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The metamorphic and structural evolution of the Phyllite–Quartzite Nappe of western Crete

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Abstract—The Phyllite–Quartzite (PQ) Nappe constitutes an external, allochthonous complex of the Hellenides on the island of Crete and shows a polyphase structural history. A first phase of deformation ($F1$) produced recumbent isoclinal folds, a penetrative schistosity, and boudinage under high-P/low-T metamorphic conditions. Mylonite formation at the top of the PQ Nappe, below the overriding Tripolitza Nappe, further boudinage, and schistosity ($S2$) represent a late tectono-metamorphic episode. Post-metamorphic small folds ($F3$), lineations, and a crenulation cleavage were formed synchronously with transport of the PQ Nappe. A last phase ($F4$) developed small folds, a fracture/crenulation cleavage, and large-scale folds after nappe movement. It is suggested that high-P/low-T metamorphism in the PQ rocks originated during subduction. Nappe transport of the higher, unmetamorphosed units, which were thrust over the PQ Nappe, began under waning metamorphic conditions. Subsequent transport of the PQ Nappe itself also occurred after the completion of metamorphism and after the formation of the mylonite at its top.

INTRODUCTION

The Hellenides represent the southeastern European part of the Alpine–Himalayan mountain chain. Their orogenic evolution took place in five Alpidic phases between the Middle Jurassic and the Middle Miocene (Jacobshagen 1979). As an external part of the orogen, western Crete was affected only by the latest, Middle Miocene event. This phase resulted in a high-P/low-T metamorphism of the Phyllite–Quartzite (PQ) Nappe and the southward transport of different allochthonous units, including the PQ Nappe, over an autochthonous (?) basement (Jacobshagen 1979). Subsequent faulting (Angelier 1978) led to a break-up of the Hellenide orogen and to the present situation of Crete as an isolated link between the Greek mainland and southeastern Turkey (Fig. 1).

The tectonic evolution of the Hellenide orogen may be explained by a Wilson cycle model (e.g. Jacobshagen 1979, Jacobshagen *et al.* 1978). Accordingly, the high-P/low-T metamorphism, documented in the PQ Nappe of western Crete, originated during subduction. Subsequent compressional phases led to the transport of the allochthonous complexes. Some authors, however, advocate a model of diapirism as a cause for gravitative transport of nappes, denying any subduction (e.g. Baumann *et al.* 1976, Wachendorf *et al.* 1980).

Therefore, it is a matter for dispute whether the metamorphism of the PQ rocks is related to subduction in an early stage of orogenesis (e.g. Jacobshagen 1979, Seidel 1978), or whether it originated during transport of the Cretan nappe pile (e.g. Wachendorf *et al.* 1980) in a late-tectonic event. In order to reveal a time relation between metamorphism, structure and mylonite formation (thrusting), structural and micro-structural investigations were carried out in the PQ Nappe and at its contact with the overlying Tripolitza Nappe.

The Phyllite–Quartzite Nappe

The Phyllite–Quartzite (PQ) Nappe constitutes a major, allochthonous complex of the Hellenides on Crete (Fig. 1). It is bounded by thrust planes separating it from the underlying autochthonous (?) "Plattenkalk" (platy limestone, Jacobshagen *et al.* 1978) and Tripali units and from the overlying Tripolitza Nappe which is essentially unmetamorphosed (Sannemann & Seidel 1976). Petrological investigations in the PQ Nappe of western Crete (e.g. Seidel 1977, 1978, Seidel & Okrusch 1977) revealed the metamorphic parageneses glaucophane–lawsonite–pumpellyite–aragonite–albite in metabasalts and quartz–muscovite–paragonite–chloritoid–lawsonite in metapelites. They led Seidel (1978) to estimate P/T conditions of 7–9 kb and 300–400°C. In rocks of appropriate composition critical metamorphic minerals, for example glaucophane, lawsonite, and chloritoid are distributed all over western Crete (Seidel 1978). No variations in the grade of metamorphism were observed in the area investigated during the present study (Fig. 2).

Lithologically the PQ Nappe of western Crete can be divided into an upper sequence of phyllites and quartzites and a lower sequence of phyllites and carbonate rocks (Kalamos sequence, Seidel 1977), locally intercalated with evaporites and rare metabasalts. Most of the observations presented here concern the phyllite–quartzite sequence, although the carbonate–phyllite rocks underwent the same structural and metamorphic evolution. The phyllite–quartzite rocks were selected since they are better exposed than the

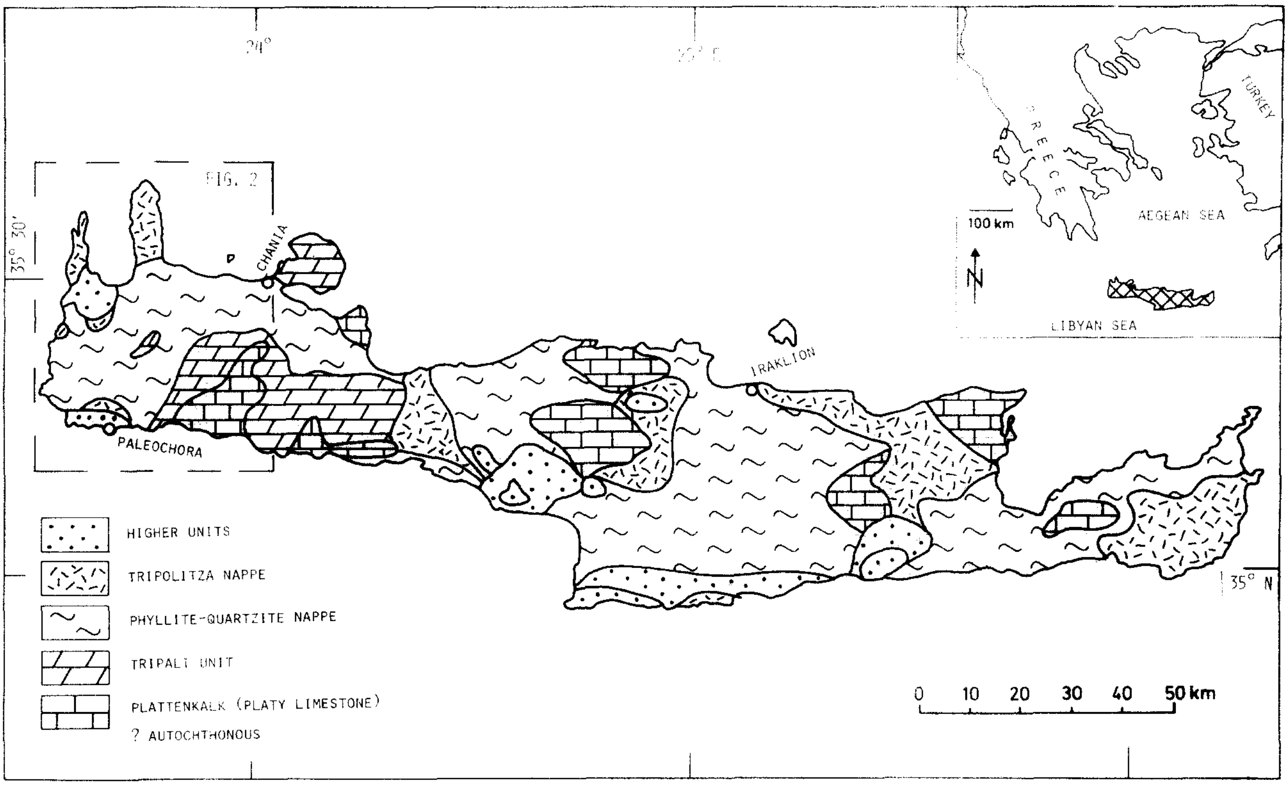


Fig. 1. Tectonic map of the Hellenides on the island of Crete, from Jacobshagen *et al.* (1978). Post-orogenic sediments are omitted. The box in the western part of Crete indicates the outline of the map, Fig. 2. Inset is the location map of Crete in the eastern Mediterranean.

other rock types of the PQ Nappe and do not show significant lithological variations over the actual area. These rocks also display a relatively clear contact with the overlying Tripolitza Nappe, at least at the localities indicated on Fig. 2, whereas other contacts, often debris-covered and/or overprinted by the post-Hellenidic fault-tectonics (Angelier 1978), are less suited for the present study.

DEFORMATION AND METAMORPHISM

The regional structure of western Crete is dominated by an open, E–W trending antiform (Figs. 2 and 3; Kopp 1978). Earlier structural investigations documented an intensive deformation of the PQ rocks on a small scale (Greiling & Skala 1979) and gave first indications of different structural phases (Greiling 1979). Further studies led to the recognition of the structural sequence described below and its relationship to metamorphism and mylonite formation. Though all phases may not be discernible in any single outcrop, they can be shown to occur all over the area investigated (Fig. 2).

Synmetamorphic deformation

The earliest recognizable structural elements in the PQ Nappe of western Crete were generated during the above-mentioned high-P/low-T metamorphism. This first ($F1$) phase comprised isoclinal folding, formation of a penetrative schistosity and flattening. Recumbent, isoclinal folds with two distinct, alternating axial directions (NE–SW, NW–SE; Fig. 4) were documented earlier (Greiling & Skala 1979). They do not show overprinting relationships and are, therefore, interpreted as a synchronous, conjugate set of fold axes. The different axial directions may also be due to a subsequent reorientation of varying intensity during the $F3$ phase (see below). Lineations resulting from bedding/schistosity intersections show the same orientation.

The axial plane fabric ($S1$) occurs as a penetrative schistosity parallel to the bedding in the phyllites, whereas the competent quartzite (and carbonate) beds were dissected into mullions at fold hinges and to boudins on the limbs. Under the microscope chloritoid porphyroblasts clearly show the time relationships between mineral growth and the formation of the schistosity. 'Windmill'-type pressure fringes (Zwart & Calon 1977) are common as well as S-shaped inclusion trails in the porphyroblasts, generally with a connection to the external schistosity (Fig. 5). These fractures indicate crystal growth during flattening (Zwart & Calon 1977). Chloritoid growth obviously began before, or at an early stage, in the formation of the penetrative schistosity (synchronous with isoclinal folding, $F1$) and persisted throughout that phase.

Late-metamorphic deformation

Boudinage outlasted $F1$ folding since fold hinges

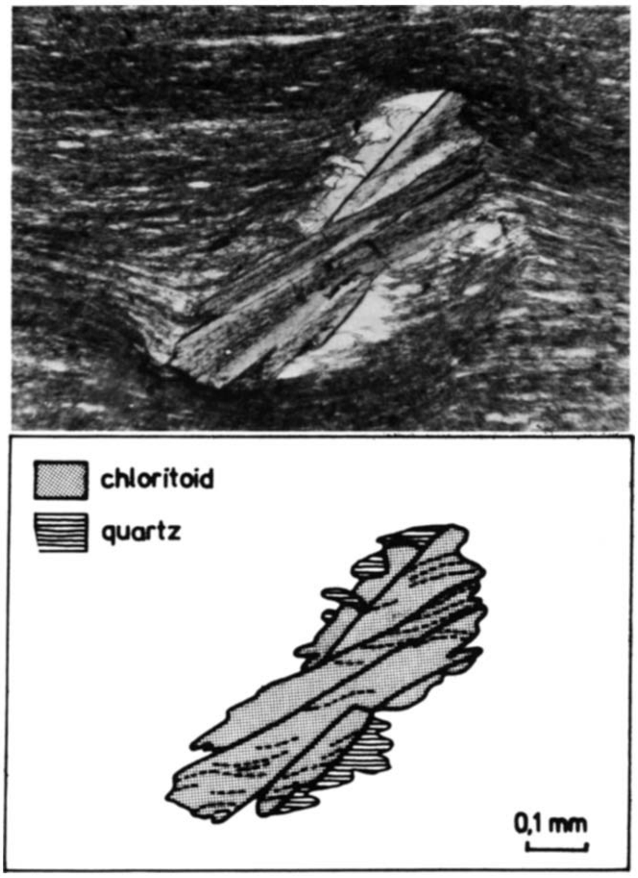


Fig. 5. (a) Aggregate of chloritoid porphyroblasts where pressure fringes of quartz indicate clockwise rotation of the crystals (during flattening). Slightly S-shaped inclusion trails are continuous with the S 1 schistosity (S_i continuous with S_e). S 1 outside porphyroblasts (S_e) is partly deformed by later events. (b) Explanatory sketch of Fig. 5 (a): dashed lines show slightly S-shaped inclusion trails (S_i), corresponding to S 1 schistosity. Sample G 80 K5, 200 m E Kefali (see Fig. 2).

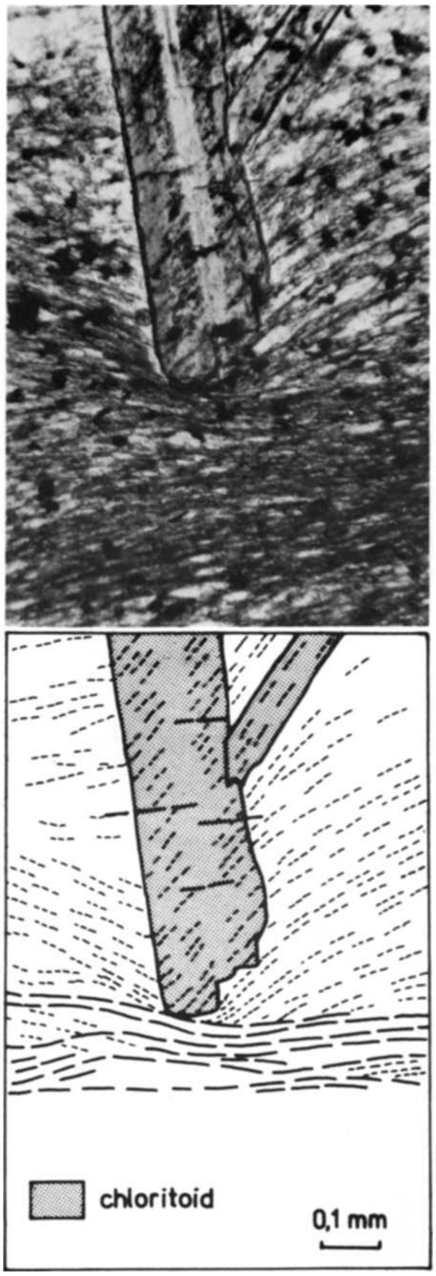


Fig. 6. (a) Chloritoid porphyroblast (upper part of photograph) within a 'competent domain' where the *S* 1 schistosity is hardly affected by later deformation. Outside this domain (lower part of photograph) *S* 1 is overprinted by a nearly parallel later schistosity, *S* 2 which also cuts the chloritoid porphyroblast. (b) Explanatory sketch of Fig. 6 (a): dashed lines show *S* 1 schistosity, heavier lines represent the later, *S* 2 schistosity. Sample G 80 K5, 200 m E Kefali (see Fig. 2).

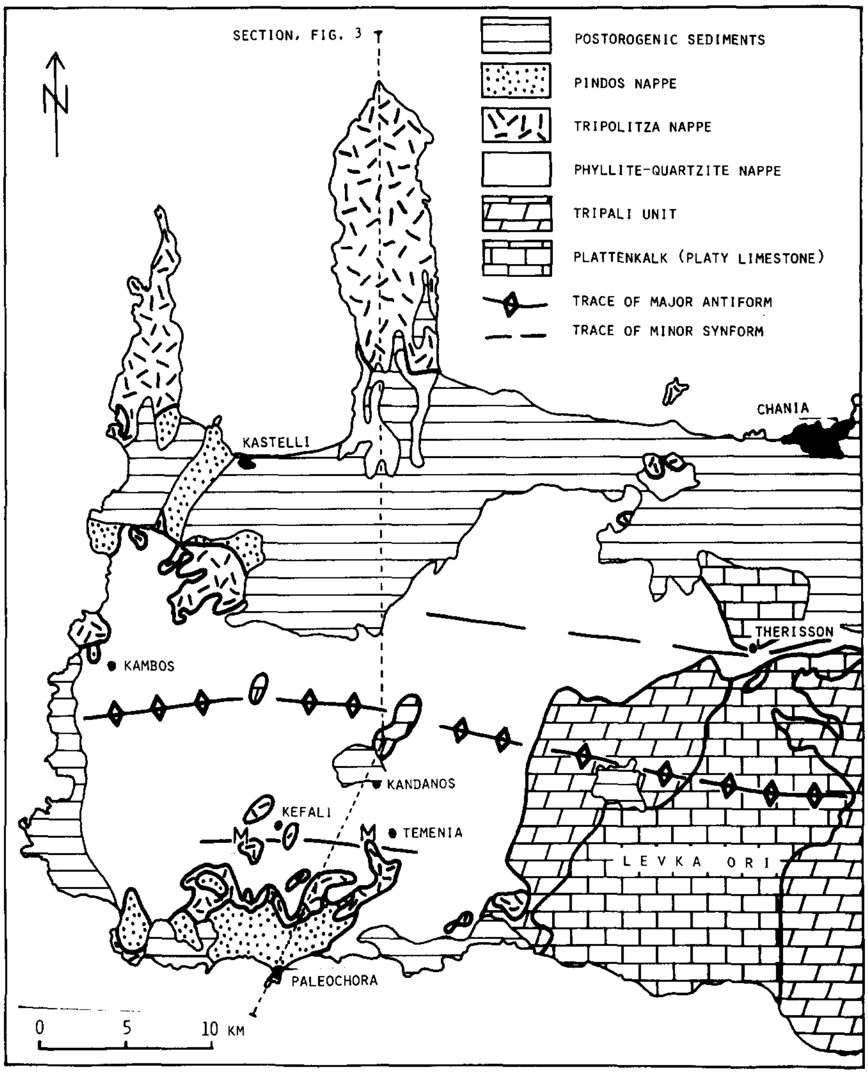


Fig. 2. Structural sketch map of western Crete, based on the geological map of Crete by Creutzburg *et al.* (1977). Tectonic contacts, in particular the approximately N–S trending ones, are often overprinted by post-orogenic faults. M indicates relatively well exposed mylonite at the contact between the PQ and Tripolitza Nappes.

occur isolated as boudins. The *S* 1 fabric is superimposed by a second, generally subparallel schistosity (*S* 2). It curves around the chloritoid porphyroblasts, but is not connected to their internal S-surfaces (Fig. 6) and is thus younger than chloritoid formation and (the peak of) metamorphism. Very rare boudin long axes, directed approximately N–S, are the only linear features observed.

In the topmost 50 m of the PQ Nappe, below the Tripolitza Nappe, the *S* 1 fabric is more strongly overprinted and partly destroyed by *S* 2, which grades into a mylonitic schistosity. True mylonite is restricted to a

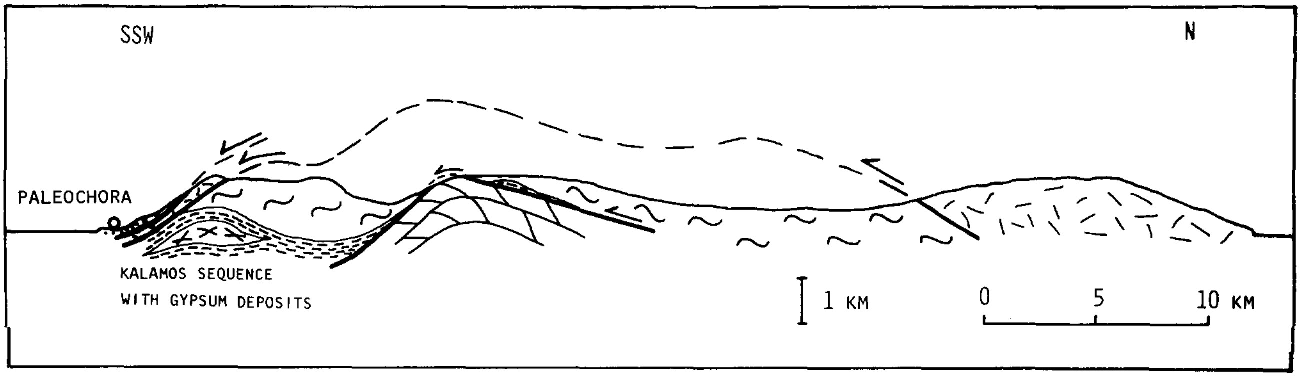
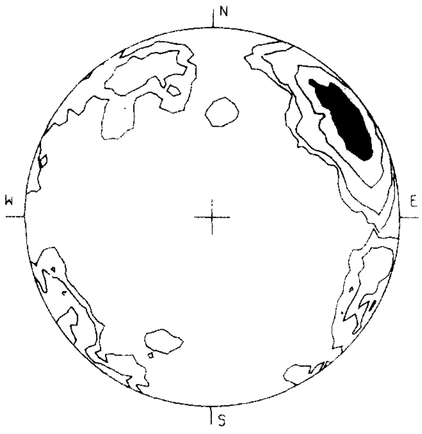
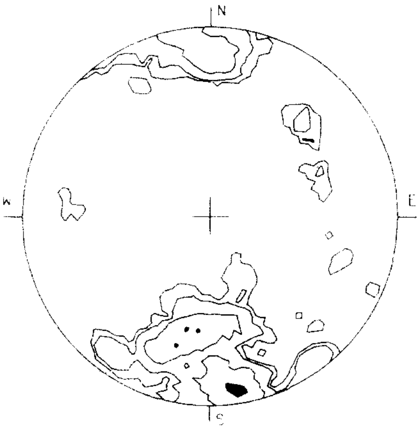


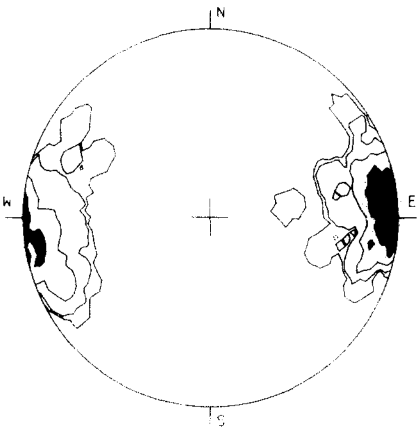
Fig. 3. Schematic cross section through western Crete. For location see Fig. 2. Post-orogenic sediments are omitted. Vertical scale is exaggerated by a factor of two.



F 1 - LINEAR FEATURES N = 328



F 3 - LINEAR FEATURES N = 137



F 4 - LINEAR FEATURES N = 82

Fig. 4. Equal-area diagrams (lower hemisphere) showing directional data of linear features attributed to different deformation phases. The second deformation ('*F* 2') revealed too few linear data and is omitted. Contour intervals are 1, 2, 5 and 10% per 1% area.

zone, a few m wide, where the phyllite–quartzite material of the PQ Nappe and the carbonate material of the Tripolitza Nappe are mixed together.

Subsequent recrystallization affected carbonate and white mica as well as quartz and hematite in discordant veins, but did not affect chloritoid.

Post-metamorphic deformation

The next phase (*F* 3) led to the formation of small folds and lineations with a N–S direction and a crenulation cleavage (*S* 3, Figs. 4 and 7), cutting the earlier schistosities. Pebbles were elongated and reoriented parallel to the N–S axial direction. Local variations in the intensity of deformation can be observed, showing that strain decreases towards the mylonite zone at the top of the PQ Nappe (Greiling 1980). These intensity variations may explain an apparent absence of *F* 3 features in the south-western part of the area (Greiling 1979).

A last phase of folding in an E–W direction (*F* 4, Fig. 4) caused the development of a fracture cleavage or, where it is less intense, a weak crenulation cleavage (*S* 4). The *S* 4 cleavage cuts the *S* 3 fabric (Fig. 7) and is thus younger. The *F* 4 folds range in size from microscopic to km-scale and can be correlated to the regional antiform of western Crete (Figs. 2 and 3). They involve both the PQ Nappe and (in contrast to the earlier fold phases) also the underlying and overlying structural units, including the autochthonous (?) basement.

DISCUSSION AND CONCLUSIONS

Tectonic evolution

A first, penetrative deformation (*F* 1) in the PQ Nappe of western Crete occurred during high-P/low-T conditions. Subsequently the unmetamorphosed Tripolitza Nappe was thrust over the PQ Nappe. Mylonite formation was restricted to a narrow zone at the top, and a synchronous schistosity (*S* 2) was developed in the whole PQ Nappe. Recrystallization in the mylonite suggests that the PQ Nappe either still retained the temperature to provide heat for recrystallization in the mylonite, but not in the overlying Tripolitza Nappe, or that recrystallization was due to heat accumulated during mylonite formation. Though the second alternative cannot be completely excluded, the first model is preferred, since recrystallization of white mica can also be observed in and below the mylonite zone. The remobilization of quartz and hematite in veins near the thrust plane suggests the presence of a fluid phase in connection with Tripolitza Nappe transport. However, the emplacement of the

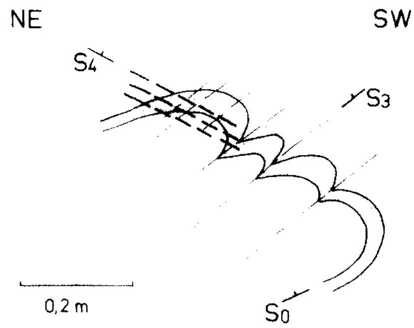


Fig. 7. *F* 3 small folds with *S* 3 axial plane cleavage (thin broken lines) in a quartzite bed (dotted) alternating with phyllites. Folds and cleavage are cut by a later cleavage, *S* 4 (thick broken lines). Roadcut 500 m SW Kambos (see Fig. 2).

veins is clearly post-mylonitic, since they cut the mylonitic foliation (*S* 2).

Post-metamorphic deformation (*F* 3) resulted in folds and lineations as well as pebble elongation and reorientation. Their directions being N–S (Fig. 4), they parallel the N–S tectonic direction of the PQ Nappe, which is implied by the regional context (Jacobshagen 1979). These geometric relationships favour an origin of the *F* 3 phase during PQ Nappe transport. As a consequence, PQ Nappe transport may have continued after formation of the mylonite during transport of the Tripolitza Nappe over the PQ Nappe. The last folds (*F* 4), effecting the upfolding of the basement together with the complete nappe pile (Figs. 2 and 3), are younger than nappe transport.

Geodynamic aspects

According to the sequence of tectonic events outlined above, high-P/low-T conditions in the PQ Nappe of western Crete prevailed prior to the overthrusting of the Tripolitza Nappe. They could thus not have been induced during transport of the Tripolitza and higher nappes as had been suggested for central Crete by Wachendorf *et al.* (1980). Furthermore, the low cumulative thickness of the nappe pile overlying the present PQ Nappe, not exceeding 4 km, does not explain high-P conditions in the PQ rocks (Jacobshagen 1979). Therefore burial of the PQ rocks prior to nappe transport, during subduction, as proposed for example by Seidel (1978) or Jacobshagen (1979), seems to be a more probable explanation for the high-P/low-T metamorphism. Under which units the PQ rocks were subducted, and how these units were removed, prior to the emplacement of the unmetamorphosed Tripolitza Nappe, remains unsolved.

Preservation of high-P/low-T parageneses and lack of retrograde metamorphic features in the PQ Nappe require a relatively fast uplift after subduction. A relatively fast uplift is consistent with the interpretation given above, that the PQ Nappe still retained heat for recrystallization after the transport of the unmetamorphic Tripolitza Nappe over the PQ Nappe.

Subsequent further transport of the PQ Nappe, probably related to the *F* 3 phase, ceased prior to the upfolding of the basement (*F* 4). For western Crete, the possibility that the displacement of the nappe pile was triggered by an updoming of the basement, as implied by the model of Wachendorf *et al.* (1980), can be excluded. On the contrary, it may be speculated that the weight of the nappe pile, after being superimposed on the basement, led to gravitational deformation, represented for example by the irregular, dome-shaped antiforms (*F* 4, Figs. 1 and 2), on a regional scale.

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