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Penrose Conference - Extending a Continent - Naxos Field Guide

Olivier Vanderhaeghe

Maître de Conférences
Chef du département des Sciences de la Terre
UMR G2R-Université Henri Poincaré, Nancy I
BP 239
54006 Vandoeuvre-les-Nancy
+33 3 83 68 47 34

C. Hibsch

L. Siebenaller

Stéphanie Duchêne

Michel de St Blanquat

LMTG, OMP Toulouse

Seth Kruckenberg

A. Fotiadis

L. Martin

Abstract: The geodynamic evolution of the Mediterranean is controlled by Cenozoic convergence between the African and Eurasian plates (Figure 1). This convergence was accommodated by closure and subduction of the Tethys Ocean and development of the Alpine crustal accretionary wedge. The geodynamic evolution of the Mediterranean is also marked by opening of continental and oceanic basins above retreating slabs.

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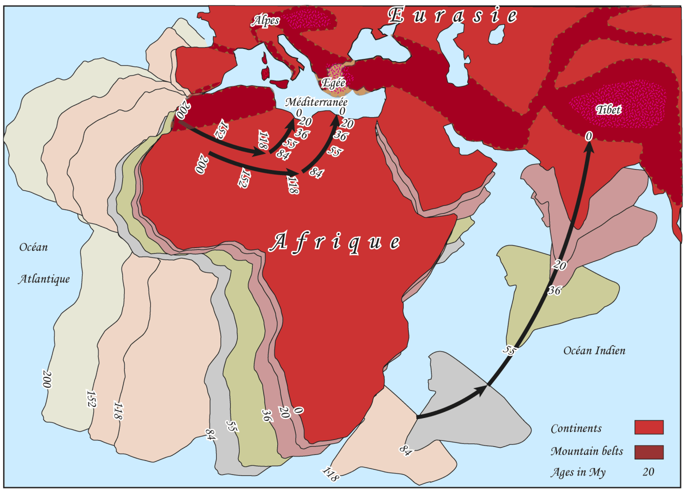
GEOLOGY OF NAXOS IN THE EAST-MEDITERRANEAN GEODYNAMIC CONTEXT

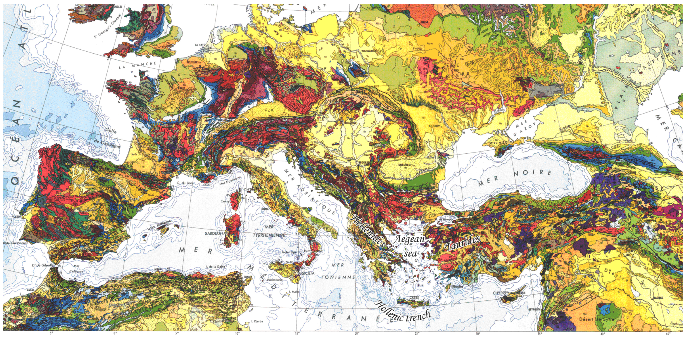
The geodynamic evolution of the Mediterranean is controlled by Cenozoic convergence between the African and Eurasian plates (Figure 1). This convergence was accommodated by closure and subduction of the Tethys Ocean and development of the Alpine crustal accretionary wedge. The geodynamic evolution of the Mediterranean is also marked by opening of continental and oceanic basins above retreating slabs.

Figure 1. Kinematics



Mesozoic Cenozoic Africa Eurasia kinematics

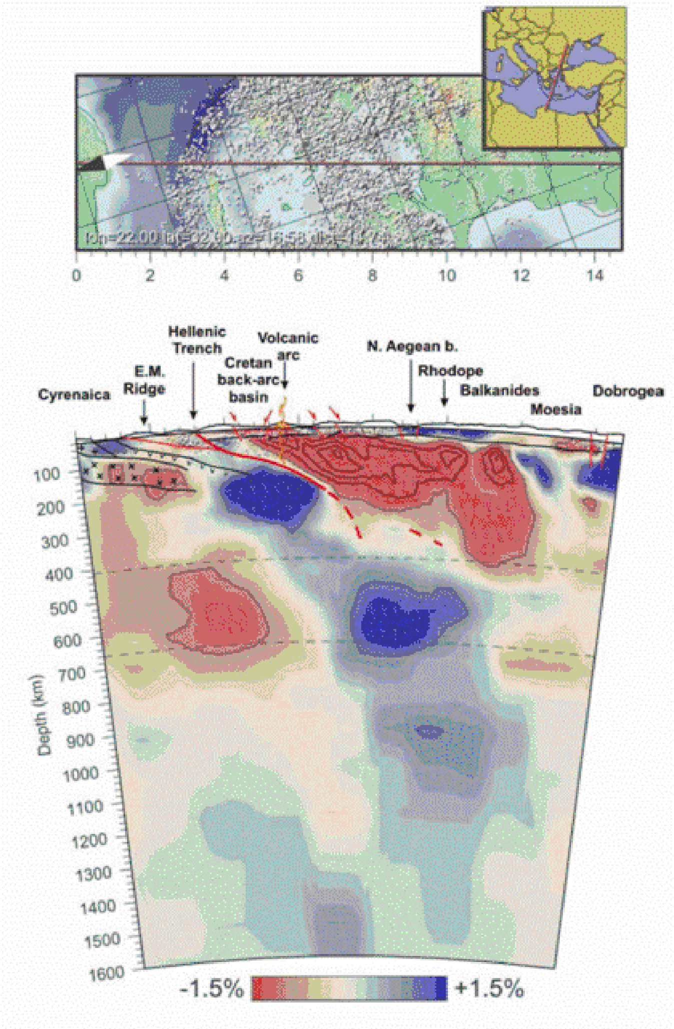
Figure 2. Geological map



Geological map of the Mediterranean

In the eastern Mediterranean, the continuity of the high mountainous massifs of the Hellenides in mainland Greece and the Taurides in Turkey is disrupted by the presence of the Aegean basin (Figure 2). The thickness of the continental crust in this region ranges from 50-55 km beneath the Taurides and the Hellenides to 15-20km beneath the Aegean and Cretan seas with intermediate thicknesses of 45km beneath Crete and 35km beneath the Cyclades (Makris and Stobbe 1984).

Figure 3. Aegean Slab



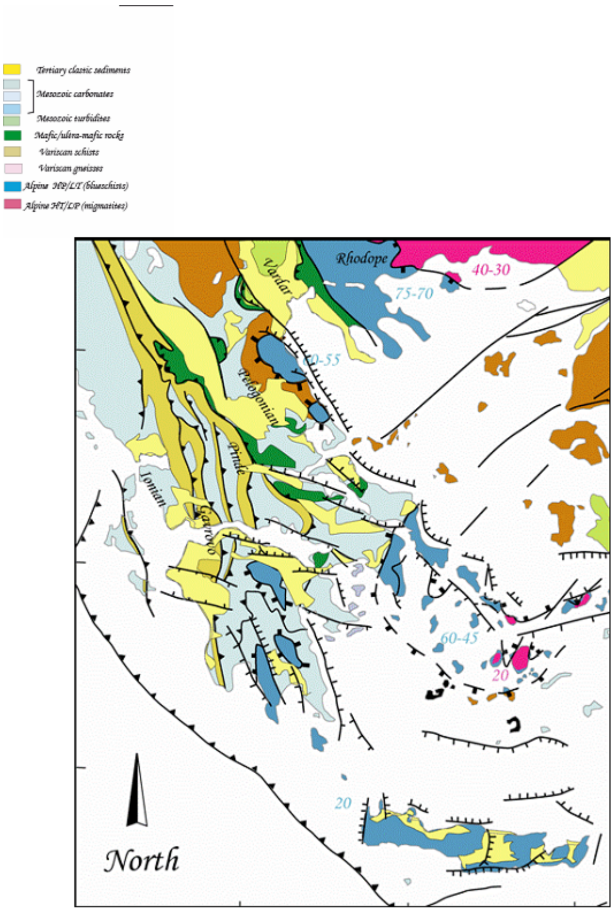
tomographic image of the Aegean slab (Bijwaard et al, 98)

The eastern Mediterranean Cenozoic geodynamic evolution is characterized by convergence between the African and Eurasian lithospheric plates accommodated at the lithospheric scale, by subduction of the Aegean slab since at least the early Cenozoic and currently active along the Hellenic trench (Spakman 1986) (Figure 3). Southward migration of calc-alkaline magmatism relative to the upper plate suggests southward slab roll-back for at least a 1000km (Fytikas, Innocenti et al. 1984). At the crustal scale, convergence is marked by the development of the

Hellenic and Aegean accretionary wedges that are exposed respectively in the Hellenides and in the Aegean Sea. The Hellenides are subdivided from North to South in the internal and external hellenides. The internal Hellenides expose the Rhodope and Pelagonian zones representing continental blocks separated by the Vardar suture zone (Auboin 1973; Bonneau 1982; Jacobshagen 1986; Papanikolaou 1989). The external Hellenides are composed by the Pindos, Gavrovo, and Ionian zones representing sedimentary cover nappes overthrusting the pre-apulian zone to the south (fig. geological map of Greece). These various zones have recorded events from subduction, obduction, and crustal thickening to crustal thinning within the context of convergence between Africa and Eurasia during Tertiary times (Dewey and Sengor 1979; Bonneau and Kienast 1982; Dercourt, Zonenshain et al. 1986).

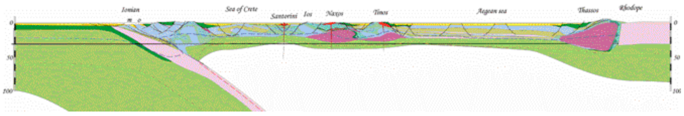
In the Aegean sea, the Attic-Cycladic Massif (Figure 4) forms a belt of metamorphic rocks exhumed along low-angle detachments (Lister, Banga et al. 1984). These metamorphic rocks have first recorded an Eocene high-pressure/low-temperature metamorphism evidenced by blueschist to eclogite facies (Andriessen, Boelrijk et al. 1979; Bonneau and Kienast 1982; Wijbrans and McDougall 1988; Buick and Holland 1989; Avigad and Garfunkel 1991; Keay 1998; Lips, White et al. 1998; Keay, Lister et al. 2002). The high-pressure/low-temperature metamorphism is overprinted by a Miocene medium pressure/medium temperature metamorphism evidenced by a greenschist to amphibolite-facies locally reaching partial melting (Jansen and Schuiling 1976; Andriessen, Boelrijk et al. 1979; Altherr, Kreuzer et al. 1982; Buick and Holland 1989; Keay 1998; Keay, Lister et al. 2001; Keay, Lister et al. 2002).

Figure 4. Greece



Geologic map of Greece

Figure 5. Aegean Sea

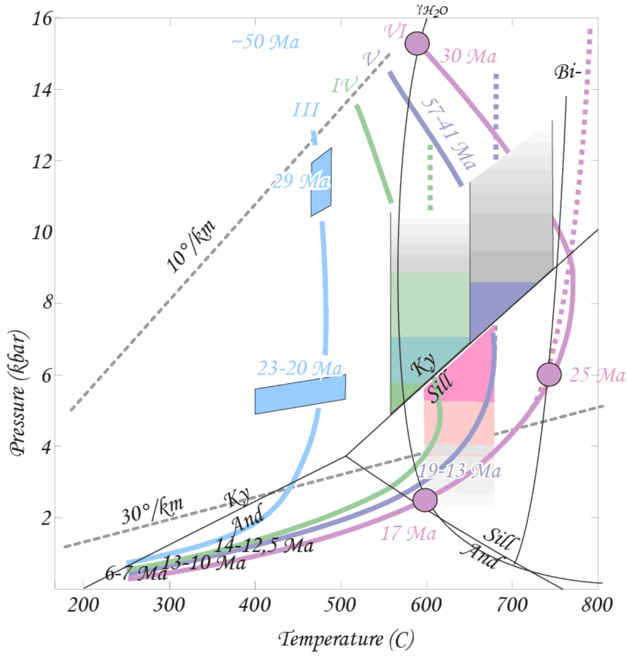


North-South lithospheric section from the Hellenic trench to the Rhodope massif across the Aegean sea (same legend as Fig. 4)

The island of Naxos in the Attic-Cycladic Massif (Figure 7) displays the most complete structural cross section of the Cyclades showing metamorphosed ante-Mesozoic rocks and Cenozoic granitoids juxtaposed to Cenozoic sediments or weakly metamorphosed rocks along detachment systems (Jansen 1973). Three tectonic-metamorphic units are distinguished. The upper unit, occurring structurally above the detachment, is composed of low-grade marble, schists and serpentinites that are overlain unconformably by dominantly detrital Cenozoic sediments (Jansen

1973). The middle and lower units are composed of high-grade metamorphic rocks located below the detachment. The middle unit is composed of a schists and marbles sequence containing mafic and ultramafic boudins (Jansen and Schuiling 1976). The middle unit is dominated by marbles at the top and by schists at the bottom. The lower unit is made of migmatites and marbles exposed in the core of an elliptical dome mantled by the metamorphic rocks of the middle unit. The structure of the island is asymmetric on an W-E section. First, the middle unit shows a structural section of about 1km to the west and 4km to the east of the dome. Second, in the western part of the island, the middle unit is intruded by a granodiorite pluton.

Figure 6. P-T conditions of Naxos



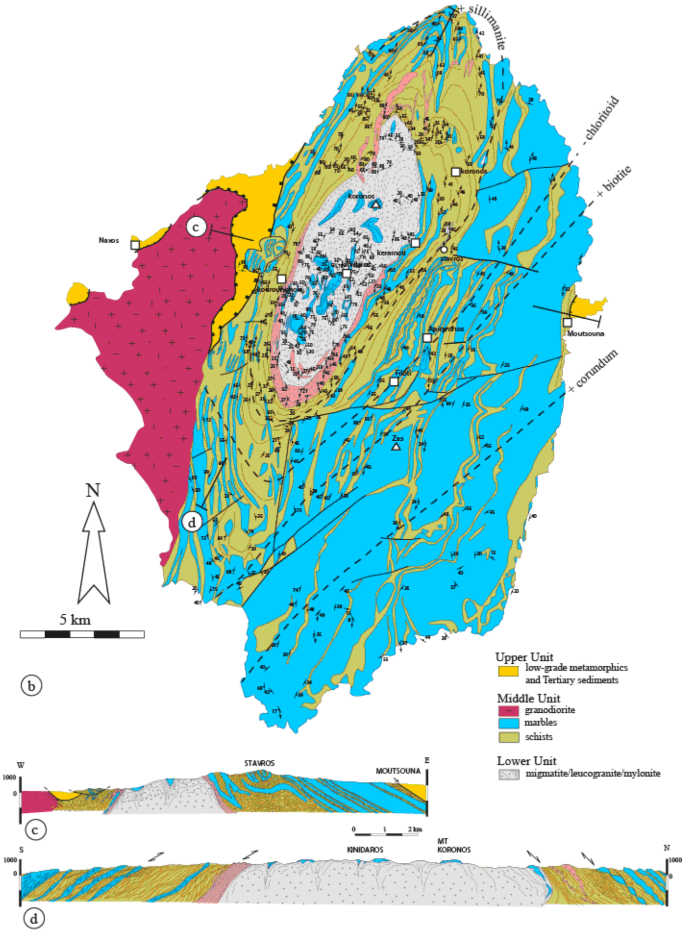
Pressure Temperature conditions of Naxos metamorphic rocks

The structural section through the middle and lower units is marked by a medium pressure/medium temperature metamorphic gradient ranging from greenschist facies in the southeastern part of the island to amphibolite facies reaching partial melting (1 GPa, 750°C) as evidenced by migmatites exposed in the centre of the dome (Jansen and Schuiling 1976; Buick and Holland 1989; Avigad and Garfunkel 1991; Duchêne, Aïssa et al. 2006) (Figure 6). High pressure/low temperature metamorphism is only represented by relics of blueschist facies minerals, such as Na-amphibole and jadeite (1 GPa, 350°C), in the metamorphic rocks of the south of the island.

Since the 1970's, numerous studies using different geochronological methods (Ar/Ar, K/Ar, Rb/Sr, Sm/Nd and U/Pb methods performed on various minerals) have been carried on the metamorphic rocks of Naxos. In the lower unit, the peak of the medium pressure/medium temperature metamorphism, corresponding to the onset of the partial melting in the core of the island, is constrained prior to 20-21 Ma by U/Pb dating on zircon crystals from migmatite samples (Keay et al. 2001, Martin et al. submitted). In the middle unit, the age of the medium pressure/medium temperature metamorphism is constrained after 19.9-27 Ma by Ar/Ar dating on phengite (Wijbrans and McDougall 1988). Whereas the migmatites of the lower unit have solely preserved the medium pressure/medium temperature paragenesis, metamorphic zircon rims yield scattered U-Pb ages around 50 Ma (Keay 1998, Martin et al. 2006, Martin et al. submitted), consistent with the 40-50 Ma ages obtained with Ar/Ar and Rb/Sr methods in samples from the south of the island (Andriessen et al. 1979; Wijbrans and McDougall 1986; 1988). (Keay 1998; Keay, Lister et al. 2001; Martin, Duchêne et al. 2006). 40Ar/39Ar ages of white micas and biotite performed in the middle and lower units indicate an age gradient from ~ 45 Ma in the metasedimentary rocks in the southeastern part of the island to ~ 10 Ma in the migmatites (Andriessen, Boelrijk et al. 1979; Altherr, Kreuzer et al. 1982; Wijbrans and McDougall 1988). The granodiorite pluton intruding the middle unit in the wester part of the island is dated at ~11 Ma by U/Pb and Ar-Ar methods (Wijbrans and McDougall 1988; Keay, Lister et al. 2001). The mineralogical and geochemical characteristics of the granodiorite suggest a composite origin combining crustal and mantellic protoliths.

Various models have been proposed to account for the tectonic evolution of Naxos. Early models recognized the allochtony of the sedimentary and low-grade unit (Auboin 1973; Bonneau 1982; Jacobshagen 1986) and interpreted it as a nappe structure emplaced by gravity sliding above the metamorphic lower structural unit. The complex structure of the marble and schist sequence characterized by recumbent isoclinal folds and HP/LT metamorphic assemblages has been attributed to burial and nappe emplacement in a plate convergence context (Bonneau, Geyssant et al. 1978; Bonneau and Kienast 1982). Based on a petrological study of the metamorphic rocks of the island, Jansen and Shuiling (1976) recognized the importance of partial melting and first proposed that the dome results from diapiric rise of the migmatites. Gautier et al. (1993) reinterpreted the basal tectonic contact of the sedimentary unit as a low-angle detachment and refined this model proposing that the dome corresponds to upwelling of the low-viscosity migmatites during regional extension. This model has been further explored using 40Ar/39Ar ages (John and Howard 1995), and fission track and U-Th/He ages on apatite (Brichau, Ring et al. 2006) indicating a general trend of northward cooling interpreted as progressive exhumation for the hanging wall of the single detachment mapped by Gautier et al. (1993, 1994). Alternatively, several authors consider that the dome structure and complex polyphased folding of the marble and schist sequence result from the combined effects of E-W shortening and regional top-to-the-NNE shearing (Urai, Shuiling et al. 1990; Buick 1991; Avigad, Ziv et al. 2001). More recent work on structures in the migmatites and geometric characteristics of the granitic vein network intrusive in the marble and schist sequence suggests that the development of the dome corresponds to upwelling of a partially molten layer in a regional context of top-to-the-northeast shearing (Vanderhaeghe 2004). The observations made during this field trip will allow addressing these models.

Figure 7. Naxos



Naxos geological map and cross sections

FIELD TRIP

The aim of the field trip is to present the main lithologic-metamorphic units exposed in Naxos and illustrate the nature of their mutual contacts. The structural, metamorphic, magmatic and sedimentary record of Naxos will be put in the context of the Aegean geodynamics and more generally in the scope of the thermal-mechanical evolution of a crustal accretionary wedge in a zone of lithospheric plate convergence. Issues stemming out of this field trip are summarized below.

Structural evolution of a crustal wedge, from accretion to collapse

The island of Naxos displays a complex structure with polyphased folding of the marble and schist sequence, doming of the migmatites, localized deformation in mylonitic and cataclastic zones and a dense network of brittle faults. The exact chronology of these structures still needs to be established. The driving force responsible for the development of each of these structures is also controversial. Does magma buoyancy play a role in the development of the migmatite dome? What are the relative roles of tectonic forces related to plate tectonics and the gravity forces associated with lateral variations of crustal thickness? At last, the significance of each of these structures in terms of the tectonic record from crustal thickening to thinning remains to be established.

Metamorphic evolution of a crustal wedge, from accretion to collapse

The structural section of Naxos exposes, as stated above, three tectonic-metamorphic units with contrasting metamorphic grade. The exact chronology of these metamorphic assemblages is only partially determined and the significance of the metamorphic gradients and offsets need to be addressed. What is the age and significance of the metamorphic assemblage of the marbles and schists of the upper unit? What is the significance of the relic blue schists assemblages preserved at the southern tip of the island? Does it imply that all rocks structurally beneath the blueschists were affected by a similar metamorphic grade or even higher? What is the significance of the metamorphic gradient from the greenschsits to the amphibolite facies rocks? Does it solely represent a contact metamorphism associated with upwelling of the migmatites or does it have a structural record? What are the causes of the transition from a low to a high geothermal gradient responsible for the genesis of blueschist and amphibolite facies rocks respectively?

Magma emplacement and detachment activity

The granodiorite pluton exposed on the west coast of Naxos is intrusive in the marble and schists of the middle unit to the south of the island and juxtaposed to sedimentary rocks along a cataclastic detachment toward its northern tip. More detailed investigation shows that the granodiorite is itself crosscut by several cataclastic zones and high-angle faults. What is the relative chronology of granodiorite emplacement and MCC development? What is the role of the detachment on pluton emplacement and conversely, what is the role of pluton emplacement on detachment development?

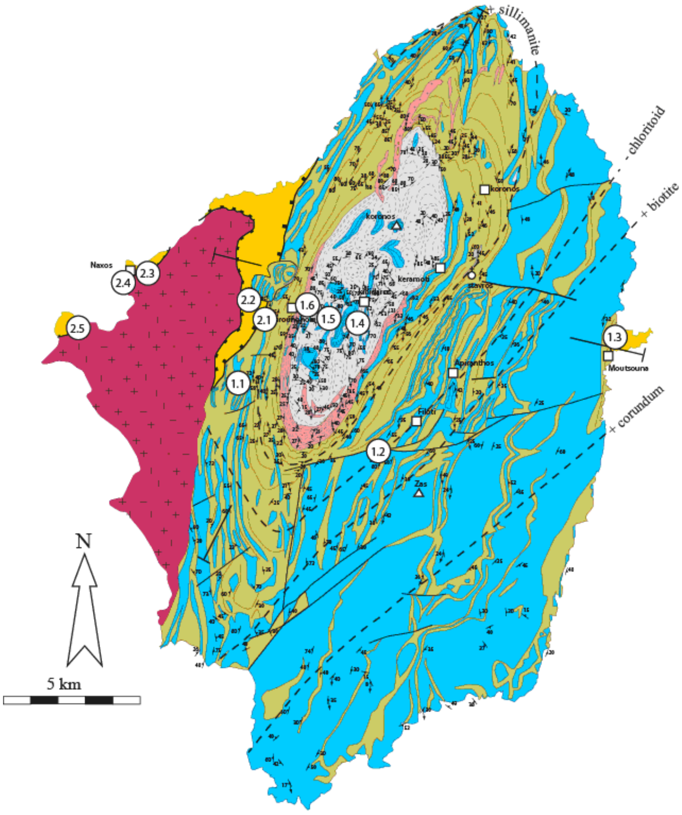
Fluid circulations during MCC formation

Fluid circulations are major vectors of matter and heat transfer and thus play an important role during the thermal evolution of crustal accretionary wedges. Recent investigations on the fluid record of MCC indicate that meteoric fluids potentially penetrate the crust down to the root decollement of detachment faults that correspond to the brittle/ductile transition (Morrison and Anderson 1998; Famin 2004; Famin and Nakashima 2004; Mulch, Teyssier et al. 2004). Rocks from Naxos display various traces of fluid circulation encompassing calcite and quartz vein networks, zones of hydrothermal alteration, zones of pervasive silicification. The characteristics of the fluids responsible for these features are only described in places. What are the nature and source of the fluids circulating during the tectonic-metamorphic evolution of Naxos rocks? Under which conditions were these fluids trapped? What controls the geometry of the various fluid reservoirs and in particular what is the role of detachments in draining fluids? What are the impact of fluid circulations in terms of mass and heat transfer?

Sedimentary record of exhumation and topographic evolution during MCC formation

One of the singularities of Naxos is to expose sedimentary rocks with deposition age similar to the age of metamorphic assemblages contained in exhumed metamorphic rocks. Although the exact timing and condition of deposition are under investigation, this sedimentary record allows reconstructing the evolution of surface topography from subsidence under marine conditions to uplift reaching aerial conditions during the development of the Naxos MCC. What is the role of erosion and lateral mass transfer in exhuming metamorphic rocks? What controls the changes in surface elevation during MCC development?

Figure 8. Field Trip



Geological map of Naxos with fieldtrip stops

Day 1: INSIDE THE METAMORPHIC CORE

8h30-9h00: Naxos (Hora) - Kato Saggri

Stop 1: Panorama (Figure 9)

(Vanderhaeghe O.)

This northward panoramic view displays the principal metamorphic and magmatic rocks exposed in Naxos below the detachment system. These rocks are subdivided in:

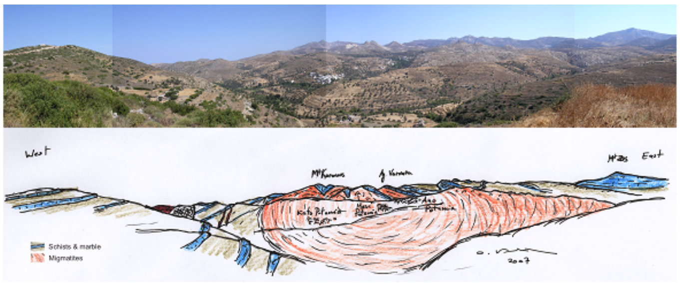
- A lower unit composed by migmatites in the core of an elliptical shape structural dome

- A middle unit comprising alternating marbles and schists with minor calc-silicates, amphibolites and ultramafics.

- An upper unit formed by low-grade metamorphic rocks and coarse detritic sedimentary rocks

The contact between the lower and middle units is delineated by a crescent-shape leucogneiss decollement. The migmatite dome is characterized by second order subdomes with a complex geometry that will be better embraced later in the field trip (Day 1, Stop 4). The marble and schist sequence is affected by overturned isoclinal folds with axes dominantly parallel to the NE-SW trending mineral lineation. Marble layers forming cliffs owing to their resistance to erosion beautifully delineate these various structures. A sharp fluvial erosional surface (so-called Traghea plain by Hejl) affects the South of the dome and will be also encountered northward (Day 2, Stop 1).

Figure 9. Naxos Dome



Panorama of the Naxos dome from the pass west of Saggri

9h30-10h00:Kato Saggri- Filoti

Stop 2: Panorama Filoti (Figure 10); (Figure 11)

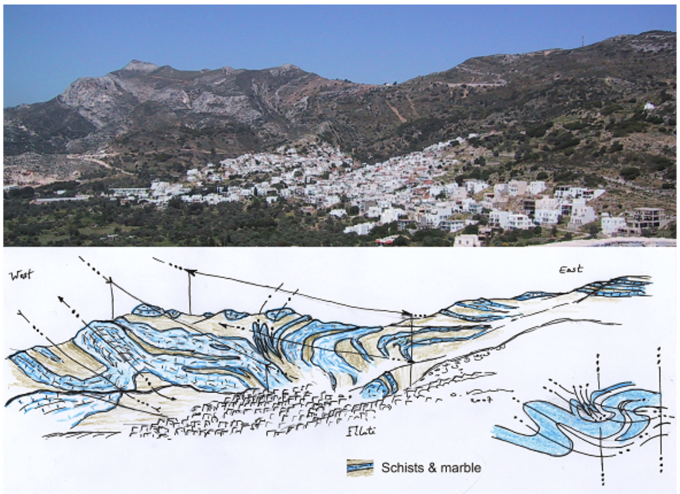
(Vanderhaeghe O.)

This northward panoramic view over the town of Filoti allows better catching the polyphased deformation of the marble and schist sequence and the structural relationship between these folds and the migmatite dome visible in the background, to the west of the panoramic view.

Figure 10. Filoti

Panorama of Filoti from North of Mt-Zas

Figure 11. Filoti Fold



Fold interference patterns over Filoti (Detail of Fig. 10)

The transposition foliation marked by marble and schists alternations is associated with isoclinal centimetric to decametric folds. Some of these fold hinges are exposed to the east of the panorama. The transposition foliation is affected by hectometric recumbent folds with an apparent west vergence as illustrated by the large recumbent antiform/synform successions exposed to the north of Filoti. These folds are actually sheath folds with an axis parallel to the NW-SE mineral and stretching lineation as observed at outcrop scale and reconstructed at map scale. To the west of the Panorama, the transposition foliation dips to the east whereas to the east it dips to the west. This change in foliation dip marks the hinge of an open upright synform with an N-S axial trace.

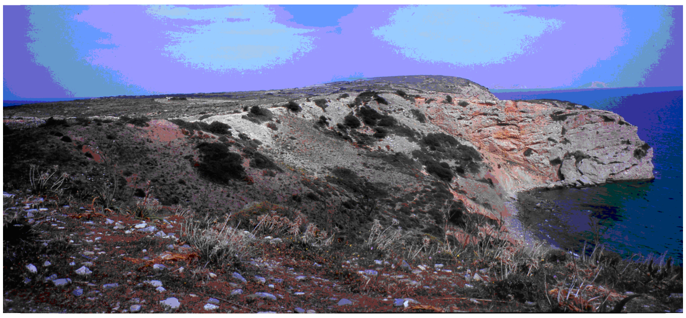
10h30-11h00: Filoti-Moutsouna

Stop 3: E-detachment fault, Moutsouna (Figure 12); (Figure 13)

(Hibsch C., Vanderhaeghe O.)

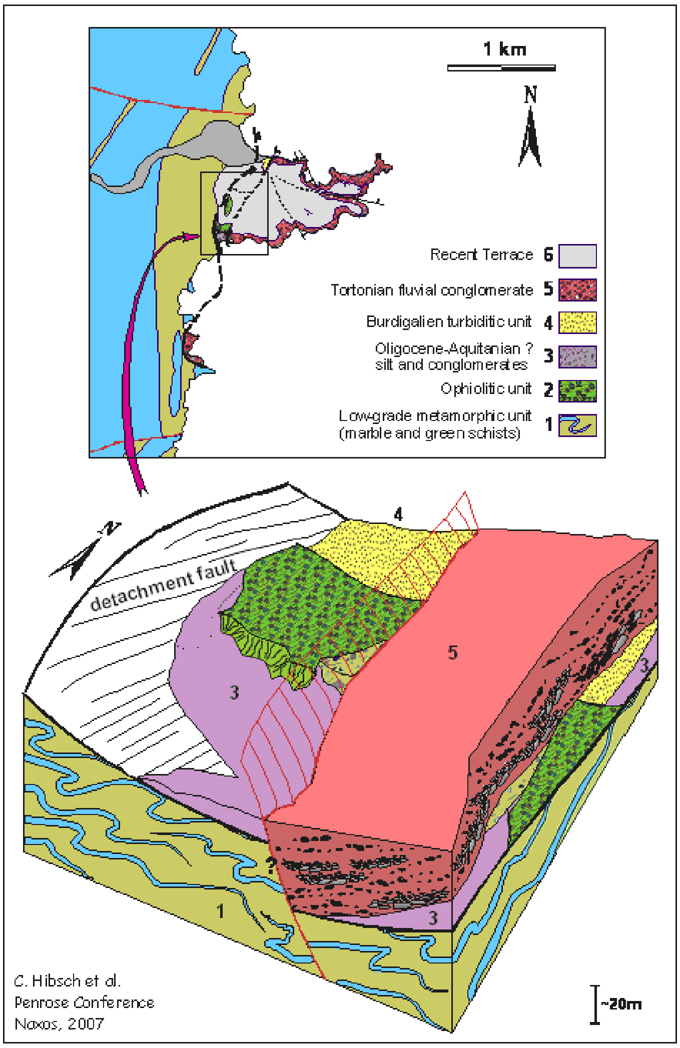
The outcrops along the shore near the port of Moutsouna displays a fault contact between green-schist facies metamorphic rocks of the middle unit and a serpentinized peridotite belonging to the upper non-metamorphic unit. The peridotites are affected by EW normal faults sealed by sedimentary deposits (Figure 13). They represent part of an ophiolitic sequence. The molassic sediment contains pebbles of the serpentinized peridotites but also from sedimentary rocks unknown in Naxos. Nummulites in some pebbles indicate shallow marine conditions during the Palaeogene coeval with the transition from thickening to thinning of the crustal accretionary wedge. These pebbles are now reworked in poorly dated Neogene sediments To the North of the peninsula Burdigalian marine turbidites are locally preserved (Figure 13). To the East in the closest islands, fresh water carbonates and travertines are widely exposed and supposed to be Serravalian to Early Tortonian in age. They provide a record of the progressive exhumation of the marbles exposed to karstification under relatively smooth surrounding landscape conditions (to be compared to the morphology of the western part of the island to be described the following day). The Burdigalian and Serravalian sediments are uncomformably overlain by two fluvial detrital sequences (green and then red continental molasse) marking a drastic geomorphic change from shallow marine to continental conditions (Figure 12). Both contain marble and schists from the underlying tectono-metamorphic units and record the progressive exhumation of the metamorphic rocks as well as surface uplift. These units are affected by variously striking normal faults which may have affected the detachment (Figure 1) 13).

Figure 12. Moutsouna



Panorama of the Moutsouna peninsula viewed to the East from the detachment

Figure 13. Moutsouna 3D



Geological map of Moutsouna peninsula and 3D view of the detachment and associated structures

12h30-13h00: Lunch break (Sandwiches)

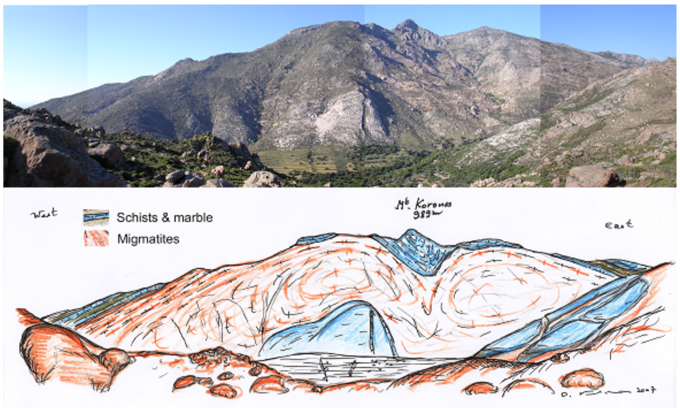
13h00-13h30: Moutsouna-Kinidaros

Stop 4: Panorama Dome and subdomes (Figure 14)

(Vanderhaeghe O., Kruckenberg S.)

This stop, to the east of the town of Kinidaros, at the intersection between the paved road and a small trail leading to Garimou springs, displays a panoramic view of the core of the migmatite dome culminating with Mt Koronos. The internal structure of the migmatite dome is delineated by large marble enclaves forming the slopes of Mt Koronos which is itself located in the core of a marble synform.

Figure 14. Naxos migmatite



Panorama of Naxos migmatite dome viewed from Kinidaros

14h00-14h15: Kinidaros-Bolibas

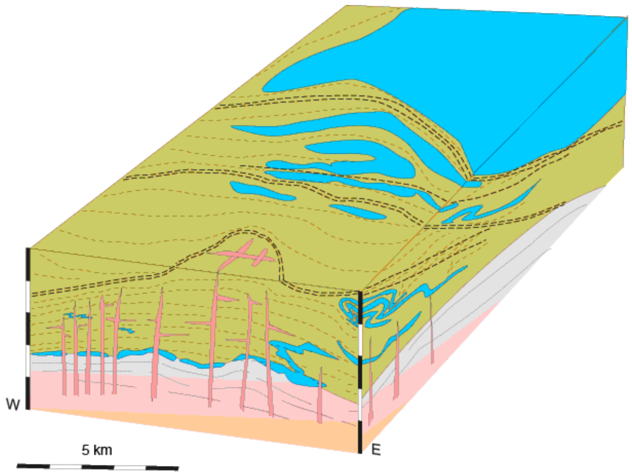
Stop 5: Migmatite cross-section

(Vanderhaeghe O., Kruckenberg S.)

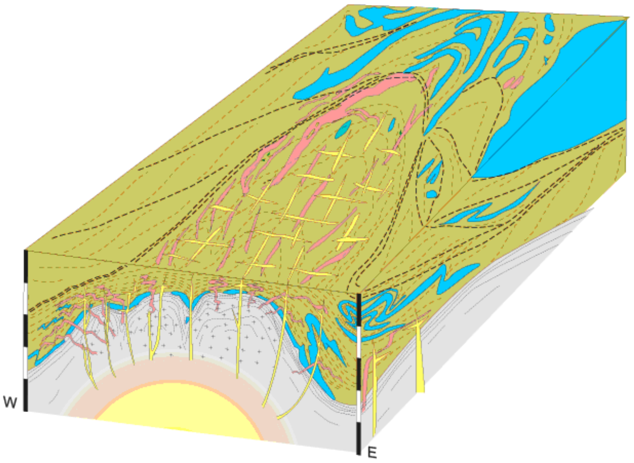
This section along a roadcut going west from the pass to the west of Kinidaros, exposes the variety of lithologic types in the migmatite dome and illustrates the relationships between structures acquired under solid and magmatic state. Marbles and associated schists and amphibolites are affected by polyphased folding with axes parallel to the stretching lineation. All these lithologies are present as enclaves in the migmatites. Migmatites encompass metatexites and diatexites dominantly derived from the schists but also potentially from the amphibolites. The synmigmatitic foliation of the migmatites, underlined by leucosome/melanosome alternations in metatexites and by the alignment of enclaves in diatexites, is roughly concordant to lithologic contacts. The attitude of this synmigmatitic foliation is at first order also concordant to the dome boundary but it delineates second order structures within the dome designated as subdomes.

These features indicate that partial melting leading to the genesis of the migmatites postdates deposition of the sedimentary sequence and that formation of the dome and subdomes was achieved while migmatites were under a magmatic state. The complex pattern of subdomes suggest that flow of the migmatites result from a combination of buoyancy driven upwelling of the magma and regional top-to-the-north shearing associated with E-W shortening.

Figure 15. Migmatite model



Stage 1: Partial melting, intrusion of leucogranite during top-to-the-northeast shearing



Stage 2: Dome formation, rotation of granitic dikes, intrusion of leucogranite, during top-to-the-northeast shearing

Model for the Naxos migmatite dome development

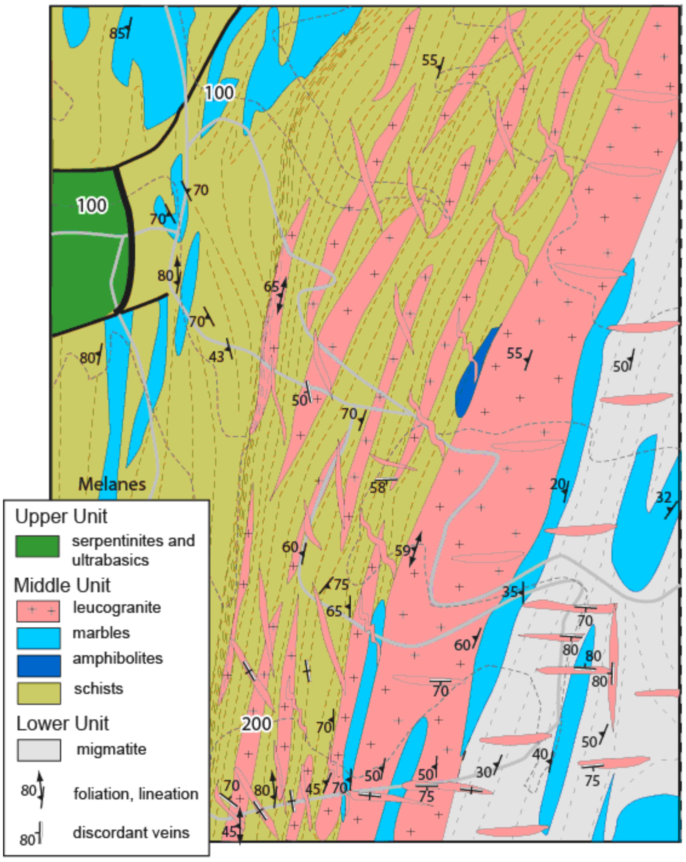
15h30-15h45: Bolibas-Kouchounohori

Stop 6: W-detachment/decollement (Figure 16)

(Vanderhaeghe O., Siebenaller L.)

This roadcut shows a continuous section across the dome boundary and the contact between the middle and upper units. To the east of the section, schists with minor amphibolites and calcsilicates contain granitic veins transposed to various degrees; totally transposed veins forming leucogneiss layers from centimeter up to several tens of meters thick. Going west, this unit is affected by increasing deformation reaching ultramylonitic fabric characterized by extreme grain-size reduction. The mylonitic zone is associated with quartz enrichment suggesting a significant input of silica associated with fluid circulation. The western side of the mylonite is associated with greenschist facies retrogression and is characterized by a dense network of veins. Low-grade marbles and schists are found structurally above this mylonite.

Figure 16. Western mylonitic contact



Geological map of western mylonitic contact between Middle and Upper units (Kouhounohori)

17h30 : Kouchounohori-Hora

Day 2: SEDIMENTATION AND FLUID CIRCULATION DURING THE DEVELOPMENT OF A METAMORPHIC CORE COMPLEX

8h30-9h00: Naxos (Hora)-Melanes

Stop 1: Panorama Melanes (Figure 18)

(Hibsch C.)

To the east of the panoramic view from Melanes (Figure 17) the contact between the non-metamorphic upper unit and the middle unit is exposed. The western side displays the faulted contact between the granodiorite and the upper unit. We will reconstruct this cross-section starting from the site of the panoramic view to the outcropping granodiorite, more or less following cross-section C-D from Fig. 18. Of particular interest is the presence of a marble and schists landslide which overlays the Paleogene and Neogene sediments.

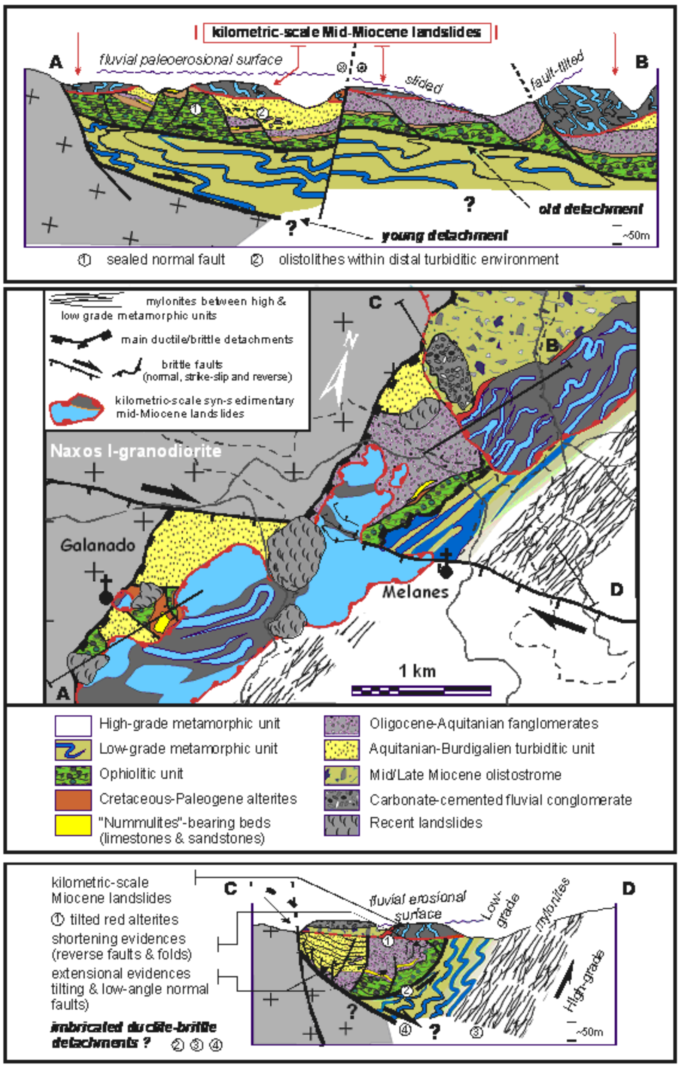
We propose that this huge kilometric-scale landslide occurred as a consequence of uplift along the tectonic contact on the western side of the dome. Marbles and schists forming the landslide were previously exposed under aerial conditions before sliding as revealed by tilted paleokarst evidences at its front (Figure 19). Collapse of the landslide is associated with olistostromic deposits (Figure 1) 20). This uplift is also marked by an increase in detrital deposits and the lack of travertine deposits which in contrast occur further west on Paros Island away from the more active tectonic border. This event is considered to be of Mid Miocene age (Serravalian-Tortonian), almost synchronous with the granodiorite magmatic emplacement along the detachment. The metamorphic rocks and the granodiorite are cross-cut by E-W striking faults (Figure 18).

Exhumation of the metamorphic rocks and transtensional faulting were more or less fossilized as revealed by the position of the Traghea fluvial erosional surface (Day 1 stop 1 and cross-section A-B Fig. 18). Remnants of this surface and overlying conglomerates (Figure 1) 21; Fig. 22) are preserved in this panorama but were northward tilted here due to the continuation of extension associated with the continuing unroofing of the granodiorite (Figure 18). At last, during this exhumation, the granodiorite has been also bordered by high-angle faults.

Figure 17. Panorama

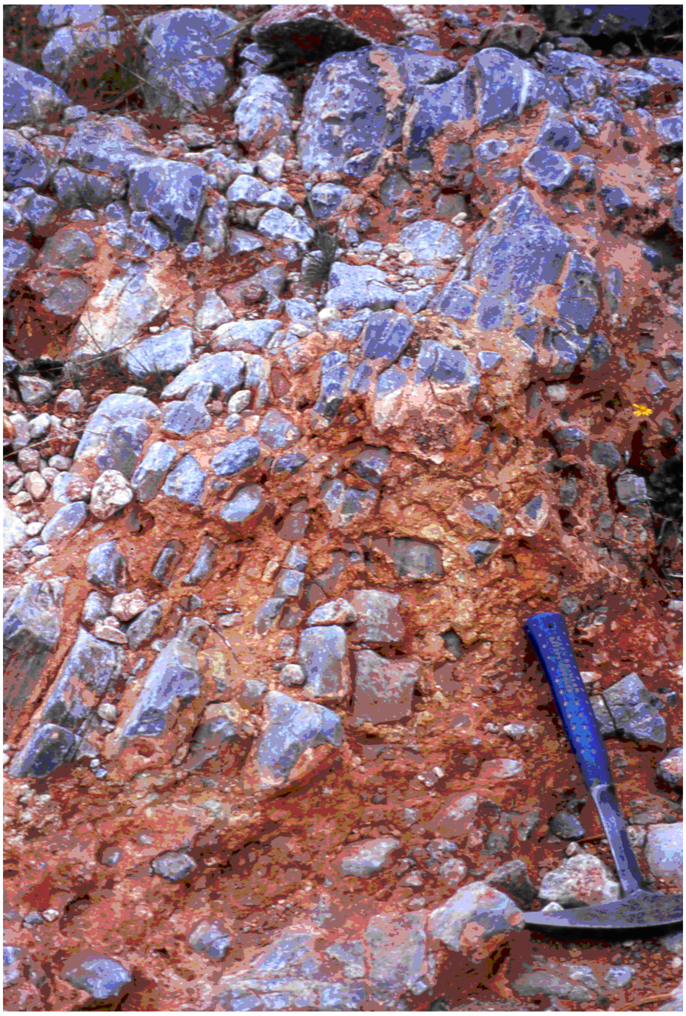
Panorama of the sedimentary unit and above-lying landslide and tilted erosional surface viewed North from Melanes

Figure 18. Galanado-Melanes



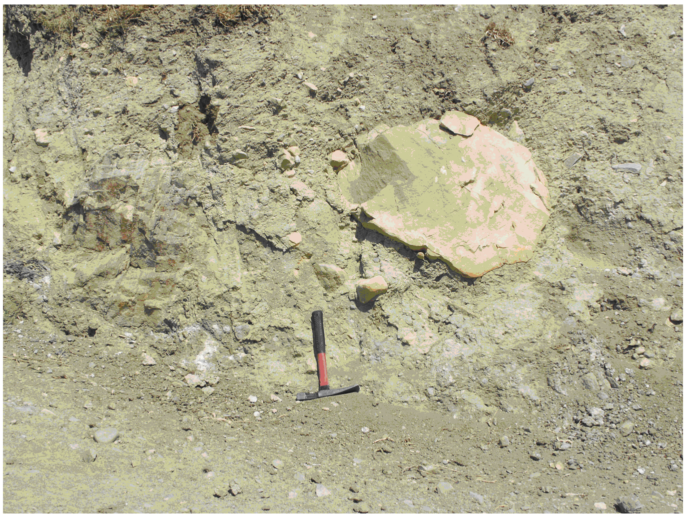
Geological map and cross-sections of the Galanado-Melanes upper Unit and tectonic borders

Figure 19. Paleokarst



paleokarst affecting the marbles (landslide North of Melanes)

Figure 20. olistostrome coeval

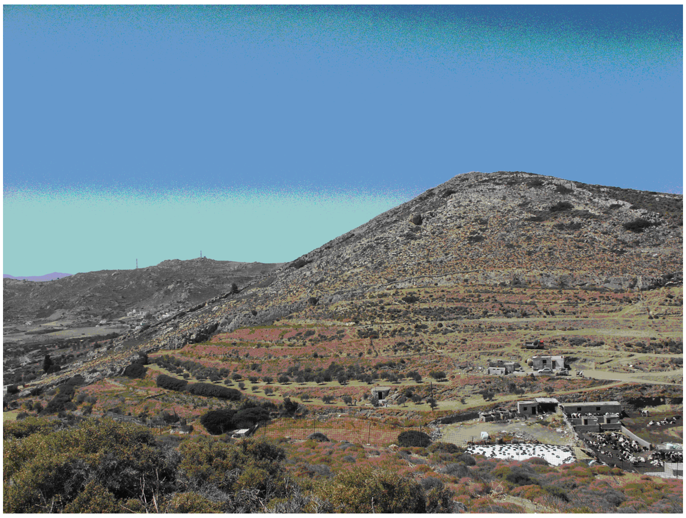


olistostrome coeval with the landslide (North of Melanes)

Figure 21. tilted indurated fluvial conglomerate

tilted indurated fluvial conglomerate

Figure 22. tilted erosional surface



tilted erosional surface facing South (viewed from the mylonite East of the landslide)

9h30-9h45: Melanes-Aghios Thaleleos

Stop 2: Cross section Aghios Thaleleos (Figure 18)

(Hibsch C.)

This cross section allows to observe various facies from the metamorphic upper unit and overlying non-metamorphic upper unit and also reach the contact with the granodiorite :

• Low grade green-schists facies rocks from an equivalent to the so-called Dryos Unit described in Paros Island

• Ophiolitic Unit and its paleo-alterite of Cretaceous or Paleogene age?

• Paleogene molassic series revealing shallow marine conditions at its base (limestones and sandstones with nummulites). This unit did not yet record the unroofing of the MCC.

• Aquitanian-Burdigalian marine turbiditic sequences with some olistolithes coeval with the thermal pulse in the migmatitic dome and which is progressively registering the unroofing of the MCC (first pebbles of metamorphic origin)

• Granodiorite affected by solid state deformation

(Observation of the paleokarst, the fluvial conglomerate and the olistostrome (Figure 19); (Figure 20); (Figure 21) are optional according to time)

It also presents some tectonic features that sould be taken into account in the discussion regarding the transition from thickening to thinning of the crustal accretionary wedge.

• tectonic contact between the low grade metamorphic unit and the non-metamorphic ophiolitic nappe

• reverse faulting between the ophiolites and Paleogene molasses but also widespread low-angle normal faulting in all sediments

• normal faulting affecting the landslide and the paleo-erosional surface

• tectonic contact between the sedimentary unit and the granodiorite (faults and associated folds)

12h00-12h30: Melanes- Aghios Ioannis

Stop 3: Granodiorite cataclastic detachment (Aghios Ioannis) (Figure 23)

(Siebenaller L.)

This outcrop displays a cataclasic detachment at the top of the granodiorite pluton and various expressions of fluid circulations. The most prominent one is expressed by a thick chlorite and epidote rich gouge with feldspar clasts that potentially correspond to retrogression of the granodiorite associated with (meteoric ?) fluid circulation during the development of the cataclastic detachment. This gouge is cemented by quartz attesting for the circulation of silica-saturated fluids. This silicification is also affecting the non-metamorphic upper unit sandstones and conglomerates just above the detachment. ENE-WSW trending faults cross-cut the gouge and are associated with goethite, siderite and calcite attesting for the circulation of Fe and Ca rich fluids in these rocks as they were exhumed closer to the surface.

Discussion arise about the role of the different cataclasites, some being associated with the detachement while others are clearly oblique and sometime partly reactivated as brittle normal faults (Figure 23).

13h30-14h00: Lunch break

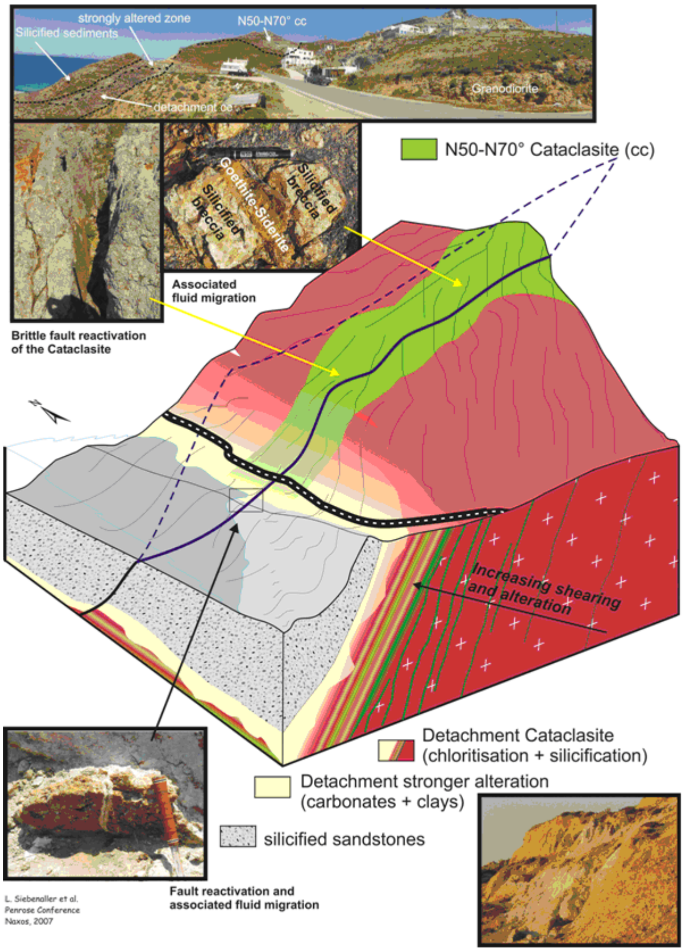
14h00-14h30: Aghios Ioannis - Hora

Stop 4 (facultative): Granodiorite, hydrothermal alteration (Naxos port)

(Siebenaller L.)

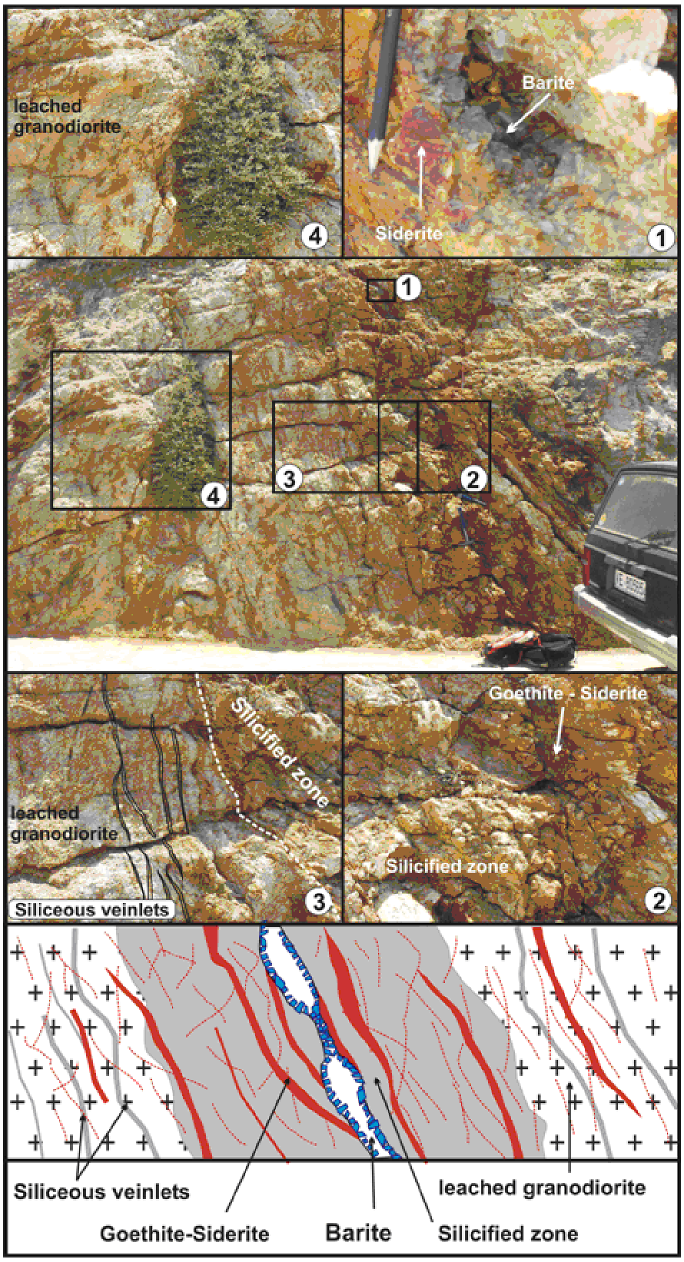
This outcrop completes the chronology of fluid-related alterations and precipitations within the granodiorite on the E-W trending faults. The granodiorite is characterized by a pervasive C/S fabric with a NW-SE trending stretching lineation and top-to-the northwest sense of shear. The granodiorite displays clay-rich zones where biotite and chlorite are absent. This suggests leaching of the granodiorite by hydrothermal fluids that have altered Fe-Mg and Si rich minerals replaced by clays. These zones contain ENE-WSW quartz veins cross-cut by goethite, siderite, calcite and barite mineralizations (Figure 1) 24). To the south of this zone, structurally below, the granodiorite is cataclastic and chlorite-rich.

Figure 23. Aghios Ioannis



3D view of the detachment affecting the granodiorite (Aghios Ioannis) and associated fluid migrations

Figure 24. Naxos port



fluid pathways in the granodiorite - Naxos port

16h00-16h30: Hora - Stelida

Stop 5: Granodiorite/sediments (Stelida)

(Siebenaller L.)

This outcrop shows the contact between the granodiorite detachment zone and the juxtaposed silicified sediments. The granodiorite below the contact is affected by numerous pseudotachyllites. These outcrops, not so far from the lodging, may allow wandering in small groups according to the points of interest (sismotectonic and ductile fabric, fluid migrations affecting the sediments and sedimentary evidences for the last steps of the exhumation.

DISCUSSION OF THE DATA PRESENTED DURING THE FIELD TRIP

The outcrops and panoramas described during this field trip illustrate part of the geology of Naxos as retrieved from published data and a multidisciplinary study conducted by the authors of this guide with the help of other colleagues. As a result of this study, we propose a model for the structural and metamorphic evolution of Naxos rocks and also for the contemporaneous evolution of sedimentary basins in the frame of the geodynamic evolution of the Aegean crustal accretionary wedge.

Structural evolution of a crustal wedge, from accretion to collapse

As seen in the field trip, the three lithologic-metamorphic units of Naxos display contrasted structural styles. This in part reflects diachronous deformation of the various units but also probably suggests mechanical decoupling among the different structural levels represented by these units.

The oldest structures preserved in Naxos are probably the foliation of the marble and schist sequence underlined by blueschists mineral paragenesis at the southern tip of the island. This structure probably records deformation near the pressure peak during burial of these rocks following the subducting slab. This foliation is partially transposed with asymmetric folds indicating a northward vergence to the south of the island. It was unfortunately not possible to see these strutures in this field trip. Folds exposed near Filoti affect the same marble and schist sequence but are structurally below. At this level, fold axes are transposed according to the NW-SE stretching lineation associated with the development of sheath folds. The mineral paragenesis associated with these structures indicates a greenschist facies overprint in a medium pressure/medium temperature environement. We interpret these structures as reflecting increasing transposition of the early HP/LT fabric following thermal relaxation during vertical shortening associated with top-to-the-northwest shearing. Sheath folds are concentrated within the middle unit at the transition between the marble-dominated sequence to the schist-dominated sequence. This might represent a decollement layer within the middle unit. Upright folding of the foliation within the middle unit records a roughly NE-SW shortening direction in part coeval with the top-to-the-northwest shearing resulting in a constrictional finite strain ellipsoid. This constriction might be locally due to the development of the migmatite dome or to flow of the marble and schists around it. However, it appears to be a general feature at the scale of the Aegean domain and we will further discuss the significance of this feature below.

Deformation of the migmatites underlined by a synmigmatitic foliation indicates that it occurs while the rocks were partially molten. The synmigmatitic foliation delineates the elliptical shape migmatite dome which indicates that the dome formation is coeval with the presence of melt. Subdomes display complex shapes that are interpreted to reflect the combination of vertical upwelling of the migmatites owing to their buoyancy partially transposed according to top-to-the-northwest shearing. The subdomes are preferentially elongated parallel to the first order dome axis and NW-SE trending vertical synmigmatitic foliations are dominant. This might indicate that development of the migmatite dome was in part coeval to NE-SW shortening.

In contrast to the simple view of a single detachment separating the upper and middle unit, our work shows a complex network of structures associated with the progressive development of detachments systems and migration of the “brittle-ductile” transition as rocks are exhumed. Part of the high-angle faults and cataclastic shear zones affecting the upper unit are rooting into a decollement horizon. In the middle unit, ductile fabrics grade into mylonitic zones. All of these structures are cross-cut by high-angle normal and strike-slip faults. These cross-cutting relationships suggest a propagation of the localized zone of deformation in space and time in response to themigration of the brittle-ductile transition during exhumation and cooling of metamorphic rocks. Landslides are surface witnesses of this tectonic activity.

Metamorphic evolution of a crustal wedge, from accretion to collapse

We interpret the age and metamorphic gradient from greenschist facies to amphibolite facies metamorphic grade exposed in the island of Naxos as representing progressive transposition of an earlier HP/LT fabric during thermal relaxation of the Aegean crustal accretionary wedge. U/Pb ages of 50 Ma obtained on zircon rims from the migmatites that are similar to Argon ages obtained in the blueschists relics suggests that all these rocks were buried in the Eocene.

Further detailed work is needed to determine metamorphic gaps between the middle and upper units and within the middle unit across the decollement horizon marked by the sheath folds.

Magma emplacement and detachment activity

To the south of the island, the granodiorite is intrusive into marbles and schists of the middle unit and yields U/Pb ages on zircon, argon ages on hornblende and biotite, and FT ages on zircon and apatite ranging between 9 and 12 Ma. By that time, the middle unit already cooled below300-200°C according to argon and fission track thermochronology and the migmatite dome was already developed according to U/Pb geochronology on zircon. This implies that part of the exhumation history of Naxos was already achieved before the emplacement of the granodiorite. Accordingly, the emplacement of the granodiorite represents a short time interval during the exhumation history. The concentration of cataclasites around and cross-cutting the granodiorite suggest that it favored localized deformation probably because it represented a local source of heat and thus a sharp rehological boundary at the time of emplacement. The spatial relationships between cataclasites and faults suggest that at the time of emplacement, the granodiorite represented a ductile/brittle transition and that shortly after, as it rapidely cooled down the brittle/ductile transition jumped deeper in the crustal section.

Fluid circulations during MCC formation

Preliminary results on the fluid circulation record in Naxos rocks allow the distinction between two crustal reservoirs. A shallow reservoir in which meteoric and basin fluids percolate and a deep reservoir containing fluids released during metamorphic reactions and magma cristallization. The transition between these reservoirs corresponds to the brittle-ductile transition which position is controlled by the thermal evolution of the crust. During crustal thinning and the development of MCC, metamorphic rocks are exhumed across the brittle-ductile transition. The distribution of fluid inclusions according to mineral textures and mircostructures of these rocks as well as the chemical composition of the various fluids records this transition from a deep to shallow reservoir. P, T, t reconstruction of these fluid inclusions indicates that this transition from a deep ductile crustal reservoir to shallow brittle reservoir is also associated with a change in the thermal regime as rocks are affected by rapid cooling as they cross the brittle-ductile transition.

Sedimentary record of exhumation and topographic evolution during MCC formation

Naxos sedimentary basins are filled mainly by coarse silicoclastic deposits that record progressive exhumation of the metamorphic units. Sedimentologic features in Naxos but also in Paros suggest:

(1) Oligocene shallow marine to continental deposits registered mainly the erosion of the underlying ophiolitic nappe with some evidences of pebbles originated from non-metamorphic nappes that are not outcropping in the Cyclades. These deposits indicate relatively poorly developed relief at the transition from thickening to thinning of the crustal accretionary wedge.

(2) Early Miocene subsidence started from reef deposits to deeper marine turibidites, recording local underwater slope instabilities (olistolithes) due to synsedimentary fault activity. These marine series, while progressively shallowing, display the increasing appearance of pebbles from the Upper metamorphic Unit. This subsidence trend is almost coeval with the thermal pulse in the Naxos migmatitic dome.

(3) Travertine, lacustrine then detrital continental deposits during Serravalian to Tortonian times registered the exhumation of the Upper than Middle metamorphic Unit. Strong relief associated to kilometer-scale landslide and olistostromic deposits characterized the active tectonic border on the western side of the Naxos dome while more quiet environments with lacustrine limestones characterized more soft landscapes with karstification of the exhuming marbles. This global change to a regional uplift and continental environments seems coeval with the granodiorite setting between Naxos and Paros. Strong co-seismic activity during this period is revealed by these landslides, pseudotachylites in the granodiorite and seismites in the sediments.

(4) From Late Miocene to possibly Pliocene times, the exhumation of the migmatites was sealed by a fluvial erosional surface while the distinct exhumation of the granodiorite kept going on in a context of active extensional and transtensional faulting. The progressive regional uplift or eustatic change following this surface is revealed by the incision of the following fluvial sequences which recorded

the erosion of the migmatitic Lower Unit. These periods are coeval with siliceous fluid migration and dacitic volcanism around 9 My. The tectonic exhumation of the granodiorite was achieved after this event as revealed by the last fluvial deposits containing pebbles of the granodiorite.

A MODEL FOR THE THERMAL-MECHANICAL EVOLUTION OF THE AEGEAN CRUSTAL ACCRETIONARY WEDGE

We present a tectonic reconstruction of the Aegean domain that addresses the evolution of topography, crustal wedge deformation and thermal evolution and leads to an assessment of the interplay between plate dynamics and surface processes on the evolution of the crust located at the boundary between the converging African and European plates.

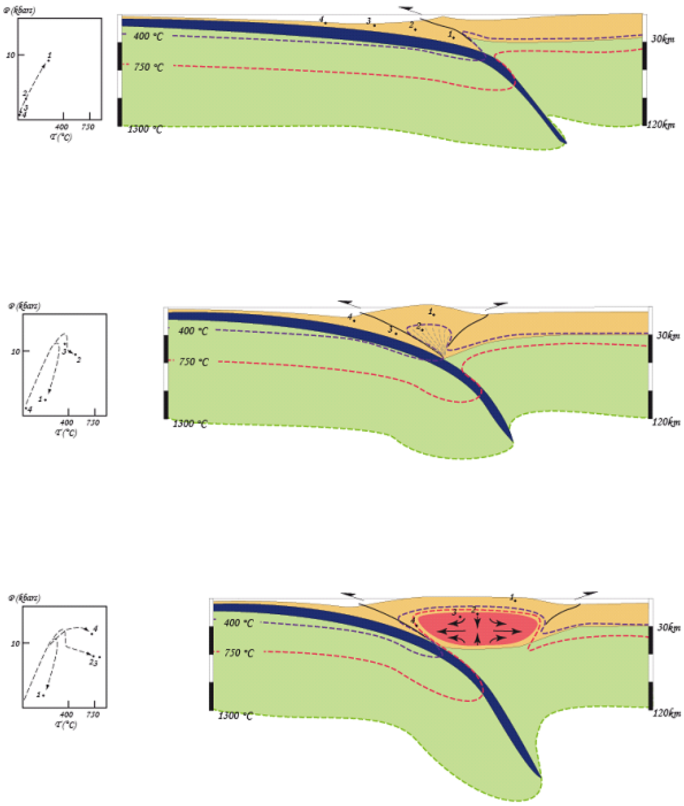
The central Aegean domain, as expressed in the island of Naxos, is characterized by the exhumation of metamorphic rocks juxtaposed to Oligocene to Upper Pliocene sedimentary basins along low-angle detachments. The metamorphic rocks comprise a Mesozoic sequence of metasedimentary rocks overlain by a weakly metamorphosed ophiolitic mélange. In contrast, the Mesozoic metasedimentary sequence is affected by a metamorphism grading from blue schist to amphibolite facies with the genesis of migmatites exposed in the core of structural domes. Inherited Mesozoic and Paleozoic cores of zircons from the migmatites are rimmed by metamorphic overgrowths dated respectively at ca. 50 Ma and ca. 15 Ma. Ar-Ar and Rb-Sr ages decrease from ca. 45 Ma in the blue schists to ca. 7 Ma in the migmatites.

These data indicate that the evolution of the central Aegean domain is characterized by (1) Eocene burial and subsequent exhumation of the Mesozoic metasedimentary rocks under a low geothermal gradient; (2) increase in the geothermal gradient and development of migmatitic domes and low-angle detachments in Miocene times coeval with surface subsidence; (3) Mio-Pliocene final exhumation of the metamorphic rocks associated to surface uplift.

This reconstruction suggests a model for the thermal-mechanical evolution of the Aegean crustal wedge that includes, (1) tectonic accretion associated to subduction and extrusion of crustal slices facilitated by slab roll-back, (2) thinning of the crustal wedge coeval with its thermal maturation and (3) final uplift and gravitational collapse in response to asthenospheric upwelling above the retreating slab. Thinning of the previously thickened crustal accretionary wedge occurs in three stages. The first one corresponds to the development of a MCC, as the crust is dominantly ductile. The second stage corresponds to the formation of a wide rift and at last, the third stage is the localization of extension in narrow rifts as the crust cools down during thinning.

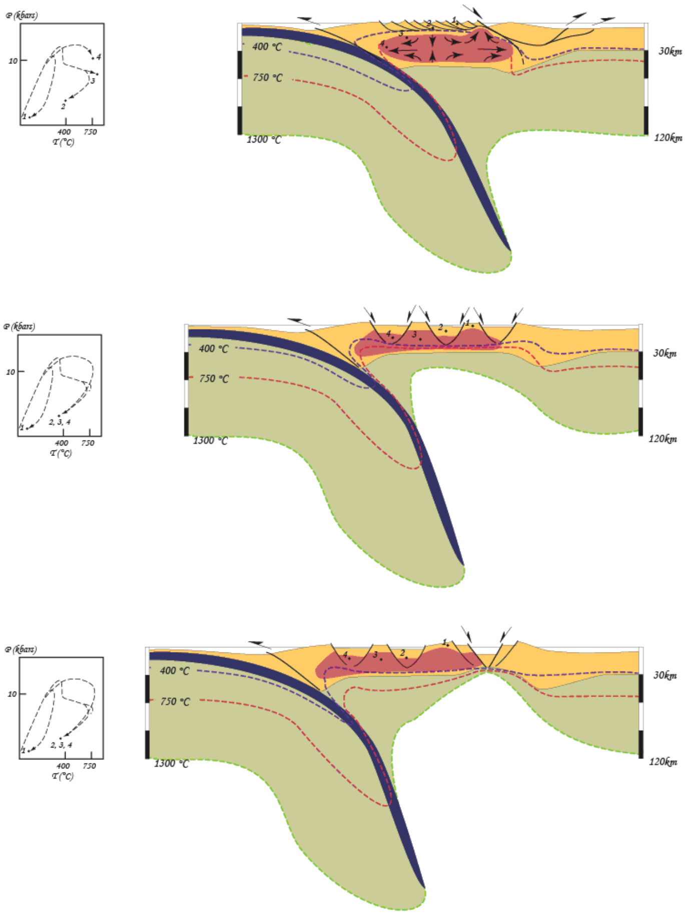
The same sequence of events affected the Rodhope massif in northern Greece but earlier in time. Indeed, HP/LT metamorphism was recorded between 75-70 My and HT metamorphism between 40-30 My. HP/LT metamorphism affected metamorphic rocks exhumed in Crete around 25 My. This suggests that subduction and exhumation of HP/LT rocks occurs above the subducting slab at the front of the crustal accretionary wedge. As the deformation front migrates southward with the retreating slab, the early accreted metamorphic rocks become passive in terms of deformation but are affected by thermal relaxation. 20 to 30 My after accretion, thermal relaxation is causing partial melting of the crustal wedge. This weakens the crust and causes localization of crustal thinning in response to slab roll-back. At last, the NE-SW shortening component observed in the Aegean domain might reflect crustal scale redistribution of mass from the Hellenides and the Taurides that are not affected to the same extent by slab roll-back.

Figure 25a. Thermal mechanical model



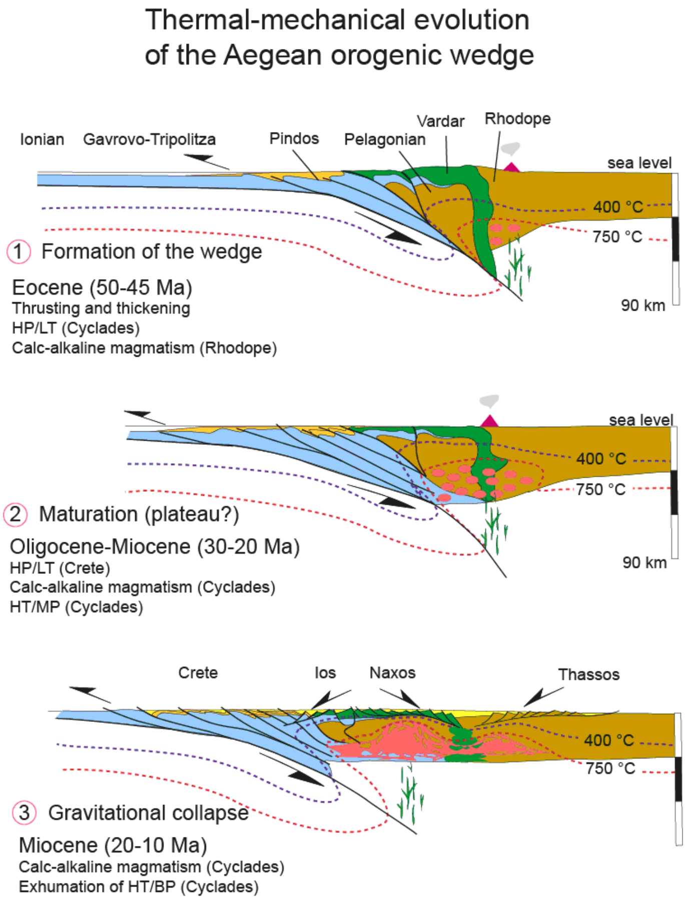
Thermal mechanical model for the evolution of the Aegean crustal accretionary wedge

Figure 25b. Thermal mechanical model



Thermal mechanical model for the evolution of the Aegean crustal accretionary wedge

Figure 25c. Thermal mechanical model



Thermal mechanical model for the evolution of the Aegean crustal accretionary wedge

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