Naxos: deformation and metamorphism in metabauxites

Naxos field course 2014, group B
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Metamorphism on Naxos

Naxos belongs to the Attic Cycladic Metamorphic complex (ACMC) which is located between the Greek mainland and SW-Turkey. The rocks of the complex underwent two main phases of metamorphism: The first one was an Eocene high-pressure, low-temperature metamorphic phase (M1), associated with large scale thrusting during an early Alpine subduction episode; the second is a result of continental extension that led to local formation of thermal domes and high-temperature, medium-pressure metamorphism in Late Oligocene-Miocene (M2, Urai et al, 1991). Feenstra (1985) describes the following metamorphic pattern on Naxos: Around a high-grade migmatic gneiss dome, there are six zones of decreasing metamorphic impact. These zones are defined by isograds that were mapped based on mineral occurrences in metabauxites and metapelites (Figure 1). The metabauxites in these zones can be classified as: diaspore-chloritoid zone (I), corundum-chloritoid-zone (II+III), corundum-staurolite zone (IV) and corundum-green spinel zone (VA+VB). In zone VI there is no metabauxite. Kyanite is found in metabauxites of zone I-III, which forms during a reaction of pyrophyllite and diaspore (Feenstra, 1996). The biotite isograd in figure 1 is defined based on the occurrence of biotite in metapelites. In metabauxites biotite only occurs in zone IV, as described by Feenstra (1996). Biotite forms during the breakdown of chloritoid, when staurolite is formed as well. Some metabauxites, however, contain coexisting chloritoid and staurolite (Feenstra, 1996). The isograds given in figure I approximately indicate the following temperatures (Feenstra, 1985): + corundum: 420°C, + biotite: 500°C, + staurolite: 540°C, + silimanite: 620°C, - kyanite: 620°C, + meltphase: 670°C. They reflect the impact of the M2 metamorphism with temperatures of 400-700°C and pressures of 5-7 kbar (Feenstra, 1985). Relicts of the M1 phase are found in the rocks of SE-Naxos. Up to the middle of zone IV the metabauxites contain muscovite, chloritoid, kyanite and clinozoisite-epidote, pointing to the M1 metamorphism (Feenstra, 1996). During this metamorphic phase temperatures and pressures of 400-480°C and 7-9 kbar were reached (Feenstra, 1985).

Bauxite and metabauxite

Bauxite is an Aluminum-ore that is a product of chemical weathering. There are two types of bauxite: laterite-bauxite and karst-bauxite. The former is formed from magmatic and metamorphic rocks whereas the latter is formed from sedimentary rocks, particularly from clay-rich limestones. Bauxites typically form compact masses and often contain ooids or pisoids (Okrusch & Matthes, 2010). The metabauxite that is found on Naxos is karst-bauxite from the Jurassic, which is contained in marble as lenses of up to 8 m thickness (Feenstra, 1996). Probably there have been 2-3 bauxite horizons that were repeated by large-scale folding and thrusting, as suggested by Urai et al. (2001). The amount of metabauxite on Naxos is negligible compared to the other rock types, but still it is wide-spread on
Figure 1: Geological map of Naxos with main lithology, isograds, metamorphic zones (I-VI) and metabauxite occurrences (from Urai & Feenstra, 2001)
the island (Feenstra, 1985). The most important mineral in karst-bauxite is boehmite (γ-AlOOH), with increasing relocation diaspore (α-AlOOH) (Okrusch & Matthes, 2010). Therefore, low-metamorphic bauxite is called diasporite. In high-metamorphic bauxites, corundum is the predominant mineral. These rocks are called emeries. Furthermore, staurolite, biotite, kyanite, magnetite and ilmenite are randomly oriented in the deposits on Naxos (Feenstra, 1985), indicating M2-metamorphism. The metabauxites on Naxos are very inhomogeneous, as stated by Feenstra (1985). The inhomogeneity is of pre-metamorphic origin, reflecting compositional layering, pisoids and ooids, concretions or veinlets.

Processes during metamorphism of bauxite

Feenstra (1985) points out that the metamorphism of the bauxites on Naxos was isochemical: The preservation of small-scale inhomogeneities, such as pisoids, in metabauxites indicates the restriction of migration of major elements during metamorphism. Moreover, chemical studies of the mentioned publication have revealed that except for the H₂O, the composition of the diasporites is generally the same as the one of the emeries. Only volatiles have been released from the deposits during metamorphism and minor amounts of CaO and K₂O have locally been added to the system.

The most important process during metamorphism of bauxite is the transformation of diaspore into corundum (Al₂O₃), which is a dehydration reaction. The temperature at which this transformation occurs is around 420°C (Urai & Feenstra, 2001). The study on the Naxos metabauxite by Feenstra (1985) shows that during the M1 metamorphic phase the P-T conditions have been within the stability field of diaspore whereas during the M2 phase dehydration of the diaspore occurred. A transition zone of 1-2 km width is described, in which the metabauxites contain both diaspore and corundum (figure 1). A stable coexistence of both phases is indicated by their epitaxial intergrowth (Urai & Feenstra, 2001). Even partial conversion of corundum back to diaspore is observed by Feenstra (1985). This is suggested to have occurred during late M2 metamorphism as an effect of substantial amounts of water still present in the deposits and relict M1-diaspore acting as crystallization nuclei. The transition zone is further characterized by the first appearance of prograde margarite, the most important mica in the emeries (Urai & Feenstra, 2001).

An important aspect of the metamorphism in metabauxites is the deformation. While the diasporite lenses occur as relatively small (0.5-4 m thick) angular and virtually undeformed bodies in strongly deformed marble, the emeries form elongated boudins that are 3-5 m thick and show strong internal foliation and lineation (Figure 2, Urai & Feenstra, 2001). Pisoids are reported to be strongly deformed in the emeries as well (aspect ratio up to 1:30). The microstructures of the emeries are described by Urai & Feenstra (2001) as indicating ductile deformation of varying homogeneity: The Fe-rich bands are strongly deformed and bent around flattened Al-rich parts. In zones of higher metamorphic grades this deformation structures are observed to be overgrown by porphyroblastic corundum of 0.05-0.8 mm grain size, with grain size increasing with increasing metamorphic grade. In high-grade emeries, Urai & Feenstra (2001) have also observed marble pockets that show a well-equilibrated texture of epitaxial grains that suggest normal grain-growth. In contrast, they found the high-grade marbles outside the emery lenses to have lobate grain boundaries and subgrains, microstructures typical for grain-growth during deformation. Thus, the emery must have been stronger than the surrounding marble, protecting the included marble pocket from deformation. The low-metamorphic
diasporite hardly show evidence for deformation, as reported by Urai & Feenstra (2001), even though the surrounding marble is strongly deformed. This is itself not astonishing, having in mind that the mineral hardness of diaspore is 6.5-7 and thus a lot higher than limestone with a hardness of 3 (though weaker than corundum, which has a mineral hardness of 9 according to the Mohs scale). The deformation of metabauxite in the transition zone consequently has to be associated with the mineral transformation of diaspore to corundum. As the transformation is a dehydration reaction, large amounts of water are expelled. Urai & Feenstra (2001) state that 6-8 wt-% of water, which is equivalent to 40-50% rock volume at the P-T conditions of phase transition, are released. Furthermore they characterize the transition with a solid volume decrease of at least 20%. In their study Urai & Feenstra (2001) suggest that during mineral transformation the fluid pressure of the expelled water in the low-permeable metabauxite and the volume decrease gave the metabauxite a comparable weakness to that of the surrounding marble. Thus they inferred that part of the strain in the marble was taken up by the metabauxites. The deformation mechanism is suggested to be a grain-sliding process associated with the loss of cohesion in the reacting diaspore-corundum mass. The process is assumed to be supported by the fine grain size of the emery. During the reaction, permeability would have increased releasing the fluid pressure to the marbles. Urai & Feenstra (2001) suggest that at the end of the transformation reaction, with decreased fluid pressure, the corundum was compacted and became stronger than the surrounding marble. Then the emeries experienced static conditions, as inferred from the above mentioned microstructure of the marble pockets within the emeries.

The factors that control the rate of prograde metamorphic processes in metabauxites are described by Urai & Feenstra (2001) as follows: heat and mass transport at the reaction site, surface reaction mechanisms, dissolution of reactants and nucleation and growth of products. They describe the escape of the generated water as being the most important factor, as high pressure of H₂O would stabilize diaspore.

Figure 2: Left: undeformed diaspore from zone I; right: deformed diaspore, close to the corundum-isograd (from Urai & Feenstra, 2001)
References


