TECHNICAL EVOLUTION OF NAXOS (AEGEAN SEA, GREECE)

provided by
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Field Trip to Naxos (Aegean Sea, Greece) - Summer Term 2014

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Abstract
The tectonic development of the island of Naxos within the Aegean Sea serves as an example for the generation of a metamorphic core complex induced by rapid extension, thinning and rapid uplift of the crust due to a subduction roll-back. Two main deformation phases are recognized from structural and petrographical data. During the first deformation phase (D1) starting in the Eocene (at around 50 Ma) the Alpine convergence left behind compressive tectonic features (B1 and B2 folds, thrusting, nappe formation, initiation of a N-dipping subduction zone) and induced HP-LT blueschist metamorphism (0.9 GPa, 480 °C) within the lithosphere. Southward crustal extension of the Aegean tectonic plate since the Oligocene (25 Ma) peaked with the exhumation of a metamorphic core complex in Miocene ages (20-16 Ma). The permanent southward roll-back of the Hellenic subduction zone induced this second phase of deformation (D2) controlled by extensional tectonics in the back-arc area. Accompanied by magmatism and associated Barrovian HT-LP metamorphism (0.6 GPa, 670 °C) the second deformation phase generated a ductile middle-crustal shear-zone (B2, B3 and B3 folds) with northward transport of the upper plate along a low-angle detachment and structural doming around the Naxos magmatic core. The tectonic development ends with the late Miocene emplacement of a granodiorite pluton and a non-metamorphic nappe, characterized by tilted, shallow dipping, listric fault blocks sliding northward upon the brittle-ductile detachment shear zone. Episodes of arc rotation are responsible for alternating stress fields within the youngest tectonic evolution of Naxos and left behind folded upright tectonic contacts and similar deformed rock throughout all structural levels (D3).

1. INTRODUCTION
This assignment deals with the poly-metamorphic tectonic evolution of the Greek island of Naxos, which is the largest island of the arcuate Cycladic archipelago, located within the southern half of the Aegean Sea between mainland Greece and Turkey (John & Howard, 1995; Urai et al., 1990). Geologically the rocks of Naxos belong to the Attic Cycladic Massif (ACM), which is part of the Aegean tectonic plate (figure 1) (Buick, 1991; John & Howard, 1995).

Steady northward (later NE) convergence and northward subduction of the African plate under the Apulian-Anatolian micro-plate resulted in a southward subduction roll-back (figure 10) in the eastern Mediterranean and a rapidly uplifted metamorphic core complex within the southern Aegean Sea (Buick, 1991; Urai, 1990).

The present-day volcanic arc of the active subduction zone is located between the ACM in the north-ern back-arc and the NW-SE trending Hellenic trench in the SW (Buick, 1991). The ACM is mainly comprised of a pre-Alpine basement and Mesozoic marbles and schists, which were affected by at least two Alpine regional tectono-metamorphic events (Urai et al., 1990).

Figure 1 (from Buick, 1991): The location of the Attic Cycladic Massif (ACM) within the present-day eastern Mediterranean. The thick arrow indicates the direction of convergence of the African Plate under the Apulian-Anatolian micro-plate; the thin arrow represents the present-day direction of extension in the southern Aegean. VA, present-day volcanic arc; He, Hellenic Trench; PI, Pliny Trench; St, Strabo Trench; Cr, Crete; NTAnTrFt, North Anatolian Transform Fault.
2. PRESENT TECTONIC FRAMEWORK

The geodynamic evolution of the Aegean region over approximately the last 50 Ma is associated with permanent convergence between Africa and Eurasia and by a progressive subduction of the Aegean slab. Permanent southward propagation of the subduction trench and the associated volcanic arc of the order of 1000 km (from the Rhodope region of Bulgaria/northern Greece to the Hellenic Trench south of Crete) has governed the regional tectonic evolution during the Cenozoic (figure 2) (John & Howard, 1995; Seward et al., 2009).

Urai et al. (1990) concluded that the present tectonic framework of the Aegean is that of a landlocked basin, which propagates along the Hellenic subduction zone, associated with the roll-back of the subducted slab. Various extensive neotectonic studies determined a (N-S) crustal extension within the last 15 Ma up to a factor of two compared to present-day movement rates (Urai et al., 1990).

After John & Howard (1995) Naxos exhibits an unusually complete structural and chronologic record of an extensional and kilometre-scale low angle ductile shear system, which was interpreted by Urai et al. (1990) and Buick (1991) as a mid-Miocene structural evolution of a metamorphic core complex (see info box).

After Urai et al. (1990) this model elegantly explains the locally occurring upper non-metamorphic crustal rocks superimposed upon deeper crustal units by sliding along shear zones and shallowly dipping detachment faults.

INFO BOX: METAMORPHIC CORE COMPLEX

A metamorphic core complex may be the result of extreme extension of the upper crust (hanging-wall). Effective unloading and isostatic compensation leads to the exposure of the typically mylonitized lower crustal (footwall) rocks. Along a low-angle dipping detachment the ductile basal mylonites are widely overprinted by (often chloritic and cataclastic) breccias, and overlain by brittle deformed, isolated hanging-wall blocks. While the blocks were mostly rotated by book shelf mechanism, the simple shear model (pulling from one direction only) explains the asymmetry of crustal stretching and a detachment which cuts the base of the lithosphere. Common features are calc-alkaline to ultramafic magmatism and shear-folds as well as associated HT-LP metamorphism (within the lower plate), volcanism and hydrothermal alteration (within the upper plate) (Lister et al., 1984; University of Illinois, 2014). See also figure 11.

Figure 3: Schematic cross-section through a metamorphic core complex (Image Source: http://bulletin.geoscienceworld.org/content/117/1/1-12/1534/F1.expansion. Visited: 28 Aug 2014)

3. SHORT GEOLOGICAL OVERVIEW

After Urai et al. (1990) and Buick (1991) the rocks of Naxos can be briefly distinguished into four units (figure 4 & 5):

(i) a Mesozoic migmatite complex (\(M_1\) & \(M_{2a+b}\) basement, predominantly leucogneiss); surrounded by

(ii) a Mesozoic metamorphic complex (\(M_1\) & \(M_{2a+b}\)) of predominantly marbles, as well as minor proportions of pelitic rocks (predominantly schists), metavolcanics and metabauxites;

(iii) a Miocene granodiorite in the western part of the island, intruded into (ii),
inducing contact-metamorphism ($M_3$), and

(iv) tectono-sedimentary, non-metamorphic, allochthonous rocks (Aquitanian to Burdigalian marine clastics and Pliocene fluvial conglomerates), which feature tectonic contacts with (ii) and (iii).

4. STRUCTURES INSIDE THE METAMORPHIC COMPLEX

Remarkable features are some scattered intrusions of ultramafic rocks and a series of Barrovian metamorphic ($M_{2b}$) isograds (Urai et al., 1990; figure 5). A number of synkinematic granitoids and pegmatites crosscut earlier foliations of the migmatite (Urai et al., 1990).

Three overlapping generations of folds can be recognized within the metamorphic complex: kilometre-scale isoclinal folds along N-S fold axes ($B_1$) are refolded by smaller, open and upright, also N-S trending folds ($B_2$). These refolded folds are gently refolded again by E-W compressive folds ($B_3$), resulting in the formation of a structural dome and leaving behind the regional foliation pattern within the unroofed metamorphic complex (figure 6) (Urai et al., 1990).

Metamorphic isograds on both schematic geological maps (figure 4 & figure 5) represent increasing metamorphic grade towards the centre of the structural dome (Buick, 1991; Schenk et al., 2007). The oval shape of the isograds seems to have its origin from $B_3$ fold generation and associated doming (Urai et al., 1990).

Thin boudinaged and N-S tilted pegmatite layers and post-$M_{2b}$ mylonites, included within the marbles of the migmatite, determine strong N-S extension during and after $M_{2b}$ also in greater depths (Urai et al., 1990; Schenk et al., 2007).

5. STRUCTURES OUTSIDE THE METAMORPHIC COMPLEX

While the central part of the granodiorite (12 Ma) in the western part of the island is undeformed, it exhibits local deformation and foliation towards the contacts with the non-metamorphic cover (Urai et al, 1990). Analysis of the sense of shear along the ductile shear zones match to a local northward movement of the upper plate (Urai et al., 1990).

Brittle shear zones with irregular arranged cataclasites and pseudotachylites partly overprint the aforementioned structures and confirm the northward transport direction of the hanging-wall (Urai et al., 1990).

6.TECTONIC HISTORY

Amongst other authors Urai et al. (1990) and Jolivet & Brun (2010) propose at least two distinct Alpine regional tectono-metamorphic stages, which affected the Cycladic archipelago, including Naxos (figure 7 & figure 8).

The Cycladic blueschist was first accommodated during the Eocene ($D_1$) along a relative cold P-T gradient placing some units close to the surface (e.g., the islands of Syros and Sifnos), while other units stayed at greater depths in the crust undergoing moderate heating (e.g., the islands of Tinos and Andros). Outcrops on the island of Naxos even exhibit migmatites, implying that heating was strong enough for partial melting to develop (Jolivet & Brun, 2010). This Eocene HP-LT ($M_1$) blueschist metamorphism was followed by the regional greenschist facies metamorphism ($M_{2a}$ at 25 Ma) (Urai et al., 1990; Schenk et al., 2007).
migmatites and/or granites were formed by that second deformation phase, and e.g. reached amphibolites facies grade (M$_{2b}$ at 20-16 Ma) inside the Naxos core (Schenk et al., 2007; Jolivet & Brun, 2010).

Striking evidence of similar age mylonitization and extensional faulting on nearby islands has been proposed by several authors (Lister et al., 1984; Gautier et al., 1993).

Figure 5 (from Schenk et al., 2007): Large simplified geological map of Naxos, providing the principal rock units, tectonic contacts and faults, and the metamorphic overprint featured by isograds. (The Naxos marble quarry (top left picture) near Kinidaros is not discussed in this assignment.)
6.1 EOCENE DEFORMATION (D₁)

During the first deformation phase (D₁) of the ACM, starting in the Eocene at around 50 Ma, the Alpine convergence induced compressive tectonic features and caused HP-LT blueschist metamorphism (M₁, 0.9 GPa, 480 °C) within a thickening lithosphere (Urai et al., 1990; Schenk et al., 2007). The mountain-building-related tectonic features comprise B₁ and B₂ folds, subsequent thrusting, nappe pile formation and the initiation of N-dipping subduction of continental margin material (Urai et al., 1990).

In contrast to younger deformations (D₂) the kinematic indicators imply a dominantly southward movement of the upper plate during D₁ (Urai et al., 1990).

In the southeasternmost part of the island relicts from Eocene D₁ are preserved within the highest structural levels (John & Howard, 1995).

6.2 OLGICO-MIOCENE DEFORMATION (D₂)

Strong evidence for a southward crustal extension of the Aegean tectonic plate since the Oligocene (25 Ma) was found by several authors. The extensional event initially was associated with a regional Barrovian greenschist facies metamorphic event (M₂a, around 25 Ma), followed by more localized HT-LP metamorphism (M₂b, 0.6 GPa, 670 °C), locally reaching the upper amphibolites facies with partial anatexis and peaked with the exhumation of a metamorphic core complex in Miocene ages (20-16 Ma) (Buick & Holland, 1989; Urai et al., 1990; Schenk et al., 2007).

Figure 6 (from Urai, 1990): Schematic 3D-sketch of the most prominent structures of the rocks of Naxos (not to scale; arrow indicates North; the segmented and rotated non-metamorphic nappe is for visualization only and is much thinner in reality).

Figure 7: The two main tectonic, magmatic and metamorphic stages (D₁ & D₂) in the Cyclades during the Cenozoic (modified after Jolivet & Brun, 2010).
Figure 8 (from Schenk et al., 2007): Schematic timetable to illustrate the relationship of metamorphism and deformation discussed in the text. M1 represents the first (compressive) deformation stage (D1) with HP-LT blueschist metamorphism during Eocene ages, M2a corresponds to the regional greenstone facies metamorphism during Oligo-Miocene ages, M3 is related to the more localized HT-LP metamorphism which corresponds to the processes of structural doming and formation of metamorphic core complexes, M2b corresponds to the contact metamorphism around the granodiorite in the western part of the island of Naxos. (Note the time axes are not scaled. Annotations (a, b, c) point to secondary references cited by the author. Details of figure b (circle) are not discussed in this assignment.)

During D2 the permanent southward roll-back of the Hellenic subduction zone was controlled by extensional tectonics in the back-arc area (John & Howard, 1995). Accompanied by plutonism and the before mentioned HT-LP metamorphism the second deformation phase generated a ductile middle-crustal shear-zone during Miocene ages, reactivating B1 and B2 folds, generating B3 folds with contemporaneous northward transport of the upper plate along the detachment and structural doming around the migmatitic core (Buick & Holland, 1989; Urai et al., 1990; Buick, 1991; Schenk et al., 2007).

Structural, metamorphic, and geochronologic studies on Naxos have proposed that the metamorphic rocks of the footwall initiated shearing while at anatectic conditions in the middle crust and that they subsequently were uplifted within a relative short time window of around 10 Ma within the mid-Miocene (20-9 Ma) (Angelier, 1978; Buick & Holland, 1989; Urai et al., 1990; Gautier et al., 1993). The onset of the shear zone may be correlated to the initiation of the regional crustal extension (Urai et al., 1990).

Gently dipping mylonitic fabrics were generated during progressively decreasing metamorphic influence from the peak of the M2a stage (20 Ma) until after the discordantly intruded granodiorite in the western part of Naxos (M3, contact-metamorphism at 13-11 Ma) (Buick, 1991). Parallel to the pluton margin andalusite is distributed in a 1200 m wide zone (aureole) indicating an intrusion across an already uplifted and tilted metamorphic complex (John & Howard, 1995).

The generation of the ACM metamorphic core complex and the associated N-S extensional tectonic regime is also responsible for the formation of a large back-arc basin throughout the Aegean (13-3 Ma), with a thinned crust (18-20 km in the Sea of Crete), high heat flow and locally rapid uplift (especially after the M3 granodiorite) of lower crustal Miocene metamorphic complexes by as much as 10-20 km (Urai et al., 1990; John & Howard, 1995). Based on calculated cooling ages between the M2 peak and the granodiorite intrusion a decompression of about 3 kbar was determined, indicating a minimum of about 10 km unloading due to uplift, erosion and crustal thinning within a period of only 3-5 Ma (John & Howard, 1995). During the late Miocene tectonic evolution (16-10 Ma) the rocks of Naxos have undergone successive cooling by extensional denudation during and after the M2a peak with calculated horizontal slip rates of 5-8 mm/yr in NNE direction (John & Howard, 1995). Similar age top-to-the-north ductile fabrics in the footwall were overprinted by N-S directed, normal sense LT brittle structures within the shear zone of the Naxos detachment fault (John & Howard, 1995). The NNE (20°) extension direction of the hanging wall indicates footwall unroofing of more than 20 km of movement in SSW direction relative to the hanging wall along the base of the Naxos detachment fault (John & Howard, 1995). The directed shear and extension, as well as stretching parallel...
fault striae are consistent with a top-to-the-north shear system featuring deformation patterns parallel to the dome axis (20°) and fit perfectly to the northeastward direction of decreasing cooling ages calculated by John & Howard (1995). Extensional top-to-the-north microstructures within the Naxos granodiorite pluton even post-date the intrusion itself indicating ongoing (but slowly decreasing) deformation during late Miocene ages (John & Howard, 1995). The tectonic development of the ACM temporarily ends with the emplacement of a non-metamorphic nappe, which was formed on top of the mylonitized granodiorite at around 10-9 Ma and is characterized by shallow dipping, SE tilted, listric normal fault blocks sliding upon the Naxos detachment shear zone (Urai et al., 1990; Buick, 1991).

**Figure 9 (from Angelier, 1978):** Late Miocene (a) to Holocene (e) directions of principal stresses within the Aegean Sea. Convergent double arrows indicate local compression, divergent arrows indicate extension. Vertical hachured pattern is minimum extent of compressional tectonic regime and horizontal hachured pattern is minimum extent of extensional tectonic regime. Black arrow indicates probable direction of convergence between African and Aegean plates. Thick line indicates inner volcanic arc.

a). Late Miocene compression (about 9 Ma), related to Central Aegean emersion probably was leading to B3 folding of the Naxos lower crust. Probably simultaneous extension occurred in Crete, in the Peri-Hellenic molassic through (stippled).

b). Compression at late Miocene. Barbed line indicates deepening of the Hellenic trench along the subduction zone.

c). End of Pliocene.
d). Early Quaternary.
e). Late Pleistocene and Holocene.

### 6.3 Miocene to Quaternary Evolution

Within the upper plate brittle shear is indicated by normal faulting, by the formation of pseudotachylites and by chloritic brecciation (catclasites). Transport of footwall-derived detritus into hanging wall basins occurred as extension proceeded (John & Howard, 1995). Tectono-sedimentary deposition of Aquitanian to Burdigalian marine clastics and Pliocene (non-marine) conglomerates indicate strong erosion due to progressive seismic-tectonic and synextensional uplift of an (today completely eroded) exotic terrane until the exhumation of the metamorphic complex (John & Howard, 1995).

In strata as young as late Miocene in Paros, Naxos, Mykonos, Kos, Samos, Icaria, Chios and Attica NNE-SSW folds, reverse faults and thrusts, as well as strike-slip fault systems were generated by a strong compression with an average direction of ESE-WNW (Angelier, 1978). Subsequent late Miocene E-W compression related to the central Aegean emersion between 13 and 9 Ma (Angelier, 1978; Buick, 1991; figure 9a) induced sub-horizontal deformation of refolded folds (B3). A mid-Miocene episode of rotation of the arc of the Hellenic subduction zone is held responsible for the E-W shortening and seems to have repeated in Pliocene ages: As displayed in the cross section below figure 4 the post-M3 tectonic contact between the granodiorite and the tectono-
sedi
timentary deposits on western Naxos features a
large antiform due to upright folding along a N-
trending fold axis (John & Howard, 1995).
As visible in figure 9 the tectonic regime within the
Aegean Sea did not remain constant within the last
10 Ma. Periodic alternations of both extensional
and compressive stress regimes were established
by Angelier (1978). While Naxos was located
within compressive regimes during late Miocene
(a, b) and early Quaternary times (d), it was ex-
posed to extensional tectonics during the end of
Pliocene (c) and late Pleistocene to Holocene (An-
gelier, 1978). The outer arc instead shows constant
The visualization of the tectonic evolution of Naxos
is supported by and summarized in figure 10 (roll-
back) and figure 11 (metamorphic core complex).

Figure 10 (from Buick, 1991):

"A cartoon model for the structural evolution of the Attic
Cycladic Massif (ACM), from the early Miocene onwards. In this
model northwards directed extension in the ACM occurred as
the result of extension in the Apulian micro-plate of the
Aegean and related steepening of the underlying subduction
zone (i.e. roll-back, as shown by unfilled arrows). In the early
Miocene regional M₂ green- schist metamorphism over-
printed M₁ blueschist metamorphism to the south of
broadly coeval arc-related volcanism. Subduction zone
roll-back began in the M₂ₐ-M₂ₐ interval (25-20 Ma); with a
result that arc magmatism migrated south to the ACM by
the time of the M₂ₐ event. (20-
16 Ma). During this time, and up until about 10 Ma, ACM meta-
 morphic complexes were ex-
humed in normal sense ductile shear zones related to basi-
formation to the north of the
ACM. At this stage tectono-
sedimentary units were em-
placed onto the deformed crys-
talline basement via low angle
detachment faults. For many of
metamorphic complexes duc-
tile extension involved move-
ment of upper levels to the
north. Continued steepening of
the subduction zone, and con-
comitant extension in the
Apulian micro-plate shifted the
locus of arc magmatism to its
present-day site, south of the
ACM, in the Pliocene."

"Note:
(i) The sketch is drawn from an absolute (hot spot) reference frame; therefore both the sub-
ducting African plate and the overlying Apulian micro-plate are moving to the north with time;
(ii) The cartoon does not attempt to show the changes in subducting slab length with time;
(iii) In the 20-16 Ma interval some extension in the present-day site of the Sea of Crete is shown.
The estimate for the basin formation in this area is from 13 to 5 Ma. [...]"
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Figure 11 (from Gautier et al., 1993): (a) Interpretative cross section of the Naxos-Paros detachment on a crustal scale. M denotes migmatites and g denotes western Naxos granodiorite. (b) Progressive evolution of a detachment zone.

7. CONCLUSION

With the purpose to reconstruct the tectonic evolution of the island of Naxos several structural and petrographical studies consistently interpreted the formation of a Cenozoic metamorphic core complex as the central and most remarkable structural element, involving middle-crustal rocks drawn upward and outward from underneath its sedimentary cover due to simple shear induced by permanent roll-back of the Hellenic subduction zone (Lister et al., 1984; Urai et al., 1990; Buick, 1991; John & Howard, 1995; etc.). Based on observations in the field and from laboratory data a poly-metamorphic development of Naxos is considered until the formation of the present-day structural pattern which crops out as a tectonically unroofed metamorphic dome on an island in the middle of the Aegean Sea. The tectonic evolution of Naxos contains at least two tectono-metamorphic deformation phases:

- **D1**: Eocene (ca. 50 Ma) HP-LT mountain-building blueschist metamorphism (M1, 0.9 GPa, 480 °C) due to the Alpine compressive stress regime featuring a thickening crust, thrust and nappe formation and the initiation of an N-dipping subduction zone.
- **D2**: regional (Barrovian) Oligo-Miocene (25-20 Ma) HT-LP greenschist (M2a) to locally upper amphibolite facies metamorphism (M2b, 0.6 GPa, 670 °C, 20-16 Ma) event with rapid N-S extension (18-20 km) and crustal thinning, rapid uplift (10-20 km) and subsequent plutonism (M3, 13 Ma).

The interval between D1 and D2 appears to be of near-isothermal decompressional character throughout the ACM (Buick, 1991). Progressive N-S stretching and brittle segmentation of the non-metamorphic upper plate and uplift of the lower plate resulted in the exhumation of a metamorphic core complex with a characteristic low-angle ductile detachment shear zone in lower levels and low-angle normal faults in its upper tectono-sedimentary levels (Lister et al., 1984). With ongoing uplift and unloading the ductile deformation patterns were step by step overprinted by more brittle structural elements (John & Howard, 1995). Several generations of flat-lying, sub-parallel folds (B1, B2 & B3), foliation and lineation record the extensive deformation of the Naxos metamorphic complex (Buick, 1991). While B1 & B2 folds have been formed mainly due to an N-S extension and characteristic top-to-the-north movement (D2) (Urai et al., 1990), B3 folds more likely resulted from episodic post-metamorphic arc rotation events (D3) in the late Miocene and in the Pliocene which produced temporarily E-W compressive stress fields. The reactivation and transposition of early structures resulted in a relatively simple structural pattern of a relative complex tectono-metamorphic history (Urai et al., 1990).
REFERENCES


