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The tectonic evolution of western Crete (Greece) since the Middle Miocene: southward migration of vertical motions in response to continuing roll-back

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Abstract

A detailed structural and stratigraphical field study of the Alpine basement as in the Middle and Late Miocene deposits of Western Crete made it possible to put better constraints on the tectonic processes, which took place in response to the roll-back of the Aegean plate from the Middle Miocene to Recent.

The major geologic units of western Crete constitute (1) a 'lower plate': the Tripali HP/LT marbles and the HP/LT metamorphic Phyllite-Quartzite Nappe, cropping out on the central part of the island in the core of the large west-Cretan anticlinorium. The lower plate is structurally overlain by (2) the non-metamorphosed 'upper plate': the classic Tripolitza and Pindos Nappes, together with an erosional product of these two: (3) the breccias of the Topolia Formation. These three units serve as the basement for (4) the Late Miocene deposits near the south coast and in the northern Kissamou-basin.

We propose a four-episode evolution of western Crete:

Episode 1 covers the interval of deposition of the Topolia Formation (between ?16 and ?12 Ma): continental breccias of northern provenance (Pindos and, mainly, Tripolitza components), deposited to the south-southwest.

Episode 2 commenced after lithification of the Topolia Formation and is marked by gravity-induced sliding towards the south (?12-10 Ma), as can be inferred from the stacking of the the upper plate-Topolia Formation sequence in the south and its near-absence in the north. At the end of the stacking episode, 10 Ma old marine sediments were deposited in the south on top of the stacked upper plate-Topolia Formation sequence.

Phase 3 (~ 9 or 10 - 7.5 Ma) was marked by both (arc-parallel) E-W extension, creating e.g. the northern Kissamou-basin, and the uplift of the central anticlinorium (finally exposing the lower plate), accompanied by gravity-induced normal movement parallel to the anticlinorium limbs of the upper

plate. The fact, that both processes occurred simultaneously can be concluded from tapering features, synsedimentary with the tilting of the northern anticlinorium limbs and growth fault analysis in the sediments deposited during this phase.

During episode 4 Crete was subjected tot uplift and concomitant tilting towards the north. At present, southwestern Crete shows the highest uplift rates, about twice as high as in the north.

We propose, that the uplift of the anticlinorium is caused by upward motion along a (blind) thrust within the framework of supracrustal slab detachment. The presence of a (blind) thrust is supported by the presence of salt domes at the anticlinal hinge.

Based on paleogeographic data it is tentatively concluded that space is generated in the south, in response to continuing roll-back. This, in turn, enables the development of a new (blind) thrust, and results in the concomitant southward migration of vertical motions. The arc-parallel, E-W extension results in more pronounced subsidence of (sub)basins in areas where (blind) thrusting is no longer active.

Introduction

Western Crete has previously been subjected to studies concerning is tectonic history, based upon data gathered in the metamorphic units, especially the Phyllite-Quartzite Nappe, in order to determine the exhumation mechanism of these High-Pressure Low-Temperature (HP/LT) units (e.g. Greiling, 1982; Jolivet et al., 1996; Thomson et al., 1999). This study combines the data and models presented earlier in literature with structural and stratigraphic data from the unmetamorphosed upper plate and oberlying Middel and Upper Miocene sediments in order to put constraints on the timing and the geometry of the surface expression of the tectonic processes, which were active since the Middle Miocene in response to roll-back and the southward migration of (western) Crete

Geologic Setting

The island of Crete is situated in the eastern part of the Mediterranean, where it forms the most southern part of the external Hellenides and the Hellenic Arc (figure 1, Ten Veen, 1998). The Hellenic Arc is thought to have formed in response to the roll-back of the Aegean Slab (e.g. Meulenkamp et al., 1988)

Crete is situated in a fore-arc position above the active northward directed subducting Aegean Slab. Wortel et al., (1993) estimated the subduction to start between 40 and 26 Ma, based on plate motion analysis and seismic tomography. Thomson et al. (1998b; 1999) estimated the onset of subduction of the HP-LT metamorphic rocks on western Crete to start between 36 and 29 Ma. These ages of onset of subduction are based on the estimated net convergence rate, resulting from the southward retreat of the overriding plate and the norhward motion of the subducting plate.

The nappe-pile found on Crete is believed to result from the subduction of the eastern promontery of the Adria microcontinent below the Aegean. The most widely used nomenclature of this nappe-pile is given by (Bonneau, 1984). The lower tectonostratigraphic units are referred to by Thomson et al., (1999) as the 'lower plate'.

Lower plate

The stratigraphically lowest unit is formed by the Plattenkalk-Tripali unit. This unit consistes of platy limestones and neritic, massive carbonate series, which were subjected to HP-LT metamorphism (cf. (Greiling, 1982), and which only crop out in the central part of western Crete. These series underly the Phyllite-Quartzite (PQ) unit: HP-LT metamorphosed carbonates, schists, metabasites and phyllite-quartzites (Bonneau, 1984), ranging in age from Upper Carboniferous to Upper Triassic (Krahl et al., 1983). This Phyllite-Quarzite unit has been the subject of many investigations with respect to the metamorphic and deformational history, in order to constrain its exhumation history. (e.g. Greiling, 1982; Seidel et al., 1982; Theye and Seidel, 1991; 1993; Theye et al., 1992; Jolivet et al., 1996; Schwarz and Stöckhert, 1996; Kuester and Stöckhert, 1997; Thomson et al., 1998b; 1999; Stöckhert et al., 1999). Peak metamorphic conditions for the Phyllite Quarzite, exposed on western Crete, are given by Theye and Seidel (1991; 1993) and Theye et al. (1992) being 400 ± 50°C and 10 ± 2 kbar. Peak metamorphic conditions were estimated, based on K-Ar and Ar/Ar, to prevail between 24 and 19 Ma (Seidel et al., 1982; Jolivet et al., 1996). Exhumation from circa 35 km to 10 km took probably also took place within the 24-19 Ma and 17 Ma at the latest (Kuester and Stöckhert, 1997) based on fission-track ages (19 ± 2 Ma)). Thomson et al. (1999) showed, that the final cooling to below 60°C took place at *c.* 15 Ma.

The Phyllite Quartzite rocks are recumbently folded (Krahl et al., 1983). Two sets of nearly isoclinal, recumbent folds are distinguished, (e.g. Greiling, 1982; Jolivet et al., 1996)): an oldest set of NNE-SSW trending fold axes and a younger set of approximately E-W trending fold axes. These representatives of ductile contraction are shown to have largely taken place under HP-LT conditions (Wachmann, 1997; Stöckhert et al., 1999).

At a depth of *c.* 10 km, brittle deformation becomes active in quartz-rich rocks (Kuester and Stöckhert, 1997). The microstructures associated with ductile deformation do not show a pervasive overprint and retrograde metamorphism, related to exhumation from *c.* 35 km to the *c.* 10 km (Stöckhert et al., 1999; Thomson et al., 1999). This implies, that the bulk of the PQ unit was exhumed as a coherent block (Thomson et al., 1999).

upper plate

On western Crete, the metamorphosed units of the 'lower plate' are structurally overlain by the unmetamorphosed 'upper plate' (cf. Thomson et al., 1999), which here consists of two former isopic zones (c.f. Aubouin, 1957): firstly the Tripolitza nappe, consisting of neritic, massive limestones that were accreted in Mesozoic and early Tertiary times on a proximal shallow-water platform (Bonneau, 1984). The Tripolitza nappe is overlain by the Pindos nappe: neritic deep-water carbonates and cherts of the same age (Bonneau, 1984). In places, the overlying flysch derived from the overriding Eurasian plate can be found (Hall et al., 1984). A stratigraphically higher unit – the Uppermost Unit – is not found on western Crete, but it can be found in central and eastern Crete and on Karpathos. It contains elements derived from the Mesozoic Pindos-ocean, as well as the Eurasian overriding plate: oceanic pillow basalts, gabbros, deep-water carbonates and cherts, serpentinised mantle fragments, and Jurassic to Late Cretaceaous HP-LT metamorphic and plutonic rocks (Thomson et al., 1999 and references therein)

It is not possible to do any thermochronology studies on the Tripolitza and Pindos units, since they mostly consist of carbonate rocks. However, in the Uppermost Unit, a thermochronology study, based on apatite fission track analysis, was carried out by (Thomson et al., 1998a; 1999). They report temperatures of *c.* 120-60°C, corresponding to the upper 4 and 7 kilometers of the crust, depending on the geothermal gradient as the maximum depth to which the Uppermost Unit was brought since it was emplaced on top of the Pindos unit, some *c.*35 Ma ago. Accelerated cooling related to increased erosion started at *c.* 16-17 Ma and the temperature of the uppermost plate did not rise ever since.

Neogene sedimentary cover

These nappe-piles are overlain by the Topolia Formation (cf. Kopp and Richter, 1983): Terrigeneous coarse breccias consisting exclusively of fragments of the Pindos and the Tripolitza nappe. These breccias are overlain by Neogene *in situ* sediments, located in the Neogene basins that first developed in the south and later in the north of western Crete. A detailed description of the various formations is given by Freudentahl (1969). We will consider features of the oldest three sedimentary formations in the northern Kissamou-basin: the Roka-formation, *in situ* carbonates formed in the photic zone, estimated to be 8.7-8.5 Ma old, the Koukounara-formation, proximal calcarenites of ~8.5-7.5 Ma, and it's distal variant: the Kissamou-clay formation: deep marine blue clays of the same age (ages: pers. comm. W.J. Zachariasse, 1999).

A schematic geologic map of western Crete is given in *figure 2*. The lower plate crops out in the center of the west-Cretan E-W striking anticlinorium. The upper plate rocks are found at both sides of the anticlinorium against it's limbs and locally as *klippen* on the Phyllite-Quartzite unit, e.g. near the village of Mili. The Neogene deposits are found in the basin of Anidri, NE of Paleohora, along the southern coast and in the northern Kissamou Basin.

During the late Middle Miocene, the break-up of the Southern Aegean was initiated by the roll-back of the Aegean slab, which finally resulted in the present-day Hellenic Arc (Meulenkamp et al., 1994). The tectonic response to this process is described by the model of supracrustal slab detachment (*figure 3*, Meulenkamp et al., 1988) over a low-angle southward dipping detachment a supracrustal slab slides southward under the influence of gravity, resulting in N-S extension in the internal Hellenides and N-S compression in the external parts as the supracrustal slab approaches the trench, where its movement is obstructed. The uplift of Crete is believed to result from the compressional tectonics in of the detachment front.

Field results

We propose a four-episode geological development of western Crete. The field expression of these episodes is described in chronological order.

Episode 1: Deposition of the Topolia Formation

<u>Topolia Formation</u>

The Topolia Formation has been previously described as terrestrial denudation masses with components derived exclusively from the Tripolitza and Pindos Nappes (Kopp and Richter, 1983). It consists mainly of coarse sedimentary breccias and conglomerates. No components derived from the Phyllite-Quartzite Nappe are found within the Topolia Formation. The Topolia Formation on western Crete is typically outcropped as large, isolated blocks.

The coarsest and most proximal deposits of the Topolia Formation (To2, cf. Kopp and Richter, 1983) consist of coarse breccias and rare conglomerates, and are often karstified. Clast sizes range from 1 to 50 centimetres, and are cemented by lacustrine mud (Kopp and Richter, 1983). The thickest parts of the Topolia Formation reach a thickness of approximately 300-400 meters. A general stratigraphy of the thickest part of the Topolia Formation was established in the Deliana gorge, and later correlated to the succession found in the nearby Topolia gorge (*figure 4*). In this column 5 members are distinguished:

1. Deepest recognizable Topolia deposits, which have a tectonic contact with the Phyllite-Quartzite nappe in the gorges of Deliana and Topolia. Karstified, massive limestone breccias that contain numerous travertine veins.
2. Poorly exposed breccias with a matrix rich in sand-sized grains.
3. Massive, ~35 meter thick karstified breccia
4. Sand-rich sedimentary breccia, only slightly karstified. The imbricated pebbles are exposed in this stratigraphic interval.
5. Massive, karstified deposits. Coarse, poorly sorted breccias.

In most parts of the To2-member of the Topolia Formation, sedimentary structures cannot be observed. In one 20 meter thick interval however (interval 4 of the general lithology of the Deliana gorge) imbrications can be observed (*figure 5*). The imbrications measured in this part of the Topolia Formation, as well as imbrications measured in very proximal deposits near Trahilos, give conclusive evidence of southward sedimentary transport (*figure 6*).

Near the southern coast of Western Crete finer and more distal deposits of the Topolia Formation are found (To1, cf. Kopp and Richter, 1983). These consist of freshwater limestones and sandstones, with occasional conglomerates (Kopp and Richter, 1983). A maximum thickness of approximately 110 meters was recorded. It is found likely that the To1 member is a lateral equivalent of the To2 member, rather than that the To1 member is overlain by the To2 member.

The Topolia Formation has been deposited southward direction from a source of Pindos and Tripolitza rocks north of Kissamou. Very proximal deposits of the Topolia Formation, were found on the Gramboussa Peninsula and near the harbour of Trahilos. The coarse Topolia deposits (To2) would thus represent proximal deposits, and the finer (To1) deposits would represent more distal deposits of one southward drainage system that was active during the Middle Miocene.

Marine deposition in the basin of Anidri (southern coast) and later in the marine Kastelli basin (northern coast) is thus distinctly separated from the deposition of the Topolia Formation.

Contacts with the nappes

Pindos Nappe

Near the town of Kioliana a sedimentary contact of the Topolia Formation with the Pindos Nappe was identified (*figure 7*). The Topolia Formation here is deposited upon the Pindos radiolarites. The upper few centimetres of the Pindos radiolarites have been reworked, and paleosols can be found. Upon the paleosols marls and occasional sand pockets are found, followed by the first sedimentary breccias of the Topolia Formation.

Tripolitza Nappe

Also between the Tripolitza Nappe and the Topolia Formation the contacts are originally of a sedimentary origin. The contact of the Topolia Formation and the Tripolitza Nappe was identified near the harbour of Trahilos.

Phyllite-Quartzite Nappe

The Topolia Formation is always found in an allochthonous position relative to the Phyllite-Quartzite Nappe (Kopp and Richter, 1983). The contacts between the Topolia Formation and the Phyllite-Quartzite Nappe are exclusively of a tectonic origin.

Episode 2: Gravity induced southward sliding of the upper plate

After the deposition and lithification of the Topolia Formation, and before the generation of the west-Cretan anticlinorium, a phase of southward sliding takes place in the upper plate. Within the present-day Kissamou basin only locally upper-plate rocks can be found and it is at least questionable if they still underlie the Neogene basin-fill. In several localities the Neogene deposits were observed unconformably overlying the Phyllite-Quartzite rocks. A relatively thin upper plate (few hundreds of meters thick, but variable in thickness down to totally absent) can be found upon the limbs of the anticlinorium, with evidence within the Pindos – after correction for the later tilting by the uplift of the anticlinorium – for low-angle south-directed normal movement. In the south the thickness of the upper plate is considerably larger (on estimation 1 to 2 kilometers). Within the Pindos, on various locations evidence for N-S shortening can be found, but the relative timing of the compressional features can only be carried out in places where slices of Topolia Formation are imbricated *(figure 8)*
Along the old road from Paleohora to Chania, only some few hundreds of meters north of Paleohora, a repetition of the members of the upper plate and the Topolia Formation is encountered.
The Tripolitza unit seems to serve mainly as the basement over which the Topolia Formation slide southward, accomodated by the weak Pindos material. The Tripolitza nappe is only encountered at the base of the upper plate, and only occasionally as slices incorporated in the Pindos material.

The stacking in the south resulted in a northward dip of the deformed upper plate in the south under a maximum angle of *c.* 30 degrees. Within the valley of Anidri, to the northeast of Paleohora, marine calcareous sands and finer deposits are found, which reveal a small northward dip, generally approximately 10°. At the base of the sequence the dip is parallel to the upper plate rocks and the Topolia Formation, as can be seen at the north entrance of the gorge of Anidri. Another indication of instability during deposition of the sediments in the basin of Anidri is the presence of large incorporated blocks of Topolia-type breccia within the sediments *(figure 9)*.
This gives the impression, that this sedimentation took place probably during or after the last phases of stacking and tilting, since these sediments were not found incorporated in the stacked sequence.

Although it has not been possible to date these sediments, the Neogene full marine deposits at the southern coast have been dated Late-Serravallian – Early Tortonian, based on the foraminiferal content (De Stigter, 1989), about 10 Ma (pers. comm. W.J. Zachariasse, 1999). These sediments have not – apart from recent normal movement – been tectonically disturbed and are hence deposited after the stacking.

Episode 2 must have thus been active after deposition and lithification of the Topolia-type breccia's and the deposition of the marine clays at the coast of Paleohora. (between ?12 to approximately 10 Ma)

Episode 3: Creation of the West-Cretan anticlinorium and the opening of the Kissamou Basin

Creation of the West-Cretan anticlinorium

The west Cretan anticlinorium is the most dominant structure of western Crete. Its hinge strikes roughly WNW-ESE and in its center the lower plate Phyllite Quartzite nappe is exposed. *(figure 2).*

In the north, near Aikirgiannis, the uplift and rotation of the (northern limb of) the anticlinorium can be timed, since the Koukounara formation – aged 8.5-7.6 Ma (pers. comm. W.J. Zachariasse, 1999) – reveals tapering, caused by the rotation of this northern limb. *(figure 10).* In the south, timing is made impossible due to lack of sediments younger than approximately 10 Ma.

The contact between the lower and upper plate can on many occasions be seen both in the north and in the south of western Crete. The contact is represented by a brittle gouge zone. In the north, this zone is on average *c.* 10 meters thick *(figure 11).* The northern contact zone gives evidence of top-to-the-north normal movement of the upper plate. In south, however, the contact zone is much thicker (100 to 200 meters) and large, meter-sized blocks of both upper plate and lower plate rocks are incorporated in the gouge zone. The southern gouge zone reveals top-to the south normal movement of the upper plate. It should be noted, that the influence of the tilting of the anticlinorium limbs is restricted to a distance of only one or two kilometers from the contact between the upper and lower plates, perpendicular to the anticlinorium axis, both in the north and in the south.

Brittle fault zones of variable thickness giving evidence of normal movement, alike the contact zones, can be found everywhere within the Phyllite Quartzite nappe. Although Jolivet et al. (1996) suggested that this stage of brittle faulting was distinctly asymmetric with a clear top-to-the-north sense of shear, we agree with the observations of Thomson et al. (1999), who did not believe it to be possible to observe any asymmetry. Moreover, the normal faulting in the southern limb reveals dominantly top-to-the-south-movement, the normal faulting in the northern limb is dominantly top-to-the-north *(figure 12)*

Brittle normal faulting with top-to-the-east and top-to-the-west movement can also be found in many locations within the Phyllite-Quartzite nappe, giving evidence of the arc-parallel extension associated with the outward migration of the Hellenic arc. *(Figure 12)*

As mentioned before, the oldest sediments in the northern Kissamou basin are the (?) 8.7-8.5 Ma old carbonates of the Roka-formation. The Roka-formation is situated on top of half-graben-blocks within the Kissamou basin, as can be seen in *figure 13*, showing the regional distribution pattern of the Roka Formation (Freudentahl, 1969); This distribution pattern reveals, that the Kissamou basin is the result of E-W extension. Moreover, extensional growth-faults, found in the Late Miocene deposits near Zachariana, in the Kissamou Formation on the south-end of the Rhodopou peninsula, as well as in the Pleistocene intramontane basin of Dris, situated on top of the Phyllite-Quartzite nappe, show that E-W extension prevailed during the Late Miocene until at least the Pleistocene. It is hence shown, that the uplift of the anticlinorium, which took place during the deposition of the Koukounara Formation, occurred simultaneous with the opening of the Kissamou basin.

Jolivet et al. (1996) suggest, that the exhumation of the Phyllite Quartzite, and thus the creation of the anticlinorium, was the result of an N-S extension, which created an extensional detachment between the lower and upper plate rocks. However, the N-S extensional features are restricted to the lower plate and its contact with the upper plate. The E-W extension can be found all over western-Crete, both in the Phyllite Quartzite as in growth faults and sediment distribution patterns within the Neogene and Pleistocene sediments. If N-S extension was the driving force in the creation of the anticlinorium, it should also have left traces in the sediments of the Kissamou basin. Especially since overprinting is not possible, because both features came into existence simultaneously. Neither the distribution pattern of the oldest sediments within the basin, nor growth faults within the Neogene sediments, show any evidence of N-S extension.

Episode 4: Pliocene and Quarternary

In the Kissamou basin, no Pliocene sediments are exposed. Traces of Pleistocene deposits can be found as terraces along the coastlines, and in the intramontane basin of Dris (Creutzburg, 1977), where a Pleistocene paleolake reveals synsedimentary tectonics under the influence of E-W extension: growth faults and growth joints. It should be noted, that the Pleistocene terraces in the south west currently reach levels of 50 meters above sealevel, whereas in the north the uplift has been much less. Present day GPS-analysis reveals the highest uplift in southern Crete, about twice as high as in the north (Pirazolli et al., 1982).

Seismics reveal (blind) thrust faults at the southern coast of Crete, giving rise to the impression, that top-to-the-south thrust tectonics are probably responsible for the uplift of Crete (ref seismiek!)

Discussion and tectonic model

During middle Miocene times, the rocks of current Crete were most likely part of the Hellenic Mountain belt, a few hundreds of kilometers north of Crete's current geographical position (Meulenkamp et al., 1994). The oldest sedimentary record which can be examined on Crete is the Topolia Formation. Based on the fission track data of Thomson et al. (1999), the deposition of these breccias probably started some 15-16 Ma ago, when the upper plate was first eroded.

The Topolia Formation can probably best be compared with foreland basin type sediments, derived from the then present Hellenic Mountain Belt. They were deposited on the foreland, from north to south. (*figure 14*) Relics of the sediment source of those times might be represented by the large peninsulas of northwestern Crete, where the most northern deposits belonging to the Topolia-Formation are found, very course, thus very proximal.

During these times, the lower plate rocks were not exposed on western Crete, although they were rapidly exhumed between *c.* 19 and 15 Ma ((Jolivet et al., 1996; Thomson et al., 1998b; 1999). Thomson et al. (1999) suggest, that the Phylite-Quartzite unit was exposed by buoyant rise as a result of roll-back, creating accommodation space in the south. This creation of accommodation space in the south led Meulenkamp et al. (1988) to the hypothesis of supracrustal slab-detachment, which predicts compressional tectonics on Crete (*figure 3).* This discussion will take the Middle Miocene deposition of the Topolia-type breccias as a starting point, after which the surface expression of the reaction of the overriding plate on roll-back of the Aegean slab can be reconstructed. According to Thomson et al. (1999), the Phyllite-Quartzite already was at shallow crustal levels by this time.

It is not well possible to determine the length of the period of time, during which the Topolia Formation was deposited, since no biostratigraphic markers are present, and fission track analysis is not possible. After the deposition and lithification of the Topolia Formation (somewhere between ?16 and 12 Ma?), a new phase of instability resulted in the earlier described gravity induced southward sliding of the upper plate (*figure 14*). Based on the age of the overlying (un)disturbed sediments, this phase of gravitational sliding and stacking is estimated to occur between ?12 to 10 Ma.
Since within the Kissamou-basin relics of the upper plate are exposed only locally and, on many occasions the Neogene sediments are deposited unconformably on the Phyllite-Quartzite rocks, the Kissamou-basin probably was a relative high area with respect to the south, and gravitational sliding on the southern slope of this high was responsible for the thinning and removal of the upper plate rocks in the north. This high probably was situated south of the sediment source of the Topolia Formation, thus indicating a first surface expression of a tectonic infill of accommodation space created in the south.

On eastern Crete, the oldest sediments in which elements of the lower plate can be recognized are of Tortonian age, *c.* 10 Ma at the latest (Postma et al., 1993). The oldest evidence for exposure of the Phyllite Quartzite is found in small conglomerate pockets (*cf.* Mesonisi Formation, Freudentahl, 1969) underlying the Roka-formation, *c.* 9 Ma or a little younger. Furthermore, the Koukounara calcarenites contain considerable amounts of Phyllite Quartzite fragments. As pointed out before, this coincides with the formation of the west Cretan anticlinorium – yet another topographic high south of the previous. The onset of development of the anticlinorium, and the coincident final exposure of the Phyllite Quartzite must thus have taken place between 10 and *c.* 9 Ma. (*figure 14*).

At the same time, E-W (arc-parallel) extension resulted in the opening of the Kissamou basin, as can be derived from the synsedimentary tectonics observed in e.g. the clays of the Kissamou Formation and the distribution patterns of the Roka formation (*figures 13 and 14*). As pointed out before, all units on western Crete have been subjected to E-W arc parallel extension. Still, the anticlinorium was lifted up, despite the E-W extensional tectonics, while the Kissamou basin could subside. This leads to a picture of localized uplift, which is stronger than the subsiding forces.

Jolivet et al. (1996) proposed a model, in which the exhumation of the Phyllite-Quartzite and finally the creation of the anticlinorium is induced by movement along a N-S extensional detachment. Thomson et al. (1999) already point out, that convincing exposures of this 'extensional detachment' are difficult to find on Crete and that the proposals for major crustal extension on Crete rely mainly on the combination of indirect metamorphic, geochronological and structural criteria.

The N-S extensional features (normal faults and shears) are restricted to the anticlinorium and its direct cover. Within the simultaneously developing Kissamou Basin, no traces of N-S extension are found. It should be noted, that E-W extensional features, are found in all formations everywhere on the island. We thus propose a mechanism in which the anticlinorium is actively 'pushed up'. As a response, normal movement under the influence of gravity – to the north in the northern limb, to the south in the southern limb (figure rose) - results in the localised N-S extensional features observed in the anticlinorium, and described by many authors (e.g. Greiling, 1982; Jolivet et al., 1996; Thomson et al., 1999).

A means of active uplift of an anticline with only local influence on the geomorphology and accompanying extensional features is blind thrusting. Apart from the localised character of the N-S extensional features, clues in favour of a model of blind thrusting as the tectonic mechanism of uplift and final exposure of the anticlinorium and the lower plate is the fact, that on the hinge of the

anticlinorium, salt domes are encountered, e.g. south of Amigdalokefali (Creutzburg, 1977). The salt is probably the stratigraphically lowest part of the Phyllite Quartzite, Paleozoic (Upper Carboniferous, Permian) in age (Krahl et al., 1983). In southwest Iran, within the active Zagros fold and thrust-belt the existance of blind thrusts has been shown by their seimic activity (Berberian, 1995). Berberian (1995) also describes salt diapirs, which intrude and rise along the (blind) thrust plane, to be ultimately exposed in the anticlinal hinge.
Moreover, these (blind) thrusts are predicted by the hypothesis of supracrustal slab detachment (Meulenkamp et al., 1988; *figure 3*).

During more recent times (Quarternary, present) the south-east of Crete reveals the highest uplift rates, almost twice as high as the north-east during the present (Pirazolli et al., 1982), which reveals the creation of another topographic high in the south. The presence of thrusts can be seen clearly on the seismic profiles of figure (ref!!), although the no timing of their activity can be given.

It can be derived from the analysis of the paleogeography of Crete that, since the deposition of the Topolia Formation, the occurrence of topographic highs migrates southward through time. This southward migration of vertical motions can be explained by the combination of creation of accommodation space in the south due to roll back with the hypothesis of supracrustal slab detachment: as roll-back continues, a new thrust develops south of the previous, which results in a new topographic high, south of the previous (*figure 14*)

It should be noted, that the Phyllite Quartzite nappe has been at shallow depth since *c.* 15 Ma (Thomson et al., 1999). The mechanism of blind thrusting within the framework of supracrustal slabdetachment and southward migration of vertical movements can thus only account for the exhumation of the Phyllite Quartzite of the last few kilometers until exposure on western Crete.

Summary and Conclusions

The tectonic history of western Crete is described in 4 episodes, which are characterized by the deposition of distinct sedimentary successions and/or the creation of distinct structural features and tectonic processes:

1. The oldest sedimentary succession of western Crete – the Topolia Formation – consists of coarse breccias, exclusively containing fragments of the Pindos and Tripolitza nappes, which unconformably overlies the Pindos and Tripolitza Nappes. The age of these breccias is estimated at 16 Ma at the oldest, based on fission track-data of Thomson et al. (1999) who estimate the onset of erosion of the upper plate by this time. The Topolia Formation is deposited from north to south, indicating a relative topographic high as a sediment source in the north.
2. After deposition and lithification of the Topolia Formation (?12 Ma), renewed instability in the north leads to gravity-induced southward sliding of the upper plate rocks, together with the Topolia-formation, which results in a considerable thinning and removal of the upper plate in the northern Kissamou basin and a stacking and thickening up to approximately 2 km of the upper plate in the south. 10 Ma old deep marine clays in the south are not influenced by the tectonics of this stacking episode.
3. Between 10 Ma and somewhat less than 9 Ma the Phyllite-Quartziete nappe – and thus the lower plate – is exposed, both in the present-day Kissamou-basin as in the core of the present-day anticlinorium. Synsedimentary tectonic features such as growth faults and tapering against the anticlinorium limb reveal, that the anticlinorium and the Kissamou-basin developed simultaneously. The Kissamou-basin came into existence in response to E-W arc-parallel extension. It is proposed, that the anticlinorium was pushed up under the influence of (blind) thrusts, supported by the presence of salt domes at the anticlinal hinge, within the frontal setting of the supracrustal slab detachment of Meulenkamp et al. (1988).
4. Growth faults and joints in Pleistocene till recent sediments reveal ongoing E-W arc-parallel extension. Furthermore, Crete is lifted up faster in the south than in the north, thus creating a picture of northward tilting. N-S seismic profiles of *ref!!* near Paleohora reveal the existence of thrusts with a top to the south movement.

Since the deposition of the Topolia Formation, the topographic highs and lows have migrated southward through time. We propose a model in which this southward migration of vertical motions is forced by new (blind)thrusts, which develop in the southern accommodation space, created by the roll-back of the Aegean slab, while subsidence of old topographic highs is accommodated by the E-W arc-parallel extension found everywhere on Crete in all (tectono)stratigraphic units.

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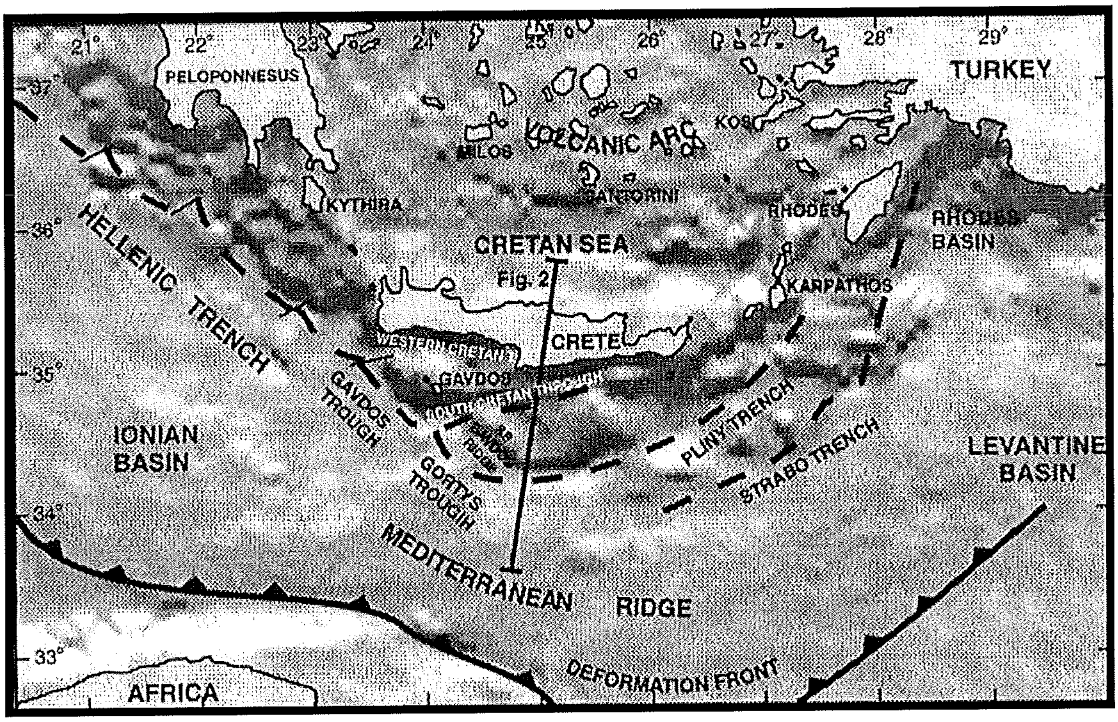

Figure 1: Geographic map of the Hellenic arc.

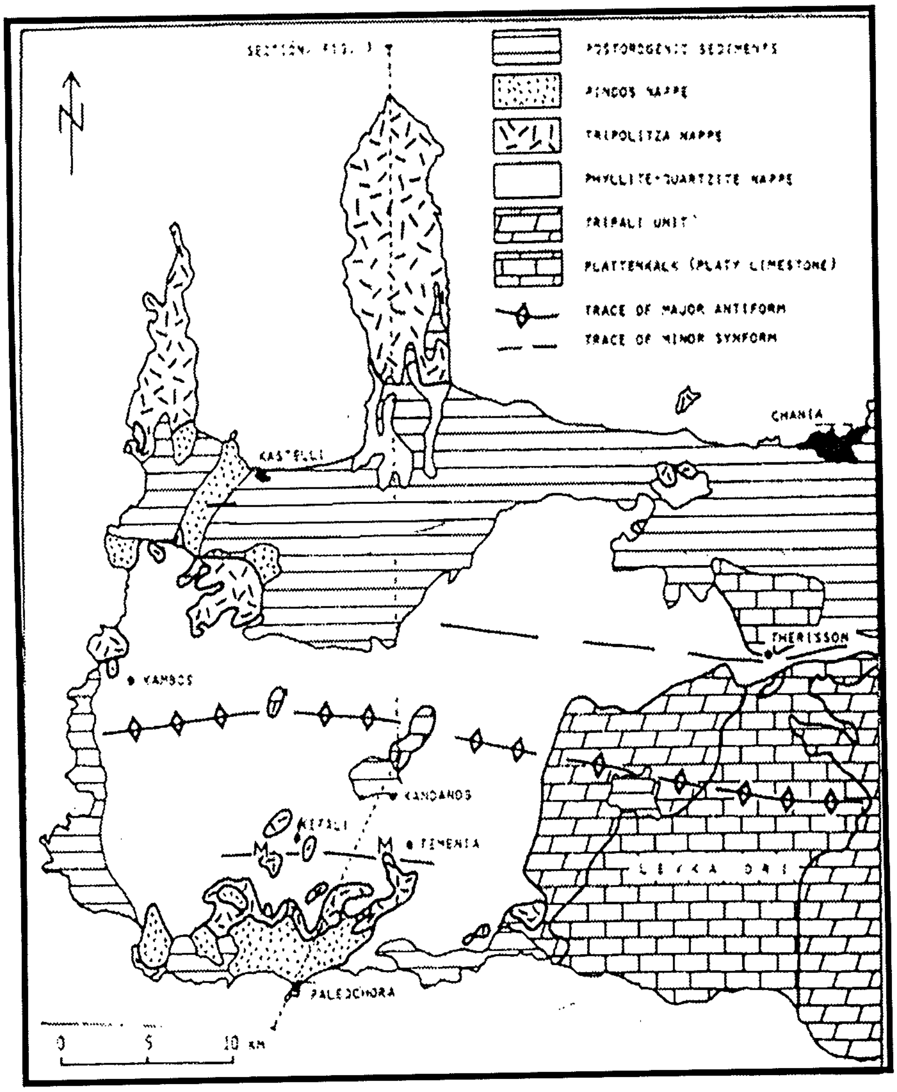

Figure 2: Geologic map of western Crete. (Greiling, 1982, after Creuzburg, 1977)

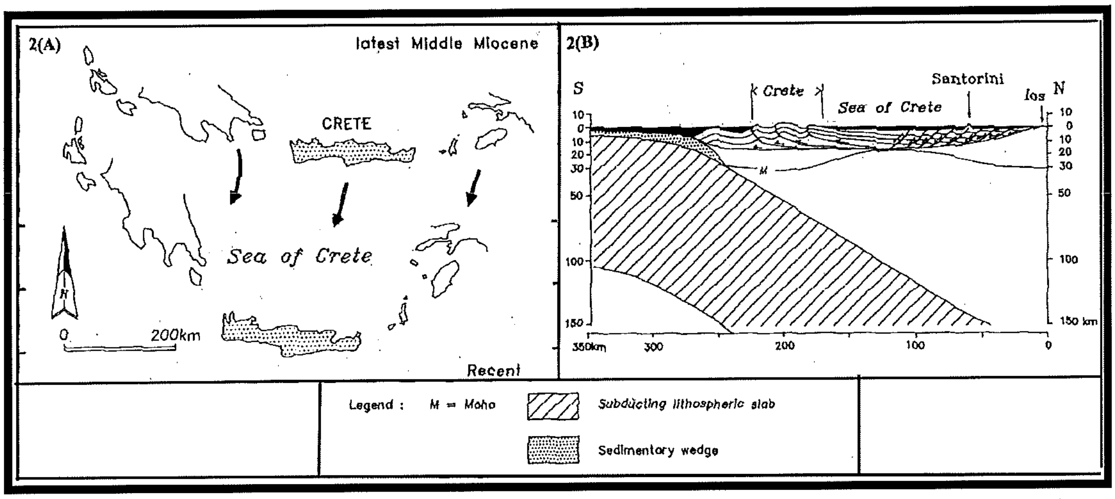

Figure 2: Geodynamic setting of Crete within the framework of arc migration and supracrustal slab detachment (Meulenkamp et al., 1988; 1994)

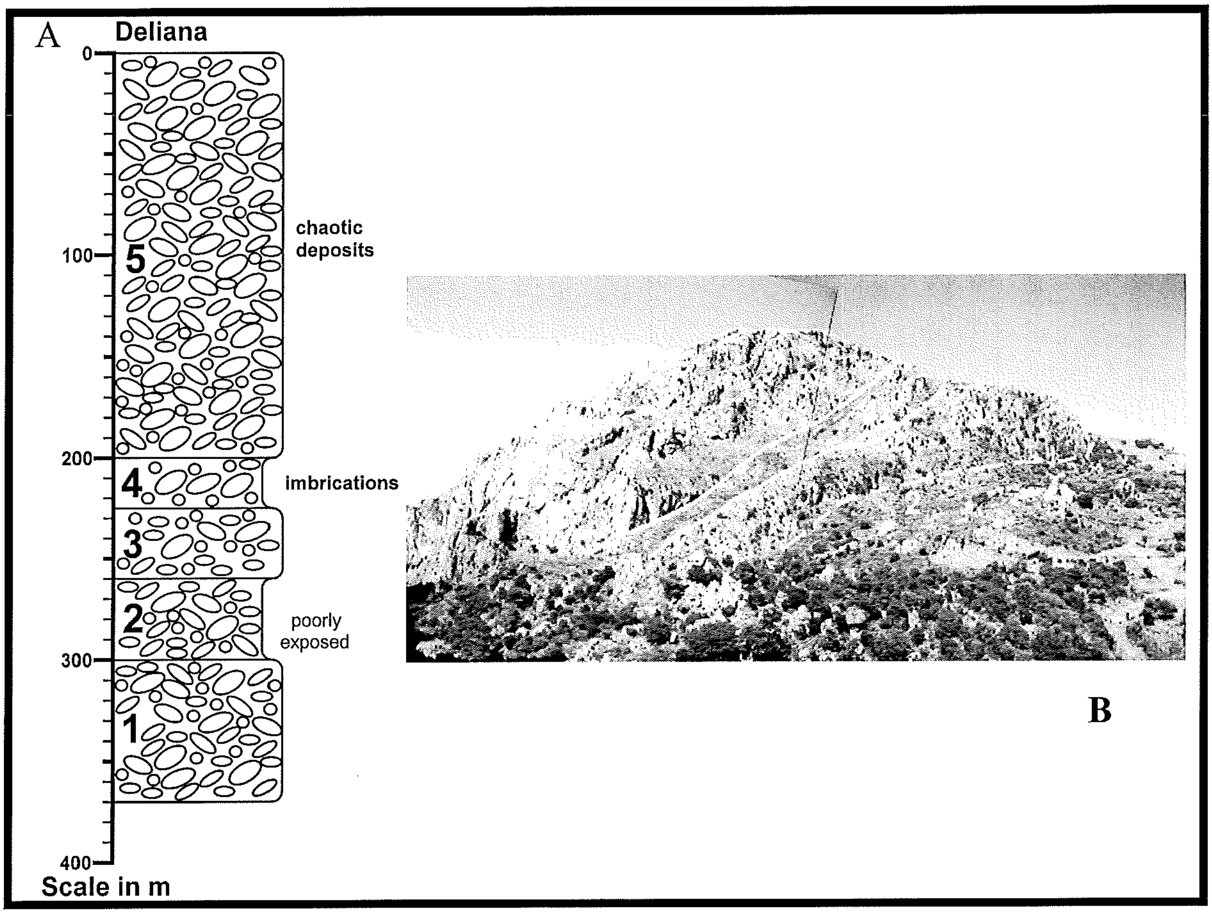

Figure 4: a) Schematic stratigraphic column of the To2 (cf. Kopp & Richter, 1983), as inferred from the exposure in the Deliana-gorge. b) Exposure of the To2 in the Topolia-gorge. Numbers refer to the stratigraphic members of 4a.

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Figure 5: Imbrications within the Topolia Formation, indicating the palaeo-flow direction.

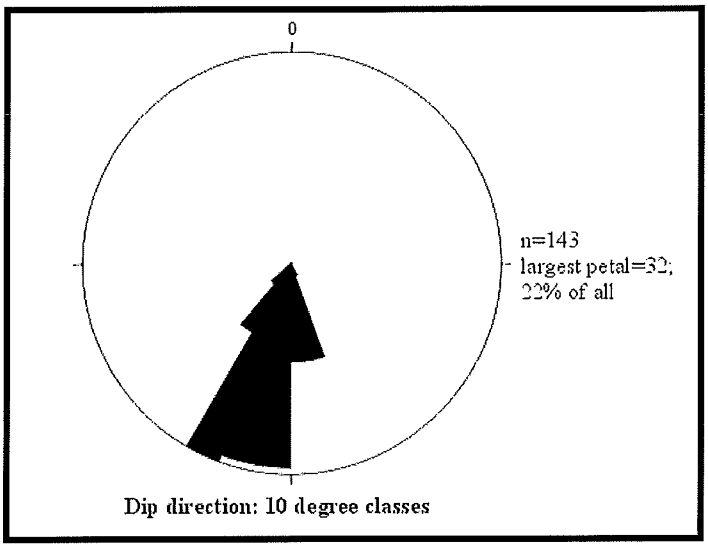

Figure 6: Rose diagram indicating the paleoflow-direction in the Topolia Formation, based on imbrication measurements. Average flow direction is appr. 200°

Figure 7: Sedimentary contact between the Topolia Formation and the Pindos Nappe near the quarry of Kioliana. At the tip of the hammer the green paleosol-horizon can be seen. Pindos material is red, Topolia-Formation is yellow/white.

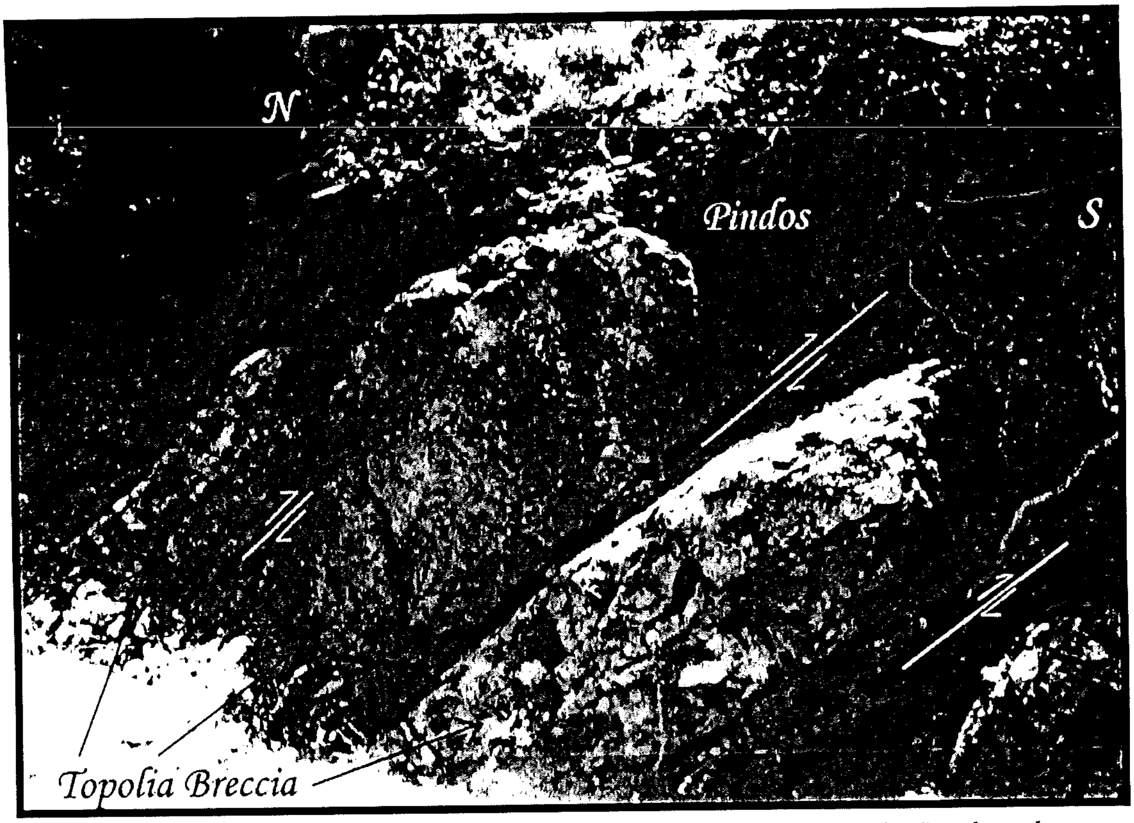

Figure 8: stacked (imbricated) slices of the Topolia Formation in the Pindos along a dustroad northwest of Paleohora.

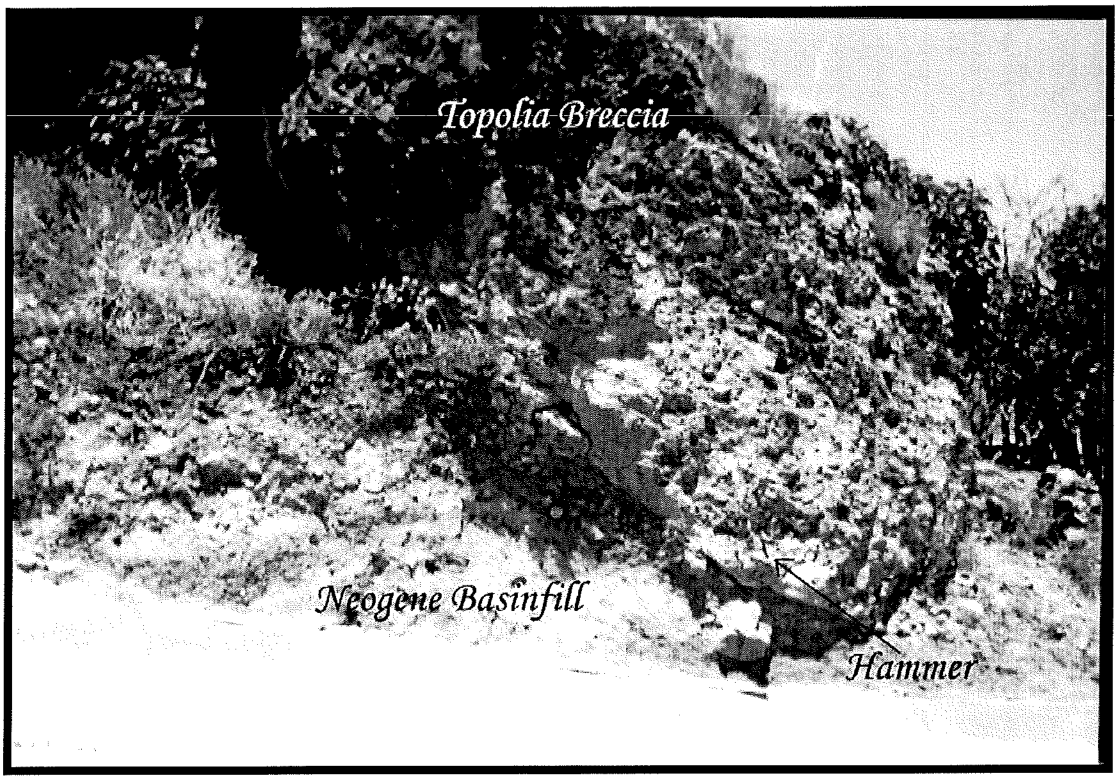

Figure 9: Large block of the Topolia Formation, incorporated in Neogene sediments in the valley of Anidri.

Figure 10: Tapering of the 8.5-7.5 Ma Koukounara Formation, synsedimentary with the tilting of the northern limb of the anticlinorium (represented by the Topolia Formation in the right of the picture.

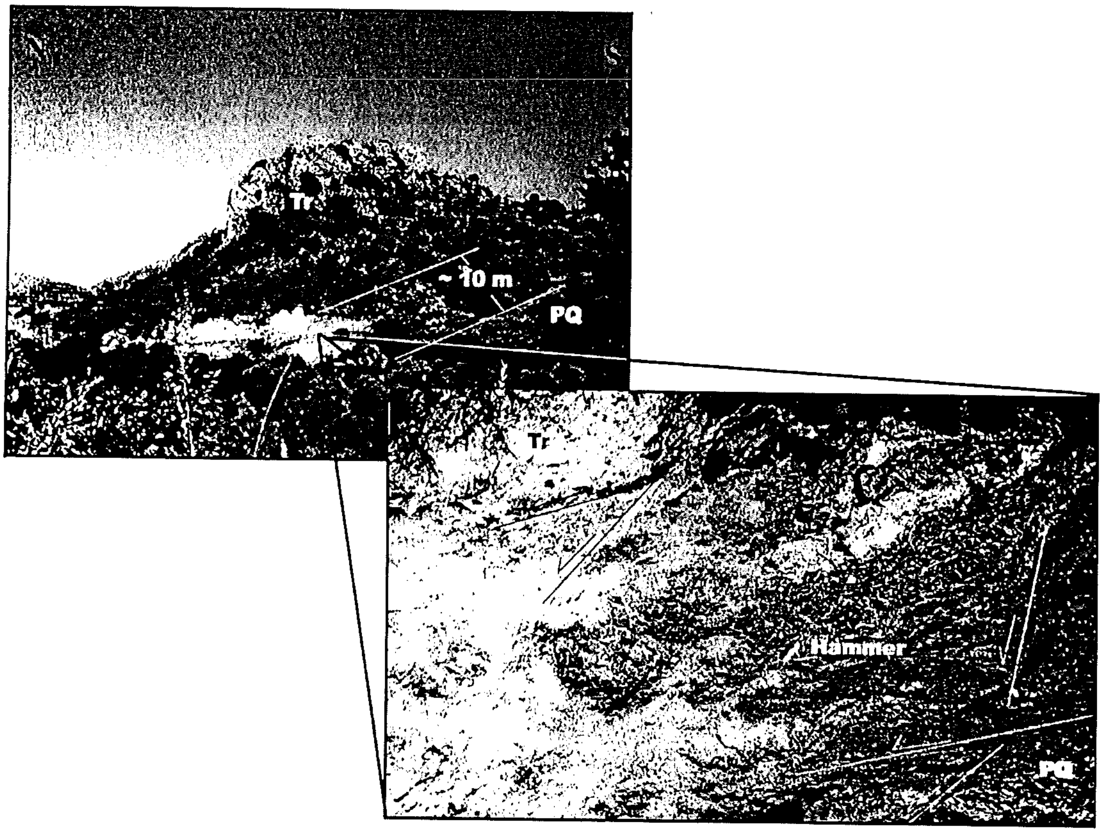

Figure 11: Exposure of the brittle gouge zone between the upper plate (Tr = Tripolitza Nappe) and lower plate (PQ = Phyllite Quartzite) on the road from Kioliana to Sirikari.

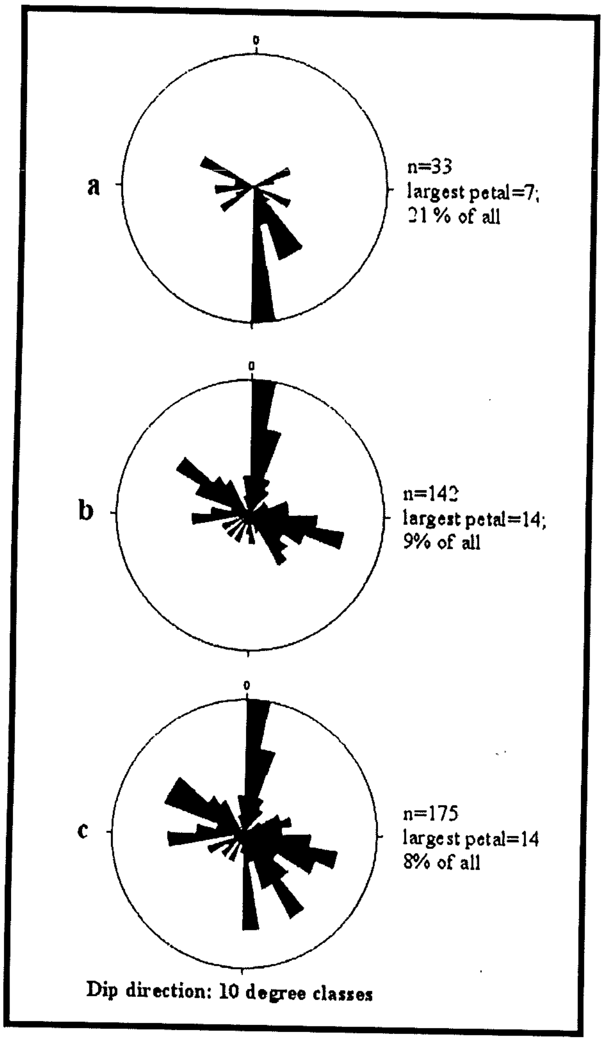

Figure 12: Rose diagrams of the dip direction of the shears and faults with normal sense of shear in the Phyllite Quartzite. a): southern limb (note: only 33 measurements), b) northern limb, c) integrated plot. Note, that E-W extension is observed everywhere, whilst the top-to-the-north sense of shear is restricted toi the northern limb, and the top-to-the-south sense of shear is restricted to the southern limb of the anticlinorium.

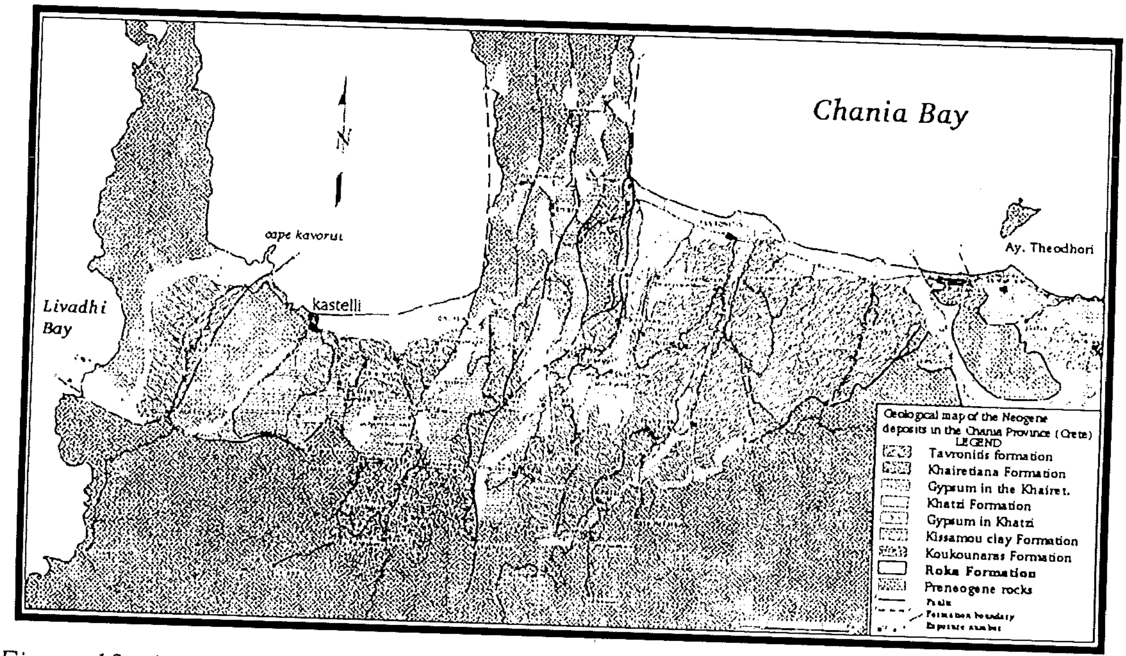

Figure 13: Areal distribution pattern of the Roka-Formation. (Freudentahl, 1969)

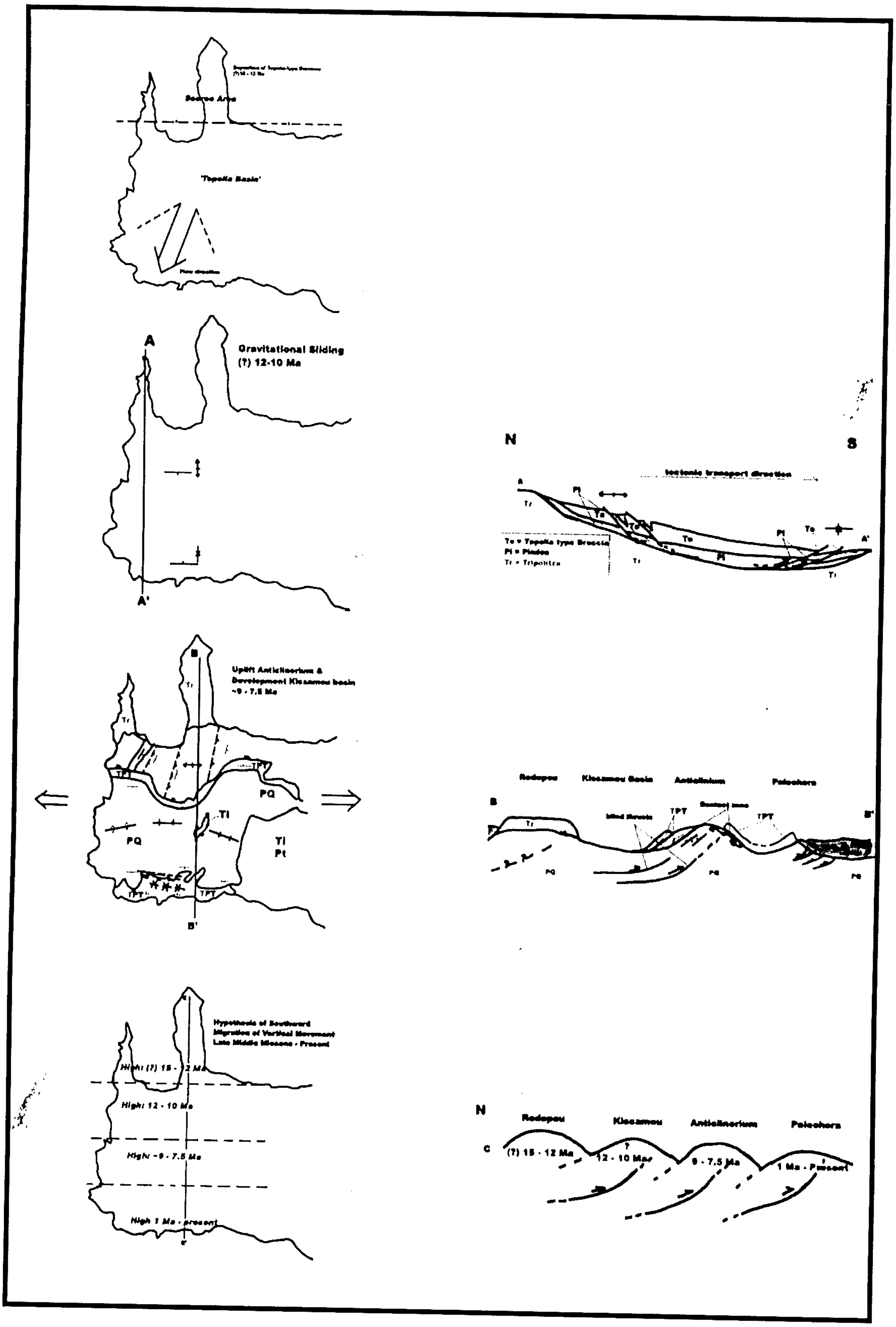

Figure 14: Southward migration of vertical motions. Uplift by (blind) thrusting within the framework of supracrustal slab detachment, subsidence by arc-parallel E-W extension.