Precambrian rocks of the Telemark area in south central Norway XI:

SUPRACRUSTAL ROCKS AND Mo-Cu BEARING VEINS IN DALEN

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Quartzites, metabasic and -acid volcanics around Dalen belong to the Bandak group, the upper part of the Precambrian supracrustal Telemark suite. These rocks were deformed into NE-trending, steeply plunging folds and were metamorphosed under P-T conditions of epidote amphibolite facies. The steep plunge of folds was caused by forceful intrusion of several granite bodies in the supracrustal rocks south of the present area. Quartz and calcite veins occur in abundance in the area confined to the mesoscopic structures in rocks. One major set of sulphide-bearing quartz veins occurs along joint planes developed perpendicular to the major fold axis. Sulphides were formed in these veins after silicates. Texturally, molybdenite, galena, bornite, chalcocite, covellite, chalcopyrite and pyrite seem to have formed in that order at various temperatures between 500 and 75°C. Molybdenite in these veins was found to be a mixture of hexagonal (2H) and rhombohedral (3R) polytypes. Besides the commonly occurring flaky variety, a fibrous variety of molybdenite is also found which seems to have formed by replacing isolated tourmaline needles in quartz. X-ray diffraction data on the two varieties are similar. Alteration of molybdenite occurs first as oxidation into molybdite and then by reaction of Ca bearing solution the latter changes to powellite.

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Introduction

Rocks of Precambrian Telemark suite comprise a volcanic-sedimentary sequence occupying a large part of southern Norway. They differ from the rocks of Bamble area to the southeast, in showing lower grade of regional metamorphism and deformation (Barth 1960). Telemark suite rocks are divided into Rjukan (oldest), Seljord and Bandak groups which differ primarily in containing varying amounts of sedimentary and volcanic material (Dons 1962). These rocks belong to a supracrustal sequence within the Precambrian belt (K/Ar age 950 ± 150 m.y. after Kulp & Neumann 1961) which extends from beneath the Caledonian belt in north to near the south coast of Norway. The supracrustal rocks assume considerable thickness in the northern part of the belt, whereas quartzofeldspathic gneisses forming basement (also granitized supracrustal rocks) occupy most of the southern part. The boundary be-

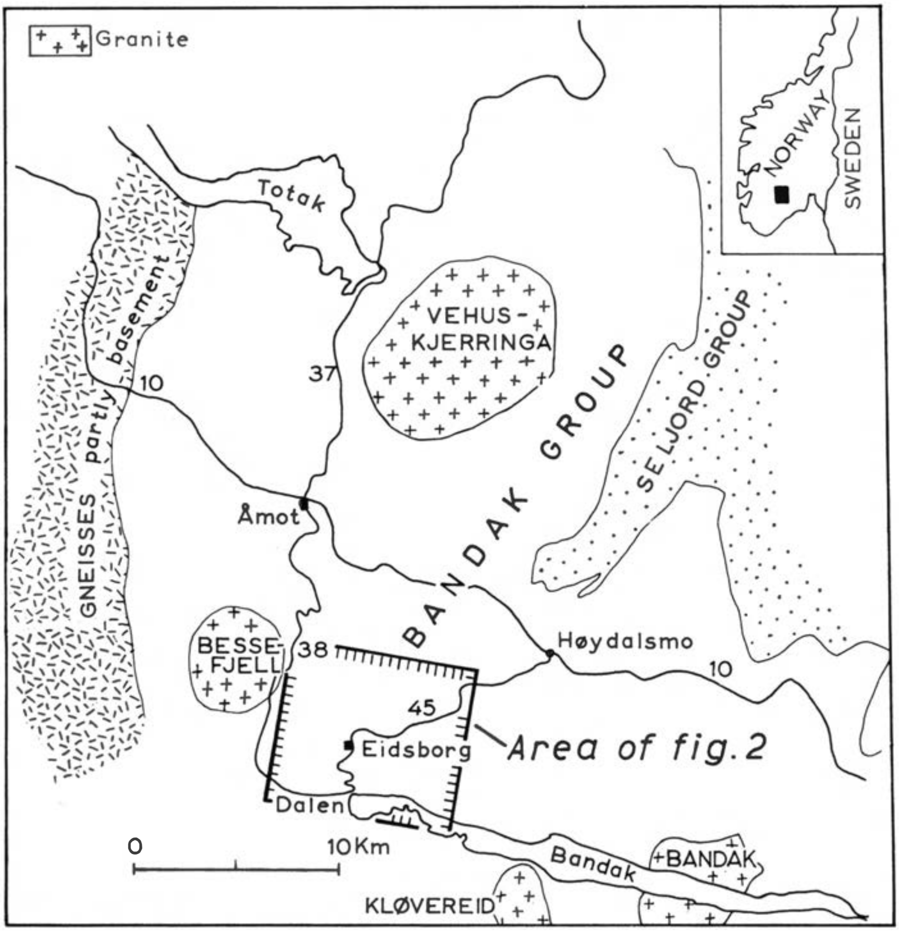


Fig. 1. Location of Dalen area. Details after Dons (1960) and E. Györy (unpublished).

tween supracrustal rocks and basement gneisses occurs a few kms south of the present area and is mesoscopically transitional involving changes in grade of metamorphism, tectonic style and mineral-chemical variations in the rocks.

The present area north of Dalen and Bandak Lake (Fig. 1) comprises rocks of Bandak group. General geologic and petrographic features of bed rocks (Fig. 2) and associated Mo-Cu bearing quartz veins occurring in the area are described here.

Geologic features

Quartzites and metabasic volcanics are main members of the Bandak group along with minor amounts of meta-acid volcanics. Intrusive rocks occupy various structural levels within the supracrustal sequence. These are mainly granitic in nature, are widely distributed and show distinct tectonic influence on the structural development of surrounding supracrustal rocks (Carter 1962, Sylvester 1964). No intrusive rocks occur in the present area.

Quartzites

Quartzites, the most common rocks found in the area (Fig. 2), are megascopically interbanded with metabasic volcanics and vary lithologically in having various admixtures of pelitic, basic and acid volcanic material. Laminations in quartzite vary considerably from fine to coarse being mostly fairly straight to undulatory and cross-bedded in places. In the southeastern and western part of the area the quartzite is semipelitic. This is termed Eidsborg quartz-schist and overlies the Morgedal sandstones in the northeast (Dons 1962). Flexural slip along bedding laminations in quartzites is seen to produce a prominent fissility augmented also by crystallization of mica on these planes. At places, often a set of fracture cleavage develops at an angle to the bedding laminations. In most cases, the fracture cleavages run across bedding laminations obliquely for a distance and then fall parallel to the lamination in micaceous layers. This con- and discordant relationship of cleavage when occurring closely spaced in pelitic quartzites produces an undulating pattern on the cleavage planes. Texturally, quartzites vary from streaky to massive and granoblastic to xenoblastic. Mica rich varieties exhibit a prominent schistosity. Quartzite occurring in the northwest is distinctly arkosic at many places. When admixed with material from basic volcanics it contains chlorite, epidote and plagioclase in various proportions. Minerals commonly found in the quartzites are quartz, muscovite, sericite, biotite, epidote, albite, K-feldspar, chlorite, calcite, sphene, apatite, pyrite, magnetite and hematite.

Some layers within the quartzites are distinctly conglomeratic and occur as 10–50 m thick beds. Pebbles in these beds are mainly disc-shaped composed of fine- to coarse-grained quartzite, gritty quartzite and vein quartz all set in a quartz rich matrix. The two larger dimensions of pebbles lie parallel to bedding lamination and also to the local cleavage set. Elongation of pebbles in the plane of bedding is commonly incipient, except in the southeastern corner where ca. 15 per cent of pebbles show elongation plunging 80° due N60° coinciding with the major fold axis. The conglomerate beds in the quartzites also contain a lenticular type of bedding described from elsewhere in quartzites of the Bandak group (Singh 1968). These lenticular beds can be very thin and flattened and at times show squeezing when caught up lying in between the pebbles. There is no evidence of tectonic deformation which may have produced flattened pebbles in the conglomerate as the surrounding more ductile semipelitic beds do not show an intensity of deformation comparable to the stress required to cause flattening of pebbles in the rather more competent conglomeratic beds. A mixture of lenticular bedding in quartzites developed under shallow-water depositional conditions and contemporaneous deposition of quartzite pebbles seem to be the probable conditions under which these conglomeratic beds were formed. Pebbles of acid lava and chlorite rich basic volcanics occur rarely in these conglomerates.

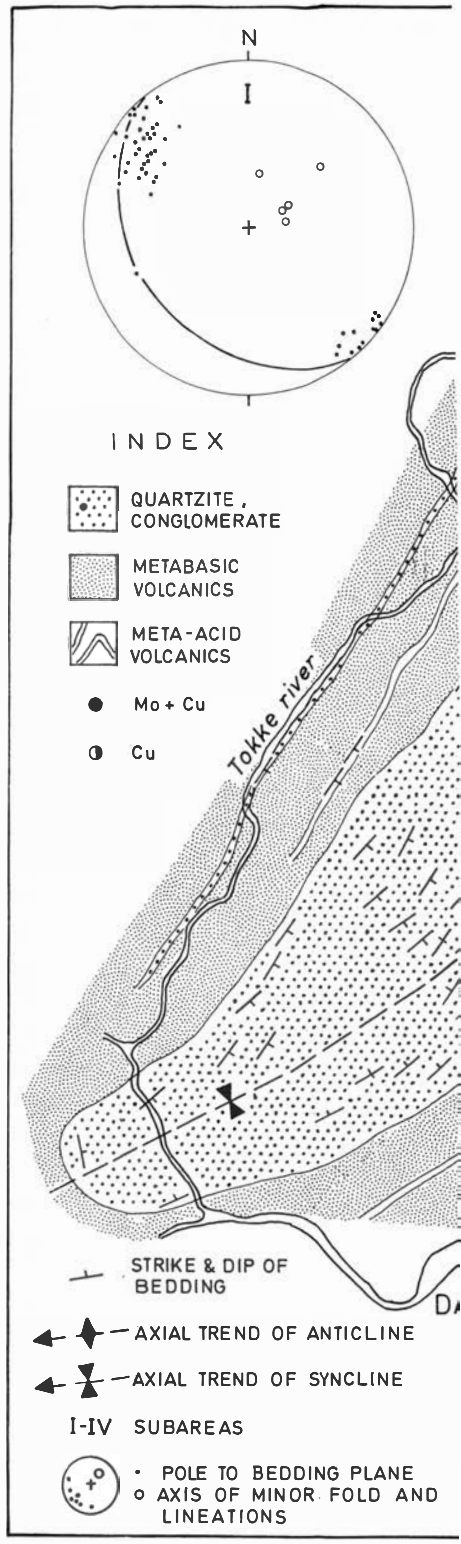
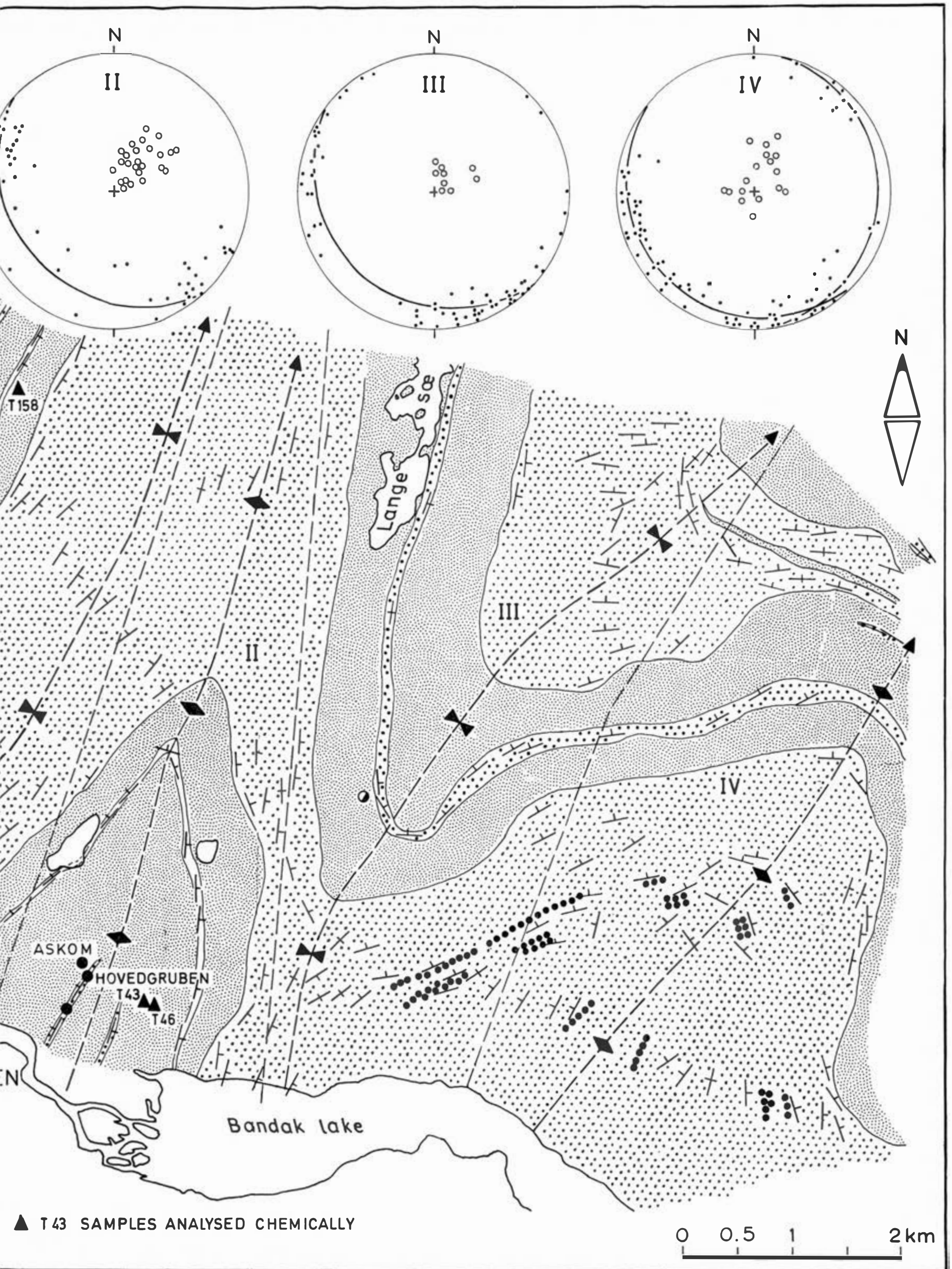


Fig. 2. Geological map of Dalen area.


N
II
N
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T43
T46
Bandak lake
T 43 SAMPLES ANALYSED CHEMICALLY
0 0.5 1 2 km

Metabasic volcanics

These occur as massive layers interbanded with quartzite, are fine- to medium-grained well jointed and at places show faint layering which normally lies parallel to the laminations in the surrounding quartzite. Its igneous texture is commonly preserved. The inequigranular texture is shown by laths of epidote and actinolite embedded in anhedral mesh of plagioclase and chlorite. At places, big poikilitic flakes of green-brown biotite and actinolite needles have grown irregularly in the fine-grained groundmass. Occasionally, the groundmass shows a strong preferred orientation of grains parallel to foliation in the rock. Some massive varieties contain amygdales filled with coarse granular aggregates of calcite, quartz and epidote. At places, massive segregations of epidote occur in well jointed rock. Minerals of the metabasics are actinolite, biotite, chlorite, epidote, albite-oligoclase (An_{15}-An_{20}), calcite, muscovite, quartz, magnetite, pyrite, sphene and leucoxene. Some admixtures of basic volcanics and pelitic quartzite contain appreciable amounts of brown biotite, quartz, chlorite, occasionally microcline, and are more strongly schistose than the pure members.

Table 1. Chemical analysis and mesonorm (Barth 1962) of metabasic volcanics from north of Dalen. For location of samples, see Fig. 2.

Oxide	T43	T46	T158
SiO_2	44.57	47.21	46.45
TiO_2	2.60	2.49	2.55
Al_2O_3	15.58	15.25	15.37
Fe_2O_3	9.26	6.78	6.06
FeO	7.97	7.86	8.29
MnO	0.21	0.24	0.24
MgO	10.19	5.80	6.05
CaO	3.90	8.78	9.36
Na_2O	2.60	3.14	2.95
K_2O	1.76	0.82	0.75
P_2O_5	0.23	0.27	0.31
H_2O+	1.20	1.14	1.55
Total	100.07	99.78	99.93
Norm			
q	4.87	0.72	–
c	6.90	–	–
ab	23.88	29.17	26.40
an	8.99	25.98	27.46
bi	17.02	8.02	7.35
act	–	12.44	10.87
ed	–	–	3.38
px	22.39	10.37	11.77
sph	5.56	5.39	5.52
mt	9.90	7.33	6.56
ap	0.49	0.58	0.67

Three chemical analyses of metabasics are given in Table 1. Uniformity in chemical composition is noted in these widely distributed samples (Fig. 2). Their composition corresponds to that of effusive alkali basalt except that they are poor in Ca and rich in iron. The calcium may have moved around locally as indicated by segregations of epidote and calcite produced as a result of metamorphism. Rather high amount of potassium in biotite rich sample T 43 seems to be an inherent characteristic of the rock since mobilization of alkalis in or out of the system is not evident from the mineralogy and texture of the rocks.

Meta-acid volcanics

These are fine-grained, glassy, light buff to grey coloured layered rocks occurring as 20 to 50 m thick bands within metabasic layers (Fig. 2). Some quartzite beds, for example the one running south from the east of sae Lange also contains a mixture of acid and some basic volcanic material. The meta-acid rocks still preserve their inequigranular porphyritic texture. The groundmass consists of fine-grained anhedral albite, quartz and muscovite generally aligned parallel to the mesoscopic foliation. The blastophenocrysts are made of albite-carlsbad twinned subhedral plagioclase grains (An_{10}-An_{15}) up to 1 mm long containing minute inclusions of quartz and sericite (Fig. 3). Microcline is present in small amounts in fine grained aggregates with quartz. Other minor minerals are calcite, chlorite, epidote, magnetite and pyrite.

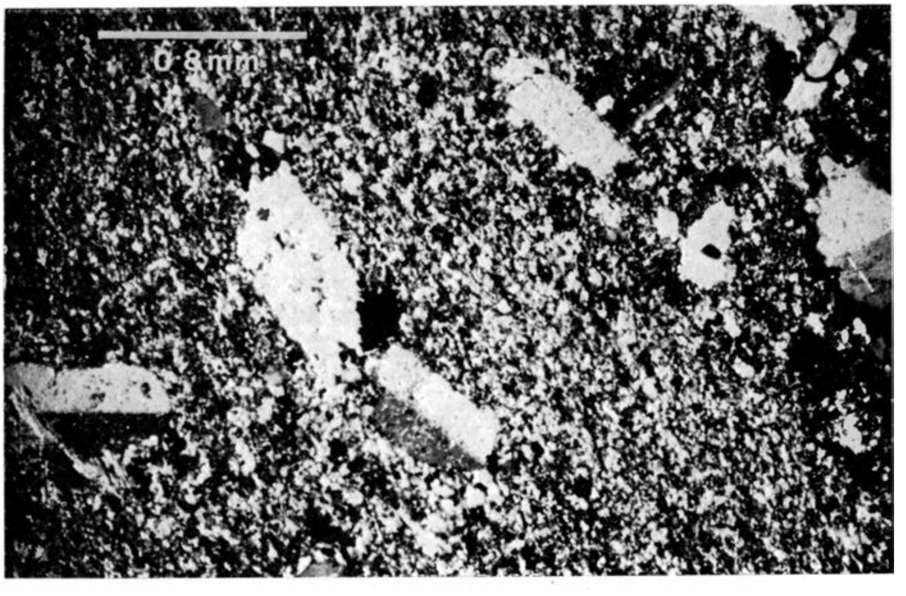

Fig. 3. Photomicrograph of meta-acid volcanic showing albite blastophenocrysts and altered groundmass. X-nicols.

Quartz veins
Most veins in the area are quartz bearing except for a few calcite-epidote ones that occur only in metabasics. The mode of occurrence and mineralogy of a set of subparallel sulphide bearing quartz veins occurring at Askom and Hovedgruben (Fig. 2) are described in detail later. Veins found in quartzites form saddle lodes in fold noses, fill gash fractures and make thin irregular veneer along joint planes. Their thickness varies considerably from a few cm to several metres and their lateral extension goes up to a few metres. Common minerals of veins occurring in quartzite are quartz, microcline, muscovite, fluorite, epidote, calcite, tourmaline, chlorite, molybdenite, pyrite, chalcopyrite, bornite and hematite. Veins found in metabasics mainly occupy joint planes and occur also as irregular masses containing a quartz-calcite core surrounded by epidote. Sulphide minerals in these veins are about the same as in the veins occurring in quartzites.

Tectonic features

The rocks of the area are deformed into NNE trending steeply plunging asymmetrical appressed folds as can be seen on the geological map in Fig. 2. Among mesoscopic structural features, a set of fracture cleavages is often developed in the quartzites. The angle between this cleavage and the bedding planes is usually small and at places where flexural slip along the latter has been strong, the two planes lie parallel to each other. The cleavage generally lies parallel to the axial plane of major folds in the area. In metabasics the cleavage is not clearly seen, instead a set of widely spaced foliation planes are frequently observed which conform with the cleavage planes in the quartzites. Often a kind of banding defined by alternating greenish epidote and dark metabasic layers is developed in metabasics due to concentration of epidote along the foliation planes.

Small scale folds are often observed in quartzites and occasionally in metabasics. The style of one set of minor folds varies from appressed asymmetrical to isoclinal. Most minor folds are concentric, but some very tight ones show later stages of shear in the nose regions (Fig. 4). Axial planes and plunge of axis of this set of minor folds are conformable with the megascopic folding as seen in the projection diagrams (Fig. 2). Another set of minor folds are open mainly monoclinal flexures with subhorizontal to low dipping axial planes and are commonly developed on vertical micaceous quartzite beds. These folds do not relate to any major deformation phase in the rocks but are caused by late stage strain adjustment in semi-competent vertical beds.

Mullions parallel to megascopic fold axis are at places well developed in metabasic, meta-acid volcanics and some coarse-grained quartzites. Mullions are also developed along vertical joint planes due to dip-slip on these surfaces. Alignment of actinolite and chlorite needles in metabasic and impure quartzites is found in several directions, some along the megascopic fold axis and mostly paralleling slip directions on joint planes and along axis of the open

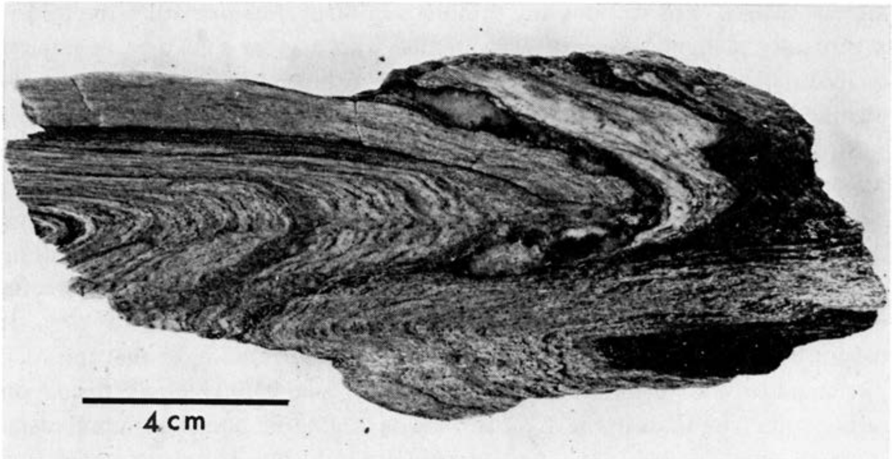

Fig. 4. Compressed minor fold in quartzite showing some shear in the nose region.

second set of folds. Most mica rich quartzite beds contain micropuckering in the direction of both fold axes.

Several sets of joint surfaces are developed in the rocks. Some are directly related to major folding, especially one set that dips 20–30° to the south and southwest. This set lies perpendicular to the axis of megascopic folds, is prominently developed and is occupied by several thick sulphide bearing quartz veins at Askom and Hovedgruben. Elsewhere in the area, this set is equally prominent but does not contain many quartz veins. Outside the area to the south at Bandaksli, a similar set of joints traverses a granite body carrying molybdenum-fluorite bearing quartz-feldspar veins.

Attitudes of bedding foliation and of linear structures from four structurally distinct subareas are given in projection diagram insets in Fig. 2. Each subarea covers a complete fold unit. In subarea I, the fold is a very appressed syncline with schistose quartzite in the core and axial trend swinging from NE in the southern part to NNE in the north. In subarea II, the anticline is rather open with steeply plunging axis towards NNE and metabasics forming its core. Quartzite bed on the eastern limb of the fold shows evidence of strong slip along bedding planes due to which the true thickness and lateral extensions of the bed are considerably reduced. Development of these slip planes has produced a strong fissility in the arenaceous beds which together with an intersecting set of joints produce well cut rectangular even-grained pieces of quartzite suitable for use as grinding and polishing slabs (whetstone). The material was quarried for this purpose in the past near the road, Dalen – Høydalsmo (Dons 1960).

The fold in subarea III is a symmetrical syncline with coarse-grained quartzite forming its core. Its axis plunges steeply due NNE in the southern part and NE in the northern. The quartzite in NE shows much small scale folding and crumpling as seen from the attitudes of bedding planes. It also contains numerous quartz veins without any sulphides in them. In subarea IV the fold is a vertically plunging symmetrical anticline with a great thickness of impure quartzite in the core. Its axis trends NE and at places reverses its plunge towards SW (Fig. 2, projection inset).

Structural analysis of the area shows that the rocks have suffered only one major phase of compressive deformation giving rise to concentric folds along NE trending axis. The regional high angle of plunge of fold axes in the area does not seem to be related to any major phase of deformation but to tilting of the folded block which might have taken place by the influence of forceful intrusion of granitic bodies in supracrustal rocks in the south of the area. If the intrusions coincided with the end phase of major folding so that the rock pile could be tilted while still under stress, it is possible to reconcile formation of high plunging folds in the area. Intrusions of granitic bodies in supracrustal rocks outside the area are found to strongly influence the structure of surrounding rocks in terms of local buckling, regional tilting and overturning of the beds (cf. Dons 1960, 1962, Sylvester 1964). Geological and geophysical studies of several granitic bodies occurring immediately south of the area suggest that forceful intrusion has caused regional large scale tilt of the overlying rocks (E. Győry, personal communication).

Metamorphism

Association of volcanic rocks with clastic sediments as represented in the area indicates a eugeosynclinal assemblage. The sandstones, basic and acid volcanics were deformed and metamorphosed under epidote amphibolite facies conditions. The original composition of metabasics corresponds to alkali basalt and that of meta-acid volcanics to a rather sodic rhyolite. In acid volcanics, the breakdown of K-feldspar and mafics has produced varying amounts of fine-grained muscovite and chlorite, respectively. Plagioclase being already of a sodic variety did not undergo much alteration as can be seen in Fig. 3. Original minerals of the basic volcanics were completely altered to epidote, actinolite, chlorite and calcite. Composition of metabasics is shown in ACF plot with compatible mineral phases in Fig. 5. In sandstones a complete recrystallization of quartz is noted. Greenish-brown biotite and muscovite with some chlorite were produced in the impure varieties.

Molybdenum-copper bearing quartz veins

Veins carrying small amounts of Mo and Cu sulphides are abundant in quartzites and metabasics of the area. One chalcopyrite-bornite-tourmaline bearing vein was discovered in the road cut in subarea III at Gunnheim (Dons 1960). No material was collected from this showing for laboratory studies. Another set of large saucer-shaped quartz veins containing molybdenite and minor amounts of copper sulphides were mined at Askom and Hovedgruben (Bugge 1963). These veins occupy a set of joint planes dipping 20–30° to the

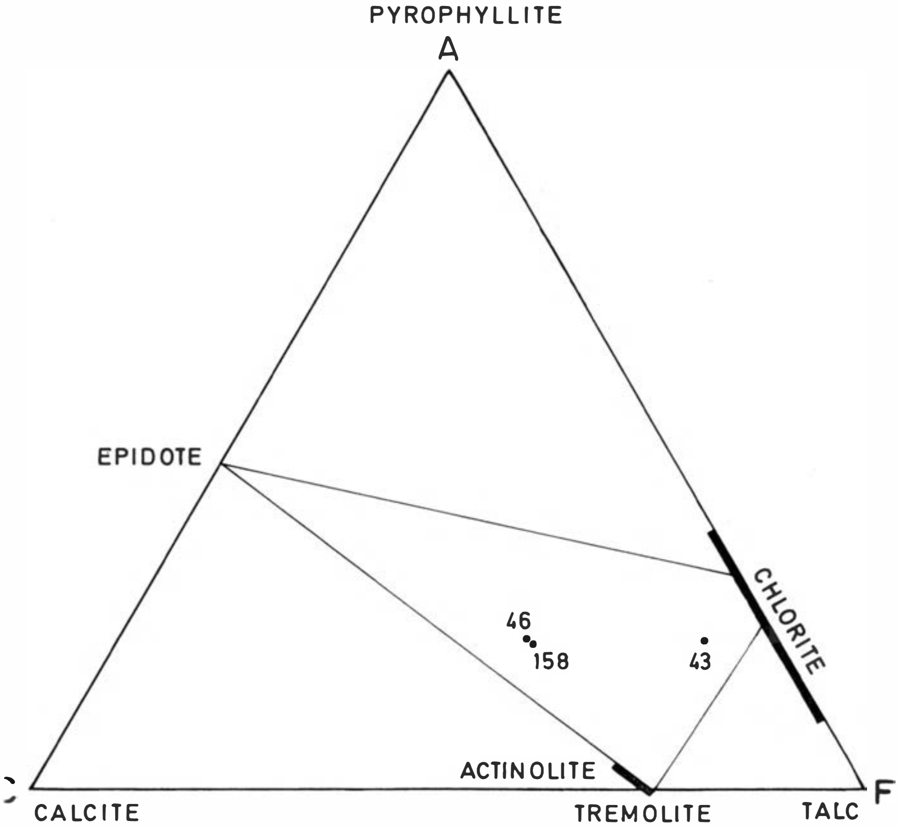

Fig. 5. ACF plot showing composition of metabasic volcanics and the compatible mineral phases.

south and southwest and lie perpendicular to the axis of the megascopic folds in the area. Mineralogy of these veins is described here in detail.

Askom

Three different veins occurring in metabasic volcanics at different levels lying one above the other have been mined here. They vary in thickness from a couple of cm to 20 cm and in lateral extension up to 36 m in EW and 76 m in NS directions. In plan, the veins are very irregular in outline. Typically, the veins are layered as in Fig. 6. Layers of black massive tourmaline, chlorite, epidote and quartz alternate with each other in various dimensions. The layers show deformation into open folds and fractures on various scales (Figs. 7 and 8). This deformation seems to have occurred due to inherent strain in the surrounding rocks that remained from a preceding phase of major stress release along the joint surfaces. The homoclinal crumples in the tourmaline layers are developed due to slip along bounding joint planes of the country rock. At some places the strain was resolved into fracture cleavages with certain amount of slip as seen in Fig. 7 and left upper corner of Fig. 8. Sulphides

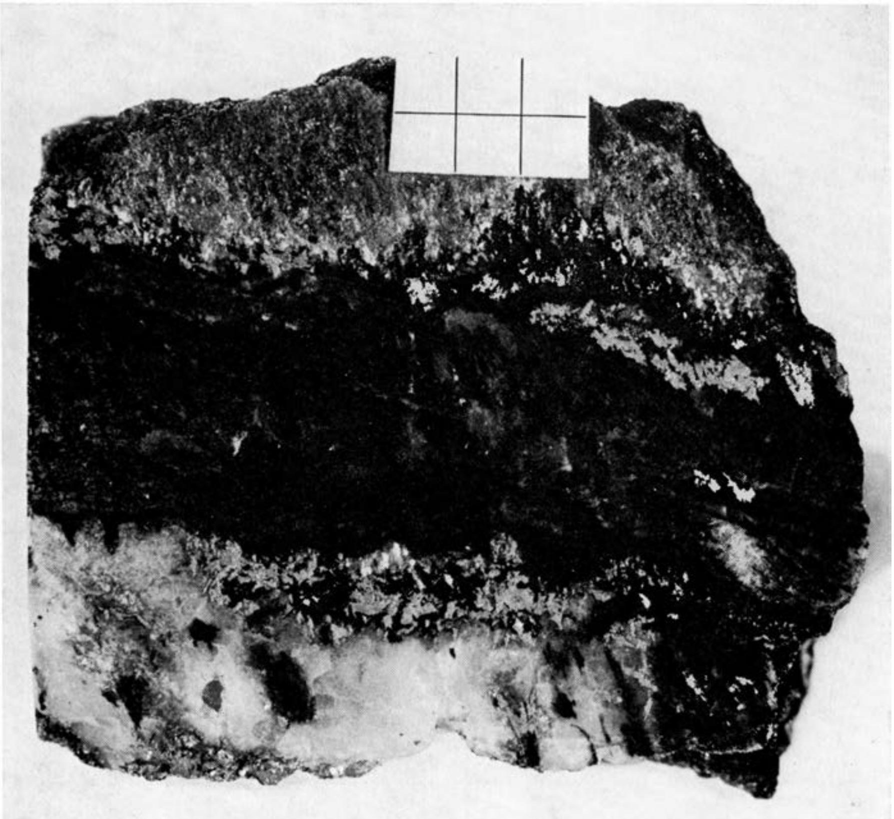

Fig. 6. Hand specimen of vein from Askom showing layering; black – tourmaline, grey – chlorite and epidote, smoky white – quartz, shining white specks – molybdenite. One division is 1 cm on scale.

occur in between the silicate layers and also between the country rock and the vein. They also occupy cleavage planes (Fig. 7). Minerals in these veins are quartz, tourmaline, chlorite, actinolite, epidote, muscovite, biotite, barite, calcite, hematite, molybdenite, bornite, chalcopyrite, chalcocite, covellite, galena, pyrite, powellite and malachite.

Hovedgruben

Veins in Hovedgruben are confined to thin quartzite bands which occur north of Dalen. There are five of these veins which have been mined out in Hovedgruben and in several small mines. The uppermost vein is thickest (up to 70 cm) and is largest in lateral extension of all the veins occurring in and around Hovedgruben. The veins consist of massive quartz containing scattered books of molybdenite, other sulphides and some tourmaline (Fig. 9). Molybdenite flakes vary in size up to 15 cm in length. Layering is developed in some thinner parts of the veins consisting of hematite, tourmaline and quartz. The veins also show some deformation as small displacements along joint

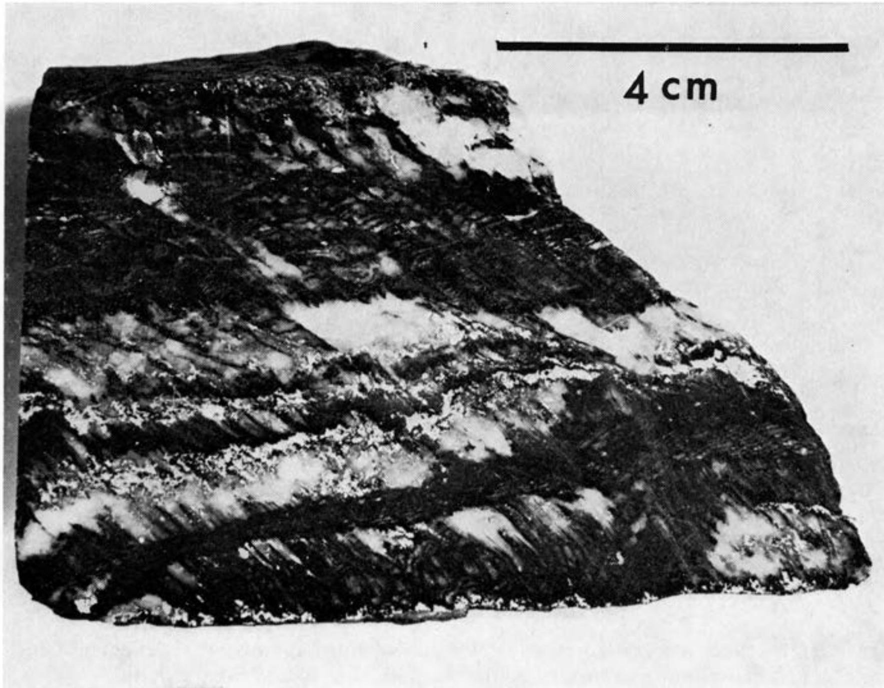

Fig. 7. Deformed layers in vein at Askom showing fractures and undulations; black – tourmaline, smoky white – quartz, shining white – molybdenite.

Fig. 8. Photomicrograph of vein showing undulated tourmaline layers in quartz and fractures in the left upper corner. X-nicols.

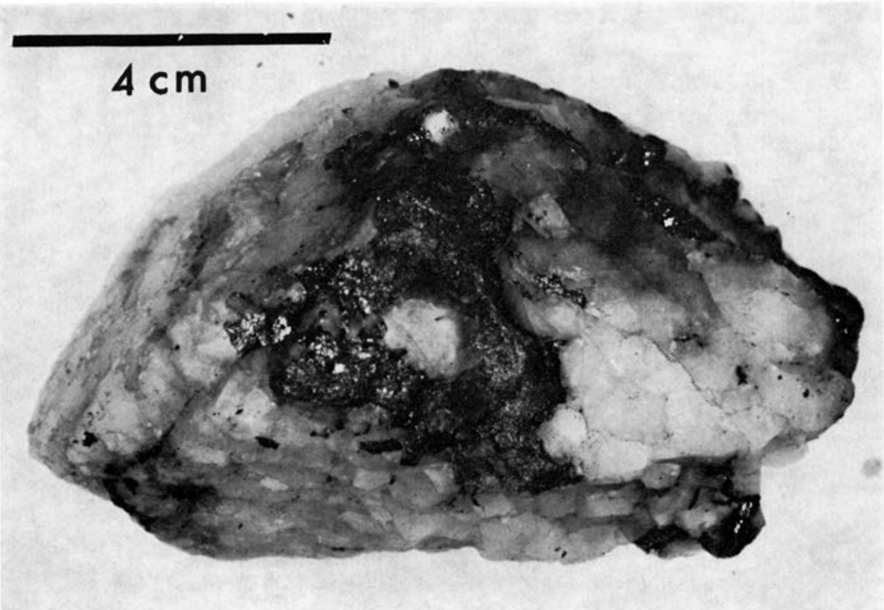

Fig. 9. Hand specimen of vein from Hovedgruben showing clots of molybdenite (shining grey) in massive quartz (smoky white), dark grey is epidote and sericite.

planes. Minerals in the veins are quartz, calcite, barite, fluorite, ankerite, muscovite, biotite, chlorite and epidote. The ore minerals are the same as in Askom but vary in proportion.

Study of ore minerals from the veins

Textural characteristics of ore minerals were studied on polished sections of the veins. Some hand-picked material of molybdenite and its alteration product powellite was X-rayed in Guinier camera to study their structural characteristics. Mainly sulphides and their alteration products are described here in detail.

Molybdenite

It is the most abundant of the sulphides at both occurrences. Mesoscopically there are two varieties of molybdenite found, one is the usual flaky type, which is most common, and the other rather occasional fibrous variety is found disseminated in massive quartz occurring only in Hovedgruben. *Flaky molybdenite* occurs in books which are commonly bent and strained. Twinning within individual flakes and intergrowth between the flakes is commonly seen. It is closely intergrown with small subhedral grains of galena. Commonly, molybdenite flakes are grown onto and into the gangue minerals and thus appear replacing the latter. When molybdenite occurs with bornite, the latter fills in between the flakes and also in between gangue and molyb-

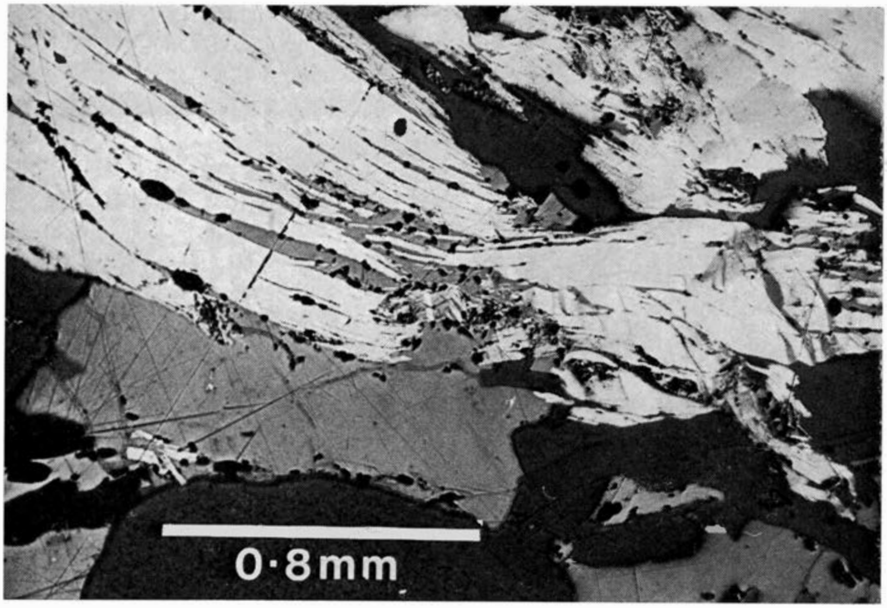

Fig. 10. Photomicrograph showing molybdenite flakes (light grey) replaced by bornite (grey); quartz is dark grey. Partly X-nicols.

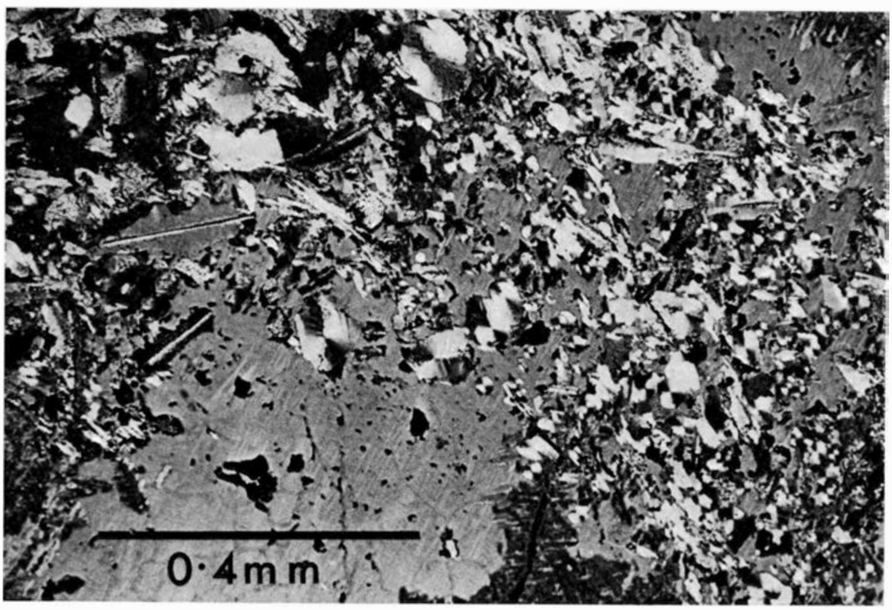

Fig. 11. Photomicrograph showing molybdenite needles (circular x-sections and longitudinal sections) and flakes floating in bornite. X-nicols.

denite (Fig. 10), and at places it completely surrounds the molybdenite (Fig. 11). Alteration of molybdenite into powellite is fairly common and varying in extent (Fig. 12). Qualitative X-ray fluorescence runs of pure molybdenite fraction show traces of selenium and copper.

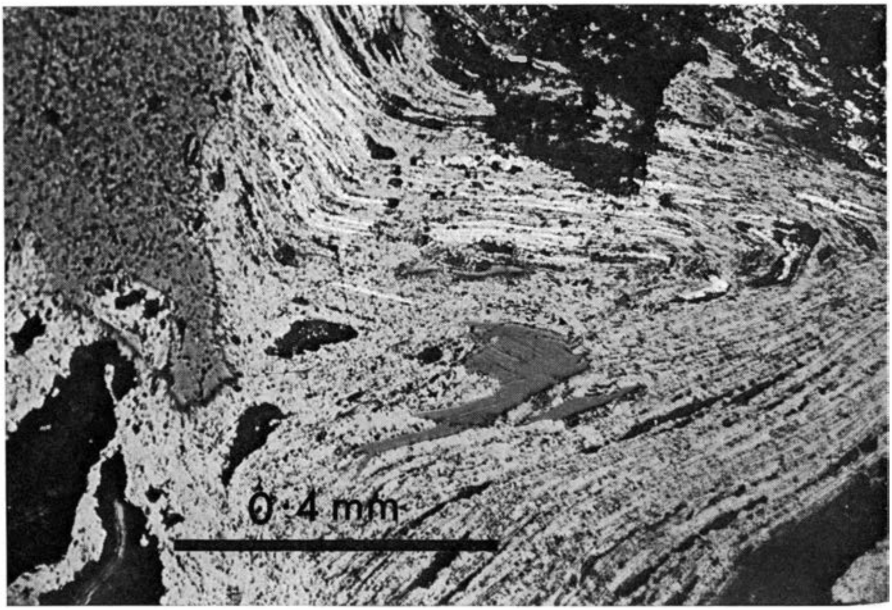

Fig. 12. Photomicrograph showing relict molybdenite (shining white) in powellite (light grey flaky), rest is gangue. Partly X-nicols.

The fibrous variety of molybdenite occurs as mushrooms of thin needles embedded in coarse quartz. The needles are commonly never larger than 10–15 mm and are up to 0.5 mm thick. It was found to occur only in some parts of the vein in Hovedgruben. In cross-sections, the needles have circular outline containing a radial roset of flakes which under crossed nicols give a butterfly structure containing a central spot occupied by a differently oriented molybdenite flake or sometimes a grain of galena (Figs. 13 and 14). In longitudinal section the needle is lens-shaped in outline and is divided into two halves by a median line along which the central flake shows a different orientation (Fig. 13 upper centre). This fibrous variety of molybdenite is quite unusual and has not been reported from elsewhere. A detailed examination of quartz-tourmaline-molybdenite relationship shows that the needle shaped molybdenite might have formed by replacing tourmaline needles and subsequently acquiring its shape in the cavity. In most cases molybdenite could also replace a little of surrounding quartz around the middle regions of the cavity where the needle is a bit convex (Fig. 13). Bornite commonly replaces the needles and at places a bunch of them can be seen floating in it (Fig. 11). No alteration was seen in this type of molybdenite.

X-ray diffraction runs were made of the two types of molybdenite. Data is given in Table 2, which shows no particular difference in atomic structure of the two. The fibrous variety thus is only a replacement structure. Data in Table 2 further show that both the earlier known structural modifications, hexagonal (2H) and rhombohedral (3R) occur mixed in the molybdenite

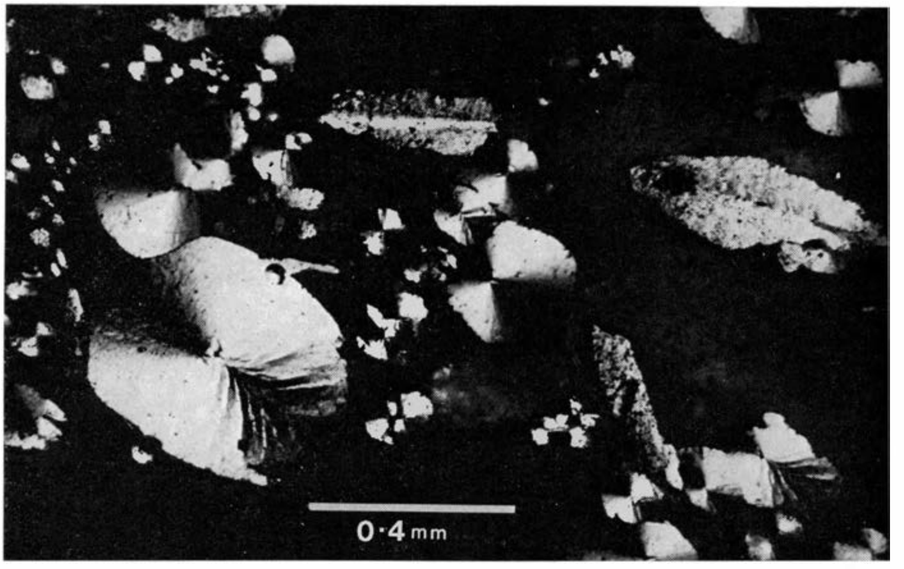

Fig. 13. Photomicrograph showing variously cut needles of molybdenite in quartz (black). Note the median line in longitudinal section in upper middle part. X-nicols.

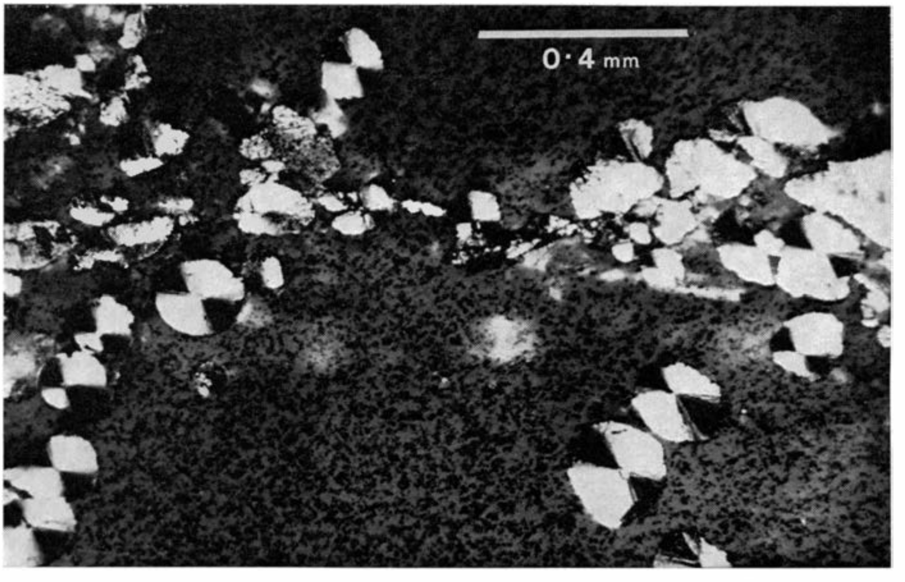

Fig. 14. Photomicrograph showing cross sections of molybdenite needles. Roset arrangement with a central grain is clearly seen. X-nicols.

from Askom and Hovedgruben. Molybdenite 2H is the most commonly found variety in nature. Rhombohedral type has been reported previously from Canada (Traill 1963), Portugal (Clark 1965), Swiss Alps (Graeser 1964) and some localities in Russia and Finland. Recent studies on the two types of molybdenite tend to show that molybdenite – 3R contains greater

Table 2. X-ray powder diffraction data on molybdenite from Hovedgruben. Flaky molybdenite from Askom gives a pattern similar to that of Hovedgruben (Fekα_1, radiation).

	Flaky molybdenite				Fibrous molybdenite			
Line No.	hkl	Type	d	$I_{Obs.}$	hkl	Type	d	$I_{Obs.}$
1	002	H	6.130	100	002	H	6.103	100
2	100	H	2.737	57	100	H	2.737	42
3	101	R	2.708	23	101	R	2.709	52
4	101	H	2.672	48	101	H	2.672	35
5	012	R	2.625	17	012	R	2.626	37
6	102	H	2.501	37	102	H	2.501	21
7	103	H	2.276	47	103	H	2.276	27
8	015	R	2.196	12	015	R	2.196	17
9	104,006	H	2.049	21	104,006	H	2.039	9
10	105	H	1.829	30	105	H	1.827	7
11	018	R	1.758	3	018	R	1.758	3
12	106	H	1.639	3	106	H	1.643	4
13	110	H,R	1.581	76	110	H,R	1.581	54
14	008,112	H,R	1.531	50	008,112	H,R	1.532	32

number of Mo atoms in structure than the hexagonal one (Clark 1970). On heating in the presence of sulphur, molybdenite – 3R breaks down to molybdenite – 2H at 600 °C (Rode & Lebedeva 1961). Clark (1970) concedes that association of the two in natural ores may indicate crystallization below approximately 500 °C. Molybdenite – 3R has also been recently observed to occur with hexagonal type from a few localities south of the present area (E. Györy, personal communication).

Galena

It occurs in small amounts as small grains intimately associated with the flakes of molybdenite and also at times replacing tourmaline needles together with molybdenite.

Bornite – chalcocite – covellite

Bornite occurs as anhedral to subhedral grains usually showing replacive relationship with molybdenite, galena and the gangue minerals. It occurs more abundantly in Askom than in Hovedgruben. Most bornite grains contain intimately intergrown chalcocite as blebs, spindles and patches (Fig. 15), and also as lattice intergrowth containing thin layers of chalcocite arranged in at least three regular directions in the bornite crystal (Fig. 16). These textures seem to have been produced by exsolution of chalcocite and bornite. Complete solid solution between the two minerals was recorded experimentally at 225 °C or above (Schwartz 1928). Detailed investigation of structural state of bornite and chalcocite was not undertaken. The other Cu bearing mineral closely associated with the above two is covellite. Both chalcocite and covellite occur in bornite in very small amounts. Therefore, X-ray powder runs on

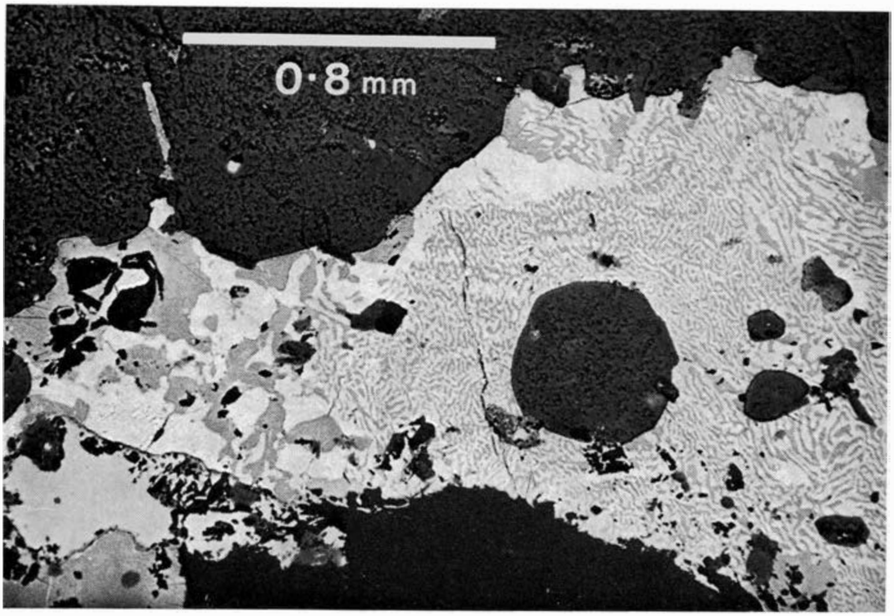

Fig. 15. Photomicrograph showing eutectic intergrowth of chalcocite (light grey) and bornite (grey). Ordinary light.

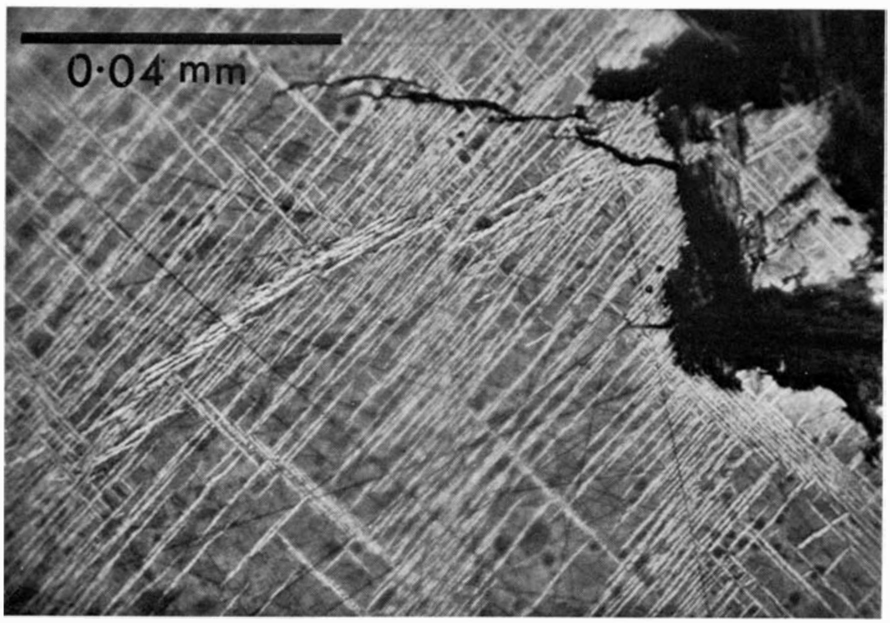

Fig. 16. Photomicrograph showing lattice intergrowth of chalcocite (light grey) in bornite (grey). Crack in upper right is filled with malachite. Ordinary light.

bornite often do not show any indication of their presence. Chalcocite often also occurs intergrown with covellite. Covellite occurs distinctly in two ways,

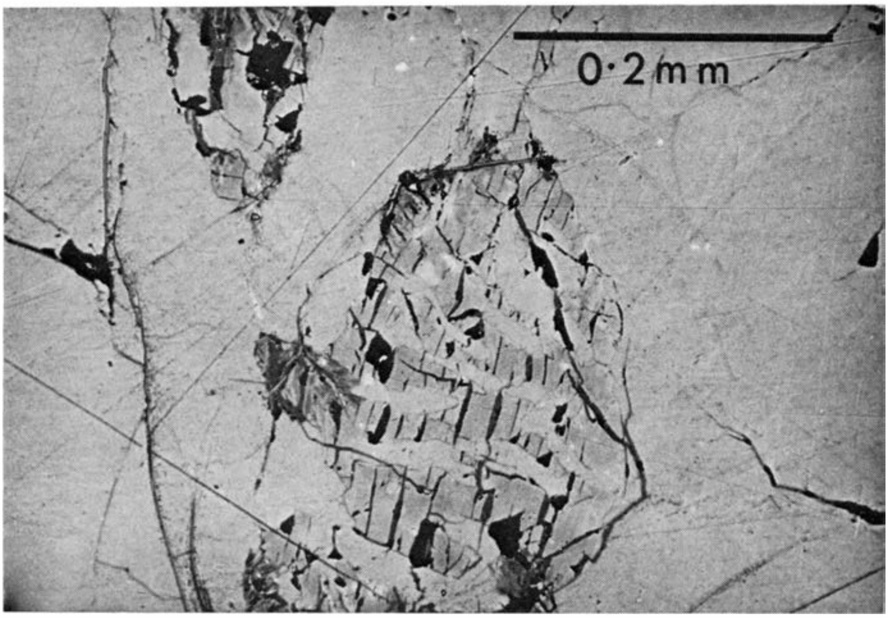

Fig. 17. Photomicrograph showing intergrowth of covellite (darker grey, patchy) in chalcocite (grey). Ordinary light.

one, as intergrowth in chalcocite and patches in bornite showing replacement (Fig. 17), and the other as veinlets along cracks in bornite and chalcocite. The former seems to have exsolved from chalcocite (70–75 °C, Bateman & Lasky 1932) and the latter as alteration in cracks, cleavages and along the boundaries between chalcocite and bornite.

Chalcopyrite

It occurs in minor amounts very closely intergrown in patches in bornite as seen in Fig. 18 where both minerals appear to replace each other. Solid solution of the two occurs at 475 °C (Schwartz 1931) and unmixing between the two is very quick when cooled slowly. In the present occurrence chalcopyrite separated out quite early from bornite and remained mobile even after the formation of chalcocite and covellite. As seen in Fig. 18, cracks in bornite filled with covellite abut against chalcopyrite boundary. And in the case of cracks which traverse across through chalcopyrite grain, there occurs no alteration of the two minerals.

Pyrite was noted only at a few places replacing most of the other sulphides. It is more common in Hovedgruben than in Askom. *Malachite* is commonly found filling cracks in bornite and chalcopyrite. Flaky *hematite* occurs in quartz veins and country rocks in Hovedgruben and usually does not show any clear relationship with sulphide minerals.

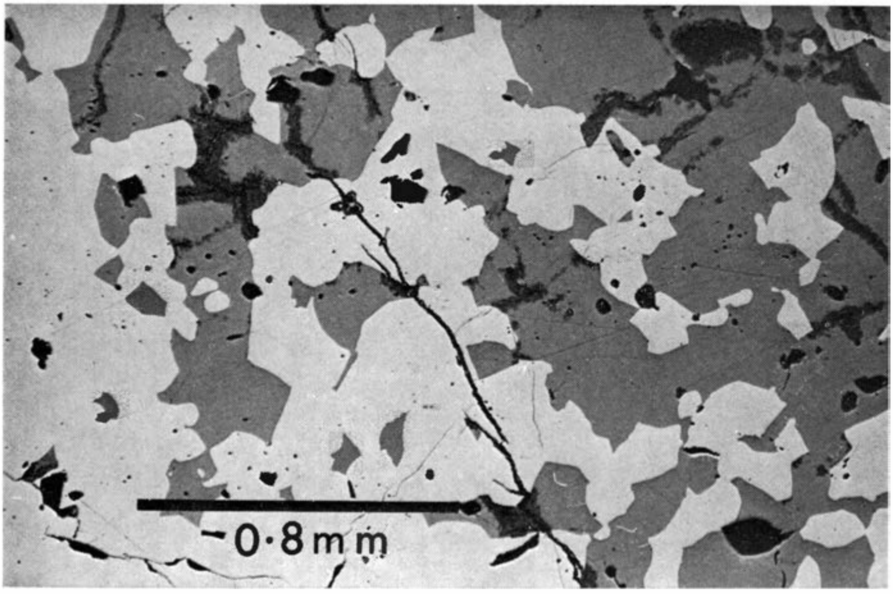

Fig. 18. Photomicrograph showing bornite (dark grey) replaced by chalcopyrite (light grey). Note that some cracks in bornite do not continue in chalcopyrite. Ordinary light.

Paragenesis of sulphides

Textural evidence indicates that Mo and Cu sulphides were precipitated after the formation of silicate and oxide gangue minerals. Among the sulphides molybdenite seems to be the first to form along with galena. Bornite-chalcocite and covellite were formed later in this order. Chalcopyrite exsolved from bornite much earlier but was deposited after the latter. Its relationships with chalcocite and covellite are not clear because the latter two are confined only to bornite. Presumably the two exsolved from bornite long after the formation of chalcopyrite and at much lower temperatures. Pyrite appears to be latest among the sulphides.

Alteration of molybdenite

Flaky molybdenite is seen readily altered to powellite ($CaMoO_4$) both in Askom as well as in Hovedgruben. At places, almost complete alteration is seen with only a few pieces of relict molybdenite remaining in powellite (Fig. 12). Mesoscopically, two types of powellite are found, one, the flaky greenish yellow occurring in between molybdenite flakes (Fig. 12), and the other as thin yellowish smear on quartz grains. The latter has a botryoidal form and seems to have been moved around and precipitated in cracks in quartz from colloidal solution. Both types of powellite were X-rayed and the data are given in Table 3 which compares well with the data given by Vegard (1926). There is no structural difference between the two types. Both are fluorescent under ultraviolet light.

Table 3. X-ray powder diffraction data on powellite from Hovedgruben ($Fek\alpha_1$, radiation).

	In situ with molybdenite			grown as smear on quartz		
Line No.	hkl	d	$I_{Obs.}$	hkl	d	$I_{Obs.}$
1	101	4.763	82	101	4.757	78
2	112,103	3.107	100	112,103	3.105	100
3	004	2.862	36	004	2.860	35
4	200	2.616	48	200	2.614	44
5	211	2.282	21	211	2.287	32
6	204β	2.097	15	204β	2.096	18
7	204	1.928	65	204	1.926	64
8	220	1.847	37	220	1.845	34
9	116	1.694	34	116	1.691	31
10	222	1.633	14	222	1.633	15
11	303,312	1.586	43	303,312	1.585	42
12	206	1.551	19	206	1.550	20
13	008,314	1.430	8	008,314	1.430	6

Besides powellite, some trace of molybdite (MoO_3) was noted in X-ray powder runs. Molybdite is not present in appreciable amount although suitable oxidation conditions exist. This may be because it is readily soluble in cold water producing $H_2MoO_4 \cdot H_2O$ acid. This acid gets neutralized under Ca rich environment to produce powellite ($CaMoO_4$) as was also noted by Maucher (1938). Since both the veins and the surrounding rocks contain considerable amount of calcite it is likely that almost all the oxidized molybdenite was transformed by the above process to powellite. It is noted that powellite was produced in situ and was also brought into solution and deposited elsewhere as thin smears on quartz and other gangue minerals.

Summary

Rocks of the area belong to a eugeosynclinal assemblage, were deformed into upright compressed NE trending folds and metamorphosed under pressure-temperature conditions of epidote-amphibolite facies. Geometry of major folds was modified considerably by igneous intrusions in the south and west of the area. Mechanism of deformation was chiefly flexural slip locally accentuated by shear in relatively incompetent beds. Quartz veins are very abundant in the rocks and show considerable variation in geometry in relationship to tectonic features in the rocks. Major Mo-Cu sulphide bearing veins in the area occupy joint planes which lie perpendicular to the axis of megascopic folds. The veins suffered minor deformation due to slip movements along the joint surfaces. Sulphides were deposited in the veins after silicates. Molybdenite along with galena was first to form followed by bornite, chalcopyrite and pyrite. Bornite at lower temperatures (225 °C and 70–75 °C) was exsolved to chalcocite and then to covellite. Crystallization of sulphides started approximately at 500 °C or lower. Vein material contained large amount of gaseous material indicated by carbonates, borosilicate, fluorite, and sulphides. Alteration of molybdenite into powellite took place first by its oxidation into molybdite and then by reaction with Ca bearing solutions. Oxidation of Cu sulphides to malachite occurred at about the same time.

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