CONTRIBUTIONS TO THE MINERALOGY OF NORWAY

No. 32. Axinite in the Norwegian Caledonides

By

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Abstract. Axinite appears to be a rather common mineral in the Norwegian Caledonides, and it forms a major or minor constituent in veins enclosed in metavolcanics (mainly greenstones), greywackes?, metagabbros, and amphibolites of doubtful origin. Associated minerals include quartz, calcite, albite, epidote, actinolite, chlorite, tourmaline, prehnite, apophyllite, muscovite, biotite, pyrite, pyrrhotite, chalcopyrite, and zincblende. Some veins simply represent filled open fissures, whereas others are of nondilational nature and made room for themselves by replacement. Axinitization of country rock sometimes occurred concurrently with the vein formation. The Caledonian axinites are characterized by high Fe + Mg/Mn ratios. The formation of the veins is considered to be an important part of the general process of host rock alteration, the veins consisting of mobilized alteration products. Axinite is closely related to epidote in its mode of occurrence.

Introduction

A notable feature of low- to medium-grade Caledonian metamorphic rocks is the abundance of epigenetic veins, the major constituents of which are quartz and/or calcite. The quartz-calcite veins around the Trondheim fjord have recently been described by RAMBERG (1960). According to this author, the veins may also contain chlorite, albite, biotite, muscovite, tourmaline, epidote, actinolite, and a few ore minerals. During a study of epidote, I found that this mineral was associated with axinite in veins at several localities around Trondheim (Fig. 1). A short visit to Western Norway disclosed that axinite also occurs with epidote in that part of the Caledonides. Axinite has only recently been reported from the Norwegian Caledonides (CHADWICK

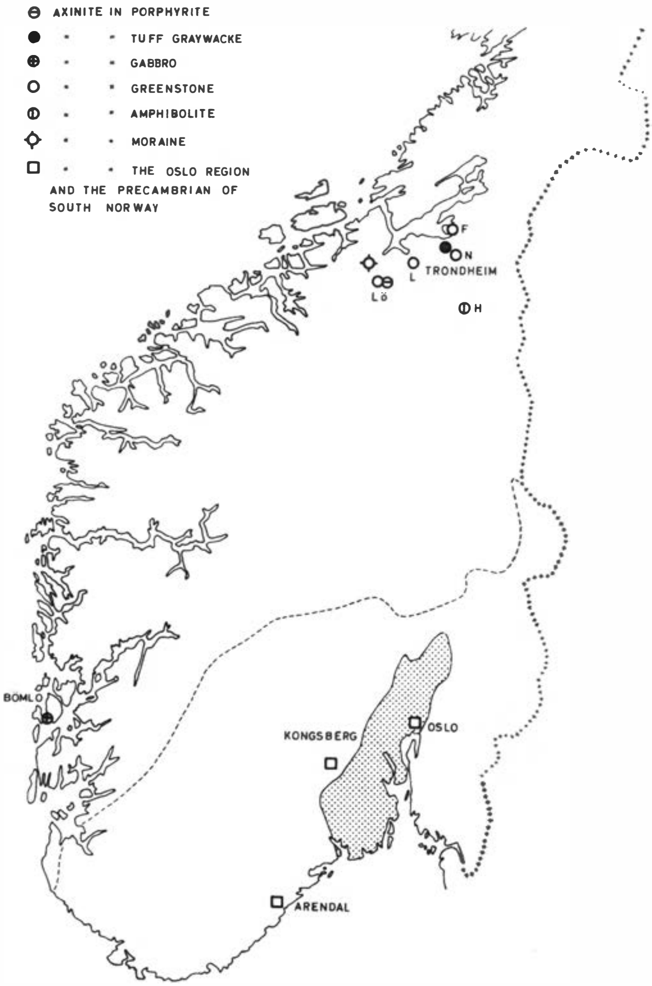


Fig. 1. Map showing known deposits of axinite in Norway. N = Nævermoen and Folla, Lö = Lökken, F = Forbordfjell, H = Haltdal, L = Ler. The south border of the Caledonian orogeny indicated by broken line.

et al. 1963), but the circumstances under which it was found (most of the localities were found in a few days by purposely looking for axinite along new lumber roads and in stone quarries) suggest that axinite is fairly widespread in greenstones and related country rocks.

The occurrence of axinite in Norway outside this mountain chain is limited. In Precambrian rocks at Kongsberg, axinite occurs associated with epidote, pyrite, fluorite, and coal blend in calcite veins (NEUMANN 1946). GOLDSCHMIDT (1911) found axinite near Oslo in contact metamorphic hornfelses, which had been soaked in a syenitic magma, and BUGGE (1943) reported the occurrence of axinite in the skarn iron ore deposits of the Arendal region.

Axinite in the Trondheim region

VOLCANICS AND ASSOCIATED GREYWACKES OF THE HOVIN GROUP

The veins described occur in an area about 20 km east of Trondheim. Above the dominantly volcanic Stören group consisting of greenstone lavas, commonly with pillow structures, and minor agglomerates (and hyaloclastites?), there follows, in inverted position, a series of tuffs, greywackes, and intercalated shales. This is the Lower Hovin group, which is generally separated from the Stören group by a conglomerate characterized by fragments of red jasper.

Rocks belonging to the greywacke suite seem to be common in the Lower Hovin group, but is difficult if not impossible to distinguish such rocks in the field from rocks of tuffaceous origin. What appear to be rhyolites or quartz-keratophyres showing strong resemblance to the Hareklett and Esphaug tuffs (VOGT 1945) undoubtedly occur, especially in the upper sequence. Fine-grained quartz-feldspar fragments are frequently noted, but are altogether absent at the axinite localities. The constituents of the rock at the Nævermoen locality (Fig. 1) are albite, actinolite, epidote, chlorite, quartz, and sphene (leucoxene). Actinolite is locally very common and gives a dark greenish colour to the rock. Dark minerals, particularly actinolite, are much less abundant in the host rock near the Folla farm, a feature which is also reflected in the composition of the enclosed veins.

The axinite-bearing quartz veins at Nævermoen are well exposed in road cuts for approximately 60 m. Axinite occurs in a number of separated parallel veins with well-defined selvages. The veins are usually short and lenticular, gash-like, their length being less than 50 cm. More persistent, often irregular, and anastamosing veins may be a few metres in length and swell considerably at places. Fragments of country rock are common, but never constitute a large proportion

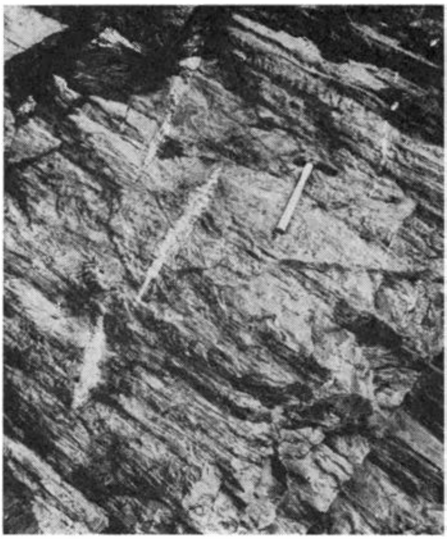


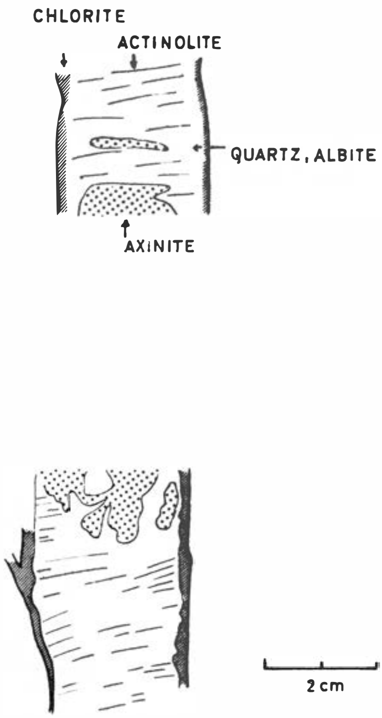
Fig. 2. Axinite-bearing veins, Nævermoen. Note prominent lineation and crossjoints.

Fig. 3. Patchy distribution of axinite in a lens at Nævermoen. The diameter of the coin is 2.7 cm.

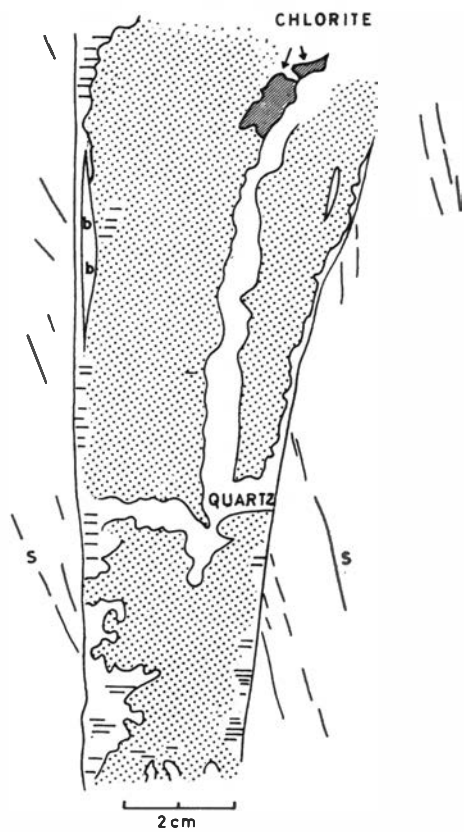
of the vein. They are without exception strongly bleached and may, therefore, easily go unnoticed. The veins usually terminate in a gradual pinching out, but their ends may branch.

The veins or lenses and associated cross-joints are related in a simple manner to the lineation of the rock, being nearly normal to it (Figs. 2–3). The lineation, due mainly to sub-parallel orientation of form-anisotropic minerals, is accompanied by a stretching as shown by the elongation of pebbles in nearby conglomerates or pyroclastic rocks. One set of shear fractures may be developed, but most of them remained closed during the deformation. KVALE (1948) noted that there are commonly slight deviations from the right angle between cross-joints and the linear structure in Western Norway (in the present case it may amount to 20 degrees), and suggested that the joints were formed by a stress differently oriented from that which produced the lineation.

Quartz, epidote, axinite, and albite are the major minerals in these veins. Small amounts of chlorite (ripidolite) are usually present, and white, asbestiform actinolite is common and occasionally very abun-



← Fig. 4. Zonal distribution of vein minerals, Nævermoen. Chlorite is confined to the margin against which the country rock is slightly bleached. The bleached zone is quite narrow, 3–5 mm in width. Actinolite fibres may extend across the vein.



→ Fig. 5. Vein rich in axinite (stippled), Nævermoen. Inclusions of country rock (b) strongly bleached. S = shear fractures.

dant. Calcite, which may abound in epidote-bearing veins at other localities, is rather rare. Pyrite and chalcopyrite occur sporadically.

A zonal distribution of the minerals can usually be recognized (Fig. 4). Axinite and a grey variety of epidote are commonly centrally disposed, but axinite sometimes fills almost the entire vein (Fig. 5). The border zone may consist of greenish yellow epidote, chlorite, and albite. Quartz occurs in different generations; calcite is invariably late.

The mineralogy clearly depends upon the width of the veins. Thus axinite and grey epidote are rarely found in narrow veins or in the tapering ends.

The vein-pattern at the Folla occurrence is similar to the previous one, but the mineral composition is much simpler. The fissures are filled almost entirely with quartz and axinite. Calcite may be present, but albite, chlorite, asbestiform actinolite, and epidote are scarce.

The axinite is violet, but less intensely coloured than the Nævermoen axinite. Occasionally the colour is bluish or yellowish brown.

Axinite is not confined to the veins at this locality, and patches of whitish axinite occur in the country rocks in the vicinity of the veins. Under the microscope it is seen that the axinite possesses a poikilitic structure and encloses corroded plagioclase laths. The axinite is closely associated with epidote of low interference colours, and it would appear that axinite and epidote jointly replaced the plagioclase.

A well-marked zone of bleaching shows up around the veins on polished specimens. This zone may extend 4–5 cm into the walls, and although the microscope does not disclose any difference between bleached and unaltered rock, spectrographic analyses show that Fe, Mn, and Mg have been leached out of the bleached zone.

CHADWICK *et al.* (1963) first recorded the occurrence of axinite in the Norwegian Caledonides. They reported axinite and clinozoisite in veins cutting Hölonda porphyrite, which they believed to be a sub-volcanic phase of Lower Hovin age. The porphyrites consist of pheno-crysts of saussuritized plagioclase and pyroxene, partly altered to hornblende and chlorite, set in a groundmass of albite, epidote, chlorite, and leucoxene.

GREENSTONES OF THE STÖREN GROUP

The majority of axinite veins are found in greenstones, which may be of various types. A massive, fine-grained variety without pillow structures is commonly veined with epidote, chlorite, etc., and axinite is an important constituent in some of these veins. Less frequently, axinite veins penetrate variolitic pillow lavas, and at one locality the host rock is a coarse-grained gabbro, containing abundant, irregular-shaped inclusions of a fine-grained greenstone, itself cut by axinite veins.

The fine-grained greenstone consists of actinolite, albite, epidote, quartz, chlorite, biotite, and calcite in varying amounts. Leucoxene may be quite abundant, and pyrite is an invariable accessory. The gabbros have a similar composition; the pillow lavas are enriched in albite.

Epidote veins occur commonly in profusion in the greenstones. The vein systems are usually irregular, but exceptions exist. The veins are narrow, often less than 1 mm wide. Swarms of sub-parallel epidote stringers are common. The axinite veins are always associated with epidote veins, and some occurrences are described below.

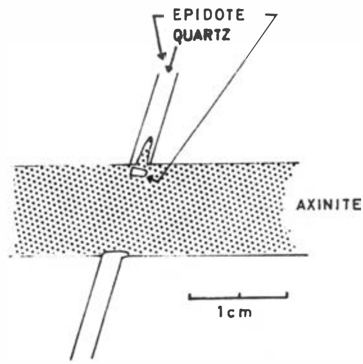


Fig. 6. Oblique intersection of axinite and epidote veins, the latter not being offset by emplacement of the former vein. Relics of epidote occur along the former epidote vein. The epidote vein is axinitized near the intersection. Forbordfjell.

On top of Forbordfjell mountain (Fig. 1), a number of axinite veins, displaying no recognizable vein pattern, occur. The veins are usually 1–10 mm wide, and almost monomineralic, but a thin central seam of calcite is not uncommon. Rarely, 2–8 mm long brownish epidote crystals occur. The axinite veins are always younger than the epidote veins, and vein intersections indicate a nondilational mode of emplacement. If offsetting of the epidote veins occurs, it is often in the wrong direction or not as would be expected from simple dilation of the walls. Ghostly relics of epidote may also occur along the former

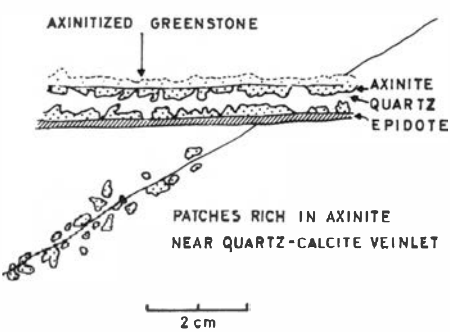


Fig. 7. Replacement origin of axinite veins indicated by oblique intersection with no displacement, gradational border on one side of the vein, and by axinitization of country rock plagioclase along narrow vein. Granmoen, Lökken.

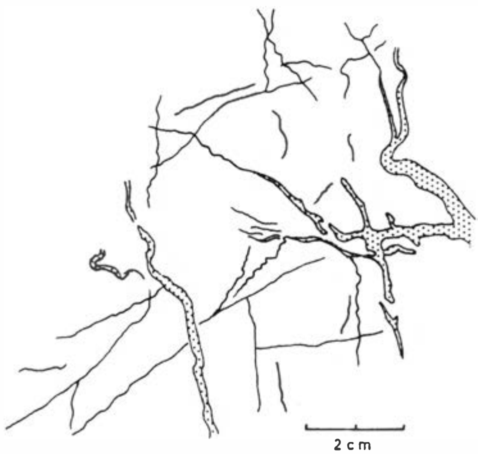


Fig. 8. Detail of branching network of axinite and epidote veinlets. The narrow, meandering stringers usually consist of epidote. Stippled: axinite. Granmoen, Lökken.

epidote vein (Fig. 6). Axinitization of epidote veins near the intersections is a common phenomenon. A ladder vein structure may be found in epidote and axinite veins. Single veins or sheeted zones of sub-parallel linked veins acted as competent layers and fractured. The fractures were then filled with quartz, calcite, epidote, and yellowish brown axinite.

The fortuitous arrangement of axinite veins is repeated at Granmo in the Lökken area. The veins are usually bimineralic: a border zone consists mainly of epidote while the central part is filled with axinite. Epidote also occurs commonly along the tapering ends. Calcite may be found in the central part of vein expansions; quartz and actinolite are subordinate. Intersections with epidote veins again show that axinite veins are younger and are indicative of replacement origin (Fig. 7).

The lack of any systematic vein pattern, and the usual meandering course of epidote and axinite veins (Fig. 8) suggest an absence of tectonic control. It is likely that the mineralization is related to cracks formed during the cooling of the lava flows. There is of course the possibility that deformation re-opened veins favourably located in relation to the stress and thereby facilitated axinitization.

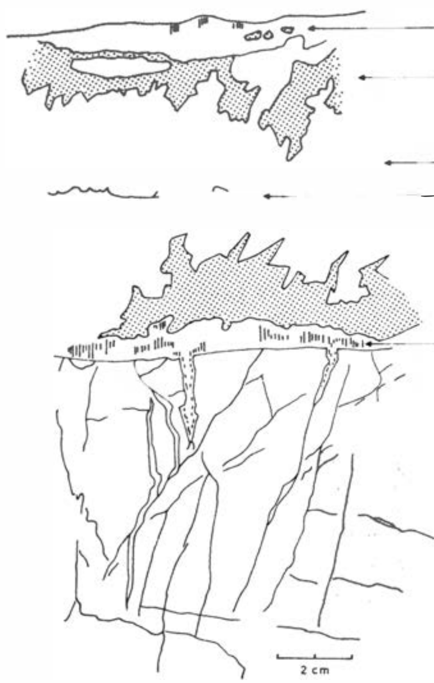


Fig. 9. Axinite- and tourmaline-bearing vein with distinct zoning. Bustad, Lökken. Apophyses and stringers in the country rock consist of quartz and epidote.

Tourmaline is associated with axinite in some veins (Bustad in the Lökken area, Ler, and Follsjö) (Fig. 9). These veins are rich in quartz, and also contain some muscovite in addition to epidote, chlorite, calcite, and pyrite. Their mode of occurrence is different from the above-mentioned veins in greenstone being gash-veins or dike-like tension veins.

AMPHIBOLITE OF THE RÖROS? GROUP

An unusual paragenesis of axinite, apophyllite, prehnite, asbestiform actinolite, calcite, ripidolite, pyrrhotite, chalcopyrite, and sphalerite occurs in a narrow vein 3 km east of the Haltdalen railway station. Epidote, albite, and quartz were not found. The vein was emplaced along a slightly curved, steeply dipping fault which cuts across the linear structure of the amphibolitic host rock at a high angle. The displacement was probably insignificant.

The amphibolite contains green hornblende, biotite, epidote-clinozoisite, and plagioclase as major minerals. Accessories are chlorite (after biotite), calcite, and sphene. A small scale banding is due to variations in the amount of dark and light constituents. The amphibolite has been depleted in hornblende, biotite, and epidote at its contact with the vein and altered to a light, almost monomineralic albite rock.

Associated pelitic schists are characterized by the assemblage kyanite, staurolite, biotite, and quartz. It is interesting to note that these schists commonly contain kyanite-bearing quartz lenses. The metamorphic grade evidently corresponds to the almandine-amphibolite facies of TURNER and VERHOOGEN (1960). The axinite-bearing amphibolite probably belongs to the Röros group, as Lower Ordovician graptolites occur in a shale which, according to VOGT (1940), appears in a stratigraphic horizon lower than the staurolite kyanite schist.

It may be mentioned that sphene was found in albite-epidote-chlorite veins on cross joints not far from the axinite locality. Although sphene is a common mineral in the rocks described, it is rarely found as a vein mineral.

Axinite in western Norway

The southern part of Bömlo island consists almost entirely of greenstones and gabbros (REUSCH 1888). An irregular network of quartz-albite veins traverses the gabbro at the Siggjavåg ferry landing. Chlorite is usually present, occasionally also tourmaline. Epidote and axinite may be locally abundant, but are usually rather scarce. The formation of epidote and axinite is connected with late epidote veinlets which permeate the gabbro in all directions and cut through the quartz-albite veins. It is evident that a main vein-building process was followed by a sequence of epidotization and axinitization, mainly at the cost of plagioclase.

The gabbro consists of augite, green hornblende (uralite), brown kaersutite, heavily saussuritized plagioclase and minor quartz, sphene, calcite, and apatite.

The gabbro is also cut by diabases and lamprophyres, but there is obviously no relation between the formation of the veins and the dikes, the latter being in all likelihood post-Caledonian.

Professor Bugge has kindly informed me that specimens of axinite from Western Norway were submitted to the Technical University of Norway at Trondheim several years ago for identification. Unfortunately, however, the specimens are lost.

Mineralogy

The following minerals are typically associated with axinite in the Caledonides and in regional metamorphic areas elsewhere: quartz, calcite, albite, clinozoisite-epidote, asbestiform actinolite, tourmaline, and prehnite. The paragenesis axinite apophyllite is unique and does not seem to have been recorded earlier.

Tourmaline is always a minor constituent when co-existing with axinite. It is, however, the sole boron-bearing mineral in a number of quartz veins and appears to be more common than axinite. Usually it occurs as fine-grained, greenish black aggregates and is easily mistaken for chlorite. Radiating groups of tourmaline needles have also been found, and more rarely tourmaline fills almost the entire vein, the needles being oriented perpendicular to the walls. The index of refraction, $\omega = 1.648–1.655$, indicates a considerable amount of the dravite component.

A number of the vein minerals contain minute inclusions of chlorite or actinolite which give them a green colour. Thus, albite may display a beautiful leek-green colour due to worm-shaped chlorite inclusions. Quartz is commonly green because of actinolite fibers (prase), and green calcite varieties have also been found. The apophyllite is dull green and crowded with tiny actinolite needles.

For a detailed description of vein minerals, the reader is referred to the paper by RAMBERG (1960). Only epidote and axinite have been studied by the present writer.

AXINITE

Variations in the chemical composition of axinite are generally confined to the relative abundance of Mn, Mg, and Fe. The Caledonian axinites are characterized by low to extremely low contents of Mn

Table 1. *Axinite analyses*

Locality	Colour	MnO	MgO	FeO	$N\gamma$[2]	$N\alpha$	D	
1a. Folla	brownish yellow	0.34	3.03	6.75		1.669		l[3]
1b. ”	bluish	0.43	2.43	7.62		1.672	3.196	h[4]
2a. Granmo	violet	0.63			1.681	1.671	3.156	l
2b. ”	”	0.75			1.681	1.671	3.205	h
3. Forbordfjell	brownish yellow	0.75				1.673		
4. Nævermoen[1]	violet	1.02	2.68	6.54	1.684	1.670	3.206	
5. Bömlo	violet	1.08						
6. Bustad	violet	1.25			1.684	1.670		
7a. Jösås, Follsjö	violet	1.30			1.687	1.675		l
7b. ” ”	violet	1.50			1.688	1.675		h
8a. Ler	violet	2.13	3.03	5.23	1.679	1.668		l
8b ”	violet	2.84	<3.0	5.97	1.683	1.670		h
9. Haltdalen	violet	3.10	1.55	6.79	1.685	1.673		

[1] $SiO_2 = 40.93$, $TiO_2 = 0.06$, $Al_2O_3 = 19.64$, $Fe_2O_3 = 0.12$, $CaO = 19.65$, (—) $2V = 70°$.

[2] Doubtful determinations are omitted.

[3] Light fraction.

[4] Heavy fraction.

Analysts: M. Ödegård and P. R. Graff.

(Table 1) and rather high Mg. The specific gravity of the axinite appeared to vary considerably even in the same vein, and the axinites from four localities were therefore separated into two fractions using methylene iodide diluted with acetone to specific gravity 3.18. The heavy fraction (h in Table 1) always proved to be the highest in Mn, the increase in specific gravity being caused by a corresponding increase in the Fe/Mg ratio. The specific gravity of the axinites is consistently low, and this must be attributed to the high content of magnesium. The refractive indices are always very low and subject to small variations only. It is evident, however, that the refractive indices, as would be expected, are dependent on the Fe + Mn/Mg ratio, and Table 1 demonstrates that the heavy axinite in each deposit has a greater refractive index.

The colour of the axinite is usually violet, but blue and yellowish varieties occur. The violet colour is believed to be due to the chromophoric effect of manganese, because it appears that the depth of the violet shade is roughly proportional to the amount of Mn. The blue and the yellowish brown axinites are poor in Mn. Manganic axinites, however, are yellowish (DEER *et al.* 1962).

Axinite may form crystals up to 10 mm at the largest, but it generally occurs in granular aggregates and seldom shows good, idiomorphic, wedge-shaped outline except when it projects into quartz or calcite, or into open cavities.

EPIDOTE

The epidote in the gash veins at Nævermoen was studied in some detail. A wide range in composition is suggested by the variation in colours. Beautiful, fan-shaped aggregates of long needles, which may occur in the central part of the lenses, are grey to nearly white. Marginally disposed epidote or epidote in narrow veins is usually oriented with its long dimension (= b-axis) normal to the walls and displays yellow to greenish yellow colours. Adopting the diagram of DEER, HOWIE, and ZUSSMANN (1962) for the relation between the index of refraction and the Al-Fe^{+++} substitution, it is found that the composition varies from approximately 10 to 30 mol % iron epidote ($Ca_2Fe_3Si_3O_{12}(OH)$). It is not uncommon that epidotes of different composition occur in the same vein, the more iron-rich always being found nearest to the walls. Oriented intergrowths, b-axis parallel, of light grey and light greenish yellow epidote, the composition of which are 10–12 and 22–24 mol % iron-epidote respectively, were noted in some lenses. A similar observation was made by STRENS (1962), who suggested, therefore, that a compositional gap exists in the solid solution series of the monoclinic epidotes. To test this hypothesis, the refractive indices of a great number of epidotes, from various veins in greenstones at other localities in the vicinity of Trondheim, were also measured. It was found that the greenish yellow epidotes vary continuously from about 23 to 30 mol % iron epidote, and the grey epidotes from 10 to 21–23 mol %. It appears that the epidotes fall in two groups, the low-iron epidotes usually characterized by grey colour, and the high-iron epidotes by greenish or yellowish colours of varying depths. We may safely conclude that epidotes formed during the conditions of greenschist facies form a continuous solid solution series up to 33 mol % iron epidote. The co-existence of epidotes of contrasting composition obviously represents a non-equilibrium assemblage.

The composition of the epidote (usually a high-iron one) in the non-dilational veins seems to be fairly constant in each locality, but may vary from one locality to another. The variation can usually be correlated with a corresponding variation in the host rock.

It is interesting that zoisite has not been identified in any vein, axinite-bearing or not. Zoisite is apparently not stable in the greenschist facies.

AXINITE-EPIDOTE RELATIONSHIPS

Axinite and grey epidote occur occasionally side by side at Nævermoen, but usually these veins contain either grey epidote or axinite, not both. Axinite-bearing veins may, however, have greenish yellow epidotes along their margins. Axinite and grey epidote are obviously later than the iron-rich epidotes. It is rather surprising that the epidotes, which co-exist with the axinite, only contain about 0.1% MnO, as the Mn^{+++}-ion may easily proxy for Fe^{+++} in this lattice. The Mn^{+++}-ion is a strong chromophore and even in small amounts confers a brownish red colour on epidotes in the range 10–25 mol % iron-epidote. It is probable that Mn was not accepted because the valency conditions were not satisfied.

In the non-dilational veins, axinite always appears to be younger than the epidote and probably often pseudomorphous after epidote.

Axinite and epidote are commonly closely associated in veins in regional metamorphic areas in this country and elsewhere. Such association is not surprising in view of the similar chemical composition of these minerals, already commented upon by von Hoerner (1910). Boron, however, while being an essential constituent in axinite, does not find entry in the epidote. The availability of boron, therefore, probably controlled the formation of axinite relative to epidote, rather than any difference in the physical conditions during their deposition.

Discussion

Apart from the fact that axinite and a few other vein minerals are absent from the rocks which enclose the veins, there is, in general, remarkably little mineralogical difference between veins and host rock. A host rock-vein similarity is demonstrated at numerous localities. Quartz, calcite, and chlorite are ubiquitous constituents, but the presence of epidote, actinolite, and albite are usually confined to the basic rocks, generally the greenstones. That the occurrence of axinite is also controlled by the composition of the surrounding rock is indicated by the fact that all known axinite-bearing vein deposits in regional metamorphic areas in this country and elsewhere are associated with rather basic igneous rocks or their derivatives: greenstones, gabbros, porphyrites, amphibolites, mafic keratophyres, greywackes, etc. The state of dependence is well illustrated at Nævermoen: as the host rock changes in composition to an epidote-rich variety with very little actinolite, greenish yellow iron-rich epidote displaces axinite and grey epidote in the veins. In an intercalated shaly layer, epidote also suddenly disappears from the veins, which then consist of calcite, chlorite, and quartz exclusively. The scarcity or absence of epidote, actinolite, and chlorite in the axinite-bearing veins at Folla is likewise matched by a depletion of ferromagnesian minerals in the host rock. The extreme low content of Mn in the axinite at this locality should also be noted.

The relationship between the rocks and their veins is strongly indicative of a host rock parentage of the constituents forming the vein. LOVERING (1963) proposed the term *lithogenic* for such mineral deposits that formed by mobilization of matter from the solid country rock. It has been suggested that Alpine veins formed in that way (CAMPBELL 1927). The veins under consideration are in many ways similar to the Alpine veins, but differ from them in the scarcity of vugs and drusy minerals. In our Caledonian veins, axinite occurs as a normal constituent of the veins equal to quartz, albite, etc., and is not related to the formation of late vugs. Additional evidence of a secretional origin is, as pointed out by RAMBERG (1960), the general isolation of the veins and the absence of connecting structures between mineralized lenses. Thus, at Nævermoen the more persistent cross-joints, along which material could have been transported from a more distant source or from donors in depth, are usually coated with a thin veneer consisting mainly of quartz. Veins, which build the intricate, connecting systems in the greenstones, have, of course, no such status of independence. Field work shows, however, that the axinite occurrences are of limited size, and on the whole isolated from each other.

In the lithogenic concept of vein formation, the distance of transport from source to site of deposition may vary within wide limits, and the mode of transportation is not implicit in the term. The bleaching of country rock around many dilational veins or their total lack of mafic minerals points to a strictly local source for a number of the constituents. Bleaching is associated with veins rich in mafic minerals like axinite, tourmaline, chlorite, and biotite. The zone of bleaching varies from a few mm up to 5–6 cm, depending somewhat on the thickness of the veins. Spectrographic analyses have shown that the bleaching is equivalent to a loss in Mg, Fe, and Mn, and a gain in Si and Na. Sampling of country rock beyond the bleached zone did not reveal any systematic variation in the amount of the major elements, nor was any consistent variation in the boron content observed in the vicinity of the veins. Country rock inclusions are invariably bleached. It must be pointed out, however, that in no case are the thin, irregular epidote and axinite veins, described from Forbordfjell and Granmo, associated with bleaching. Here, however, the fissures not only acted as a site of deposition, but also formed channelways for the diffusing ions or the solutions. It is evident that there is no one solution to the source problem applicable to all localities.

RAMBERG (1960) discussed the origin of the quartz calcite veins in terms of metamorphic differentiation. In his model, the driving force of diffusion is regarded as heterogeneous pressure due to fracturing. The importance of this principle in vein genesis has been emphasized by BOYLE (1961, 1963) and REITAN (1958, 1960). Due to varying mobility and availability of the diffusing constituents, contrasted chemical and mineralogical differences between vein and host rock may be produced. Thus, axinite and tourmaline may owe their existence in the veins to the ability of the processes involved to accumulate even insignificant amounts of boron. BOYLE (1960) pointed out that the composition of the vein is also determined by the timing of the mobilization and the fracturing. The occurrence of epidote and axinite in the late dilational veins compared with the barren composition of early deformed veins may be a direct consequence of this. The mobility of the constituents of these minerals under the conditions of greenschist facies is demonstrated by the numerous concretions and secretions of epidote in greenschists. The compositional relationship between vein and host rock suggested by RAMBERG (1960) and expressed in the following equation

$$\underbrace{\text{epidote} + \text{actinolite}}_{\text{rock}} = \underbrace{\text{chlorite} + \text{calcite} + \text{quartz}}_{\text{vein}}$$

therefore, does not conform with the present observations. Co-existent epidote and actinolite were also noted in a number of veins.

Veinlets consisting of quartz, albite, and epidote being universally present in low-grade basic metavolcanics, it seems, however, reasonable to assume a relation to host rock alteration. The metamorphism of spilites, which is similar throughout the world, involves decalcification of plagioclase, uralitization of pyroxene, consequent epidotization and carbonatization, and the formation of leucoxene at the expense of titaniferous iron ores. The rock as a whole suffers a loss in CaO and SiO_2, and calcite (if sufficient CO_2 is present) and quartz together with the minerals now being stabilized—albite, epidote, actinolite—preferably precipitate in the fractures open during this stage of the metamorphism. Veins thus result which with few exceptions are mineralogically identical with the host rock. Among the elements involved in the formation of axinite, boron and manganese occur in traces dispersed throughout the host rock and do not form minerals of their own. They were therefore not so readily available as Ca, Mg, Fe, and Si, the source of which may be found in the immediate vicinity of the veins. Thus, boron may have been a more distant traveller, but once set free, it possesses high mobility due to the inability of the common rock-forming minerals to take up boron in their lattices (RAMBERG 1952). The exact source of boron is difficult to trace. Tourmaline may be an occasional constituent in keratophyres, but being stable over a wide range of temperatures in widely different mineral assemblages, it probably did not release boron during metamorphism. This is supported by the fact that quartz veins in tourmaline-bearing micaschists of the Röros group very seldom contain tourmaline. It is more likely that boron was mobilized by the decomposition of rock minerals containing traces of this element. SUKHORNKOV *et al.* (1965) have shown that the content of boron may vary greatly within short distances in volcanic regions, and this may give an answer to why axinite is so unevenly distributed in the greenstone areas.

Various sources have contributed to the supply of the other elements concerned. Titaniferous iron ores were probably an important source of iron, which is released by the formation of leucoxene (DES-

BOROUGH 1963). An exhaustion of the iron source is indicated by the consistent decrease in the content of iron from early to late epidote in the veins. This may also explain the high content of Mg in the axinite. Ti is characterized by extreme low mobility under these conditions.

In summary, the events which led to the formation of the dilational axinite veins were broadly:

1. Formation of tension fractures in the rocks nearly at right angles to the stretching.

2. Opening of the fissure by continued deformation and simultaneous or subsequent deposition of mineral matter derived from the enclosing rock.

3. Post-emplacement deformation, which was usually feeble and caused slight undulatory extinction of quartz and more rarely axinite, strain mosaic in quartz, deformation of twin lamellae in calcite, offsetting of central twin lamellae in albite, bent epidote, and bent or broken tourmaline needles. Fault displacements are rare.

The formation of the non-dilational veins is similarly related to fractures, which may or may not be related to the deformation. The emplacement involved transportation of material along fractures and complex replacements of earlier minerals, primarily the formation of axinite after epidote.

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