Exhumation history of Naxos

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1 Introduction

The island of Naxos is situated in the southern Aegean Sea (Greece) and is part of the Attic-Cycladic Massif. The Aegean region arose during the Alpine orogeny and has undergone two major Alpine deformation events, collision and extension, involving a pre-Alpine gneissic basement (approx. 370 Ma) and Triassic metasediments (Urai et al. 1990, Gautier et al. 1993). These pre-Alpine metamorphic rocks are nowadays exposed on Naxos juxtaposed against Cenozoic non-metamorphic rocks. The exposed rocks of Naxos can be divided into four different units: 1) a migmatite complex forming a dome, that is surrounded by 2) a metamorphic complex consisting of metasediments (mainly marbles and schists), 3) an intrusive granodiorite dome and 4) a non-metamorphic nappe (Fig. 1) (Urai et al 1990). The nappe, consisting of Mesozoic non-metamorphic sediment deposits, is in tectonic contact with the metamorphic core complex (MCC) and the granodiorite dome. The MCC is built up of the migmatite dome and the metamorphic complex (metasediments).

Fig. 1: (a) Geological map of Naxos (simplified after Jansen 1973, 1977). Dashed lines indicate the isograds of the high temperature event; metamorphic grade increases from 1 to 6. (b) Cross-section through Naxos (after Jansen 1973) from WNW to ESE. (after Gautier et al. 1993)
As an introduction, the term metamorphic core complex (MCC) characterizes the exhumation of former, deeply buried crystalline rocks juxtaposed against younger non-metamorphic rocks. Exhumation is a general term describing the return of once deep-seated metamorphic rocks to the Earth's surface and is controlled by erosive and tectonic denudation (Ring et al. 1999). Naxos island is counted among the Cordilleran type Metamorphic Core Complexes. In simple terms, the Naxos MCC has been exhumed through continental extension accompanied by crustal thinning and tectonic denudation, which resulted in the isostatic uplift of lower crustal rocks.

In the following part, the attempt will be made explaining the exhumation history of Naxos. Starting with the tectonic setting, continuing with the uplift and eventually ending with the unroofing.

2 Exhumation history

The geodynamic evolution of the Aegean region is associated with convergence between Africa and Eurasia, whereby the Aegean slab (or Hellenic slab) was subducted (Seward et al. 2009). The north-dipping subducting slab was heated up with farther descent into the mantle leading to metamorphism of Triassic sediments forming high-pressure-low-temperature rocks in the Eocene (ca. 50 Ma). These rocks will later be forming the metamorphic complex after undergoing further metamorphic changes in the Miocene. The subduction of continental margin material, which reveals a high thickness and low density, caused a rapid growth of the accretionary wedge. Further accretion caused the increase of frictional resistance that finally resulted in stagnation of the subduction.

Subsequent continental extension started in the Miocene at approx. 25 Ma (or earlier) (Jolivet et al. 1999). It was triggered by the slab roll-back, which caused the overriding plate of the subduction zone to become stretched until it rifts. The roll-back of the subducting African plate is supported by the fact that both metamorphic and magmatic activity is getting younger from north to south (Keay et al. 2001). As the subduction slab retreated, the extension migrated southwards. The roll-back enabled influx of mantle magma above the retreating slab. The ascending magma provided a heat source for metamorphism, anatexis (partial melting) and magmatism (Kaey et al. 2001). Hence, the high-pressure-low-temperature metamorphic rocks of the Eocene (ca. 50 Ma) were overprinted by regional Barrovian metamorphism in the Miocene (ca. 16-25 Ma) forming a high-temperature-low-pressure metamorphic complex (Fig. 2). Furthermore, partial melting is directly connected to the formation of the migmatite dome and the leucogranite (granitoid) (Fig. 2). The migmatite experienced stronger metamorphism than the surrounding metamorphic complex and therefore exhibits higher metamorphic grades (Fig. 1). The onset of partial melting occurred prior to 20.7 Ma (Keay et al. 2001). The occurrence of magmatism generating the granodiorite pluton was induced later with progressive uplift. The accumulation of magma caused the intrusion of the I-type granodiorite into the metamorphic complex (Fig. 2) in the West of Naxos. The emplacement occurred at shallow crustal levels at approximately 12 to 11 Ma.
The continental extension predominantly resulted in the formation of the Cycladic back-arc region, including the formation of the major detachment fault and crustal thinning.

Crustal thinning of the Eocene thickened crust is referred to tectonic denudation. Both tectonic and erosive denudation led to decompression resulting in enhanced isostatic uplift below the thinned portion of the crust. Enhanced mantle heat flow led to further strong attenuation of the crust. The buoyant Moho in the lower crust is uplifted in response to the continuous thinning of the upper crust (Fig. 3).
The detachment fault evolved from a ductile shear zone from depth and progressive extension was responsible for its ongoing activity. The onset of the major low-angle, north-dipping shear zone-detachment fault system with 'upper plate moving north' sense of transport was active from approximately 20 to 9 Ma (Urai et al. 1990). It separated brittle deformed rocks in the footwall from ductile deformed rocks in the hanging wall (Fig. 3).

From 25 to 11 Ma, the metamorphic complex was moving upward in the major ductile shear zone (Fig. 2) and was deformed non-coaxially in deeper parts of the shear zone. Progressive uplift is followed by the increase of the geothermal gradient. That is a normal response related to low conductivity of the rock mass relative to the rate of uplift (Lister et al. 1984). During advanced uplift, the metamorphic complex was exposed beneath the low-angle detachment fault which was overlain by essentially unmetamorphosed material. But the non-metamorphic sediments do not exhibit contact metamorphism because the metamorphic complex has already been cooled down to lower temperatures due to rapid uplift. Additionally, the contact to colder upper-plate rocks supported further temperature drop. Slow cooling of the metamorphic rocks prevailed until approx. 11 Ma.

The granodiorite is, in contrast to the metamorphic complex, mainly undeformed. The contact between the granodiorite dome and adjacent non-metamorphic sediments only led to local deformation at ca. 9.5 Ma (Urai et al. 1990). Granodiorite ages ranging from 9 to 12 Ma due to differential depth of emplacement and/or differential exhumation during tectonic unroofing (Seward et al. 2009).

Furthermore, extension resulted in the formation of brittle, listric normal faults above the detachment fault (Fig. 3). These northeast-dipping normal faults were created near the brittle-ductile transition in the hanging wall. Extensive normal faulting led to the formation of
horst and graben structures. Sedimentary basins (grabens) were separated by blocks (horsts) tilted towards the southwest. Further subsidence occurred due to crustal thinning that is connected to progressive extension. Later on, the basins were filled syn-extensional with Miocene, non-metamorphic sediments and ophiolites. The detachment fault displaced these sediments over crystalline basement. The emplacement of this non-metamorphic nappe is dated to 9.5 Ma (Urai et al. 1990). It is considered that the non-metamorphic nappe has been deposited while the MCC was still buried because it does not contain components from the metamorphic complex (Kuhlmann et al. 2004).

The final exhumation of the Naxos metamorphic core complex involved relatively rapid upward movement along the detachment fault. Subsequently, the MCC was drawn upwards from beneath the fracturing and extending upper plate (Fig. 2). Over time, erosion eventually reduced the hanging wall exposing the MCC to the surface at approximately 8 Ma (Keay et al. 2001). Dating of Middle to Upper Miocene sediments indicate rapid erosion until about 8.5–7 Ma (Seward et al. 2009).

Naxos island, including the metamorphic core complex, the granodiorite dome and the non-metamorphic nappe, arrived at the surface approximately 4 Ma ago (Urai et al. 1990).

3 Discussion

Various models for the development of Naxos state that the exhumation of the metamorphic core complex is ascribed to one single event (Lister et al. 1984). But new studies suggests a more complex exhumation process, which is controlled by more than one single detachment fault (Seward et al. 2009).

Although numerous workers studied the formation of Naxos, there is still uncertainty about what caused partial melting and magmatism on Naxos (Keay et al. 2001). Mainly four diverse proposals for thermal models have been made by different workers:

- Barrow (1893)
- Read (1957), England and Richardson (1977), Hollister and Crawford (1986), Oxburgh (1972)
- McKenzie and Bickle (1988), Wickham and Oxburgh (1985)

4 Summary

The exhumation history of Naxos island is based on the two Alpine deformation events, collision and extension. The roll-back of the Aegean slab caused the influx of mantle magma, which was the heat source for the rock forming processes: metamorphism, anatexis and magmatism. Metamorphism in the Eocene and Miocene generated metasediments, which form the metamorphic complex. Partial melting gave rise to the migmatite and leucogranite (granodiorite). From 25 to 11 Ma, the core complex moved upwards along the low-angle detachment fault. At about 11 Ma, the granodiorite intruded into the core complex in the West of Naxos. Further rapid uplift along the detachment fault led to the MCC being dragged out from be-
neath the detachment fault. In the course of time, erosion exposed the MCC to the surface at approx. 8 Ma. It took another 4 Ma of sedimentation and erosion, until Naxos island, as it is known nowadays, arrived at the surface.

5 References


