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THE GEOLOGY OF THE LØKKEN AREA
Sør Trondlag Norway

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PREFACE:

During the summer of 1966-67 a team of undergraduate geologists from Imperial College was invited by the resident mining company at Lokken, to investigate the geology in an area enclosing the mine. The team comprised Mr.E.H.Rutter, Mr.G.M.Kershaw and myself, and was guided both in the field and later at Imperial College by Dr.W.Skiba. Local assistance in the field was provided by the mining company. In all, six weeks were spent on location in the field and followed up by a years work in the laboratory.

The final script was submitted in May, 1967 as part of my final B.Sc. year's work.

John May
Imperial College
April 1967.

CHAPTER I

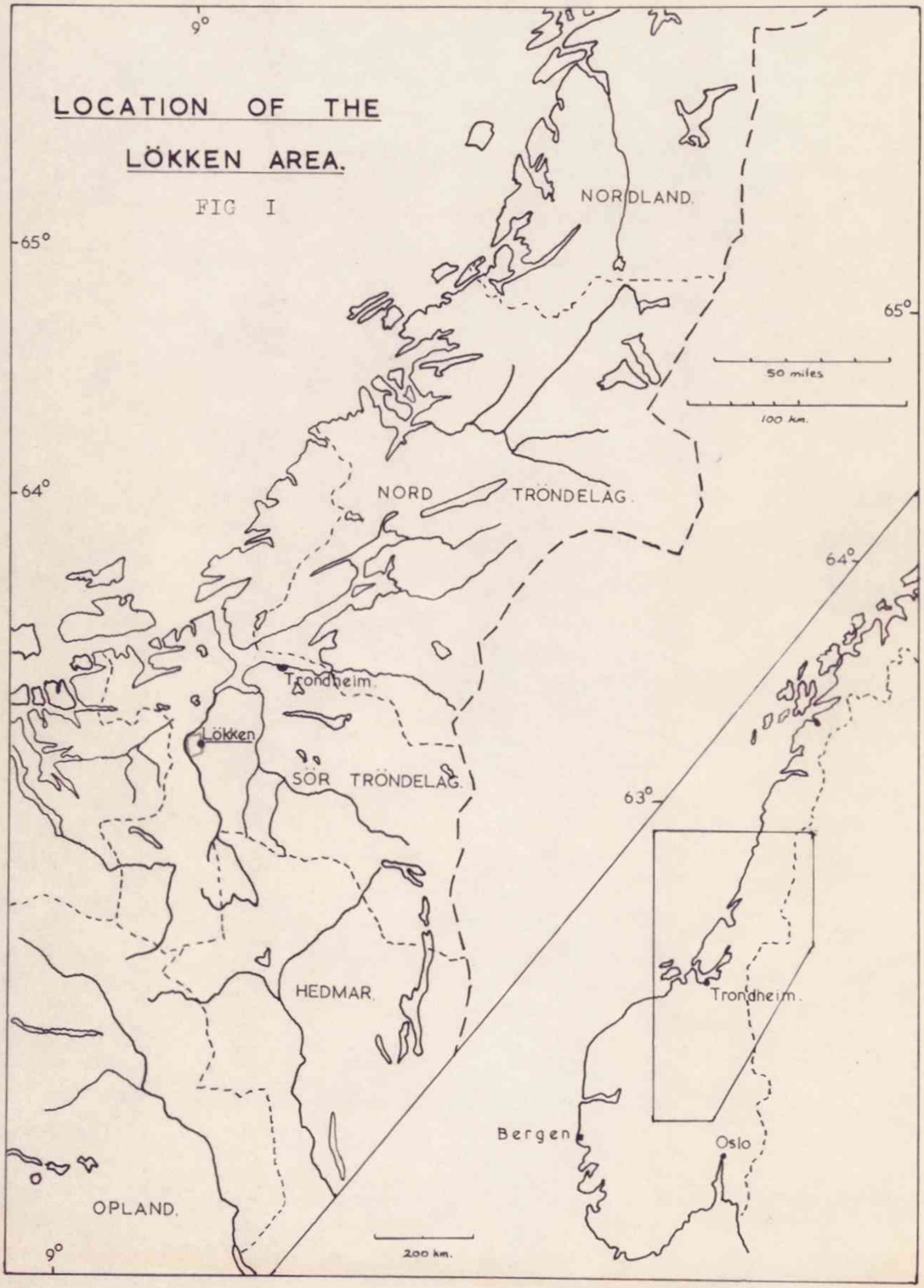
THE PROBLEM

The Lokken area of Norway includes an extensive belt of metamorphic rocks which have been classified under the general name of greenschists. In addition to the metamorphic rocks it has lately been established that this belt is also an extensive belt of mineralisation of the massive sulphide type. The general problem was therefore to investigate in more detail the nature, origin and economic aspects of these rocks. In order to do this the problem was approached in 3 ways, from a chemical-petrological view, from a structural view and from an economic view. These were then made the subject of the 3 theses submitted.

From the point of view of this report the rocks provided a classical example of greenschist metamorphism and so provide a chance for a more detailed study petrologically of that particular facies of metamorphism. In order to acheive that aim however, it was thought that an extensive detailed chemical survey should be carried out since this would give some insight into the chemical controls operative during the process of metamorphism. Also the chemistry was thought to be the most useful tool in evaluating the original character of the rocks since the classical petrological techniques were found to be of somewhat limited use.

A problem, which was not envisaged when the project was commenced is also to be found in the Lokken area since it provides an area classical, almost, for the study of a suite of rocks termed spilites.

The above represent to some extent the theoretical problems to be found at Lokken but perhaps the problem which may shed most light on all of these is the field problem, simply stated as, how does one map in the field an extensive outcrop of seemingly "monotonous variable" rocks. If this report can do a little to shed light onto this aspect then a step forward has been made.



LOCATION OF THE LÖKKEN AREA.

FIG I

THE AREA

The area chosen for study is some seventy kilometres southwest of Trondheim in the county of Sor Trondlag. The small sketch map fig. 1 is included to show the location of the area. The area is marginally terminated in the west by the Orbla River valley which runs roughly north-south. The valley occupied by the township of Lokken Verk was used to define the eastern margin of the area. The southern boundary was arbitrarily fixed by the geological occurrence of a contrasting rock group, the Hovin Group (see later map and stratigraphic succession). The chief object was to map the greenstone area and so the mapping ceased at the southern extent of that group. The northern extent of the mapping is somewhat less well defined since the object of the excercise was to map as far north as possible in the time available. To some extent the mining helped this choice since they were in possession of aeromagnetic maps of this area and suggested that a geological map of the same area be made.

At a later date, however, it was found necessary to severely reduce the size of the area to be covered in detail since the nature of the complexities which subsequently arose did not permit the expansion of the detailed work as was first envisaged.

The laboratory work is in fact confined to merely one complete strike section but from this, much detailed knowledge has been derived.

The field area defined above will subsequently be termed the Lokken area.

The topography of the area is best described as a peneplaned surface, the average elevation being about three hundred metres. The topography shows little sign of control by either structure or ancient geology and is due mainly to the effects of the last glacial period, with some direct superficial mining effects e.g. the fissures opened under the ski jump due to direct mining at depth below.

The area is extensively wooded in the north by tall pine forest and has thick mossy vegetation underfoot. The lower areas are covered by open bog areas which taken together with the thick moss serve to substantially reduce the area of exposure both in wood and clearing.

The greatest disadvantage with respect to exposure is the total lack of continuity along the strike. Thus the exposures are frequently isolated and connection with any other is extremely difficult. This has been one of the fundamental drawbacks, in earlier attempts, to map the area.

Apart from road and river exposures, the typical type of exposure is usually a well weathered surface in the wood, rounded or nearly so in curvature and on which it is extremely difficult to obtain field readings and information. In extreme cases it was even difficult to obtain fresh samples not withstanding the use of a sledge hammer. For these reasons the area serves as a typical example of the inestimable value of preliminary reconnaissance work. The key, well exposed parts, were determined and the field work centred upon these instead of time being wasted in aimless wanderings in densely wooded areas (the latter sometimes found a desirable pleasure however). It would be as well to state here that a reasonably soundly based prior assumption had been made, that was of an east-west or nearly east-west strike. The reconnaissance work was then based on this. This assumption was proved by later work to be more or less substantially correct.

Nowhere was the nature of the terrain such as to make it inaccessible, but the work in the wooded north of the area was in places found most difficult to work in. This was due mainly to lack of land marks and bad compass navigation (due to the large pyrite load beneath!). Some assistance was provided by the mining company and a swift survey of the area was made. No pretence is made that this was as extensive as work in the south where a great deal of the actual field work was concentrated.

Maps of the area (topographic) are in existence but these were found unsatisfactory even after enlargement for mapping purposes. The mapping was therefore carried out on aerial photographs scale 1:15000. Subsequently a map has been constructed from them. The inaccuracies of such a constructed map are well appreciated but compared with the use of such a map to this report it is felt that they are entirely adequate.

PREVIOUS WORK ON THE AREA

The mine has been established since 1654 and in the circumstances the amount of previous work is voluminous and some established facts have become accepted with respect to the ore and the surrounding rocks. It is not the ultimate purpose of this report to review the previous work and conclusions but the brief record given below is useful for reference.

The mine has numerous aeromagnetic and electromagnetic maps of the area and some of these have been interpreted geologically but others still remain uninterpreted. In general these methods have been most use when applied to areas very close to known ore or known geological features such as vaskiss and gabbro.

A number of unpublished reports have been written on the area and Prof.T.Strand has produced an unfinished map. Most of the work however, if not all is recorded in Norwegian so that almost nothing has been produced in English.

It may be noted that Messrs. Chadwick, Blake, Rawlings and Beswick of Imperial College worked on an area over to the east but very little of the work is directly applicable to this report.

LABORATORY METHODS USED

Minerals in this section were determined by reference to Kerr (1959) Micrometric analysis were made with the Swift Automatic point count with a total number of points per section being approximately one thousand. The accuracy is approximately 0.290.

Geochemical work was carried out as follows. The rock samples were crushed (hand hammer and mechanical crusher) sieved and stoned STORED in two bottles.

For strontium determinations on feldspar, the samples were washed to remove the "fines", dried and the ferromagnesians separated by the Frantz Isodynamic separator. Purified feldspars and yttrium standard were mixed, pelleted and scanned in the range 0.45A- 0.73A on the x-ray fluorescence spectrometer. For minor elements nickel and chromium the crushed samples were mixed in anodes with a palladium-carbon mix and burnt on the optical spectrograph (classical method). Determinations were made by photographically recording the results on Kodak glass plates and comparison with an included internal standard W-1 (to be found on plate 3).

Major element analysis was then carried out on the same samples in the following ways.

Calcium, magnesium, total iron (Fe_2O_3) and manganese were determined using appropriate diluted solutions and standard solutions on the Unicorn Mars Absorption Spectrometer.

Sodium and potassium were determined in the classical way of the flame photometer.

Phosphorus and titanium were determined on the Unicorn spectrometer using the appropriate light source and four centimetre cells.

In all seventeen samples were analysed for the above major and trace elements (minor). Only a selected eight of these samples were however analysed for silicon (SiO_2) since the time for determination was prohibitive. It is worth noting here that the use of rapid analysis techniques was never considered since accuracy was the main purpose of the exercise and the small variations needed when dealing with a limited range of rocks can be lost within the method limits. Aluminium was not determined but was obtained by difference but the aluminium figures have not been used in any determinations. Loss on ignition (H_2O,CO_2) was obtained for the eight samples for which SiO_2 was obtained in order that the Al_2O_3 might approach the true value.

The accuracy of the results is difficult to assess but it is hoped it is within the narrower limits possible. Ca, Mg Fe_2O_3 and Ma results were obtained twice to check the accuracy.

THE ACTUAL FIELD PROBLEMS

In this section a brief review of the problems which arose in the field will be described and in some cases the method of overcoming them will be stated. Some of the problems are more fundamental to the thesis and solutions to them are considered in later sections.

The initial problem of exposure has already been stated and so little time will be spent here on it. The lack of wood exposure and the nature of it when found was a decided disadvantage in field correlation. Many attempts of field strike correlation were made and these were found most successful in the south where the area was somewhat dissected by valleys along the strike and general exposure was better. Extension along the strike was here achieved for about 500m but again frustration was the end product when bogland took the place of good exposure. In the north even such correlation was impossible and so the field mapping is somewhat isolated exposure mapping. This places great emphasis on later comparison of hand specimens for this was about the only way of overcoming the scattered outcrop s.

Structural work in the area is also extremely difficult due to the nature of exposure and lack of a substantially good three dimensional surface in which to work. The structure of the area was essentially worked on by Mr.E.H.Rutter but a short simplified summary is provided later and it is hoped that it is adequate for the purposes of this report.

The field attack was fairly simple, preliminary reconnaissance work was carried out and the well exposed areas located and the areas of less exposure marked out. The well exposed sections were then extremely extensively worked and the most advantage taken. Most of the structural detail is derived from them. In this way a detailed field skeleton was constructed and the body of the system was then systematically filled in by traverse across the areas. The question of correlation between the skeleton parts rises however and here the geologist must place great faith in his field work.

The area was quickly divided up on the basis of three well defined rock types already long established - gabbro, felsite (a general field term) and greenstone (forming extensive areas). To map with respect to these rock types only is not essentially difficult and can be achieved with a fair degree of accuracy. The largest problem is however the extensive outcrop of rock which has always previously been termed greenstone. Some criterion for subdivision of this rock type was the chief aim of this work. Various previous attempts at this aim have been made but it is hoped that as a result some workable differences with a sound scientific basis will be erected.

In the field the greenstones are problematic rocks, they can be distinguished from the gabbro usually with distinct ease but times arise when this becomes extremely difficult. It must be pointed out however that only lack of exposure introduces scepticism in the position of the gabbro boundaries with respect to the host greenstone. The felsites can merge into greenstone but the accepted previously named rock type - felsite - is a clearly defined field rock for Lokken. It is suggested that the term felsitic greenstone should not be used.

To return to the greenstones themselves, they range in colour from all shades of green to dark greys and colour was found no useful indicator. In the past the rocks have been mapped on light and dark greenstone as a basis but there is a complete gradation between these two in the field and subsequent work has shown this to be no valid criterior for mapping on a scientific basis as two essentially different rocks can have the same colour. Variability in grain size and S.G. were all physical properties useable in the field for division.

Taking all these variable physical characters into account the rocks in any given continuous sequence could be divided up by some or all of the characters. It is now the aim of this work to put this field division on a scientific basis workable if possible throughout the area.

GEOMORPHOLOGY OF THE LOKKEN AREA

As previously stated the area is best described as a peneplaned surface the elevation being on average about three hundred metres. The area has suffered glacial action and shows some classical features of glacial geomorphology. The two valleys themselves, occupied by the river Orbla and Lokken Verk itself are examples of U shaped valleys with flat bottoms (now used as arableland) and extremely steep sides, sometimes approaching the vertical almost. Hanging valleys are another glacial feature to be found in both these valleys.

The valley bottoms themselves are covered with alluvium and it is clear from the well formed river terraces that there have been several distinct periods of uplift of the land causing the river Orbla to cut down into previous river terraces.

The above large scale features can also be matched with smaller features such as glacial striae to be found on the fresher glacial surfaces.

Glacial erratic material is somewhat limited in its extent and most rock exposures can be taken as in situ exposure. In general the highest features are formed of the greenstone, whilst the lower lying flatter bogland are generally found as gabbro. This is so much the case that one might easily map the gabbro masses on vegetation alone.

SUMMARY OF THE GEOLOGY OF CENTRAL NORWAY

The geology of central Norway can be divided into 3 broad groups of rocks; the Caledonian or basal gneiss, the Eocambrian spragmites and the Hovin, Storen and Roros groups. Lokken lies in the Storen group of rocks and is surrounded by Hovin and Roros rocks with basal gneiss and Eocambrian to the north-east and south-east.

The Caledonian gneiss

The Caledonian or basal gneiss as the name indicates is the lowest group of rocks in the structural sequence and probably also the oldest group in the stratigraphic column. The gneiss is overlain by Eocambrian rocks and the Hovin, Storen and Roros groups of rock.

In essence the Caledonian gneiss of central Norway is very similar to the Archean gneiss found in SE Norway. It is thought that the gneiss consists of Pre Cambrian rocks which have been highly metamorphosed and tectonically intercalated with Eocambrian and Cambro-Silurian rocks. Such has been the tectonic transformation of the gneiss that any possible angular disconformity which may have been present between the gneiss and Cambro-Silurian rocks af the Trondheim region has been completely obliterated.

Eocambrian sparagmites

The Eocambrian rocks compose what is known as the sparagmite succession, originally a term used to describe a metamorphosed feldspathic sandstone but now includes a wide range of rock types; sandstone; shale; limestone and conglomerate (the sparagmite conglomerates have been interpreted as formerly being a glacial tillite).

The sparagmites are essentially a sedimentary succession and are stratigraphically older than the fossiliferous Cambro-Silurian. Eocambrian is used to indicate the close association between the true sparagmites and the fossil bearing cambrian rocks, although it is most probable that the formation extends into the Pre Cambrian.

The Upper part of the Eocambrian succession is the equivalent of the Scottish Dalradian rocks.

The sparagmite succession is fairly extensive and extends to the east into Sweden where it is found to be mineralised although no deposits have been found in Norway.

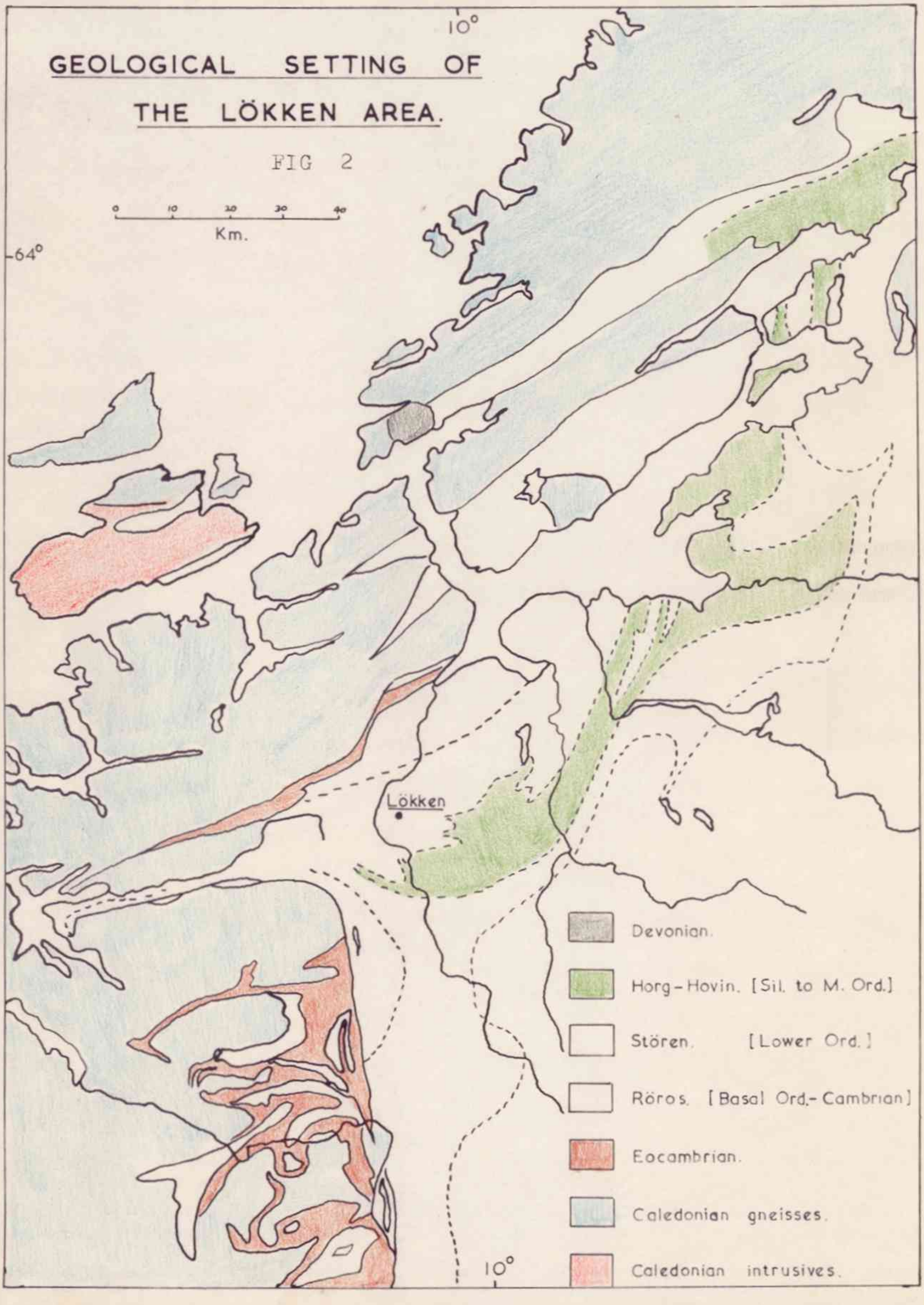
In the north the Eocambrian is tectonically overlain by Cambro-Silurian rocks and itself overlies the basal gneiss. Intrusives are not common in the sparagmite succession.

Hovin Storen Roros Rocks

Running south east through Trondheim and Lokken is a broad depression in which metamorphosed Cambro-Silurian rocks have escaped erosion. The three groups of rocks, the Hovin, Storen, and Roros, have been dated Silurian - Middle Ordovician, Lower Ordovician - Cambrian, and Basal Ordovician - Cambrian respectively. It has however been found that the higher the rocks are in the structural succession the lower is the grade of metamorphism. Thus the rocks in the centre of the synclinorium are hardly metamorphosed whilst at the base of the succession just above the Caledonian gneiss garnet grade occurs. The rocks of the Hovin, Storen, and Roros groups are mainly meta-argillites although metavolcanics are common in the Storen group where they are represented as greenstones after being metamorphosed to the greenschist facies grade. Intruded into the Storen group are masses of gabbro whilst locally there are large intrusive bodies of trondjemite (a type of granodiorite).

The General Stratigraphic succession around Lokken

	Nyplassen Beds: metamorphosed shales, sandstones
HOVIN GROUP Lower-middle Ordovician	Fjeldheim Beds: metamorphosed shales, sandstones, limestones
	Fjeldheim Conglomerate (absent in area mapped)
unconformity	
STOREN GROUP Middle-upper Cambrian	Mainly metamorphosed basic volcanics with gabbro, felsite, basic dykes.
possible unconformity	
ROROS GROUP Pre Cambrian	Chlorite schists Garben schists.



GEOLOGICAL SETTING OF THE LÖKKEN AREA.

FIG 2

GENERAL GEOLOGY OF THE LOKKEN AREA

The Lokken area is situated in an extensive belt of greenschist metamorphic rocks best described as metavolcanics. In the area the grade of metamorphism has reached the greenschist facies epidote - albite - chlorite. Nowhere is schistocity well developed and so the rocks justify the local term stone rather than schist.

The rocks mapped were all belonging to the Storen group although the sedimentary member of the stratigraphically higher Hovin group was used as the southern boundary.

The Storen group in the area mapped consisted of a pile of metavolcanics with very little sedimentary material present or discernible. Included in the pile are sparodic lens of jasperoid rocks and the black sedimentary shale rich in pyrite (locally known as vaskiss) but these are restricted to a few isolated occurrences.

The Storen group was originally named by Kjerulf 1875 and are of uppermost Cambrian in age. Vogt 1945 suggested a general correlation with the Arenigian Ballantrae volcanic rocks of the Southern Uplands of Scotland.

In the syncline to the south the Hovin Group were traced and this although metamorphosed was a distinct band. No trace could be found however of the lower most Fjeldheim conglomerate and it must be considered absent in this area. This has been stated by Blake, Chadwick, Rawlings and Beswick who also found the conglomerate to be impersistent.

The Storen metavolcanics are cut by at least three separate intrusive phases. The major of these is a period of emplacement of extensive laccoliths of gabbro which are cross cutting to the pile of meta - volcanics but must themselves be regarded as meta gabbro. A smaller phase of intrusive activity is represented by the acid felsites which unlike the meta gabbro seem to be sill like and more conformable with the meta volcanics.

The structure of the area shows two clear phases of folding on roughly north-south and east-west axes so as to form a basin type structure centring about Lokken. The earlier E-W folding is assymetrical with a steep northern limb and a shallower dipping southern limb. In places the northern limb tends to be vertical to overturned. From pillow lava exposures no certainty about way up could be deduced and so, little value can be placed on way ups except where the exposure is very good. The general plunge of the area is to the west but this must change to the west of the Orbla river since east plunges were observed there. This variance in plunge gives rise to the second phase of folding and gives rise to the basin effect.

Deformation in the area is generally very slight and pillows show no signs of large amounts of deformation and in the south they show almost none at all. Schistocity is not developed at all in the rocks except for rocks at the contact with the acid felsites, but this is not a regional effect. (Schistocity here has been used to mean a cleavage).

The area is not adaptable for the location of faults but there would seem to be at least two prominant fault directions, one north-south, the other east-west. The faults are best picked up on the surface when mapping the contrasting felsites but in the mine workings the gabbro and greenstone also show extensive faulting but these are not discernible on the surface. The throw on the faults is extremely difficult to estimate but the evidence is that some major faults mainly on a north-south trend cut the area.

The central structure of the area mainly because of its economic aspect is a major thrust which also runs roughly north-south but seemingly turning to the west in the south. The surface evidence for this thrust is extremely vague and it can only be seen in three exposures but it has been more exactly mapped from the mine workings where it frequently outcrops, and also from some dam foundations. The movement on the thrust is from the north. A new smaller thrust slice was mapped for the first time. From the mine workings the thrust plane plunges to the west at about 20°, and in mine plans shows no signs of being folded, but in fact the thrust plane has been folded twice. The plunge however is uniform in the mine at 20°. Minor structures accompanying the thrust are visible down the mine but only at one surface locality was any minor structure seen to be associated with the thrust, this was in the form of a small folded quartz vein.

Included in the greenstone are two minor members, the jasperoid lenses and a sedimentary shale locally as vaskiss. The jasperoid rocks are a contrasting red in colour and extensively epidotic veined. They are sparodic in occurrence and no predictability about their whereabouts can be deduced in the field. They seem to turn up in apparently extensive greenstone areas. A later description is provided.

The vaskiss is a black shale band conformable to the general strike of the metavolcanics. It is rich in pyrite but usually thin and weathered out. The mining company have sufficiently defined the vaskiss by physical surveys to enable them to accurately locate it in bineholes. Again a later description is provided.

These latter two horizons are included within the Støren group the vaskiss rightly so, but so little is known about the origin of the jasperoid rocks that any further conclusions are beyond the scope of this work.

At this point some mention must be made of the actual ore body. It is in the form of a lensoid mass plunging uniformly to the west at approximately 9° (almost parallel to the thrust). It is seemingly conformable to the vaskiss and so to the greenstones in which it is found. It is in the form of massive pyrite (70 - 75% pyrite). It has been deformed by the folding and is a highly concentrated mass and little diffuse into the country rock except for a small band of locally known impregnation ore. Various hypotheses have been put forward for its origin and again it is beyond the scope of this work to further that aim in any way at all other than providing further knowledge about the greenstones in which it is found. For detailed work on the ore the work of Mr.G.M.Kershaw is important.

CHAPTER II

THE META-GABBRO

The meta-gabbro was represented by Carstens as being present in three masses and these will subsequently be known as the Bjernlwand mass (the most northerly occurrence of meta-gabbro), the Fagerlwand mass and the main meta-gabbro mass.

The Bjernlwand mass occurs to the north of the Lake Bjernli and was mapped as such by Carstens 1951. In the field only a quick review of this mass was made, the aim being to check its actual position on the map. In this aim assistance by Mr.Sagvold was found invaluable since his knowledge of local terrain was found remarkable.

The Fagerlwand meta-gabbro was established as being a thrust bounded mass, being bounded by the main thrust on its eastern margin and having a thrust slice as a western margin. These two thrusts pinch together in the north and south forming an ellipsoidal mass of gabbro. It is exposed on the margin of Bjernlwand where it is pegmalitically developed. It is further exposed as a mass to the north of Fagerlwand.

The main meta-gabbro mass is by far the largest development of meta-gabbro in the area and its location was mapped in detail. The boundaries are by no means exact since exposures of actual contact or near contact rocks is poor, the actual contact being seen in three places only.

From all appearances these meta-gabbros are intimately connected and as a result of field work and later thin section work no distinction could be made between any of them. It is more probable that they were emplaced as one mass from the same source and their present seemingly disconnected position could be the result of thrusting and faulting.

Meta-gabbro is not limited to this area but occurs to the east near Høidal and directly to the west of the Orbla. The relationship with the meta-gabbro to the west of the Orbla is one of much interest since the gabbro can be traced almost up to the river but on crossing the river the marginal outcrop becomes much larger. The possibility of a fault existing along that part of the Orbla must not be excluded, but in a survey made to the north with Mr.Rutter no displacement of the mica schist rocks could be found, (a northerly marker horizon off the actual map). An alternative explanation could be that the main meta-gabbro mass is more extensive to the southwest and to some extent this may be true since gabbroic rock types were found in that region. If this were so then it would transform the main gabbro mass into a size more akin to its extremely close westerly neighbour, it merely then having been faulted and displaced to the south some 200m.

Faults and thrusts in the gabbro

From evidence in the mine and some surface evidence it is clear that the gabbros have been extensively faulted and also bear a close relationship with the thrust. The outcrops are fault and thrust bound in many places, but in actual fact the thrust is never seen in gabbroic rocks but is always found in sheared greenstone rock. There seems little doubt however that the gabbro was a controlling influence in localising the thrust. Faults are not easy to deduce on the surface and no real certainty can be placed in their exact location and throw.

Banding and other layered effects

In the actual area mapped banding was not seen but the road exposure to the west of the Orbla presents an exposure showing vertical banding, the gabbro becoming pegmatitic in parts of the exposure. This was the only banding seen in the gabbro which otherwise seems devoid of such features.

A granophyre type rock has been reported from exposures west of the Orbla but is at the moment represented by one specimen and so must be further investigated before far reaching conclusions are made. On the whole the gabbro gives few clues to the shape and structural identity. The above are at the moment however only facts but it is suggested that the ideas which follow the facts be followed up with more work in both field and laboratory.

Xenoliths of greenstone are common in the gabbro masses especially near the margins, but actual mapping of xenoliths was found impossible due to the scale of mapping and poor exposure. It may however be pointed out that the main gabbro appears to be cut by a traceable band of greenstone but the significance of this is not yet understood.

Contact metamorphism

This is completely absent from the adjacent rocks which have been traced up to the contact showing little or no change in character. The explanation most favoured by the author is that at the time of intrusion the country rock (meta volcanic was still sufficiently hot enough to absorb the heat effects of the incoming gabbro and so prevent all traces of contact metamorphism).

It is usually the case that the highest grade of metamorphism is preserved and so it would be expected that the aureole to a hot gabbro mass would be both extensive and persistent above greenschist metamorphism. It is this which leads to the idea that the contact metamorphism must have been absent prior to greenschist metamorphism.

Geochemistry of the gabbro

Carstens in his work divided the gabbros up into two groups on a geochemical basis based on whole rock analyses.

1)	$\overset{Al_2O_3}{\cancel{H_2O_3}}$	14.38
	TiO_2	1.53
	Fe_2O_3	3.35
	FeO	7.99
	CaO	12.41
2)	Al_2O_3	18.86
	TiO_2	0.49
	Fe_2O_3	1.99
	FeO	4.59
	CaO	15.18

This work has not been verified and so its significance is not fully understood since there seems little connection with thin section observations.

Strontium determinations were attempted by X.R.F. and optical spectrometry on extracted feldspars from 16 samples. The grains were also mounted on slides and were found to contain numerous inclusions of epidotic material.

The strontium results proved to be very indecisive, the main feature being their low value for such rocks and near uniformity for all samples. This work has not been fully exploited but the spectrographic plates are available for further study.

Petrography

The gabbros show a typical range in hand specimen of most of their physical properties. The colour varies from melanocratic to some leucocratic gabbroic greenstones. The distinction between greenstone (coarse grained) and gabbro was not always clear in the field. Most specimens are coarse grained size 3-4mm. but some pegmatitic developments can be found, the most notable one being on the side of Lake Bjernli where the feldspars are really well developed. Pegmatite is also developed at the road exposure of the main mass (west of Orbla river) but here the gabbro is mainly of mafic consistency.

The feldspars look deceptively fresh in hand specimen and clear feldspars can seemingly be determined with the naked eye. Usually however the form of the feldspar was a white colour and idiomorphic in shape. The ratio of ferro-magnesians to felsic material was fairly constant over the whole of the masses at about 1:1. Some patches of a more ultra mafic nature could occasionally be found.

In this section the gabbro shows very little of its original mineralogy although its textures are to some extent preserved. The effects of metamorphism are almost complete with all the sections examined showing the same features.

Feldspar is somewhat in excess of the mafic constituents amounting

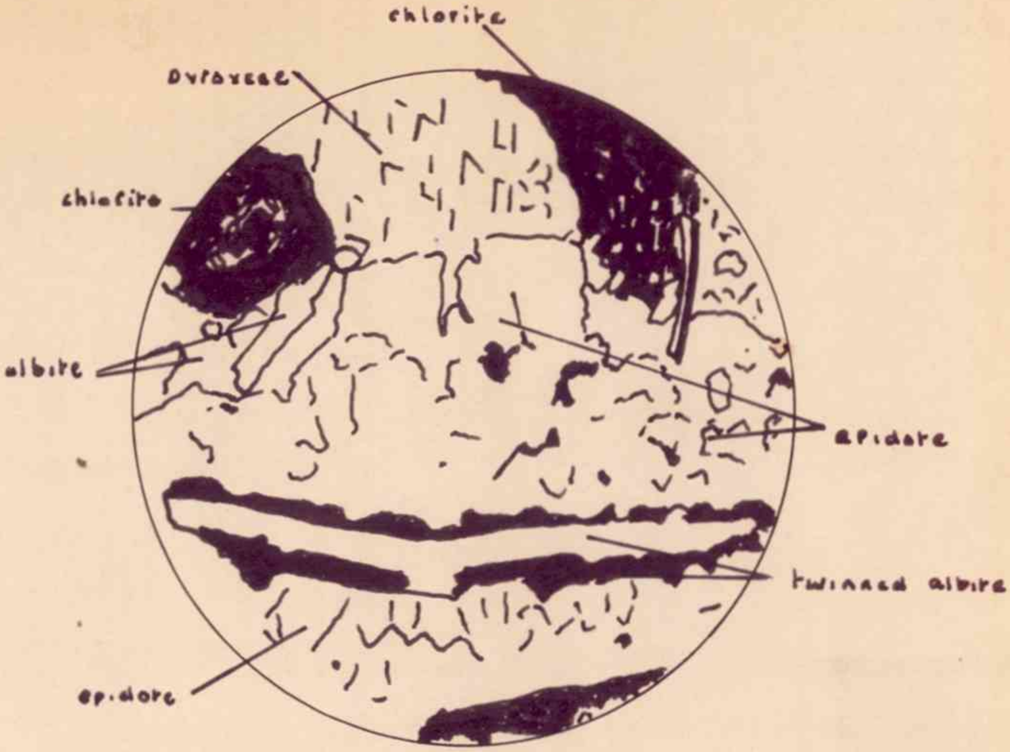


FIG 3

1 mm.

Note the coarse texture of the section.
This reflects primary igneous texture but secondary mineralogy. Pyroxene is the only primary mineral present and this is in a state of alteration to the appropriate amphibole. Drawing supposed to show how the feldspar can be seen to be bent.

to approximately 60%. The plagioclase is albite in nature and can be divided into two separate forms. The original nature of the feldspars cannot be seen and in no slide examined was any sort of relic feature seen which may have given some clue as to its identity. Two types of feldspar are seen in the gabbro and are described below.

1) Large feldspars with original shape preserved.

Here the albite is extremely like the original feldspar in shape and shows broad albite twins with frequent carlsbad twining and the very occasional pericline twining still visible. The albite twins can in some cases be seen to be deformed and bent or fractured crystals are common. The feldspars are platy in habit but no orientation could be deduced. As stated these feldspars are albite in composition this being determined by R.I. equal or less than C.B. (An 10% approx.) They differ from the usual form in that the calcium has been removed in the form of epidotic material (epidote zoisite) which in some cases is poikalitic in otherwise clear albite or has migrated to the boundary and can be seen to almost coat the new feldspar.

2) Matrix type feldspar

The feldspar here breaks down into a fine aggregate of epidotic material in a matrix which looks like albite but which presumably contains some calcite, the actual matrix being difficult to define. In some cases the actual feldspar type is preserved but this is the exception not the case.

Of the two types the first seems to predominate but mine specimens seem to show an increase in the second. There is some indication that albite may provide a general matrix filling but this may be a case of where the feldspar breaks down and the epidotic material is aggregated together leaving patches of clear albite.

Of the original ferro-magnesians only clino pyroxene can at this stage be discerned (olivine is completely absent). The pyroxene is abundant but is always in arrested stage of alteration to a light coloured (pale green) fibrous amphibole (probably actinolite in nature). It is altering profusely along cleavage directions and around the edges which give the mineral a ragged appearance in thin section. The amphibole is intimately connected with the pyroxene and replacing it in all stages.

Chlorite is sparse in occurrence and probably is derived from the break down of the pyroxene, this being an alternative reaction to the one producing amphibole. Chlorite usually occurs along with amphibole rather than alone.

Of the opaque minerals ilmeno-magnetite is probably the commonest present. Its occurrence is usually in the form of complex clusters and aggregates showing some alteration to leucoxene.

THE QUARTZ KERATOPHYRE

The term felsite is a general field term, useful in the field to denote a particular acid rock type. In later detailed work however this term is usually superceded by a more specific term which sheds more light on the nature of the actual rock. This was the approach used in this case. The term felsite was used during the actual field work but in the light of recent work has been completely replaced by a more specific term - quartz keratophyre.

The felsites were mapped by previous Norwegian workers and found to crop out in 3 areas:-

1) the large mass in the north west.
2) a lens directly below the ski jump.
3) small bands north of Bjernlivand village.

to these a new occurrence was added which cropped out in the centre of Bjernlivand village.

The quartz keratophyre rocks are quite easily distinguished in the field from spilites, although references are made to kerotophyres. The writer however feels, that the term quartz keratophyre should be restricted in field use, and that there are no near relatives to the felsites. In the field the quartz keratophyre weathers to a white surface, but when fresh is a massive dark grey rock with a peculiar type fracture.

In thin section the rock is quite unlike any of the sections of spilite available. It is coarsely micro crystalline consisting of quartz and albite. The section breaks up into yellow and grey polarising

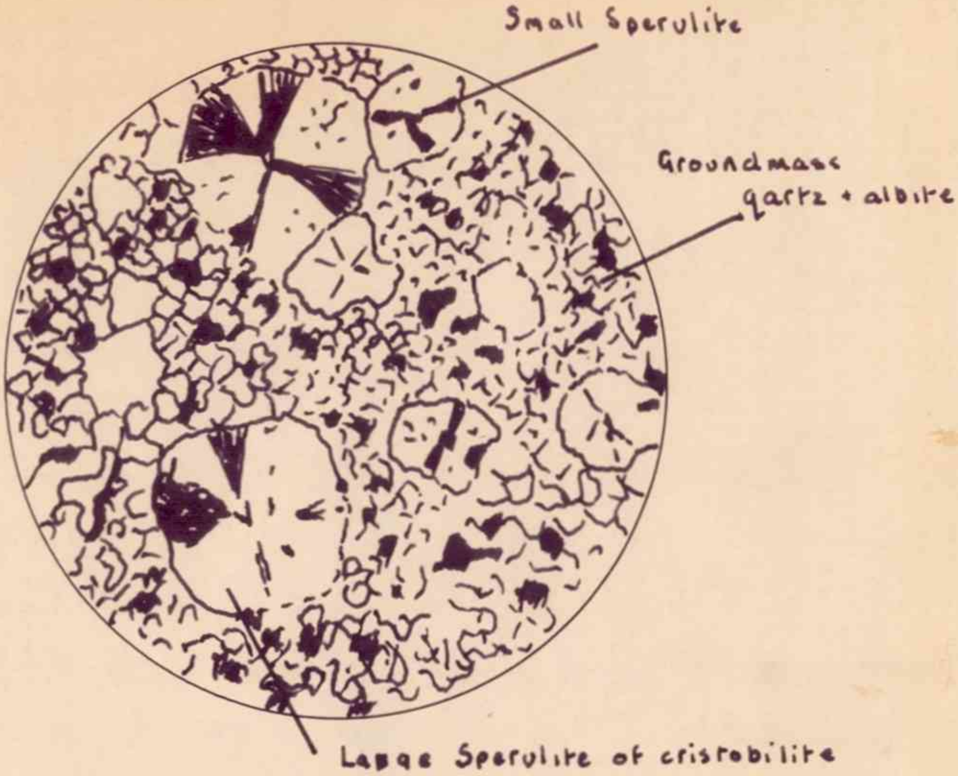


FIG 4

1mm.

Thin section of quartz keratophyre.
Section shows excellent sperulitic texture.

areas bearing no relationship to original texture. Included in this micro crystalline mass are spherulites of cristobilite and albite feldspar phenocrysts. The spherulites are almost rounded in section and show no signs of strong deformation. The ferro-magnesian numeral is represented by wispy micaceous bands which seem to miss the phenocrysts and spherulites and form a network for the microcrystalline ground mass. The material has been identified as stipnomelane and this is important in the later section on metamorphism.

It is thought that the quartz keratophyres represent an intrusive phase of acid magmas into the stratified spilites. The quartz keratophyres appear conformable with the spilite and so perhaps they are best described as acid sills. Schistocity is developed in the rocks both above and below the quartz keratophyre sills and this is used as evidence for intrusion rather than extrusion. The quartz keratophyres have been folded and metamorphosed along with the spilite country rock and so must have been fairly early in the chronological table. The magma was probably rich in soda hence the abundance of sodic feldspar at the present time. It could have crystallised as a glassy ground mass with spherulites of quartz and phenocrysts of feldspar (soda rich). The glass probably represented a eutectic crystallisation of quartz and feldspar. Subsequently the glass devitrified into its present microcrystalline form. Lack of ferro magnesian minerals lends support to the above hypotheses of a eutectic crystallisation. The absence of perlitic structure can impose a second interpretation on the quartz keratophyre. If the magma cooled relatively slowly glass would be prevented from forming and the present holocrystalline state could represent a primary crystallisation structure (igneous textures are preserved in the spilite and gabbro). The slow cooling would again fit into an intrusive rather than extrusive picture.

Rather than the outcrops being regarded as isolated intrusions it is suggested that all the outcrops are merely erosional outliers of one intrusive sill. The thickness of the large mass to the north west is however puzzling since usually the masses are extremely thin. The thickness however could be due to folding and subsequent erosion, the section now seen being an almost vertical northern limb of a fold.

One feature which the quartz keratophyre rocks show in particular is jointing which is almost columnar in some exposures. All the rocks show jointing which can be divided into two general types:-

i) cross joints perpendicular to the fold plunge

ii) nine systematic joints.

The cross joints can be traced throughout the area as having almost constant orientation.

MINOR INTRUSIVE PHASE

Basic type dykes of very restricted outcrops are to be found at certain localities within the area. The best locality is in the east side of Lake Bjernli but basic dykes are also abundant down the mine. The dykes are thought to represent the latest phase of intrusive activity. They are distinctly cross cutting to the greenstone. They have undergone metamorphism but do not seem to be as folded or contorted as one might expect for such early dykes.

PORPHYRITIC SPILITE

This rock outcrops on two localities on the map and forms a distinct field rock type. The rock consists of phenocrysts of epidote and hornblende. The original character of the phenocrysts is thought to have been pyroxene and the appropriate feldspar. The two are however set in a fine grained ground mass of epidote, feldspar, chlorite and amphibole.

Mr.Rutter found a similar rock type in the Draysit area. It is also interesting to note that Blake, Chadwick, Rawlings and Beswick reported finding a similar rock type some 10 kilometres to the east of Lokken. Here it is apparently better developed and has warranted the use of the name Holonda porphyry. A possible link between all three rocks is almost certain although samples of the Holonda porphyry have not actually been seen.

THE JASPEROID ROCKS

These occur in the field in various isolated and scattered outcrops which, on the scale of the air photographs used, proved almost too small to indicate on the map. They are distinctive rock types in the field usually being red in colour due to iron staining, and extensively veined by epidotic material. An occurrence was found in the west of the area where pillow lava was seemingly replaced by a dull reddish grey jasperoid type rock. The exposure was a small overgrown quarry, the jasper having been used for road metal.

Generally the occurrence is haphazard, usually being in the form of lensoid masses in otherwise extensive areas of metavolcanics.

Jasperoid rocks are classical associates of spilitic suites and are often quoted in the literature as radiolarian cherts. In the Lokken jaspers no radiolarian remains have ever been found, the rock being entirely made up of micro crystalline quartz.

On these grounds therefore is offered as an alternative explanation that they represent late stage hydrothermal activity by waters enriched in silica.

SEDIMENTARY (non tuffaceous material)

Intercalated sedimentary material was found to be entirely absent from the volcanic material except for one peculiar member, of definite sedimentary origin but unknown derivation, locally known as vaskiss. It is discernible in the field as a rusty looking rock usually extensively weathered out. A fresh surface shows it to be a black shale with rich pyrite layers interbanded with shale. The outcrops are extremely limited and it is only found at three surface outcrops.

The vaskiss is extremely important to the mine since it is believed to be conformable with the actual ore. For this reason physical surveys have been extensively carried out and the vaskiss although not actually outcropping is one of the best mapped rock types of the area. An extremely detailed report can be found in the work of Mr.G.M.Kershaw.

The only other sedimentary unit found was a suspect tuff layer ¼" thick, found inbetween two spilite horizons.

The Hovin group was neither mapped nor studied therefore no description is given.

CHAPTER III

INTRODUCTION

The term greenstone was adopted by local geologists and workers because it provides a simple description of the rocks which extend across from the east (Hoidal) to the west (Drayset) and completely make up the significant rock type of the Lokken area. The rocks correspond to the more normal name of greenschists, but lack of a schistocity has brought about the use of the more descriptive term stone.

The rocks are dominantly green in colour but subtle variations into greys and purples can be seen. On the whole therefore the term greenstone excellently describes the field appearance of 90% of the metavolcanics around Lokken.

Mineralogically the greenstones show a remarkable consistency over the entire area, the assemblage being - albite - epidote - chlorite - amphibole. This is the stable assemblage for greenschist metamorphism which has been classically attained throughout the area. Variability is however found in textures and proportions of minerals and an attempt will be made to correlate these with original character.

NOTES ON NOMENCLATURE

Some confusion has arisen over the nomenclature to be applied to the greenstones since various possibilities exist:

a) the rocks are metamorphic rocks and metamorphic terminology could describe them.

b) the rocks have been now established as igneous and an igneous terminology could be used.

c) the spilite terminology has been applied.

In short the situation is that the rocks have a metamorphic mineralogy and igneous textures. To use therefore either terminology would be ignoring apparent evidence shown by the rocks.

The spilite terminology does however seem to combine a mineralogy similar to the metamorphic ones and also combine a range of textures applicable to the rocks. It is however rather unfortunate that the rocks chemically are not all spilites. It is felt however that such knowledge is not so readily available as the previous knowledge and it is therefore better in the circumstances when naming the rocks to turn a blind eye to it.

It is suggested therefore that the terminology of the spilites be applied directly to all the rocks.

It has however been found necessary when subdividing these rocks to apply a strict metamorphic terminology since spilites do not encompass such finer division.

FIELD OCCURRENCE

The spilites have two common field forms, well developed pillow structure and massive structureless lava. In all cases it is not easy to distinguish the two since the smooth glacial surfaces found in the forest betray little of the structure beneath them. A statistical study of pillow to non pillow lava has not been made but of the seventeen samples analysed three were definite pillow lavas, and nothing exemplary could be found in any of their properties.

A somewhat detailed description of locality LM 3A is given, because the exposure, a small quarry, indicates how magnificently pillows are developed at Lokken. At the same time the glaciated upper quarry surface can be examined to demonstrate how little of the actual structure is shown.

The upper surface of the quarry is a smooth glacial surface in which arcuate structures ressembling possible pillow shapes can be seen. On this surface alone the nature of the structures in the quarry below would never be thought of.

The quarry itself provides fresh three dimensional pillows for study. The exposure is such that for once the application of the term pillow is justified. The general dip is north 30° with a pitch to the west of $20 - 30^{\circ}$. Upside down or right way up? The author thinks right way up. The pillows are almost undeformed tectonically and any flattening which has taken place can be explained simply in terms of compaction. The smaller the pillows the less even the compaction deformation, and some almost round examples can be seen. All the pillows have a polished dark green chloritic outer surface. This is a secondary development of chlorite, possibly from included tuffaceous or sedimentary material. The average pillow size is one - two metres but extremes at either end can be found. The larger pillows are seen to be internally breaking up into smaller pillows due to rapid cooling.

Texturally the pillows show a coarse centre grading outwards into a fine grained margin. Any matrix originally around the pillows is not represented as the chloritic coating. The pillows show concentric zoning easiest seen in the form of epidote content. This is usually in the form of a visicular layer passing into a dense epidotic layer very near to the actual margin of the pillow. Radial fractures of the pillows are common and calcite filling the fractures indicates that the late process of carbonitisation was widespread.

It has already been noted that flattening due to compaction takes place. Mr.Rutter describes deformed pillows from more highly disturbed areas, which have been tremendously elongated in one direction. An interesting demonstration of self deformation due to compaction is shown on the side of Bjernlward. Here the pillows are small, less than one metre, and have been broken whilst the exterior carapace was solid and the interior molten. Once the shell has broken the interior has flowed out leaving the broken rim "floating" in molten material. It is suggested that weight of overburden would be sufficient to do this. In thin section the outer skin shows a glassy nature, which is in keeping with any ideas for a rapid chilling of the exterior whilst the centre could have remained molten.

Pillow lava is not the commonest field form of spilite and making

ikke samme lok. som
barstens's opprinnelige
T. S.

up the majority (80%) is the massive structureless variety. The usual outcrop form is entirely massive with no structures whatsoever. Schistocity is absent but does develop over to the west. It has been suggested that a schistocity exists at Lokken but the general use of the word schist for rock description cannot be applied at Lokken. Jointing and fracturing are developed in the exposures but have been excluded under the term of structures as used above.

The massive outcrops show a complete range in texture from coarse to fine grained. The colour range is also present. The exposure LM 42-43 showed a banded appearance which was first thought to be indicative of pyroclastic rocks. Subsequent investigation has shown this not to be the case, the nature of the banding being thought at the moment to be some secondary metamorphic grading of epidote.

Secondary veining of the massive rocks by epidote and calcite is common. This gives the rocks agglomeratic affinities in the field and in fact they have been described as such. It is suggested however that this is once again a phenomena due to metamorphic segregation. The so called agglomeratic fragments can be matched up either side of the infilling matrix and this suggests veining. Calcite of secondary origin is seen throughout the area and is concentrated near the actual ore body.

Replacement of pillow lavas was first reported by Carsten, who described a mine exposure of massive pyrite with pillow structures in it. Prof.T.Strand also examined the exposure and saw the same structures but remained unconvinced that they in fact were pillow structures.

The exposure has now been destroyed by the mine. The author however can report a small exposure in the northwest IM.? where the pillow lava shows a peculiar reddening and are being replaced by chert. Jasper is found associated with the exposure.

Abundant small scale joints and fractures are found in the greenstone. Crush zones and small scale shear zones are common, usually with an east-west orientation and a steep dip to the north. Sometimes extensive crushing of the rock along these shears has taken place, and jasper inclusions can be seen. None of the shears show mineralisation. The last statement may be aminded, since the mine at Hoidal is bound by an east-west shear. The joint pattern has already been described for the felsites.

MINERALOGY (texture not described)

The mineralogy is constant throughout the whole area, although the proportions and textures do differ. The minerals are those class-ically stable under the metamorphic conditions. The main constituent minerals are feldspar, epidote, chlorite, amphibole. Acessories are present.

Feldspar

The feldspar has optically been identified as albite (An less th 10%). The optical determination has been the same for every slide. The method used for identification was refractive index in comparison to canada balsalm. No relics of any more An rich feldspars were ever found, either preserved alone or as relic cores. Inclusions of ferro-magnesian material (epidotic) is however common. Feldspar extracted from the gabbro (- coarser grains) were full of inclusive material.

Two generations of feldspar have been recognised:

1) large feldspars ragged in appearance but thought to textural represent the original igneous feldspar.

2) vague feldspatic areas usually in the ground mass and though to be recrystallised feldspar due to metamorphism.

During the course of chemical investigation it has become apparent that the nature of the feldspar with respect to An content is not as even as the above picture makes out. It is however unfortunate that the grain size of the rocks makes optical determinations difficult. I is suggested therefore that the feldspar types are extracted and ana-lysed for soda content.

Epidote:

Usually identified as epidotic material including both epidote and zoizite members. Again no precise determination has been carried out.

Chlorite:

The identification of chlorite was also left as such since again extraction and chemical analysis is the best technique applicable.

Amphibole:

The amphibole was determined optically as being a member of the tremolite - actinolite series. No further determination was made. The distinction between this amphibole and hornblende was mainly deduced on preochroism.

Accessories:

Simply listed they are; sphene, stipnomelane, hornblende, pyroxene and opaque minerals (pyrite, phyrotite, magnetite and ilmenomagnetite).

METAMORPHISM

The spilites are petrologically metamorphic rocks although their igneous nature has been chemically proved. The best term to describe them, is therefore metavolcanics.

In describing the metamorphism much of the work has been derived from Winkler.

The mineral assemblage which the rocks now show, is classical for that described as greenschist facies (Winkler B1). The best characteristic feature of this facies to be found in the rocks, is the constant association of albite and epidote (zoisite). Chlorite is not an index mineral of greenschist facies. Turner and Vertoogan define the upper boundaries of the green schist facies as the change in An content of the feldspar from An less than or equal to 70% to An greater than or equal to 15% as reported by some workers is used as the boundary. Optically the two feldspars are easy to distinguish.

Establishment of the actual facies is straight forward but placing the rocks into an appropriate sub facies is more difficult. This is because the index minerals are to some extent chemically controlled and the limited chemistry of the metavolcanics does little to help this.

According to Winkler the subfacies are:

B.1.1. quartz - albite - muscovite - chlorite

B.1.2. quartz - albite - epidote - biotite

B.1.3. quartz - albite - epidote - almandine

For metamorphic basic rocks however the following is used:

B.1.1. albite - epidote - chlorite - actinolite - sphene $\pm$ stipnomelane $\pm$ quartz

B.1.2. albite - epidote - chlorite - actinolite - sphene $\pm$ biotite $\pm$ quartz

B.1.3. albite - epidote - hornblende $\pm$ almandine $\pm$ biotite $\pm$ quartz

The actual defining minerals are therefore biotite, stipnomelane and hornblende.

From the spilite stipnomelane and hornblende have been reported but of extremely limited occurrence. It is thought that the chemistry would allow hornblende to form and so its absence to a regional extent can be used to exclude sub facies B.1.3. Both biotite and stipnomelane would not form with the chemistry the rocks possess and therefore distinction between subfacies B.1.1. and B.1.2. cannot be found. It is probable that no one grade persisted over the whole area and the hornblende present may reflect a rise in grade. Mr.Rutter worked on some sediments to the north where the subfacies is definable and projection of his results into the area may help.

During metamorphism the textures in many of the rocks were preserved. This can best be appreciated in some of the more coarser members which still exhibit a clear igneous texture, in the arrangement of the feldspars into laths and the relative positioning of which must have been ferro-magnesians. Although both have undergone metamorphism both gabbro and felsite show original textures.

The metamorphism has caused some mineral segregation which in places has caused extensive net veining of the rock. The resulting rock then looks almost like an original agglomerate. The large scale representative of this is banding which can be seen on one exposure (not everyone believes this banding to be metamorphic). In the field no structures other than pillows were found on a large scale. It is interesting to note that Mr.Rutter has found graded bedding, over the west, which has not been destroyed by metamorphism.

GEOCHEMISTRY OF THE SPILITES

A strike section was chosen for analysis because it was felt that as the section covered half the area mapped, across the strike, some connection must be preserved between each specimen. This was in direct contrast to a random selection of samples from all over the area, for which relating the final data would have been more difficult. In all seventeen samples were analysed for both major and trace elements. Bulk samples of the rock were used for the analysis. The strike section was divided up into seventeen units in the field using the physical characters available.

Tables I and II present the chemical data for the major and minor elements, comparison figures for classical rocks are found in table III. Location of the actual specimens can be found on the map.

The analyses both for major and trace elements show a remarkable semblance to published data for basic volcanic rocks. The data also shows that the suite represented is entirely basic with no acid or true intermediate types. The question as to whether any of the samples represent tuffs may be considered here. The chemical analysis would only be expected to distinguish tuffs, derived from basic volcanic material, if one or more of the major constituents, say olivine, was not present in the tuff. There is however no evidence in the field to suggest that any significant break to place, during which weathering could have taken place so removing a major constituent from the rocks, later to erode and form tuffs. Therefore from a chemical point of view the sequence may contain tuffs. It is however certain to say that the sequence analysed contains no non volcanic sedimentary material.

It is worth noting that the minor element analyses although falling within accepted limits for igneous rocks, show some values which are extremely low for basic rocks. It may also be stated that the minor elements are generally on the low side for basic rocks. This may indicate that the minor elements have been affected by the metamorphism, a feature not shown by the major elements.

There are however good graphical relationships between all the elements, both major and trace elements. Further work on the trace elements could be interesting in this respect.

In comparing the results with published data, table III (Nockolds) remarkable similarities are recorded between both ordinary basalts and spilites. The area can therefore be regarded as an example of spilitic rocks interbedded (or intermixed) with ordinary basaltic rocks. The latter is not an uncommon occurrence in spilite descriptions, (the term basalt and spilite are here used in a chemical sense only). The Lokken area seems therefore to provide an example of a spilitic association, the majority of the rocks being however basalts.

General elemental analysis

Trace elements

Ni. : range 9 - 200 ppm — generally in the basic range but some
Cr. : range 19 - 330 ppm — very low values indicative more of acid rocks.

Yr. : the spectral line was looked for as it is generally found in acid rocks. Absent in all cases.

Co. : general comparison was made and the values were all much the same. This characteristic of cobalt which usually is more constant than Ni and Cr.

Major elements

SiO_2 : range 46.0 - 53.0 (not determined for all samples) 53.0% SiO_2 was taken as not being indicative of true intermediate rocks. The SiO_2 content can therefore be concluded to cover the whole basic range (SiO_2 for spilites 49.0 - 51.0 average). Some attempt to estimate SiO_2 for the remaining samples using other elemental characteristics was made. In no case did the calculated analyses exceed the above limits.

TiO_2 : range 0.5% - 1.0% fairly constant for all the samples, generally lower than expected.

(Fe) : determined as total iron Fe_2O_3 (Fe_2O_3 + FeO). Range 10 - 13.0%. Not of real value since FeO is desirable.

MnO : approximately ?.2% for all samples.

MgO : range from 5.0% - 10.0%. Show an excellent antipathetic relationship with CaO. These are expected values for basic rocks varying with SiO_2. content.

CaO : range from 7.0 - 12.0%. These are somewhat higher than expected for such rocks especially since some are soda enriched. This may well be accounted for however since CO_2 was not determined and assuming all CO_2 present as $CaCO_3$ (calcite in slides) then allowing for the Ca in $CaCO_3$ the actual CaO would be much reduced.

TABLE I

Complete Chemical Results

(both major & minor element analysis is given.)

	4	1	2	17	16	15	14	13	12	11	10	9	8	7	6	5	3
LM N°	23	24	25	34	35	36	38	39	40	41	42	43	44	45	46	47	48
SiO_2	49·0	53·0	50·4	44·8						46·4	52·2	50·5			46·8		
TiO_2	0·7	0·8	1·0	0·6	0·8	0·5	0·6	0·5	0·5	0·6	0·6	0·6	0·7	0·6	0·7	0·7	0·5
Al_2O_3	16·8	14·1	15·2	16·2						17·4	13·2	15·7			16·8		
Fe_2O_3	12·2	9·8	13·4	13·0	11·8	11·2	11·3	10·5	11·6	9·3	11·3	12·8	12·5	10·0	10·6	13·4	10·2
MnO	0·19	0·2	0·28	0·19	0·16	0·15	0·18	0·18	0·22	0·15	0·17	0·20	0·14	0·15	0·18	0·21	0·17
MgO	5·8	6·5	4·4	8·0	7·7	8·6	8·0	8·2	7·8	7·8	9·9	4·9	6·2	6·6	7·5	6·2	7·0
CaO	6·8	8·8	7·7	9·2	8·6	7·9	8·8	9·7	7·6	7·6	10·7	8·8	6·2	12·4	11·9	6·4	9·3
Na_2O	5·2	4·7	4·8	3·1	3·9	3·3	3·9	3·0	4·3	4·3	2·4	4·3	5·0	2·8	2·7	5·0	3·8
K_2O	0·2	–	0·03	0·6	–	0·7	0·1	0·7	–	–	0·5	0·1	–	0·2	0·5	–	–
P_2O_5	0·13	0·09	0·15	0·10	0·09	0·09	0·08	0·07	0·07	0·06	0·09	0·09	0·07	0·07	0·09	0·09	–
H_2O+	3·0	1·8	2·5	4·1						3·6	2·4	3·4			3·1		
H_2O-	0·2	0·1	0·1	0·2						0·1	0·1	0·1			0·1		
Total																	
Ni	29	72	9	110	84	130	82	120	150	220	21	23	27	60	64	21	76
Cr.	48	180	18	250	180	250	200	290	330	330	19	14	41	250	300	25	190

COMPARATIVE CHEMICAL ANALYSES

	I	II	III	IV	V	VI	VII	VIII
SiO_2	68.9	54.5	54.6	54.6	48.2	43.8	51.2	48.2
TiO_2	0.5	1.4	1.5	1.9	1.8	1.7	3.3	2.7
Al_2O_3	14.5	17.2	16.4	15.6	15.5	6.1	13.7	14.8
Fe_2O_3	1.7	3.2	3.3	3.0	2.8	4.5	2.8	0.56
FeO	2.2	4.6	5.2	7.8	8.1	8.7	9.2	9.25
MnO	0.07	6.16	0.15	0.17	0.17	0.18	0.25	0.23
MgO	1.1	3.2	3.8	8.2	8.6	22.5	4.5	5.6
CaO	2.6	5.8	6.5	10.5	10.7	10.1	6.9	8.8
Na_2O	3.9	5.1	4.2	2.6	2.3	0.8	4.9	4.9
K_2O	3.8	3.6	3.2	0.9	0.7	0.7	0.7	0.4
H_2O	0.6	0.8	0.7	0.8	0.7	0.6	1.9	2.6
P_2O_5	0.16	0.39	0.42	0.3	0.27	0.3	0.29	0.2

TABLE 2

SiO_2	50.5	52.3	51.5	50.7	51.9	5.22	47.2	49.3
Ni	80	100	70	7	10	15	400	1500
Cr	400	200	500	-	-	-	1000	2500

I Average silicic rock
II Average intermediate rock
III Average intermediate rock
IV Average subsilicic rock
V Average subsilicic rock
VI Average ultramafic rock

all taken from Nockolds

VII Average spilitic rock
VIII Average spilitic rock

taken from Turner & Verhoogen.

Na_2O : range 2.5% - 5.0%. probably the most interesting element determined. It was assumed the values would show very little range in soda prior to analysis. The range above is completely graduated none falling at the lower end however. Taken with the facts that all rocks approximate to 50% albite and all the feldspar is determined at An = 7.0% approx., the range is somewhat difficult to explain.

K_2O : extremely low to absent using major element techniques

P_2O_5 : constant at 0.1% approx.

Triangular diagrams have been plotted for:-

$Fe_2O_3 - Na_2O + K_2O - MgO$

$MgO + Fe_2O_3 - Na_2O + K_2O - CaO$

$K_2O - Na_2O - CaO$.

These were then compared with the similar diagrams produced by Nockolds and Allen. As was expected however the points tended to cluster on all the diagrams once more emphasising the limited range within the rocks analysed. The only conclusion which can be drawn from the plots is that they may represent the basic beginning of Nockolds and Allens trends. It is interesting to note that they overlap into the field of rocks described by Nockolds and Allen as parental magma or cumulative rocks. The chemical data however does not lend itself in any way to thinking these rocks as cumulative.

Graphs for the interrelationships between the elements have been plotted and it is remarkable to see how well the relationships still

FIGURE 5

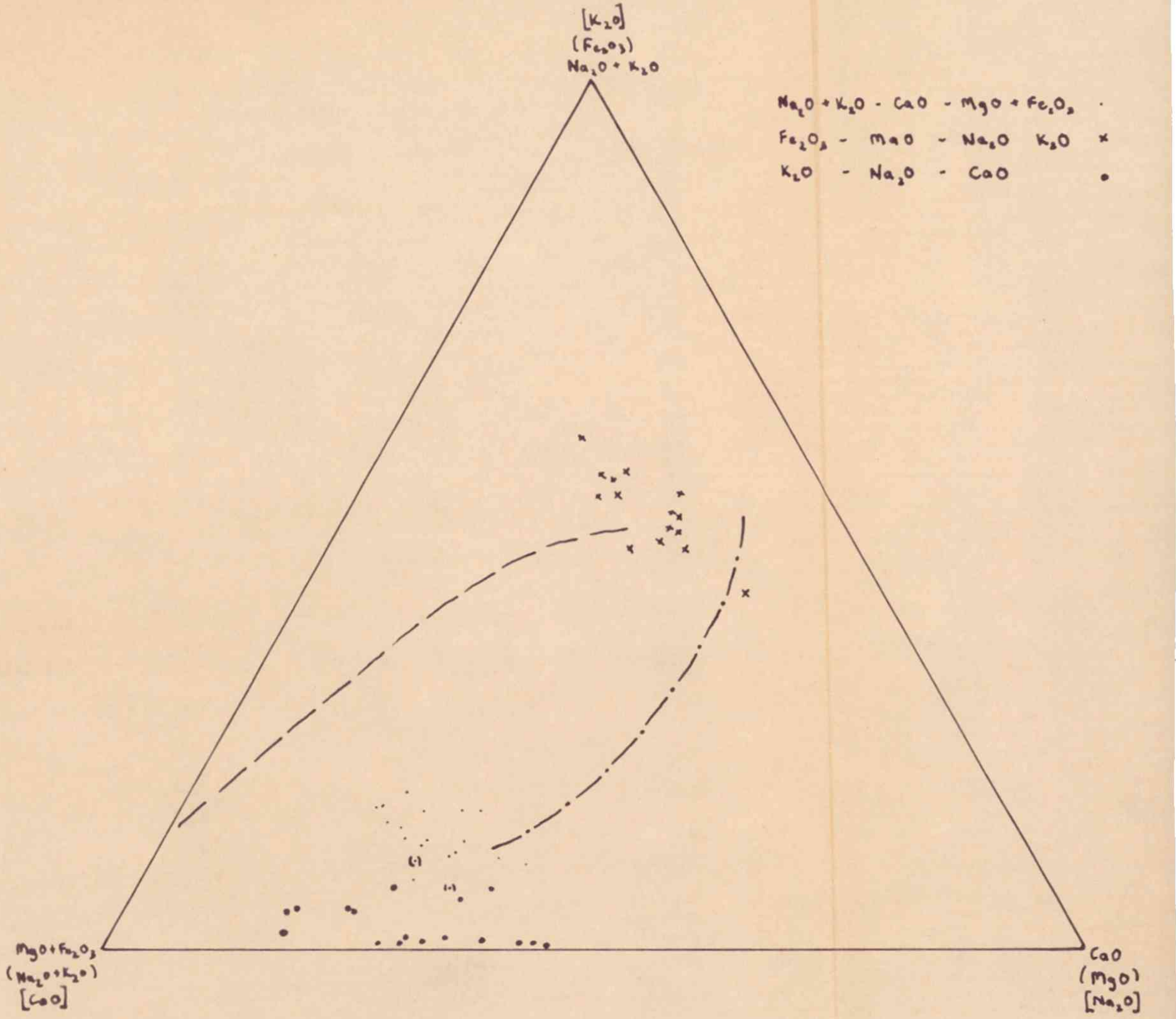
Triangular plots of,

Na_2O K_2O - CaO - MgO Fe_2O_3

Fe_2O_3 - MgO - Na_2O K_2O

K_2O - Na_2O - CaO

The actual elements plotted are the same as those plotted by Nockolds. The two trends shown on the diagram are reproduced from Nockolds actual diagrams. Note how allthe poits cluster at the starting ends of the two trends .The clusteringshows the relative small variation chemical composition observed in the analyses.



[K2O]
(Fe2O3)
Na2O + K2O
Na2O + K2O - CaO - MgO + Fe2O3 ·
Fe2O3 - MgO - Na2O K2O ×
K2O - Na2O - CaO •
MgO + Fe2O3
(Na2O + K2O)
[CaO]
CaO
(MgO)
[Na2O]

hold after metamorphism. This is even more remarkable when the comparative limited chemical range is taken into account. The above even holds for the case of Na_2O. For this reason the conclusion that metamorphism has done little to alter the bulk chemistry seems perfectly valid. It also seems to indicate that, assuming the Na_2O content to be secondarily derived, no process of mass introduction has been operative.

More over strict control over soda must have been the case.

Some segregation of material on a small scale has been described and accorded to metamorphism. It seems however that even the relatively small sample used for analysis, has completely removed this uneveness.

Assuming no bulk chemical change due to metamorphism it is now proposed to chemically subdivide the rocks. Since metamorphism has left unaltered the chemistry it is suggested that the divisions have some parental basis. Later the same groupings will be shown in thin section. At the moment it is proposed to letter the groups as A B and C but names are suggested later on.

Group A :	$SiO_2 < 47\%$	includes all low SiO_2 members
	$Na_2O < 3.5\%$	all members are lowest Na_2O
	$Ni > 100$ ppm	
	$Cr > 250$ ppm	no overlap occurs with respect to trace elements.
	MgO high $7.5 - 10.0\%$	possible ranges but
	CaO high $9.2 - 12.0\%$	some overlap.
Group B :	SiO_2 approx = 50.0%	highest soda with an SiO_2 range corresponding to classical spilite figures.
	Na_2O 74.5	
	$Ni < 30$ ppm	strict control again here

	Cr	< 50 ppm		
	Fe_2O_3	high	12.0 - 13.5%	possible ranges
	MgO	low	4.5 - 6.0%	
Group C:	SiO_2	> 50.0	some overlap with Group B	
	Na_2O		intermediate between A and B	
	Ni	70 - 85 ppm	range of 15 ppm	precise control here.
	Cr	180 - 200 ppm	range of 20 ppm	

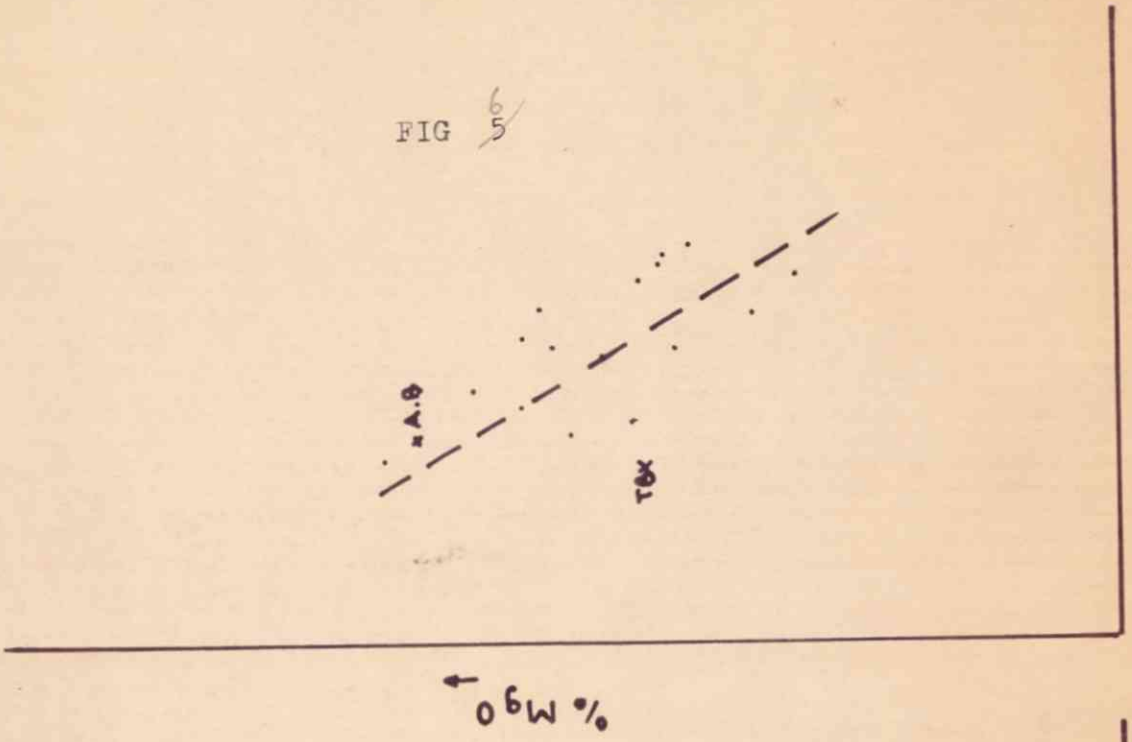
No clear limits for other major elements.

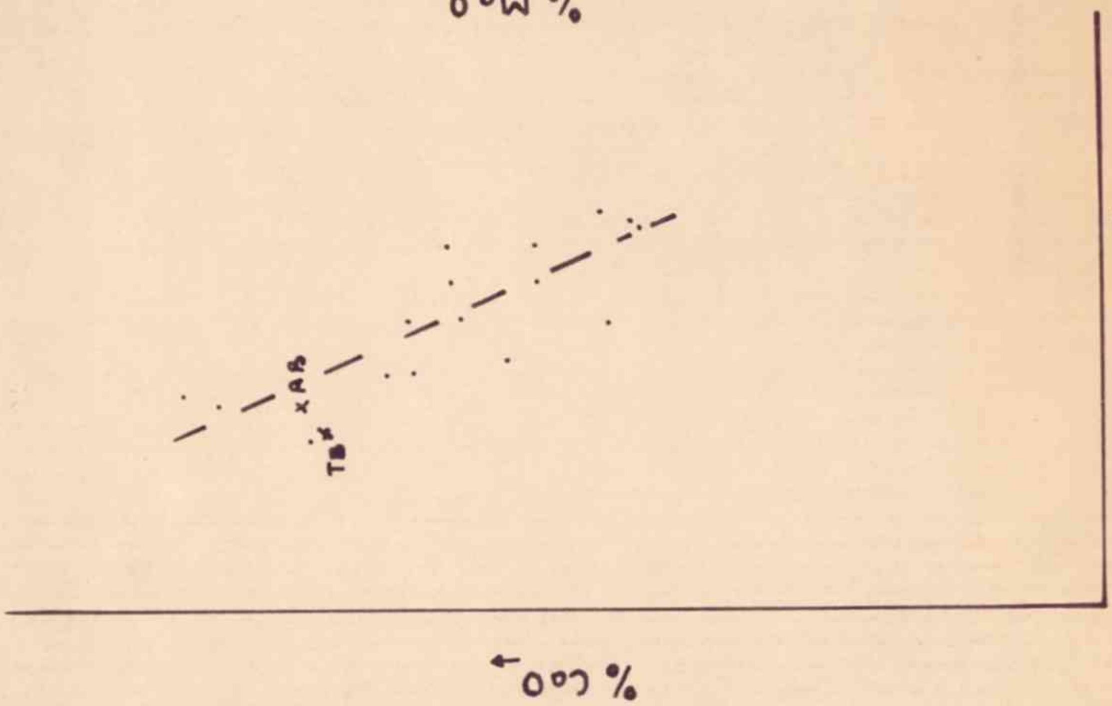
The above chemical subdivision is the one which was used to group the rocks initially. From here the grouping was tested in thin section and hand specimen. Group C not clearly defined chemically except for trace elements, is the most distinct in thin section.

The divisions made are open to criticism on many grounds, both theoretical and practical and this is fully realised. Since however the aim of the work was a subdivision this alone may justify the above.

Initially SiO_2 content was used to divide up the rocks, mainly because most petrologists accept very little else due to lack of understanding of the other elements with respect to rock genesis. It is however very clearly shown that minor elements, far easier to obtain and probably more accurate, are the most useful guide. (ignoring the supposed metamorphic readjustment!) The other major elements do show division but these are not as readily demonstrable as the above.

FIG ~~5~~ 6





Plots showing the relationship between soda & both magnesium & calcium.

SODA METAMORPHISM AND BRIEF NOTES ON SPILITES

The evidence for regarding albite crystallisation as a primary phenomena seems, as in most cases with spilites, to be obliterated by later metamorphic events. Battey, Amstutz and others claim that spilites can form a distinct state of primary volcanic rocks.

Most cases do seem to show however that the albite is of a secondary nature. To explain this many methods have been employed for introduction of soda into the system. Spilites nearly always show an enrichment in soda. It is recognised that the soda content of basic magma is considerably lower than that of spilites. Perhaps the largest objection to the introduction of soda from external sources, is that, it is common to find normal basalts interbedded with spilites. This clearly indicates that a selective mechanism must operate during the introduction of the soda.

The above is very much the case at Lokken. The area has previously been described as an area of spilitic rocks. Careful analysis has now shown many of these rocks to be normal basalt types. Some however have these high soda contents which the classical petrologist will not accept as primary for basaltic rocks.

In the case of Lokken two answers arose to the problem:

1) that the feldspar content might vary considerably enough to change the analytical results.

2) all the feldspar was not albite.

It may be said that in the light of present knowledge neither of these two is applicable. The problem still therefore remains unsolved but a summary of the facts is made below:

1) Some adjustment of soda has taken place either by external sources or internal readjustment. Here it may be noted that no soda poor members were found.

2) There has been strict control with respect to other elements.

3) Mass introduction was not the case..

It is probable that both metasomatic and metamorphic processes contributed to the above state. A suggestion is made that further extensive soda determinations are made and the area possibly contoured with respect to soda. Also may it be suggested that some of the feldspars of both types be extracted and the precise Na content obtained.

OPTICAL SUBDIVISION OF THE SPILITES

The spilites have been optically divided into three groups and appropiately named. The following is a short petrographical description of the types:

Type A albite - epidote fels.

This is the most diverse group and may be called the 'sack' group. The modal analysis is:

albite	50%
epidote	35%
amphibole	10%
chlorite	5%

Although called the albite - epidote feldspars it is the lack of chlorite that characterises the group in thin section. The textures are highly variable from semi gabbroic to fine grained porphyritic varieties. In both fine and coarse grained varieties albite and epidote dominate throughout. In some coarse varieties pyroxene may be seen but usually in an advanced state of alteration.

(No   is included due to diversity of the Group 1)

Type B albite - chlorite fels.

As group A shows the variability, so this group is one of the easiest to identify especially in hand specimen.

The modal analysis is:

albite	48%
epidote	17.6%
amphibole	9.5%
chlorite	24.0%
others	1.0%

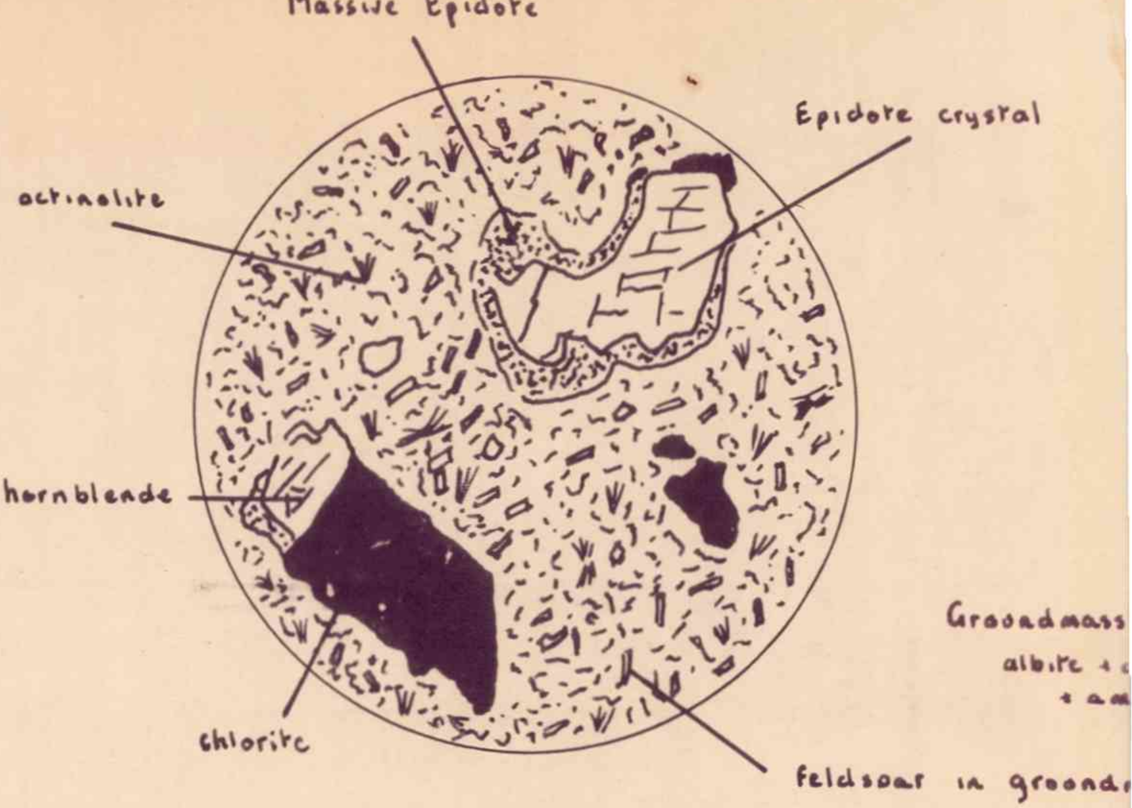


FIG 7

1mm

Thin section of type b albite chlorite fels.
Compare this with figure 8..
This is not a true section but is composite to show the various types of phenocrysts if they in fact reprresent such.

The shales are all fine grained with porphyries usually of feldspar (now albite) and hornblende (presumably pyroxene). In direct comparison with group C this group lacks the large ragged feldspars. The fine grained matrix seems to be composed of feldspar and chlorite with some amphibole. The feldspar recurs also in the ground mass as small twinned laths, ragged in outline and probably an original texture although recrystallised.

The epidote seems to have segregated in these specimens, and occurs in clusters and veins usually replacing the large feldspars.

Chlorite occurs throughout the groundmass but also as dense shapeless areas of ragged fibrous clusters.

In hand specimen the group shows a darker colour grey-green to black and is somewhat higher in S.G. The characteristic feature is however that they tend to sparkle in hand specimen, the light reflecting from chlorite cleavage flakes.

Type C albite - epidote - amphibole fels.

This is highly characteristic in this section. The modal analysis is:

albite	51%
epidote	23%
amphibole	15%
chlorite	9%
others	2%

The comparative grain size is much larger than the others and the textures with respect to the feldspars is unique. It is this group

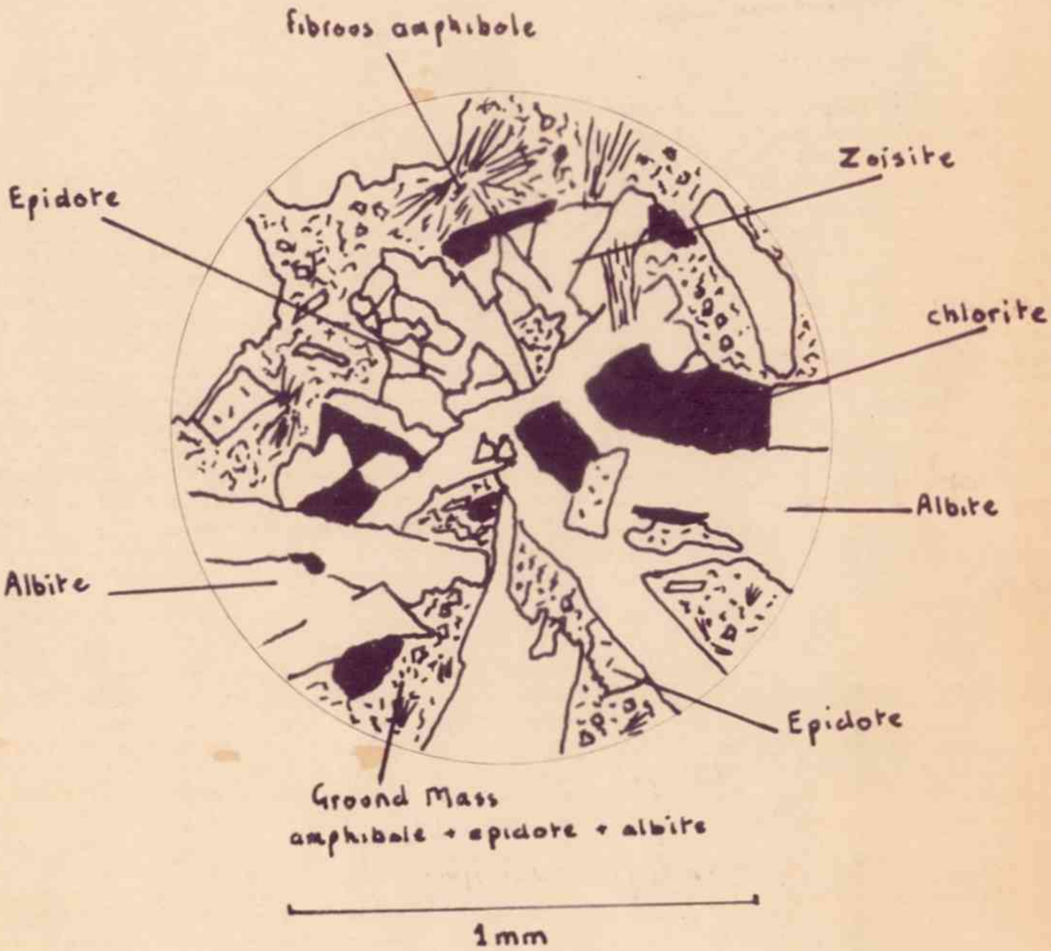


FIG 8

Type C albite epidote amphibole

This the most distinctive of the groups since it is consistent in this form. Compared with other slides the textures in thse slides are coarse. The feldspar laths are taken to represent the original igneous form. None of the mineralogy is primary it is entirly metamorphic.

which shows the relic igneous textures well. The feldspars dominate as large ragged laths with the ferromagnesians being interstitial. Some segregation on the part of epidote again occurs. Amphibole although only a smaller percentage is somewhat more dominant.

The sections again show the two generation feldspars. The first, the large twinned laths have been described and the second is the vague matrix type as found in the gabbro and other coarse textured rocks.

Pyroxene is again present on some sections as highly altered crystals (usually replaced by hornblende).

Identification in hand specimen is not easy to describe but there is a regularity in appearance to the group. The colour is medium green for the greenstones and the grain size is equal for the whole group. The grains look like a typical fels type rock.

The identification in hand spe imen is not claimed to be easy and applicable but group B can be easily recognised. After this it is a matter of getting one's eye in for group C and the rest fall into group A.

In thin section texture separates group C and then the abundance of chlorite separates the others.

If mapping on hand ape imens is possible as claimed then a strict control can be kept by discrete use of thin sections.

The relationships of these groups to origin, metamorphism or stratigraphy is not at the moment known. They just represent possible mapping criterior.

GENERAL PETROLOGY:

The Lokken greenstones are a classical example of the pretectonic volcanic activity associated with geosynclines. That is, they represent an early stage vulcanism associated with subsidence and sedimentation in the geosynclinal trough.

Taken on a regional scale they are in association with described geosynclinal sediments (Hovin group). Also the pillow structure which they exhibit is further evidence that the volcanic activity itself was submarine in nature.

Usually such rocks are found associated with basic intrusives and chert deposits. In the case of Lokken, the basic intrusive phase is represented by the large gabbro masses which can be taken as the equivalent of many of the serpentines usually associated with this suite. The cherts are usually described as radiolarian cherts. In Lokken these are represented by the jasperoid lenses and although no radiolarian remains have been found, they both represent the same siliceous rich material.

It is difficult to assess the different roles of sediment and volcanic material infilling in the trough since only the volcanics have been worked in. It may be that after vulcanism began the trough became filled with only volcanic material but ideas such as this are only supposition.

Petrologically the volcanics do not show the usual range found in such rocks. The classical cases show spilite assemblages associated with classical volcanics ranging from basic to acid. In the case of Lokken however, the spilites seem to be associated with only the basic volcanic member. The acid phase may be represented as a later intrusive phase. Further work, especially to the north, may also show the range into intermediate volcanic material. If this is the case then the area will indeed be classical for spilite study.

It may not be valid to separate the spilites from the ordinary volcanic material since both are of the same origin. It may be concluded however that some process affected the lavas after extrusion and prior to metamorphism. This process converted certain members of the suite to spilites and did not convert the other members. The process was one of metasomatism which caused a pre metamorphic conversion to the feldspars to a form less An rich; this new form not being the same in all cases and now producing the two distinct forms.

PETROGENISIS:

It is not proposed to deal here fully with this topic but to point out a few suggested ideas. The whole subject is intimately tied up with the petrogenisis of spilites and enough has been written on that subject to indicate it is an intricate problem.

The environment of deposition is certainly marine on the evidence of pillow formation and the marine sediments - Vaskiss and Hoven group - associated with the rocks.

The present mineralogy in the rocks is not primary, but is it in fact entirely metamorphic? It is suggested that the mineralogy is of two generations. A first generation metasomatism mineralogy formed soon after deposition and a second generation metamorphic mineralogy. The evidence for this lies in the authors belief that all the albite feldspar is not metamorphic in origin. Two feldspar types have been identified in thin section and these represent the two generations. The large feldspars with ragged outline are first generation whilst the vaguer Stapilen feldspar is the recrystallised second generation metamorphic feldspar.

The genesis of the first generation feldspar is the most difficult. It formed after deposition and before metamorphism. It requires an introduction of soda into the system. These sources may be late magmatic fluids or included brines. The introduction also requires strict chemical control. These are a few of the problems tied up here with the genisis of spilites.

It is now suggested that prior to metamorphism all the feldspar was of an enriched An content and that the metamorphism provided a recrystallising force. The metamorphism is however unlikely to have converted An rich plagioclase into albite.

The ferro magnesians are the metamorphic products and it is difficult to estimate the effect of the supposed soda-rich fluids on the original ferro-magnesians. It may be that all the mineralogy is first generation feldspar since little change would be required to stabilise this in greenschist conditions.

CHAPTER IV

STRUCTURAL HISTORY

The Lokken area was part of the Caledonian orogenic zone and therefore tha structural history is somewhat complex. The following is a brief structural history but the detailed work and thesis containing the conclusion is that of Mr.Rutter.

The area has been subjected to three main phases of folding, two of which are quite apparent, the third somewhat more difficult to see. These will subsequently be called F_1, F_2, and F_3 in accordance with Mr. Rutters interpretation.

The F_1 phase of folding was a period of isoclinal nappe formation on axes approximately east-west. The main attribute of this phase in connection with the Lokken area is that the schistocity is a direct result. Also associated with F_1 was the metamorphic period (up to greenschist grade). The isoclinal folding is not a feature uncommon to Lokken but is a main structural episode concerning the whole of central Norway.

The schistocity imposed by F_1 was then subject to folding itself by a second phase, F_2. This also appears to have been on axes roughly trending east-west. That is coaxial with F_1. Mr. Rutter however who has carried out a detailed structural analysis of both F_1 and F_2 concludes that there is a slight angular divergence between the axes of F_1 and F_2. This has been calculated to be about 5°. The main attribute of the F_2 phase is that it produced the structure commonly referred to as the Lokken syncline and the schistocity dips measured are in fact F_2.

Evidence has been produced that the term should be the Lokken synform but the author does not fully understand this at the time of writing. No metamorphism has been found associated with F_2.

Finally the F_3 folding took place on axes roughly N-S and caused a flexing of the Lokken synform and so giving the area a regional plunge to the W. Effects of F_3 flexure can also be seen in the attitude of the thrust plane. To the east of the Orbla the regional plunge is east and this forms the basin structure referred to earlier on.

Superimposed on the folding are a thrust phase producing north-south running thrusts and a fault phase producing two fault directions east-west and north-south. The chronological timing of these two according to Mr.Rutter is:-

thrusting -- late F_2

faulting - late F_3

A chronological summary of structural events can be made:-

F_1 folding and metamorphism	E-W
F_2 folding	E-W
thrusting	N-S
F_3 folding	N-S
faulting	N-S and E-W

The thrusting has always been regarded as highly significant at Lokken since it is connected in some way with the ore. The explanation seems that the thrust could have localised along the ore.

The ore body is however regarded as pre F_1 since the F_1 stretching direction is parallel to the elongation of the ore body.

The movement on the thrust is difficult to estimate but the opinion of all three workers is however that it was only relatively small, a few 100m only. The direction of movement has been deduced as strike slip movement from the north to the south.

A significant problem arose by the location at Drayset of thrusting similar to that seen at Lokken. The Lokken thrust has been well mapped as running north-south through a convenient line of lakes, and then swinging to the west in the south. Unfortunately it seems the fate of everybody to cease mapping the thrust at that point mainly because surface exposure of the thrust is absent completely and also the lakes cease being convenient. The possibility undoubtedly exists however that the thrust at Lokken swings west, Vs up the Orbla river valley and finally links up with the thrusts found at Drayset. Further mapping in this vital area described above would solve this question.

The faulting is interpreted as being the latest major structural feature. It seems obvious that the area is cut by some large faults but lack of a detailed stratigraphy makes their proof extremely difficult. The possibility of a large north-south fault existing in the position now occupied by the Orbla river was investigated. A displacement of the gabbro was accepted but apart from this little evidence could be found and the problem still remains.

REGIONAL EVENTS

These are given in chronological order as far as possible:

A series of lavas was poured out from submarine vents. The actual vents have not been located but according to regional work by Carstens and others the source (or sources) was close to the Lokken area, if not directly in it.

The pile was then intruded by a basic and acid phase, the basic phase producing large gabbro masses whilst the acid phase produced a more minor episode of intrusion. The emplacement of a massive pyrite ore body must then have taken place, although the actual source (magmatic?) and mode of emplacement are unknown. At about the same time as the emplacement of the ore body the sedimentation and subsequent deposition of the vaskiss must have taken place. (Perhaps there is a common source for the two). The area then became part of the Caledonian orogeny and metamorphism and isoclinal folding (F_1) took place. This was followed by two further phases of folding (F_2) and (F_3). The (F_2) coaxial with (F_1) whilst accompanied by extensive thrusting from north to south (F_3) as opposing north-south trends.

After all these episodes the stabilised mass once more was extensively faulted on north-south and east-west trends.

CHRONOLOGICAL TABLE

1) Sedimentation	: mainly basic volcanics, some sediments on a regional scale.
2) Intrusion	: gabbro masses quartz keratophyre sills (small basic dykes?)
3) Mineralisation	: emplacement of massive sulphide ore body (vaskiss)?
4) First cycle of orogeny	: folding metamorphism corresponding alteration of feldspar (or recrystallisation) by metamorphism or metasomatism into albite and epidote.
5) Second cycle of orogeny	: folding and thrusting of already deformed rocks.
6) Third cycle (same orogeny)?	: latest folding of rocks.
7) Faulting	: basement stabilised and faulted.

CHAPTER V

SUMMARY OF CONCLUSIONS RESULTING FROM THIS WORK

Geochemical

The work has shown that there has been no mass adjustment of elements in the rocks during processes which affected them. This provides a check on the method used to determine the first statement, that is geochemical techniques are valid in establishing the original character of the rocks. This is basically the same approach as used by Taylor on New Zealand metamorphic rocks.

The chemistry has shown a way the rocks can be subdivided into groups and which has subsequently been tested in both thin section and hand specimen.

The investigations into the trace elements has once again demonstrated that with major element control trace elements can be useful tools in determining rock types. In this case it has been shown that trace element analysis is by far the most accurate means of subdivision provided a prior SiO_2 control is known. Trace elements are also somewhat easier to determine than major elements such as SiO_2 and MgO.

A more theoretical problem has been shown to exist in the different ways major and trace elements behave during secondary processes.

Petrological

The main member of the Lokken suite is basic material with no known intermediate members and only a slight volume of acid material.

The area has demonstrated the classic example of greenschist metamorphism in basic igneous rocks and it has left the author in no doubt that in this particulat field there is a definite lack of present knowledge.

The area has also proved to be classic for the study of spilitic relationships.

Petrogenisis has briefly been touched upon but more problems arise than were solved. Petrogenisis of the Lokken greenstones is merely a case of spilite petrogenisis.

Out of the confusion of the greenstones has arisen a possible method of field mapping the basic volcanics present.

FUTURE WORK IN LOKKEN

It is hoped that much of the future work has been pointed out in the relevant chapters of this thesis, but some general aims may be outlined.

In the view of this work the first aim should be to try and thoroughly map the greenstones, since this will not only help the petrological interpretation but may also be of economic value.

The gabbro masses should be examined in greater detail for again there is a possible classic story to be found. A soda contour map would provide a useful tool in interpretation.

Finally the felsite rocks to the west at Drayset may provide examples of the, so far, missing intermediates.

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NOTES

GEOLOGICAL MAP OF THE LÖKKEN AREA

MAP 2.

LEGEND

3	sample nos
③	chemical analyses
3	slide nos
	sketch field trends
	geological boundaries

SCALE 1:15.000

mts 500 — 0 — 500 — 1000 — 1500 mts

J. MAY, 1966