoid series of Spilia", reported by DERYCKE et al. (1974) and DERYCKE & GODFRIAUX (1976) is compatible with the anchimetamorphism of the phyllites in the same unit (KISCH 1974), and is presumably contemporaneous.

However, DERYCKE et al. (1974) have noted the overprinting relationships of metamorphic assemblages in the Pelagonian allochthon of the Ossa and Lower Olympos (Kato Olympos), DERYCKE & GODFRIAUX (1976) briefly note the polyphase nature of the lawsonite-albite and the lawsonite-glaucophane-jadeite assemblages in the Ossa unit. From amphibolites and phengite-schists and -gneisses of the Flambouron unit around Sikourion (southwestern Ossa) and the Lower Olympos DERYCKE et al. (1974) have described greenschist-facies assemblages separated from glaucophane-bearing rocks - presumably of the "flyschoid series of Spilia" - by mylonitic breccias the cement of which is overgrown by high-pressure assemblages; this relationship shows that at least the second phase of glaucophanitic metamorphism is younger than both the greenschist-facies metamorphism (DERYCKE & GODFRIAUX 1976; see also GODFRIAUX in DERCOURT et al. 1977, p. 45), and the subsequent deformation phase juxtaposing the Sikourion rocks (Flambouron unit) and the "flyschoid series of Spilia" (Ossa unit).

The later high-pressure metamorphic phase is considered by DERYCKE & GODFRIAUX (1976; see also GODFRIAUX in DERCOURT 1977, p. 45) to be *"penecontemporaneous"* with the post-Maastrichtian but pre-Middle-Eocene thrusting of the Flambouron unit upon the Ossa unit, and older than the post-Middle-Eocene emplacement of both these units (= Pelagonian allochthon) on the Olympos sequence. The discovery of Paleocene fossils in the "flyschoid series of Spilia" (I. Godfriaux 1977, oral comm.) show that the metamorphism in this unit and its equivalents in the "mylonitized zone" around the Olympos window cannot be older than late Paleocene; according to SMITH & MOORES (1974, p. 177) this phase is possibly post-part Eocene.

It is inconceivable that the Olympos "flysch", the highest term in the Olympos sequence, could have undergone such metamorphism without overburden. This leaves two possibilities:

1. One can accept DERYCKE & GODFRIAUX' (1976) pre-Middle-Eocene age of the lawsonite-albite metamorphism. This implies that its compatibility with the similar degree of anchimetamorphism in the "flyschoid series of Spilia" and in the Olympos "flysch" is a mere coincidence, and that they took place at different relative positions and times, respectively as a result of the post-Eocene and pre-Middle-Eocene emplacement of the Flambouron unit upon the Ossa unit, and of the post-Middle-Eocene emplacement of both upon the Olympos sequence.

2. However, the overprinting relationships of the younger high-pressure assemblages on the cements of the mylonitic breccias and on CT2-phase folds in the "flyschoid series of Spilia" (I. Godfriaux 1977, oral comm.), both of which are considered pre-Middle-Eocene by DERYCKE & GODFRIAUX (1976) and must be post-Paleocene in view of the age of the "flyschoid series of Spilia" only give a *maximum age* for this metamorphism. Contrary to DERYCKE & GODFRIAUX' (1976) views, these relationships allow for a younger, possibly post-Middle-Eocene age for this high-pressure metamorphism. Thus, it may be argued that the lawsonite-albite facies metamorphism - if contemporaneous with the anchimetamorphism of the phyllites and the Olympos flysch - is younger than claimed by DERYCKE & GODFRIAUX.

Moreover, BARTON (1976) has reported a metamorphic fabric in the phyllonites of sedimentary origin at the base of the upper unit (presumably equivalent to the "mylonitized zone" of GODFRIAUX) at the northwest margin of the Olympos window; the extent and age of recrystallization during emplacement of the Pelagonian sheet is indicated by a whole-rock isochron of 40 m.y. (late Eocene) found by BARTON on eight phyllonites within the lower 20 m of this upper unit, which marks the thrust.

There are therefore strong arguments for the view that the similarity in the degree of anchimetamorphism in the "flyschoid member of Spilia" and in the Olympos "flysch" close to the thrust reflects their common post-Middle-Eocene (probably late Eocene) lowest-grade metamorphic evolution during or after the emplacement of the Pelagonian allochthon upon the Olympos sequence.

It is attractive to attribute this metamorphism to the effects or after-effects of the overthrusting: either to frictional heat, or to increased load pressure and perturbation of the geothermal gradient, followed by the gradual restoration of the geothermal gradient perturbed by the thrust (after OXBURGH & TURCOTTE 1974).

In order to make a case for frictional heat, one would have to show that the anchimetamorphism in the Olympos "flysch" is very closely related to distance from the thrust zone. Since the Olympos "flysch" has been collected only close to the mylonitized zone, no data on this point are available from the flysch itself, and further collecting is required. However, the degree of recrystallization may very well in part be related to the degree of internal deformation, which decreases away from the thrust surface and is reported by BARTON (1975) to be weak in all but the structurally highest sheet within the platform. Such localized heating, resulting in Rb/Sr homogenization and metamorphic fabric close to the thrust, ist favored by BARTON (1975).

Recently, BARTON & ENGLAND (1979), using calcite-dolomite geothermometry on the Olympos-platform carbonates, have concluded to an inverted thermal gradient below the Olympos thrust (– 50 °C/km in the uppermost 1 km), which they interpret as a result of shear heating accompanying emplacement of the Pelagonian allochthon.

However, anchimetamorphism of the Olympos "flysch" as a result of loading and subsequent thermal relaxation under the overthrust Pelagonian allochthon, after OXBURGH & TURCOTTE (1974) remains an alternative explanation.

OXBURGH & TURCOTTE (1974) have pointed out that in a thrust sheet an initial cooling to a temperature close to one half the initial temperature takes place within a few million years after thrusting. This temperature minimum occurs progressively later upwards in the thrust sheet; it is followed by a steady temperature increase at all depths. In the basement immediately beneath the thrust sheet, the temperature will rise rapidly to about half the initial temperature at the base of the thrust, followed by slower heating. Near the interface below a thrust sheet 10 km thick, the temperature after 10 and 20 m.y. would be respectively 0.71 and 0.78 times the initial temperature.

The heating of the basement at high pressure, and the initial rapid cooling of the base of the thrust sheet, both at essentially constant high pressure, could account for the high-pressure metamorphism in the Ossa unit, and with simultaneous metamorphic dehydration of the basement for the polyfacial succession of higher-temperature greenschist-facies and lower-temperature but high-pressure blueschist-facies metamorphism in the Flambouron unit of the Pelagonian of the Ossa and the Lower Olympos.

England & Richardson (1977) have pointed out that metamorphism of a tectonically thickened continental crust or sediment wedge "is likely to take place in a thermal regime where temperature increases by conductive relaxation whilst concurrently pressure decreases by erosion of the pile". The actual metamorphic conditions registered near the interface will therefore depend on the onset and rate of uplift: extended thermal relaxation would result in progressively higher-temperature metamorphism, whereas early and rapid uplift would result in "quenching" of the initial low-temperature, high-pressure metamorphism.

Although no detailed data are available on the uplift history of the Olympos region, the presence of pebbles of Pelagonian origin (cf. Brunn in Aubouin et al. 1963) in the clastic Lower Oligocene to Miocene "molasse" sequence of the late-tectonic Meso-Hellenic trough - largely deposited on the former sub-Pelagonian zone to the west - suggests that rapid uplift of the Pelagonian zone started comparatively soon after the thrusting (cf. Smith & Moores 1974, p. 179).

This interpretation would still require that the base of the Pelagonian thrust sheet was, at or before the time of thrusting, at a higher temperature than was ever attained by the uppermost part of the underlying Olympos sequence (the Olympos "flysch"); a somewhat greater difference in degree of incipient metamorphism than actually found would be expected in the "flyschoid series of Spilia" than in the Olympos "flysch".

We may try to account for this apparent inconsistency by suggesting that the strong folding of the Ossa unit, and its overthrusting by the Flambouron unit took place only a comparatively short time earlier - possibly as little as 6 m.y., the duration of the Middle Eocene (Lutetian). As a consequence, the perturbation of the geothermal gradient as a result of this earlier thrusting had not yet relaxed, so that the temperatures in the lower part of the Pelagonian allochthon were still low (explaining why no greenschist facies was apparently ever attained in the Ossa unit).

More study of phyllosilicate mineralogy in the Olympos "flysch" further removed from the Pelagonian thrust, and radiometric ages from the "flyschoid series of Spilia" will be required to decide between the various alternatives.

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