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The structure and regional significance of the Talea Ori, Crete

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Abstract—On the basis of detailed geological mapping in the Talea Ori of Crete, metamorphic rocks previously interpreted as basement to the Plattenkalk Series are re-interpreted as down-faulted parts of the overlying Phyllite–Quartzite Series nappe. A supposed unconformity separating these two units is shown to be a high-angle fault. The Phyllite–Quartzite Series and overlying nappes were affected by two major deformational phases, whereas the Plattenkalk Series has a simpler structural history and was folded and imbricated by southwards-directed overthrusting which emplaced the Phyllite–Quartzite Series nappe and other overlying nappes in the Oligocene. We reject previous models of a huge inversion of the Plattenkalk Series and we also consider that considerable local inversion by tight to isoclinal folding and thrusting means that the stratigraphic thickness is much less than previously appreciated. The differences between the structural and sedimentological histories of the Plattenkalk Series and the overlying nappes implies that they were separated by a major crustal discontinuity, such as a transform or transcurrent fault, before the Oligocene overthrusting.

INTRODUCTION

CRETE consists of a structural pile within which up to seven major nappes and several minor slices have been recognized. The nappes were emplaced between the early Eocene and early Miocene and the nappe pile uplifted in the Miocene. Subsequently, the whole island has been extended by normal faulting which is related to Neogene and Quaternary extension in the region north of the Hellenic Trench complex (Fig. 1). As a consequence Crete now has the form of a number of uplifted blocks bounded by grabens which trend approximately E–W and N–S (directions which are approximately parallel and normal to the Hellenic Arc).

The Talea Ori of north central Crete (Fig. 1) is one of the horst blocks in which the three lowest units of the Cretan nappe pile are exposed. These are (proceeding downwards): the Tripolitza nappe, the Phyllite–Quartzite nappe, and the Plattenkalk Series. The upper two units are generally agreed to be allochthonous although there is some controversy surrounding their original relative palaeogeographic relationships (see for example, Bonneau 1973, Kuss & Thorbecke 1974, Aubouin *et al.* 1976, Jacobshagen *et al.* 1978). In the Talea Ori region the Tripolitza nappe includes well-bedded, shallow-marine limestones and dolomites with local stromatolitic horizons, generally unfossiliferous due to extensive recrystallisation and fracturing. The Phyllite–Quartzite nappe includes a variety of lithologies: basic volcanics, carbonates and siliciclastic sediments, which

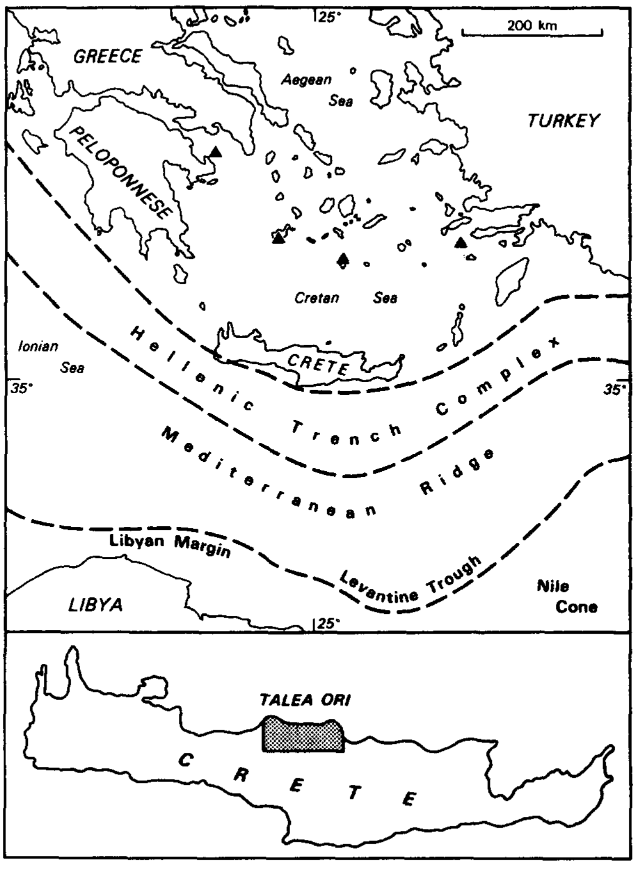


Fig. 1. Location of Crete in the context of principal tectonic units in the Eastern Mediterranean. Triangles are Plio-Pleistocene volcanoes. The stippled area of the inset map is the area of the Talea Ori shown in Fig. 2.

have suffered polyphase deformation and low-grade regional metamorphism. The Plattenkalk Series consists of a sequence of dolomites and limestones almost entirely devoid of terriginous debris. Its tectonic status on Crete is not certain because it is the lowermost unit exposed on the island and it has proved difficult to determine whether or not it is autochthonous. The Talea Ori region is particularly significant because it includes the oldest part of the Plattenkalk Series sequence exposed on Crete and the suggestion has been made that in this region a pre-Norian metamorphosed basement to the carbonate sequence can be observed (Epting *et al.* 1972). We have re-mapped this critical region at a scale of 1:20,000 in order to test this suggestion and previous hypotheses concerning the structure of the region. Our mapping has resulted in a considerable revision of the structure of the region and the relationship of the Plattenkalk Series to its supposed basement, and leads to a re-interpretation of the structural development of the island.

PREVIOUS INTERPRETATIONS OF THE TALEA ORI

Previous interpretations of the Talea Ori are based on the mapping of Epting *et al.* (1972) who claim to have recognized a continuous stratigraphic sequence from late Permian through to at least Jurassic age. The older part of this sequence was divided by them into several units and includes shallow marine carbonates and siliciclastics of late Permian to early Triassic age (recent palaeontological work has extended the lower age limit of this sequence to early Permian: König & Kuss 1980). These rocks are said to be overlain, with an angular discordance, by Norian stromatolitic dolomites which pass up into Jurassic cherty limestones ('Plattenkalk'). Epting *et al.* (1972) attributed the angular unconformity to late Hercynian deformation with erosion and/or non-deposition in the late Triassic. They also considered that Alpine metamorphism of upper-greenschist facies is responsible for recrystallization of carbonates and conversion of the siliciclastics to phyllites. Because no rocks of Palaeozoic age had previously been recognized at the base of the Plattenkalk carbonates they proposed the term 'Talea Ori Series' (synonomous with 'Talea Ori Group' of Kuss & Thorbecke 1974, and 'Ida Series' of French workers) to include all the Palaeozoic and Mesozoic rocks of this sequence. Creutzburg & Seidel (1975) prefer to use the term 'Plattenkalk Series' on the grounds of historical priority and this is the term we have continued to use.

On the basis of inverted sedimentary structures in the lower part of the Plattenkalk carbonates, Epting *et al.* (1972) suggested that the entire sequence was inverted by Alpine folding. Bonneau (1973) shows this as the inverted northern limb of a huge syncline with an axis trending approximately E–W overturned to the south and facing south, with a wavelength of several kilometres. Kopp (1978) stated that this sequence '. . . forms the strongly overturned limb of an anticline 30 km in length, the northern limb of which is cut off by a nappe thrust'.

Problems with previous interpretations

Our reconnaissance work in Crete in 1979 caused us to have doubts about previous interpretations of the Talea Ori region. No other regions have been reported from Crete where such extensive inversion of strata is observed and where overturned folds of such dimensions are suggested. We found that the metamorphosed siliciclastic and carbonate rocks were highly deformed yet there appeared to be little recognition of this on the previously published map of Epting *et al.* (1972). Units of variable facies were defined and mapped and a continuous, albeit inverted, sequence was assumed despite the complex history of deformation and metamorphism and despite the paucity of fossils. We found it difficult to reproduce the thicknesses estimated for many of the units recognized using the published outcrop widths and observable repetition by folding; there appeared to be a considerable overestimate of stratal thicknesses. Estimated thicknesses of almost 3 km for the carbonate part of the Talea Ori Series also appeared to be at variance with our observations suggesting a transition from a very shallow marine, to a deeper marine, slowly accumulated sequence. Some of the units mapped were defined in stratigraphic terms while shown to be thrust bounded and truncated at the late Triassic unconformity, implying a major intra-Triassic orogenic event not known elsewhere in the region. Finally, the Permo-Triassic part of the Talea Ori sequence appeared to be lithologically very similar to metamorphosed Permo-Triassic rocks of the Phyllite–Quartzite nappe which structurally overlies the Plattenkalk Series elsewhere on the island. Consequently, we remapped the Talea Ori region using lithological units as the basis for our mapping. The resulting map (Fig. 2) is significantly different from that of Epting *et al.* (1972).

RESULTS OF THE REMAPPING

We have separated the area into two lithological groups which for simplicity we refer to here as the Plattenkalk Series and the metamorphic rocks. This is not intended to imply that the Plattenkalk Series is unmetamorphosed. It is a useful lithological division because it separates a carbonate sequence virtually devoid of siliciclastic material (Plattenkalk Series) from lithologically more varied rocks which include subordinate and generally impure carbonate rocks. It is also a significant structural division since it separates two groups of rocks with entirely different structural histories: the Plattenkalk Series is deformed by only one phase of folding and thrusting whereas the metamorphic rocks have a polyphase deformation history.

The boundary between these two groups of rocks was regarded as an unconformity by Epting *et al.* (1972) but

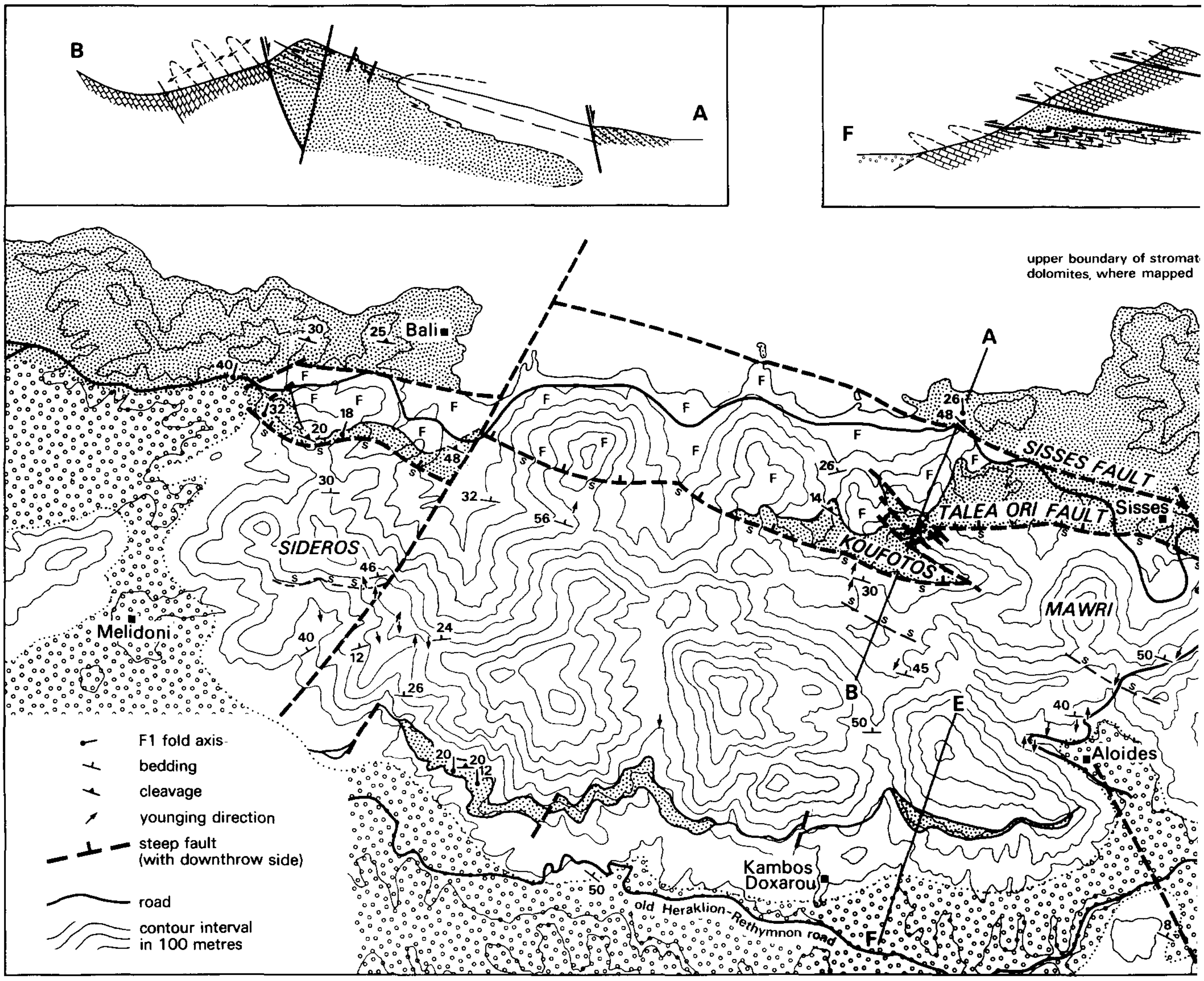
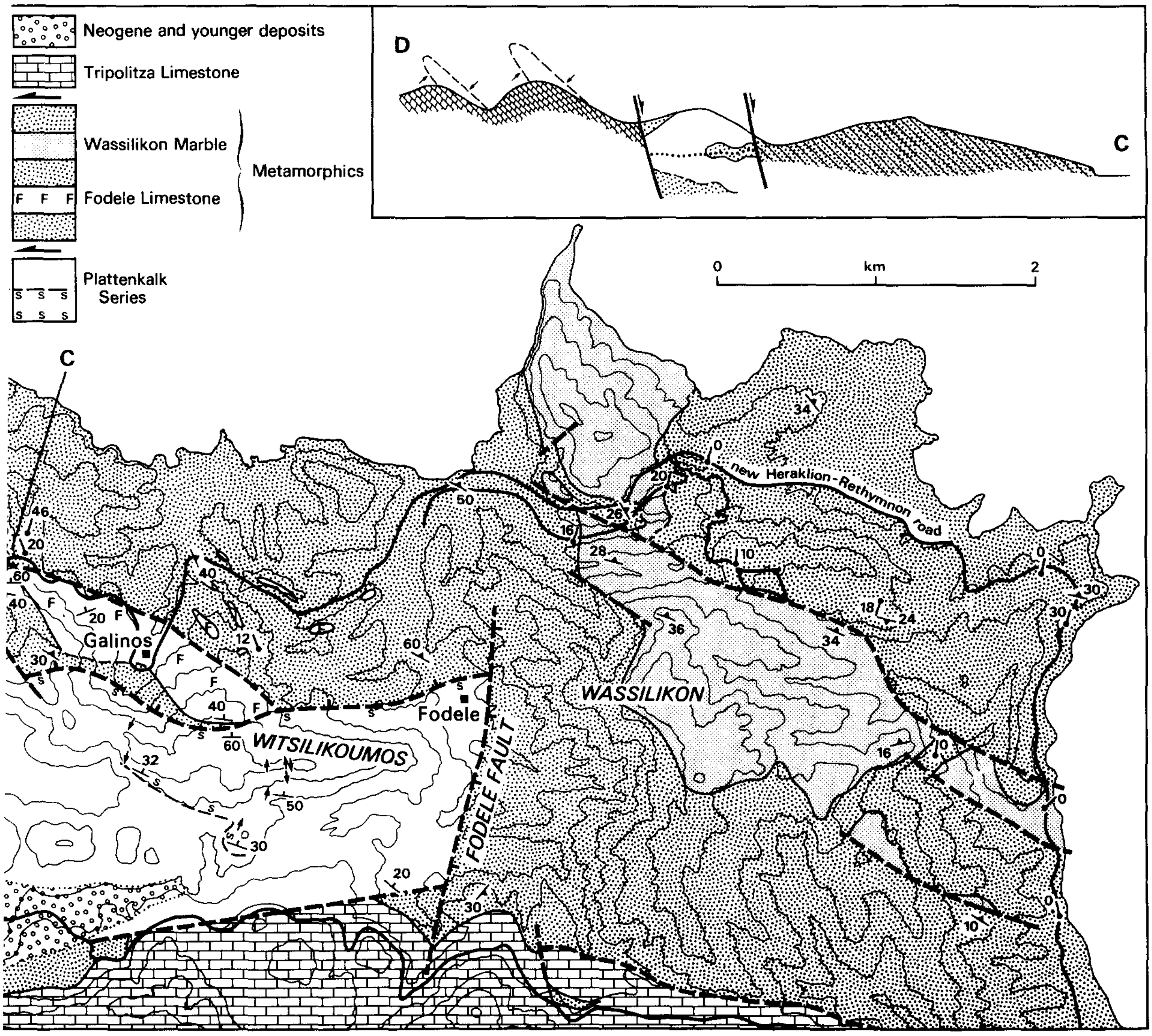


Fig. 2. Geological map of the Talea Ori based on 1:20,000 scale mapping. Cross-sections are drawn with vertical and horizontal scales equal, but at about twice the scale of the map.


Neogene and younger deposits
Tripolitza Limestone
Wassilikon Marble
Fodele Limestone
Metamorphics
Plattenkalk Series
D
C
0
km
2
C
new Heraklion-Rethymnon road
Galinos
Fodele
WITSILIKOUMOS
WASSILIKON
FODELE FAULT
46
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our mapping (Fig. 2) shows it to be a steeply northwards-dipping fault trending roughly WNW–ESE and referred to here as the Talea Ori fault. This interpretation is consistent with its simple outcrop pattern, its locally observable attitude, and the fact that it truncates structures and lithological units in both the Plattenkalk Series and the metamorphic rocks. In view of these observations we have searched carefully for evidence of the angular unconformity claimed by Epting *et al.* (1972) and examined the conglomerate-filled karstic solution pocket illustrated schematically by them (p. 266) and interpreted as evidence of this unconformable relationship. The metamorphic rocks north of the Plattenkalk Series in the Koufotos area (Fig. 2) include onkoidal carbonates, dolomitic conglomerates, chlorite–carbonate phyllites, dolomitic phyllites and dolomitic quartzites; all are highly flattened and show evidence of two major phases of deformation (see below). Fragments of these rocks are found in the breccio-conglomerate of Koufotos, together with clasts of the stromatolitic dolomites of the Plattenkalk Series which are younger than the supposed unconformity. Furthermore, the conglomerate can be traced for only a short distance along the contact, and according to the illustration of Epting *et al.* (1972) and our own observations the conglomerate itself is undeformed although individual clasts were deformed before incorporation. We, therefore, regard this solution pocket as a Neogene feature filled by locally derived material; similar Neogene breccio-conglomerates are quite common, often high in the Talea Ori, suggesting that the present landscape is a rejuvenated Neogene feature. Only on the north side of Witsilikoumos, southeast of Galinos, have we observed a deformed dolomitic conglomerate at the contact between the Fodele limestone and the Plattenkalk Series. As on Koufotos the conglomerate cannot be traced along the contact for more than a few metres, and since both the lower part of the Plattenkalk Series and the metamorphic rocks include several lithologically similar conglomerate bands we interpret this as one of those bands truncated by the fault.

The Talea Ori fault is one of several steep faults that cut the Talea Ori horst-block into several smaller fault blocks. We suspect the presence of others not shown on the map but we have been unable to prove their presence without aerial photographs in areas of little lithological contrast. All these faults are of Neogene to Quaternary age. They are not peculiar to the Talea Ori but are common to all of Crete and the southern Aegean and are related to Neogene–Quaternary crustal extension. Where a sense of movement can be determined they prove to be normal faults. Their effect in the Talea Ori is to complicate mapping since they juxtapose lithologies from different structural levels. Two other major faults have been named for the purpose of description: the Fodele fault runs roughly N–S through Fodele village, terminates the Plattenkalk Series exposed to the west, and to the east causes the appearance of metamorphic rocks which are not exposed elsewhere in the Talea Ori, probably by downthrow from higher structural levels. The Sisses fault is sub-parallel to the Talea Ori fault and about 2 km to it north, also dips northwards, and is also probably a normal fault. It is truncated by the Talea Ori fault just west of Fodele.

Structure of the metamorphic rocks

A number of problems handicap an understanding of the sequence and structure of the metamorphic rocks. In general, they are very poorly exposed and deeply weathered and, therefore, we have had to rely heavily on road sections and such parts of the coast as are accessible (much of the coast is steep, high cliffs). There are only two distinctive lithological markers which can be mapped across the area: the Wassilikon marble and the Fodele limestone. Except for the Fodele limestone, which locally is highly fossiliferous, fossils are rare and it is not possible to erect or map formal stratigraphic units as attempted by Epting *et al.* (1972). We have discovered no way-up criteria in any of the lithologies in the metamorphic rock sequence and finally, the presence of steep faults inhibits the correlation of lithologies across the area (see above).

Two major deformational phases are recognizable in the metamorphic rocks. The earliest recognizable episode (*D*1) has produced a penetrative cleavage (*S*1) which is axial planar to tight to isoclinal mesoscopic folds with approximately N–S fold axes (Fig. 3a). The cleavage dips at a low angle, and the fold axes plunge at a low angle, both generally northwards, although with local variation due to the effects of later deformation. The *S*1 cleavage is variably developed and depends on lithology: pelitic rocks and impure carbonates have acquired a good penetrative cleavage, whereas in pure carbonates, quartzites and conglomerates the cleavage is poor or absent. For example, the volcanic rocks vary from greenschists with no relict igneous features to massive greenstones with only a widely spaced cleavage and containing relict igneous pyroxenes and igneous features such as amygdales, albeit somewhat flattened. We suspect, but have been unable to prove because of the absence of way-up criteria and lithological markers, and the effects of later deformation, that the *D*1 episode may also have caused very large-scale isoclinal folding of the metamorphic rocks.

The second deformational episode (*D*2) is variably developed in the Talea Ori. Where recognizable its most consistent feature is an approximately E–W fold axial direction with a low plunge. Both the style and degree of development of the *D*2 structures vary considerably, again partly controlled by lithology. East of the Fodele fault and north of the Sisses fault, *D*2 folds are generally observed in interlaminated thin quartzites or limestones and phyllites. They are tight to open, asymmetrical folds overturned southwards and have a gently northwards-dipping axial planar crenulation cleavage. In thick slate sequences the *D*2 episode has usually produced only a crenulation of the *S*1 cleavage, whereas in thick quartzites no folds are observed and the *D*2 deformation has been accommodated by shearing and slip along

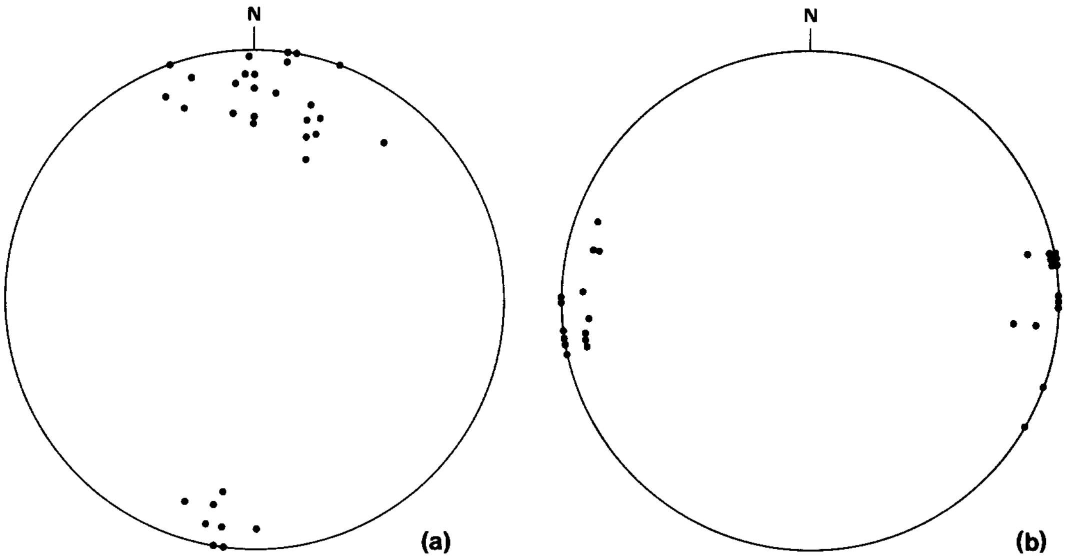

Fig. 3. (a) *D*1 fold axes in the metamorphic rocks. Equal-area projection, lower hemisphere, 32 axes. (b) Fold axes in the Plattenkalk Series. Equal-area projection, lower hemisphere, 30 axes.

lithological boundaries, particularly along thin slate interlayers.

In the fault block between the Sisses fault and the Talea Ori fault *D*1 fold closures were only rarely observed. Mapping demonstrated the presence of macroscopic *D*2 isoclinal folds with E–W axes and gently northwards-dipping axial surfaces. In thinly interlaminated dolomites, limestones and phyllites adjacent to the Fodele limestone, *D*2 mesoscopic structures are tight to isoclinal folds coaxial with the macroscopic folds. Asymmetric tight folds are overturned southwards and commonly have a well-developed axial planar crenulation cleavage (*S*2) with a low northwards dip. In many localities thin sections showing that the cleavage is a crenulation cleavage is all that proves the *D*1 deformation phase.

Structure of the Plattenkalk Series

In contrast to the metamorphic rocks the Plattenkalk Series is deformed by only one phase of folding. This has produced very tight to isoclinal folds with E–W axes (Fig. 3b) and horizontal to northwards-dipping axial surfaces. The plunge of the fold axes is negligible. In many parts of the Plattenkalk Series the fold closures are not directly observable but repetition by folding is inferred from observations of way-up structures in the carbonates, such as cabbage-like structures and cut-offs in algal stromatolitic dolomites and limestones, channel structures in calcarenites and graded bedding and bottom structures in calc–turbidites. We have observed repeated inversions in all well-exposed sections of the Plattenkalk Series with good way-up structures (e.g. Sisses–Aloides road section, south slopes of Sideros). Fold closures can be observed in places but are particularly obvious and well-exposed in the Plattenkalk Series where thinly bedded limestones contain interlaminated thin cherts. The best-exposed section we have observed is in the N–S trending valley north of the village of Kambos Doxarou where a tightly folded sequence of bedded cherty limestones is well displayed in the hillsides and cliffs. This section in particular makes it clear why the repetition of the Plattenkalk Series has been overlooked previously, since only small changes of dip are observed as fold hinges are crossed (Fig. 4) and unless fold closures are observed, or good way-up structures are evident, the repetition is not obvious. In the cherty limestones a prominent lineation parallel to the fold axes is produced on bedding surfaces due to the contrast in ductility between the limestones and cherts during folding; the cherts have become boudinaged with the long axes of the boudins parallel to the fold axes, and locally have acquired an axial-planar cleavage in the hinge zone of folds, while the limestones have deformed in a more ductile manner and have not developed a cleavage. Epting *et al.* (1972) suggested inversion of the entire sequence on the basis of observation of a limited number of way-up structures, and this inversion was interpreted by Bonneau (1973) and Kopp (1978) as the inverted limb of a huge overturned fold. Our observations do not support this interpretation but show that although much of the Plattenkalk Series is inverted this is due to local repetition of the sequence by mesoscopic overturned tight to isoclinal folds.

Further repetition of the Plattenkalk Series sequence by thrusting can also be proved on the hillsides north of the old road between Rethymnon and Heraklion. A gently northwards-dipping wedge of metamorphic rocks is enclosed by folded bedded cherty limestones and can be traced for about 10 km along strike eastwards from Melidoni. The metamorphic rocks include thinly laminated quartzites, quartzose phyllites and dolomitic phyllites which are locally folded by northwards-plunging *D*1 isoclinal folds. Because they are lithologically similar to the metamorphic rocks exposed further north between the Talea Ori fault and the Sisses fault, and like those

Fig. 4. Style of folds in thinly bedded limestones and cherts of the Plattenkalk Series. Both photographs taken about 300 m north of Kambos Doxarou on a footpath leading from the village into a major valley running north towards Koufotos. (a) Axes are horizontal and trend 080°. Axial planes dip northwards. (b) Axes are horizontal and trend 084°. Axial planes dip northwards.

rocks are deformed by both *D*1 and *D*2 folds we consider this wedge to be a slice of the metamorphic rocks incorporated during thrusting. Although the contacts between the metamorphic rocks and the Plattenkalk Series are poorly exposed, tracing the lower boundary across the hillsides indicates that the contact is folded whereas the upper surface is a simple northwards-dipping plane. This implies a sequence of events including thrusting of the metamorphic rocks onto the Plattenkalk Series, folding of both on E–W axes followed by further thrusting resulting in imbrication of the earlier structures (see Fig. 2, section E–F). The sudden juxtaposition of quite different lithologies in the Plattenkalk Series along low-angle surfaces suggests that the whole Plattenkalk Series is imbricated in a similar manner although we have been unable to map out these imbricate slices.

The early stages of deformation occurred under conditions that allowed ductile folding of the Plattenkalk Series and syn-tectonic metamorphism of both the Plattenkalk Series and the metamorphic rocks. We are currently attempting to determine the conditions of metamorphism although this is hampered by the limited range of lithologies in the Plattenkalk Series. Our evidence so far suggests that folding occurred at temperatures approximately equivalent to those of the lower-greenschist facies. The later stages of deformation, resulting in imbrication of the sequence, occurred under less ductile conditions, and presumably at lower temperatures.

STRATIGRAPHY OF THE TALEA ORI

The status of the metamorphic rocks

Epting *et al.* (1972) considered the metamorphic rocks to be the pre-Norian basement to the Plattenkalk Series. They suggested that an intra-Triassic event is responsible for an angular discordance separating the two groups of rocks, although they regarded the sequence below the unconformity as structurally simple and stratigraphically continuous. Our work indicates that this interpretation is very improbable. We have argued above that the Talea Ori metamorphic rocks are faulted into contact with the Plattenkalk Series, and the recognition of a polyphase history for these metamorphic rocks different from that of the Plattenkalk Series supports our argument. We, therefore, suggest that the Talea Ori metamorphic rocks are more reasonably interpreted as downfaulted parts of the Phyllite–Quartzite Series nappe. This is supported by the following observations or relationships.

(1) Lithologically the Talea Ori metamorphic rocks closely resemble metamorphic rocks indisputably assigned to the Phyllite–Quartzite Series elsewhere on Crete.

(2) The ages of metamorphic rocks proved in the Talea Ori range from early Permian to early Trias. No post-Triassic rocks have been found. These are the same as ages obtained from the Phyllite–Quartzite Series elsewhere on Crete.

(3) The sequence of structural events recognizable in the Talea Ori metamorphic rocks is essentially similar to that recognized in the Phyllite–Quartzite Series of west Crete (Greiling 1979, 1982, our unpublished observations) and central and east Crete (our unpublished observations).

(4) A similar metamorphic history is evident for both the Talea Ori metamorphic rocks and the Phyllite–Quartzite Series. Simplified, this is (i) crystallization of phyllosilicates to define an *S*1 cleavage, (ii) largely post-*S*1 static growth of porphyroblastic minerals including chloritoid, albite, ferro-carpholite and lawsonite, (iii) phyllosilicate growth to define an *S*2 cleavage and recrystallisation around rotated porphyroblasts. The metamorphism, which is intimately associated with deformation (e.g. Greiling 1982), is accepted to be of Tertiary age (Seidel 1978). The model of Epting *et al.* (1972) would thus require the coincidence of an intra-Triassic orogenic event affecting the Talea Ori metamorphic rocks below the Plattenkalk Series identical to the Alpine orogenic event affecting the Phyllite–Quartzite Series nappe which is structurally above the Plattenkalk Series.

The Wassilikon marble is regarded by us as a member of the Phyllite–Quartzite Series, an interpretation which differs from that of Epting *et al.* (1972) who correlated the Wassilikon marble with limestones of the Tripolitza nappe which overlies the Phyllite–Quartzite nappe. The latter is not a plausible correlation because there is a lithological transition between the Wassilikon marble and adjacent lithologies of the metamorphic rocks, and all are folded by *D*1 folds. Unlike the Tripolitza limestone the Wassilikon marble is intensely deformed and flattened.

Stratigraphy of the metamorphic rocks

An attempt is made in Fig. 5 to compile a stratigraphy of the metamorphic rocks of the Talea Ori based on palaeontological dating and lithological mapping. Lithologies which are structurally adjacent to one another and also show gradational relationships have been interpreted as having primary depositional contacts. The lower part of the sequence, which is exposed in the area west of the Fodele fault, is moderately well controlled palaeontologically (Epting *et al.* 1972, König & Kuss 1980). However, in the upper part of the sequence east of the Fodele fault no fossils have been found and no other dates are available. We suggest that this part of the sequence is of Anisian–Carnian age for the following two reasons.

(1) The most probable correlatives of the basic volcanic rocks are volcanic rocks of early Ladinian age known throughout the Mediterranean region (Bernouilli & Jenkyns 1974, Pe-Piper 1982). This is the only significant episode of basic volcanism known in the Permo-Trias in this region.

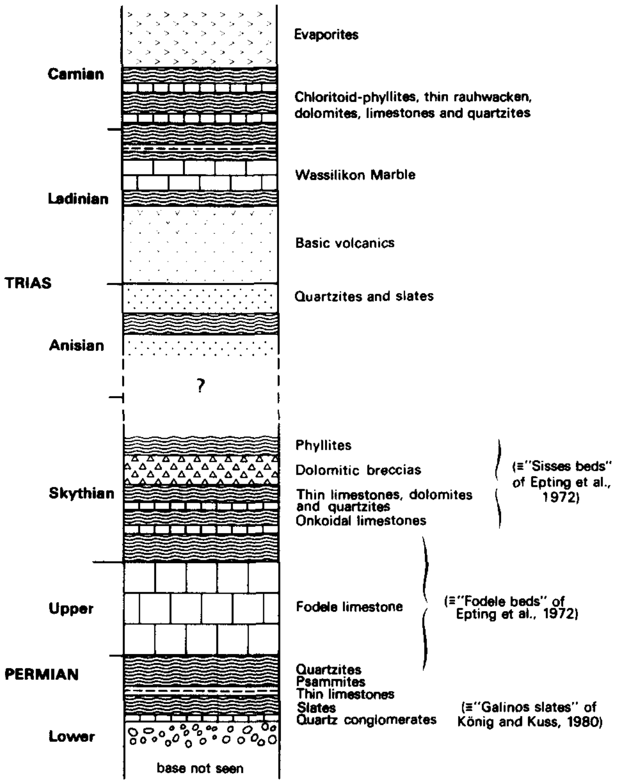

Fig. 5. Stratigraphy of the metamorphic rocks based on palaeontological dating and lithological mapping. Not to scale. For discussion see text.

(2) A lithological transition is observed in the eastern Talea Ori from volcanics through carbonates (Wassilikon marble) into intercalated chloritoid-phyllites, thin dolomites and limestones, and rauhwacken. This strongly suggests the transition to evaporites of Carnian age, well-known throughout the Alpine region. Gypsum bodies, undated, are known from the Phyllite–Quartzite Series of Crete and we consider them to be remnants of the Carnian evaporites.

We have not attempted to estimate the original thickness of the sequence because of the effects of deformation. Flattened conglomerates and amygdales indicate locally high strains which will lead to an underestimate of original thickness, whereas repetition by isoclinal folding and thrusting will cause an overestimate. Estimates of 1700–1800 m (Epting *et al.* 1972, König & Kuss 1980) are based on the assumption of a continuous sequence, inverted but otherwise undeformed, and take no account of the structural complexity of the metamorphic rocks. The overall thickness of the sequence need only have been a few hundred metres to produce the present distribution of metamorphic rocks, although it could have been considerably greater.

We have found no evidence indicating deep-water sedimentation, whereas there is abundant lithological evidence (well-rounded quartz conglomerates, onkoidal limestones, dolomitic breccias and conglomerates, rauhwacken) and palaeontological evidence (Epting *et al.* 1972, König & Kuss 1980) at several different levels in the sequence indicating accumulation in continental to shallow-marine environments. We, therefore, consider that all of these rocks were originally deposited on continental crust and suggest that they represent early Permian to late Triassic sediments deposited on Hercynian basement, now exposed locally in eastern Crete.

Stratigraphy of the Plattenkalk Series

A stratigraphy of the Plattenkalk Series is compiled in Fig. 6 which is based on evidence from throughout Crete. This is the first such compilation that has been attempted. Except at the bottom and top of the Plattenkalk Series fossils are absent and we have relied upon lithological correlation to construct the simplest consistent sequence. This is possible because each of the eight units recognized is lithologically distinctive and a composite column can be compiled because in different areas the same relative order of units is observed. Only the lowest and highest parts of the sequence are dated: Epting *et al.* (1972) reported Norian ages for the stromatolitic dolomites and König & Kuss (1980) suggested that the upper boundary of these dolomites corresponds to the Triassic–Jurassic boundary while the top of the sequence is dated as Oligocene by deformed *Globerigina*-bearing meta-marls in eastern Crete (Fytrolakis 1972) and Psiloritis (Bonneau 1973).

The picture of the Plattenkalk Series that emerges from this compilation is of a transition from very shallow to deeper marine sedimentation. The sequence begins with Norian stromatolitic dolomites which indicate intertidal sedimentation and are followed by coarse carbonate breccias passing up into channelled and graded calcarenites marking sudden and rapid early Jurassic subsidence of the Triassic carbonate platform. Intertidal carbonate deposits imply deposition on continental crust, or conceivably intra-oceanic islands, and we interpret these stratigraphic relations as indicating that the Plattenkalk Series was underlain by continental crust which subsided due to extension and thinning in the early Jurassic. The breccias and calcarenites pass up through finer-grained calc–turbidites into calmer basinal deposits of the bedded limestone–chert sequence. These basinal conditions probably prevailed during most of the later Mesozoic, with carbonate deposition throughout the whole period, and occasional disturbances recorded by local slumped chert horizons or channelled calcisiltites. Only in the early Oligocene was there any significant siliciclastic input, with a few metres of marls or calcareous shales sometimes referred to misleadingly as Plattenkalk 'flysch'.

As in the Talea Ori, we have observed in all major exposures of the Plattenkalk Series throughout Crete repetition of the sequence by flat-lying tight to isoclinal folds with E–W axes. The attitudes of the axial planes vary, due to late large-scale open folds (amplitudes up to several kilometres) which deform all the nappes; in general, axial planes dip north in northern Crete, are horizontal in central Crete, and dip south in southern Crete. In eastern Crete we have observed further repetition of the sequence by listric thrust faults, although the

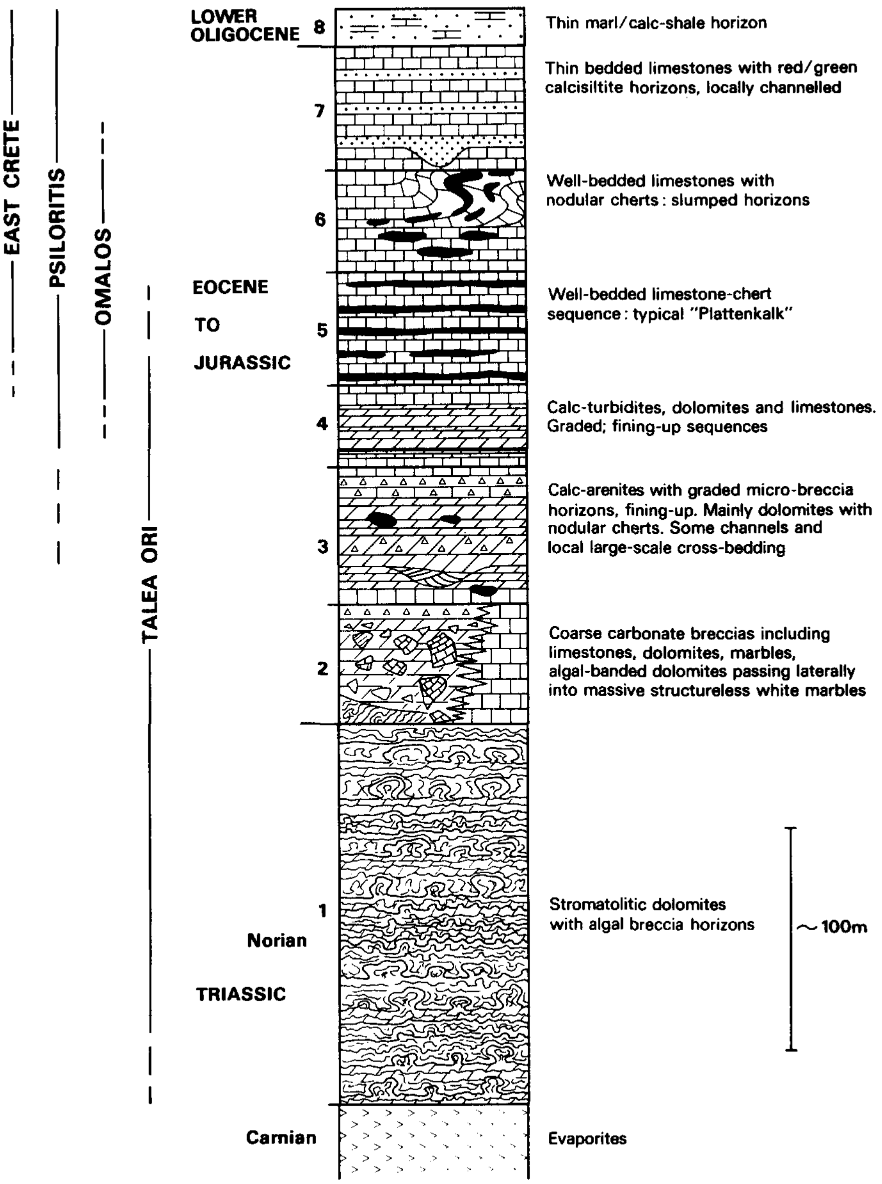

Fig. 6. Stratigraphy of the Plattenkalk Series of Crete. Lines to the left of the column show which parts of the succession are exposed in which parts of Crete. The column is drawn approximately to scale and the entire thickness is estimated to be not greater than 1000 m. The thickness of the Triassic stromatolitic dolomites in particular, may be overestimated since only proved repetitions were taken into account when estimating thicknesses.

importance of this is difficult to assess because of the lack of easily correlatable horizons. However, we are in no doubt that everywhere on Crete the Plattenkalk Series is significantly repeated by folds and thrusts and, therefore, we consider that previous estimates of the thickness of the Plattenkalk Series are excessive. Epting *et al.* (1972) estimated 2600 m for that part of the Plattenkalk Series exposed in the Talea Ori, but such thicknesses can only be obtained from observed outcrop widths by assuming no repetition. On well-exposed sections, where all folds can be proved, the total vertical thickness is greater than three times the measured stratigraphic thickness on those sections. Although we are uncertain of the total number of repetitions this is a minimum factor because it assumes recognition of all folds by direct observation of closures, or inference from unambiguous way-up evidence. In reality, neither of these conditions is satisfied and therefore our estimate of the total thickness of the Plattenkalk Series of approximately 1000 m may itself be an overestimate.

RELATIONSHIPS BETWEEN THE PLATTENKALK SERIES AND THE OVERLYING NAPPES

In the Talea Ori and elsewhere on Crete only Permian and Triassic ages have been recorded from metamorphic rocks of the Phyllite–Quartzite Series yet metamorphism is dated as early Tertiary (Seidel 1978). Where then, are the post-Triassic rocks of this nappe? Two explanations have been proposed. The first suggests that the Phyllite–Quartzite Series is part of an isopic zone separate from those represented by the overlying nappes, and implies that Jurassic, Cretaceous and Tertiary rocks are present in the Phyllite–Quartzite Series but have been undetected because of the effects of metamorphism. The second explanation suggests that the Phyllite–Quartzite Series is the basement of the overlying Tripolitza nappe which is composed of Mesozoic carbonates and Tertiary flysch. Because of lithological and faunal evidence for a transition between the Tripolitza and Phyllite–Quartzite Series we prefer the second explanation, and propose that the reason for the separation of a once-continuous sequence into two nappes was the presence of thick Carnian evaporites which provided a detachment horizon allowing the two parts of the sequence to deform separately. In support of this suggestion we have observed thin gypsum layers in the lowermost (Carnian) limestones of the Tripolitza nappe in central Crete, and large, complexly folded discontinuous gypsum bodies are present in the Phyllite–Quartzite Series in both eastern and western Crete.

The Phyllite–Quartzite Series and all the overlying nappes have been deformed by the *D*1 event, producing N–S trending fold axes and generally tight to isoclinal flat-lying folds, although the style and degree of deformation varies with lithology. The deformation occurred in the early Tertiary (probably Eocene) and was the culmination of E–W compression which was marked intially by thick flysch sedimentation in the upper nappes. In contrast, the Plattenkalk Series is not deformed by the *D*1 event, nor is there any sign of the change from carbonate to siliciclastic sedimentation recorded by the higher nappes in the Palaeocene–Eocene. In the Plattenkalk Series there is no evidence for other than continuous carbonate deposition during this period with a very slight input of siliciclastic material only in the early Oligocene. Only the *D*2 event deforms both the Plattenkalk Series and the overlying nappes, and this must therefore have occurred after the early Oligocene and before the mid-Miocene, the latter date given by the oldest dated parts of the thick Neogene 'molasse' which unconformably overlies all the nappes.

We, therefore, conclude that before the Oligocene the Plattenkalk Series was sufficiently far from the region represented by the Phyllite–Quartzite Series and overlying nappes to ensure the sedimentological and structural isolation of the Plattenkalk Series. We have suggested above that both regions were underlain by continental crust and since there is no evidence for intervening oceanic crust we consider that this implies that a major crustal discontinuity, such as a transform or transcurrent fault, separated the two regions during at least the late Mesozoic and early Tertiary.

The middle and late Mesozoic and early Tertiary part of the Plattenkalk Series is a distal carbonate facies. We have suggested (Hall *et al.* in press) that the proximal equivalent of the Plattenkalk Series is partially preserved in western Crete in the Tripali Unit which occupies a structural position between the Plattenkalk Series and the Phyllite–Quartzite Series. It consists of recrystallized carbonate breccias with rare Liassic shallow-water fossils (Kopp & Ott 1977) and the breccias resemble those in the lower part of the Plattenkalk Series, which are probably also of early Jurassic age (Fig. 6). Elsewhere in Crete the proximal equivalent of the Plattenkalk Series has never been seen and must have been over-ridden during emplacement of the Phyllite–Quartzite Series and overlying nappes. Therefore, the surface now separating the Plattenkalk Series from the Phyllite–Quartzite Series and overlying nappes must be a zone of very significant overthrusting (of the order of hundreds rather than tens of kilometres).

Regional considerations indicate that the *D*2 event must have involved southwards-directed overthrusting, initiating the present pattern of convergence in the Hellenic Arc. The Plattenkalk Series must, therefore, represent an isopic zone to the south of those represented by the higher nappes (Tripolitza and Pindos zones) and consequently is unlikely to be equivalent to the Ionian or Pre-Apulian zones. We consider the Plattenkalk Series to represent an isopic zone south of anything known on the Greek mainland. The change from E–W convergence, which produced the N–S (*D*1) structures of the Phyllite–Quartzite Series and overlying nappes, to N–S convergence, producing southward thrusting and E–W (*D*2) structures in the whole nappe pile, occurred in the early Oligocene. We suggest that this change caused the transform/transcurrent fault separating the two regions to become the location of intra-continental thrusting and this change, deduced from structural and stratigraphic evidence on Crete, is consistent with major plate motions deduced from the Atlantic opening history. Relative motion between Africa and Europe changed from transcurrent to convergent in the late Eocene (Dewey *et al.* 1973, Biju-Duval *et al.* 1977).

Our work does not resolve the problem of whether the Plattenkalk Series is a nappe or an autochthon. However, the style and intensity of folding suggests at least some detachment, and we consider it to be no coincidence that the oldest parts of the Plattenkalk Series are Norian intertidal stromatolitic dolomites. This suggests that the Plattenkalk Series was also underlain by Carnian evaporites along which it became detached during the *D*2 event. We therefore prefer to regard the Plattenkalk Series as at least parautochthonous, and probably a nappe, even though our work does not support the huge overturned fold structure previously proposed for the Talea Ori.

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