# Minerals of the banalsite-stronalsite series in amygdules from the Brunlanes ultramafic volcanic series

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## Introduction

Banalsite was first described from the Benallt manganese mine, Lleyn Peninsula, Wales by Smith et al. (1944), while stronalsite was described as an alteration mineral in veins cutting mafic metatuff xenoliths at Rendai, Kochi, Japan (Hori et al. 1987). Their general chemical formula is $ANa_2Al_4Si_4O_{16}$, where *A* is Ba and Sr, respectively. The study by Liferovich et al. (2006b) has confirmed that there is a complete solid-solution between banalsite and stronalsite. A third tectosilicate closely related to the above mentioned species, lisetite, $CaNa_2Al_4Si_4O_{16}$, has been described from the Liset eclogite pod, Selje, Norway (Smith et al. 1986). Liferovich et al. (2006b), however, has shown that lisetite has limited miscibility with banalsite-stronalsite. The crystal structures of stronalsite and banalsite have been determined by Liferovich et al. (2006a).

Due to its inconspicuous appearance banalsite and stronalsite have hitherto been found at only about 15 localities worldwide, typically from alkaline ultramafic rocks, rodingite, jadeite and from metasomatic rocks enriched in Fe-Mn oxides and carbonates, and in most of the localities banalsite and stronalsite are only minor constituents. For an overview, see www.mindat.org/min-504.html and www.mindat.org/min-3804.html. However, more localities will most probably be discovered in the future.

Certain lava flows of the Brunlanes ultramafic volcanics are rich in white, porcelain-like amygdules, which have received a minimum of attention by previous geoscientists. During an investigation on the mineralogy of these amygdules it became clear that minerals of the banalsite-stronalsite solid solution series are an important constituent. We hereby report the widespread occurrence of banalsite-stronalsite in amygdules in the Brunlanes ultramafic volcanics, and the first record of these minerals in basaltic rocks. In Norway tiny amounts of banalsite and stronalsite have previously been reported from the Mikkelvik alkaline stock, Ringvassøy, Troms by Bøe (2000) and Zozulya et al. (2009), respectively.

## The Brunlanes ultramafic volcanics

The Brunlanes ultramafic volcanic series is situated in the extreme southwesternmost part of the onshore continental Carboniferous-Permian Oslo Rift. The Brunlanes volcanics belong to the basaltic family, but they more concisely represent a series consisting of olivine melilitites, melilitites, nephelinites and basanites, i.e. they are very undersaturated, ultramafic, alkaline magmatic rocks (Dahlgren unpubl.).

Most of the volcanics are lava flows, represented by both aa and pahoehoe lavas, but subordinate pyroclastic deposits also occur. The phenocrystal phases include abundant clinopyroxene, magnesian olivine, apatite, Ti-magnetite and perovskite. Formerly it was believed that the Skien nephelinite lava series, situated north of Brunlanes, represented the oldest volcanism in the Oslo rift (Segalstad 1979, Anthony et al. 1989). New data, however, demonstrates that the Brunlanes volcanics are slightly older. The lower part of the Brunlanes volcanic series yield Late Carboniferous U-Pb perovskite ages of 300.2 ± 0.9 Ma (pyroclastic surge) and 300.4 ± 0.7 Ma (olivine melilitite aa-flow) respectively, whereas perovskite from a pyroclastic unit underlying the oldest lavas at Skien yield a slightly younger age of 298.9 ± 0.7 Ma (Corfu and Dahlgren 2008).

The bulk part of the Brunlanes ultramafic volcanics are found in the cliffs of Saltstein east of Mølen and the adjacent peninsula of Oddane. The volcanic series strikes north-south and dips 40-50° east. The base of the volcanic series, in the west towards Mølen, is not exposed due to cover by the extensive Younger Dryas "Ra" moraine. Late Silurian sandstones are exposed at Fugløya, situated immediately west of Mølen, but it is not yet known whether the volcanic series rest unconformably on these Silurian strata or, as in the Skien district, on Late Carboniferous sediments (Dahlgren & Corfu 2001).

To the east of Saltstein and north of Oddane the volcanic series has been transected by later nepheline syenite and larvikite plutons. Consequently the volcanics have been contact metamorphosed. The metamorphism is severe near the pluton boundary, but already a few tens of meters away from the boundary the volcanics have been reasonably well preserved. Fresh melilite has never been observed (only pseudomorphs are seen in thin section from some flows), but reasonably well preserved olivine and fresh perovskite is abundant. Clinopyroxene appears unaltered throughout the sequence except when within a few meters from the syenite contact. Mapping of the entire volcanic series in scale 1:100, detailed logs of continuous stratigraphic profiles, petrography and geochemistry shows that there is no stratigraphic repetition due to faulting within the series. The total thickness of the volcanics is at least 800 meters (Dahlgren unpubl.).

The volcanics are ultramafic and silica undersaturated. That means high MgO (typically 10-19 %) and low $SiO_2$ (typically 32-40 %). This is characteristic for magmas that have been generated by limited partial melting deep within the upper mantle, probably at least at 100 km depth. The Brunlanes volcanics are also Ca-rich (12-18 % CaO), Na-rich (0.5 to 3 % $Na_2O$) and characterized by high abundances of many trace elements, for example: Strontium typically in the range 1000-2300 ppm, and barium typically in the range 500-1500 ppm (Dahlgren unpubl. whole rock analyses).

## Amygdules

Many volcanic rocks are highly porous. Their porosity depends on several factors related to their chemical composition, their content of volatiles ($H_2O$, $CO_2$ etc.) on the time of eruption, the style of eruption etc. The Brunlanes pyroclastic rocks were deposited as ignimbrites and surges, i.e. the magmas became highly fragmented during explosive volcanism. These deposits consist of lithic clasts (fragments of older lavas and fragments of already solidified rocks from the magma chamber) and phenocrysts embedded in a matrix of glass fragments and microlites. In the pyroclastic rocks secondary minerals are typically are found in post emplacement vertical degassing conduits and as tiny grains in the altered glassy matrix. Lavas generally erupt from a vent and flows more or less violently out onto the surface. Frequently considerable amounts of volatiles are being kept within the melt during the emission of basaltic lavas, but as the lavas cool on the surface, the volatiles expands, due to decompression, and form vesicles. In the Brunlanes lavas vesicles are abundant in certain parts of both the aa- and pahoehoe lavas. Typically these vesicles, and in the case of aa-lavas, also the cavities interstitial between the fragments in the upper and lower flow breccias, have been secondarily filled with white minerals. Thus the original gas vesicles now stands out as white spots and masses, as amygdules (i.e. vesicles now filed with secondary minerals), within an otherwise almost black rock background.

The amygdules in the aa-lavas typically vary from subrounded, centimeter-sized to irregular, amoeboid, up to several centimeters large (Fig 1). Commonly the cores of the aa-lava flow

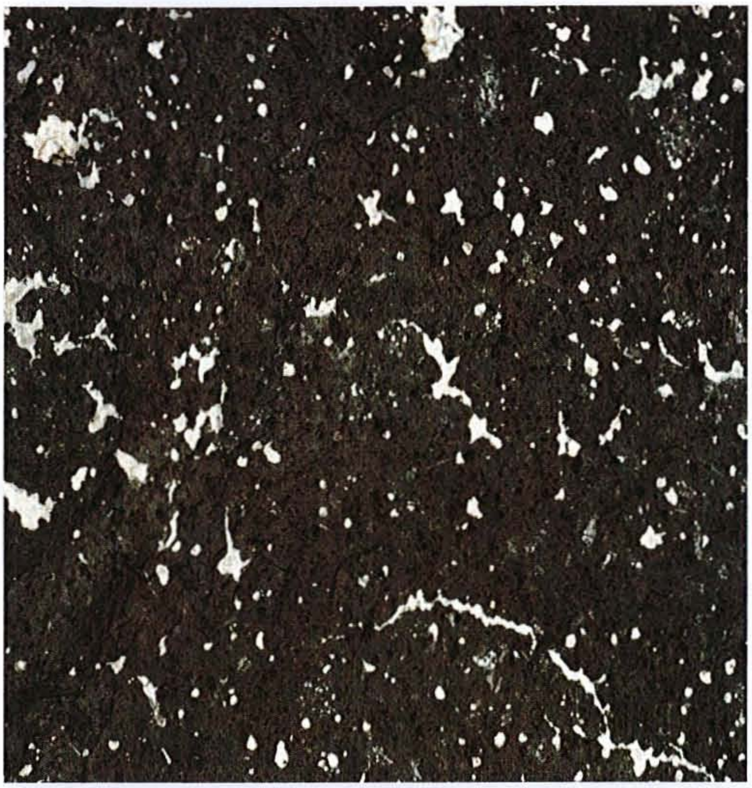

***Fig. 1.*** *Amygdules in aa-lava from Saltstein, Brunlanes. The small, spherical white amygdules are about 1 cm across. Typical for the aa-lavas are the larger, amoeboid amygdules and the mineralized tensional cracks (lower right). Photo: S. Dahlgren.*

units contain few amygdules, but frequently tensional cracks that formed during the flow of relatively viscous lavas crosscuts the dense cores. These cracks are also filled with white minerals. The pahoehoe lavas are especially rich in amygdules, and may contain amygdules across the entire thickness of a lava flow. The size, shape and distribution of the amygdules vary different flows and may even vary considerably from bottom to top within single flow units (Fig 2). Some characteristic features are:

***Spongy pahoehoe.*** These typically occur in the uppermost decimeters of some flows, and the volume between of amygdules may by far exceed (up to 70%) the volume of rock matrix. Generally these amygdules are small, from 0.1 to 3.0 mm in diameter, and are almost spherical (Fig 3).

***Pipe vesicles.*** These features typically are fingerlike, vertical vesicles that formed near the base of the cooling lavas. They may be up to 15 cm long and 2 cm thick.

***Horizontal, irregular vesicle "trains".*** These are conspicuously concentrated along certain horizons within single lava flows. They were formed during prolonged flow, in pulses, and accompanying inflation during the emplacement of these lavas. These trains of amygdules thus represent vesicles formed repeatedly near the roof of increasingly growing roofs on increasingly shrinking lava tubes and they are frequently elongated. Sometimes these original cavities represent gas blisters of considerable size (0.5 cm long and 10 cm thick; Fig. 4).

The minerals in the amygdules are very fine-grained. In thin sections under the polarization microscope it is difficult to distinguish the various mineral species because all possess shades of gray and their textures are complex and not quickly interpreted. Evidently not all minerals are in equilibrium, and clearly some minerals form at the expense of others. The

*Fig. 2. Cross-section of an inflated pahoehoe lava from Saltstein, Brunlanes. Black rock in the upper part of photo represents the upper crust of the flow (about 0.5 m thick). The zone with amygdule trains parallel to the upper crust represent vesicles formed in a lava tube where lava pulses accreted lava en vesicles to the lave tube roof. Big white areas in the foreground represent mineralized gas cavities (the biggest one is 20 cm long). Photo: S. Dahlgren.*

detailed sequence of mineral formation, reaction relationships etc. has, however, not yet been established. In some of the larger amygdules fibrous zeolites may be visible by the naked eye. Otherwise, XRD analysis is the most practical way of identifying the minerals. This technique was the mean that lead to the discovery of the banalsite-stronalsite series minerals in the Brunlanes basalts.

XRD analyses on amygdules from basalts at Saltstein and Oddane on Brunlanes have shown that albite and analcime are the most common and ever-present minerals. In addition, minerals of the banalsite-stronalsite series, thomsonite, natrolite, sodalite, cancrinite and nepheline have been identified, but the amount of the accessory minerals in the different amygdules may vary from being prominent to zero. A few very tiny grains (only a few µm) of

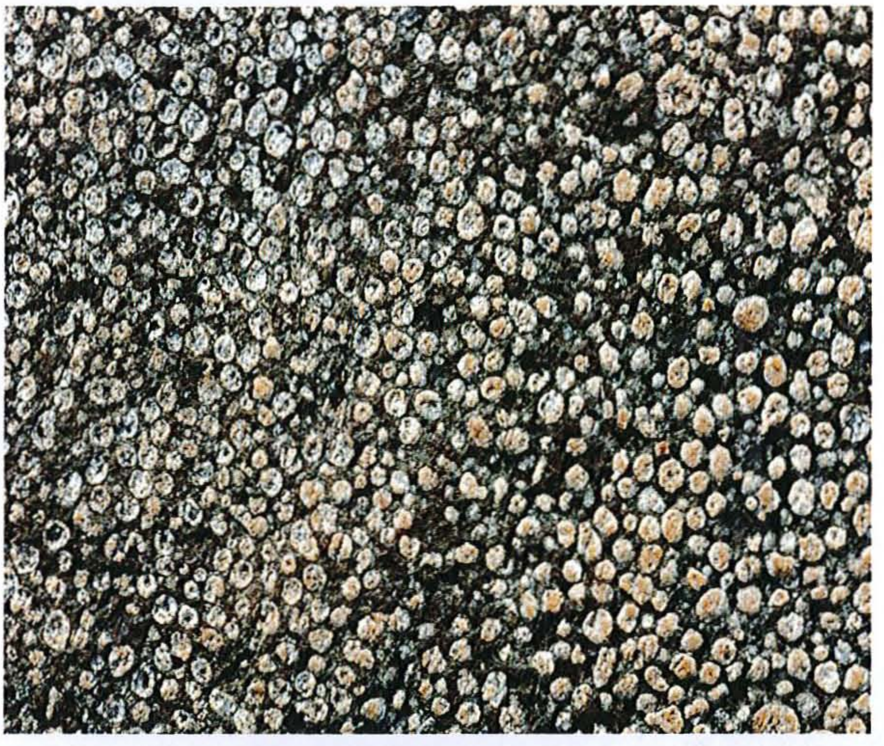

***Fig. 3.*** *Spongy pahoehoe lava, Saltstein. The amygdules constitute more than 50 % of the volume, and each of the amygdules are about 2-3 mm in diameter. Photo: S. Dahlgren.*

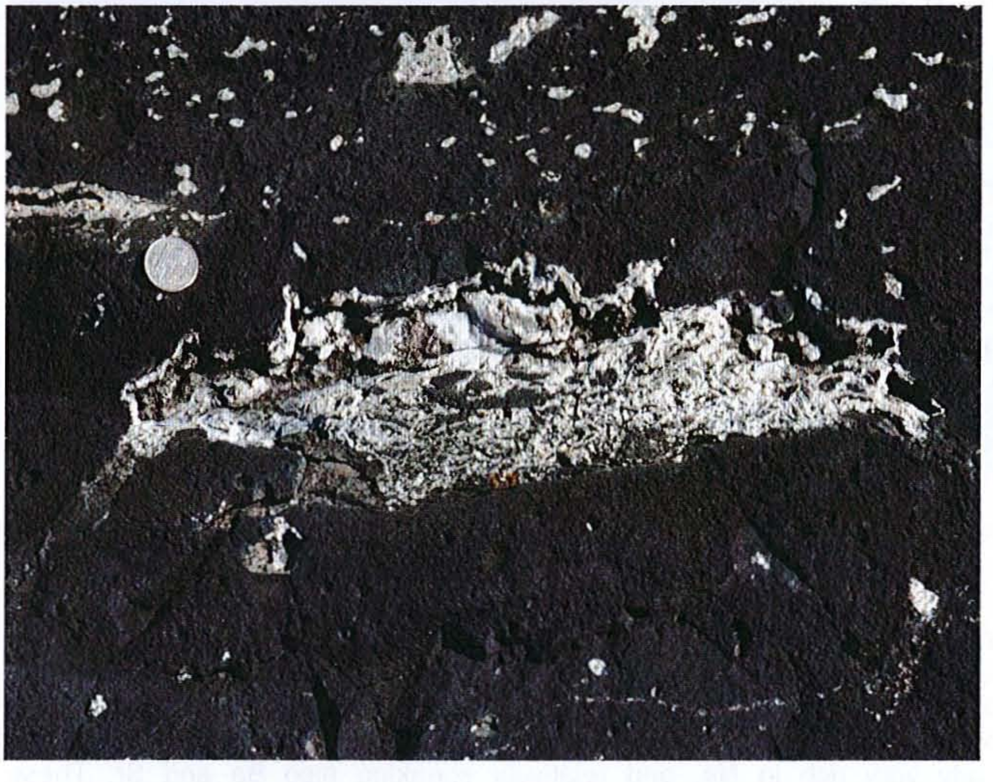

***Fig. 4.*** *Close–up of large mineralized gas cavity in a pahoehoe lava from Saltstein. 10 kr coin for scale. Photo: S. Dahlgren.*

is contact to the syenite intrusion the amygdules may contain grossularite, albite and epidote, and this assemblage evidently a contact metamorphic one formed from already existing mineralized vesicles.

### Minerals of the banalsite-stronalsite series

Several amygdules from the basalts at Saltstein near Mølen were analyzed on their bulk chemical composition using semiquantitative XRF analyses. The total amount of Ba and Sr were calculated into percent banalsite-stronalsite, assuming negligible substitution of Ba and Sr in the other minerals present. Although barite has been observed in SEM our impression is that this is a very minor phase, but it may in some instances bias our calculations. The result shows that the amount of banalsite-stronalsite may be up to 15 % of the total mineral content of the amygdules. Most amygdules, however, have a rather low content of banalsite-stronalsite, probably down to zero. The minerals of the banalsite-stronalsite series occur as irregular grains up to 100 µm across, often concentrated in certain parts of the amygdules. Semiquantitative chemical analysis (SEM/EDS) show that the composition, in mol-% banalsite (Bns) and stronalsite (Sns), varies from approximately 55%Bns/45%Sns (i.e. banalsite) to 40%Bns/60%Sns (i. e. stronalsite). Our study indicates that stronalsite seems to be more common than banalsite.

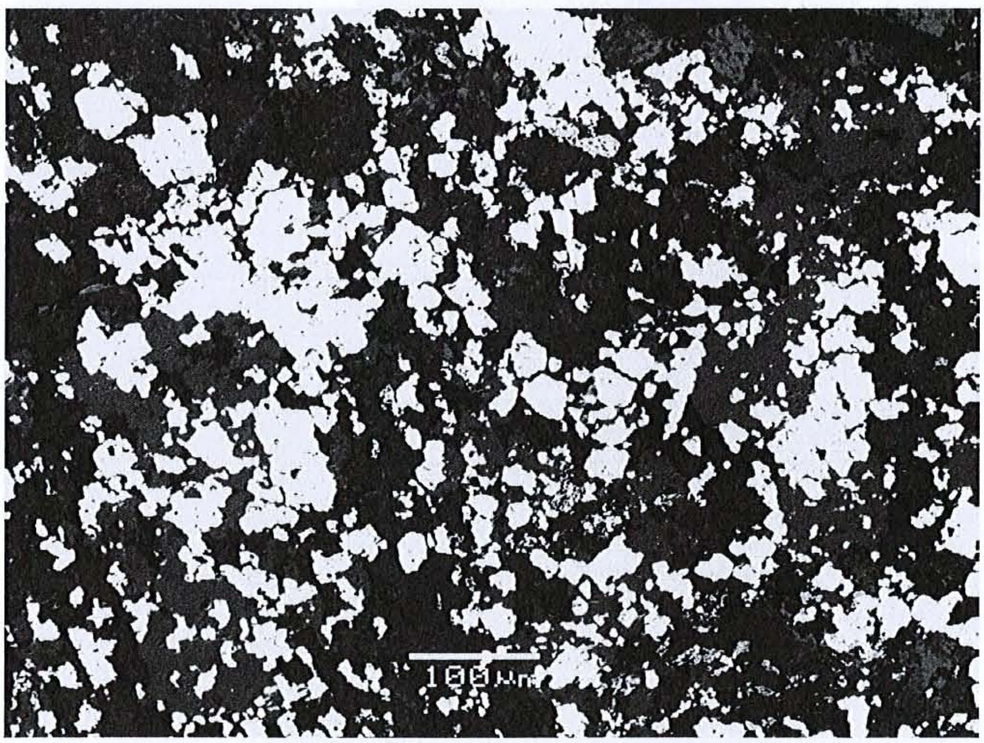


***Fig. 5.*** *Back-scatter SEM image showing minerals of the banalsite-stronalsite series (white) in analcime and sodalite (dark grey, black). Photo: A.O. Larsen.*

### Origin of the amygdule minerals

The minerals in the amygdules, as well as within the aa-flow tops and cracks are similar and thus require a common mode of formation. The mineral association albite + analcime ± nepheline ± natrolite ± sodalite ± cancrinite ± calcite ± banalsite ± stronalsite ± barite ± thomsonite is clearly very rich in Na, and relatively speaking also Ba and Sr. These components must also have been present in the fluids that precipitated the amygdule minerals.

The great original volume of vesicles makes pahoehoe lavas very porous and permeable rocks. Aa-lavas may be more dense, but their upper and lower flow-breccia zones obviously also are very porous and permeable. The Brunlanes volcanics series most likely was prone to post eruption infiltration of $H_2O$-$CO_2$ fluids. These fluids may have originated as meteoric water which percolated the volcanic pile, leached the glassy lavas and became especially enriched in Na, Sr and Ba. Subsequently these solutions precipitated albite, nepheline, calcite, analcime, stronalsite and banalsite, as well as a few other minerals, within the vesicles, to form the amygdules, as well as on cracks and in flow-top breccias. Later these amygdules were subjected to contact metamorphism near the ascending syenite intrusion and grossularite, epidote, albite assemblages formed.

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