ON ANTHOPHYLLITE AND SOME REACTION ZONES IN ANORTHOSITE

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Abstract. Anthophyllite-hornblende-almandite form reaction zones in anorthosite at Grønengja, Sunnfjord, West Norway. Anthophyllite may have formed from orthopyroxene by constant-volume reaction, and the reaction zones appear to be the almandite amphibolite facies equivalent of the orthopyroxene-clinopyroxene-garnet reaction zones from the Bergen Arc anorthosites.

Introduction

Anorthosites in northern part of Sunnfjord, West Norway, are schistose with some relics of massive andesine- or labradorite-rock. The schistose facies has a chemical composition which corresponds to normal labradorite anorthosite (N.-H. KOLDERUP, 1928, p. 54), but a high content of clinozoisite or zoisite, white mica and acid plagioclase make the term *meta-anorthosite* appropriate. During reconnaissance geologic mapping I often have noted inclusions of amphibole in these meta-anorthosites. The amphibole usually is hornblende or actinolite, and in one single case anthophyllite and hornblende. The anthophyllite appears to be surrounded by a reaction zone. The present paper gives the paragenesis of anthophyllite and a discussion on the formation of some reaction zones in anorthosites.

The locality for the described anthophyllite is south of Storneset on the island Grønengja about 5 km E of Florø. Anorthosites and related rocks make up most part of the island. A narrow zone of garnetiferous mica schist or feldspathic quartzite separates this anorthosite from a complex of basal gneiss.

Reaction zones at Grønengja

The anorthosite at Grønengja is of the massive type. In the field a slight saussuritization might be revealed by a characteristic milky white colour. Locally, abundant dark inclusions occur (fig. 1). The inclusions are lens-formed with the two longest dimensions parallel to a weak foliation in the anorthosite. The core of the inclusions consists of an aggregate of light sepia-brown anthophyllite columns. The average length of the columns is about 2 mm with some columns as much as 1 cm long. Hornblende and garnet occur in a zone between anthophyllite and plagioclase or as layers in the anorthosite. Garnet forms small granules about 1—2 mm in diameter and appears to be concentrated on the border between hornblende and plagioclase. The texture and mineral composition was studied in three thin sections.

Anthophyllite aggregates

The columns of *anthophyllite* are colourless and randomly oriented. Indexes of refraction on cleavage flakes are $n_1 = 1{,}652\ (\pm\ 0{,}003)$ and $n_2 = 1{,}637\ (\pm\ 0{,}003)$. The axial angle was measured on U- stage: $2V_z = 70°\ (\pm\ 2°)$. These properties correspond to anthophyllite $Mg_{70}Fe_{30}$ (Parker, 1961, Tröger, 1959).

On the grain borders and along fracture zones talc, prochlorite and biotite are sometimes present. Quartz occurs as round inclusions or as aggregates of equant grains between the anthophyllite columns.

Hornblende in about 0,5 x 1 mm columns with local slight granulation on the borders. Maximum extinction $Z/C = 22°$. $2V_x = 74°\ (\pm\ 3°)$ (U-stage). On cleavage fragments the indexes of refraction are: $n_1 = 1{,}663\ (\pm\ 0{,}003)$, $n_2 = 1{,}654\ (\pm\ 0{,}003)$ which corresponds to a content of about 25 mol % Fe^{II}MnTi-component (Parker, 1961). Round inclusions of quartz occur near the contact against anthophyllite.

Almandite in equant or skeletal grains which often occur near the border between plagioclase and hornblende. $n = 1{,}790\ (\pm\ 0{,}005)$. Cell dimension: $a = 11{,}54$ (X-ray powder film). The most likely composition (Winchell, 1958) is $pyr_{38}alm_{62}$ with 32 % sp ($pyr_{26}alm_{42}sp_{32}$).

Inclusions of brown biotite. In one case marginal alteration into prochlorite.

Biotite occurs in aggregates, in the granulated marginal zone of some

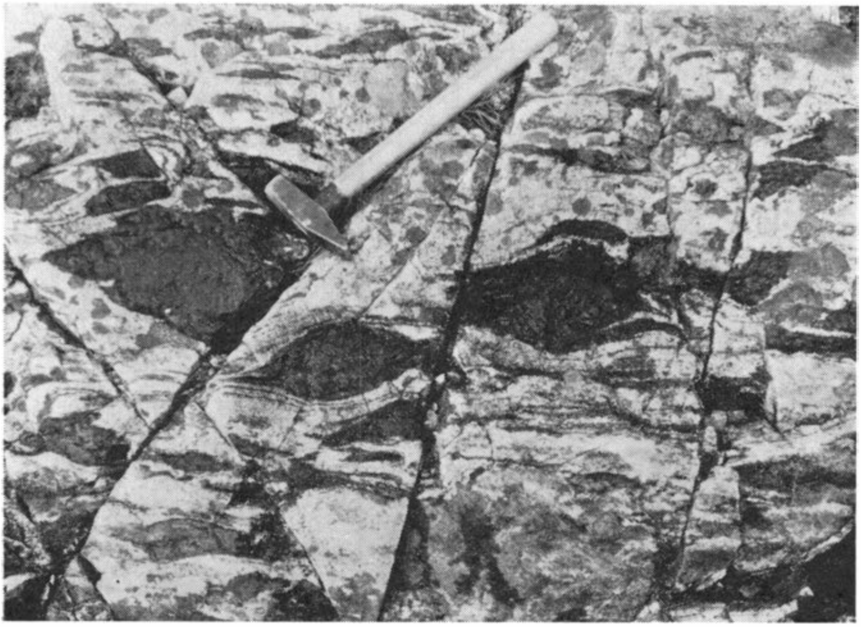

Fig. 1. Dark inclusions in anorthosite at Grønengja, Eikefjord.

hornblende columns or as single books in pure plagioclase-rock. Distinct pleochroism with X colourless and $Y = Z$ red-brown. $n_y = 1{,}623$ ($\pm$ 0,003). A powder mount had biotite with inclusions of rutile parallel $\{110\}$.

Prochlorite is present in small amounts. Pale green colour with slight pleochroism, high relief and low birefrigence. Elongation negative (Z subperpendicular basis) and parallel extinction.

Quartz form small round inclusions in anthophyllite or in hornblende near the anthophyllite aggregate. Quartz also occurs in aggregates of equant grains. Extinction is usually sharp without undulation.

Plagioclase grains in the anorthosite are about 2 x 2 mm and finely twinned. Bent lamellae are found locally and have unsharp, undulose extinction. Every grain is clouded due to abundant inclusions of tiny blades or prisms. On grain borders these inclusions are big enough to show the anomalous blue tint of clinozoisite. The saussuritization is not severe, however, for the plagioclase is still and andesine An 37 (maximum extinction $X'/010 = 20°$ determined on the U-stage).

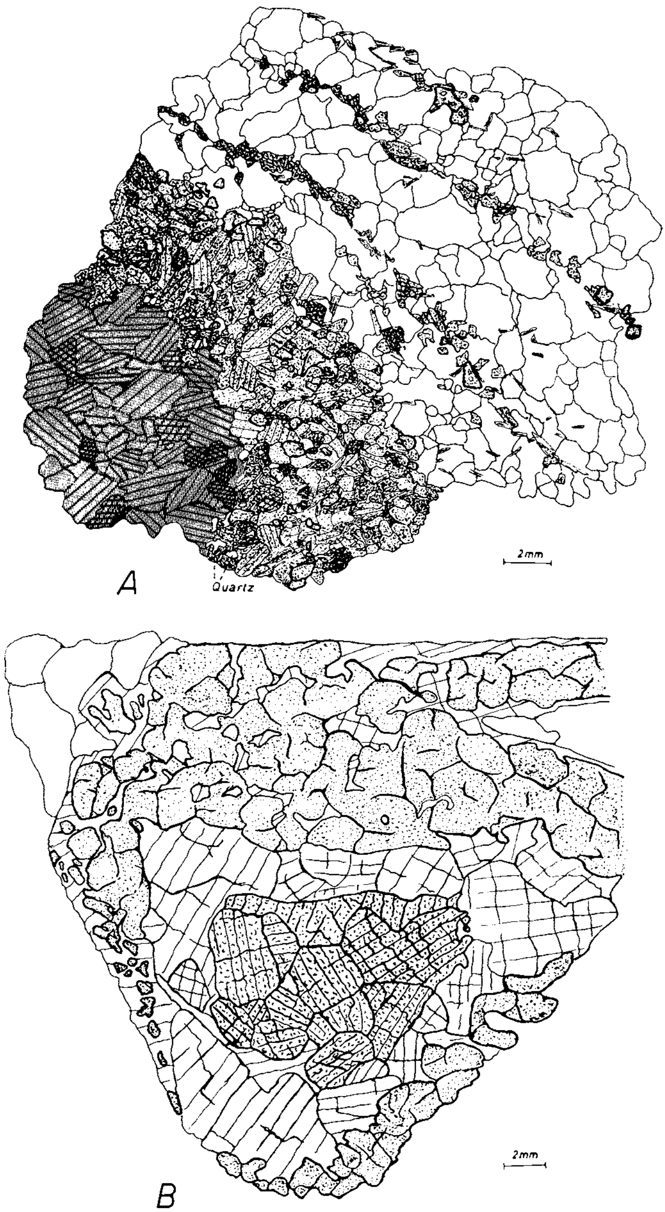

Fig. 2. Reaction zones in anorthosites. A. Anthophyllite-hornblende-almandite reaction zone with subordinate biotite and quartz from Grønengja, Sunnfjord. B. Bronzite-diallage-garnet corona from Flesland near Bergen.

The structure of the reaction zone is illustrated and compared with an orthopyroxene-clinopyroxene-garnet corona from the Bergen Arc anorthosites in fig. 2.

Stability of anthophyllite

Anthophyllite with less iron than Mg_{40} Fe_{60} is readily synthetized (BOYD, 1959 pp. 392). BOWEN and TUTTLE (1949) and YODER (1952) produced anthophyllite as transistent phase and concluded that anthophyllite might be unstable in the presence of water vapour. The experimental results might be explained in three ways which are illustrated in fig. 3:

1. The field of anthophyllite is too narrow to be detected by the experimental methods. Energy barrier against formation of anthophyllite is surpassed only outside this narrow field of stability.

2. Anthophyllite has a field of stability at higher water pressure than utilized during the experiments (FYFE, TURNER and VERHOOGEN, 1958, pp. 162).

3. Anthophyllite has a field of stability in systems with water deficiency (YODER, 1952, pp. 612) or in systems where load pressure is in excess of water pressure.

FYFE (1962) has recently given strong support to the first alternative. He produced magnesian anthophyllite as a persistent phase in the presence of water vapour. The upper stability limit at 2000 bars pressure is near 760° C ± 10°.

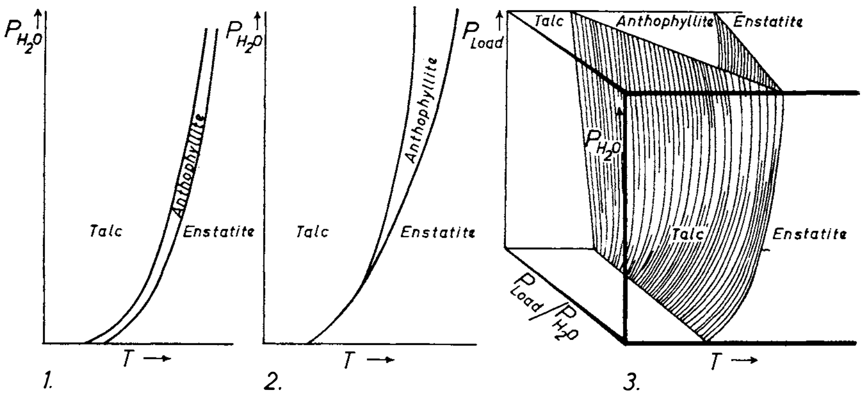

Fig. 3. Hypothetical stability relations for anthophyllite.

Origin of anthophyllite and zonar structures in anorthosite

Relic-minerals or pseudomorphs are not recorded in the anthophyllite aggregates at Grønengja. This anthophyllite therefore may be the product of primary, early crystallization. However, transformation may take place with complete destruction of the original mineral, and it is necessary to discuss any possible metamorphic formation of anthophyllite.

The zonar structures of dark inclusions in anorthosite at Grønengja should be compared with corresponding structures reported from the Sogn and Bergen Arc anorthosites. Eskola (1921), described inclusions of olivine-rock in anorthosite near Aurlandsfjord in Sogn. Aggregates of olivine were surrounded there by an anthophyllite zone. The anthophyllite was a colourless, fibrous variety with the fibres oriented perpendicular to the border against the olivine aggregate.

Olivine may be transformed into anthophyllite by addition of silica and water. Large-scale replacement of dunite by anthophyllite-rock has been noted by Anderson (1930), and in small-scale anthophyllite may form by deuteric or diaphtorethic reactions. The transformation may be illustrated by the equation

$$7\ Mg_2SiO_4 + 2\ H_2O + 9\ 2iO_2 = 2\ Mg_7Si_8O_{22}\,(OH)_2$$

If the system is closed for water and silica, the transformation will take place without significant volume change. But the reaction involves a considerable H_2O- and SiO_2-metasomatism, and the volume once occupied by olivine would then increase by almost 80 %. Olivine parentage for the anthophyllite at Grønengja cannot be discarded, but is improbable because the rocks have formed at depth and because olivine has never been recorded in the anorthostites of northern Sunnfjord.

The dark inclusions in anorthosites of the Bergen Arc consist of orthorhombic pyroxene, clinopyroxene and garnet. These inclusions have been described by C. F. Kolderup (1903), Eskola (1921), N.-H. and C. F. Kolderup (1940) and Rosenqvist (1952), and a typical structure is illustrated in fig. 2 B. The core consists of bronzite surrounded by diallage and an outer zone of garnet. Rosenquist discussed the origin of diallage and garnet. He maintained that garnet in many cases replaces bronzite and the anorthite content of plagioclase. Double coronas with an inner zone of diallage and an outer zone of garnet were thought to have originated by reactions in two steps.

I. Reaction between bronzite and plagioclase to form diallage.
II. Reaction between diallage and plagioclase to form garnet.

These two steps of reaction probably explain many of the diallage-garnet coronas. In some cases, however, garnet form the inner and diallage the outer zone. True coronas are less common than reaction zones with equigranular garnet and diallage evenly distributed. Such reaction zones have eclogite composition and cannot be distinguished from bands or lenses of eclogite in the anorthosites of the Bergen Arc. The layering of eclogite and anorthosite is so characteristic for these anorthosites that the mineral pair diallage-garnet must be interpreted as primary crystallization products. This interpretation is in accordance with the interpretation of C. F. Kolderup and Eskola, and, in my opinion, we have still no conclusive evidence against the hypothesis of primary crystallization of these minerals.

The coronas or reaction zones in the Bergen Arc anorthosites give evidence that the two minerals bronzite and plagioclase were incompatible during the formation of the rocks. If bronzite formed as an

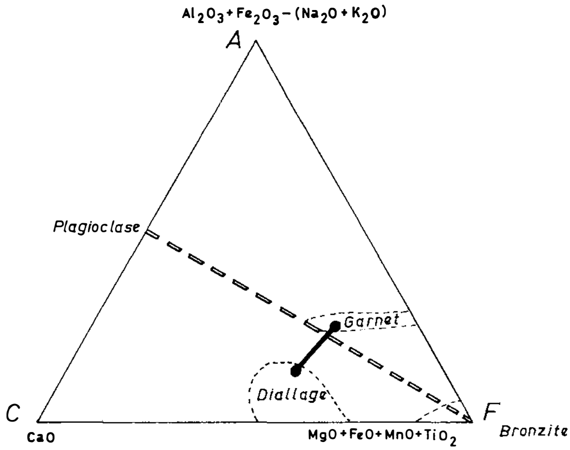

Fig. 4. Schematic ACF-diagram to illustrate instable association plagioclase-bronzite (broken line) and stable association diallage-garnet (full line). Analyzed diallage and garnet from the Bergen Arc anorthosites (C. F. KOLDERUP, 1903 and 1930).

early segregation product, it would react with plagioclase to form diallage and garnet.
The combined reaction

$$\text{bronzite} + \text{plagioclase} = \text{diallage} + \text{garnet}$$

is illustrated in the ACF diagram at fig. 4, in which the compositions of diallage and garnet from the Bergen Arc anorthosites are plotted (analyses given by C. F. KOLDERUP, 1903 and 1930). The products have about same content of ferromagnesia, and the reactions thus implies an uneven distribution of aluminia and lime between the two phases. The tie-line between diallage and garnet is parallel to tie-lines between coexisting clinopyroxenes and garnets given by M. J. O'HARA (1959). The reaction is more complicated, however. Ferrous iron and magnesia will be quite differently distributed in diallage and garnet. According to the analyses, the weight per cent ratio of FeO/MgO in garnet is three times that of diallage. As regards ferrious iron and alumina, the ratio Fe_2O_3/Al_2O_3 is more than three times higher in diallage than in garnet.

Thus the interaction between bronzite and plagioclase is complicated by the limited solubility between the different *F* and *A* components in the ACF diagram.

The reaction will be followed by a volume contraction and should be favoured by high load pressure. YODER and TILLLEY (1959) studied eclogite melts at 10 000 bars pressure. Under anhydrous conditions they obtained primary crystallization of clinopyroxene and plagioclase or only clinopyroxene. Under hydrous conditions clinopyroxene and amphibole were formed. They did not succeed in producing garnet as stable phase and concluded that clinopyroxene + garnet were not stable in the earth's crust at temperatures above 700°. At temperatures below 700°, clinopyroxene + garnet may be formed by solid-state transformation from basalt at 10 000 bars under anhydrous conditions. At some pressure in excess of 10 000 bars it is presumed that materials of basaltic composition crystallize as eclogite at all temperatures below the solidus under anhydrous conditions. Indeed, natural basalt was transformed to eclogite between 10 000 and 14 000 bars and 500° by Kennedy (YODER, 1961).

ROSENQVIST (1952) proposed that diallage and garnet in the Bergen Arc anorthosites were formed by metamorphism in the presence of insufficient water within the epidote-amphibolite facies. When Yoder added water to his eclogite melts at 10 000 bars, they crystallized to clinopyroxene and amphibole. Water evidently favoured formation of amphibole, but neither during the wet nor during the dry conditions of experiments was any garnet formed. Lack of water during metamorphism is very difficult to prove. The rival hypothesis that garnet and diallage were formed above the temperature of hydration of these minerals, is equally probable. If so, the diallage-garnet rocks of the Bergen Arc anorthosites represent a transition to true eclogite facies. This is in accordance with Eskolas original interpretation, and the author regards this most probable.

The Egersund anorthosites have plagioclase and orthopyroxene in stable association and represent true granulite facies. If such anorthosites were brought into conditions of eclogite facies, orthopyroxene would react with plagioclase to give clinopyroxene and garnet. If crystallization began in granulite facies and continued in eclogite facies, reaction zones around orthopyroxene would form at the same time as primary crystallization of clinopyroxene and garnet. The latter condition probably reflects the formation of the Bergen Arc anorthosites.

If anorthosites were brought from granulite facies into amphibolite facies, the association plagioclase-orthopyroxene would give way to anthophyllite-hornblende-almandite or plagioclase-hornblende-almandite. Anthophyllite might have formed according to the reaction:

$$7\,MgSiO_3 + SiO_2 + H_2O = Mg_7Si_8O_{22}(OH)_2$$

In this transformation silica must be supplied and is not probable because the presence of small inclusions of quartz in the anthophyllite or in the hornblende of the immediate contact to anthophyllite indicate that silica was liberated during the formation. Therefore, an equation which involves simultaneous liberation of magnesia would give a better representation:

$$9\,MgSiO_3 + 3\,H_2O = Mg_7Si_8O_{22}(OH)_2 + SiO_2 + 2\,Mg^{++} + 4\,(OH)^-$$

Great quantities of water should be available to remove the magnesia in solution.

The volume relations involved in this reaction brings out some interesting features:

$$9\,MgSiO_3 + 3\,H_2O = Mg_7Si_8O_{22}(OH)_2 + SiO_2 + 2\,Mg^{++} + 4\,(OH)^-$$

904 gm	(54 gm)	780 gm	(60 gm)	Removed in
283 cc	Introduced	Ca 274 cc	(23 cc)	solution.

If we consider the system as open for silica and magnesia, we can neglect their volume contributions, and the transformation is seen to take place at almost constant volume. Silica was probably not completely mobile during the reaction, — some of the silica probably migrated into the hornblende border-zone and part of it remained in the anthophyllite aggregate as quartz inclusions. Thus it is probable that the transformation of orthopyroxene into anthophyllite took place at exactly the same volume — in perfect agreement with Lindgren's volume law. Volume constancy during transformation is also indicated by the lacking or only sporadic occurrence of undulation banding or other strain effects in quarts.

Although the evidence is far from conclusive, the anthophyllite at Grønengja thus might be interpreted as formed from orthopyroxene. Orthopyroxene is present in the massive relics of anorthosites in northern part of Sunnfjord, but has most places been transformed into monoclinic amphibol. If the anthophyllite at Grønengja has not formed from orthopyroxene, it might have formed by primary, early crystallization in anorthosite.

Whatever mode of formation, anthophyllite will be in disequilibrium with plagioclase under the conditions of almandite-amphibolite facies, and the transformation

anthophyllite + plagioclase = hornblende + almandite

will take place. The reaction zones of hornblende and almandite thus are the lower facies equivalent of the diallage-garnet reaction zones in the Bergen Arc anorthosites.

Mineral facies of the anorthosites

A characteristic feature of anorthosites of the Bergen Arc and Sunnfjord is the rapid local alteration between rocks in different metamorphic facies.

The schistose meta-anorthosite in Florø—Eikefjord area often has the composition albite-clinozosite-prochlorite-white mica-quartz and is associated with a biotite-epidote-albite-almandite gneiss. This

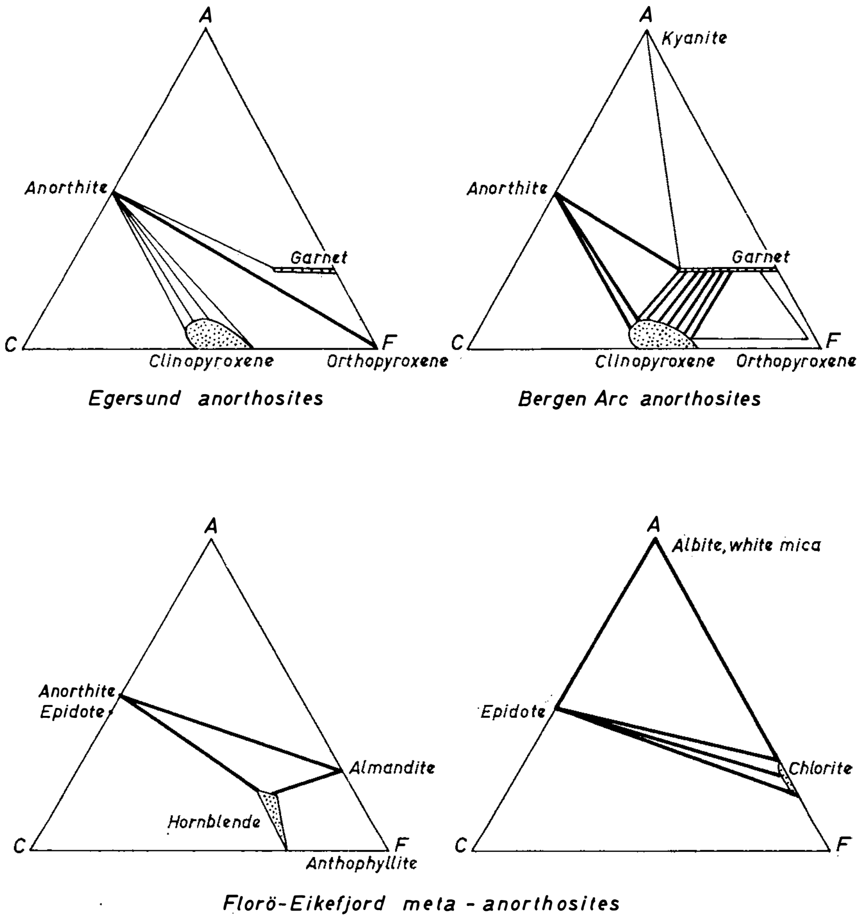

Fig. 5. Mineral associations in some anorthosites in Norway.

anorthosite therefore belongs to the highest part of greenschist facies. Mineral associations of this and other anorthosites in Norway are compared in fig. 5.

ROSENQVIST (1952 pp. 94) suggested that the metamorphism of the Bergen Arc anorthosites took place in the "saussurite facies" (= epidote-amphibolite facies of Eskola) and that lack of water favoured development of anhydrous minerals. However, we have no evidence that anhydrous minerals like clinopyroxene and garnet were formed contemporaneous with the hydrous minerals hornblende, chlorite, epidote or zoisite during metamorphism of anorthosite and related rocks. The anhydrous and hydrous minerals rather formed at different time and at different levels of the crust.

The schistose meta-anorthosites are in structural harmony with Cambro-Ordovician schists, and the hydrous minerals therefore formed during the Caledonian orogeny. The rapid alteration of rocks in different states of metamorphism probably reflects incomplete retrogressive metamorphism of an old anorthosite complex during the Caledonian orogeny. Adjustment to lower facies took place in zones of intense movement where crushing and easy access of water favoured granulation and mineral transformations. Zones of meta-anorthosite therefore might be interpreted as Caledonian shear-zones.

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