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GEOLOGICAL AND PETROGRAPHICAL INVESTIGATIONS IN THE ARENDAL DISTRICT

BY

JENS BUGGE

WITH 15 FIGS. IN THE TEXT AND 4 PLATES

Abstract. The rocks of the Arendal district in Sørlandet, Norway, are all of pre-Cambrian age and belong to the Kongsberg—Bamble formation. This paper chiefly deals with the south-western part, which is shown in the geologocal map, fig. 13 and marked by the hatched triangle on fig. 1.

Evidence is cited to show that the oldest rocks are of supra-crustal origin, including quartzites, limestones, effusives, para-gneisses etc. The banded gneisses, so common in pre-Cambrian formations, are also supposed to belong here.

During an orogenic period the rocks were strongly folded and invaded by igneous and migmatic rocks, ranging in composition from hyperites, norites and hypersthene diorites to charnockites and granites. During this time the rocks of the old complex were to a high degree changed to migmatites and granites.

The skarn-iron ores of Arendal all belong to the old supra-crustal system and are of metamorphic origin.

They have been mined for more than 250 years and were in the 18th century among the most important in Norway.

Some of the mines are about 250 m deep, but the total production is only about 2 3/4 mill. tons. After 1870 there has been work only at Klodeborg and Bråstad, which were abandoned in 1920. Tectonics and mineral parageneses of the deposits are briefly discussed.

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Preface.

The investigations in the Arendal district were carried out during the years 1937 and 1938 for the Geological Survey of Norway on the initiative of Director Carl Bugge.

The collection of the Survey, geological maps, rock specimens, slides etc.,chiefly collected by the Director, were kindly put at my disposal. I would thank him for his valuable advice and the many helpful discussions of the problems, which have been of the greatest importance for my work.

My sincere thanks are also due to Professor V. M. Goldschmidt for his kind help and advice and for the great interest he always has shown in my investigations.

The laboratory research was carried out at the Mineralogical Institute of the Oslo University and the Director, Professor Barth, kindly placed all the equipment of his institute at my disposal. For his valuable criticism of the manuscript and all his assistance both in my present work, and previously, I am greatly indebted.

The microphotos were taken by Mr. J. Stadheim and the maps drawn by miss D. Engelsrud.

Mineralogisk Institutt, Oslo.
August 4, 1939.

Previous Work.

The first detailed investigations of the ore district were carried out by Th. Kjerulf and T. Dahll 1861 (Fig. 15).

J. H. L. Vogt has in several papers discussed the origin of the ores. He regarded them as contact-metamorphic, and also mentioned the similarity to many skarn-ores in Middle-Sweden.

Quite recently, Thorolf Vogt (1937) has tried to compare the Bamble formation with the Svionian in Sweden. He bases his contentions on the relationship between the ore-deposits in the two districts, and he also emphasizes that the rocks of the Bamble formation strike in the same direction (NE—SW) as those of the Svionian.

Interesting facts about the archean of Southern Norway are also published by W. C. Brøgger, O. Holtedahl, T. F. W. Barth, I. Oftedal et alii.

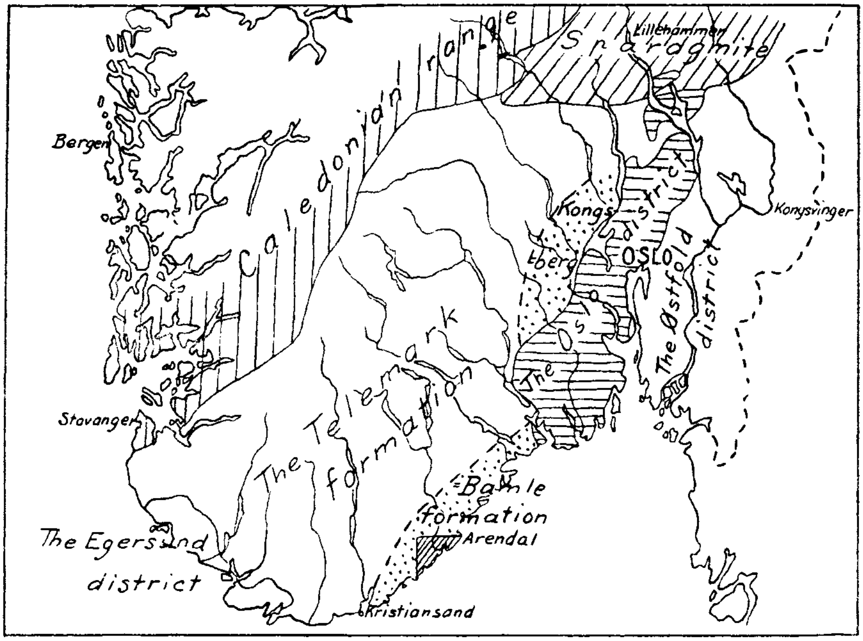

Fig. 1.

In recent years the Bamble formation has been systematically mapped by the Geological Survey of Norway Olaf Andersen (1931), Arne Bugge (1928, 1936), Carl Bugge (1917), and we can now partly follow and reconstruct the geological history.

I. Geological Description.

1. Quartzites.

Quartzites have been described from several parts of Sørlandet, but their origin is still a matter of discussion among Norwegian geologists.

They often occur in connection with hyperites (or amphibolites) and seem also to pass by gradation into true granites. Some geologists (e. q. y. Arne Bugge) have therefore entertained the idea of a possible magmatic mode of origin of the quartzites. Further investigations have shown, however, that the quartzites have a wide distribution and belong to a formation which I can only explain as sedimentary. The rocks are best preserved in the north-western parts of the Arendal district and wedge out towards NE and SW. Here they often are migmatized and granitized to a high degree, and we may pass from true quartzites to true granites in the strike directions.

The south-eastern border of the quartzite formation extends from Rorevatn—Løddesøl—Rossedalen towards NE. Towards SE the quartzites form a broad transitional zone which merges into the next zone which I have named *the Regional-migmatite zone* (see page 21).

The quartzites are always wholly recrystallized and I have never found any traces of clastic structures. Transparent varieties are common. The strike varies from N—S to NE—SW and the dip is usually vertical.

They always contain small well-oriented biotite scales, giving the rocks a gneissic aspect. Grains of feldspars are common. It usually is an acid saussuritized plagioclase where zoisite, sericite and calcite is observed in the ground mass. Potash feldspars are not so common and seem to be limited to the borders of the quartzite areas. While the plagioclases may be regarded as clastic relics, the microcline mostly is of metasomatic origin.

Minor constituents of pneumatolytic origin are tourmaline (shorlite), rutile and zircone. Of these minerals tourmaline is the most important and is sometimes the only mineral besides quartz. It is interesting that tourmaline usually occurs in connection with the quartzites and very seldom is found in other rocks. The pure quartzites seem to be more resistive to granitisation than the impure, and while these and the other rocks may be migmatized and granitized to a high degree, the pure quartzites occur as relics only granitized in the peripheral parts.

Sillimanite occurs, but seems to be more rare than in other parts of the Bamble formation.[1] It is described from several parts of the Arendal district by Arne Bugge and other geologists.

Quartz is generally strongly pigmented, due to small inclusions, often occurring in parallel lines (the Boehm striation), partly representing liquid inclusions. Investigations of the petrofabric have not yet been carried out, but are of the greatest importance (see A. Hietanen 1938).

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[1] Instead of the Kongsberg-Bamble formation I commonly use the shorter name the Bamble formation.

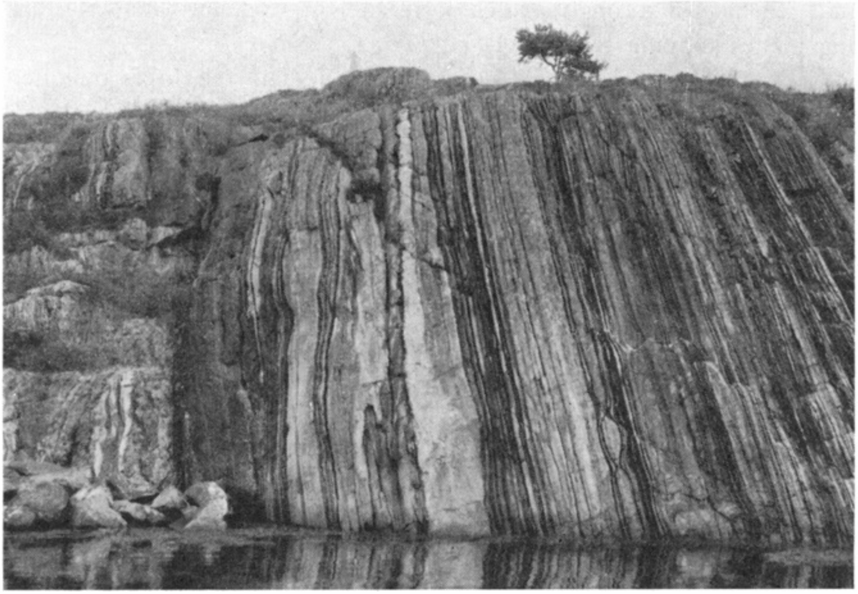

Fig. 2. Banded gneiss. Morvigen, Landvig.

2. Conglomerates.

Rocks, resembling conglomerates, from several parts of the Bamble formation, have been described under the name pseudoconglomerates. In the Arendal district, at Krogen, Rorevann, we find similar rocks. Possibly, they represent highly metamorphic quartz-conglomerates. The pebbles, mostly consisting of quartz, are highly deformed and stretched. Since similar rocks are found elsewhere in the Bamble formation, they may help us to find discordances in the old supra-crustal systems.

3. Banded Gneisses.

In the Arendal district we find banded gneisses in the belt of rocks bordering the coast. They are built up of alternating dark and light "bands" of varying thickness, from a few cm up to several meters. The "bands" consist of amphibolites, biotite quartzites, dioritic and granitic gneisses. Seen from a distance, both the strike and the dip seem to be very constant. Usually the strike is about NE—SW and the dip 50—80° SE (Fig. 2), but detailed investigations show that we have a strongly folded formation of isoclinal folds with folding planes dipping SE (Pl. I, Fig. 1).

Both a horizontal and a vertical plane cut the folds obliquely and, knowing the projection on both these planes, we are able to construct the folds. Due to the marked difference in colour of the bands, it is generally easy to distinguish the different bands or layers even when they are strongly deformed. The effect of different orientation of the folding axes is shown in Fig. 3.

The amphibolites contain as essential minerals green amphibole and plagioclase with 40—60 % An.

The amphibole is usually coarsely crystallized and gives the rock a gneissic structure. Often it is poicilitic, containing rounded grains of plagioclase. Relics of both orthorhombic and monoclinic pyroxenes bestow on the rock a similarity to the hornblende norites belonging to the charnockite series (arendalite).

The original structures are always obliterated, but investigations of the tectonics of the banded gneisses indicate that the layers originally were lying nearly horizontally; the amphibolites are therefore best explained as basic effusives.

The acid rocks, exhibiting a very varying composition, may partly be explained as effusives (leptites), partly as sediments, and partly as metasomatic rocks. Occasionally we find small areas of biotite quartzites, resembling the north-western quartzites, and certainly representing relics not obliterated during the granitisation. Transitional zones between all the types of rocks are characteristically present, they must have been formed during the metasomatism, thus representing a stage in the homogenisation of the rock complex.

In some areas, the banded gneisses are seriously deformed. We find agmatites, nebulites, dictyonites, ptygmatites etc. (Pl. I, Fig. 2). The amphibolite bands are often broken and the fragments show every transition from amphibolites to diffuse, partly assimilated rock types. The minerals of the original amphibolite have become unstable, and have been changed to minerals in equilibrium with those of the surrounding rocks, amphibole to biotite etc.

It is impossible to understand the formation of the agmatites if the acid rocks, especially the quartzites, under certain thermodynamical conditions did not behave like a plastic mass that broke the more rigid amphibolite "bands" into fragments and encircled

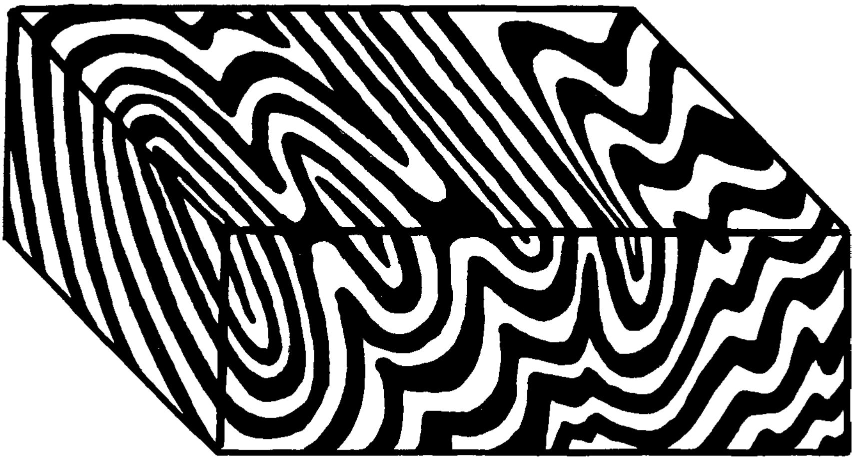

Fig. 3. The effect of different orientation of the folding axes in banded gneiss.
To the left: Axes pitching 50—60° SW.
In the middle: Axes horisontal.
To the right: Axes pitching 30° NE.

them. The foliation is always concordant with the contours of the fragments.

When the amphibolites obtained a certain degree of plasticity they did not break, but were folded in a way rembling the ptygmatic folding.

This zone of plastic deformation I have called *the special migmatic zone* of the banded gneisses. (Observed at Halvorshl.,Torungen, Spærhl.)

The true ptygmatites consist of strongly folded, narrow, granitic or aplitic dikes lying in a still more acid rock, usually of a massive structure. They are common in the migmatite-zones of the banded gneisses.

The origin of the ptygmatites has always been a matter of discussion. In the present area they probably were formed through plastic deformation of straight aplitic dikes, in the same manner as mentioned for some of the amphibolite folds. Before the rocks reached the condition of plastic deformation they passed through a zone where fracturing took place. For instance, at Indre Torungen we may see how aplitic material filled straight, parallel fractures, originated through folding-faults (Pl. II, Fig. 3).

By the following plastic deformation the dikes became more rigid than the country-rock, and the ptygmatites developed.

Experimental investigations also support this explanation (O. M. Erdmannsdörfer 1938).

4. Limestones.

The limestones between Grimstad and Kristiansand have been described by Olaf Holtedahl (1917). He mentions their stratification and is in favour of a sedimentary origin. The several occurrences (Hærøya, Rivingen, Fladerivingen, Maløy etc.) show great resemblance, and Holtedahl thinks they represent nearly the same stratigraphical horizon.

They appear chiefly in a narrow zone along the coast in north-east—south-western direction and seem to be limited to areas of banded gneisses. At Esketveid on the opposite (north-east) side of the Grimstad granite the limestone-zone appears again in the strike direction, and can now be followed as a strongly folded skarn-limestone zone for several kilometers in NE direction (Fig. 14). Occasionally, the limestone is still preserved (Ranneklev, Nøddebro, Klodeborg), but is usually replaced by skarn minerals and iron ore. Some of the best-known deposits of iron ore occur within this zone, thus indicating a genetic relation between the limestone and the ore.

The limestones often appear as thin layers alternating with quartzitic and dioritic gneisses (gneiss-banded limestones). The origin of the last-mentioned dioritic rocks is uncertain, for their chemical and mineralogical composition is often changed through reaction with the limestones. Small dark stripes, chiefly containing biotite, often indicate highly metamorphic sandstones.

Occasionally we find greater masses of limestones. The island Fladerivingen (200 m long and 100 m broad) chiefly consists of limestone. It has broken up younger amphibolites and granitedikes and flowed around the fragments as a plastic mass, filling every crack and fracture (Fig. 4) without any marked reaction on the contact.

Certainly the limestone does not lie in the place where it was first formed. By elevated temperature and under sufficient differential stress the limestone yielded in a quasi-plastic fashion. Solution took place where the pressure was sufficiently high, and the material was deposited at other places where the pressure was weaker, thus causing a gradual deformation of the rock (Riecke's principle).

Fig. 4. Plastic deformation in limestone. Fladerivingen SW of Grimstad.

In order to explain the comparatively great size of the deposit (Fladerivingen) it seems most probable that it developed from a gneiss-banded limestone situated at a somewhat deeper level. Due to differential stress, the limestone was squeezed along the bedding- or foliation-planes, fractures etc., occasionally concentrating to greater masses.

5. Hyperites.

Hyperites are known from many parts of the Bamble formation. In the north-western part of the district they appear as coarse-grained abyssal masses. Further south-east they occur as dikes of varying size, from some meters to 50—60 meters breadth. Following the strike of the country rock, we find on the coast a broad zone of hyperite-dikes and bodies. On Tromøy, one of the dikes was followed about 6 km from Kongshavn to Færvig. Large dikes are also seen on the southern parts of Hisøy and Gjervoldsøy, on Mærdø, inner Torungen, Ærø, Bratthl., Halvårshl., and Hasleodden where they are cut off by the Grimstad granite, appearing again on the islands on the opposite side of this granite. Important indications of the intrusive character of the hyperites are the mineralized zones (fahlbands) in the country rock near the contact. The hyperites are younger than the supra-crustal rocks and have forced their way up, cutting the banded gneiss (fig. 5). The rocks are medium- to coarse-grained, showing ophitic structure. The unmetamorphic types contain plagioclase, monoclinic and rhombic pyroxene, some amphibole, spinnelide, magnetite, apatite, garnets etc. The plagioclase may constitute about 50 vol. per cent of the rock and contains from 40—70, usually about 50 per cent An. The crystals are lath-shaped, displaying most of the feldspar twins, possibly with albite and pericline twins in preponderance. The second main mineral in the south-eastern district is a pigeonitic pyroxene, forming a mesostasis between the other minerals, often including them.

The optical properties for two pyroxenes (from Tromøy) measured on the Fedorow stage are as follows: (1) Pigeonite $+2\,V_{Na}=16^\circ$, $c:\gamma_{Na}=39^\circ$, $\alpha_{Na}=1.690$, $\angle\ (110) \sim 93^\circ$. The plane of the optic axes is (010). The pyroxene contains small brown interpositions of ilmenite (?) ‡ 100.

2. Augite $+2\,V_{Na}=52^\circ$, $c:\gamma_{Na}=44^\circ$.

After Winchell (1935) the composition should be:

	Pigeonite	Augite
Diopside	14	30
Hedenbergite	6	30
Clino-enstatite	56	20
Clino-hypersthene	24	20

The pyroxenes are often zoned with decreasing CaO from the core towards the periphery. They often exhibit a fine lamellation parallel to the plane of the optic axes, resembling the perthite structures, formed by exsolution of homogeneous mix-crystals. The crystals show great resemblance to the augite—perthite described by W. Wahl (1907, 1908) and it is probable that they represent a stage in the unmixing of a pigeonite. Recent investigations (T. F. W. Barth 1936, Tsuboi 1932) indicate that pigeonites only appear in the intrusive and effusive, but not in the abyssal stage of a rock. Being stable only at high temperature they exist at normal temperature metastably. With increasing temperature under metamorphism, they will tend to unmix, thus giving one diopsidic and one enstatitic pyroxene

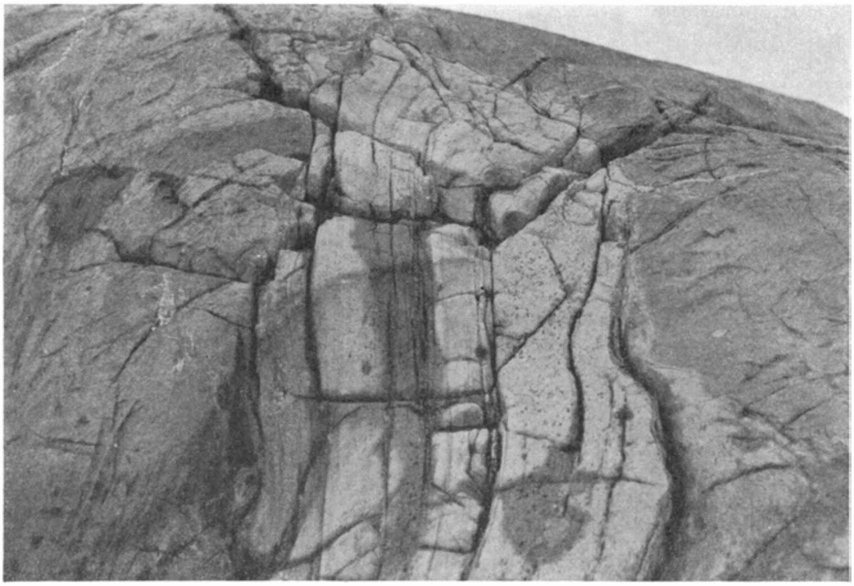

Fig. 5. Hyperite cutting banded gneiss. Ærø.

Between pyroxene and plagioclase a corona structure is usually encountered. From the pyroxene and outward the coronas are composed of hypersthene, brown hornblende, and garnet (Pl. II, Fig. 4).

In the hyperites of the north-western district I have never found pigeonitic pyroxene. Instead they contain augite and hypersthene, often resembling the Kragerø hyperites, so excellently described by W. C. Brøgger (1935).

Through later processes the hyperites are often amphibolitized, the larger bodies only in the peripheral parts, the smaller ones often completely.

6. Arendalites[1] (Charnockite-rocks, Urgranite).

These rocks range in composition from norites and hypersthene diorites to charnockites and granites. Both the chemical and the mineralogical composition testify to a direct consanguinity between the several types. They are related in space and time, reaching from Søndeled to Øiestad.

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[1] These rocks, being of metasomatic origin, will be given a more detailed description in another paper.

Hypersthene granites from Søndeled was first mentioned by Olaf Andersen. The wide distribution of the hypersthene diorites and hypersthene granites was pointed out by Carl Bugge who has carried out most of the field investigations.

It is difficult to distinguish these rocks — which often show a gneissic structure — from the other gneisses with which the arendalites always form a broad transitional zone, consisting of rocks that I have called *border-migmatites.*

The arendalites have the peculiar brownish to greenish colour as commonly observed in the monzonite — charnockite rocks. Usually they are medium-grained, showing an equigranular, hypidiomorphic texture, which in the metamorphic facies may be granoblastic to gneissic.

The Basic Division (ca. 48—55 % SiO_2).

The basic members of this series usually appear in the intermediate and acid rocks as flakes or diffuse dikes of varying size. They wedge out along the strike (ca. NE—SW) and can seldom be followed over greater areas.

The types vary from gabbros, norites and jotun norites to hornblende gabbro and amphibolites.

Table 1 shows the analysis of a typical hornblende norite from Solbakken, Langsev (Pl. III, Fig. 5).

The mineral content is plagioclase, amphibole, hypersthene, magnetite, apatite, some secondary quartz, and scapolite.

The plagioclase is determined $\perp \alpha$ by the extinction

$$\beta : 010 = +13^\circ, \text{ giving } Ab_{70}\ An_{80}.$$

The hypidiomorphic crystals, having both albite and pericline twins, show signs of cataclastic deformations and are often broken or bent. Sometimes they are changed to a strongly pigmented mass for which no optical datas can be given. This mass contains small grains of scapolite and seems to represent a stage in the replacement. Since no calcite is visible, the CO_2 (0.55 %) is probably concealed in the small inclusions of the pigmented mass.

The essential dark minerals are greenish-brown hornblende and ortho-rhombic pyroxene. Hornblende often surrounds pyroxene which it also replaces (Pl. III, Fig. 6). The extinction $c : \gamma_{Na} = 17^\circ$; the angle of the optic axes $= 2V \sim 80^\circ$. The pleochroism is: $\gamma =$ dark

Table 1.

	Weight %	Molprop. × 10000	Norm	Niggli
SiO_2	49.28	8172	or 3.28	si 113
TiO_2	1.30	162	ab 35.89	al 20
Al_2O_3	14.77	1445	an 21.51	fm 49
Fe_2O_3	4.30	269	———	c 21
FeO	8.74	1216	Σ sal.... 60.32	alk 10
MnO	0.24	34	wo 7.25	k 0.08
MgO	6.76	1677	en 3.86	mg 0.48
BaO	0.02	1	fs 2.48	si^1 140
CaO	8.31	1481	fo 9.04	qz −27
Na_2O	4.25	685	fa 6.42	
K_2O	0.56	59	ap 0.84	
H_2O-	0.09	50	il 2.50	
H_2O+	0.47	261	mt 6.26	
P_2O_5	0.35	25	———	
CO_2	0.55	125	Σ fem... 38.65	
S	0.04		H_2O.... 0.56	
	———		CO_2.... 0.55	
	100.03		———	
			Sum ... 100.08	

Anal. Ing. Klüver.

brownish green, $\beta =$ brown, $\alpha =$ pale yellowish brown. $\gamma > \beta > \alpha$. The refractive indices as determined by the immersion method are:

$$\gamma_{Na} = 1.682, \quad \alpha_{Na} = 1{,}660.$$

According to the tables of Esper Larsen the composition will be about: $Ca_4Na_2\ (Mg, Fe)_9\ (Al, Fe)_4\ Si_{13}O_{44}\ (OH)_4$

$$\text{where } \frac{Mg}{Fe} = 1.4, \quad \frac{Al}{Fe} = 4.8$$

Hypersthene. The angle between the optic axes is $2V \sim 65°$, the pleochroism $\gamma =$ pale bluish green $\beta \sim \alpha =$ pale pink. The refraction index $\gamma_{Na} \sim 1.695$ thus giving a hypersthene $en_{79}\ fs_{21}$.

The Intermediate Division (ca. 55—65 % SiO_2).

Table 2 shows the analysis of a more basic member of this division, a gabbro from Neskilen, Tromøysund.

The mineral content of this gabbro is plagioclase, ortho-rhombic and monoclinic pyroxene, hornblende, quartz, apatite and magnetite.

Table 2.

	Weight %	Molprop. × 10000	Norm	Niggli
SiO_2	55.15	9144	Q 6.99	si 148
TiO_2	0.95	119	or 3.11	al 26
Al_2O_3	16.45	1610	ab 30.76	fm 42
Fe_2O_3	2.77	173	an 26.98	c 21
FeO	6.90	960	———	alk 11
MnO	0.15	21	Σ sal.... 67.84	k 0.09
MgO	5.14	1275	wo 2.83	mg 0.49
CaO	7.30	1301	en 12.75	si^1 144
Na_2O	3.64	587	fs 8.82	qz 4
K_2O	0.53	56	ap 0.91	
P_2O_5	0.38	27	il 1.81	
H_2O	0.25	139	mt 4.01	
	99.51		Σ fem... 31.13	
			H_2O.... 0.25	
			Sum ... 99.22	

Anal. J. Bugge.

The plagioclase, forming hypidiomorphic crystals, is determined $\perp \alpha$ by the extinction angle $\beta : 010 = +19°$ giving Ab_{63} An_{37}.

The rhombic pyroxene has the following optic properties:

Pleochroism: γ = bluish green, β = yellowish brown, α = pale pink refractive index $\gamma \sim 1{,}710$ thus giving a hypersthene: en_{72} fs_{28}.

It often shades into monoclinic pyroxene without sharp borders.

The monoclinic pyroxene has the optic angle $+2V = 60°$, extinction angle $c : \gamma = 45°$ and refractive index $\gamma_{Na} = 1.723$ and may thus be a diopsidic pyroxene with about 45 weight perc. hedenbergite.

The hornblende has the following optical properties:

$-2V_{Na} \sim 80°$, $c : \gamma_{Na} = 21.5$, refractive indices: $\gamma_{Na} = 1.680$, $\alpha_{Na} = 1.659$ and pleochroism γ = dark green, $\beta \sim \alpha$ = yellowish green.

The composition of this hornblende is very close to that described on page 83.

Biotite, with refraction index n = 1.642 on cleveage flakes and pleochroism γ and β dark brown, α — pale brown, is of minor importance.

Table 3.

	Weight %	Molprop. × 10000	Norm	Niggli
SiO_2	64.59	10711	Q 13.83	si 229
TiO_2	0.71	89	or 4.23	al 31
Al_2O_3	14.80	1448	ab 52.71	fm 38
Fe_2O_3	2.05	128	an 8.55	c 8
FeO	4.95	689	c 0.67	alk 23
MnO	0.16	23		k 0.07
MgO	3.35	831	Σ sal.... 79.99	mg 0.46
BaO	0.04	3	en 8.31	si^1 192
CaO	1.96	349	fs 6.53	qz 37
Na_2O	6.24	1006	ap 0.44	
K_2O	0.72	76	il 1.35	
H_2O-	0.10	55	mt 2.97	
H_2O+	0.24	133		
P_2O_5	0.19	13	Σ fem... 19.60	
CO_2	tr.		H_2O ... 0.34	
S	0.06			
			Sum ... 99.93	
	100.16			

Anal. Ing. Klüver.

Table 3 represents the analysis of an acid member of the intermediate division, a quartz-hypersthene diorite (arendalite) from Solbakken, Langsev (2 meters south of the hbl. norite described page 82).

It contains plagioclase, quartz, hypersthene, some biotite, magnetite and apatite. The plagioclase determined ⊥ α by $\gamma : 001 = +7°$ gives Ab$_{86}$ An$_{14}$. The crystals are often broken or bent, and have albite and pericline twins. The quartz is highly pigmented and shows undulating extinction.

The hypersthene has the optical angle $-2V_{Na} = 60°$, pleochroisme γ — bluish green, β — brown, α — pale pink and refraction index $\gamma_{Na} \sim 1.713$ corresponding to a hypersthene en$_{70}$ fs$_{30}$.

The other minerals are of accessory importance.

The intermediate division includes a great variety of rocktypes, all characterised by rhombic pyroxene and an acid plagioclase often being antiperthitic (Fig. 6).

In the same rock we may find feldspars of different composition, andesine or obigoclase, antiperthitic acid plagioclase, perthite and microcline. Several types exhibit an astonishing similarity to rocks of the charnockitic tribe of the Egersund district and of the Bergen—Jotun tribe of the Norwegian Caledonian igneous series.

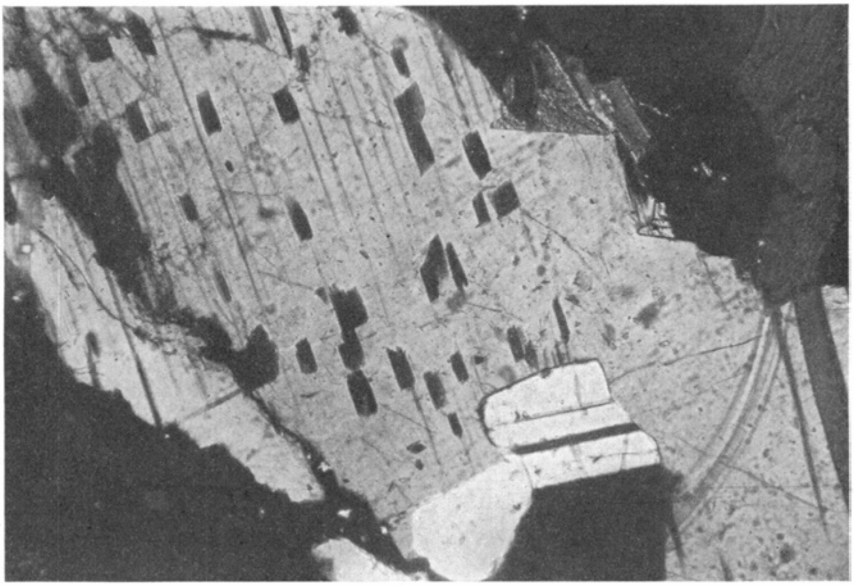

Fig. 6. Antiperthite in Arendalite. ×60, nic. crossed.

The quartz-hypersthene diorite with acid antiperthitic plagioclase, I have called *arendalite* because it is typical of the Arendal district and represents a member of the charnockite series which apparently is in want of a new name.

From enderbite, described by Tilley (1936), it is distinguished by a more acid, antiperthitic plagioclase. The content of hypersthene ranges from 10—20 %, that of quartz around 20 %, whereas enderbite exhibits 3 % and 42 % respectively.

The Acid Division (> 65 % SiO_2).

The intermediate rocks pass continuously into the acid types with members corresponding to every stage in the transition. Table 4 represents the analysis of a typical charnockite from the Langsev mining district.

This rock contains plagioclase, perthite, quartz, hypersthene, biotite, magnetite and apatite.

The plagioclase is determined ⊥ PM and varies in composition from 8—12 % An, more acid when containing antiperthitic spots of potashfeldspars than in pure plagioclase.

Table 4.

	Weight %	Molprop. × 10000	Norm		Niggli
SiO_2	70.28	11655	Q 20.36		si 314
TiO_2	0.26	32	or 11.01		al 38
Al_2O_3	14.40	1409	ab 55.18		fm 25
Fe_2O_3	1.89	118	an 3.52		c 3
FeO	2.62	365	C 0.42		alk 34
MnO	0.14	20			k 0.16
MgO	1.17	290	Σ sal....	90.49	mg 0.32
CaO	0.71	127	en 2.90		si^1 248
Na_2O	6.53	1053	fs 3.10		qz 66
K_2O	1.87	198	ap 0.10		
P_2O_5	0.04	3	il 0.49		
H_2O	0.22	22	mt 2.74		
	100.13		Σ fem...	9.33	
			H_2O ...	0.22	
			Sum ...	100.04	

Anal. Jens Bugge.

Antiperthite determined $\perp \gamma$ by $\alpha : 001 = +16^\circ$ gives Ab_{92} An_8. The Hypersthene has the following optical properties:

The optic angle $-2V_{Na} \sim 60^\circ$, pleochroisme:

γ = bluish green, $\beta \sim \alpha$ = pale pink and refraction index $\gamma_{Na} \sim 1.717$ corresponding to a hypersthene en_{67} fs_{33}.

The biotite has the pleochroisme γ and β dark brown α — colourless, The refractive index, measured on the cleavage flakes: $n = 1.641$. The flakes commonly are surrounded by an opazite border, constituted of rutile and magnetite, formed through resorbtion of the biotite.

The acid division also includes a great variety of rock types, quartz—hypersthene diorites, charnockites, biotite or amphibole granites etc. They are characterized by a strongly perthitic feldspar (Pl. IV, Fig. 7), but contain, usually, feldspars of different compositions as mentioned also for the rocks of the intermediate division. Where plagioclase borders to potash feldspar it is common to find myrmekite (Pl. IV, Fig. 8).

It is proposed that rocks of the whole series, ranging from the basic to the acid division, be called *arendalite rocks*.

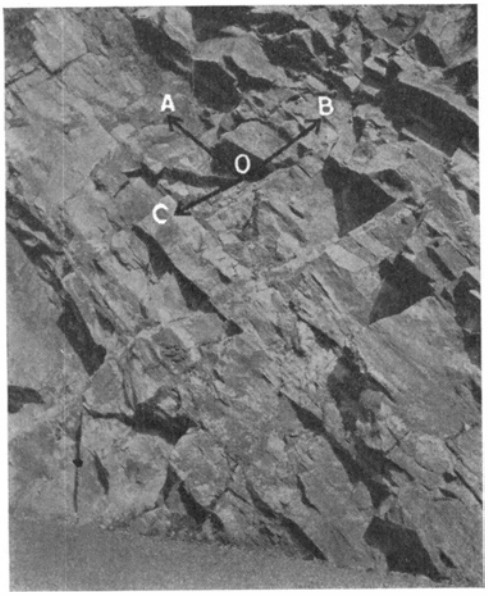

Fig. 7. Arendalite, Strømmen, Hisøy.

Tectonics.

The main cleavage directions are shown by the cross O—A B C in the Fig. 7. The strike and the dip are always observed parallel to the plane O A B. The strike varies about N 30—40° E and the dip 50—70° SE and are parallel to the foliation planes of the country rocks. The fractures parallel to C O B (flat-lying cross joints) are often filled with pegmatite dikes of a thickness varying from some cm up to several meters.

As mentioned above, the arendalites pass through the broad zone of border-migmatites into the country rocks. When we cross the strike we find quartzite, amphibolite, granite, and arendalite in alternating bands or zones. Even in the central parts of the arendalite it is not unusual to find relics of the older rocks. The ore districts Solberg, Torbjørnsbo, Langsev, are, for instance, such relics of the old complex.

It is interesting that the arendalite sometimes shows eruptive character indicating a magma, which has forced its way upward, pushing the other rocks away, while at other places, especially in the south-eastern part it continuously passes into the banded gneisses.

7. Quartz—Biotite Diorite.

The diorite south-west of the Grimstad granite is on the map marked in the same way as the arendalite. The rocks are massive, greyquartz diorites with abyssal character. On the coast they pass continuously into banded gneisses and migmatites. They are not yet studied in detail, but probably represent members of the arendalite series. They correspond to the coastgranite of Arne Bugge.

8. Granites.

In the Arendal district we can distinguish between the following types of granitic rocks[1]:

1. The oldest red granites.
2. The granite pegmatites.
3. The Grimstad granite.

The Oldest Red Granites.

The large bodies of granites with abyssal character are chiefly situated in the northern or north-western part of the district. From the coast towards north-west they increase in amount and size, until at Nelaug we meet the great Telemark granites.

As usual for migmatite granites, they pass through a broad transitional zone into the surrounding rock types. In the southern parts of the Arendal district (Fig. 13), the granites only form dikes of varying size, usually following the strike of the countryrocks. The largest of them are usually accompanied by swarms of smaller dikes.

The granitic liquors have often caused a marked granitization in the pre-existing rocks, the dikes therefore are usually accompanied by broad zones of injection gneisses.

The dikes of granite are medium- to fine-grained. From the ore district T. Dahll (1861) describes them as red quartzites.

The chief constituents are microcline and quartz, subordinary plagioclase, biotite, diopside, magnetite etc.

The most frequent of the dark minerals is biotite, but this depends to a certain degree upon the composition of the country rock. When the dikes cut zones of skarn they may for instance contain diopside, titanite, epidote etc. instead of biotite.

The Granite Pegmatites.

Pegmatites have a wide distribution and are found in all the rocks mentioned, as "schlieren", dikes or big masses occupying several hundred m^2. In the migmatic and gneissic areas schlieren gneisses (arterites) are very common. The pre-existing rocks have been quite infiltrated with granitic liquors (ichor) that partly caused

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[1] Here is not included the charnockites, which are described under the acid division of the Arendalites.

a feldspathization and partly segregated as schlieren. It seems impossible to regard the granitic material as formed by differentiation of a magma. A palingenic origin (at a deeper level) in the manner proposed by Sederholm is more reasonable. The observations of T. F. W. Barth (1930) and Olaf Andersen (1931) are also in accordance with this mode of origin.

During discussion of the origin of the small pegmatite bodies (the Arendal district) in the Bamble formation, O. Andersen writes: "In view of these facts the conclusion seems necessary that all this communication between the magma and the openings where pegmatites are formed, either inside or outside the granite, to a large extent has taken place through very narrow channels. Further evidence for this conclusion is found in the following circumstances: The small cracks now filled with pegmatite have no visible interconnecting channels, and the granites with their adjacent rocks show very few traces of large, continuous openings through which a widespread communication between the magma and its surroundings can have taken place. The pegmatites in general give the impression of being closed bodies, the openings giving access to the liquids from which they crystallized must have been of such fineness that they escape detection by field methods, they may have been almost capillary continuations of unvisible cracks. This, in my opinion, constitutes one of the fundamental differences between pegmatites and ordinary igneous dikes and is a point to be considered when the genesis of pegmatites is discussed."

The dikes may be from a few dm up to several meters thick, and it is common to find pegmatitic and aplitic dikes in close connection. They transverse the rocks in several directions, often filling flat-lying joints, striking about NW—SE and dipping 20—30° NE. In the mine Torbjørnsbo we find four such parallel dikes, the distances between them being some meters.

The big, coarse-grained bodies of pegmatite are very interesting. They often appear in connection with hyperites and are frequently seen near the borders of the great areas of quartzite. At Løddesøl they can be followed several hundred meters as small ridges, 50—60 m broad. It is significant that these great masses occur in close connection to the quartzites. As mentioned, the quartzites commonly resist granitization and often seem to be impervious to the granitic liquors (ichors). When these liquors on their way upward met with large quartzite bodies they could not soak through them, but had to flow around, thus forming accumulations around the edges of the quartzite bodies. Now they are seen in the terrain as long ridges surrounding the quartzite areas. (For a more detailed description of pegmatites from the southern Norway see O. Andersen (1928, 1931), T. F. W. Barth (1928), W. C. Brøgger (1906, 1922)).

The Grimstad Granite.

This granite occupies a circular area (about 50 km^2) east of Grimstad. It is a red, coarse-grained granite of a uniform structure. In addition to the main rock type we find smaller areas of more basic rocks, genetically connected with the main type, but older than this. They are situated in the strike directions of the great amphibolite dikes at the coast and, probably, they are formed through assimilation of material from these rocks. Even if they are formed in this way they may very well look like rocks formed by fractional crystallisation.

Except for the dikes of diabase and the great dikes of rhomb-porphyry, the Grimstad granite is the youngest rock in the Bamble formation. Usually it displays a sharp eruptive contact against the older rocks, with vertical borders. (For a more detailed description see I. Oftedahl 1938.)

9. The Regional Migmatites.

Between the north-western quartzite—hyperite formation and the southern arendalites lies a broad zone with migmatic rocks, viz. alternating bands of quartzites, amphibolites, arteritic gneisses, granites etc. The zone represents the supra-crustal rocks, amphibolites etc. in highly metamorphic facies. I have called the rocks *regional-migmatites* as distinct from the above-mentioned border- or contact-migmatites (pag. 82). Both of them are formed by melting and migmatization in connection with injection of magmatic solutions, which in the regional-migmatites were usually of granitic composition. The processes may be analogous to the *regional- and contact-metamorphism*, but have proceeded at deeper levels of the earth's crust.

Since these rocks appear in a rather intimate connection, I have not, on the map, usually distinguished the different rocks.

We find rocks resembling the banded gneisses of the coast, but the best indication of pre-existing supra-crustal rocks in the district is given by the skarn zones.

10. The Skarn Zones.

Under the general description of the rocks, I have mentioned the deposits of skarn and limestone in the zones of the regional-migmatites. They occur alternating with quartzitic, dioritic, amphibolitic and granitic rocks. Certainly we here have a formation of sedimentary mode of origin.

The deposits of iron ore are situated in these zones and the limestones have been of major importance for the genesis of the iron ore. There exist transitions between the limestone and the skarn, and the mineral parageneses of the skarn indicates that it represents contact metamorphic limestones.

The longest zone (see Fig. 14) is followed continuously over a distance of 7 km, viz. from Klodeborg to the Grimstad granite. Since the last 400 meters are covered by quaternary deposits, I could not find the exact borders. The zone appears again on the islands south-east of Grimstad. North-eastward it can be followed discontinuously ca. 7—8 km from Klodeborg to Solberg, Torbjørnsbo and Langsev. Deposits of limestone are also known both farther to the south-west and farther to the north-east, making altogether a total length of 40—50 km (the main skarn zone).

Other than this chief zone, we find smaller limestone areas, in zones nearly parallel to the chief zone. At Løddesøl, near the border of the quartzites and the regional migmatites, I have found a zone of skarn and limestone which I have followed for 300—400 meters north-eastward.

Near the road ca. 1 km north of Bjorbekk in Øiestad limestone is also found.

On Fig. 14 I have marked the mines of the chief zone. When we count all the shafts, the big as well as the small ones, there are about 100 between Esketveid and Klodeborg.

The rocks of the skarn zone pass by gradation into the surrounding rocks.

II. The Main Skarn Zone.

1. Mineralogy.

The most important minerals of the skarn deposits are: monoclinic pyroxene, garnet, vesuvianite, amphibole, epidote, zoisite, phlogopite, biotite, magnetite, scapolite, tourmaline, apatite, titanite, serpentine, rhodonite, pleonaste, babingtonite, datolite, analcime, pyrite, and chalkopyrite.

Pyroxene.

Monoclinic pyroxene is one of the most important skarn minerals. When together with garnet in the coccolite-kolophonite skarn it contains more iron than when it is encountered in contact with calcite and magnetite.

The optical properties of pyroxenes belonging to the coccolite type are: Axial angle: $+2V \sim 60°$, extinction angle: $c:\gamma_{Na}$ 43—44°. The refractive indices were measured by the immersion method in Na — light:

Langsev	$\alpha = 1.700$,	$\gamma = 1.720$
Torbjørnsbo	$\alpha = 1.695$,	$\gamma = 1.720$
Lærestveid	$\alpha = 1.690$,	$\gamma = 1.715$.

The colour is pale green to olive-green. Pleochroism cannot usually be seen.

The data correspond to a diopsidic pyroxene with 37—50 weight % hedenbergite, but small irregularities in the properties indicate small percentages of sesquioxydes; they seem, however, to be of minor importance. In an analysis of a coccolite (from ca. 1910) Doelter gives the following percentages:

Al_2O_3 1.37 weight %, Fe_2O_3 1.08 weight %.

The pyroxene of the diopside type is pale green to colourless. The extinction angle varies from 38—41°, and the optic angle $2V = 60°$. The following data were determined on a pyroxene from Klodeborg: $+2V = 60°$, $c:\gamma = 38.5$, and refractive indices $\alpha_{Na} = 1.670$, $\gamma_{Na} = 1.700$ corresponding to a diopside with 9 weight % hedenbergite.

Garnet.

Kolophonite is the predominating garnet. It is of a reddish brown colour and occurs usually together with coccolite in holohedral crystals of 1—5 mm diameter. The approximate composition can be deduced from the specific gravity and the refractive index. I used Clericis solution and Mohr-Westphals balance to determine the specific gravity, and the immersion method for the refraction index.

No. 1	Langsev	n = 1.83,	sp.gr. = 3.68
No. 2	Nøddebro	n = 1.83,	sp.gr. = 3.80
No. 3	Klodeborg	n = 1.83,	sp.gr. = 3.80

Number one corresponds to $An_{60}Gr_{40}$ and the other two to $An_{45}Gr_{86}Al_{23}$ (An = andradite, Gr = grossular, Al = almandine).

In the ternary diagram of Philipsborn (1928), the garnets would have a composition marked by the dark triangle of fig. 8. It is not unusual to find grossular—andradite garnets and pyropealmandine garnets together. The last-mentioned type commonly occurs in the amphibole schists and in the amphibolites.

Vesuvianite.

Vesuvianite seems to be a rare mineral in the skarn deposits. I have only found it at Nøddebro where it occurs with calcite, diopside and garnet. On account of its reddish brown colour, it may be confused with garnet. It is anomalously biaxial, positive with a very small optic angle. Birefringence weak and refractive index, n—1.705. Certainly it is one of the oldest skarn minerals.

Amphibole.

The amphiboles belong to two different series:

1. Tremolite—actinolite.
2. Common hornblende.

The tremolite—actinolite minerals are of less importance in the ore deposits. They are chiefly found in those deposits of limestone where metasomatic processes played a minor rôle (e. g. Løddesøl and the islands SW of Grimstad).

The hornblende skarn frequently follows the granite dikes, representing a reaction product between the granite magma and the older skarn.

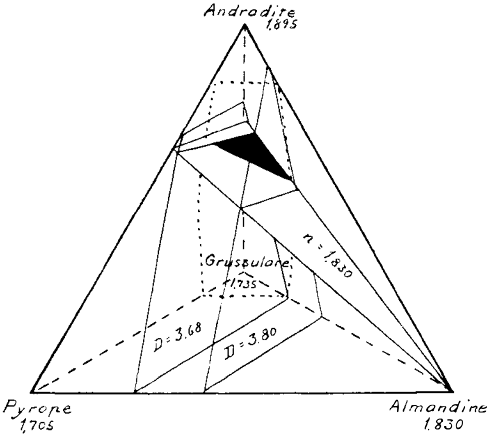


Fig. 8.

In hornblende—epidote—plagioclase—skarn from Lærestveid I made the following observations: The optic angle $2\,V_{Na} \sim 80^{\circ}$, extinction angle $c:\gamma = -18^{\circ}$, pleochroism: α = pale yellow, β = green, γ = bluish green.

refraction indices $\alpha = 1.633$, $\beta = 1.640$, $\gamma = 1.653$.

Disregarding Al_2O_3 the tables of Winchell give the composition:

$Ca\,Mg_2\,Si_2O_9$ = 80—85 weight %
$Ca\,Fe_2\,Si_3O_9$ = 2— 7 weight %
$Na\,FeSi_2O_6 + Fe_2O_3$ = 12—15 weight %

Epidote.

In some of the iron ore deposits, epidote is one of the most important skarn minerals. The green prismatic crystals may be 5—10 cm long and are elongated parallel to the b-axis, but the epidote is often found in dense masses too. Epidote from Solberg: Optic angle $-2\,V$ large, pleochroism: α and β = colourless, γ = pale yellow, refractive indices:

$\alpha = 1.731$, $\beta = 1.750$, $\gamma = 1.761$.

This corresponds to a composition

$(OH)\,Ca_2\,Al_2Si_3O_{12}$ 77 mol %
$(OH)\,Ca_2\,Fe_3\,Si_3O_{12}$ 23 mol %

Mica.

The mica-skøls or skarns form short "bands or dikes" among the other skarns. The predominating mica minerals are phlogopite and normal biotite. I have determined a phlogopite from calcite—phlogopite skarn, Langsev: It is nearly colourless and the pleochroisme faint. The optic angle —2 V = 1—2°, and the refractive index determined on cleavage flakes n = 1.605. According to Winchell's diagram the composition is:

Phlogopite	38	mol %
Eastonite	38	—
Annite	12	—
Siderophyllite	12	—

Biotite from a skøl at the Tengstevid deposit has the pleochroism γ and β: brown, α: pale yellow and is biaxial negative, —2 V very small.

The refractive index on cleavage flakes, n = 1.625, corresponds to a normal biotite with ca. 25 % of each of the four constituents.

Magnetite.

Magnetite seems to be the only ore mineral present in the ore deposits of the Arendal district. However, determinations with the ore microscope have not yet been made and the ore may contain a little hematite. The ore usually forms steeply dipping stocks or lenses in the more central parts of the deposits.

The ore has brecciated the coccolite—kolophonite skarn (see J. H. L. Vogt, 1908, 1918) and is certainly younger than the skarn. Nearly all the mines are water-filled and, therefore, usually it is not possible to investigate the ore in detail. For some of the mines we have a description by J. H. L. Vogt, who also deals with the production and other economic relations. I have taken from his book the analyses (1906) published on page 27:

	Klodeborg	Torbjørnsbo	Langsev
Fe_3O_4	66.30	73.56	60.79
SiO_2	11.30	11.50	23.28
Al_2O_3	1.20	3.75	2.76
MnO	1.95	0.87	0.78
CaO	9.20	7.20	10.93
MgO	6.90	2.46	4.08
P_2O_5	0.06	-	-
S	0.82	0.032	-
Sum	97.73	99.37	102.92
Fe	48.9	53.29	44.02
P	0.035	0.018	-

Klodeborg

Fe_2O_3	47.36	Cu	traces
FeO	17.00	Pb	-
MnO	1.95	As	0.017
SiO_2	11.40	S	0.041
Al_2O_3	1.20	P_2O_5	0.032
CaO	9.00	CO_2	4.60
MgO	6.15	H_2O	0.55
BaO	-		
TiO_2	0.28	Sum	99.99
ZnO	0.013		
NiO, CoO	0.18	Fe	46.45
		Mn	1.55
		P	0.014

Vogt also gives the following averages from Klodeborg:

Fe	43—49 %
P	0.063 %
Mn	1.70—2.00 %
Zn	0.25 %

Scapolite.

Scapolite frequently occurs in dense, greasy masses as small veins in the skarn, but scattered small prismatic crystals can also be seen.

Optical constants for scapolite in a small vein from a coccolite—kolophonite skarn at Langsev are:

Uniaxial negative, refractive indices:

$$\omega = 1.570, \quad \varepsilon = 1.545.$$

This corresponds to the composition

Marialite 56 mol %, Mejonite 44 mol %.

At Alvekilen scapolite occurs in connection with magnetite, monoclinic pyroxene and saussuritised andesine. It shows transitions to the feldspars and is secondary after this mineral. Probably it originated a little later than the ore because small veins of scapolite are found in the ore (fig. 9).

Tourmaline.

Tourmaline is a rather rare mineral. It forms black crystals a few cm long in the skarn at Klodeborg and Alvekilen. It is uniaxial negative, with pleochroism ω = dark green, ε = pale grey and refractive indices:

$$\omega = 1.650, \quad \varepsilon = 1.625$$

corresponding to a schorlite composition.

Titanite.

Titanite occurs in microscopically small crystals in several skarns. Occasionally the crystals obtain a size of 1—2 cm.

Apatite.

The small, clear blue crystals always occur in the iron ore. They are uniaxial negative with refractive index $\omega = 1.640$.

In addition to the minerals mentioned, several others occur. They are not dealt with in this paper, but would certainly be of great interest for a more comprehensive description of the parageneses than it is the intention to present here.

2. Petrology.

Skarn, originally, is a Swedish term for the rather coarsely crystallized silicates which frequently occur as gangue minerals together with iron ore and commonly associated with limestone.

At the Arendal skarn deposits we can distinguish the following types:

Coccolite—kolophonite	skarn
pyroxene (diopside)	„
garnet (chiefly kolophonite)	„
amphibole	„
epidote—zoisite	„
mica	„
scapolite	„

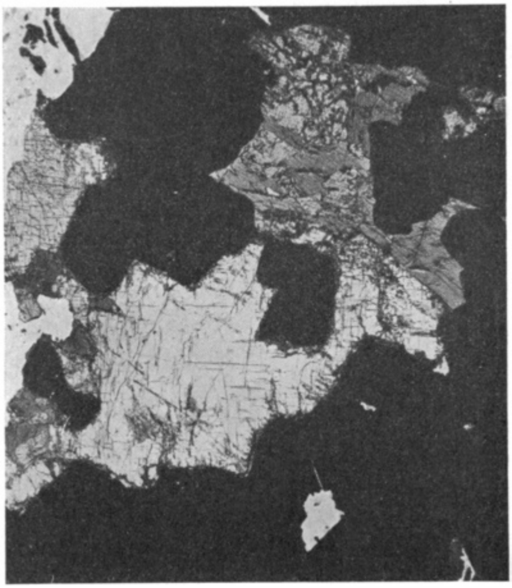


Fig. 9. Skarn iron ore, × 17$^1/_2$, ord. light. Magnetite, scapolite and some hornblende. Alvelandet, Tromøy.

Thorolf Vogt (1937) has classified the skarn iron ores according to the dominantsilicate minerals.

1. Garnet and monocline pyroxene, some spinnelides. The Torbjørnsbu type. Resembling the Persberg type of Harald Johanson.
2. Monocline pyroxene with some calcite, scapolite and spinnelide. The Klodeborg type.
3. Monocline pyroxene and hornblende with or without calcite, epidote,and scapolite. The Bråstad-Lærestveid type. Resembling the Björneberg type of Harald Johanson.
4. Calcite with some biotite and clorite. Ore from Solberg at Arendal. Resembling ore from Skärstöten.
5. Serpentine. Ore from Bråstad. Resembling the Bergsäng—Gubbotype of Harald Johanson.

The coccolite—kolophonite skarn was formed by metasomatic processes in the limestones in connection with the intrusion of the arendalites. The ore deposits always occur in close connection with these rocks and are never found at a distance from them. The mineral composition indicates an infusion of FeO, Fe_2O_8 ane MgO into the limestones. The analyses of the arendalites seem to verify this assumption, for their norms show an excess of the oxides mentioned.

The skarn protected the more central parts of the limestones against further metasomatic changes and much of the material in the minerals here met with (diopside, tremolite etc.), is derived from impurities in the limestones.

In this connection the mineral paragenesis found in the Løddesøl-limestone is of interest. Olivine, diopside, tremolite, calcite occur together and indicate normal contact metamorphic products of dolomites. With "normal contact metamorphism" I do not mean contact metamorphism in the usual sense. It is not an ascending magma which has caused the metamorphism, and we cannot here distinguish between an outer and inner contact zone, but we must emphasize that the metamorphism has taken place under the large regional foundering of the whole region. Olivine is one of the first minerals formed by the dedolomitisation. As distinct from tremolite and diopside it is usually serpentinized and occurs in the shape of rounded grains in a calcite—matrix. A similar serpentine—calcite skarn I have found in one of the mines also, and possibly we have had dolomites here too.

Regarding the temperatures at which these processes took place, the vesuvianite is of importance. T. F. W. Barth who has studied the deposits of skarn near Kristiansand writes:

"Die Metamorphose weist auf eine Temperatur die eben unterhalb des Stabilitätsfeldes des Vesuvians liegt. Lokal hat sogar die Temperatur, aber nur während ganz kurzer Zeit, den Bildungsbereich des Vesuvians überschritten." He thinks that the metamorphism has occurred below 500° C.

At the Arendal deposits the temperature also seems only locally, and for a short time, to have reached the stability field of vesuvianite. As mentioned, I have observed this mineral only at Nøddebro and it is difficult to tell whether or not it was ever formed at any of the other deposits. It may have disappeared or the chemical environment may have been unsuitable for its formation.

The ore was formed later and in connection with the intrusion of the granite dikes. It is a fact that several of the granites and pegmatites have a high percentage of magnetite and in the more northern parts of the Arendal district we find relatively large deposits of iron ore in the granite, viz: Lyngrot and Solberg in Holt, described as magmatic by J. H. L. Vogt.

The most common minerals that occur in the ore are diopside, calcite, scapolite, and apatite. Diopside may have formed in various ways, either by a normal contact metamorphism of the impure limestone, or, secondarily, from the coccolite-kolophonite skarn. If the iron of these minerals was removed by leaching, and recrystallized as magnetite, then the garnets would partly change to other minerals or other compositions and the pyroxene would probably become more diopsidic. N. H. Magnusson describes such a reaction from a Swedish locality (1929). The last-mentioned process is theoretically quite interesting but certainly of small importance. Diopside occurs as a typical contact mineral. The opposite reaction seems to be more probable, for magnetite seldom occurs in connection with the coccolite—kolophonite skarn. The formation of garnet and hedenbergite can be expressed in terms of the following reaction (N. H. Magnusson):

$$Fe_3O_4 + 4\ CaCO_3 + 5\ SiO_2 = Ca_3\ Fe_2\ Si_3O_{12} + Ca\ Fe\ Si_2O_6 + 4\ Co_2.$$

In regard to the genesis of the iron ore, scapolite, tourmaline, apatite etc, indicate that pneumatolytic agencies, derived from the granitic solutions, were instrumental in the formation of the ore, thus in their mode of origin resembling that of the contact metasomatic deposits of the Oslo region (V. M. Goldschmidt 1912). The granitic solutions rich in water and other volatile constituents permeated the skarns and the other strongly folded rocks of the ore deposits wherever they found suitable openings inducing replacements of the existing minerals by aquaeous minerals, such as amphibole, epidote, mica etc. Fractures and joints in the neighbourhood of the granitic dikes are usually filled with amphibole, epidote etc. The pyroxene may be replaced by hornblende, the uralite still containing a core of pyroxene. The epidotization in places proceeded so far that epidote is among the most abundant of the skarn minerals.

The minerals of the basic effusives, sills and dikes, were also changed and gave rise to schists or masses of skarn of hornblende and mica. The plagioclase has in places disappeared but forms often a saussieritic mass between crystals of hornblende, epidote and mica.

Among the youngest minerals encountered in the deposits are pyrite and chalkopyrite which fill small cavities in the skarn, and were formed at low temperature by hydrothermal processes.

3. Geological Description.

The longest of the skarn zones is drawn in Fig. 14. Almost continuously it can be followed from the Grimstad granite to Solberg, only interrupted where no skarn is found, between Nøddebro and Seldal and between Klodeborg and Solberg. The strongly folded rocks of the oldest complex can be seen all the way.

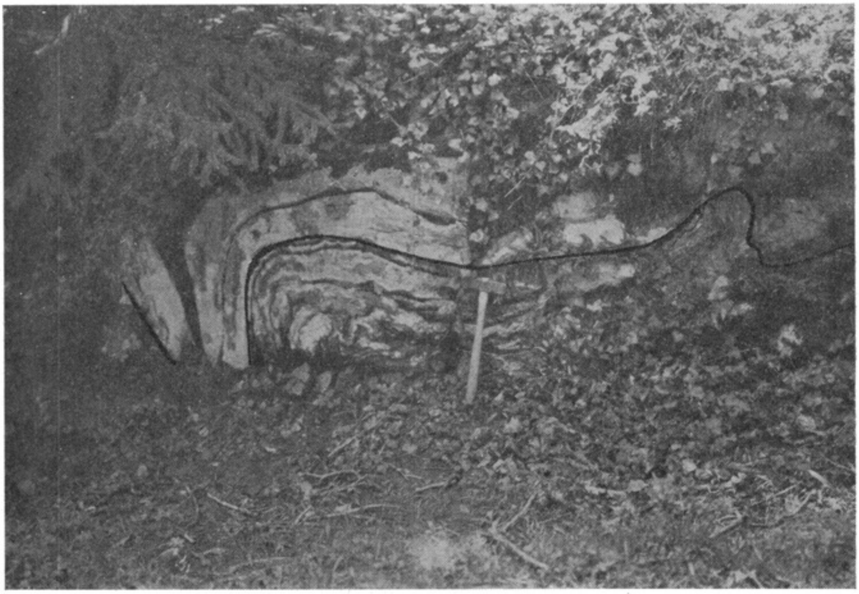


Fig. 10. Gneissbanded limestone from Klodeborg.

The zone is approximately straight, the breadth varies. It passes by transitions into the country rocks. On the map I have drawn rather arbitrarily a border line to indicate the zone, which is, or has been, of economic importance, as a demarcation of the area where skarn, mines, pits or other workings, or ore, commonly are found. All such workings from the mining periods are marked on the map, and it is seen that all are situated within the skarn zones.

The limestone is commonly replaced by skarn silicates and ore, but in some places, viz: Ranneklev, Nøddebro, and the mine of Klodeborg the limestone is partly preserved.

The limestone is frequently met with in vein-like masses, probably formed from circulating solutions, which in some places have dissolved the sedimentary limestone and redeposited calcite in fissures or crevices with "eruptive-like" aspect. In certain parts, as in the north-western part of the Klodeborg area, the limestone probably lies rather near its original place. Fig. 10, from the Klodeborg area displays some layers of gneiss-banded limestone and fig. 11 the same layers in the opposite direction at a distance of ca. 25 meters. The

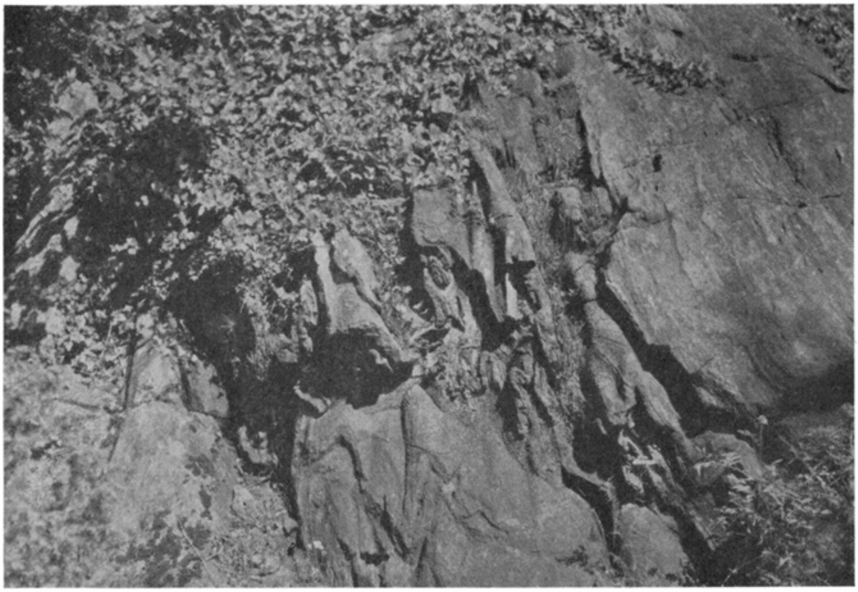


Fig. 11. Gneissbanded limestone from Klodeborg.

folding axis dips ca. 45° towards SW and on a horizontal plane the bands therefore will form wavy lines normally to the projection of the folding axis, as I have shown in fig. 3.

In the south-eastern part of the Klodeborg area there are large isoclinal folds with the folding plane striking NE—SW and dipping 60—70° SE. The mines are considerably larger in this part of the area and the layers of limestone have here in a higher degree been metamorphosized to skarn than have the flat lying beds in the northern part. Probably the ascending solutions could better find their way parallel to the foliation planes of the rocks than normal to the planes. The fact that the limestone at elevated temperature and under sufficient differential stress yields in a quasi-plastic fashion (page 78) has in the mining district been of importance and has influenced the size of the various ore deposits. Harker (1932) writes: "When a bed of limestone is involved in a system of closely oppressed folds, it may become entirely dissolved away in the middle limbs of the folds, the material being transferred to the crests and troughs which were places of relative relief."

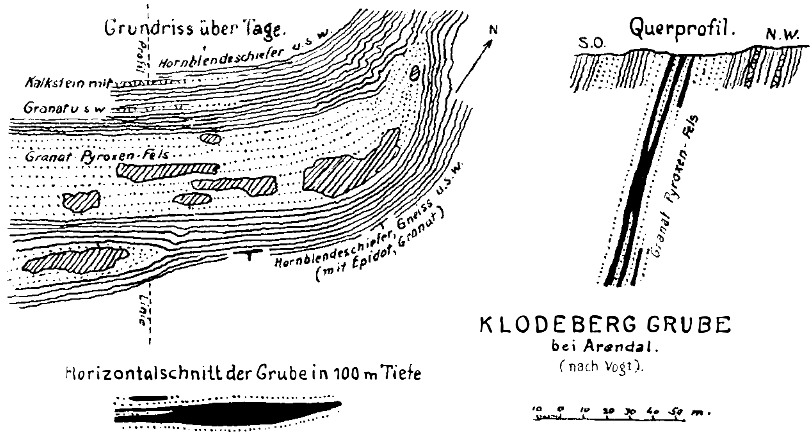


Fig. 12.

In this way the limestone may be squeezed out to lenses or rulers which have their longest axis parallel to the stress direction of the country rocks, just as in the case of many lenses of ore. J. H. L. Vogt writes about the mines of Klodeborg as follows: "The mine dips about 65° SE and besides shows a pronounced rake of about 23° towards SW." The direction of the axis of the ore coincides with the linear stress of the country rock. (Fig. 12.)

As a rule, the mines have their longitudinal direction towards NE—SW, but occasionally mines are found which are elongated in the direction NW—SE and dipping towards SW and these mines are connected with synclines and anticlines in a folding system with the axis dipping towards SW (Mikkelsberg west of Seldal, several of the Lærestveid mines etc.).

Almost without exception the mines in the whole district arrange themselves along several parallel lines or zones, the spacing between the lines is a few meters, but varies somewhat with the size of the folds. This structure is particularly well brought out on the map of Klodeborg and Langsev, fig. 12 and 15. Occasionally the folds may be followed from one of the zones mentioned to another.

The mines of Solberg, Torbjørnsbo and Langsev belong to the same large zone, but they are all completely surrounded by arendalite rocks. Th. Kjerulf and T. Dahll undertook a very detailed mapping of the ore-bearing region. The map gives an excellent picture of the structure of the mining districts and may, with a few corrections, very well be used to-day. The authors especially emphasize the complete bending of the schists around the mines. Langsev is terminated towards NE and Torbjørnsbo towards SW. The two fields are mutually somewhat displaced, they seem to be quite separated from each other by the arendalite rocks. They probably represent one large fragment of the old complex which, during the uprise of the magma, cracked in two.

The rather strongly inclined strata along the borders are mainly caused by the mutual movement and friction between the magma and the old complex. The foliation is always conformable with that of the arendalites and concordant with the margins.

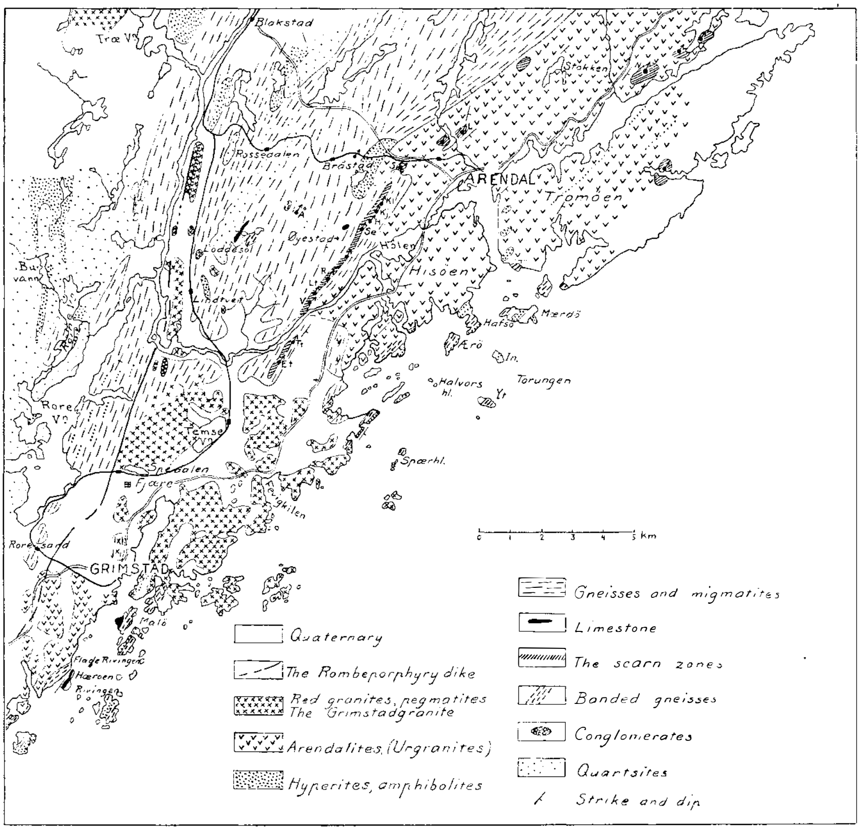


Fig. 13.

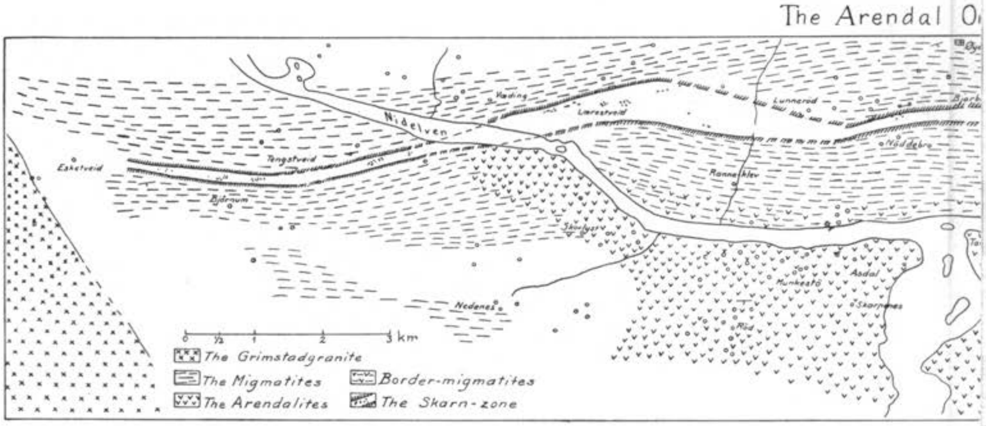

The Arendal O
Vading
Lunnerød
Bjørb
Lænestveid
Nidelven
Nøddebro
Esketveid
Tengstveid
Ronnekleiv
Bjørnum
Skovbyen
Asdal
Nedenes
Hunkestø
Skarpnes
Rød
0 ½ 1 2 3 km
The Grimstadgranite
The Migmatites
Border-migmatites
The Arendalites
The Skarn-zone

Fig.

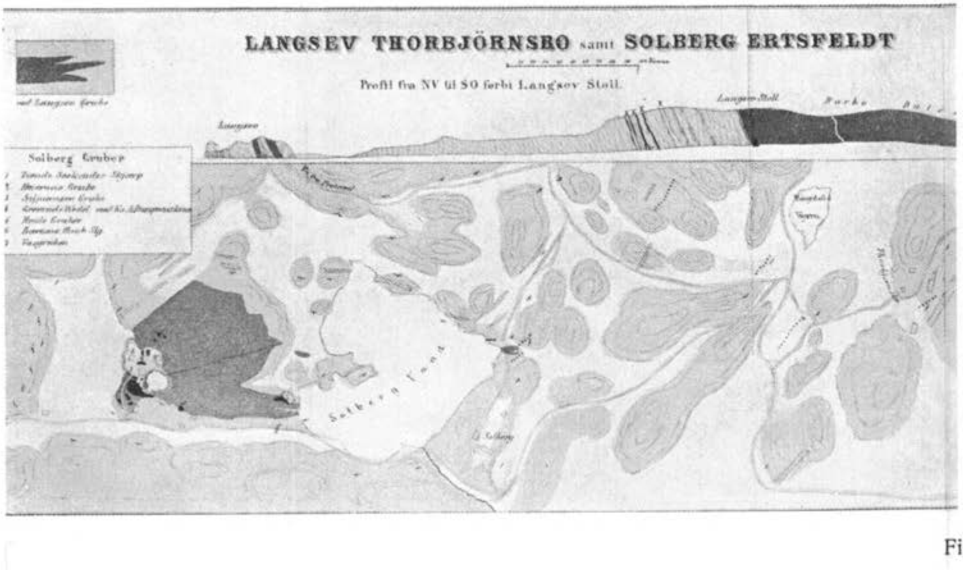
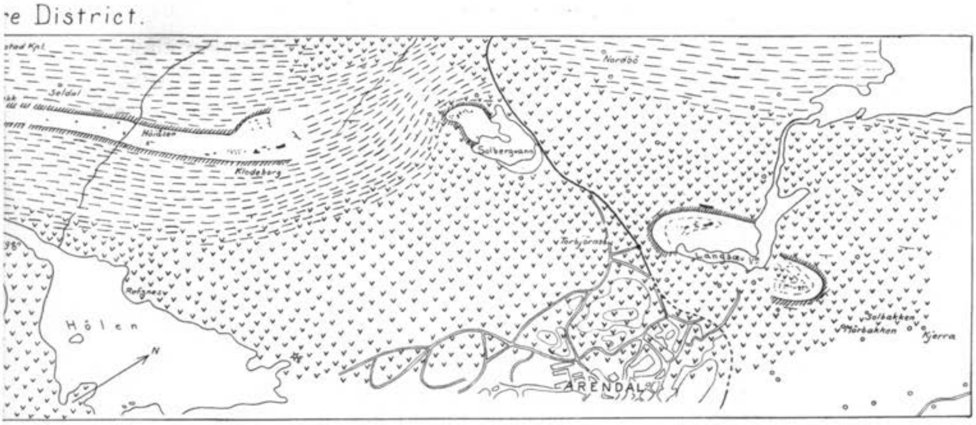

LANGSEV THORBJÖRNSRO samt SOLBERG ERTSFELDT
Profil fra NV til SO forbi Langsev Stoll.
Langsev Stoll
Solberg Gruber
Solberg Vand
Solberg

Fig.


e District.
stad Knt.
Seldal
Hörästen
Klodeberg
Nordbö
Solbergvann
Torbjörnsbu
Langsæv
Refsnes
Hölen
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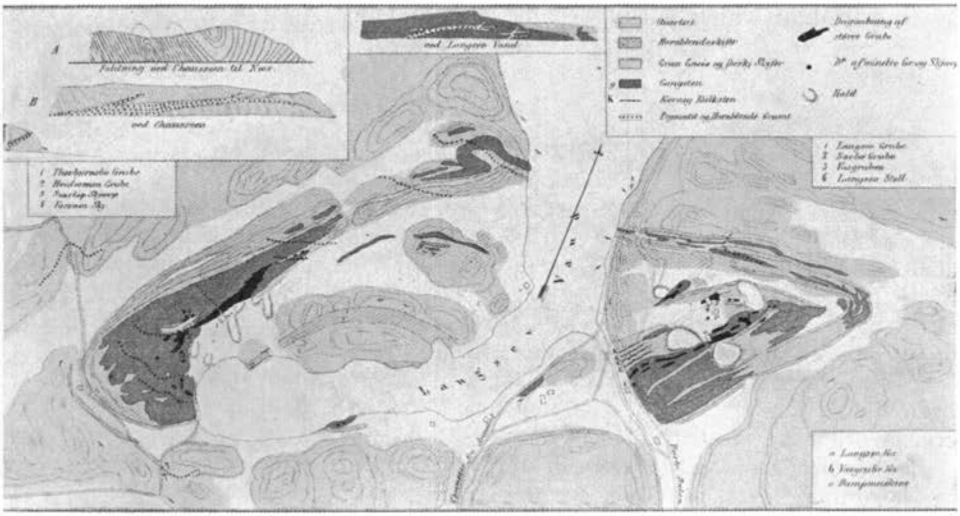
ARENDAL
Solbakken
Mörbakken
Kjerra

14.


A
B
ved Chausseen
ved Langsæ Vand
Hornblendeskifer
Gangsten
Kornig Kalksten
Hald
Langsæ Grube
Langsæ Stoll
Langsæ Vand

15.

It can be seen from the map of Kjerulf and Dahll that, like the schists, the dikes of granite bend around the mines. This picture is, however, not quite correct, for just at the bend the intrusive dikes are replaced by pegmatitic and granitic gneisses, but otherwise they usually follow the foliation and thus, in the same way as the schists, tend to bend together with them.

The Solberg area (see Fig. 14 and 15) is situated rather near the border between the arendalites and the old complex. Between Klodeborg and Solberg one sees the folding axis, which at Klodeborg dips steeply towards SW, lying rather flat, in places horizontally. Near the border of the arendalite rocks the schist layers are bent strongly upwards, in the border zone itself the layers are reversed with steep dips in the opposite direction. The Solberg area is completely detached from the old complex being entirely surrounded by arendalite. Towards SW the igneous rock is, however, so strongly mixed with material from the old complex that it perhaps ought to be considered as a border migmatite.

Probably the magma was not introduced by a single act of injection. It was probably slowly eating its way into the old complex, the material of which partly became assimilated.

Summary.

Rocks of sedimentary origin and probably also of effusive origin are common among the oldest rocks in the Bamble formation. The wide distribution of quartzites in the north-western part of the Arendal district is decidedly in favour of a sedimentary origin, and the main limestone-skarn zone which can ee followed for several kilometers in the direction of the strike, should, I suppose, by similarly interpreted.

Thus far no decisive proof of the existence of effusive origin has been found, but the structure of the banded gneisses indicates a supracrustal origin of these rocks.

The strongly folded rocks of the old complex were later invaded by hyperites, arendalites and granites. The name arendalite has been introduced for a new rock series ranging in composition from norites and hypersthene-diorites to charnockites. The types are related both in space and time and seem to form a batholith which is cut rather near the roof.

The skarn ore deposits lie in the skarn-limestone zones and are of contact metasomatic origin.

The correlation between the Bamble formation and other Archean districts is as yet very uncertain. Several Scandinavian geologists have tried to compare it with the Archean in Sweden and especially with the leptite formation of central Sweden. The present investigation has demonstrated a great similarity in the geology of the two districts. In both districts the oldest rocks are of supra-crustal origin, the limestones appear chiefly in connection with effusives, and the urgranites make up highly differentiated series. The post orogenic eruptions seem also to resemble those of the Bamble formation. Common leptites are scarce in the Bamble formation; usually they have been metamorphosed to leptite gneisses.

The charnockites often show a close resemblance to the charnockites of the Egersund districts and there may exist a connection between the two districts. In the Arendal district we have, however, never found bigger masses of anorthosites which are so common in the Egersund district.

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EXPLANATION OF PLATES

Pl. I

Fig. 1. Folds in banded gneiss. Spacing of limbs 5—6 m. Folding axes dipping 10—50° SW. Morvigen, Landvig.

» 2. From the migmatitezone of the banded gneiss. Østre Spærhl., Øyestad.

Pl. II

Fig. 3. Parallel aplitic dikes transversing the acid gneiss. Indre Torungen.

» 4. Microphoto of Hyperite, Tromøy. × 17 1/2.

P = pigeonite.
Pl = plagioclase.
s = magnetite-hypersthene-symplectite.
hy = hypersthene.
H = hornblende.
G = garnet.

Pl. III

Fig. 5. Microphoto of hornblende norite. × 17 1/2, ord. light. NE of Langsev ore district.

Pl = plagioclase.
H = hornblende.
hy = hypersthene.
m = magnetite.
a = apatite.

» 6. Hornblende replacing hypersthene (uralite). × 63, ord. light.

Pl. IV

Fig. 7. Microperthite in charnockite. × 60, nic. crossed.

» 8. Myrmekite in charnockite. × 60, nic. crossed. Klåholmen.

Fig. 1

Fig. 2

Fig. 3

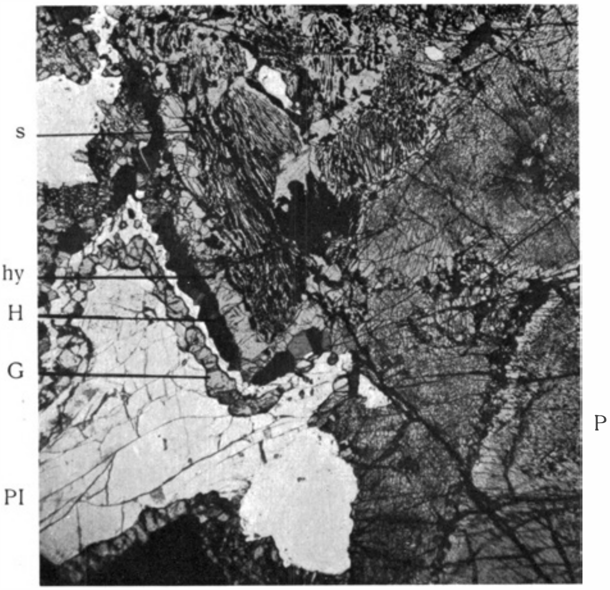

Fig. 4

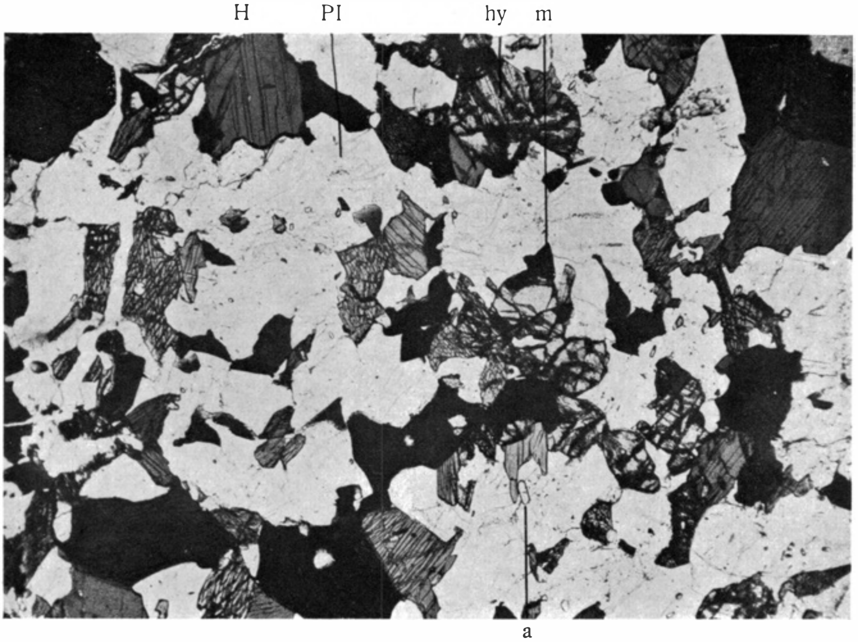

Fig. 5

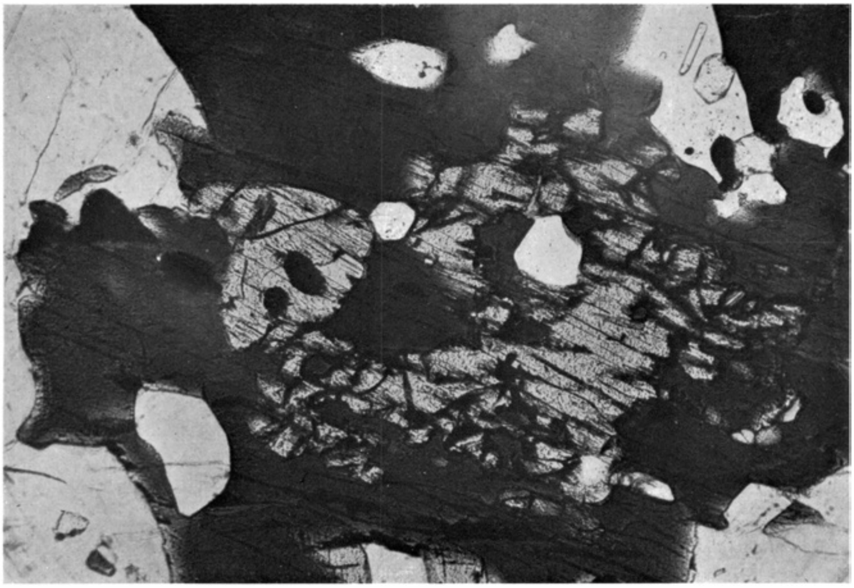

Fig. 6

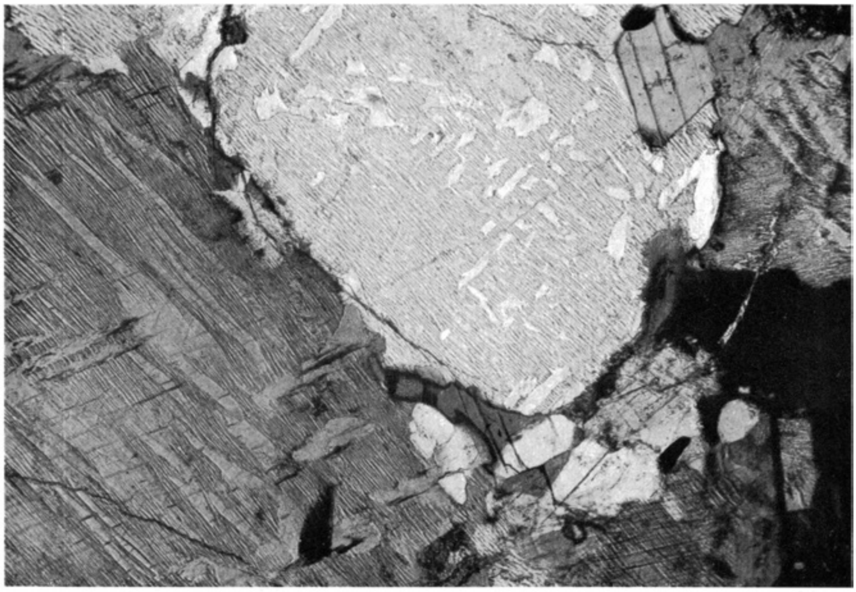

Fig. 7

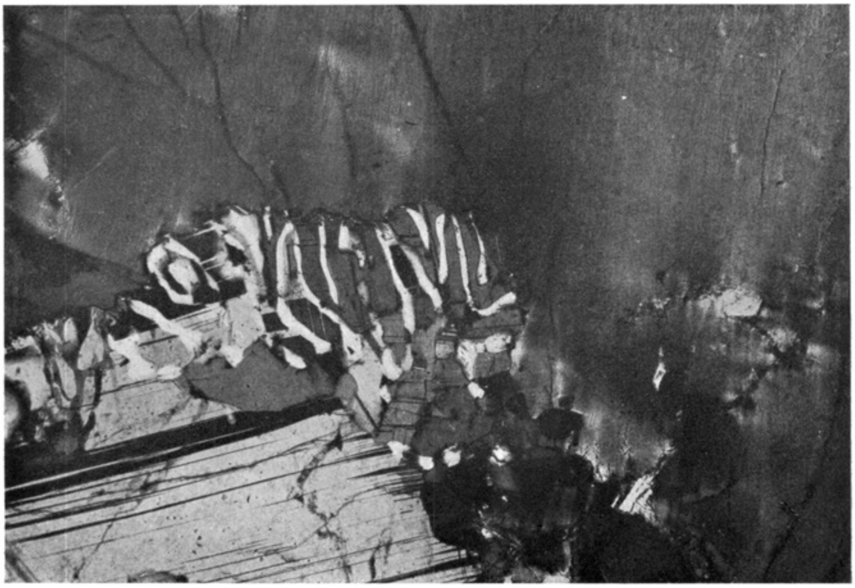

Fig. 8