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Sammendrag

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1) Hall, C. et al. : "Geological setting of the Skorovas ore body within the allochtonous volcanic Stratigraphy of the Gjersvik Nappe, Central Norway."

2) Reinsbakken A. : "Geology of the Skorovas Mine: A Volcanogenic Massive Sulphide deposit in the Central Norwegian Caledonides."

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# Geological setting of the Skorovas orebody within the allochthonous volcanic stratigraphy of the Gjersvik Nappe, central Norway*


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Synopsis

*The Skorovas orebody is one of the chief stratiform base-metal deposits within the allochthonous greenstone belt of the Central Norwegian Caledonides. It is contained in the volcanic level of a complex eruptive association of Lower to Middle Ordovician age defined as the Gjersvik Nappe. The rocks of this nappe are contained as a depressed segment of the larger Köli Nappe and defined to the north and south, respectively, by the Börgefjell and Grong–Olden basement culminations. The principal components of this nappe are a plutonic infrastructure of composite gabbroic intrusions within which has been emplaced a series of dioritic to granodioritic (trondhjemitic) bodies that form the roots of a consanguineous submarine polygenic volcanic sequence. The eruptive rocks are overlain unconformably by a sequence of polymict conglomerates and calcareous flysch sediments, the composition of which suggests immediate derivation by erosion from the underlying igneous complex.*

*Pre-tectonic segregations, veins and vesicle fillings of epidote, albite, chlorite, carbonate and quartz related to primary volcanic flow structures in the lava pile provide evidence of pervasive in-situ sea-floor metamorphism, and this interpretation is verified by the abundance of nearly monomineralic epidote clasts in the derived conglomerates.*

*The relationship of the eruptive and sedimentary suites is interpreted in terms of the evolution of an ensimatic island arc, of Lower to Middle Ordovician age, which underwent uplift and erosion prior to emplacement on the Fennoscandian basement during the climactic stages of collision tectonism of the Caledonian Orogeny in Silurian times.*

*The entire igneous and sedimentary assemblage has been affected by the tectonic stages of allochthonous emplacement, but the gross differences in competence between the component lithologies has resulted in a particularly heterogeneous style of deformation in [illegible] folding, componental sliding, fracturing and penetrative metamorphic refabrication have been governed largely by the geometry of the most competent lithologies, notably gabbro, diorite and granodiorite (trondhjemite) intrusives and, within the extrusive sequence, compact dacitic flows and their spilitized aphanitic equivalents (keratophyres). The heterogeneous pattern of deformation is resolved in terms of two main stages of folding complicated by componental sliding movements.*

*Mineralization occurs at two levels in the eruptive sequence. The layered gabbros and lensoid metagabbros of the plutonic infrastructure contain small cumulus bodies of nickel-, copper- and platinum-bearing pyrrhotite–pyrite–magnetite ore of magmatic derivation. Mineralization of this type is at present only known in sub-economic quantities.*

*The Skorovas orebody, in common with other widely dispersed volcanic exhalites in the Gjersvik Nappe, occurs within the volcanic sequence at a level marked by episodes of explosive dacitic volcanism and associated fumarolic activity. The Skorovas orebody consists of approximately 10 000 000 tons of massive and disseminated predominantly pyritic ore with an approximate average grade of 1.3% Zn and 1.0% Cu, together with trace amounts of Pb, As and Ag. The complex lensoid geometry of the orebody is resolved in terms of the disjunction of a single stratiform unit by tight isoclinal folding and componental movements, probably involving both translation and rotation.*

*Enrichment of sphalerite, chalcopyrite and, locally, galena within the magnetite–pyrite ores at the stratigraphic top and margins of the ore lenses is interpreted as a primary feature. The banded magnetite–pyrite ores are commonly associated with magnetitic cherts or jaspers and are thus transitional in aspect to the thin, iron- and silica-rich, base-metal-depleted, exhalative sedimentary horizons that occur extensively within the extrusive sequence of the Gjersvik Nappe. These are interpreted as the products of settling of colloidal iron and silica hydrosols following explosive dispersal into an oxidizing submarine environment. They are valuable time-stratigraphic markers and indicators of way-up in complicated structures and are a potentially valuable tool in exploration for massive sulphide bodies formed in limited reducing environments.*


The belt of metamorphosed Lower Palaeozoic rocks, chiefly of Ordovician age, within which the important stratiform pyritic copper- and zinc-bearing orebodies of the Scandinavian Caledonides are located extends over 1500 km from Rogaland in southwestern Norway to Nord Troms. The divisions of this complex metallogenic belt have been described by Vokes [73] and Vokes and Gale,[75] and Fig. 1 shows the relationship of the principal districts to the thrust front of the Caledonian allochthon. The culminations of the underlying Precambrian basement, together with the effects of erosion, have produced the segmentation of the allochthon on which the division into separate districts is broadly based. Structural and stratigraphic correlations along the length of the belt are made difficult by the structural complexity of the allochthon, the sparsity of fossil remains and the penetrative effects of tectonic deformation and regional metamorphism. Sufficiently detailed studies have been made, however, in the regions of South Trøndelag (Trondheim district),[49,50,52] North Trøndelag (Grong–Gjersvik district)[40] and the geographically adjacent areas of Jämtland and Västerbotten in Sweden [81,82,83] to show that the stratiform ores of Skorovas, Joma, Stekenjokk, Løkken and Röros lie within the Köli Nappe, which is the upper


*UNESCO–IUGS International Geological Correlation Programme, project no. 60: Correlation of Caledonian stratabound sulphides. Norwegian–British contribution no. 1.

structural unit of the Seve–Köli Nappe complex first defined by Törnebohm.[68] The broad correlation within the Köli structural level can reasonably be carried into the Sulitjelma district of Nordland,[39,80] and in all probability this correlation can be extended into the ore district of Nord Troms.

It is clear that the separate districts that comprise the Ordovician province of stratiform pyritic ores lie at a broadly comparable structural level in the Caledonian allochthon of the Scandinavian peninsula, but there are significant differences in the stratigraphy and metamorphic grade of the host rocks from district to district. In general, the Ordovician host rocks comprise a varied assemblage of supracrustal volcanic and sedimentary rocks with closely associated plutonic masses of ultrabasic, basic and acid composition. The conspicuous quantity of basaltic to andesitic volcanics in the supracrustal sequences, taken together with their deformed and metamorphosed condition, ranging in grade from lower greenschist to almandine amphibolite facies, has led to the familiar use of the terms greenschist and greenstone in descriptions of the stratigraphy of various districts.[61] Goldschmidt[22] early lent authority to this usage by defining the 'Stamm der grünen Laven und Intrusivgesteine' as an important constituent rock kindred of the south and central parts of the Caledonian allochthon at the structural level now under discussion.


**Fig. 1** Synoptic geological map of Scandinavian Caledonides showing main districts of stratiform volcanogenic ores at Köli structural level

It is generally recognized that the stratiform pyritic orebodies have a close genetic relationship to the volcanic rocks with which they are associated[73] and that this relationship originated with the formation of tholeiitic and calc-alkaline eruptives at the margins of the Caledonian orogen in Ordovician times.[15,16,47,75] The genetic process that relates the ores and host rocks has been masked by the effects of metamorphic recrystallization and polyphase deformation, which affected both ores[73,74] and host rocks during the process of allochthonous tectonic emplacement consequent upon collision of the Scandinavian and Laurentian cratons during Middle Silurian times.[10,24] The palaeoenvironmental interpretation of the rock assemblages contained in the structural elements of the Köli nappe is clearly of the greatest importance in interpreting the genesis of the associated ores; in a region of the tectonic complexity displayed by the Caledonian allochthon, however, it is clear that the primary geological framework must be established by a study of the field relationships at a level of regional detail such that the ore deposits can be considered at the scale of the geological phenomenon responsible for their formation. If a volcanogenic origin is postulated, an understanding of the volcano-stratigraphy and structure in an area that extends from 1 to 10 km outside the orebody itself must be sought. This has been the basis on which the present study of the environment of the Skorovas deposit was undertaken.

## Regional structural and stratigraphic setting

Existing knowledge of the major structural and stratigraphic units of the Grongfelt originated with the regional geological mapping undertaken by Statsgeolog Steinar Foslie[12,14] during the period 1922–27, the details of which were amplified and interpreted by T. Strand[14] and C. Oftedahl. More recent regional studies by Zachrisson[81] in the adjacent Swedish area of Jämtland and Västerbotten have given an idea of the succession of structural units within the Köli Nappe sequence between the Grong and Stekenjokk areas. A compilation from these sources is made in Fig. 2, which shows the main second-order tectonic divisions that have been recognized within the Köli level of the Seve–Köli nappe. Combining the terminologies of Foslie,[12] Oftedahl[41] and Zachrisson,[81] there are four divisions to be recognized. The first and uppermost of these is the Gjersvik Nappe, within which lie the Skorovas (Sk) and Gjersvik (Gj) orebodies. Below this lies the Leipik Nappe, within which, by extending the structural interpretation of Zachrisson, the Joma orebody (Jo) must lie. Below this lies the Gelvernokko Nappe and, finally, the Lower Köli Nappe unit, within which are situated the Stekenjokk orebodies (St) (the Stekenjokk malm and the Levimalm).[82]

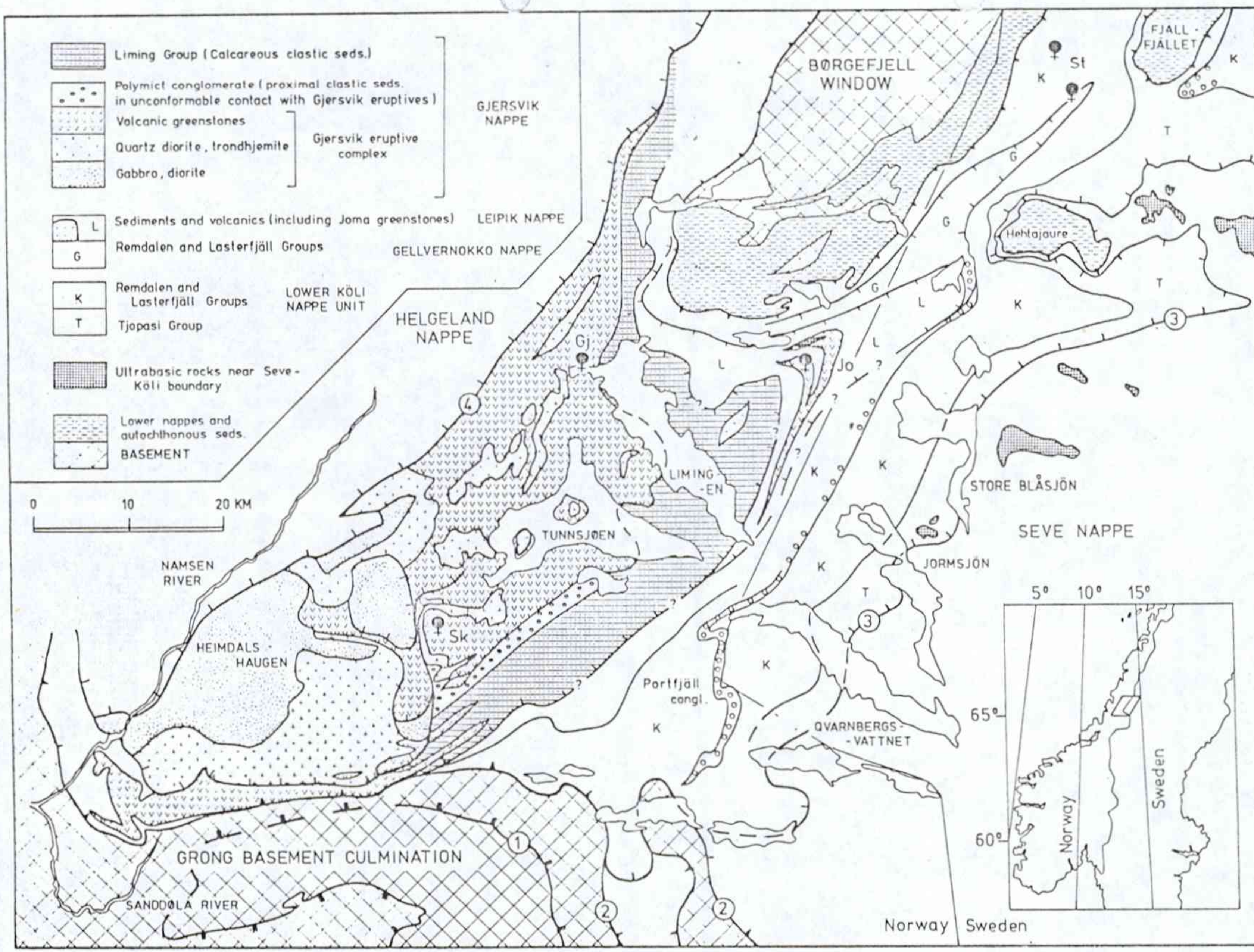



Fig. 2 Map showing location of main ore deposits in Grong–Stekenjokk district (Sk, Skorovas, Gj, Gjersvik, Jo, Joma and St. Stekenjokk) and main structural and stratigraphic units that can be distinguished within Köli Nappe. (1) Thrust at base of Olden basement nappe; (2) thrust at base of Seve–Köli Nappe; (3) thrust separating Seve and Köli sequences within Seve–Köli Nappe Complex; (4) thrust separating Gjersvik Nappe at top of Köli Nappe sequence from high-grade metamorphic rocks of Helgeland Nappe Complex. Boundaries based on geological information from Foslie, Oftedahl, Zachrisson, Gee and Gustavson

The broad classification into the second-order tectonic units shown in Fig. 2 provides a useful basis for descriptions of the regional geology, but the exact status of the second-order thrust boundaries is difficult to establish because these are taken, for the most part, to follow stratigraphic boundaries.[41,81] For the purpose of the present discussion, however, the precise location of the second-order structures and their relative tectonic status is less important than the plutonic and stratigraphic relationships preserved within the Gjersvik Nappe itself. In Fig. 2 the upper tectonic contact with the Helgeland Nappe [23] is clearly defined. The plutonic and supracrustal stratigraphy is revealed in the passage from southwest to northwest across the area of the map covering the Gjersvik Nappe. Without precise knowledge of the relative ages and finer lithological divisions of the various units the following sequence is conspicuous. Large masses of gabbro and granodiorite (trondhjemite) in the southwest are succeeded spatially to the northeast by the Gjersvik volcanic greenstone sequence with the contained orebodies at Skorovas and Gjersvik. A period of relative quiescence is indicated by the presence of a marble bed intermittently preserved at the uppermost level of the volcanic greenstone sequence. The marble is best preserved in the terrain north of the Limingen Lake, but a limited thickness is found to the NNE of Skorovas mine in the terrain to the south of Tunnsjøen. The volcanics with the overlying marble are followed by a spectacular polymict conglomerate, the typical aspect of which is shown in Fig. 12. The final part of the sequence is made up by the clastic sediments of the Limingen group, composed by a variety of schistose conglomeratic, sub-arkosic and phyllitic rocks, the majority of which are distinctly calcareous.

Oftedahl,[41] in his discussion of the nappe units of the Grongfelt, defined a thrust boundary of intermediate significance that separates the polymict conglomerate and the Limingen sequence of calcareous and conglomeratic metasediments, so that the Gjersvik Nappe, in its original definition, does not include the Limingen Group. It seems reasonable, however, to extend the compass of the Gjersvik Nappe to include the sediments of this group, which seem to be laterally related, in part, to the basal polymict conglomerate and to have derived most of their clastic components from the Gjersvik plutonics, greenstones and overlying limestones.

The rocks of the Gjersvik Nappe have, so far, yielded no fossil remains to give a basis for precise dating and correlation with stratigraphies in adjacent segments of the Seve–Köli Nappe. The volcanic and plutonic units of the Gjersvik eruptive complex do, however, bear certain similarities to the rocks of the Støren Group [72] in the Trondheim region. The Støren Group, locally, overlies schists of the Gula Group containing *Dictyonema flabelliforme*.[62] The contact between the two groups is, however, markedly tectonic [16] and, thus, the graptolite fossil evidence can only be used to suggest a possible maximum age of Upper Cambrian–Lower Ordovician (Tremadocian) for the Støren Group, and it is conceivable that the tholeiitic eruptive activity recorded in the Støren sequence [16] could have been initiated yet earlier in Cambrian time.

It has generally been proposed that the Gjersvik Group is of equivalent age to the Støren Group [45] and, by implication, that the two groups represent similar stages in the morphological and magmatic evolution of the Caledonian orogenic margin in central Scandinavia. Stratigraphic and geochemical evidence suggests, however, that the eruptive sequence of the Gjersvik Nappe is more evolved in terms of calc-alkaline character [16,47] – a matter that is given further consideration in a later section of this paper. Gale and Roberts have therefore suggested that the Gjersvik eruptives are of younger age than those of the Støren Group,[16] and a partial correlation, at least, with the andesitic greenstones of the Lower Hovin Group (Forbordfjell, Hølonda and equivalent greenstones)[53,72] seems reasonable. The age of the youngest Gjersvik eruptives therefore probably lies within the Arenig–Caradocian range, whereas the graptolitic fauna of the Bogo shale within the Lower Hovin Group, which overlies the Støren Group in the Trondheim region, is interpreted as belonging within the *Didymograptus hirundo* zone.[57] The Støren Group thus has a defined minimum age in the range Arenig to early Llanvirnian.

A further aspect of the stratigraphic correlation between the Lower and Middle Ordovician sequences in the Trondheim and Grong districts concerns the tectonic and stratigraphic status of various polymict conglomerate horizons that occur at intervals within the Lower and Upper Hovin Groups and, notably, that which overlies the Gjersvik eruptive sequence.

The widespread occurrence of conglomerates (Venna,

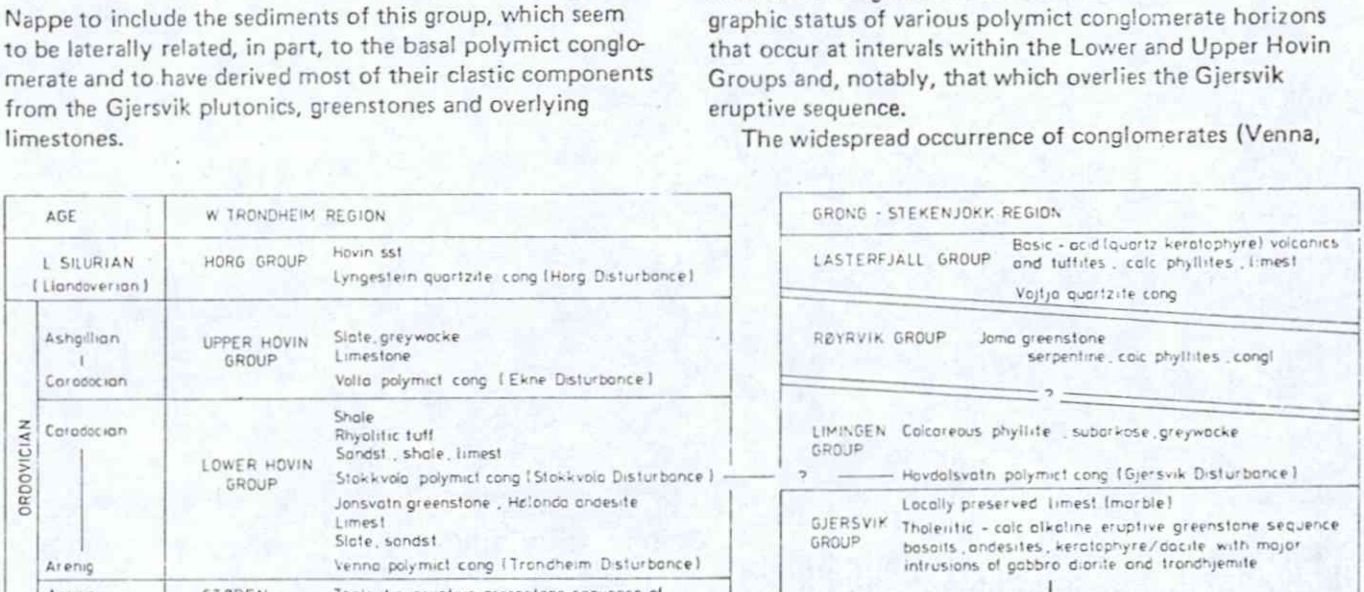



**Fig.3** Inferred stratigraphic correlation between Lower Palaeozoic sequences to south and north of Grong Culmination. Correlation is approximate and based on information from Vogt,[72] Zachrisson,[82] Oftedahl [45] and Roberts.[53] Tectonic disjunction within the two areas is shown schematically by oblique parallel lines

Lille Fundsjø and Steinkjer conglomerates)[53] at the base of the Lower Hovin Group, overlying the Støren Group, led Holtedahl [26] to propose a tectonic event of regional significance that he termed the Trondheim Disturbance. Further comparative studies of stratigraphy in the Trondheim region led to the recognition of similar polymict conglomerates at higher stratigraphic levels. Vogt [72] identified an Ekne (Caradocian) Disturbance and also movements in the Lower Silurian which produced the basal quartzite conglomerate of the Horg Group (Lyngestein Conglomerate), which identified a Horg Disturbance. Further work by Roberts [53] has suggested additional refinements to the chronology of uplift and erosion in the Trondheim District during the mid-Ordovician, a separate event in Mid-Lower Hovin times being marked at the level of the Stokkvola conglomerate.[53] Tectonic evolution in the Trondheim region in Lower to Middle Ordovician time was evidently punctuated by episodes of vertical uplift and erosion, the Trondheim Disturbance being but the first of these. The polymict conglomerate, which overlies the Gjersvik eruptives at the base of the Limingen sedimentary series, evidently records a disturbance of the Trondheim type, which, to avoid confusion, will be named the Gjersvik Disturbance. This disturbance is probably most closely related in age to the Stokkvola event.[53]

Fig. 3 shows the inferred general stratigraphic correlation between the Lower Palaeozoic sequences in the Grong and Trondheim regions. Zachrisson [82] has cited the faunal evidence in support of a (Lower ?) Silurian age for the Stekenjokk orebodies, which lie within the lower part of the sequence of basic to acid volcanic rocks composing the upper part of the Lasterfjäll Group (Fig. 2); this means that the rocks composing the Gjersvik, Leipik and Gelvernokko nappes and the upper parts of the Lower Köli Nappe have a probable age range from Lower Ordovician to Lower Silurian, matching the age range of the Trondheim Supergroup as defined by Gale and Roberts.[16] The Skorovas and Gjersvik ore deposits lie within the Gjersvik Group of volcanic greenstones and must be approximately Lower to Middle Ordovician in age. It is, however, interesting that in the Stekenjokk area, accepting the fossil evidence of Zachrisson, conditions suitable for the formation of stratiform pyritic ores also existed in Lower–Middle Silurian times.

### Tectonic style within Skorovas area of Gjersvik Nappe

The programme of field mapping in the Skorovas area, with which the present writers have been actively involved since 1971, was designed to re-examine the major structural and lithological boundaries within the plutonic to volcanic sequence of the Gjersvik Group and to extend, as far as possible, the geological interpretations of Foslie and Oftedahl as they affect the Skorovas area. Mapping in the scale range of 1:2000 to 1:10 000 has also enabled the first serious attempt to delineate the principal lithologies within the volcanic sequence, which were uniformly designated as greenstones by Foslie [12] on the 1:100 000 scale map of the Trones quadrangle. The Skorovas area, as shown in Fig. 4, lies close to the eastern boundary of one of the main plutonic massifs of the Gjersvik Nappe. From Fig. 2 it is clear that the massifs have distinctly tectonic boundaries of low to intermediate angle (Fig. 6). The plutonic rocks within these boundaries frequently preserve their original igneous fabrics, little modified by the penetrative effects of tectonic deformation. The volcanic rocks and minor intrusives outside them, in contrast, generally show intense penetrative tectonic fabrics. The plutonic massifs all have tectonized envelopes and the intrusion of the complete range of basic to acid plutonic rocks evidently took place prior to the main tectonic event, which led to the emplacement of the Gjersvik Nappe within the allochthon and which was also responsible for the generation of major isoclinal folds and the early axial plane schistosity that is generally well developed within rocks of the volcanic sequence.

Because of gross differences in competence between the various rock types, notably between the plutonic masses and the supracrustal volcanic cover, this particularly heterogeneous style of deformation characterizes the intermediate level of the Gjersvik Nappe, the pattern being controlled, on the largest scale, by the form of the major gabbro, diorite and granodiorite bodies. Within the volcanic sequence itself, high-level doleritic dykes and sills, together with compact dacitic flows and their spilitized aphanitic equivalents, exert a more local influence.

In common with adjacent parts of the allochthon,[81,82] the history of regional deformation can be resolved in terms of two major stages, the first of which produced the principal Caledonian 'grain' of the terrain, creating isoclinal folds of the style illustrated in Fig. 5, and imposing the early schistosity mentioned above. It was during this stage that the main thrust and slide horizons that separate the plutonic and volcanic levels of the Gjersvik eruptive sequence were established. The plutonic bodies evidently behaved as massive tectonic wedges, piercing and, in part, overriding the superjacent volcanics to create the present pattern.

It should be emphasized that such planes of high tectonic strain also exist in several lesser orders within the volcanic sequence. These surfaces, as was noted above, are similarly formed at lithological boundaries, showing marked contrasts in competency, and can partly be explained in terms of componental movements along the thinned and extended limbs of isoclinal folds of the early basaltic lavas and pillow breccias. These rocks, under the influence of intense local strain, suffer a complete penetrative reorganization of their mineralogy to form chlorite–albite–epidote schists devoid of any earlier volcanic fabric. In the field the existence of these surfaces and the flattening produced in the adjacent units creates a peculiarly lenticulated style of deformation through which the early isoclinal fold pattern must be traced. The 'lenticulate style' appears to be a characteristic feature of highly deformed volcanostratigraphy and associated plutonics in other regions, notably in the Mauretanides of West Africa (G. Pouit, personal communication). Minor fold structures of the early generation are not conspicuously evident within the volcanostratigraphy and are best observed in the finely stratified tuff bands and associated cherts and iron-rich chlorite schists of the exhalite facies (Fig. 7(*a*)). They can also be mapped over several tens of metres by following coherent chert horizons, acid tuff bands and dykes, and thence into the larger isoclines of the type illustrated in Fig. 5.

The configuration of these larger isoclines, taken together with the stratigraphic and structural evidence provided by the mapping of the surface of unconformity separating the eruptive sequence and the conglomerate series, demonstrates, at the present level of erosion, that the volcanic sequence in the Skorovas district lies inverted within the lower limb of a major southeast-facing fold, the identity of which can be broadly equated with the Gjersvik Nappe.

The second stage of deformation, superimposed on the grain of the early isoclines and schistosity, has created an open system of broad folds, which have resulted in an irregular pattern of dome and basin structures, the major axes of which evidently bear a relationship to the contacts of the plutonic massifs lying to the west and north (Figs. 2 and 4(*a*)). The formation of the open dome and basin structures is accompanied by further movements along the low-angle planes generated during the first stage of deformation. These movements led to the creation of minor folds and a second-stage crenulation cleavage, which is typically local and specifically associated with these horizons of high strain. The scale of the phenomenon is variable and Fig. 7(*b*)) shows part of the well-developed belt of second-stage folding in the volcanic sequence at the southwestern margin of the Grøndalsfjell massif. The vergence of the axial planes of these and other similar late folds implies that the principal tectonic stress responsible for this deformation was imposed from a west to northwest direction.

The deformation history can be interpreted in the following way. (1) Creation of the nappe, isoclinal folds and the early schistose fabric, together with the several orders of internal thrust horizons, was a consequence of the stresses imposed during the main stage of emplacement of the allochthon during Mid-Silurian times. (2) The second generation of tectonic structures is considered to have been imposed upon the first as a consequence of equilibration between the depressed Scandinavian basement and the imposed load of the allochthon. The depression of the granitic basement into a field of higher temperature and pressure can have given rise to plasticity of the basement, enabling local isostatic adjustments to take place by the initiation of a system of domes and basins in the basement. The second fold phase in the Skorovas region is interpreted as a consequence of forces imposed on the volcanic sequence by the massive plutonic bodies as they slid under the influence of gravity in an east to northeast direction from the flanks of a basement dome in the vicinity of the Grong culmination.

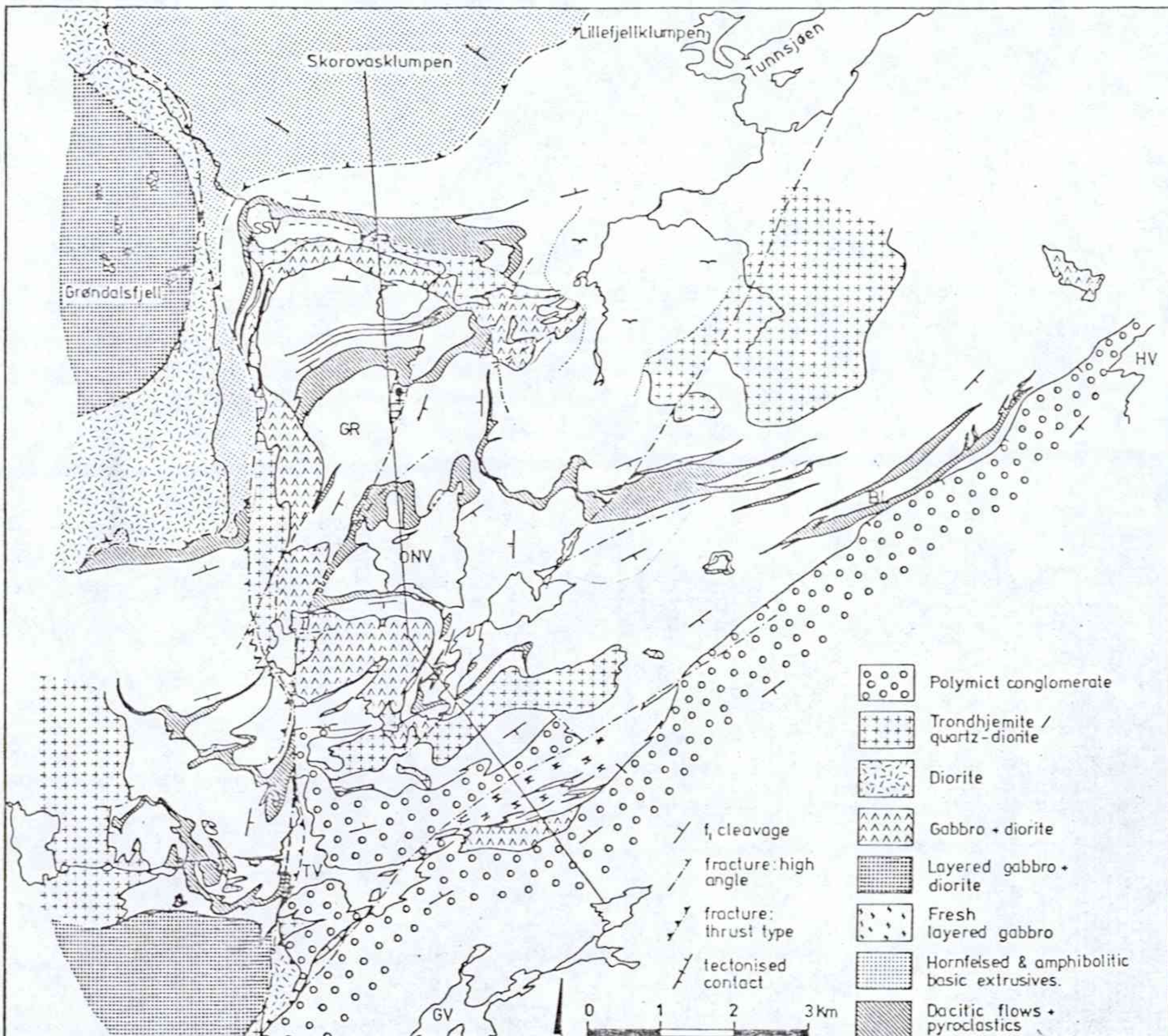


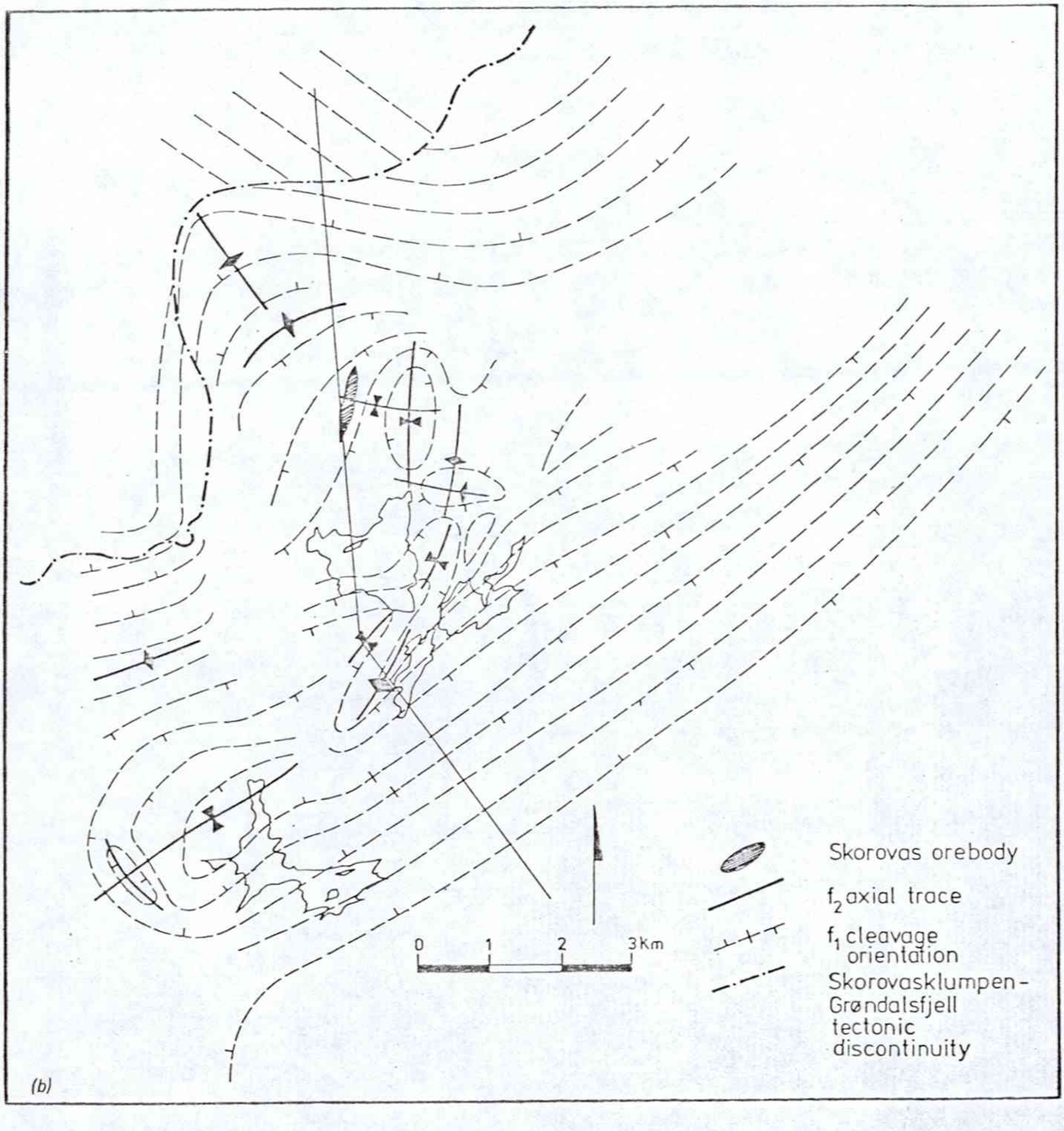

Fig. 4 Simplified geological map (*a*) of Skorovas area with line of section (Fig. 5) indicated (SSV, Store Skorovatn; GR. Grubefjellet; ONV, Øverste Nesåvatnet; TV, Tredjevatnet; Bl, Blåhammeren; HV, Havdalsvatnet) and synoptic map (*b*) (see page 134) of principal structural trends

In addition to the fold and low- to intermediate-angle thrust structures created during the first two periods of folding, the topography and geology of the Skorovas area has been strongly influenced by the formation of a complex system of high-angle faults and fractures. For the most part these have suffered small displacement of the order of metres, but along the southwest contact of the Gjersvik eruptive complex with the polymict conglomerate oblique slip normal faulting has resulted in a vertical displacement of the order of 500 m (Figs. 4(*a*) and 5). The trend of these fractures is predominantly in a NNE to northeast direction and their formation post-dates the main periods of folding in the area. The late fracture patterns in the Skorovas area remain a problem for future investigation. In all probability they can be attributed to the final stages of Caledonian tectonism, but the influence of later events, such as basement reactivation during Mesozoic rifting, cannot be discounted.

## Plutonic members of Gjersvik eruptive sequence in Skorovas area

On the 1:100 000 scale map of the Trones quadrangle compiled from the work of Foslie [12] the plutonic rocks of the Skorovas area occur in two groups. The first group comprises the tectonically bounded massifs of Grøndalsfjell and Nesåpiggen, which, though they have strongly tectonized envelopes, preserve much of their original igneous fabric in the interior. The second group occurs as an arcuate belt lying within the volcanic succession to the north, west and south of the Skorovas ore deposit (Fig. 4(*a*)). The plutonic rocks of this belt have been subjected to the penetrative deformation that affected the enclosing volcanic rocks and have responded tectonically as part of the volcanic level during deformation.

The plutonic rocks of the Skorovas area were divided by Foslie into two principal compositional groupings, as shown in the map of the Trones quadrangle.[12] Gabbros



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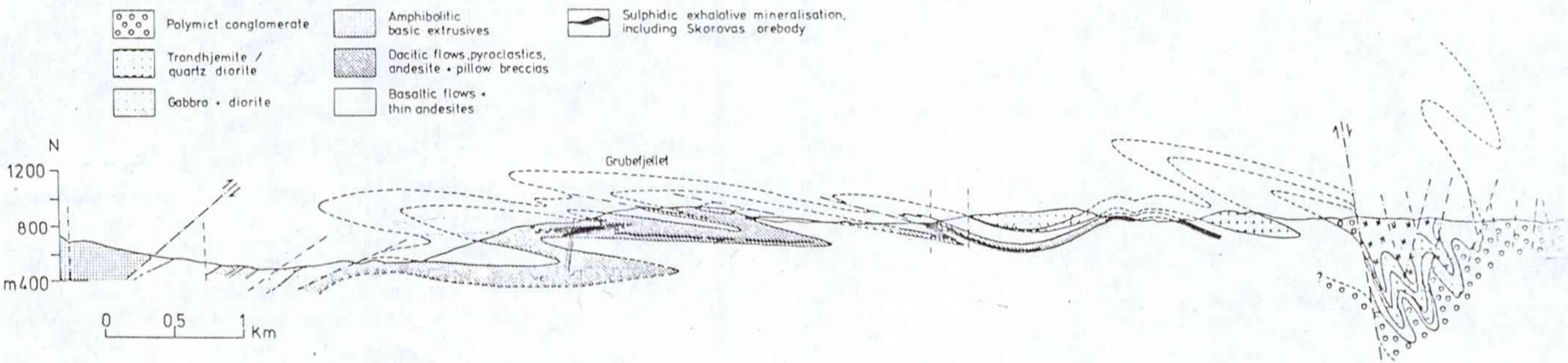


**Fig. 5** Simplified geological section through Skorovas area

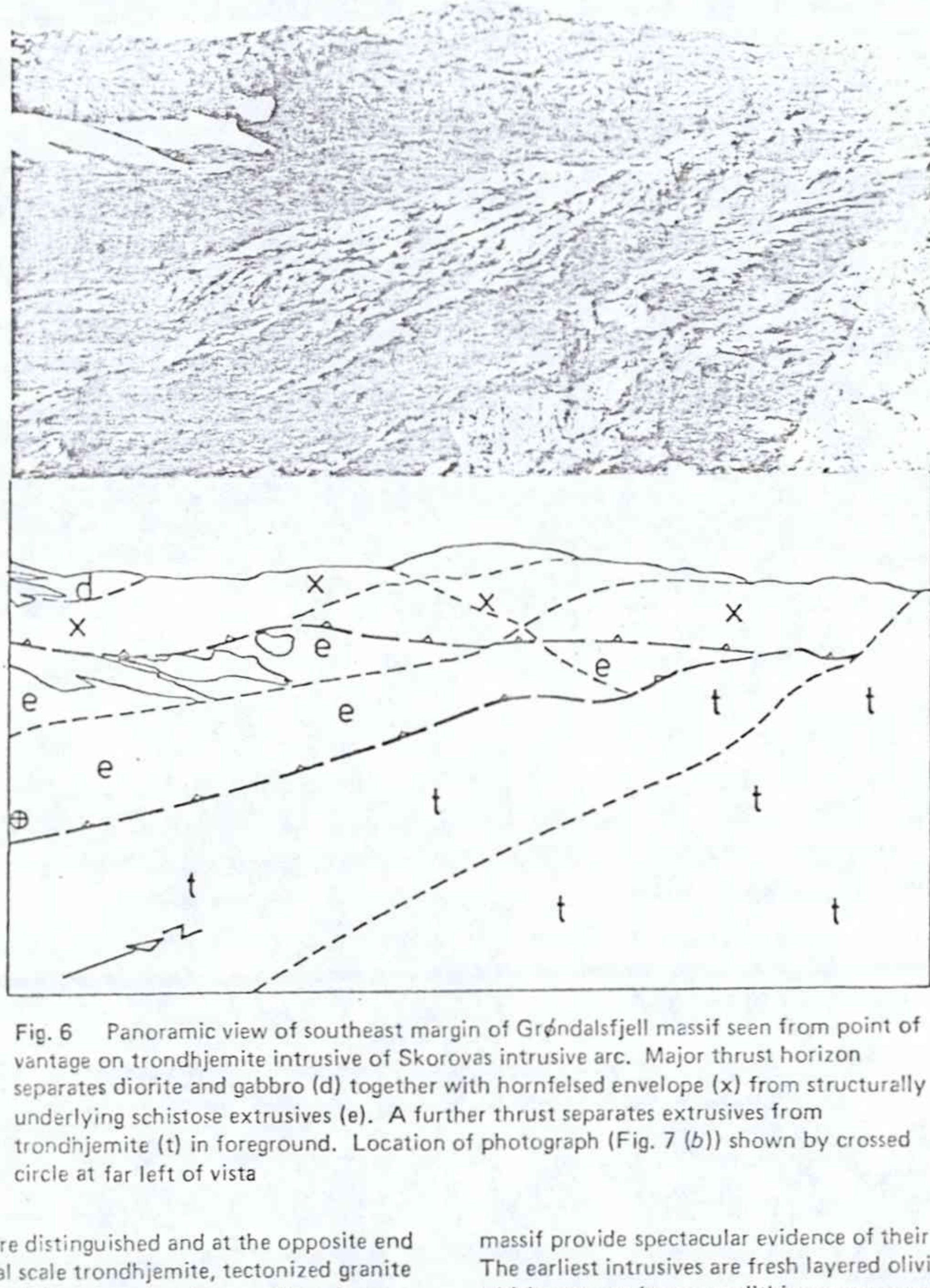


Fig. 6 Panoramic view of southeast margin of Grǿndalsfjell massif seen from point of vantage on trondhjemite intrusive of Skorovas intrusive arc. Major thrust horizon separates diorite and gabbro (d) together with hornfelsed envelope (x) from structurally underlying schistose extrusives (e). A further thrust separates extrusives from trondhjemite (t) in foreground. Location of photograph (Fig. 7 (*b*)) shown by crossed circle at far left of vista

of various facies were distinguished and at the opposite end of the compositional scale trondhjemite, tectonized granite and granitic dykes and sills were also shown. There is no reference on the map to the occurrence of intermediate dioritic rocks in the immediate area of Skorovas, although Foslie was undoubtedly aware of their existence because diorites are mapped as a thin border zone to the north of the Grǿndalsfjell massif and to the west of Heimdalshaugen. The detailed mapping carried out by the present writers has shown that dioritic rocks of intermediate composition form an important component in the plutonic sequence and that a definite relative chronology of intrusion can be recognized.

It has already been noted that the plutonic sequences in the Grǿndalsfjell and Nesåpiggen massifs and the plutonic bodies that compose the arcuate intrusive belt (Fig. 4) are tectonically separated, and it is convenient to discuss their plutonic histories separately.

### *Grǿndalsfjell massif*

The starkly exposed rocks that compose the Grǿndalsfjell massif provide spectacular evidence of their relative ages. The earliest intrusives are fresh layered olivine gabbros, which occur as large xenolithic masses or rafts with maximum dimensions of the order of 70 m x 200 m, contained in a matrix of metamorphosed gabbro and hornblende diorite. The cumulus layering of the gabbro bodies is sub-vertical in attitude with a predominantly east–west trend. This must be accepted as evidence of significant post-cumulus displacement.

The composition of the layered gabbro varies from troctolite to hypersthene gabbro and in all facies hypersthene occurs, either as a reaction rim around olivine or as independent ophitic grains. The mineralogy of the gabbro is thus compatible with crystallization from a tholeiitic magma.[25,67]

The nature of the xenolithic relationship is shown in Fig. 8(*a*), and it is clear that the hornblende diorite is a major component of the Grǿndalsfjell massif. The peripheral contacts of the fresh layered gabbro with the diorite display a distinctive pattern of retrograde alteration, which partly follows the primary igneous layering and partly exploits crosscutting joints to produce a distinctive weathered surface (Fig. 8(*b*)). The alteration leads to the uralitization and chloritization of the augite and hypersthene, the serpentinization of the olivine and saussuritic degradation of the calcic plagioclase to produce albite, epidote, clinozoisite and calcite. In the troctolitic facies of the gabbro the growth of considerable quantities of chlorite within the plagioclase accompanies this breakdown. The alteration is ascribed to the contribution of water from the dioritic magma, which led to a retrograde subsolidus hydration in the pre-existing mass of layered gabbro.

The various facies of altered gabbro may extend for a considerable distance beyond the boundaries of the fresh layered rocks, and the distinction between altered gabbro and hornblende diorite is made in the field on the basis of the persistence of fluxion banding and layered structure within the surrounding aureole of hydration. The hornblende diorite is characteristically composed of subhedral dark green grains of hornblende together with saussuritized plagioclase of intermediate composition and accessory Fe–Ti oxides. The iron oxides are frequently altered to sphene and the hornblende is generally partly chloritized.

One of the most striking features of the hornblende diorite is the occurrence of coarse patches and pegmatoidal veins, 0.5–3 m wide, consisting of euhedral hornblendes, commonly up to 10 cm in length, set in a matrix of andesine feldspar together with accessory amounts of magnetite and pyrite. The pegmatoid veins show rhythmic banding parallel to their contacts. This can be interpreted as a result of episodic deuteric crystallization from hydrous fluids circulating within the largely-consolidated dioritic body. These rocks can be justifiably described as appinites, and their presence implies that the level of exposure seen in the eastern margin of the Gróndalsfjell massif corresponds to the upper portion of a differentiated dioritic body.[25,78]

At the margins of the hornblende diorite, close to the contact of the plutonic mass with the enclosing greenstones, a quartz-diorite facies occurs locally.

At least two generations of impersistent basic dykes cut both the gabbro and the diorite with its appinitic facies. The dykes are thin, usually less than 20 cm in width, and have a northeastery trend with steep dips to the northwest. They are composed of fine-grained hornblende and plagioclase, together with minor iron oxides, and are locally porphyritic with plagioclase crystals up to 7 mm long.

The final eruptive event within the Gróndalsfjell complex was the emplacement of a swarm of leucocratic porphyritic granodiorite dykes, which show a predominantly northeasterly trend and dip steeply to the northwest. The dykes are commonly 1–2 m thick and can be followed for distances of 1–2 km before they pinch out. Close to the margins of the plutonic mass, and also within it, these dykes show well-developed tectonic foliation and, locally, mylonitic facies, which demonstrates that the northeast-trending fracture system has been the focus of significant post-intrusion tectonic strain. The granodiorite dykes are composed dominantly of sodic plagioclase (roughly of

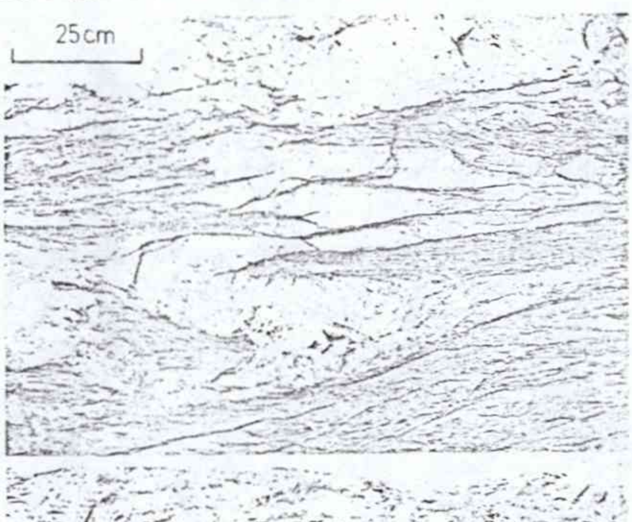


Fig. 7 Typical dislocated isoclinal style seen in minor folds of first generation in chert bands to south of Nesåklumpen (*a*) (top) and (*b*) localized post-schistosity folding and incipient crenulation cleavage of second generation formed in zone of high strain in schistose greenstones adjacent to tectonic boundary of Gróndalsfjell massif. Location of photograph is shown in caption to Fig. 6

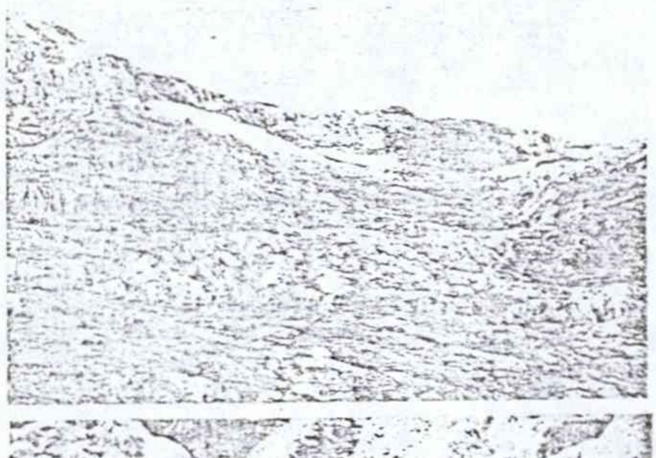

Fig. 8 Northeast face of Gróndalsfjell massif displaying occurrence of rafts of unaltered layered gabbro (dark) within dioritic matrix (*a*) (top) (rafts are of the order of 60–100 m x 200 m) and (*b*) field appearance of hydrated, uralitized envelope that borders large xenolithic masses of fresh layered gabbro on Gróndalsfjell (Fig. 8(*a*). Troctolitic gabbro shows strong differential weathering of pyroxene, feldspar and olivine, producing pitted surface. Uralitized assemblage weathers uniformly by comparison

oligoclase composition), quartz and accessory microcline, biotite, hornblende and sphene. The ferromagnesian minerals are generally partly chloritized and the feldspars have been variably altered to fine micaceous aggregates (sericite or paragonite). Because of the modal composition of these dykes, which is dominantly oligoclase together with quartz and with only accessory amounts of potash feldspar, the rocks may properly be described as trondhjemite in the sense of the definition applied by Goldschmidt in 1916.[22]

This summary of the igneous relationships preserved within the plutonic massif of Grøndalsfjell shows clearly that a considerable volume of dioritic magma was emplaced, probably at an intermediate to high crustal level, evidently by invading a pre-existing mass of layered gabbro, which is the oldest and presumably the deepest representative of the plutonic assemblage in the Skorovas area. It may be added that magmatism must also have been bimodal – that is to say that the magmas were supplied from two genetically different sources, the first tholeiitic and the second calc-alkaline. A range of similar igneous relationships occurs in the Nesåpiggen massif to the south (Fig. 4).

In addition to the main gabbro-diorite body of the Grøndalsfjell massif delineated by Foslie on the map of the Trones quadrangle, a significant mass of 'fine-grained gabbro' is also shown lying directly to the north of Skorovatn. This forms the imposing topographic feature of Skorovasklumpen in the basal slope of which lies the extension of the main thrust surface, which is interpreted as separating the tectonically 'massive' plutonic level from the highly deformed volcanic level. This feature is shown on the geological map of the Skorovas area and in the accompanying structural synthesis (Fig. 4). Investigation has shown that Skorovasklumpen and the narrow belt of similar character that can be followed along the eastern margin of the Grøndalsfjell massif are composed predominantly of metamorphosed basic volcanic rocks, together with interbands of acid (dacitic-keratophyric) composition and a proportion of high-level basic intrusive material. The basic rocks of the belt adjacent to the Grøndalsfjell massif are partly incorporated in a xenolithic screen of considerable complexity. The original igneous contact of the diorite with the volcanic country rocks is preserved intact within the main tectonic boundary (Fig. 4(*a*)) and can be mapped over a distance of 4 km. Original volcanic structures, notably pillow forms and vesicles, are preserved within xenolithic masses and testify to the volcanic origin of the country rocks. Similar textural evidence of volcanic origin has been found within the basic sequence that composes Skorovasklumpen.

The reason for the classification of the rocks of Skorovasklumpen as fine-grained gabbros by Foslie [12] and other workers lies in their amphibolitic metamorphic grade, which has produced a mineralogy dominated by hornblende and intermediate to calcic plagioclase. The presence of epidote as a constituent mineral throughout a significant part of the amphibolitic sequence implies that these higher-grade rocks span the epidote amphibolite facies to enter the field of amphibolite facies. Since there is no association with pelitic rocks, a precise description of the prograde regional metamorphism of the basic rocks of the Skorovas area depends chiefly upon a determination of the progressive changes in the composition of the hornblende and plagioclase, which must await further detailed work. Broadly, however, the mineral assemblages accord with the sequences regarded by Miyashiro [31,32,36] as typical for the regional metamorphism of mafic rocks at low to intermediate pressure.

One of the conspicuous features of the mineralogy of the amphibolite facies rocks of Skorovasklumpen is that pyrrhotite replaces pyrite as the accessory iron sulphide – an observation that is readily made in the field. The amphibolitic lavas locally display distinct pentrative tectonic lineation of the amphiboles, and this lineation can be observed in the amphibolitized volcanic xenoliths in the diorite. Amphibolite grade metamorphism evidently took place under the influence of early tectonic stresses with which the emplacement of the gabbro-diorite massif was partly synchronous. The establishment of a precise chronology for these events will depend upon the evidence provided by future detailed petrographic work. It is probable, however, that the contact aureole of the Grøndalsfjell massif and the amphibolitic rocks of Skorovasklumpen compose a continuum within the field of low to intermediate pressure in which regional and contact metamorphism converge.[34]

*Rocks of the arcuate intrusive belt*

The intrusive arc differs from the plutonic massif of Grøndalsfjell in three distinctive ways: (1) no unmetamorphosed gabbroic bodies have been found in which a plagioclase–pyroxene–olivine assemblage is preserved; (2) penetrative deformation has produced distinctly tectonic fabrics throughout most of the arc and mineral assemblages are reduced, for the most part, to those stable within the greenschist facies; and (3) quartz-rich dioritic to granodioritic rocks compose a large part of the complex and the eastern extremity of the arc joins a large granodiorite mass to the south of Tunnsjøen (see Fig. 4(*a*)).

Apart from these significant differences, which can probably be explained in terms of the higher level of emplacement of the arc complex within the volcanic sequence, the relative chronology of intrusive episodes in the arc is the same as that observed in the Grøndalsfjell massif. The most basic rocks are the oldest and the successively younger intrusions become increasingly silicic.

The degree of deformation within the plutonic arc is often extreme; but, locally, the original geometry of intrusion is preserved as shown in Fig. 9. The range of compositions present in the rocks of the arc is very wide and includes hornblende gabbro, diorite and granodiorite (trondhjemite). The definition of the petrographic character of each generation is complicated by the incorporation of xenoliths of earlier basic volcanic and plutonic rocks as well as by extreme deformation, local silicification and reduction of the primary minerals to greenschist assemblages.

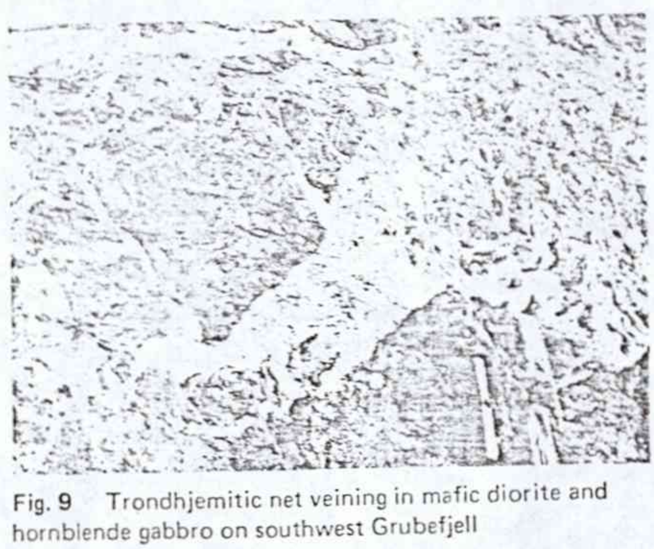

**Fig. 9** Trondhjemitic net veining in mafic diorite and hornblende gabbro on southwest Grubefjell

It is sufficient for the purpose of the present discussion to confirm the presence of gabbro, diorite and trondhjemitic granodiorite as components of the arc and to suggest that these are, in part, equivalent to the plutonic complex observed in the Grøndalsfjell massif. Prior to the major stages of Caledonian deformation leading to the allochthonous emplacement of the Gjersvik Nappe, it is assumed that the rocks of the intrusive arc and those of Grøndalsfjell were part of the same complex plutonic continuum.

### Volcanic rocks of Gjersvik eruptive sequence in Skorovas area and their metamorphic condition

The volcanic rocks of the Gjersvik eruptive complex are of geological and economic interest for they are the host rocks of the Skorovas deposit. The volcanic succession has suffered extremely from the effects of deformation and low-grade metamorphism under conditions of the greenschist facies. These modifications, together with the primary complexity of the volcanostratigraphy, have been obstacles to the systematic mapping of the greenstones.

It has long been recognized that the Gjersvik greenstones are composed of a sequence of basic to acid rocks, including basalts, andesites and keratophyres of distinctly spilitic affinity.[21,41] Because of the confinement of systematic geological studies to the immediate vicinity of the Skorovas mine itself, previous summaries of the volcanic stratigraphy have been limited. During the present study an attempt has been made to document the range of primary volcanic structures that can be observed at the macroscopic scale within the acid and basic members of the stratigraphy and to examine their geometry with respect to metamorphism and deformation.

It is difficult to assess the relative volumes of basic and acid rocks within the volcanic sequence, but it can be said with confidence on the basis of regional mapping that, in the general area of Skorovas, the dominant volcanic rock types are basalts and basaltic andesities with lesser amounts of andesitic and keratophyric rocks. This fact is apparent from the relative outcrop of acid and basic rocks shown in Fig. 4(*a*), although this can only be treated as an approximate guide. Because of the deformed and dislocated condition of the sequence and the present level of erosion, the maximum thickness of volcanics is difficult to assess. A reasonable estimate based on constructed geological sections, taking into account the effects of tectonic flattening and extension, can be given as 3–4 km.

The sedimentary component within the pile is limited to very thin, but stratigraphically persistent, iron- and silica-enriched beds produced as a result of chemical dispersion during volcanic activity. Banded calcareous greenschists, which have been considered by previous writers to be of sedimentary origin, can be explained as tectonic facies originating from metamorphosed and flattened basic flow units.

The primary mineralogy of all the rocks in the volcanic succession has been degraded to assemblages of the greenschist facies. Textural evidence shows that the creation of the greenschist facies assemblages took place during two episodes, the first of which was prior to the first stage of penetrative tectonic deformation. The evidence confirming this metamorphic chronology is best preserved within the basic members of the sequence.

#### *Basaltic and andesitic lavas*

The state of deformation of the basaltic rocks varies according to their position with relation to the early isoclinal folding, the numerous lower-order thrust horizons and adjacent competent flow units or intrusives. It is possible, however, in the vicinity of Skorovas, to observe pillowed sequences in which the original geometries are nearly preserved, as shown in Fig. 10. The dimensions of pillows are variable, but diameters within the range 0.5–2 m are typical. In addition to pillowed basaltic flow units, there is a significant volume of deformed meta-hyaloclastite pillow breccia associated with the basaltic unit, which structurally overlies the orebody (see Fig. 17). The pillow breccia lithology is locally transitional to tuffaceous and agglomeratic basic pyroclastic facies and can be traced within a radius of 3 km around the orebody.

The abundance of amygdales, ranging in size from 2 to 10 mm and, exceptionally, reaching sizes of 5 cm, indicates that the lavas were erupted at relatively shallow depths, probably of the order of 100–500 m.[29,37] The primary mineralogy has been completely replaced or pseudomorphed by assemblages composed of chlorite, albite, epidote, actinolite, calcite and sphene. Stilpnomelane, regarded by Miyashiro[36] as atypical of low- to medium-pressure

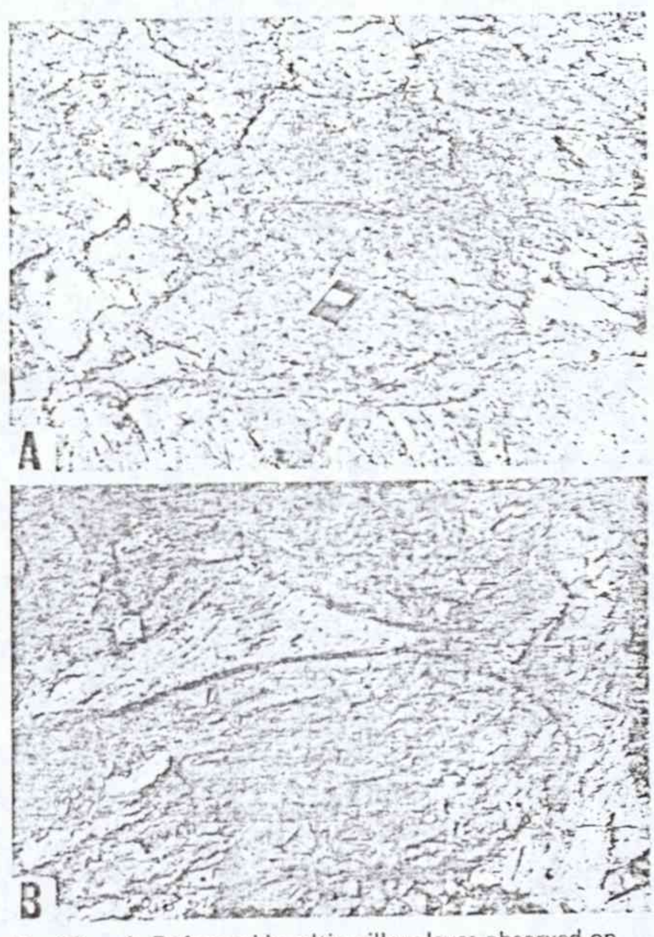

Fig. 10 *A,* Deformed basaltic pillow lavas observed on northern slopes of Grubefjell below orebody. Cuspate bodies of grey chert that occupy interstices between pillows are conspicuous. In cases of extreme deformation survival of these chert bodies within chloritic schist provides a useful guide to original volcanic structure of rocks.
*B,* Basaltic pillows from flow exposed on southwest shore of Tredjevatnet. Eruption of pillowed basalts followed deposition of a dispersed exhalite horizon in vicinity of Tredjevatnet centre. Layer of ferruginous silica gel, disturbed during eruption of the basalts, formed a jasper matrix for the pillows. Chloritized chilled margin of pillows is conspicuous. Significant amounts of pyrite are also found in association with jasper pillow matrix, the pillow lavas lying stratigraphically but a few metres from horizon of massive pyrite

regional metamorphic assemblages, is a conspicuous component of the basaltic andesites in the mine area. This can probably be explained in terms of the iron enrichment shown by these rocks (analysis 3, Table 1). Stilpnomelane, in common with the other greenschist minerals, occurs dispersed throughout the body of the rock and also as monomineralic fillings in amygdales and in crosscutting veinlets. The dominant mineralogy of the amygdales within the pillowed basalts varies widely. Combinations of two of the common greenschist mineral species are usual, involving quartz, epidote, calcite, chlorite, albite and pyrite. Actinolite is not usually found in amygdales. Within certain parts of the Skorovas area the dimensions of the amygdales and their mineralogy have been useful in discriminating between individual flow units, although amygdale mineralogy certainly cannot be applied as a universally reliable criterion of stratigraphy.

Within the more massive andesitic and basaltic rocks, original flow textures are preserved by the orientation of the altered plagioclase microlites. Augite phenocrysts are pseudomorphed by actinolite and chlorite and the accessory iron–titanium oxides are largely replaced by sphene. The basalts are not conspicuously porphyritic and igneous textures are frequently concealed in the meshwork of fine actinolite, chlorite, epidote–clinozoisite and albite into which the rocks have been transformed.

The effects of greenschist metamorphism are not only apparent at the micro scale but are also demonstrated by the gross redistribution of the rock components, which has produced massive bands and lenticular knots and spheroidal bodies, the mineralogy of which is predominantly epidote with lesser amounts of albite, quartz, etc. These bodies with dimensions of the order of tens of centimetres are arranged parallel to the surfaces of the pillow structures or as discontinuous layers parallel to flow surfaces within massive basalts and basaltic andesites. The typical form of these bodies is shown in Fig. 11.

The epidote-rich segregations are evidently pre-tectonic. During the first period of penetrative deformation the chloritic mass of the pillowed basalts has tended to develop a good schistose fabric and the geometry of the pillows, as a whole, has become flattened to varying degrees. The epidote layers have behaved as competent bodies and have deformed by brittle fracturing; in extreme cases the epidote bodies are preserved as cataclastically reduced streaks and boudins within the highly flattened pillows. The textural evidence clearly demonstrates that an important episode of greenschist metamorphism was responsible for pervasive alteration and gross reorganization of the mineralogy of the basic rocks prior to the tectonic event responsible for the early penetrative schistosity in the Skorovas region.

Deformation of the volcanic pile also took place under conditions of the lower greenschist facies and the mineralogy established during the primary metamorphic episode was not changed, but tectonic facies were produced as a result of further redistribution and segregation of the various mineral species.

The metamorphic alteration that took place in the earliest event prior to the deformation of the rocks can be

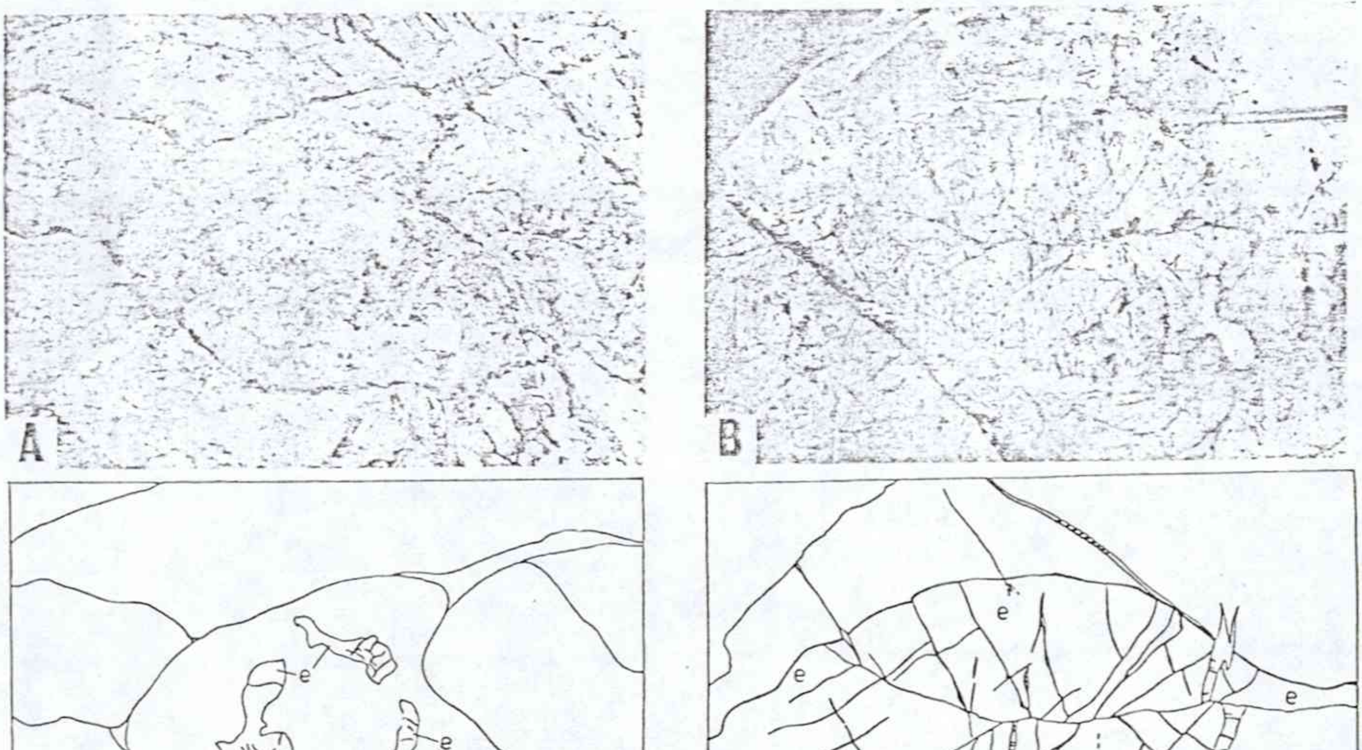


Fig. 11 *A*, Pillowed basaltic lavas from northwest of Havdalsvatn showing development of pre-deformational metamorphic segregrations of epidote-rich materials (e) parallel to pillow margins. During tectonic flattening epidote layer has responded by developing a system of brittle fractures. *B*, Lenticular segregation of epidote (e) of pre-deformation age in massive andesitic lavas southeast of Store Skorovatn. Conjugate pattern of brittle fractures produced during deformation of competent lenses is explicitly developed, as in generation of dilatant fractures filled with quartz, chlorite and carbonate

Table 1 Whole-rock analyses of Skorovas volcanics. Analyses (1–9) with average values of ocean-floor basalt (10; Cann[4]) and island arc tholeiite (11, Pearce and Cann[46]) for comparison. 1, Porphyritic quartz keratophyre, Grubefjell; 2, quartz keratophyre, Grubefjell; 3, andesite with stilpnomelane, Grubefjell; 4, andesite, Grubefjell; 5, andesitic clasts in agglomerate, Grubefjell; 6, pillowed basalt, Grubefjell; 7, pillowed basalt, Grubefjell; 8, basalt, 6 km southwest of Grubefjell; 9, basalt, northeast Øverste Nesåvatn

| % | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 72.23 | 70.39 | 53.07 | 59.34 | 56.12 | 50.15 | 49.30 | 48.99 | 50.13 | 49.61 | 52.86 |
| $Al_2O_3$ | 11.82 | 12.27 | 14.13 | 15.40 | 12.20 | 13.70 | 13.81 | 16.55 | 14.76 | 16.01 | 16.80 |
| $TiO_2$ | 0.80 | 0.27 | 0.77 | 1.06 | 0.96 | 1.54 | 1.89 | 1.30 | 1.24 | 1.43 | 0.83 |
| $Fe_2O_3$ | 2.14 | 3.37 | 6.48 | 3.49 | 3.31 | 3.31 | + | + | + | + | + |
| FeO | 1.28 | 0.44 | 6.62 | 6.01 | 6.44 | 7.78 | 14.70• | 13.97• | 14.95• | + | + |
| MnO | 0.03 | 0.01 | 0.19 | 0.23 | 0.11 | 0.16 | 0.21 | 0.17 | 0.15 | 0.18 | + |
| MgO | 0.36 | 0.45 | 4.40 | 2.68 | 4.70 | 4.70 | 5.49 | 5.74 | 6.00 | 7.84 | 6.06 |
| CaO | 1.27 | 0.24 | 4.66 | 2.38 | 4.44 | 4.89 | 4.92 | 5.33 | 3.50 | 11.32 | 10.52 |
| $Na_2O$ | 7.50 | 8.00 | 5.21 | 7.50 | 6.25 | 8.81 | 6.47 | 6.88 | 7.30 | 2.76 | 2.08 |
| $K_2O$ | 0.07 | 0.02 | 0.51 | 0.19 | 0.02 | 0.52 | 0.43 | 0.66 | 0.55 | 0.22 | 0.44 |
| $P_2O_5$ | 0.24 | 0.03 | 0.10 | 0.18 | 0.12 | 0.17 | 0.11 | 0.06 | 0.03 | 0.14 | + |
| Loss on ignition | 1.06 | 2.24 | 1.90 | 2.24 | 3.57 | 2.81 | | | | | |
| Total Fe as $Fe_2O_3$ | 3.56 | 3.86 | 13.83 | 10.17 | 10.46 | 11.95 | + | + | + | 12.63 | 11.45 |
| Total | 98.90 | 99.49 | 98.04 | 100.70 | 98.24 | 98.54 | 99.54 | 99.64 | 98.24 | | |

• Total Fe as FeO.
+ Value not obtained by analytical method used.

ascribed to contemporaneous alteration of the volcanic rocks *in situ* as a result of the thermally driven circulation of sea water in the upper layers of the lava pile close to the site of eruption on the Ordovician sea-floor. Considerable evidence has accumulated in recent years to show that *in-situ* alteration of the mineralogy of submarine basalts to produce assemblages of greenschist and lower amphibolite facies is a phenomenon of wide occurrence within the upper layers of the sea-floor.[33,35] Humphris[27] recognized that the metamorphic assemblages in recent submarine basalts from the Mid-Atlantic Ridge can be divided into chlorite-dominated and epidote-dominated types. It is suspected that this division reflects a process of metamorphic segregation similar to that seen in the basalts of the Gjersvik sequence.

The *in-situ* hydrothermal alteration processes evidently involve the convective circulation of large volumes of sea water relative to the altered rock. Water : rock ratios of the order of $> 10^4$:1 were calculated by Spooner and Fyfe[59] and the alteration process is believed to extend to a depth of at least 2 km within the lava pile.[59,60]

The *in-situ* sea-floor metamorphism of the Gjersvik volcanic sequence was evidently an important event and, as well as causing gross mineralogical changes by chemical redistribution within the scale of individual flow units, bulk changes in the chemical composition of the lavas also occurred, leading to the conspicuously spilitic chemistries shown by the analysis in Table 1.

The recognition of the pervasive pre-deformation *in-situ* sea-floor metamorphism of the Gjersvik basalts also helps to resolve the controversy that surrounds the tectonic status of disturbances of the Trondheim type.[11,51,55] The polymict conglomerate that unconformably overlies the volcanic sequence was formed prior to deformation and allochthonous transport of the Gjersvik Nappe. This is easily demonstrated on a local scale by the pervasive schistose fabric of the matrix and the distinctive stretching of the competent clasts parallel to the axes of the early isoclinal folds (Fig. 12(*A*)). It can also be demonstrated on a regional scale by mapping the level of unconformity through the isoclinal folds of the first deformation (see Fig. 5).

The conglomerate is composed of boulders directly derived from the plutonic and volcanic sequence that underlies it. Locally, the composition is dominated by marble clasts with associated pebbles of jasper, and in other places the clast population is dominated by boulders of phaneritic granodiorite (trondhjemite), diorite, meta-gabbro and various of the resistant volcanic rocks. Pebbles of keratophyre are common, but of greatest interest are the pebbles of the metamorphic epidote assemblage (Fig. 12(*B*)), which have evidently been derived by erosion of the metamorphosed basalts.

Final and conclusive evidence is thus provided for a Lower–Middle Ordovician metamorphic event pre-dating the Gjersvik Disturbance. The metamorphism was produced by the thermal and hydrothermal effects associated with the contemporaneous eruptive activity embodied in the Gjersvik Nappe. The tectonic movements involved in the formation of the polymict conglomerate were predominately vertical as opposed to lateral and must have been related to an early stage of tectonic evolution within the belt of Lower–Middle Ordovician eruptives of which the Gjersvik Complex was a part.

The status of a possible metamorphic event pre-dating the Trondheim Disturbance has been discussed elsewhere.[11,65] Further investigation will probably reveal the ubiquity of sea-floor-hydrothermal metamorphic assemblages as clastic constituents of the polymict conglomerates of the Venna and equivalent horizons. It may be regarded as axiomatic that such assemblages should be incorporated into the conglomeratic rocks produced by episodic uplift of the Ordovician sea-floor and that the history of metamorphism would be as extended as the history of submarine volcanism.

Magmatic activity in the belt continued after the erosional event. The evidence for this is provided by quartz–feldspar porphyry dykes that cut both the eruptive complex, the unconformity and the overlying conglomerates prior to the first phase of deformation. These dykes are similar in composition to other granodioritic rocks within the eruptive complex and are regarded as the latest product of calc-alkaline magmatism within the Skorovas area.

*Acid to intermediate flows and pyroclastics*

There are, within the Skorovas region, a range of acid lavas, tuffs and agglomerates, which are locally abundant and form horizons that can be traced laterally over considerable distances (see Fig. 4(*a*)). These rocks are of critical interest because they are closely associated with both the Skorovas orebody itself and with a variety of iron- and silica-rich sediments, which, following the conceptual terminology of Carstens [6,7,8] and Oftedahl,[42] are appropriately described as 'exhalites'.

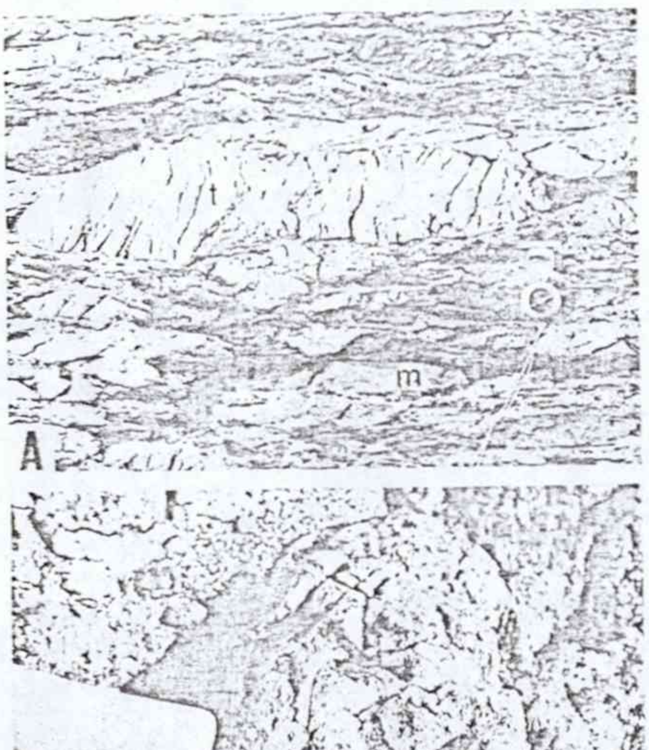


Fig. 12 *A*, Typical appearance of polymict conglomerates as seen to northwest of Havdalsvatnet. Flattened boulder of trondhjemite (t) displays tectonic fracture pattern characteristic of its brittle behaviour. Associated boulder of marble (m) has deformed in a ductile fashion. *B*, Large pebbles of pre-deformational epidote-rich metamorphic segregations derived by erosion from underlying lavas are a common constituent of greenstone-bearing facies of polymict conglomerate. Example photographed close to unconformity on southern shore of Tredjevatnet

Because of the deformation of the volcanic sequence and the inherent lateral variability of the volcanostratigraphy it is not possible to describe a unique and widely applicable type succession. The distribution of the various facies of acid rocks within specific parts of the Skorovas area suggests that a minimum of four centres of acid pyroclastic eruption were active. Their products are preserved, as far as it is possible to tell, at an approximately similar level in the volcanic sequence. In the vicinity of the Skorovas orebody there is stratigraphic evidence of at least two pyroclastic levels, the lowest of which is exposed in the basal slope of Skorovasklumpen to the north of Store Skorovatn (this is shown in Figs. 4(*a*) and 5).

The orebody itself evidently lies within the vicinity of one eruptive focus, which will be called the Grubefjell Centre. The other centres, tentatively distinguished, lie west and southwest of Tredjevatnet (the Tredjevatnet Centre), to the east of Överste Nesåvatn (the Nesåvatn Centre), and further east in the terrain near Blåhammeren (the Blåhammeren Centre). The main belts of acid rocks shown in Fig. 4(*a*) serve to identify these centres. It is difficult to judge whether the centres represent independent volcanic structures or lateral eruptions on the flanks of a single polygenetic edifice.

The acid volcanic horizons show a range of well-preserved pyroclastic fabrics to which Oftedahl [41,42] drew specific attention. Various agglomeratic facies are visible in the acid horizons in the immediate vicinity of the mine (see Fig. 14). Distal pyroclastic facies include fine tuff bands with associated exhalite sediments (Fig. 15(*a*)). Such horizons are spread over large areas and are thus valuable stratigraphic markers.

Pyroclastic facies can frequently be traced laterally into compact porphyritic and aphanitic bands of keratophyric aspect – presumably, flows or highly modified tuffs. In the vicinity of the Blåhammeren Centre porphyritic flows are physically continuous with porphyry dykes from which the eruptions appear to have originated. The dykes, in turn, can be traced towards the large mass of trondhjemite that occurs at the eastern end of the northern limb of the intrustive arc. The disjunction caused by déformation at the margins of the intrusive masses and within the volcanic sequence, however, denies a conclusive statement concerning the connexions between the plutonic and volcanic levels during climatic episodes of acid eruptive activity.

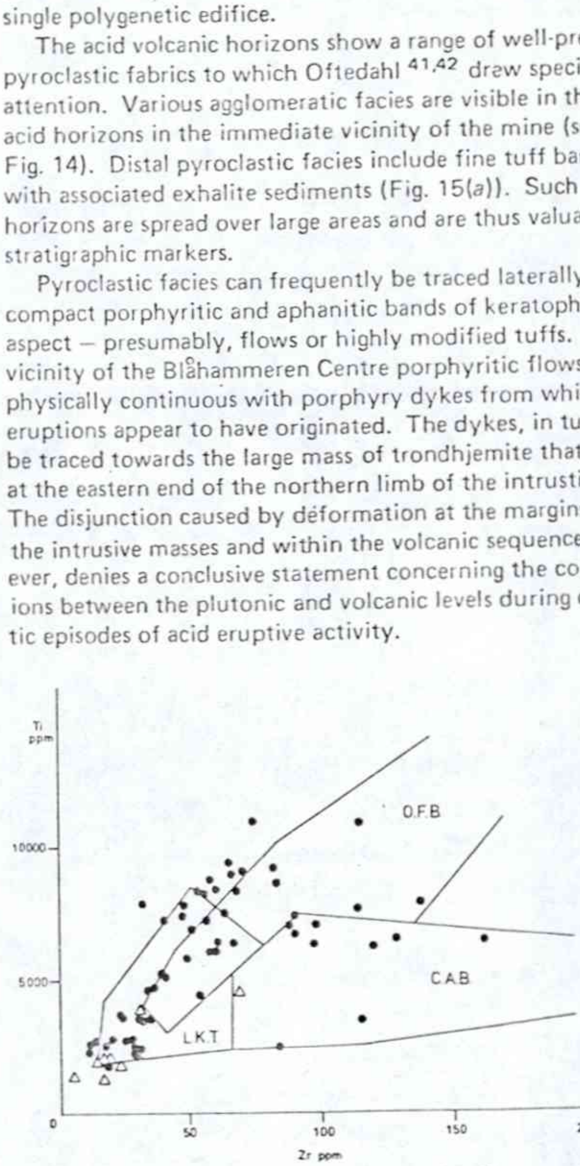


Fig. 13 Plot of Ti versus Zr contents for Skorovas basic extrusives (circles) and basic intrusives (triangles) showing abundance of low potash (island arc) tholeiites (LKT). Distinct trend towards field of calc-alkaline basalts (CAB) and grouping towards ocean-floor basalt (OFB) also shown

Chemistries of the acid extrusive rocks from the Skorovas ore level are distinctly soda-rich (see analyses 1 and 2 in Table 1). Petrographically, the rocks display a modal composition dominated by albite and quartz, occurring both as phenocrysts and as the constituents in the aphanitic groundmass, which is a mosaic of albitic plagioclase microlites and quartz. Whatever mafic silicates may have been present are now represented by dispersed chlorite. Pyrite is usually present as an accessory. The rocks are properly described as quartz keratophyres [25,76] and, taking into consideration the analyses from the basaltic and intermediate rocks shown in Table 1, it is clear that the Skorovas volcanic rocks are a spilitic suite.

The question is immediately raised as to the relationship that such a volcanic suite might have to the plutonic rocks at various structural levels in the immediate vicinity of Skorovas. The brief account of the plutonic rocks given above demonstrates the wide variation in the condition of metamorphism and deformation displayed by these rocks; there is no suggestion, however, that the compositions are abnormally sodic and the feldspars, though degraded by saussuritization, have original compositions in the range labradorite, in gabbro, to oligoclase, in trondhjemite.

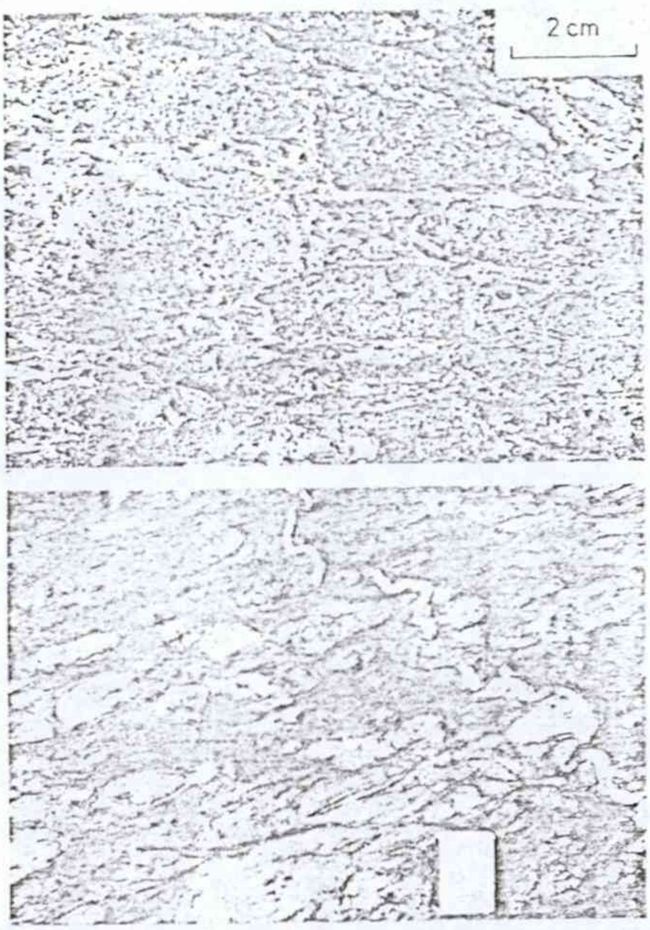


Fig. 14 Blocky pyroclastic texture (*a*) (top) seen in keratophyric flow unit on Grubefjell about 1200 m west of Skorovas orebody. Pyroclastic fragments are slightly flattened and siliceous matrix stands out as a reticular pattern. Flow is part of major acid horizon with which orebody is associated. (*b*) Agglomeratic facies of keratophyric horizon shown in (*a*). Locality is in immediate vicinity of ore horizon above mine entrance on northeast Grubefjell. Acid fragments are partly silicified and tectonically flattened. A competent quartz vein with orientation close to principal stress responsible for flattening during first stage of penetrative deformation has responded by buckle folding

Goldschmidt has given analyses of the type trondhjemites from the Trondheim district and from localities in western Norway that show total $Na_2O$ values in the range 4.3–6.0 wt % and $K_2O$ values in the range 1–2.5 wt %. This gives a typical $Na_2O$:$K_2O$ ratio for trondhjemite of the order of 3:1. Partial analyses of three trondhjemitic rocks from the Skorovas intrusive arc [56] show that the $Na_2O$ contents fall in the range 2–4.5 wt % and $K_2O$ values fall in the range 1–2.5 wt %. $Na_2O$:$K_2O$ ratios are of the order 1:1.5–3:1. This range is clearly of the right order for trondhjemitic to granodioritic rocks with $SiO_2$ contents of about 70 wt %. The $Na_2O$: $K_2O$ ratios of the spilitic rocks are one to two orders of magnitude greater than those seen in the regionally associated plutonics (see Table 1).

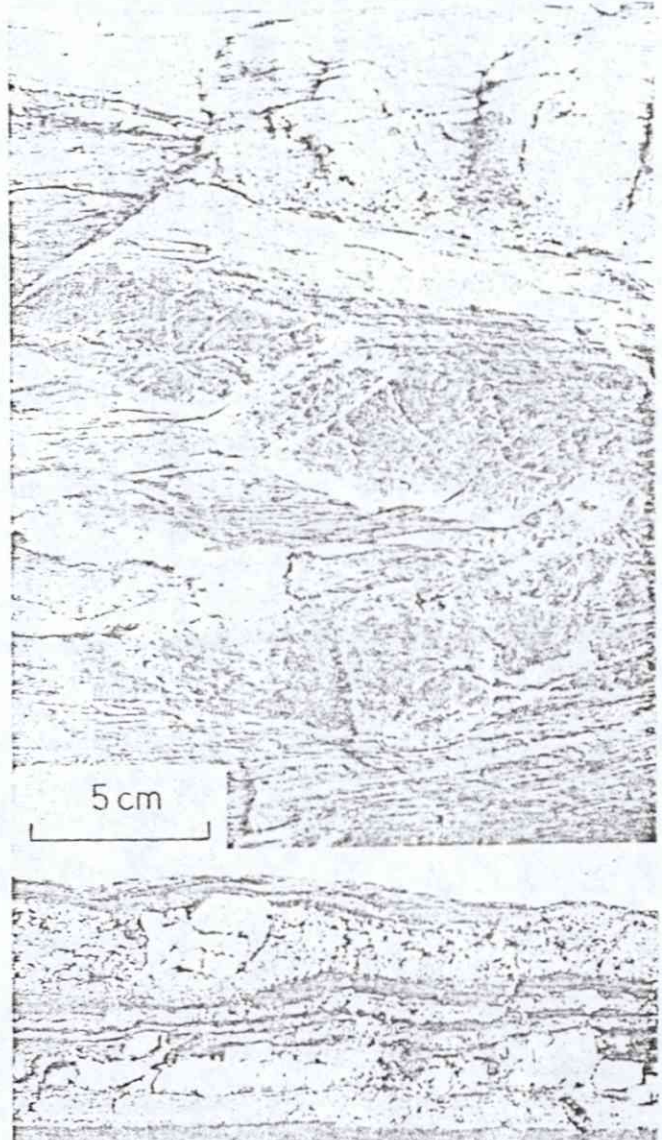


Fig. 15 Exhalite horizon (*a*) (top) 2 km east of Øverste Nesåvatn. Stratigraphic sequence is complex and made up of graded lapilli tuffs overlain by pink to brown coloured banded cherty sediments incorporating magnetite, hematite, stilpnomelane and iron-rich amphiboles. Purple chert band shows isoclinal fold style of earliest deformation with conspicuous refraction of early cleavage. (*b*) Banded pyrite–magnetite sediment typical of reduced facies of iron-rich exhalites (vasskis). Large pyrite porphyroblasts have suffered cataclasis and dislocation to varying degrees. Specimen from 1.5 km north of Blåhammeren. Scale in cm

A comprehensive programme of whole-rock analysis is being undertaken at the present time to establish the major differences in chemistry between the plutonic and the volcanic sequences, but it is clear that the most significant chemical difference does lie in the conspicuous enrichment in sodium, which has evidently occurred in the whole range of the volcanic suite.

The chemical discrepancy displayed by the volcanic and plutonic suites of the Skorovas area has been the root of a lengthy controversy concerning the affinities of spilitic rocks in general. The problem has been discussed by Wells,[76,77] Sundius [66] and Vallance,[69,70] among others, and it is clear, after the review of the problem by Vallance,[69,70] that the case for post-eruptive metasomatic alteration of alkali contents by circulating sea water is strong. Taken in conjunction with the textural evidence described above, there seems little reason to doubt that the spilitic character of the Skorovas volcanic sequence is the result of metasomatism, which accompanied the sea-floor metamorphism of the volcanic rocks during Lower Ordovician times. This metasomatic alteration by circulation of heated sea water changed the chemistry of the rocks, notably enhancing the $Na_2O$ content and concealing the natural magmatic consanguineity of the volcanic and plutonic rocks.

*Magmatic affinity of Skorovas eruptives and their tectonic significance*

The relative mobility of the major elements in basic and acid rocks during metamorphic alteration poses obvious problems with regard to the determination of the magmatic affinity of eruptive sequences and the confirmation of consanguineity within them. Cann,[4] in 1970, recognized the possibility of using certain elements, notably Y, Zr, Nb and Ti, which were unaffected by severe secondary alteration processes, as indicators of the magmatic affinity of ocean-floor basalts. Pearce and Cann [46] subsequently extended this concept for use in determining the tectonic setting of basic volcanic rocks by empirically defining the ranges of variation of the stable trace elements in suites of basaltic rocks collected from various defined oceanic and island arc environments.

Sixty-nine basaltic rocks from various parts of the Skorovas district have been analysed for stable trace elements. In Fig. 13 the values for Ti are plotted against those for Zr with reference to the fields of various basaltic magma types as defined by Pearce and Cann.[46] In addition, the Ti/Zr values for eight associated gabbroic to dioritic rocks from the intrusive arc are superimposed. These rocks were chosen for their even phaneritic texture and lack of conspicuous layering. The plot shows that the basaltic rocks of the Skorovas district concentrate in the field of island arc tholeiites with a notable trend towards the field of calc-alkali basalts. It is also possible to recognize a grouping of values towards the field of ocean-floor tholeiites. The coincidence of the analysed values in the plutonic rocks with the field of island arc tholeiites is regarded as a confirmation of consanguineity in the groups of basic plutonic and volcanic rocks falling in this field.

Study of the trace elements suggests that the eruptive sequence in the Skorovas area originated in a tectonic setting in which basaltic rocks typical of an immature island arc were being generated.[19,28] Moreover, a knowledge of the field relationships in terms of the chronology and relative volumes of the eruptive rocks at the plutonic and volcanic levels confirms this view. Little quantitative information is available concerning the relative volumes of the various eruptive products in mature calc-alkaline arcs and in immature tholeiitic arcs. Baker [2] has given some comparative estimates based on observations of the South Sandwich Island volcanic sequence, and these are judged to be in the same order of proportion as those observed in the Skorovas area, notably basalt ⩾ andesite > dacite and rhyolite (or their spilitized equivalents). In the case of mature calc-alkaline arcs the relationship is of a distinctly different order – andesite ≫ basalt. The field evidence, taken in conjunction with the supporting information from chemical analysis and petrographic examination, forces the conclusion that the eruptives of the Skorovas area are, in fact, the constituents of an immature island arc of Lower to Middle Ordovician age formed within an ensimatic setting peripheral to the Laurentian or the Scandinavian craton. The eruptive sequence, its magmatic evolution terminated, was emplaced as the structural and stratigraphic core of the Gjersvik Nappe during the climactic stages of the Caledonian orogeny in mid-Silurian times. The tectonic decapitation of the island arc is believed to have originated with the collision between the Scandinavian craton–arc margin and a Laurentian counterpart;[10,24] the tectonic transport involved in the process of emplacement is estimated to have been at least 200–250 km.[16,17,63,64]

Skorovas orebody and peripheral exhalative mineralization

The description of the volcanic host rocks given above confirms the association between the Skorovas orebody and an eruptive sequence originating in an immature ensimatic island arc of Lower to Middle Ordovician age. It is appropriate to consider the morphology and mineralogy of the ore deposit and the peripheral exhalite mineralization of the Skorovas region in terms of the exhalative volcanic hydrothermal origin proposed for it by Oftedahl.[41,42]

The orebody is situated within a part of the volcanic sequence displaying distinctly calc-alkaline character. Apart from the keratophyric pyroclastic and flow units, at the level of which the orebody is located, the sequence includes a thickness of basaltic andesites and rocks in the range of silica contents appropriate to andesite and dacite, now represented by spilitized equivalents. The precise stratigraphic location of the orebody with respect to the acid horizons is difficult to establish owing to the disjunctive tectonic style, but there is no doubt that the association

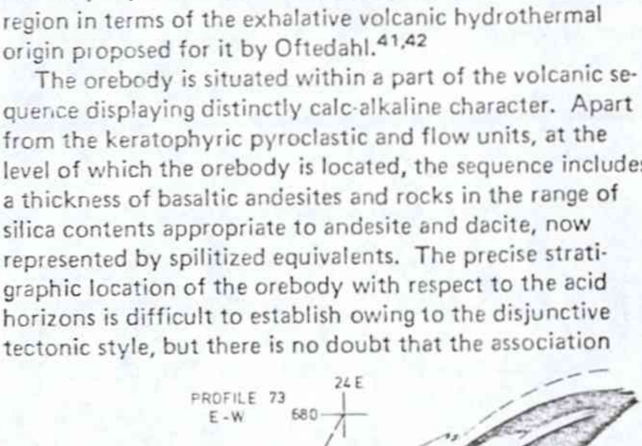


**Fig. 16** Two sections of east orebody at profiles 59 and 73 east–west situated 140 m apart along morphological axis of orebody. Progressive development of a first-phase isoclinal fold is illustrated together with complex digitated style of isoclinal closures. Open style of second fold phase shown by undulation of lower contact of ore on profile 59 east–west

between ore and keratophyric extrusive rocks is intimate (see Figs. 4(a), 5 and 17).

The Skorovas orebody, at the present state of development, is estimated to comprise between 8 000 000 and 9 000 000 tons of massive sulphide ore, including 1 500 000 tons of essentially pyritic ore with minimal base-metal content. From the initiation of production in 1952 until 1975–76 approximately 4 700 000 tons of ore were milled to produce pyrite fines with an average grade of 1.2% Cu, 1.8% Zn and 45% S. This concentrate was marketed primarily for its high sulphur content. Following the decline in the market for sulphur-rich concentrates, a new beneficiation plant has been constructed for the production of Cu and Zn concentrates. Present ore reserves are calculated as approximately 2 000 000 tons with an average grade of 1.15% Cu and 2.29% Zn. It is a difficult problem to assess the average grade of the mineralized body as a whole since this clearly depends upon the geological-economic criteria chosen to define it. It is, nevertheless, possible to state that the mineralogy is dominantly pyritic and that the sulphur content of massive ore is of the average order of 35 wt % with Zn $>$ Cu $\gg$ Pb. Zinc content is of the order of 2 wt % and Cu $\leqslant$ 1 %.

*Structural style of orebody*

The morphological complexity of the Skorovas orebody caused by tectonic disjunction of isoclinally folded lenses and the extreme tectonic deformation of the wallrock envelope has been a considerable obstacle to the clear formation of a genetic model.[20]

The orebody can be described as an *en-échelon* array of closely spaced groups of massive sulphide lenses, the distribution of which has created an elongate ore zone with a length of approximately 600 m lying in a north to NNE orientation and with a width of the order of 200 m. A representative cross-section of the orebody is shown in Fig. 17.

The lenticular bodies have their principal planes orientated parallel to the axial planes of first-phase isoclinal folds and the individual lenses are apparently, to a significant degree, the products of partial disjunction of fold limbs within that fold system. In detail, as is shown by Fig. 17, the ore zone shows a longitudinal division into an eastern and a western orebody. This division may reflect the shape of the orebody at the site of accumulation prior to deformation. The lateral extremities of the ore lens systems characteristically show multiple digitation and bifurcation and there are frequently zones of sulphidic impregnation reaching ore grade that lie between the digitations of massive ore. As Gjelsvik [20] noted, discordance is locally observed between the contacts of some of the larger massive lenses and the schistosity of the wallrocks. This evidence, together with the irregular geometry of the orebody as a whole, was used in support of an epigenetic mode for the formation of the deposit, although Gjelsvik conceded that early folding had probably been an influence in creating its present morphology and that emplacement took place immediately following the eruption of the volcanic sequence in Lower Ordovician times.

It is possible to explain the local discordance between early schistosity and the contacts of the massive lenses in terms of the contrast in the mechanical behaviour of the base-metal-poor pyritic lenses and the volcanic wallrocks during the flattening and isoclinal folding of the first stage

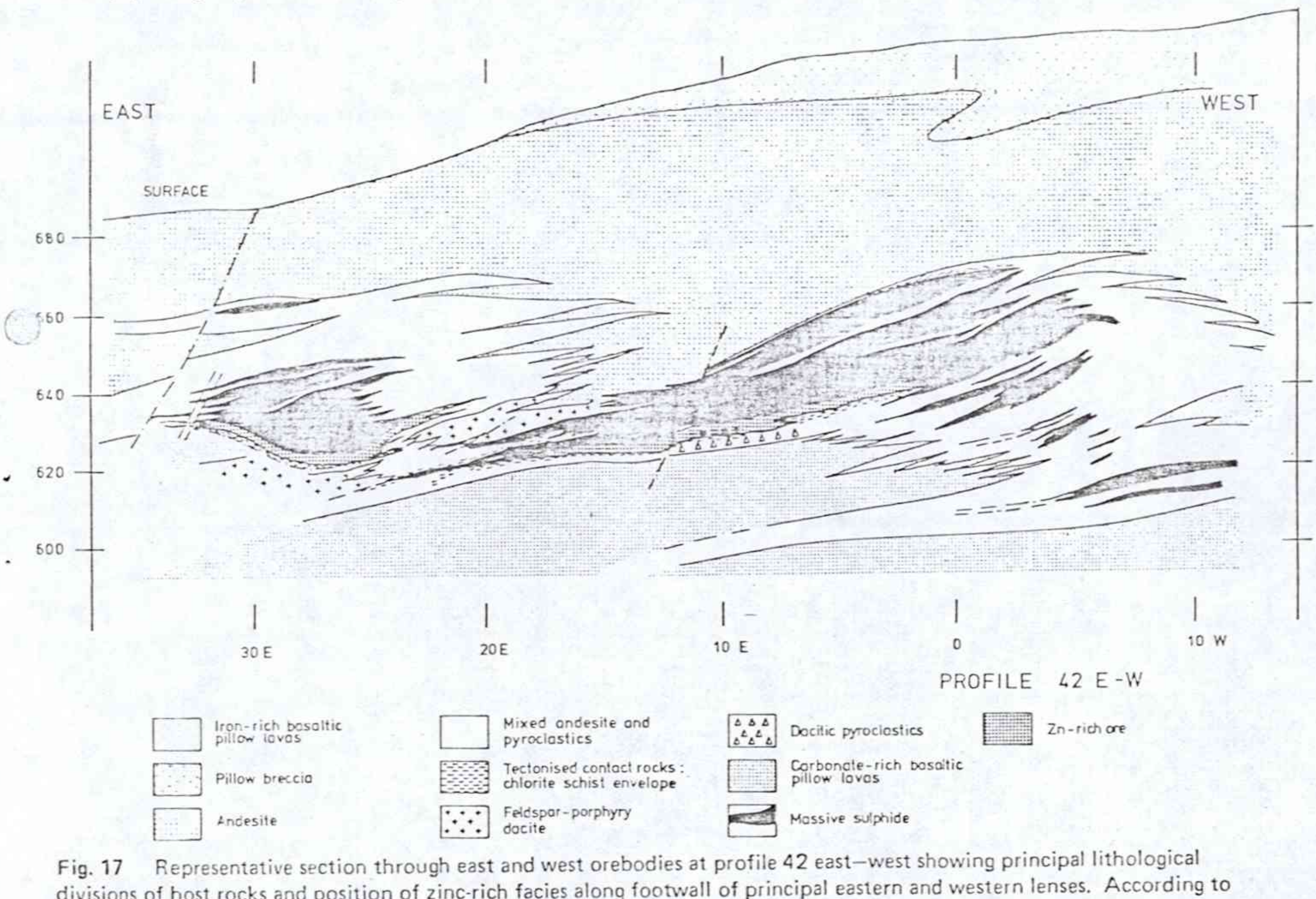


Fig. 17 Representative section through east and west orebodies at profile 42 east–west showing principal lithological divisions of host rocks and position of zinc-rich facies along footwall of principal eastern and western lenses. According to structural interpretation zinc-rich level is stratigraphic top of ore. Complex digitation of ore is well illustrated

of deformation. The disjunction created by componental movements at the ore contacts during this early phase must also have been magnified in response to the stresses imposed during the second period of folding.

The early deformation in the immediate contact zone of the orebody was sufficient, because of the contrast in competency, to create a schistose tectonic facies composed predominantly of chlorite, carbonate and, locally, talc. These components were derived by segregation from the altered basic host rocks – andesite, basaltic, andesite and basalt. The schistose tectonic envelope is shown locally in Fig. 17. The creation of this envelope facilitated the continuance of componental movements within the vicinity of the ore contacts during later deformation.

The history of structural deformation within the orebody can be summarized as follows:

(1) Early isoclinal folding, accompanied by creation of a schistose envelope with componental movements in the vicinity of the orebody contacts, led to a tectonically disjunct style.

(2) Periods of post-schistosity deformation produced folds of various scales. In the immediate contact zone small folds of up to several metres in wavelength occur sporadically in response to local variation in orebody geometry. The orebody as a whole, however, was folded on a broad open style, which is typical of later deformation in the Skorovas region. This is shown in the isometric projection (Fig. 16).

(3) The final episode of deformation was marked by high-angle fractures of low displacement with a general northerly trend.

The early isoclinal structures display axial alignment in a north to NNE direction with axial planes dipping at approximately 25° towards the east. This is reflected in the axial elongation of the orebody. The later open folds, part of the regional dome and basin system shown in the structural analysis (Fig. 4(*b*)), have steeply dipping axial planes and an axial trend of approximately NNW orientation concordant with the pattern of the adjacent structural basis, on the flanks of which the orebody lies.

### *Mineralogy and stratigraphy within orebody*

The bulk composition of the Skorovas orebody reflects a mineralogy of comparative simplicity. Pyrite, sphalerite, magnetite and chalcopyrite are the dominant ore mineral species. Pyrrhotite is conspicuously absent. Galena occurs in much smaller amounts, and arsenopyrite and tennantite occur locally as accessory constituents. This mineralogy accounts for the average range of trace and minor metallic elements recorded in analyses of the orebody, the following values being considered as representative averages: Co, 100 ppm; Ni, 20 ppm; As, 300 ppm; Ag, 10 ppm; and Au, 0.1 ppm. Cadmium is notably enriched in sphalerite-rich facies of the ore, reaching values of several hundred ppm, and Mn reaches similar values in the pyritic facies. Most of the minor chemical variation can be accounted for by diadochic substitution within the common ore minerals. Arsenic and silver are notably contributed by arsenopyrite and tennantite, and grains of native gold have been observed as inclusions of 5 $\mu m$ in size in arsenopyrite from peripheral parts of the ore. The principal gangue mineralogy of the ore consists of chlorite, quartz and calcite, together with lesser amounts of sericite and, locally, stilpnomelane.

The structural and stratigraphic evidence summarized here and by other authors [20,21,41] has confined the choice of genetic models for the orebody to the following alternatives: (1) syngenetic deposition of the stratiform orebodies under submarine conditions as a result of emission of metal-rich fluids in the vicinity of an acid eruptive centre or (2) epigenetic emplacement of the orebody by replacement of part of the volcanic sequence in the vicinity of the eruptive centre, this taking place during post-eruptive hydrothermal activity in early Ordovician times.

If the first alternative is to be given favour, it would be desirable to be able to recognize some evidence of stratigraphy within the orebody. Gjelsvik [20,21] conducted a systematic analytical study of the major base-metal contents of ore from 43 drill-holes on selected profiles spanning the length and breadth of the orebody. The results of this study showed that the contents of zinc and copper varied antipathetically, zinc showing a tendency towards enrichment in the peripheral zones of the orebody and copper tending to concentrate in enriched core regions. It was also noted that the overall content of copper and zinc showed an increase towards south of the orebody. In the southern part Gjelsvik noted that zinc, in particular, is enriched towards the hanging-wall and in the eastern and western extremities of the ore lenses. In the central zone it is enriched in the vicinity of the footwall contact (Fig. 17). In the northern part of the orebody the composition is essentially pyritic, with minimal base-metal content. The analytical data prove a systematic variation in base-metal content both laterally and vertically within the orebody, and this is confirmed by petrographic studies and field observation.

In the course of the present study it has been possible to recognize facies of the ore that are probably of chemical-sedimentary origin and those which are essentially tectonic. The pattern described by Gjelsvik [20,21] probably reflects the influence of both processes. The primary textural evidence for the operation of sedimentary processes in ore deposition is given by the graded banding of the pyritic ores in which rapid changes of modal composition and grain size occur from band to band. This type of texture is shown in the banded pyrite, sphalerite magnetite ore of Fig. 18(*C*). It is highly unlikely that such banding is of tectonic origin. Moreover, where tectonism has had a pervasive effect on the ore, the textures are of distinctly tectonic style (see Figs. 18(*B*) and 18(*D*). Figs. 18(*A*) and 18(*B*) show that the deformation of the pyritic lenses was marked by mutual impaction and cataclasis of the constituent grains. Any gross tectonic flattening or extension of the lenses must have been accomplished by relative movement between the individual grains accompanied by cataclastic degradation. This mechanism has been described as macroscopic ductility by Atkinson,[1] who has also shown that cataclasis is probably the only significant deformation mechanism available to pyrite, under dry conditions in the $P-T$ range appropriate to the greenschist facies. It is unlikely that deformation took place under dry conditions,[48] but the range of textural evidence strongly suggests that, within the massive pyrite, cataclasis was the dominant deformation mechanism. Atkinson [1] also notes that the strength of polycrystalline pyrite is strongly and inversely dependent on porosity. Large volumes of the Skorovas orebody are composed by nearly monomineralic close-packed aggregates of pyrite with low porosity and, when lithified, these masses must have behaved in a highly competent manner relative to the adjacent chloritized lavas and pyroclastics. Under the influence of the tectonic stresses prevailing during the first period of deformation it seems reasonable to propose that the style of deformation within the orebody may have been controlled by the development of narrow zones of cataclastic flow within which much of the tectonic strain would have been accommodated. In this way, the formation of a disjunct lenticular arrangement of ore lenses could be explained as well as the rarity of well-preserved isoclinal structures.

Tectonic mineralogical facies of the orebody are undoubtedly recognizable in the base-metal-enriched lenses and extremities on the lateral periphery of the ore. Zinc values are enhanced by an order of magnitude and lead values by two orders of magnitude. This is shown by analysis 5 in Table 2. The typical foliated texture of this ore is shown in Fig. 18(*D*), which also displays the incipient development of a crenulation cleavage related to the second phase of deformation.

Tectonic mechanisms are not, however, the sole explanation of the peripheral enrichment of base-metal values; nor do they completely explain the separation between maximum zinc and copper values in the pyritic ores. There appears to be a definite stratigraphy in which cupriferous pyritic ores (analyses 1 and 2 in Table 2) are overlain by zinc-rich ores with laterally developed facies rich in banded magnetite and carbonate. Analyses for these ore types are shown as 3 and 4 in Table 2.

It appears also that a distinct primary lateral variation may also have been present to account for the generally depleted levels of copper and zinc in the northern part of the orebody. Final evidence of the operation of chemical-sedimentary processes in the formation of the orebody is provided by the occurrence of magnetitic and hematitic chert bands (jasper) in the foot- and hanging-walls of the orebody stratigraphically overlying the magnetite and zinc-rich facies.

Evidence of a primary stratigraphy within the orebody clearly exists despite considerable tectonic modification. It is also plain that the metal distribution can be interpreted in terms of a stratigraphic zonation, which resembles that found in orebodies of undisputed volcanic exhalative origin in such areas as the Miocene Green Tuff belt of Japan.[30]

The detailed palinspastic reconstruction of the lateral and vertical facies variation within the complex Skorovas orebody is the subject of a current study by Reinsbakken

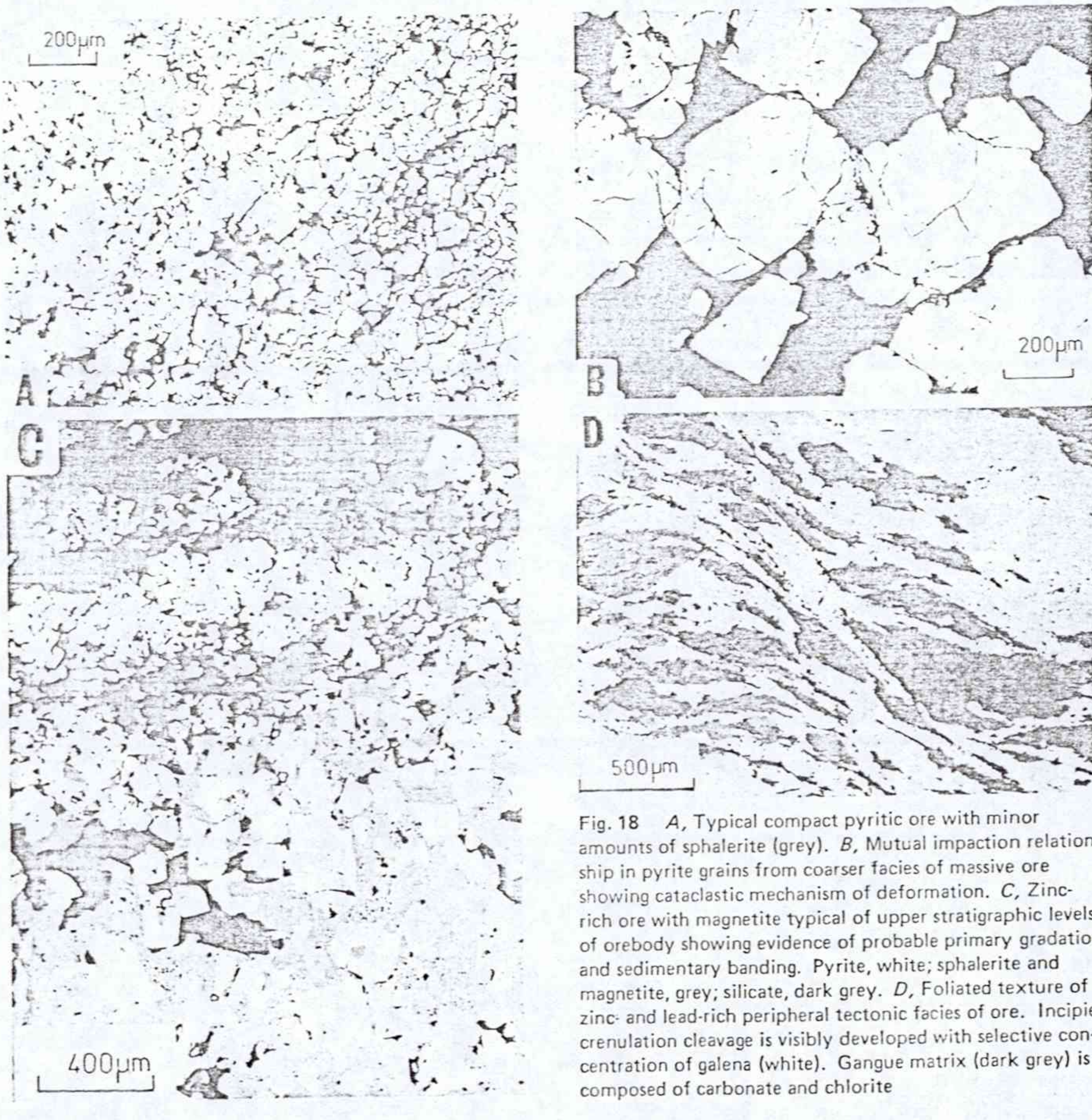


Fig. 18 *A*, Typical compact pyritic ore with minor amounts of sphalerite (grey). *B*, Mutual impaction relationship in pyrite grains from coarser facies of massive ore showing cataclastic mechanism of deformation. *C*, Zinc-rich ore with magnetite typical of upper stratigraphic levels of orebody showing evidence of probable primary gradation and sedimentary banding. Pyrite, white; sphalerite and magnetite, grey; silicate, dark grey. *D*, Foliated texture of zinc- and lead-rich peripheral tectonic facies of ore. Incipient crenulation cleavage is visibly developed with selective concentration of galena (white). Gangue matrix (dark grey) is composed of carbonate and chlorite

and will not be discussed further here. It may be said, however, that the zonal distribution of copper and zinc within the pyritic mass suggests that precipitation of the ore minerals could be explained in terms of an evolving chloride-complex model such as that used by Sato to explain

Table 2 Average metal values for Skorovas ore types and sulphide facies of an extensive exhalite

| % | *1* | *2* | *3* | *4* | *5* | *6* | *7* |
|---|---|---|---|---|---|---|---|
| S | 46.80 | 47.20 | 38.90 | 42.28 | 27.50 | | 51.10 |
| Cu | 1.09 | 2.30 | 0.99 | 0.79 | 1.47 | 0.06 | 0.20 |
| Zn | 0.15 | 0.80 | 3.90 | 9.33 | 44.20 | 0.02 | 0.41 |
| Pb | 0.03 | 0.04 | 0.05 | 0.04 | 4.00 | 0.01 | |

1, Massive pyritic ore (27 samples); 2, copper-rich ore (14 samples); 3, banded magnetite-rich pyrite–sphalerite ore with carbonate (18 samples); 4, pyritic zinc-rich ore at stratigraphic top of orebody (13 samples); 5, Zn–Pb–Cu-rich peripheral ore – probably a tectonic facies (2 samples; 6 massive base-metal-depleted pyrite or 'vasskis', Havdalsvatn (1 sample); 7, relatively enriched pyritic ore, Skorovas (30 samples).

zonation within the Kuroko deposits.[55] The applicability of such a model depends on the existence of conditions such that the metal- and sulphur-enriched hydrothermal solutions are not rapidly and widely dispersed into the dominantly oxidizing conditions of the submarine environment. This requirement must be met by topographical barriers in the vicinity of the hydrothermal emanations or by density contrasts between the emanating brines and sea water.[54] It is upon the presence or absence of the conditions outlined that the distinction between the hydrothermally intensive and the hydrothermally extensive exhalite phenomena in the Skorovas area is based.

*Peripheral exhalative mineralization*

The magnetitic cherts and jasper found at the stratigraphic top of the Skorovas orebody signify the restoration of chemically normal oxidizing conditions in the vicinity of the orebody. These ferruginous siliceous horizons represent a continuum between the intensive and extensive facies of mineralization (see Fig. 19). The relative frequency of the association between acid pyroclastic horizons of various facies and banded magnetite–pyrite and chert in the Skorovas area, and within the Grongfelt as a whole, was one of the primary inspirations for the theory of exhalative-sedimentary ore genesis expounded by Oftedahl in 1958,[41,42] who carried forward the concepts formulated by C. W. Carstens [7,8] in his studies of the Leksdal type of sedimentary sulphide deposit in the Trondheim district. Oftedahl [42] emphasized the association between acid pyroclastic activity and the formation of the iron- and silica-enriched sediments. Understanding of the various exhalative facies has been carried forward in the course of the present study.

The main characteristics of the extensive peripheral exhalites are noted below.

(1) The exhalite horizons are relatively thin, 0.1–2 m in thickness, are laterally persistent within the volcanostratigraphy and can be traced over distances of the order of several kilometres.

(2) Internal variations of stratigraphy occur in detail. The sequence is always marked, however, by a change from a reducate sulphidic or magnetitic banded stratum to an oxidate ferruginous chert (jasper). These changes occur in a vertical sense (Fig. 20) and also, generally speaking, in a lateral sense.

(3) The sulphide facies are characteristically impoverished in base metals other than iron and manganese (see analysis 6, Table 1).

These widespread bands can be explained by a mechanism of explosive volcanic dispersal during the climactic dacitic eruptions associated with the various volcanic centres. In the course of such a process rapid and complete mixing of the residual hydrous fraction of the dacitic magma with oxidizing sea water will have occurred. The base metals will have been subjected to infinite dilution in the course of such a process, leaving oxidized iron and silica hydrosols in suspension. The hydrosols will have suffered greater dispersion than the pyroclastic fragments and by subsequent settling will have produced a thin stratum of iron- and silica-rich sediment that extends well beyond the limits of the latter. It is for this reason that the extensive exhalite horizons are so named. They also constitute valuable time-stratigraphic markers within the intrinsically variable volcanostratigraphy.

The sulphide–magnetite mineralogy of the reducate facies is to be ascribed to post-depositional bacterial reduction of iron, deposited in the oxidized condition. A typical facies of this type is shown in Fig. 15(*b*).

The simple stratigraphy shown in the ideal section (Fig. 20) can be regarded as the product of a single dispersal event. Some exhalites, however, give evidence of episodic explosive and fumarolic activity that results in a complex cyclic stratigraphy in which tuff bands are intercalated

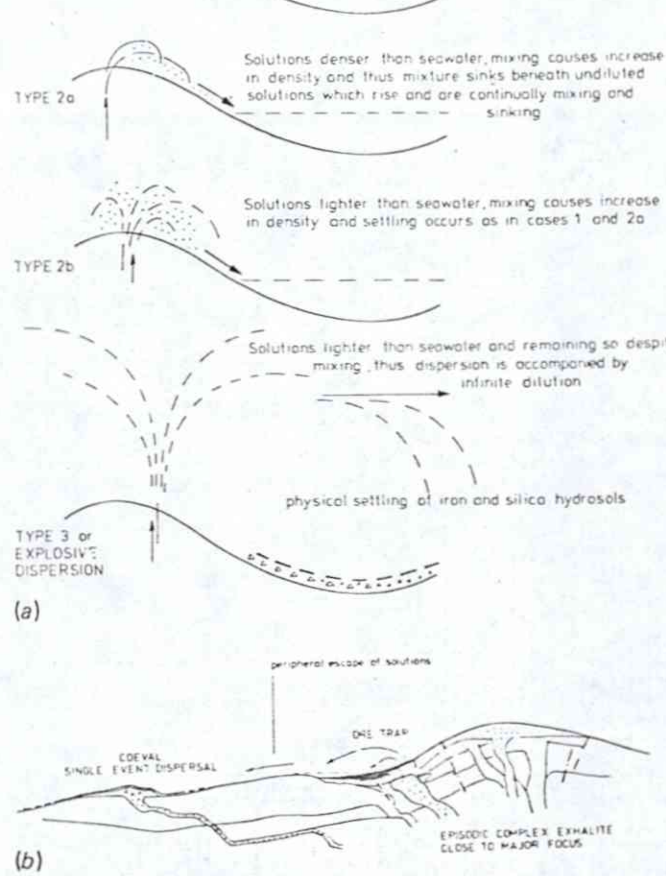


Fig. 19 Scheme of interaction of hydrothermal brines with sea water (*a*) (top) (after Sato [54]) and schematic eruptive and hydrothermal events in Skorovas volcanic centre during climactic dacitic episode (*b*)

with iron-enriched chert bands that show a complex mineralogy, including stilpnomelane, iron-rich amphiboles and chlorites, together with a spinel, commonly of magnetite composition (Fig. 15(*a*)).

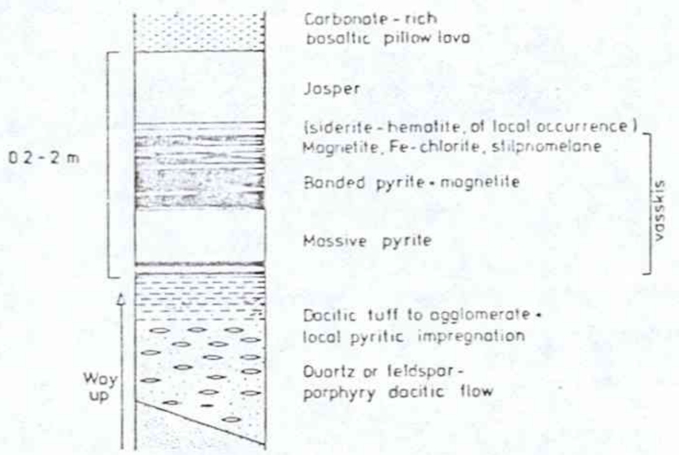


Fig. 20 Ideal section showing products of single event dispersal in extensive exhalite as observed in vicinity of Blåhammeren centre

As well as being valuable time-stratigraphic markers, the exhalites may be developed as a tool in identifying vent-proximal and vent-distal environments and have obvious value as a guide in exploration. An investigation of exhalites as an exploration tool is currently being carried out in the Skórovas area by Ferriday, Halls and Hembre.

## Conclusions

It was recognized in the early stages of the present study in 1972 that the Skorovas area provided a unique window on the eruptive and ore-forming processes that take place within a Palaeozoic island arc environment. An attempt has been made in this paper to describe the major eruptive, hydrothermal metamorphic and tectonic processes that have acted to produce the present geology of the Skorovas area in the context of its position in the Gjersvik Nappe.

Attention has been specifically directed to the hydrothermal processes that take place at the volcanic level, but it is important to record the occurrence of cumulus ores of magmatic origin within the plutonic complex. At Lillefjellklumpen, to the north of Skorovas (see Fig. 4(*a*)), a small platinum-bearing pyrrhotite—chalcopyrite—pentlandite lens has been found in association with a minor body of metagabbro. This occurrence was described by Foslie and Johnson-Høst in 1932.[13] The present study has shown that small cumulus bodies of chalcopyrite—pentlandite-bearing ore occur at a variety of sites in the layered gabbros of the deeper plutonic level. At the present time these bodies are of incidental economic interest only. The whole range of phenomena described can therefore be said to typify the ore-forming environment within an ensimatic pericratonic island arc, and only the porphyry style of sub-volcanic mineralization appears to be absent. This may, however, reflect the immature character of the arc.

The study has also placed the Gjersvik, Trondheim and related disturbances in their proper geological context as episodes of uplift associated with the stages of evolution of a pericratonic arc system in Lower to Middle Ordovician times. Vertical movements of this style can be said to be a characteristic feature of the evolution of arc systems,[71] and Murphy[38] has described fault-bounded back-arc basins of Tertiary age in Indonesia that contain up to 8-km thickness of clastic sediments, which were deposited under subaerial to shallow marine conditions. It is, perhaps, a debatable exercise to attempt to correlate the timing of such movements, which may be intrinsically of intra-arc origin, with tectonic events of differing style taking place in other provinces of the Caledonides that could have been located, in Lower Ordovician times, on separate geographically and tectonically isolated margins of the orogenic system.[3]

## Acknowledgment


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# Geology of the Skorovass Mine: A Volcanogenic Massive Sulphide Deposit in the Central Norwegian Caledonides

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The Skorovass orebody is one of the major stratabound base-metal sulphide deposits within the allochthonous belt of the Central Norwegian Caledonides and is contained within the volcanic eruptive part of the Gjersvik Nappe, a subordinate structural element of the larger Koli Nappe sequence of the Scandinavian Caledonides. The orebody occurs within the metavolcanic sequence at a level marked by an episode of explosive rhyodacitic volcanism and associated fumarolic activity.

Detailed geological investigations have outlined a complex, partially inverted volcano-stratigraphy which in simplest terms can be subdivided into three major units. Whole-rock major element geochemical data from the various volcanic units show that the greenstone eruptives range in composition from basaltic through to rhyodacitic, and the trace element data show concentrations and trends similar to those of low-K tholeiites from island arcs. The Skorovass eruptive sequence is interpreted as having formed as an ensimatic tholeiitic island arc to the west of the Fennoscandian continent during probable Lower to Middle Ordovician times, and subsequently thrust southeastward on to the Fennoscandian continent during the Silurian.

The Skorovass deposit consists of ca. 10M.tonnes of dominantly massive and minor disseminated pyritic ore with an average grade of 1.0 % Cu and 1.5 % Zn together with trace amounts of Pb, Ag, As and minor Cd. Four major ore types (facies) have been delineated and used as mappable lithostratigraphic units within the various ore lenses, and the Cu and Zn values from the massive sulphide orebodies show a clear antipathetic zonation with the Zn-rich ores concentrating at the stratigraphic top of the ore-lens system, which is itself immediately overlain by lenses and bands of jaspilite and magnetitic chert. A cross-cutting sulphide vein system (stringer-zone) has been found directly beneath and extending up into the Cu-rich part of the massive sulphide ores and is interpreted as the 'feeder-zone' or 'root-zone' to the massive ore. The Skorovass orebody is interpreted as having been deposited directly on to the sea-floor from metalliferous hydrothermal brines emanating out on to the sea-floor to form a synvolcanic-exhalative massive sulphide deposit.

The rocks have undergone two main periods of penetrative deformation under lower greenschist facies metamorphism during which time the orebody and its enclosing rocks obtained their present configuration of complex, lensoid, en èchelon geometry.

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## Introduction

In recent years attention has been focusing on the Caledonian-Appalachian orogenic belt in the light of the 'new plate tectonics' (Wilson 1966, Dewey 1969, Miyashiro 1972, Gale & Roberts 1974, Vokes & Gale 1976) and on the volcanogenic sulphide mineralization associated with island arc volcanism at destructive plate boundaries (Horikoshi 1969, Clark 1971, Sillitoe 1972, 1973, Sawkins 1972, 1976, Lambert & Sato 1974, Garson & Mitchell 1977 and Sato 1977).

Recent publications on the greenstone belt of the Grong district and its associated pyritic deposits (Gjelsvik 1960, 1968, Halls et al. 1977) have helped to set the Skorovass deposit in a more modern context in the light of current theories of plate tectonics and associated mineralization. Halls et al. (1977) have given a detailed account of the regional tectonic and stratigraphic setting of the Skorovass deposit. The Skorovass deposit has also recently been cited by C. J. Dixon (1979) in his *Atlas of Economic Mineral Deposits* as "a good example of the type of base metal-bearing pyrite deposit that occurs along the Caledonian-Appalachian fold belt". With the increasing attention that has been given to the Skorovass deposit, it seems only apt that a detailed account of the mine geology should now be presented. This paper summarises the regional tectonic and stratigraphic setting of the Skorovass orebody ably dealt with by Halls et al. (1977), provides a more detailed account of the volcano-stratigraphy and geochemistry of the host rock lithologies and of the various sulphide facies of the orebody itself, and discusses the relationship between the mineralization and volcanism in the light of the now accepted volcanogenic, syngenetic-exhalative model of sulphide deposition. A preliminary account is also given of the lithologies of the various volcanic units and the stratigraphic relationship between these volcanic units and the enclosing sulphide ores. This data forms part of a continuing doctoral thesis project by the author at the Geological Institute, NTH, Trondheim.

### LOCATION

The Skorovass mine lies in the heart of the central Scandinavian Caledonian mountain chain within the southwestern part of the 'Grong district' directly southwest of the large lake Tunnsjø, approximately 25 km west of the Swedish -Norwegian border at latitude 64°38' N and longitude 13°04' E (Figs. 1 & 2). The tiny mining community of Skorovatn lies in a valley bottom at an elevation of 500 m a.s.l. enclosed on three sides by completely barren mountains which reach an elevation of 900 m a.s.l.. The mine itself is situated on the north-facing slope of the mountain Grubefjell at an elevation of 620 m a.s.l. (Fig. 3) where the main adit extends due south for several kilometres directly beneath the main orebody.

### HISTORY

The first record of sulphide discovery at Skorovass dates back to Sept. 1873, although some prospecting in the district had been carried out earlier. With



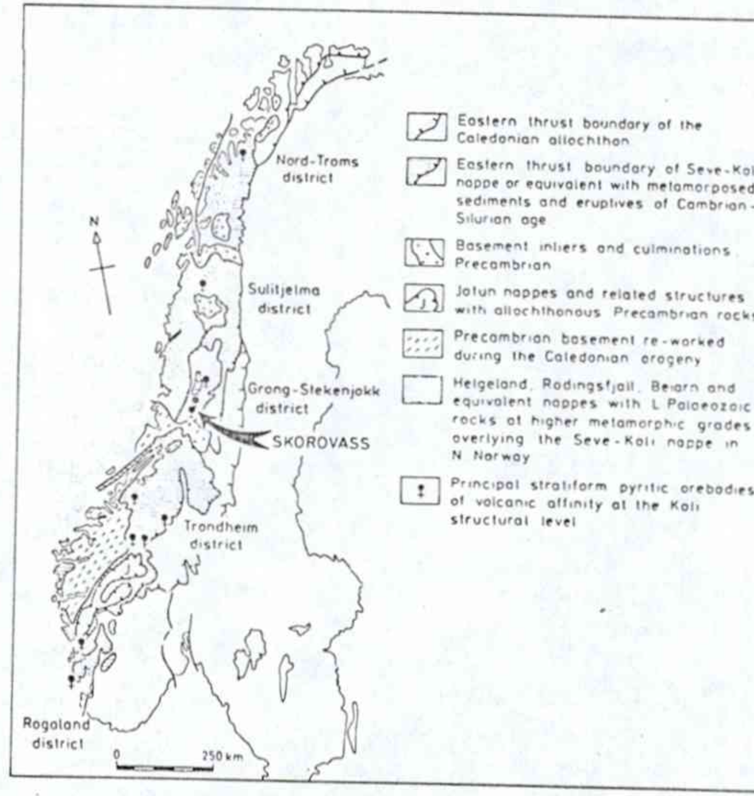



*Fig. 1.* Synoptic geological map of the Scandinavian Caledonides showing the main districts of stratiform volcanogenic ores and location of the Skorovass orebody (After Halls et al. 1977).

its large rusty zone over the surface projection of the northern extent of the main ore zone (reported to be Norway's largest post-glacial gossan), the Skorovass mine area must have been a source of curiosity for many an early traveller. The 'Gammelgruva' (old mine) was first staked in 1910 on a 3–4 m thick massive pyrite lens, the surface projection of the main ore zone, and an intense exploration drilling survey plus the driving of an exploration adit was carried out by Elektrokjemisk A/S during the period 1913–1916. A second period of intense exploration was carried out from 1935 to 38 under the leadership of state geologist Steinar Foslie. The Skorovass mine was finally put into production in November 1952, although some desperate attempts to open the mine had been made by the German occupational forces during the second world war.

The Skorovass mine produced crushed pyrite from 1952 up to the autumn of 1976 when a selective flotation plant was put into operation producing both copper and zinc concentrates.

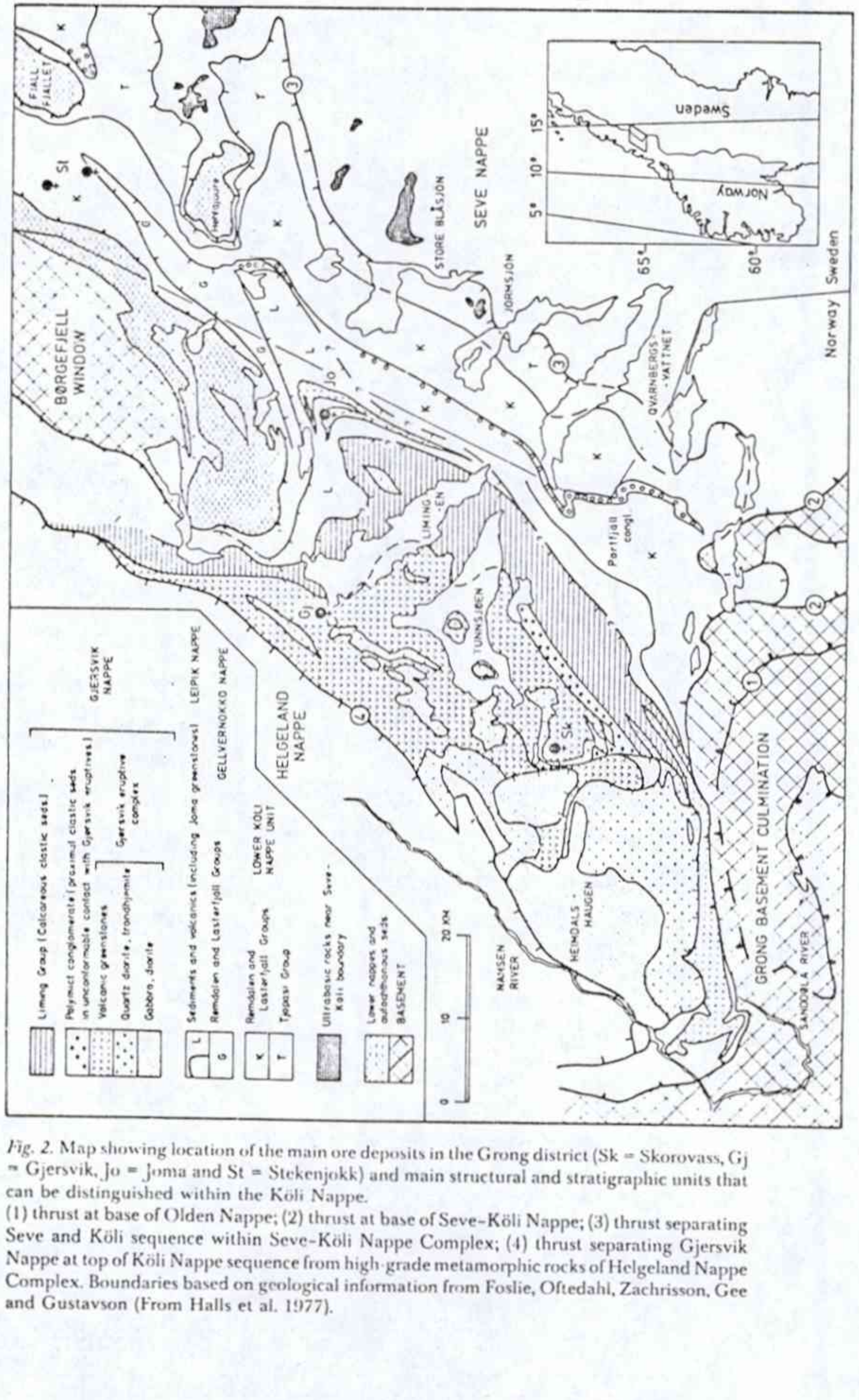



*Fig. 2.* Map showing location of the main ore deposits in the Grong district (Sk = Skorovass, Gj = Gjersvik, Jo = Joma and St = Stekenjokk) and main structural and stratigraphic units that can be distinguished within the Köli Nappe.
(1) thrust at base of Olden Nappe; (2) thrust at base of Seve-Köli Nappe; (3) thrust separating Seve and Köli sequence within Seve-Köli Nappe Complex; (4) thrust separating Gjersvik Nappe at top of Köli Nappe sequence from high-grade metamorphic rocks of Helgeland Nappe Complex. Boundaries based on geological information from Foslie, Oftedahl, Zachrisson, Gee and Gustavson (From Halls et al. 1977).



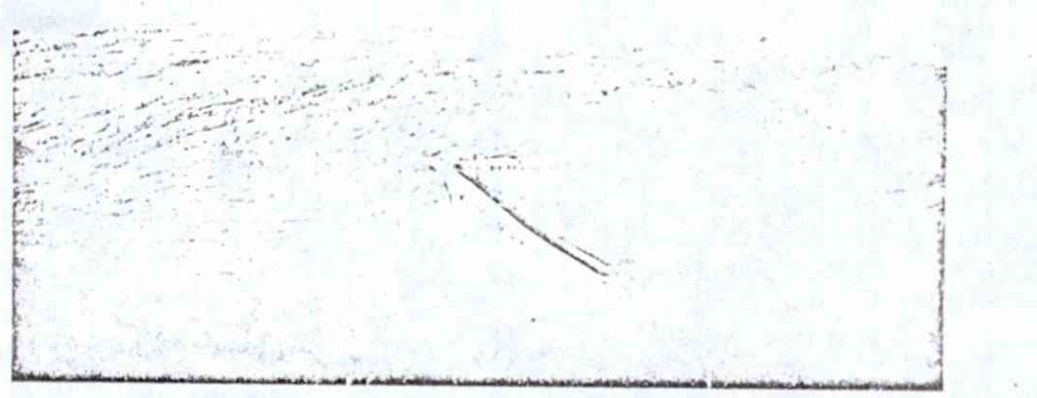


*Fig. 3.* South view of the Skorovass mine with the mine entrance and waste dump to the top right of the tramway. Note the almost complete outcrop exposure on Grubefjell in the background. The conspicuous benching or layering across the photograph parallels the prominent schistosity and was earlier interpreted as lava flows.

## Regional setting

The Skorovass deposit occurs within the allochthonous greenstone belt of the Central Norwegian Caledonides and is located at the acid volcanic level of a complex eruptive sequence of probable Lower to Middle Ordovician age known as the Gjersvik Nappe (Halls et al. 1977). The Gjersvik Nappe constitutes the low-grade metamorphic, uppermost unit of the larger Seve-Koli Nappe Complex, structurally overlain to the west by the higher grade metamorphic rocks of the Helgeland Nappe Complex (Gustavson 1975) and structurally underlain to the east by the lower tectonic units of the extensive Koli Nappe sequence, and is confined to the north and south by the Borgefjell massif and the Grong-Olden basement culmination, respectively (Figs. 1 & 2). The principal components of the Gjersvik Nappe are a plutonic infrastructure of composite gabbroic intrusions within which has been emplaced a series of dioritic to granodioritic (trondhjemitic) bodies which form the roots of a consanguineous submarine polygenic volcanic sequence (Halls et al. 1977). According to Furnes et al. (1980) this is "perhaps the most completely developed ensimatic island arc segment in Scandinavia in terms of variety of magmatic products". The igneous complex is overlain unconformably by a sequence of polymict conglomerates and calcareous flysch sediments, derived by erosion directly from the underlying magmatic rocks (Fig. 4).

Pre-tectonic segregations, veins and vesicle fillings of epidote, albite, chlorite, carbonate and quartz related to primary volcanic flow structures in the lava pile provide evidence of pervasive *in-situ* sea-floor metamorphism

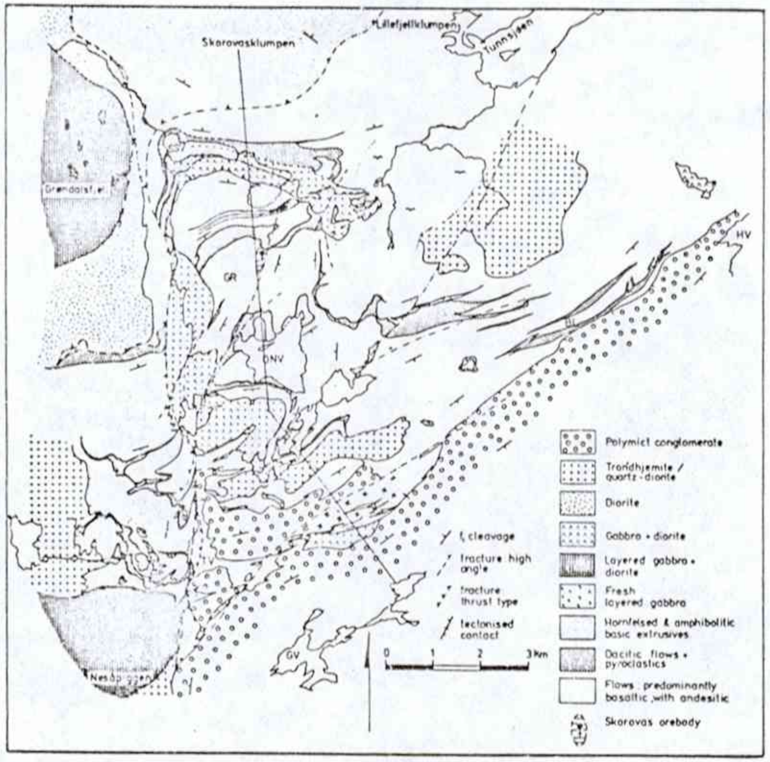



*Fig. 4.* Simplified geological map of the Skorovass area (SSV = Store Skorovatn; GR = Grubefjellet; ONV = Øverste Nesåvatnet (From Hails et al. 1977).

(Spooner & Fyfe 1973) and this is verified by the abundance of nearly monomineralic epidote clasts in the derived conglomerates (Halls et al. 1977).

The relationship of the eruptive and sedimentary units is interpreted in terms of the evolution of an ensimatic island arc of Lower to Middle Ordovician age which underwent uplift and erosion prior to emplacement on to the Fennoscandian basement during the climactic stages of collision tectonism of the Caledonian orogeny in Silurian times.

The entire igneous and sedimentary assemblage has been affected by the deformational processes of allochthonous emplacement but the gross difference in competence between the component lithologies has resulted in a particularly heterogeneous style of deformation in which folding, componental sliding, fracturing and penetrative metamorphic recrystallization have been governed largely by the geometry of the most competent lithologies. These are notably gabbro, diorite and granodiorite (trondhjemite) intrusives and, within the extrusive sequence, by compact rhyodacitic flows and their



spilitized aphanitic equivalents (keratophyre). The heterogeneous pattern of deformation is resolved in terms of two main stages of folding complicated by componental sliding movements.

## Volcanic Stratigraphy and Greenstone Geochemistry

Primary volcanic structures and textures have been described from the western part of the Norwegian Caledonian greenstone belt and have been used successfully in deciphering the volcano-stratigraphy and providing way-up determinations as an aid to interpreting the numerous fold structures found in these area (Furnes 1972, 1973, 1974, Furnes & Skjerlie 1972, Gale 1975, Grenne et al. in press). Detailed mapping within the Skorovass mine area (1:2,000 scale) has helped to document the many primary submarine volcanic structures and textures that have not previously been described from this area, e.g., close-packed pillows and associated pillow breccias and hyaloclastites, amygdales, flow breccias and flow-top breccias, banded tuffs and agglomerates, and acid explosion breccias and lapilli tuffs (Figs. 5a–d & 6). The use of these primary volcanic structures in conjunction with the intrusive relationship and whole-rock geochemistry has helped to delineate a volcanic stratigraphy within the immediate mine area which comprises a metavolcanic sequence ranging in composition from basalts and andesites through to rhyodacites.

### VOLCANIC STRATIGRAPHY

The volcano-stratigraphic sequence of the Skorovass mine area can be divided into three major units (Fig. 6):

1) the Lower units, the oldest volcanics in the area, which comprise dark chlorite-rich metabasalts and minor Fe-rich metabasalts, occurring predominantly as massive flows and close-packed pillow lavas.
2) the Middle units, an intermediate to acid volcanic complex of massive andesitic and dacitic and stilpnomelane-bearing metavolcanics, capped by a rhyodacite 'dome' and accompanying 'explosion breccia' and mixed tuffs which are intimately associated with the massive-sulphide mineralization.
3) the Upper units, the youngest volcanics, which immediately overlie the basic tuffs and sulphide mineralization, are composed of relatively Ca-Mg-rich basaltic to andesitic greenstones occurring predominantly as pale, epidote-rich, close-packed pillow lavas and minor porphyritic massive flows.

*Lower Volcanic Unit (units A+B)*

The Lower Volcanic Unit consists of two minor units, A and B (Table 1, Fig. 6). The lowermost unit, *Unit A*, is dominated by dark green chloritic and minor epidote-bearing metabasalts which occur mostly as massive lava flows and minor flow breccias. Some areas are dominated by pillow lavas with epidote-rich rims and cusps and associated pillow breccias and hyaloclastites.

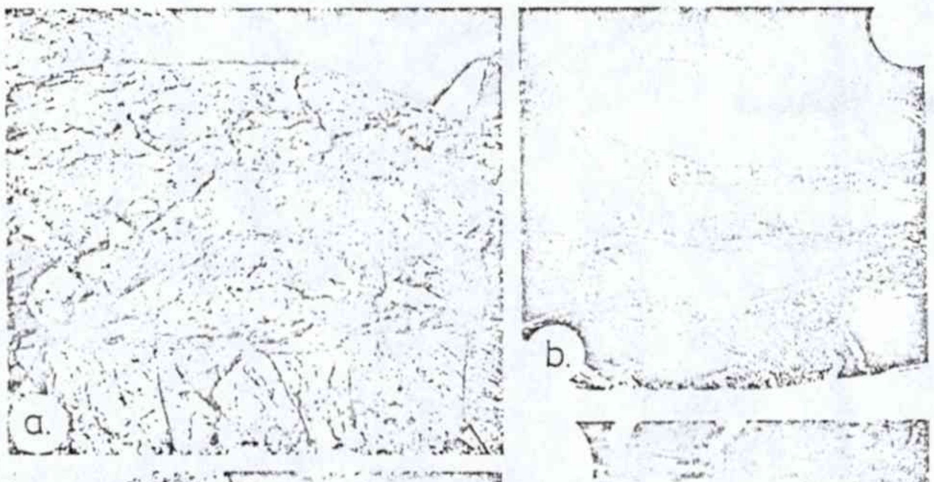



*Fig. 5* (a–d). Photographs of primary volcanic structures and textures found at Skorovass:

(a) Deformed Fe-rich metabasaltic pillow lavas, *unit B* of the Lower Volcanic Unit from beneath the orebody on west Grubefjell. Cuspate bodies of white-grey chert that occupy interstices between pillows are conspicuous. A flat-lying massive andesitic dyke cuts the pillowed sequence in the lower part of the photograph.

(b) Strongly flattened volcanic breccia with angular fragments of dark, magnetite-disseminated meta-andesite set in a paler matrix of epidote and chlorite tuff or hyaloclastite from the upper levels of *unit C*, the lower part of the Middle Volcanic Unit. Note the tiny quartz- and chlorite-filled amygdales and the pale reaction rims surrounding the individual fragments (coin diameter 1.5 cm; this same size coin is used on all other photographs).

(c) White rhyodacite 'explosion breccia' showing angular unsorted acidic volcanite fragments, partly silicified and tectonically flattened, set in a darker fine-grained tuff matrix rich in chlorite and sericite.

(d) Dense, greyish, felsic, 'quartz-eye' lapilli tuff showing the diffuse, welded-contact nature of the individual paler felsic-acidic fragments.



At the uppermost contact of this unit, especially within the mine area, there is an upward gradation into a distinct horizon og Fe-rich metabasalts, *unit B;* these occur mainly as close-packed pillow lavas. The Fe-rich greenstones have a characteristic dark greenish-grey, almost black colour and are strongly magnetic (finely disseminated magnetite), and contain conspicuous quartz- and chlorite-filled amygdales and tricuspate greyish-white chert-filled interstices between the individual pillows (Fig. 5a). In many places the Fe-rich pillowed metabasaltic sequence is separated from the overlying younger volcanics by a thin persistent horizon of grey chert and thin bands of magnetite, locally termed the Iron Formation (Fig. 6 & 7).

*Middle Volcanic Unit (units C+D)*

These units consist of a complex of intermediate to acid metavolcanics which forms a prominent stratigraphic sequence throughout the Skorovass district and which thickens noticeably within the immediate mine area (Fig. 4). The lowermost unit, *unit C,* forms the greater part of this sequence and consists predominantly of very dense, massive meta-andesitic flows with minor quantities of associated breccia material occurring as flow breccias and flow-top breccias and with local minor zones of pillow lavas and associated pillow breccias (Fig. 5b). This intermediate volcanic sequence, *unit C,* is quite variable in composition as minor metabasalts and metabasaltic andesites also occur within the dominating aphanitic lavas. The rocks of this sequence are characterized by their dense, compact nature and pale greyish-green coloration, reflecting an increase in aphanitic albite and minor quartz; they are also relatively magnetic, reflecting a content of finely disseminated magnetite (Fig. 5b). Quartz, epidote and minor stilpnomelane occur in conspicuous large amygdales, gas-bubble rims and tension gash and fracture fillings.

Stilpnomelane is a characteristic mineral of the intermediate volcanic sequence (*unit C*) occurring as diffuse brownish patches and concentrations throughout the sequence in both the massive lavas and the pillow lavas and associated pillow breccias. However, it occurs most noticeably concentrated in areas dominated by numerous acid volcanic dykes that intrude the Lower and Middle Volcanic Units and form feeders to the large acid extrusive 'domes' that cap the intermediate volcanic sequence in the vicinity of the Skorovass orebody (Fig. 6).

The acid volcanic series, *unit D,* forms the uppermost division of the Middle Volcanic Unit and is a conspicuous and resistant sequence of rhyodacitic dykes and thick bulbous bodies or 'domes' of white rhyodacite and associated angular breccia or 'explosion breccia' (Horikoshi 1969) directly overlying and flanking the main rhyodacite 'domes' (Fig. 5c.). Comparable phenomena have been reported from the Miocene Kuroko-type deposits of Japan by Horikoshi (1969) where the tuff breccias are considered to be contact products between the dacite magma and the seawater, and the explosion breccia as products of 'steam explosions' on the flanks of the dacite lava domes. Similar domes of rhyodacite occur in the Gjersvik area 30 km NE of Skorovatn (Lutro 1979).

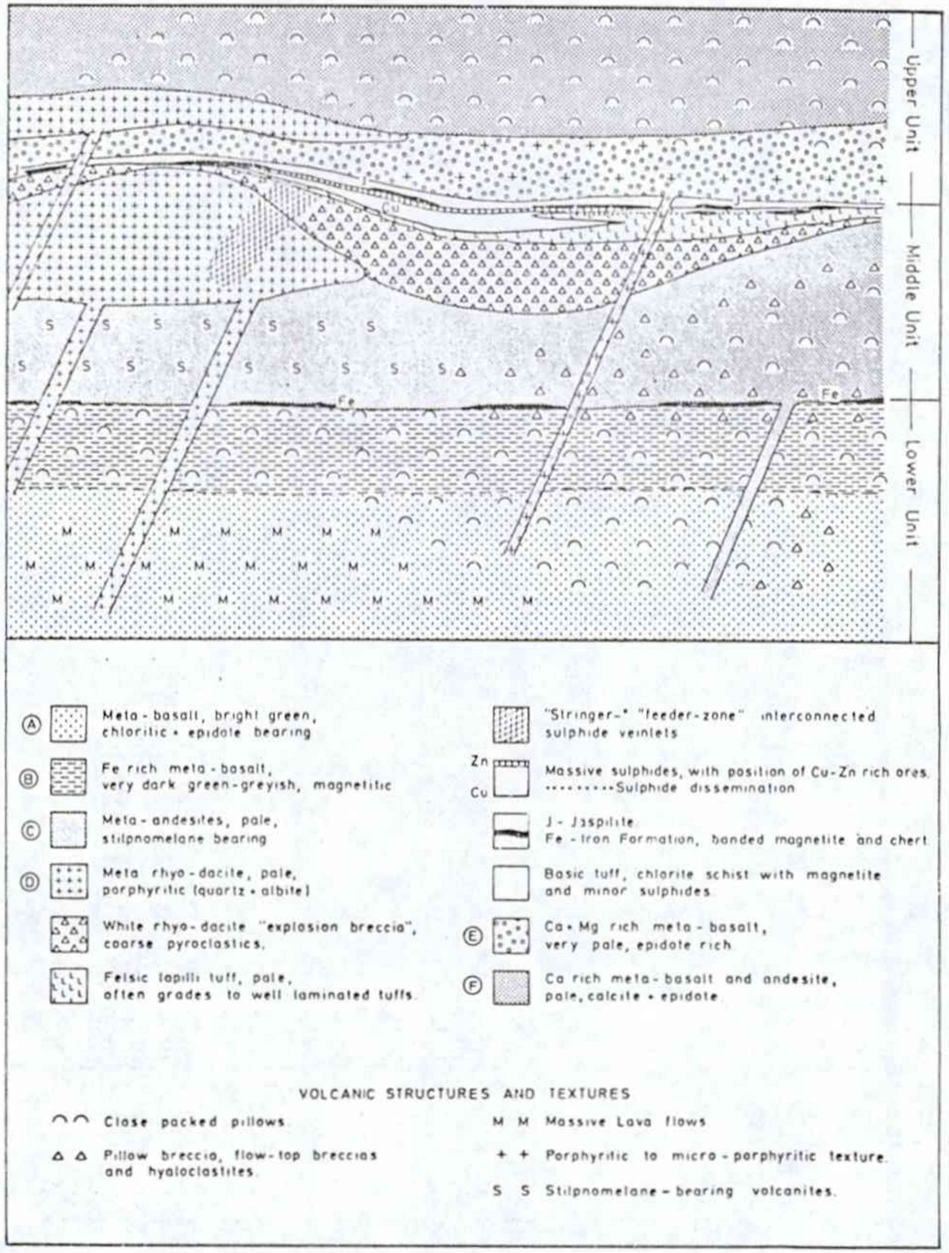



*Fig. 6.* Schematic diagram showing the stratigraphic relationships between the various volcanic units and the position of the Skorovass orebody. Circled capital letters (A–F) in the legend refer to the units shown in Table 1.



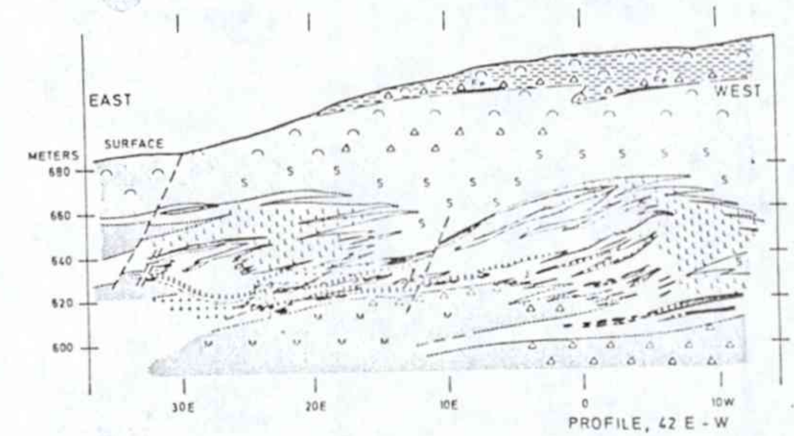



*Fig. 7.* Representative section through the 'East' and 'Main' orebodies at profile 42 E–W showing the principal lithological divisions of the host rocks (same legend as in Fig. 6) and the position of the Zn-rich ore facies along the footwall, associated with jaspilite and banded magnetite and chert exhalites. According to structural interpretation, the Zn-rich levels represent the stratigraphic top of the ore. The complex digitation of the ore is well illustrated, demonstrating the style of the early isoclinal folding and the transposition of a single ore horizon into numerous elongate, en échelon lenses such as those found on the west side of the 'Main' orebody.

The metarhyodacites are conspicuously aphanitic, almost flinty in nature, albite- and minor quartz-porphyritic and generally pale green to apple green in colour reflecting the minor chlorite mineralogy. However, dark grey, massive metarhyodacites with sparse disseminated magnetite are found immediately beneath the massive ores. As seen in Fig. 6 the white rhyodacite 'explosion breccia' is directly and gradationally overlain by a sequence of pale tuffs, generally visibly fragmental and referred to as lapilli tuff (Fig. 5d.); these grade upwards into well-laminated (primary layered) acid (felsic) and more basic tuffs containing varying amounts of albite-quartz-epidote-sericite and chlorite in the matrix. Away from the large rhyodacite 'domes' and centres of acid explosive volcanism, the acid (felsic) tuffs thin rapidly and become noticeably finer grained and more laminated in character. The massive-sulphide ores at Skorovass occupy a stratigraphical position at the top of this 'explosion breccia' – lapilli tuff – laminated acid (felsic) tuff sequence and are immediately overlain by a thin horizon of dark, chlorite-rich, basic tuffs, with hematitic chert or jaspilite and magnetite-rich bands occurring at the upper contact of the ore zone. These basic tuffs form the uppermost member of the Middle Volcanic Unit and presumably represent a period of relative quiescence between the main episodes of volcanic activity.

### *Upper Volcanic Unit (units E+F)*

The upper volcanic sequence consists of a thick pile of pale, carbonate-rich metabasaltic pillow lavas to the east and south-east of the mine area (unit F), and an underlying thin inconsistent unit of very pale relatively Ca-Mg-rich massive metabasaltic flows and minor pillowed horizons (unit E). These younger metavolcanics are quite restricted in occurrence in the actual mine area, because of the structural inversion of the area where much of the upper sequence lies beneath the present erosion level below the orebody, but they increase markedly in thickness to the east and south-east of Skorovatn.

*Unit E*, the lowermost Ca-Mg-rich metabasaltic sequence, is conspicuously very pale, and rich in epidote, albite, actinolite and calcite. It is noticeably porphyritic and much coarser grained than the older aphanitic volcanics – the main reason why these rocks have previously been mistakenly called gabbros. Numerous dykes of this unit are found cutting all the older volcanic sequences, including the sulphide mineralization of the orebody, forming feeders to unit E (Fig. 8). The conspicuous, metamorphosed, mafic porphyritic patches or crystals comprise actinolite and chlorite pseudomorphs after presumed pyroxene crystals.

*Unit F*, the major portion of the Upper Volcanic Unit, consists almost entirely of a thick sequence of pale, carbonate-rich pillowed metabasalts with only minor massive flow units. The pillows have epidote, actinolite and carbonate-rich rims and cusps, and numerous carbonate-filled amygdales occurring in a zone immediately beneath the pillow rims. Some individual pillows also show an internal porphyritic texture. Minor metarhyodacitic flows and dykes also occur in the Upper Volcanic Unit. These are conspicuously quartz- and albite-porphyritic, pale green and devoid of magnetite.

## GREENSTONE GEOCHEMISTRY

As a more detailed geochemical investigation of the Skorovass volcanics is now in progress, only a brief interim summary of the results and preliminary

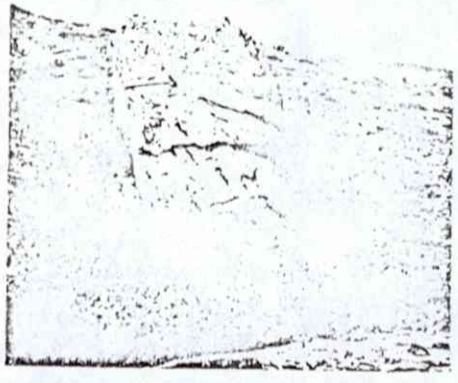


*Fig. 8.* North view along a 1.5 m-thick vertical dyke of microporphyritic metabasalt, *unit E* of the Upper Volcanic Unit, that cuts through very schistose, rusty, sulphide-disseminated felsic tuffs. The prominent schistosity ($S_1$), dipping at ca. 30° to SE, is developed in both the dyke and the enclosing tuffs, showing that the dyke was intruded prior to $F_1$ deformation.



conclusions will be given here. Because the volcanic rocks at Skorovass are so extremely fine-grained and aphanitic and generally devoid of any recognizable primary volcanic textures, the use of major and trace element chemistry has been necessary to distinguish the various volcanic units in the volcano-stratigraphy, especially the units which have similar coloration and surface weathering features, i.e., basalts, basaltic-andesites and andesites.

The volcanic stratigraphy comprises a sequence of extrusive rocks ranging in composition from basalts and andesites through to rhyodacites, a volcanic suite which is characteristic of immature tholeiitic island arcs (Miyashiro 1974). This metavolcanic sequence has a characteristic spilitic chemistry which is reflected in the high $Na_2O/K_2O$ ratios (Table 1), and which is believed to be attributed to pre-tectonic sea-floor metamorphism (Halls et al. 1977).

*Table 1.* Mean major element whole-rock analyses from the 6 volcanic units (A–F) within the Skorovass mine area. Part of the whole rock analyses (15 samples) were carried out at NGU employing analytical methods as described by Faye & Ødegård (1975) and the remainder at the Geological Institute, NTH, where the main elements except sodium were analysed by X-ray fluorescence (Philips PM 8000) using glass beads prepared according to methods by Padfield & Gray (1971). Na was determined by wet chemical methods (AAS) and ferrous iron by titration with potassium dichromate.

| % | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| $SiO_2$ | 48.94 | 48.98 | 57.76 | 70.21 | 48.88 | 51.35 |
| $TiO_2$ | 1.67 | 1.46 | 1.12 | 0.55 | 0.72 | 1.50 |
| $Al_2O_3$ | 14.35 | 14.93 | 14.12 | 12.07 | 15.15 | 15.43 |
| $Fe_2O_3$ | 3.49 | 5.99 | 4.15 | 2.42 | 2.51 | 4.09 |
| FeO | 9.24 | 11.16 | 5.90 | 2.16 | 6.42 | 7.97 |
| MnO | 0.38 | 0.29 | 0.23 | 0.09 | 0.19 | 0.20 |
| MgO | 5.47 | 5.53 | 3.27 | 0.80 | 6.88 | 4.56 |
| CaO | 5.55 | 2.71 | 3.16 | 1.16 | 9.32 | 4.86 |
| $Na_2O$ | 3.90 | 2.97 | 5.46 | 6.84 | 4.04 | 5.23 |
| $K_2O$ | 0.04 | 0.40 | 0.36 | 0.31 | 0.43 | 0.26 |
| $P_2O_5$ | 0.10 | 0.11 | 0.15 | 0.11 | 0.05 | 0.12 |
| L.O.I.* | 5.38 | 4.86 | 3.28 | 1.42 | 5.65 | 3.63 |
| Total | 99.70 | 99.39 | 99.05 | 99.70 | 100.24 | 99.20 |
| No. of analyses | 7 | 4 | 10 | 11 | 4 | 7 |

* = Loss on ignition.
A (Lower Unit) – metabasalt, dark to moderate green, chloritic + minor epidote.
B (Lower Unit) – Fe-rich metabasalt, very dark green–greyish, magnetitic.
C (Middle Unit) – meta-andesite, some stilpnomelane-bearing.
D (Middle Unit) – metarhyodacites, minor albite porphyritic.
E (Upper Unit) – metabasalts, pale, epidote (Ca+Mg)-rich, often porphyritic.
F (Upper Unit) – metabasalt + andesitic basalt, pale, Ca-rich, epidote-bearing.

Based on the 43 analyses so far available, a comparative study of the whole rock major element chemistry of the various volcanic units from Skorovass (Table 1) appears to demonstrate that each unit has distinctive chemical characteristics, which can also be seen in the AFM diagram (Fig. 9) and Ti-Zr diagram (Fig. 10). The Fe-rich greenstones (unit B) for example, show a much higher total Fe content (ca. 16 % $Fe_2O_3$) than the lowermost metavolcanics (unit A) of the same sequence, and the basic metavolcanics of the Upper Volcanic Unit (units E+F) show a more varied chemistry with generally lower Fe and Ti than the older metabasalts from the Lower Volcanic Unit (units A+B). The acid metavolcanics (unit D) also show a distinct spilitic chemistry with very low $K_2O$ and high $Na_2O$ contents and have therefore been classified as metarhyodacites to emphasize their high silica content, although they are in fact more like the dacites that have been described from the Miocene volcanogenic Kuroko-type deposits at Kosaka, Japan (Horikoshi 1969).

The AFM diagram of the Skorovass Mine volcanics appear to show two separate trends in the spread of the analytical data (Fig. 9). One is an iron-enrichment trend within the tholeiitic field of Irvine & Baragar (1971), and embraces the oldest volcanics, units A+B, where the Fe-rich basalts are interpreted as differentiation products from a tholeiitic parent magma.

A second major trend occurs along the division line separating the tholeiitic and calc-alkaline series reflecting the development of the intermediate and acid volcanic products (units C+D) of the Middle Volcanic Unit, and corresponds to the 'distinctly calc-alkaline character' of Halls et al. (1977).

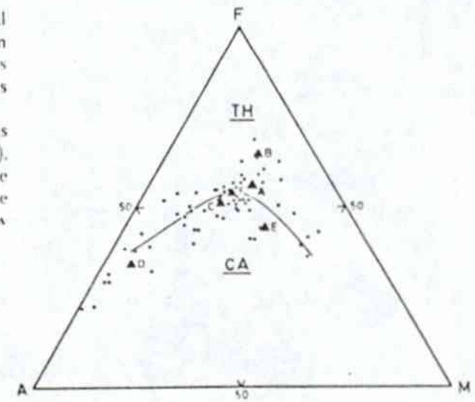
These two trends are almost identical to the trends described by Stanton & Ramsay (this volume) from the Solomon Islands, where they interpret the iron-enrichment trend as a differentiation trend from a tholeiitic parent magma.

The second trend, towards the alkali apex is interpreted by Stanton & Ramsay as the development of the calc-alkaline series by fractional crystallization dominated by intermediate and acid volcanics, and a corresponding loss of the aqueous volatile phase and the production of the exhalative stratiform ores. The Skorovass orebody is similarly intimately associated with acid volcanics marked by episodes of explosive rhyodacite volcanism and associated fumarolic activity.

The two trends can also be detected in the Ti-Zr discriminant diagram (after Pearce & Cann 1973) (Fig. 10) where the spread of the analytical data (dots) shows a prominent trend from the OFB field into the low-K tholeiite field (LKT), which roughly corresponds to the development of the lowermost, oldest, volcanic units (A+B); and a second minor trend into the CAB field represented by the intermediate and acid volcanic rocks (units C+D) of the Middle Volcanic Unit. Although the use of such discriminant diagrams (Ti-Zr) has been restricted to basic volcanics, it has been shown here at Skorovass that it is the intermediate and acid volcanic units that are responsible for the CAB trend.



*Fig. 9.* AFM diagram of the total analytical data (dots) and the mean values (triangles) of the various Skorovass volcanic units, A-F, as shown in Table 1.
A = $Na_2O$ + $K_2O$; F = total iron as FeO and M = MgO (all in weight %).
The curved line separates the tholeiitic and alkaline field above from the calc-alkaline field below (after Irvine & Baragar 1971).



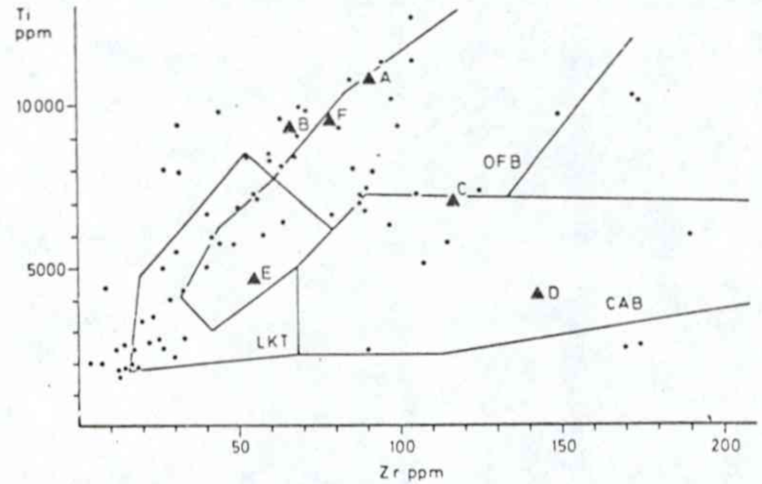




*Fig. 10.* Ti-Zr discrimination diagram (Pearce & Cann 1973) showing the mean values (triangles) of the various volcanic units from Table 1 compared to the spread of the total analytical data (dots) taken from Halls et al. (1977) and Reinsbakken (1977). It should be noted here that both andesites and rhyodacites from the Skorovass volcanics are included in this diagram although the use of such diagrams has been restricted to basic volcanics. The calc alkaline trend in the case of the Skorovass volcanics is a reflection of the andesitic and rhyodacitic composition.

According to Fox (1979), who examined the possible volcano-petrochemical variations and affinities of the host rocks of most of the stratabound, volcanogenic deposits of the Kuroko type using standard means and discriminant analyses, such a comparison indicates that the volcanogenic deposits in felsic terrains are not restricted to the classical calc-alkaline rock association as previously thought, but can actually be hosted by rocks showing a wide range of iron contents. Fox showed that in most Canadian Shield deposits the Zn-Cu ores usually have iron-rich felsic hosts and that in most Japanese, Iberian and Tasmanian deposits the Pb-Zn-Cu ores have iron-poor felsic hosts. He concluded that most of the Zn-Cu-rich Kuroko-type ores of the Canadian Shield are in fact hosted by subalkaline rocks having petrochemical affinities from strongly tholeiitic to strongly calc-alcaline. Moreover, Fox states that "regions characterized by tholeiitic differentiation may have smaller and less dispersed volumes of rhyolite and coarse pyroclastic rocks than in calc-alkaline regions (although the tholeiitic rhyolite is more likely to be quartz-porphyritic)" – which is indeed the case at Skorovass. More recently, MacGeehan & MacLean (1980) have studied the Archean Zn-rich stratiform massive sulphide deposits at Matagami, Quebec, where the massive sulphides form part of the original stratigraphy as stratiform lenses clustered within 'calc-alkaline' centres, most commonly on the flanks of rhyolite domes or other felsic accummulations. They have shown that the massive sulphide deposits, which were originally thought to lie within calc-alkaline rocks, occur within a bimodal basalt-rhyolite suite of tholeiitic affinity, and that the apparent 'calc-alkaline' affinity of the rhyolites or felsic rocks is due to the widespread hydrothermal alteration that accompanied sub-sea-floor geothermal activity.

It may thus be suggested that the Zn-Cu-rich volcanogenic ores of Skorovass occur in acid rocks showing similar petrochemistry to iron-rich, felsic tholeiites such as those found in the Canadian Shield.

Lutro (1979) has shown that similar metarhyodacites from the Gjersvik area, 30 km north of Skorovass, are comparable to dacitic rocks thought to represent differentiates from tholeiitic basalts.

Stilpnomelane is a conspicuous mineral in the intermediate and acidic part (units C+D) of the Skorovass volcanic sequence and occurs concentrated particularly in the vicinity of the orebody and the main extrusive centre and near the numerous acid volcanic dykes, as diffuse shadows, vesicle fillings and fracture fillings along with quartz, epidote, magnetite and minor pyrite. According to recent investigations on the exhalative mineralization in the Skorovass district by Ferriday and others (in prep.), stilpnomelane is a prominent mineral of the silicate exhalite facies. These authors contend that the components of the silicate exhalite have been derived by leaching of Fe, Ca, Al and silica from the volcanic pile as a result of pervasive spilitization by convectively circulating fluids. Stilpnomelane is also found associated with some of the Fe-rich, magnetite-bearing, metabasalts in the immediate mine area. This stilpnomelane-bearing unit has a rather special chemistry, as it is relatively enriched in Fe, Ti and Na and depleted in Ca and K when compared to the rest of the Fe-rich metabasaltic samples of unit B and especially when compared to 'normal' Fe-enriched tholeiites. This special chemistry most probably reflects a period of intense hydrothermal alteration.

## Skorovass Orebody

The orebody occurs as an en échelon array of closely spaced massive-sulphide lenses producing a N–S to NE–SW oriented elongate ore zone (Fig. 7). The ore zone has a width of ca. 200 m, a thickness of up to 50 m, and an overall length in excess of 900 m at the present state of development, although known massive-sulphide mineralization extends well to the south of the presently mined ore-lenses. The orebody consists of ca. 10 million tonnes of massive-sulphides averaging 1.0 % Cu and 1.5 % Zn, of which 1.5 million tonnes are essentially pyritic ore devoid of appreciable base metal contents. Production from 1952 to 1976 yielded 4.7 million tonnes of crushed pyrite having an average grade of 1.15 % Cu, 1.8 % Zn and 45 % S. Present reserves (1978) are calculated at about 2 million tonnes with an average grade of 1.15 % Cu and 2.29 % Zn, reflecting the Zn-rich peripheral ore-lenses now being mined. Trace and minor metallic elements recorded in analyses from bulk samples of the orebody give the following representative averages: Co, 100 ppm; Ni, 20 ppm; As, 300 ppm; Ag, 10 ppm; and Au, 0.1 ppm. Cadmium is noticably enriched in sphalerite facies of the ore, reaching values of several hundred ppm, and Mn reaches similar values in the pyritic facies (Halls et al. 1977).



The bulk composition of the Skorovass orebody reflects a comparatively simple mineralogy, dominated by pyrite, sphalerite, chalcopyrite and magnetite in decreasing order of abundance. Accessory amounts of tennantite, arsenopyrite and galena are also present. Pyrrhotite is conspicuously absent. The principle gangue minerals are chlorite, quartz and calcite together with minor sericite, talc and actinolite. For more information on the Skorovass deposit see Foslie (1926), Oftedahl (1958), Gjelsvik (1960, 1968), Halls et al. (1977) and Reinsbakken (1977).

'Massive-sulphides' are here defined as ≥ 50 vol. % sulphides, and 'disseminated' as < 50 vol. % sulphides.

### SULPHIDE ORE-FACIES

Systematic analytical studies along selected mine profiles show that zinc and copper contents vary antipathetically, zinc being richer in the peripheral zones of the orebody and copper concentrated in the cores of the massive ore (Fig. 7). Although tectonic deformation has destroyed almost all traces of primary (sedimentary) structures, detailed mapping (1:200 scale) has demonstrated that certain ore-facies can be used as lithostratigraphic marker-units within the orebody.

Four major ore-facies or ore-types have been separated within the Skorovass orebody, based on textural and chemical variations. These are shown in Table 2 with their mean sulphur and base-metal values:

1) Type *I a–d* ore-facies, fine-grained, compact, massive pyrite ore.

2) Type *II a–c* ore-facies, zinc-rich, massive sulphide ore.

3) Type *III* ore-facies, pyrite-disseminated chlorite schists.

4) Type *IV* ore-facies, distal exhalative mineralization – 'vasskis'.

*Table 2.* Mean sulphur and base metal values of the various ore types (facies) from the Skorovass orebody and an extensive distal exhalite facies ('vasskis') from the Havdalsvatn area, 12 km east of Skorovass.

| Wt. % | Ia | Ib | Ic | Id | IIa | IIb | IIc | III | IV |
|---|---|---|---|---|---|---|---|---|---|
| S | 45.58 | 46.97 | 51.06 | 37.05 | 36.21 | 42.28 | 27.50 | 33.54 | -nd-* |
| Cu | 2.63 | 1.10 | 0.20 | 0.74 | 0.41 | 0.79 | 1.40 | 1.09 | 0.06 |
| Zn | 0.77 | 2.14 | 0.41 | 3.98 | 3.95 | 9.33 | 42.53 | 1.03 | 0.02 |
| Pb | 0.04 | 0.05 | -nd-* | 0.06 | 0.11 | 0.04 | 3.98 | 0.01 | 0.01 |
| No. of samples | 14 | 27 | 30 | 18 | 14 | 13 | 2 | 7 | 1 |

-nd-* = not analysed for.

Ia : Cu-rich massive pyritic ore with minor bands of magnetite.
Ib : Compact massive pyritic ore, forms major part of the Skorovass orebody.
Ic : S-rich massive pyritic ore, devoid of base metals (referred to as 'Skorovass vasskis').
Id : Carbonate + minor magnetite banded massive pyritic ore, often Zn-bearing.

IIa : Quartz-sphalerite and pyrite banded massive ore with tectonic lensoid-boudinage structure.
IIb : Massive Zn-rich ore at the stratigraphic top of the ore horizon, with minor pyrite interbanding.
IIc : Zn-Cu-Pb-rich peripheral ore band – 'proximal exhalite'.

III : Disseminated pyrite in carbonate and minor magnetite bearing chlorite schists (referred to as 'sedimentary pyrite ore').

IV : 'Distal exhalite' ('vasskis'), fine-grained pyrite and minor magnetite banded mineralization from ca. 12 km E. of Skorovass (Havdalsvatn area).

The boundaries between the four major ore-facies are quite sharp and the relative stratigraphic distribution of the ore-facies within an idealized basin of deposition is shown in Fig. 11.

The major ore-facies I and II are further subdivided into several subfacies based on textural and chemical variations. These generally show gradational boundaries, although they do display some systematic mutual relationships with reference to their stratigraphic position in the postulated original basin of deposition.

## *Type I ore-facies*

By far the most dominant ore-types at Skorovass are compact, massive pyritic ores which for mapping purposes can be divided into four chemically and texturally distinct units (types Ia–d).

Copper-rich, compact pyritic ores, *type Ia,* are widespread throughout the ore deposit and form a conspicuous zone along the periphery of the ore zone which is now interpreted as its stratigraphic base, and in many cases are found immediately overlying or adjacent to a sulphide-veined 'stringer zone'. The Cu-rich pyritic ores are yellow-coloured (fine-grained chalcopyrite) and



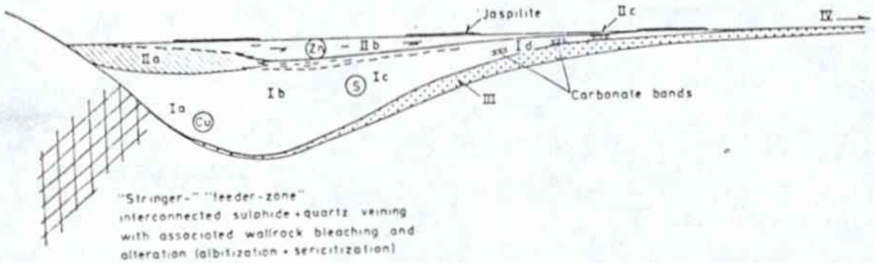



*Fig. 11.* Schematic diagram of the postulated original basin of deposition showing the relative stratigraphic position of the various Skorovass ore types (facies). Symbols for the various ore types are from Table 2.

generally display a marked tectonic banding with only minor, thin, primary bands of magnetite present. Fragments of acid volcanic or felsic (albititic) material are noticeable in the lower reaches of the massive ores in the vicinity of the sulphide 'stringer zone' (Fig. 13a). The average grade of this Cu-rich facies is 2.6 % Cu and 0.8 % Zn (Table 2) but the Cu content varies greatly between 2 to 5 % across the Cu-rich ore zone; values greater than 5 % Cu are seldom found in the massive pyritic ore. Copper values greater than 5 % represent larger concentrations of chalcopyrite occurring along fractures and massive ore boundaries where they are interpreted as representing mobilization and redeposition related to the Caledonian deformation.

*Ore-type Ib,* compact massive pyrite ore, constitutes by far the most dominant and simplest ore facies in Skorovass and is composed of almost totally monomineralic pyrite in a minor quartz matrix. It has a very dense, compact, extremely fine-grained (0.01–0.1 mm grain-size), almost flinty nature (Fig. 13b), often with a brecciated or cataclastic macro-texture with clear quartz as fracture fillings (Fig. 16). A conspicuous facies of the massive compact pyritic ore is *type Ic,* which has been separated from *type Ib* on the basis of its almost total lack of base metals and extremely high S content (averaging over 50 % S); this has been colloquially termed 'Skorovass vasskis' because of its pale almost white colour. This facies is more or less restricted to the northern part of the main orebody where it forms the thickest part of the Skorovass deposit, up to 50 m (north of profile 42 E–W, Fig. 7).

A much more distinctive variety of the compact massive pyrite ores is *type Id,* a carbonate-rich pyritic ore carrying noticeable amounts of Zn. This forms a prominent zone peripheral to and along the footwall of the main orebody, and on structural evidence forms the stratigraphic top of the massive pyritic ores (Figs. 7 & 11). Thin white bands of carbonate (calcite) and minor magnetite, quartz and chlorite form distinct layers in this unit (Fig. 13c), and the pyrite ore is noticeably coarser grained, almost sugary in nature, and occurs as friable pyrite sand where the carbonate matrix has been leached out by the acidic mine waters. The carbonate and minor chlorite matrix suggests that there may be a relationship between this type Id ore and the adjacent type III ore.

*Type II ore-facies*

The type II ore-facies comprises the Zn-rich ores i Skorovass. *Subfacies IIa,* a well banded quartz-sphalerite and fine-grained pyritic ore, forms a distinct mappable horizon adjacent to the Cu-rich and compact pyritic ores. The subfacies IIa is notable for its small-scale banded, lensoid-boundinaged structures (Fig. 13d) which are interpreted as tectonically reoriented primary layers of dark silica and sphalerite, and pale fine-grained pyrite, the individual pyrite grains being cataclastically deformed and flattened. This particular unit can be followed throughout almost the entire length of the ore zone at the same stratigraphic level and is one of the best marker horizons within the orebody. This subfacies also has a very characteristic and consistent chemistry with mean values of 0.4 % Cu, 4 % Zn and 36 % S (Table 2), reflecting the quartz and sphalerite bands within the pyritic ore.

The most dominant subfacies of the type II ores, however, in terms of volume and lateral extent, is *subfacies IIb,* a massive, Zn-rich, dark brown sphalerite ore. This occurs mainly in the southern extension of the Skorovass deposit, concentrated in the upper and peripheral parts of the ore lenses, where it lies above, and draped around, a core of massive Cu-rich and compact pyritic ore. The zinc-rich layers are directly in contact with and overlain by thin horizons of dark chloritic schists (basic tuffs) and lenses of jaspilite, as well as minor thin bands of magnetite and chert. Jaspilite lenses of various shapes and sizes, also occur 'floating' within the massive sphalerite at the upper contact of this Zn-rich unit, attesting to a more plastic behaviour of the sphalerite ores under tectonism as compared with the more competent jaspilite. The sphalerite has also generally developed a strong foliation which conforms to the main schistosity in the surrounding volcanic rocks. Tennantite has been found locally concentrated in patches along the contact zone between the massive sphalerite ores and the chlorite schists. This Zn-rich ore-subfacies (type IIb) varies considerably in both texture and composition and shows a marked transition into the massive pyritic ores below; a complete gradation occurs from massive pyritic ore with minor sphalerite bands, through to thick layers of almost pure sphalerite, up to 2–3 m thick, with only minor thin bands of pyrite (Fig. 12 & 14a.). Consequently, great variations in Zn-content are found within this massive sphalerite-rich ore and although the mean Zn value for this ore type is about 9 %, thick sections (1–3 m) of almost pure sphalerite are found having mean values of up to 45 % Zn.

*Ore-type IIc,* Pb- and Cu-bearing massive sphalerite ore forms a very distinctive thin horizon (50 cm. max.) which is almost totally restricted to the northernmost lateral extension of the eastern orebody (Fig. 7). Like subfacies IIb it forms the stratigraphic top of the massive pyritic and Zn-rich ores, and is directly overlain by small jaspilite lenses and dark chlorite schists. This unit (type IIc), while being of very local occurrence, forms a rather unique horizon in that it is the only place in Skorovass where Pb is found in appreciable amounts. It is composed of a very distinct, dark brown, strongly foliated sphalerite containing a very dark Fe-rich amphibole (grunerite?) and minor clear quartz, galena and chalcopyrite (Figs. 14b & 17). Because of its very local occurrence, this unit has been interpreted as a 'proximal exhalite', after Ridler (1971, 1973).



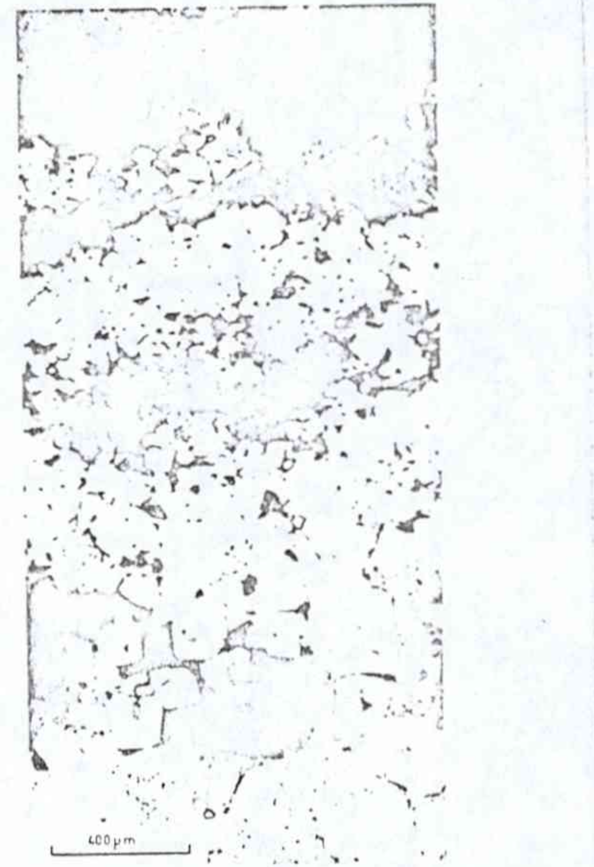



*Fig. 12.* Photomicrograph of *type II b ore.* Zinc-rich ore with magnetite (dark-grey), typical of the upper stratigraphic levels of the orebody, showing layering of pyrite (white), magnetite and quartz (dark grey to black). Sphalerite is also present (pale grey).

*Type III ore-facies*

A rather thick unit of pyrite-disseminated chloritic schists, previously termed 'sedimentary pyrite ore', occurs as a consistent horizon beneath the compact pyritic ores of the main orebody. This shows a great lateral extension and is associated with numerous smaller massive ore lenses beneath and to the west of the main orebody (Fig. 7). This unit (III), is composed of a strongly disseminated pyrite occurring as coarse individual grains and as fine dustings in a greatly varying carbonate- and minor sericite-rich chloritic schist; the coarser pyrite grains are associated with the carbonate-rich schists while the fine pyrite dustings are found mainly in the dark chlorite-rich bands or lenses (fragments?) (Fig. 14d). This pyrite-disseminated chlorite schist unit generally displays a marked schistosity parallel to the boundary of the massive ore, and the individual chlorite-rich bands are strongly lensoid suggesting a strong tectonic reworking and flattening of the individual 'fragments', related to the $F_1$ isoclinal folding.

Minor, thin, magnetite-rich bands or zones and minor layers richer in Zn occur in this unit, strongly suggesting a relationship between this type III, disseminated ore and the carbonate-rich, type Id pyritic ore which immediately overlies it. The pyrite-disseminated chloritic schists occur as a lateral extension of the main massive pyritic ore zone and can be found both above and below the massive ore lenses to the west of the main orebody where it is difficult to establish true stratigraphic relationships because of the intense isoclinal folding and related schistosity which dominates this area.

### *Type IV ore-facies*

Thin horizons of exhalative mineralization related to the Skorovass episode of mineralization can be found in a 10 to 15 km-wide area surrounding the orebody. Detailed investigations by Ferriday et al. (in prep.) have shown that both oxide and sulphide facies occur and that they are composed of iron and manganese oxides, as well as sulphides and silicates, together with quantities of ferruginous chert, and that they are "the result of precipitation of Fe–Mn and silica hydrosols following wide dispersal of exhaled fluids into the oxidizing marine environment" (op. cit.). The sulphide exhalite facies, composed of extremely well laminated sedimentary pyrite beds and interbeds of magnetite and dark Fe-rich silicates, notably chlorite (Fig. 14c), occur as very thin, locally restricted bands within the total exhalite stratigraphy. The exhalites appear to be controlled not only by the changes in the nature of the exhaled fluids, but also by the sea-floor topography (small traps or local basins) where the physico-chemical conditions generally remained reducing under relatively restricted sea-water circulation, resulting in the precipitation of the sulphide facies from the exhaled, dilute, metal-poor fluids. The sulphide and oxide exhalites from the Skorovass district are identical to the 'vasskis' mineralization as described by C. W. Carstens (1919, 1922, 1932, 1944) and H. Carstens (1955) from the greenstones in the western Trondheim district, and typical of 'distal exhalites' as defined by Ridler (1971, 1973) from the Archean greenstone belt of the Canadian Shield.

### SULPHIDE STRINGER ZONE

A flattened stockwork system of interconnected pyrite and quartz veining with associated wall-rock alteration (bleaching due to pale aphanitic albite and minor quartz) (Fig. 15a–d) occurs in an elongate zone cutting through the acid and minor basaltic rocks directly beneath and adjacent to the Cu-rich massive sulphide ores (Figs. 6 & 11). The individual thin sulphide veins are found to coalesce upwards into larger zones of intense albite alteration and



veins or channels of sulphides that project directly up into the thick Cu-rich massive pyritic ores. This interconnected system is interpreted as belonging to the 'feeder-zone' or 'root zone' of the ores, attesting to their submarine hydrothermal-exhalative origin. Zones of extreme hydrothermal alteration, sulphide veining and impregnation are dominated almost totally by albite and minor sericite and quartz and occur in an area of many smaller, irregular, massive pyrite lenses that grade up into the main pyritic ore zone. Individual fragments of the pale albititic alteration products are found within the lower reaches of the Cu-rich pyritic ores (Fig. 13a) and a band of fragmental albitite, forming a distinct horizon beneath the massive ore, has been interpreted as a coarse tuff or slump deposit of hydrothermally altered volcanic material explosively ejected along with the metal-rich emanating fluids from the conduit channels out on to the surrounding sea-floor.

### ORE GENESIS

Textural evidence indicates that certain ore-facies are probably of chemical-sedimentary origin and that the Cu-Zn zonation pattern is a primary dispersion effect within the basin of deposition and can be interpreted in terms of a stratigraphic zonation – Cu consentrated at the base and Zn towards the top – resembling that found in the ores of undisputed submarine, synvolcanic, exhalative origin in such undeformed areas as the now famous Kuroko-type deposits of Japan (Sato 1977).

Additional evidence favouring the operation of chemical-sedimentary processes in the ore formation is provided by the occurrence of magnetitic and hematitic chert bands (jaspilite) in the stratigraphic hanging wall of the orebody overlying the Zn-rich ore facies. Thus, the formation of the Skorovass ores is interpreted as the result of direct precipitation from hot metalliferous brines emanating through fracture zones or conduits out on to the sea-floor and being deposited under reducing conditions in a submarine topographic basin (trap) in the vicinity of the acid volcanic eruptive centre.

## Metamorphism

The earliest event to have affected the volcanic rocks of the area is that of a pre-tectonic metamorphic alteration. This *in-situ* sea-floor metamorphism is ascribed to contemporaneous alteration of the volcanic rocks as a result of the thermally driven circulation of sea water in the upper layers of the volcanic pile (Halls et al. 1977). Bulk changes in the chemical composition of the lavas occurred leading to the conspicuously spilitic chemistry.

Later tectonic deformation of the volcanic pile in Silurian times took place under conditions of lower greenschist facies metamorphism but the mineralogy established during the primary episode was not changed. Further north and northeast, however, upper greenschist facies conditions were attained in parts of the greenstone sequence (Lutro 1979).

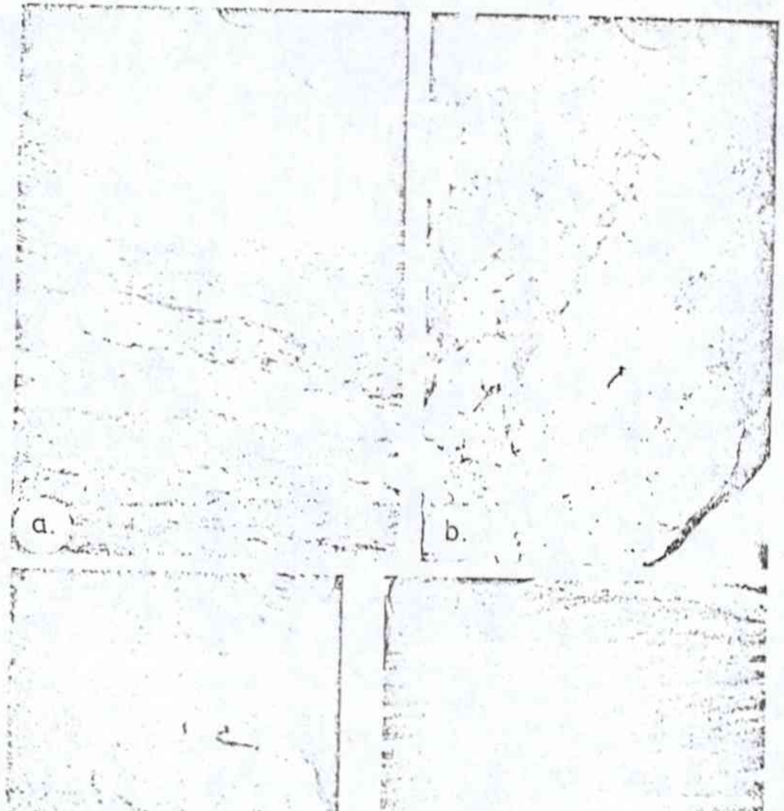



*Fig. 13 (a–d).* The major ore type (facies) from the Skorovass orebody (see also Fig. 14).

(a) *Type I a ore.* Cu-rich massive pyritic ore, tectonically banded with a thin primary band of black magnetite showing a weak development of minor $F_2$ crenulation folds. Note the large lensoid fragments of albititic alteration material (grey).

(b) *Type I b–c ore.* Extremely fine grained, compact, massive pyritic ore with minor clear quartz (dark) as matrix and fracture fillings. Sphalerite (dark grey) is prominent at the bottom of the photograph.

(c) *Type I d ore.* Carbonate-rich massive pyritic ore showing a coarser pyrite grain size in calcite matrix and with a white carbonate band (or vein?) showing the ptygmatic style of $F_1$ plastic deformation which is peculiar to this carbonate rich horizon.

(d) *Type II a ore.* Tectonically banded and lensoid-boudinaged quartz-sphalerite and pyrite-banded massive ore. Darker bands are composed of quartz with finely disseminated sphalerite, and the paler bands of extremely fine-grained, cataclastically deformed pyrite.



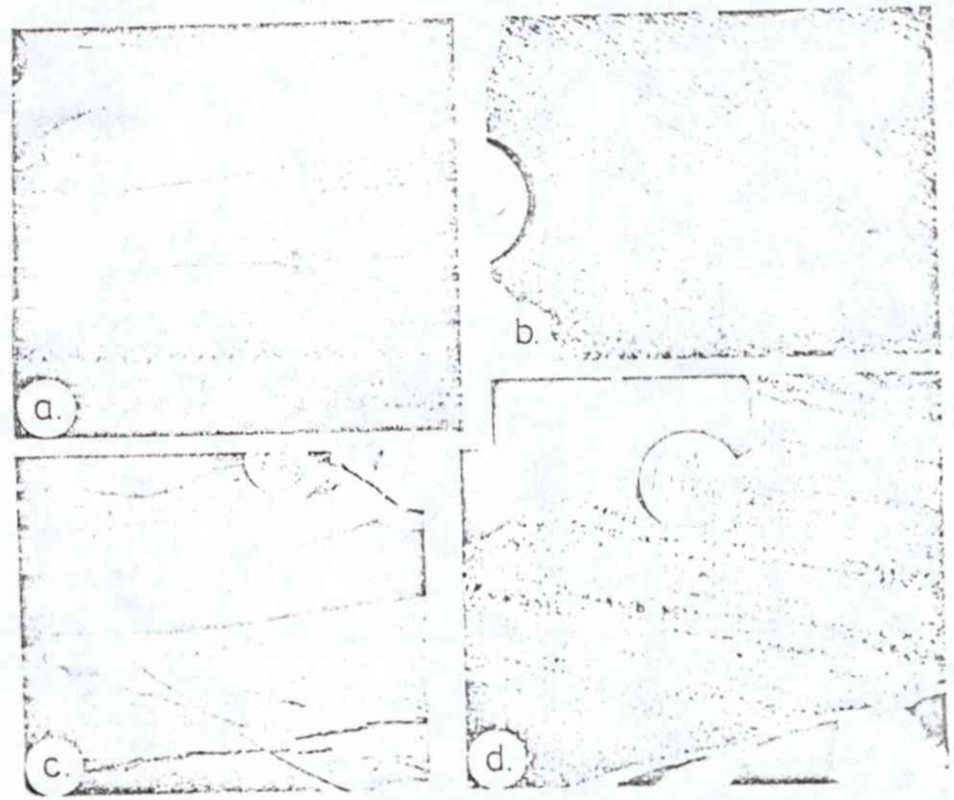



*Fig. 14 (a–d).* The major ore types (facies) from the Skorovass orebody.

(a) *Type II b ore.* Primary sedimentary and tectonically banded massive Zn rich ore. Sphalerite (pale) and clorite (dark) bands are set in thicker layers of fine grained pyrite. Note the partially rotated white felsic (albititic) fragment attesting to the tectonic nature of the banding.

(b) *Type II c ore.* Massive Zn Cu Pb-rich peripheral ore. Strongly foliated massive sphalerite (grey) with minor chalcopyrite and galena (white) and dark silicates, mostly a dark Fe-rich amphibole (grunerite?).

(c) *Type IV ore:* Typical 'distal exhalite' mineralization ('vasskis'). Sedimentary-banded, base-metal depleted, massive pyrite, interbanded with silicate material (dark) composed primarily of Fe rich chlorite. From the Tredjevatnet area ca. 10 km south of the Skorovass mine.

(d) *Type III ore:* 'Sedimentary' or disseminated pyrite ore. Strongly schistose ($S_1$) disseminated pyrite bands and fine pyrite dusting in chloritic schists (dark) and minor carbonate-rich bands (light). Large, idioblastic pyrite crystals show the matrix effect of pyrite porphyroblastic growth.

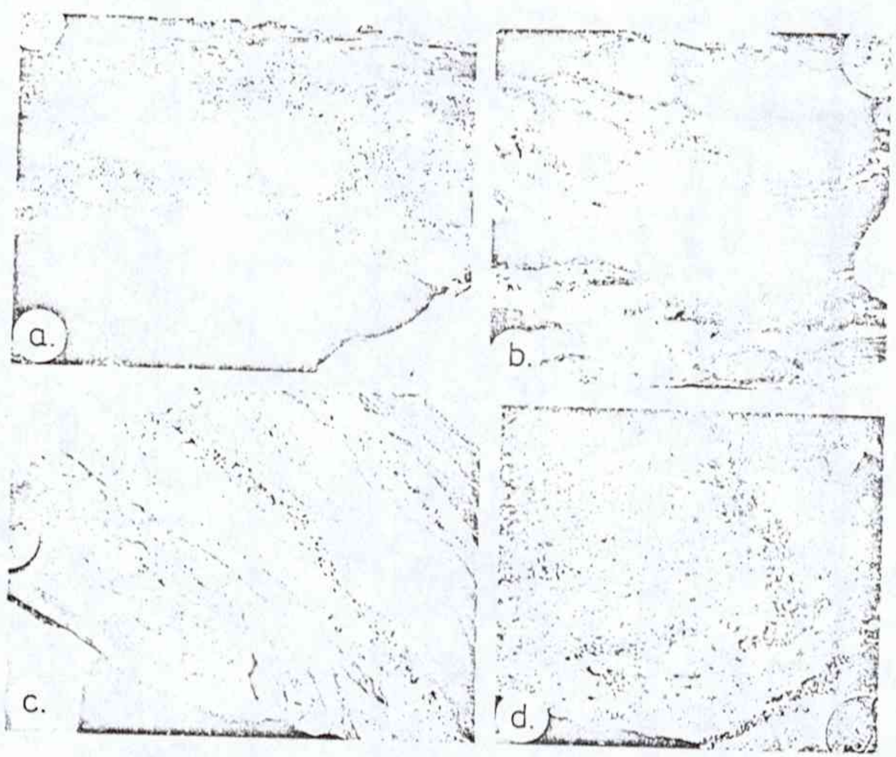



*Fig. 15.* (a–d). Series of photographs from the 'feeder-zone' directly beneath the Cu-rich massive sulphide ore, showing the progressive development of hydrothermal wall-rock alteration associated with the sulphide veins of the 'stringer-zone':

(a) Dark aphanitic metabasalt cut by interconnected veins of quartz and coarse-grained pyrite showing initial traces of pale hydrothermal bleaching alteration at the vein boundaries (aphanitic albite and quartz).

(b) A more advanced stage showing more intense hydrothermal alteration surrounding the sulphide veins.

(c) The end product of hydrothermal alteration with the formation of large areas of pale, completely albitized material (originally called 'keratophyre') which is associated with thick sulphide veins found directly beneath and partly within the lower reaches of the massive sulphide ore itself. Note the fragmental, partly zoned nature of the albititic alteration material near the coin. This is interpreted as a zoned alteration product with the darker zones representing a dusting of very finely disseminated pyrite. The fragmental nature was probably governed by the original fracture pattern through which the emanating fluids passed up through the 'feeder zone', now represented by the sulphide veins. Similar fragmental albitite also occurs as local breccia horizons stratigraphically beneath and partly within the lower reaches of the Cu-rich massive pyritic ore. (Note the small fragment of pale 'albitite' in the Cu-rich sulphide ore. (Fig. 13 a.)

(d) Quartz-eye porphyritic, albititic sericite schist from the intensely sulphide impregnated, completely altered central part of the 'feeder–stringer zone' showing much fine-grained dusting and impregnation of pyrite. The coarser grained pyrite and quartz veins are noticeably sheared parallel to the prominent schistosity ($S_1$), indicating that the pyrite veining and associated alteration must have occurred before the first phase of deformation ($F_1$) and is consequently not related to secondary remobilization associated with folding.



## Tectonics

At the present level of erosion, the volcanic sequence in the Skorovass district lies inverted within the lower limb of a major SE-facing fold loosely known as the Gjersvik Nappe (Halls et al. 1977) (Figs. 4 & 7). The area has undergone two periods of major deformation during which the orebody and its enclosing volcanic rocks obtained their present configuration of complex, lensoid, en échelon geometry (Fig. 7).

The first phase of deformation, $F_1$, occurred during the period of overthrusting and emplacement of the Gjersvik Nappe on to the Fennoscandian basement. During this process the supracrustal rocks were affected by a major penetrative deformation, producing early isoclinal recumbent folds accompanied by the creation of an axial plane schistosity ($S_1$). During the subsequent stage of main thrusting and sliding, horizons separated into massive wedges along planes of high tectonic strain and overrode one another. Such planes of sliding were generally located along major lithological boundaries between units showing marked contrasts in competencies – a componental movement along the thinned and extended limbs of isoclinal folds, accompanied by flattening and the production of a 'lenticulate style' (Halls et al. 1977). Because of the gross differences in competence between the various rock-types (e.g., carbonate-rich pillow lavas versus the compact, aphanitic massive rhyodacite flows and dykes), a particularly heterogeneous style of deformation is characteristic of the extrusive levels of the Gjersvik Nappe in the Skorovass area, the pattern being controlled on the larger scale by the forms of the more competent members, the intrusive massifs and acid extrusive domes and intrusive dykes.

Early, recumbent, isoclinal folds display gentle axial plunges to the S-SSW, which roughly parallels the elongation of the orebody, and have axial planes ($S_1$) dipping approximately 25° to the SE. Tectonic banding within the ores parallels the main schistosity ($S_1$) in the enclosing schist envelope and represents an axial plane structure accompanying the first phase isoclines. Phase I isoclinal axial trend ($F_1$) is reflected in the elongation of the main ore body. Individual lenses are apparently the product of partial disjunction and translation of fold limbs within the fold system – the lateral extremities of the ore lens system characteristically showing multiple digitation and bifurcation (Fig. 7).

Minor fold structures of the early generation are not particularly common within the massive volcanic sequence and are best observed in the finely stratified tuff bands and associated, more competent cherts and iron-rich chlorite schists of the exhalative facies. Early isoclines are also preserved at the contacts of the massive ores with the surrounding schistose envelope and within the well banded sphalerite and chlorite-rich facies of the ore itself.

The second stage of deformation, superimposed on the grain of the early isoclines and $S_1$ schistosity, has created a system of broad open, upright folds which have resulted in an irregular pattern of dome and basin structures. The formation of these open dome and basin structures was accompanied by further movement (shortening) along the low angle planes generated during phase I, and these movements led to the creation of minor fold crenulations and a local second stage axial plane cleavage ($S_2$). The second phase crenulation folds ($F_2$) show a consistent axial trend plunging ca. 12–15° towards the SE (164°) and with axial planes dipping moderately to the NE. This period of post-schistosity deformation produced folds of varying magnitude from minute crenulations (often microscopic) and drag folds, to rather large, open, undulating folds. Detailed structural studies will be required to determine the mutual and temporal relationships of these post-schistosity structures.

The final episode of deformation is represented by a complex system of high-angle normal faults and conjugate fractures, dominated by NNE–SSW to NE–SW and E–W trends and showing vertical displacements of up to 2–3 m from within the mine (Fig. 7). These faults and fracture zones penetrate both the ores and the enclosing schists and have created stability problems within the mine.

## Tectonic Deformation of the Ore

Where tectonism has had a pervasive effect on the ore the textures are distinctly of a tectonic nature, and any gross tectonic flattening and extension of the ore lenses must have been accomplished by relative movements between the individual grains accompanied by cataclastic degradation, called 'macroscopic ductility' by Atkinson (1975). Textural evidence strongly suggests that, within the massive pyritic ores, cataclasis was the dominant deformation mechanism (Fig. 16). Atkinson (1975) noted that the

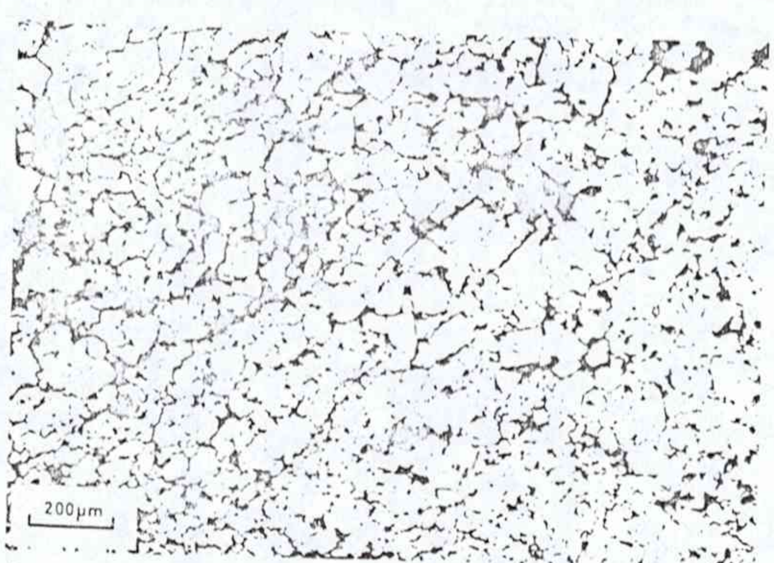



*Fig. 16.* Photomicrograph of *type I b–c ore.* Typical compact very fine-grained pyritic ore with minor amount of sphalerite (grey) and quartz (black) as matrix filling, and with cataclastic deformation of pyrite grains (cubes).



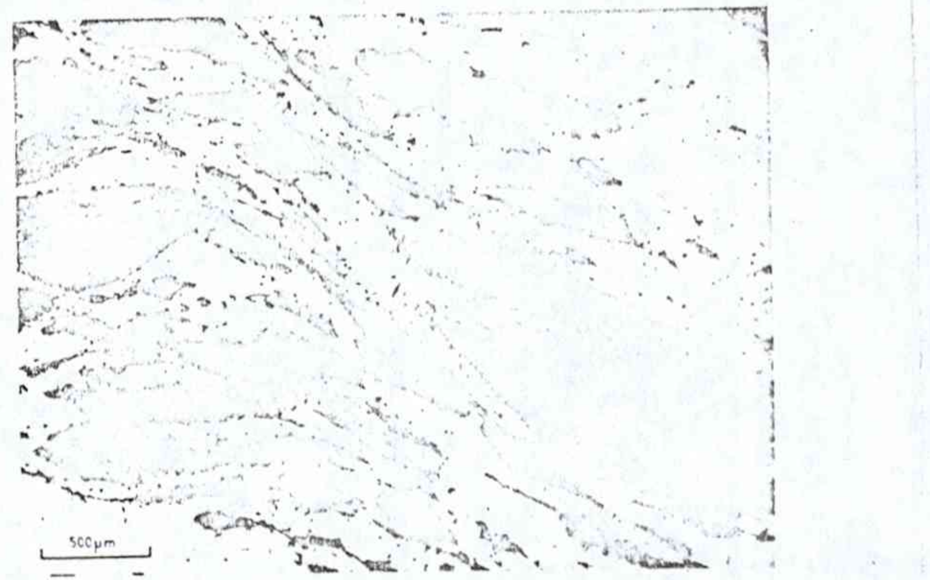



*Fig. 17.* Photomicrographs of *type II c ore.* Zn–Cu–Pb peripheral ore facies showing a well developed foliate texture which corresponds to the prominent schistosity ($S_1$) in the surrounding volcanics. An incipient crenulation cleavage ($S_2$) is also developed along which there is selective concentration of galena and chalcopyrite (white). The dark foliated minerals are Fe rich amphibole (grunerite?) and quartz.

strength of polycrystalline pyrite is strongly and inversely dependent on porosity. Large volumes of the Skorovass orebody are composed of nearly monomineralic close-packed aggregates of fine-grained pyrite with low porosity and, when lithified, these masses must have behaved in a highly competent manner relative to the adjacent chloritized lavas and pyroclastics.

During phase I, the style of deformation within the orebody may have been controlled by the development of narrow zones of cataclastic flow within which much of the tectonic strain would have been accommodated. This produced a disjunctive lenticular arrangement of ore lenses (Fig. 7). The sphalerite-rich and chlorite-carbonate-rich banded ores, on the other hand, appear to have behaved differently under early isoclinal fold deformation, as most of the sphalerite rich ores display a strongly developed planar fabric, comparable to that in the enclosing chloritic schist envelope (Fig. 17). Phase II crenulations with associated axial plane cleavage are also found developed in the sphalerite-banded ore in much the same manner as in the enclosing schists.

## Conclusion

A detailed investigation of the volcanic lithologies has led to the establishment of a volcano-stratigraphy for the host rocks of the Skorovass deposit.

Continuing studies of the geochemistry of the individual volcanic units are showing that the Skorovass volcanics originated in an environment producing basaltic and intermediate lavas of island arc tholeiitic character with a slight calc-alkaline affinity, and as previous stated by Halls et al. (1977), "the orebody is situated within a part of the volcanic sequence displaying distinctly calc-alkaline character". This study shows that the calc-alkaline trend is a reflection of the intermediate to acid volcanic compositions of extrusive rocks that show an intimate association with the sulphide orebody, and that these acidic or felsic lavas can be of tholeiitic origin, as suggested by Fox (1979), Lutro (1979) and MacGeehan & MacLean (1980).

The Skorovass eruptive sequence is interpreted as having formed as an ensimatic tholeiitic island arc to the west of the Fennoscandian continent during probable Lower to Middle Ordovician times and subsequently obducted and thrust southeastward following continental collision at the climactic stages of the Caledonian orogeny during the Silurian.

From an area of such complex volcanic extrusive and intrusive nature as an island arc (e.g. the Skorovass area), detailed knowledge of the volcano-stratigraphy is necessary to help interpret the trends produced on both major element and trace element discriminant diagrams such as the commonly used AFM diagram and the Ti-Zr diagram of Pearce & Cann (1973). Uncritical and blind use of such diagrams without prior knowledge of the volcano-stratigraphy can lead to misleading interpretations of the palaeovolcanic environment.

Detailed investigations of the complex polyphase deformation of the Skorovass orebody and enclosing volcanic rocks have permitted a palinspastic reconstruction of the lateral and vertical ore facies within the original basin of deposition and have demonstrated the intimate relationship between the massive sulphide ores and the explosive acid volcanism and associated fumarolic activity, now found as the sulphide veins of the 'feeder zone'. The formation of the Skorovass orebody must therefore be seen in the light of a volcanogenic hydrothemal-exhalative mode of deposition.

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# EVALUATION

# OF

# PROSPECTING WORK

# AND ORE POTENTIALS

# IN SKOROVAS

Oslo, March 10, 1982
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# 1. INTRODUCTION

## 1.1 Location:

The Skorovas orebody containing about 10 million tons of massive pyritic ore represents one of the major basemetal deposits in the greenstone belt of the Central Caledonides. Skorovas is located in the southwestern part of the Grong district, 280 km north of Trondheim.

## 1.2 History:

An intense exploration drilling program and the driving of an exploration adit were carried out by Elkem a/s during the period 1913 to 1916. The mine was put into production in 1952.

Until 1975 about 4.700.000 tons of bulk sulphide concentrates were sold. Due to a decline in the market and the price for bulk concentrates, a selective flotation plant was put into operation in 1976.

## 1.3 The Main Orebody:

The length of the orebody is approximately 700 m with its main axis in a north to NNE direction (See fig. 1). The width of the oreody averages about 200 m. As a result of tight isoclinical folding and partial disjunctions of fold limbs, the ore has a lensoid en échelon geometry.

The grade of the base metals varies in the orebody with Zn being richer in the peripheral zones and copper tending to concentrate in the core region. The overall content of Cu and Zn shows an increase towards the south of the orebody.

The crude ore production in the years 1977 to 1981 has been about 1.1 mill. tons with an average grade of 1,22% Cu and 2,83% Zn.

A representative average of some trace-elements are as follows: Ni - 20 ppm, As - 300 ppm, Ag - 10 ppm and Au - 0,1 ppm. The silver values are mainly found in arsenopyrite and tennantite. Native gold has been observed as small inclusions in arsenopyrite.

Estimated ore reserves as of January 1, 1982 are about 436.000 tons averaging 1,35% Cu and 2,5% Zn. In addition there are about 3 million tons of pyritic ore averaging 0,23%Cu and 0,56% Zn.

1.4 Summary of Prospecting Work:

Geological investigations date back to 1930 when S.Foslie carried out regional mapping in the Grong district. As a consulting geologist he also supervised the ore exploration before the mine was put into production.

In recent time Halls et al. and A.Reinsbakken have conducted geological investigations in the area. A total of 10 graduate geologists have contributed to the work by Halls et al. in the period 1971-1977.

The recent geological investigations have made significant contributions to the understanding of the geology in the area which is the basis for ore prospecting.

A geological environment of andesitic and rhyodacitic rocks in association with volcanic breccias are considered to be favourable for the occurrence of ore. Also deformation processes as tight isoclined folding may contribute to the occurrence of economic ore deposits.

Geophysical explorations date back to 1958. Most of the investigations have been carried out by the Norwegian Geological Survey and Terratest (see fig. 4). Because of the relatively high resistivity of the country rocks in Skorovas, electric and electromagnetic methods have been useful. Air-borne measurements from helicopter have identified shallow pyritic mineralizations. Among the ground methods the turam-method has been of particular value, locating objects at depth of about 200 m.

Geochemical investigations of stream sediments have been carried out by the Norwegian Geological Survey, Terratest and the Mining company itself. The survey was of a regional character. (See fig. 3).

The mine has up to 1980 had its own geologist for mine geological work, for supervising prospecting field work and for interpretation work.

1.5 Summary - Results and Prospecting Status:

The marginal deposits Syd and Sydøstmalmen have been found by drilling to check geophysical anomalies, (See fig. 1). They are located about 200 m below surface.

The tonnages and grades of the marginal massive ores are as follows:

Sydøstmalmen 430.000 t assaying 1,4%Cu, 0,2%Zn

Sydmalmen 520.000 t assaying 0,9%Cu, 1,5%Zn

The mineralizations are occurring within an impregnation zone located between the marginal ores.

The deposits are not considered to be fully delineated in laterial directions. There are also certain possibilities of repetition of mineralization at deeper levels because of the tight isoclinal folding pattern.

About 17 other pyritic occurrences have been located. The occurrences and their status are listed in table 2-5. A map showing the locations is presented in fig. 2.

Out of the geophysical anomalies that warrants a further check, the I.P.anomalies just west of the Main orebody should be given priority. (See fig. 5). The anomalies may reveal a possible additional ore reserve, and more drilling is recommended to check the anomaly.

The majority of all explorational activities took place before detail geological information of the area was available. The recent geological information and the following up objects and anomalies described above support the general statistical experience that a mining district has a proven favourability for the occurrence of ore.

As a result of depressed base metal prices in the last years the profits in mining have been limited. In such a situation the Mining company had to prioritate rationalization in the mine instead of prospecting.

Based on modern geological information and on improved geophysical techniques we recommend to follow up exploration in an area of 54 $km^2$. (See table 1 and Fig.7).

## 2. TOTAL COST AND UNIT PRICE FOR PROSPECTING WORK

The following chapter lists the prospecting reports, deposit evaluation and work that has been conducted in the Skorovas area. Exploration drilling and mine-claims are also included. Based on today's costs for prospecting work, a value on the various services has been set.

| | Scale | | Value (NOK) |
|---|---|---|---|
| **2.1 Base maps** | | | |
| Aerial photographs | 1:20000 | | |
| Aerial photograph mosaics 280 km2 | 1:10000 | | |
| Topographic maps 280 km2 | 1.10000 | | |
| Topographic maps 3 km2 | 1:2000 | | 350.000 |
| **2.2 Geological maps and reports** | | | |
| Foslie, 1922-1927 | 1:100000 | | |
| Gjeldsvik, 1965 | | | |
| Grønnhaug, 1970 | 1:25000 | | |
| Huseby, 1971 | 1:10000 | | |
| Halls et al. 1971-1977, 12 manyears | 1:10000, 1:25000, | 1.800' | |
| Reinsbakken 1975-1977, 2 manyears | 1:2000, | 300' | |
| Mine maps and profiles, 4 manyears | 1:200, | 600' | 2.700.000 |
| **2.3 Geochemical investigations** | | | |
| Terratest 1970 60 km2 | 1:20000 | 80' | |
| NGU/Skorovas 1972-75 260km2 | 1:50.000 | 135' | 215.000 |

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Terratest 235 samples analyses on V, Ni, Fe, Ag, Pb, Cu, Zn and Co.

NGU/Skorovas 320 samples analyses on Cu, Zn, Ni, Co, Pb.

Fig. 3 shows the investigated areas.

## 2.4 Geophysical Investigations

| | | | |
|---|---|---|---|
| Terratest aeroplane E.M. investigations 1962 | 280 km2 | 280' | |
| Terratest helicopter E.M. investigations 1972 | 20 km2 | 245' | |
| NGU, helicopter E.M. investigations 1974 | 250 km2 | 525' | |
| NGU, Turam investigations 1938, -59 and 74 | 20 km2 | 220' | |
| NGU, I.P., S.P. and VLF-investigations 1979 | | 40' | 1.420.000 |

Fig. 4 shows the investigated areas.

## 2.5 Exploration drilling

| | |
|---|---|
| Exploration drilling, 20.000 m including core analyses | 7.000.000 |

Grade control drilling on the main ore is not included

A map showing the majority of all drillholes is shown on fig. 1.

## 2.6 Mining project evaluation

| | |
|---|---|
| Syd-, Sydøstmalmen & Skiftesmyr, 1 manyear | 200.000 |

Skiftesmyr is a marginal pyritic deposit situated about 50 km south of Skorovas.

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## 2.7 Mining Claims

3 old lengdeutmål (staked claims) covering the mine

2 new utmål (staked claims) covering the southern part of the deposit

16 mutinger (claims) at the southern part of the Skorovas field

23 mutinger (claims) that we now have applied for. Various parts of the Skorovas field.

| | |
|---|---|
| Taxes claim, 2 years | 20.000 |

Fig. 5 shows the claimed areas.

## 2.8 Administration

| | |
|---|---|
| Salary for project managers and mining geologist, 10 manyears | 1.500.000 |
| Total cost for prospecting | 13.405.000 |

# 3. GEOLOGICAL INVESTIGATIONS

## 3.1 Introduction

Geological investigations and reports were made as far back as 1922. By the recent work of Halls et al. (1971-77) and Reinsbakken (1974-77), geological maps that form a good basis for further explorations have been developed.

The geological investigations by Halls et al. were carried out as a joint project between Elkem a/s, NTNF, NTH, the Royal School of Mines and Imperial College of London. Ten graduate geologists have made significant contributions to the investigations by field work and reports. The geological mapping was done in the scale 1:10 000 and the results have been put together on a map in the scale 1:25 000. Referring to the enclosed publications of Halls et al., Fig. 4 shows a simplified map.

A.Reinsbakken was during the period 1974-1977 involved in a Skorovas research project. He has done detailed mapping in the mining area (1:2000) and within the mine (1:200). He is presently working on his doctorate which we expect will be of importance in the interpretation of ore controlling structures. His work is expected to be concluded in 1983.

## 3.2 Ore controlling environments and deformations

The geology is very well described in the enclosed publications of Halls et al. and Reinsbakken. We have endeavoured to bring to attention the geological environment and deformation process that we considered to be of importance in the further exploration of the area.

The major part of the Skorovas area is dominated by greenstones of basaltic to andesitic compositions. The greenstone area is intruded by gabbroes and dioritic rocks.

The ore is associated with the greenstones at a level marked by an episode of explosive rhyodacitic volcanism. Relatively rough breccias are occuring indicating a close relationship with a volcano. Primary ore solutions are interpreted as having been trapped on a sea floor basin from metalliferous solutions coming from the volcanic area.

The structural deformations are as follows:

1) Isoclinal folding displaying axial alignments in a north to NNE direction. This is reflected by the axial elongation of the ore body. The axial planes are dipping towards the east. The lenticular ore body has its plane orientated parallel to the axial planes. Geological sections of the ore body show that deformations have partly been so strong that disjunction of foldlimbs have occurred. It is assumed that economic quantities of ore may have occurred partly as a result of the strong deformation processes.

2) Periodes of more open folding having an axial trend of approximately a NNW orientation. The axial planes are almost vertical.

3) The final deformation is represented by a complex system of normal faults with a generally northerly trend.

### 3.3 Evaluations of areas favourable for the occurrence of ore

The known ore mineralizations and the located mineralization objects Skorovaslia, Finnkjerringhullet and Drikkevatnet Syd are forming a centerline through an area about 4-6 km wide and with a length of about 9 km. (See fig. 2). That area is considered to be most favourable for the occurrence of ore.

Within that area the prominent rhyodacitic rocks running east of the Main ore body and the same type of rocks running north and west of Store Skorovatn is supposed to be a good marker indicator for the occurrence of ore.

The tight isoclinal folding pattern may indicate possible repetitions of ore-mineralizations below the known ore mineralizations.

Referring to Fig. 4 and 5 in the enclosed publication of Halls et al., there are structural indications that the rocks in which the Main ore occurs may be repeated towards depth as a result of a rather big isoclinal fold. The results from drillholes 10035 and 10071 support these structural indications.

Away from the rhyodacitic marker indicators (of explosive volcanism) in the eastern directions the acid tuffs thin out and become more laminated in character. This peripheral structure is not considered to be too favourable for the occurrence of ore.

# 4. GEOPHYSICAL INVESTIGATIONS

## 4.1 Evaluation of geophysical methods

Geophysical investigations have been carried out in the period 1958 to 1979. In sulphide ore exploration the electric and electromagnetic (EM) methods are most important. In Fig.4 there is a map of the investigated areas and it shows the methods that have been used. The usefulness of geophysical methods are evaluated against results from investigation on well known objects as the Main ore and Syd-and Sydøstmalmen.

1) Air-borne E.M. investigations give rather diffuse anomalies of the Main ore, the reason is assumed to be navigation problems.

2) Helicopter-borne E.M.investigations (1972,1974) give good indications of the outcrops of the Main ore.

3) Ground surveys as Turam, Induced polarization (IP) and resistivity measurements give distinct anomalies of the outcrops of the Main ore and its continuation towards south below the overlying rocks.

   The marginal ore deposits Sydmalmen and Sydøstmalmen are located about 200 m below the surface level. It is noteworthy that the turam method reveals distinct anomalies from the mineralization level. The anomalies from I.P. and direct current soundings surveys are, however, rather diffuse.

4) The audiomagnetotelluric method (A.M.T.) reflects the Main ore, but the anomalies above the Syd- and Sydøstmalmen are rather diffuse. It is assumed that the anomalies from Syd- and Sydøstmalmen would have been more distinct if high frequence VLF resistivity measurements had been available and used to support and enhance A.M.T. interpretations.

   The resistivity contrast between known pyritic mineralizations and country rock is very high in the Skorovas field. Therefore the area is in general a good object for geophysical electric and electromagnetic investigations. The depth of penetration of some methods is estimated to be as follows.

| | | |
|---|---|---|
| Helicopter investigations | ca. | 50 m |
| VLF investigations | " | 100 m |
| Turam investigations | " | 300 m |
| AMT investigations | | 1000 m |

## 4.2 Results from geophysical explorations and evaluations of anomalies

We have already mentioned that the marginal ore deposits Syd- and Sydøstmalmen have been found as a result of geophysical investigations. Turam surveys played a central role in the investigations.

Also other concrete pyritic mineralization objects have been detected. With reference to table 2-5 and Fig. 2 the following mineralization occurrences have been picked up by helicopter measurements and turam investigations:
5,9,10,11,12,13,14,15,16,17,18 and 19.

Most of the distinct turamanomalies are further investigated. Rather weak turam anomalies are occuring west of the known ore structures, see Fig.5. By comparing the results with the geological maps by Hall et al. the following anomalies may be explained;

Anomaly A a fracture zone

" B a thin exhalite horizon

" C-D the border between andesitic and rhyodasitic rocks.

It is difficult to explain the anomalies E and F by the geological structures. We can see (See Fig. 2) that anomaly F also reveals IP anomalies. The anomaly is decreasing from about 5% to 2% towards the south.

The main ore shows rather distinct IP anomalies (7-9%), but also the nearest area west of the main ore represents an anomale area. The anomale areas is not considered to be well enough checked by drilling, and it is rather interesting as additional ore tonnage to the Main ore may be found.

As previously mentioned, the rock formation in which the Main ore is located may be folded down in a rather big isoclinal fold. A.M.T. investigations in this area are rather limited, but weak anomalies indicate a conductor 8-900 m below ground level.

## 5. GEOCHEMICAL INVESTIGATIONS

The investigated area is shown in Fig. 3. The analyses are based on stream sediments, and the investigations are of regional nature.

So far, the results have not been studied well enough to give a proper evaluation of the field results.

From the tables 2-5 listing the mineralization objects it follows that geochemical investigations played a central role in identifying Grønndalselva (object 1) and S.Lillefjelldoma (object 2). (See Fig. 2). We consider them to be following up Zn.objects.

## 6. PRELIMINARY PROPOSAL FOR FOLLOW-UP EXPLORATION WORK

### 6.1 High priority investigation objects

The most interesting geological structures and pyritic mineralization objects are located within the 22 km2 area 1 (See Fig. 7).

By checking the IP-anomalies just west of the main ore body it may be possible to locate additional ore that can extend the life of the mine in Skorovas. The IP anomalies indicate conductors below the footwall level of the mine. It is recommended about 7 more drillholes. The direction of the drillholes should be based upon a closer study of ore structures in the mine.

The zone between Syd- and Sydøstmalmen represents a rather uniform electrical conductor. This conductor has been thoroughly checked by drilling, but areas do exist both within the Marginal ores and in profile 1300 S where drilling has not been done. Sydmalmen and its openings toward Finnkjerringhullet is considered to be interesting as a potential Zn-ore.

Because of interesting geological environment and easy road access and infrastructure, it is reasonable to give priority to investigations of the andesitic and rhyodacitic structure running north and east of Store Skorovatn. The object Skorovaslia (Object 6, See Fig. 2) is situated in the eastern part of that structure. Because of existing power lines in the area geophysical investigations will be difficult. To limit noise from powerlines, a so called differential turam investigation method should be tried to select drilling targets.

The turam anomalies E and F are rather weak, but based on geophysical considerations they may indicate interesting Zn mineralizations. I.P.investigations on the anomalies should be considered prior to drilling.

## 6.2 Second priority investigation objects

A lower priority should be given to area 2-3 (32 km2) (See Fig. 7). Down-the-hole geophysics and A.M.T. investigations should be performed in guiding further drilling on the objects Drikkevatnet Syd and Grubtjønna. (Object 12 and 11).

The pyritic objects Nesåflya and Nesåfoten (objects 13 and 5) are not explored by ground geophysics or drilling. More detailed mapping and ground geophysical investigations should be done to get a basis for planning of drilling.

The object Langtjønna within area 3 has been the subject of some VLF investigations. More ground geophysics and detail mapping should be performed on that object.

A deep-exploration area is marked within area 1. As previously mentioned, A.M.T-investigations reveal rather deep located anomalies (800-1000 m) a lower priority should be given to further investigations.

The Western peripheral objects Grønndalselva and Lillefjelldoma (object 1 and 2) are regarded as interesting follow-up Zn-objects (See Fig. 2) Gaizern (object 20), is a follow-up Mo-object. As a first phase of exploration, however, we feel priority should be given to objects closer to the mining district.

## 6.3 A procedure for follow-up explorations

On the basis of already described pyritic mineralization objects an area of 54 km2 should be followed up. (See Fig.7).

The previously turam investigated area within the mining area is rather limited (10 km2) and it is considered worthwhile to cover most of the area once more by geophysics. A frequence turam investigation method should be tried.

Within area 1 the geographical relationship between follow-up objects are rather close and it is suggested that the total area is investigated systematically.

With respect to the low priority areas, a systematic investigation of all the areas is recommended before concentrating too much work on already detected follow-up objects.

In general the following procedure for further explorations is recommended,

1. Geological structure analysis, VLF resistivity investigations, at a profile spacing of 100 m.

2. Turam investigations (frequency turam). Space between profiles 200 m.

3. Regional A.M.T. investigations. Space between profiles 1 km.

4. Drilling and down-the-hole geohpysics.

Possible ore is supposed to be structurally controlled. More structural interpretation work is recommended by study of existing geological maps and by more field work. Structural analysis and VLF investigations are of importance to optimize "heavy" turam investigations. A.M.T. investigations are expected to be of value to get information on deep structures. It should also be used as follow-up exploration on specific anomalies and located objects. By the additional use of VLF resistivity data A.M.T. interpretations can be improved.

Rough estimates for costs are given in table 1.

## 7. CONCLUSION

Geological maps are the basis for explorations. The majority of explorations in the Skorovas district have been carried out before modern detailed geological maps were accessible.

As a result of depressed base metal prices in the last years, the profits in mining have been limited. In such a situation the Mining company had to prioritate rationalization in the mine instead of prospecting.

Today we have good, detailed geological maps giving indications of favourable ore structures. By using improved geophysical methods the vertical dimension can be explored more satisfactorily.

A mining district has a proven favourability for the occurrence of ore. Within the Grong field area the Skorovas district represents a favourable area for exploration for both zinc and copper ores.

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## 8. APPENDICES

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| R.Jensen | - | Price setting on prospecting work |
| A.Reinsbakken | - | Geology of the Skorovas Mine: A volcanogenic Massive Sulphide Deposit in the Central Norwegian Caledonides (NGU 360) |
| NGU<br>Terratest | - | Geophysical and geochemical reports. |

COST ESTIMATE FOR FURTHER EXPLORATION WORK

TABLE 1

| Area/Object | Structural mapping and analyses, interpret. | VLF resistivity | Frequency Turam | A.M.T. | Diamond Drilling | Follow-up geophysics, Down-the-hole geophysics | Administr. interpret. evaluations | Sum Costs |
|---|---|---|---|---|---|---|---|---|
| High priority | 6 mths. | 230 km - 3,8 mths | 115 km-2mths. | 23 km-<br>1,5 mths | 8000 m | . | 2 years | |
| Area 1,22 km2 | 120.000 | 115.000 | 210.000 | 230.000 | 4 mill. | 300.000 | 900.000 | |
| West of Main Ore IP-anom. | | | | | 1000 m<br>500.000 | 40.000 | | |
| Syd-and Syd-østmalmen | | | | | 1500 m<br>750.000 | 40.000 | | |
| | 120.000 | 115.000 | 210.000 | 230.000 | 5,25 mill | 380.000 | 960.000 | 7,2 mill.<br>~ 2 years |
| Low priority. | | | | | | | | |
| Area 2-3,32 km2 | 1 year<br>240.000 | 330 km<br>165.000 | 165 km<br>300.000 | 34 km<br>340.000 | 10.000 m<br>5 mill. | 300.000 | 2 years<br>960.000 | |
| "Deep Ore Exploration" | 1 mth.<br>20.000 | | | 18 km-<br>1 mth.<br>180.000 | 20.000 m<br>800.000 | 100.000 | | |
| | 260.000 | 165.000 | 300.000 | 340.000 | 5,8 mill. | 40.000 | 960.000 | 8,2 mill.<br>~2 years |

TABLE OF PROSPECTING OBJECTS

TABLE 2

| Object nr. | | TYPE OF MINERALIZATION | STRIKELENGTH/ THICKNESS | GEOLOGICAL ENVIRONMENT | GEOPHYSICAL AND GEOCHEMICAL ANOMOLIES | DIAMOND DRILLING | REMARKS |
|---|---|---|---|---|---|---|---|
| Grønndalselva | 1 | Massive pyritic and diseminated Zn mineralization | 20m/1-2m | Basic extrusives | Zn-anomali | - | Spalerite (light in outcrops. Should be followed up as a Zn object. |
| S.Lillefjelldoma | 2 | -"- | 200m/thin | Basic extrusives with thin acid horizons | Zn-anomali | - | Reason for Zn-anomaly not found. Should be followed as a Zn-object. |
| Grønndalsvatnet | 3 | Massive and diseminated pyritic | ?/up to 0,3m | Andesitic and dioritic intrusions | Cb-anomali Magnetic -"- | - | Not a follow-up object |
| Finnkrudoma | 4 | -"- | | Rhyoducitic and andesitic rocks | Weak Cu- and Zn-anomali Weak EM anomalies. | - | -"- |
| Nesåfoten | 5 | Pyritic and magnetite | 30m/1-2m | Rhyodacitic pyroclastic rocks and andesitic rocks. Strong isoclinal folding | Helicopter anomali | - | Geological environment is interesting. Should be followed up by detail geological mapping and turam investigations. |
| Skorovaslia | 6 | Massive pyritic mineralizations | ?/Up to 1m thick | Rhyodacitic and andesitic rocks | Zn-anomali | 10076 (Negative) | Geological environment is interesting extending west around Store Skorovatn. The zone should be followed up. |
| The Main Ore | 7 | 10 mill.tons pyritic ore | 700m/Up to 30m | Rhyodacitic pyroclastic rocks and andesites. Strong isoclinal folding | Distinct geophysical anomalies | | The mine is almost depleted. |

TABLE OF PROSPECTING OBJECTS

TABLE 3

| Object nr. | TYPE OF MINERALIZATION | STRIKELENGTH/ THICKNESS | GEOLOGICAL ENVIRONMENT | GEOPHYSICAL AND GEOCHEMICAL ANOMOLIES | DIAMOND DRILLING | REMARKS |
|---|---|---|---|---|---|---|
| Syd-and Sydøstmalmen 8 | Sydøstmalmen/Cu 430.000t 1,4%Cu, 0,2%Zn<br>Sydmalmen 550 000t 0,9%Cu, 1,5%Zn | 200m/5m<br>200m/5m | Rhyodacitic pyroclastic rocks and andesites. Strong isoclinal folding | Distinc turam-anomalies | | Marginal deposits. Geological environments and deformation structures are similar to the main ore. Deposits are partly open and more drilling is recommended. |
| Finnkjerring-hullet 9 | Pyritic mineralizations | 200m/1-2m | Similar to Syd and Sydøstmalmen | Turam anomaly | 10053 | It is possible that the mineralisations represent a continuation of Sydmalmen. The object should be followed up by charged potential and possible more drilling |
| NØ Drikke-vatnet 10 | Pyrite and chalcopyrite | 200m/0,5m | Rhyodasitic rocks and basic extrusives | Helicopter anomaly<br>Turam "<br>VLF "<br>Weak geochemical anomalies for Cu and Zn | 1044, 1043, 1030,10029, 1056,10072 | The mineralizations which represent thin Cu rich zones are relatively well followed up. |
| Gurbtjønna 11 | Pyrite, magnetite and sphalerite | 50-100m/ thin | Andesitic to basaltic rocks. Strong deformation | Helicopter anomaly<br>Turam anomaly | 10074, 1037, 10038,10039, 10040,10041, 10042 | Grades of base metals are interesting, but CP and drilling show limited tonnage of mineralizations. Deep ore exploration should be considered. |

TABLE OF PROSPECTING OBJECTS

TABLE 4

| Object nr. | TYPE OF MINERAL-IZATION | STRIKELENGTH/ THICKNESS | GEOLOGICAL ENVIRONMENT | GEOPHYSICAL AND GEOCHEMICAL ANOMOLIES | DIAMOND DRILLING | REMARKS |
|---|---|---|---|---|---|---|
| Drikke-vatnet Syd 12 | Pyrite and magnetite | 1500m/ variable | Andesitic and rhyodasitic rocks. Pyroclastic. Strong isoclinal folding. | Helicopter anomaly<br>Turam "<br>VLF " | 1057, 1058, 1059, 1660, 4 old drill holes | The mineralizations may represent a continuation of Sydmalmen and Finnkjerringhullet. *Deep ore exploration is recommended.* |
| Nesåflya 13 | Pyrite and magnetite | 750m/ variable | Andesitic rocks | Helicopter anomaly<br>VLF "<br>Distinct geochemical Pb-anomaly | - | Accompanying exhalites can be traced up to object 12. *Deep ore exploration is recommended.* |
| Stamnes-tjønna 14 | Pyritic mineralizations | 1500m/0,3m | Calcareous lavaes and acid extruxives | Helicopter anomalies | - | Associated with peripheral exhalites. Not a too promising follow-up object. |
| N.Lang-tarmen 15 | " | 1000m/ variable | Basic extrusives and acid instrusives. Strong deformations. | - | - | The object should be considered followed up by sampling and VLF investigations. |
| N.Krongle-fjell 16 | " | 300m/ variable | | Helicopter anomaly<br>VLF " | - | Associated with a peripheral exhalite horizon. Not an interesting follow up object. |

TABLE OF PROSPECTING OBJECTS

TABLE 5

| Object nr. | | TYPE OF MINERAL-IZATION | STRIKELENGTH/ THICKNESS | GEOLOGICAL ENVIRONMENT | GEOPHYSICAL AND GEOCHEMICAL ANOMOLIES | DIAMOND DRILLING | REMARKS |
|---|---|---|---|---|---|---|---|
| S.Lang-Tjønn | 17 | Pyritic minerlizations | 1100m/300m | Quartz porphyry and pyroclastic pillow lavaes. | Helicopter anomaly Zn and Pb anomaly | - | To some degree the geological environ-ments are similar to enrivonments of known ore. The object should be followed up by turam investigations |
| Blåham-maren | 18 | Pyrite, hematite and magnetite | 500m/300m | Thin tuff horizons and calcareous lavaes. | Helicopter anomaly Zn and Pb anomaly | - | Associated with peripheral exhalite horizon. Not an interesting follow-up object. |
| Havdals-vatnet | 19 | Pyrite and magnetite | 1-2km/thin | " | Helicopter anomaly | | " " |
| Gaizern | 20 | Disseminations of molybdenite pyrite and chalcopyrite | 1500m (based on VLF inves-tigations)/ 400m | Basic volcanics and tuffs with intrusions of diovite | VLF anomaly | - | The object was detected by geol-ogical mapping. Mineralizations are lacking detailed investigations. It is considered to be an interesting follow-up Mo. object. |

## 8. APPENDICES

| Appendix | Table/Fig. |
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| Map over located mineralization objects. | Fig. 2 |
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| Preliminary proposal to follow-up exploration | Fig. 7 |


Fig.1
MAP OF IDENTIFIED ORES
AND DRILLHOLES.

ELKEM SPIGERVERKET A/S
SKOROVAS GRUBER
GRUBEFJELLET
M.1:5000 Ekv.2m


Fig.2
MAP OF LOCATED MINERALIZATIONS OBJECTS.

Elkem a/s
Engineering Division
Oslo, Norway


Fig. 3 MAP SHOWING GEOCHEMICAL INVESTIGATED AREAS.

Elkem a/s
Engineering Division
Oslo, Norway


Fig.4
MAP SHOWING LOCATION OF
GEOPHYSICAL INVESTIGATED AREAS.

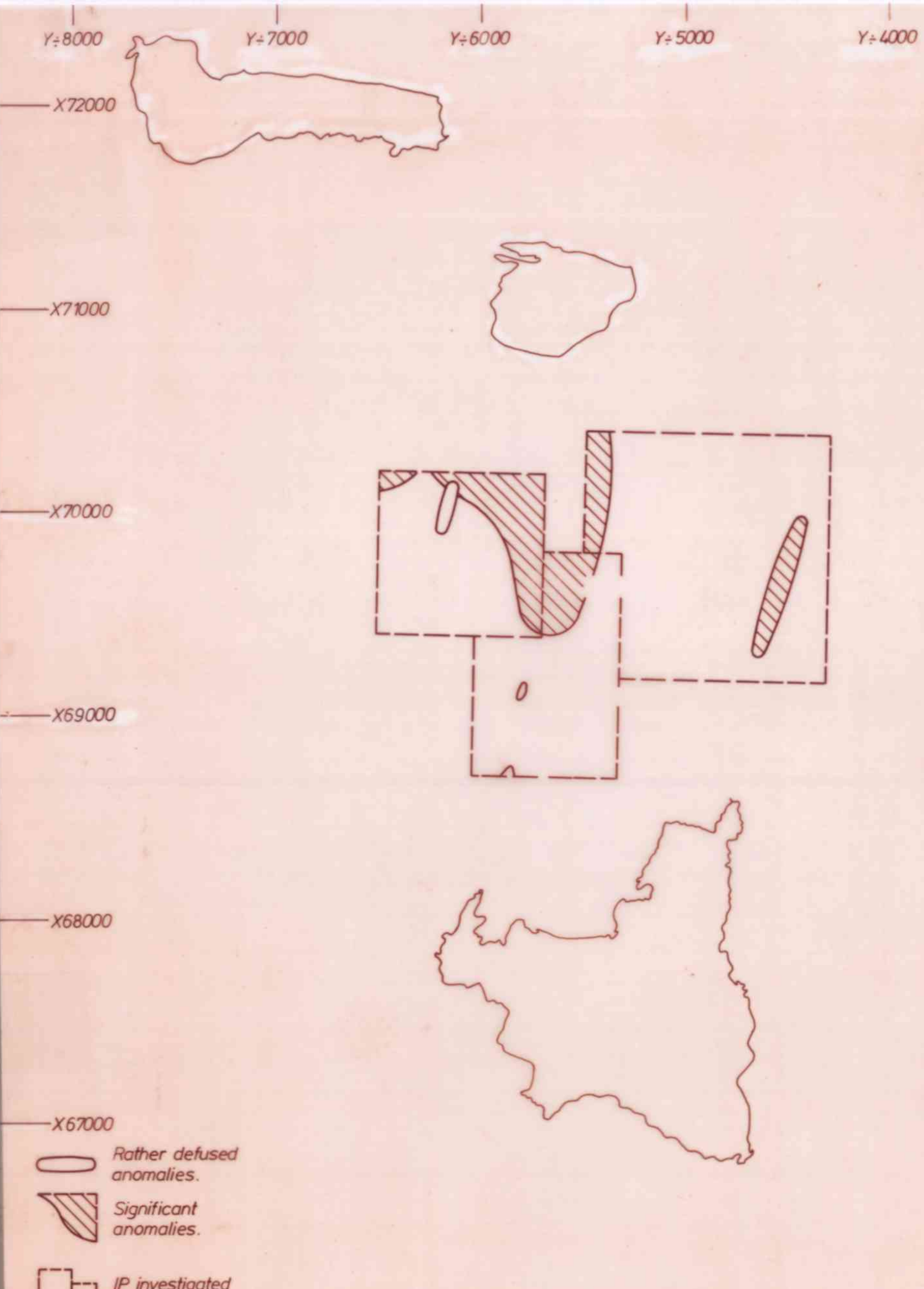


Fig.5

IP ANOMALIES IN
THE MINING AREA OF SKOROVAS.

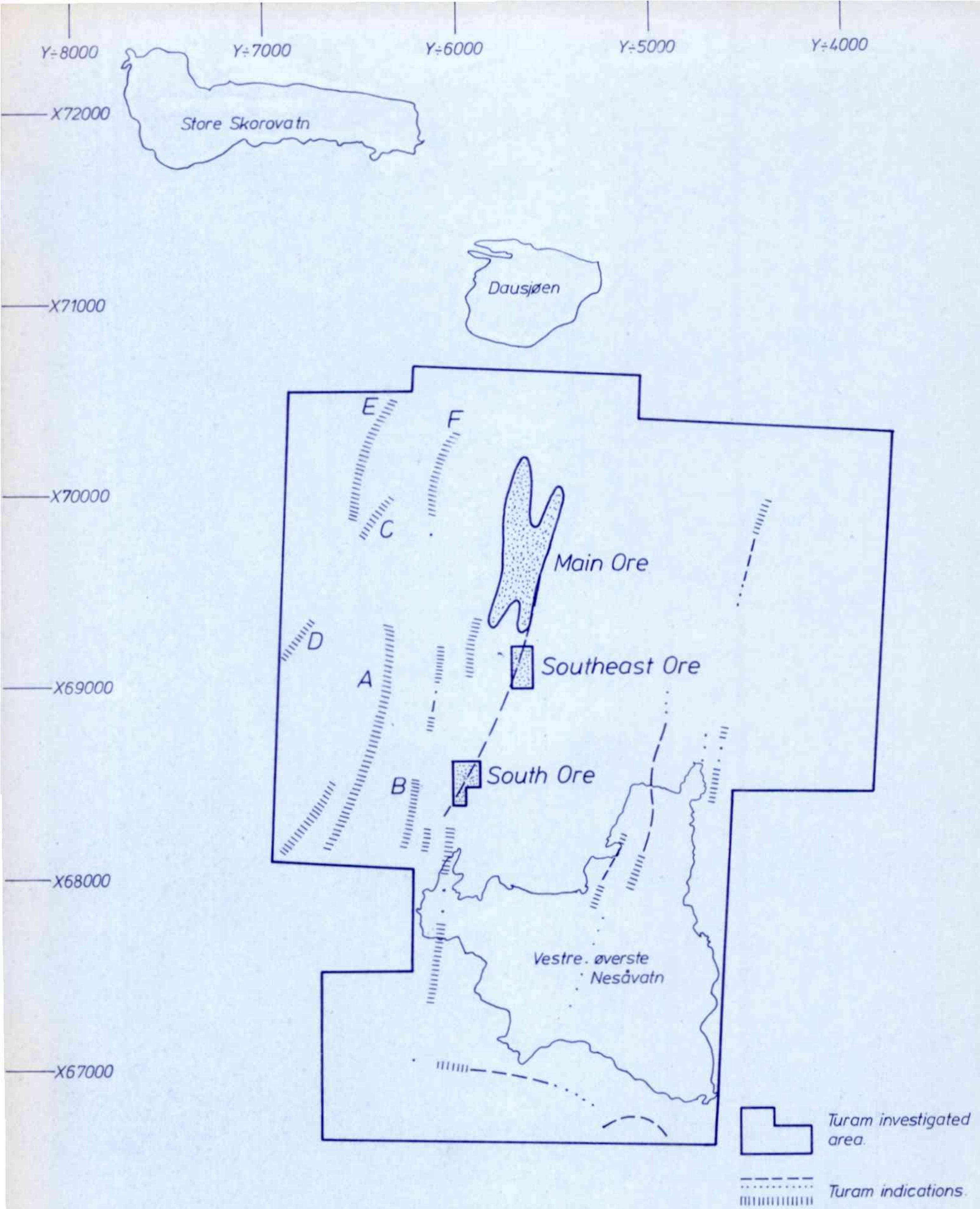


Fig.5
TURAMANOMALIES IN
THE MINING AREA OF SKOROVAS.

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Engineering Division
Oslo, Norway


Fig. 6
LOCATIONS OF CLAIMS IN
THE SKOROVAS DISTRICT.

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Engineering Division
Oslo, Norway

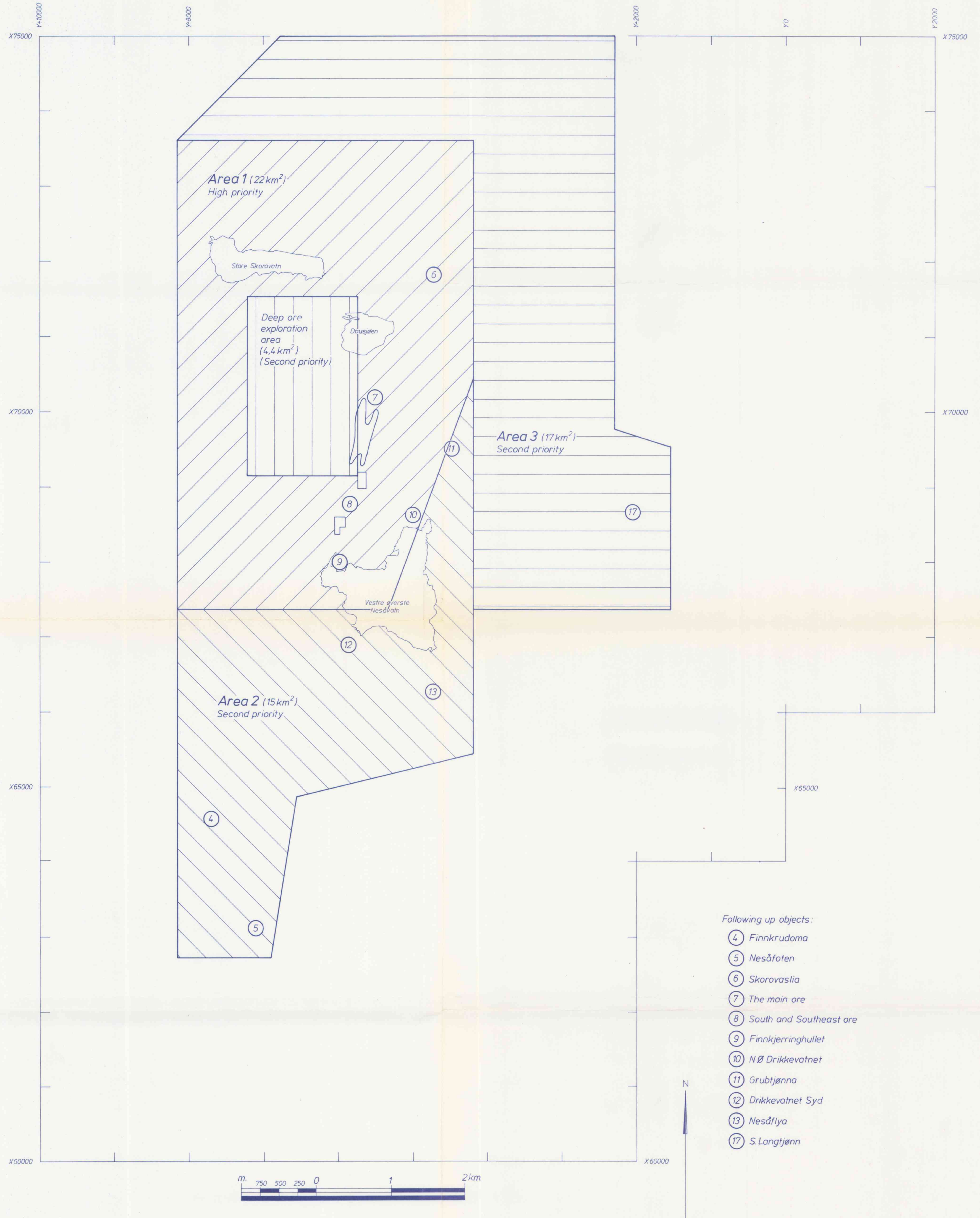


Fig. 7
PROPOSALS TO FOLLOWING UP EXPLORATIONS.

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Oslo, Norway