SVERIGES GEOLOGISKA UNDERSÖKNING

SER. Ca AVHANDLINGAR OCH UPPSATSER I A4 NR 60

MICHAEL B. STEPHENS (Ed.)

STRATABOUND SULPHIDE DEPOSITS IN THE CENTRAL SCANDINAVIAN CALEDONIDES

7th IAGOD SYMPOSIUM
AND NORDKALOTT PROJECT MEETING

EXCURSION GUIDE NO 2

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With contributions by Tor Grenne, Omari Mwinyihamisi, Arne Reinsbakken, Michael B. Stephens, Krister Sundblad, Mats Y. Willdén and Ebbe Zachrisson

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Falu copper mine has been continuously mined for more than 900 years. Copper plate engraving from 1687 in Dahlberg's *Svecia Antiqua et Hodierna.*

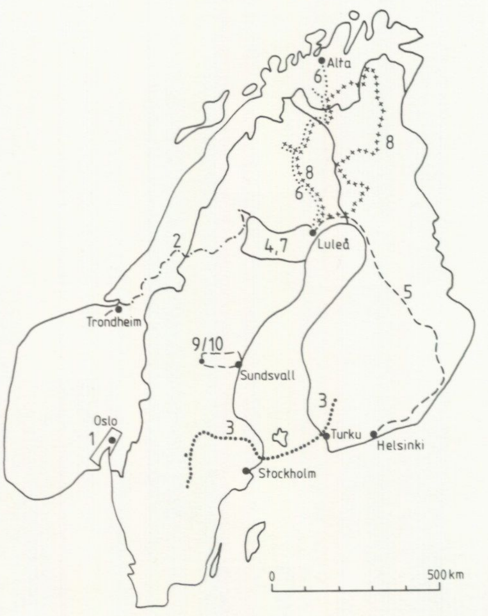
FOREWORD

Mining has ancient traditions in Scandinavia and Finland. In Bergslagen, Sweden, numerous mines produced Cu, Fe and Ag already during the medieval period. Some of them, e.g. Falun and Dannemora, are still active and are thus among the oldest operating mines in the world. Minerals like scheelite, gahnite and långbanite were first recognized in this region and the word skarn (originally having a pejorative connotation in Swedish meaning crap and whore) was used as a name for a certain mineral association for the first time by the old miners in Bergslagen. The most famous mining districts in Norway are Kongsberg, where silver was produced 1623–1957, and Røros, where copper was mined from 1644 until recently. The first mine in Finland was the Ojamo iron ore deposit, which was opened in 1540.

In addition to these ancient workings, ore bodies in several new mining districts have been exploited during the last century. Some of the most important of these occur in northern Sweden such as the Kiruna iron ores, the sulphide ores in the Skellefte district, the Laisvall Pb-mine and the Aitik Cu-Au mine. The sulphide ores in the Outokumpu district and in the Vihanti-Pyhäsalmi area are the most well-known Finnish deposits discovered during this century. In Norway, numerous deposits of pyrite and base metals were discovered round the turn of the century in the Sulitjelma and Grong districts and have been of major importance for the Norwegian mining industry. The discovery of extensive Mo-mineralization in the Oslo area, Norway and Pt-mineralization in the Kemi area, Finland have not led to any significant mining but have revealed new aspects of the metallogeny in the Nordic countries.

As a result of this long tradition in mining, the question of how ores are formed has been debated longer than any other geological problem in Scandinavia and Finland. It is therefore of special interest for the Nordic countries that the International Association on the Genesis of Ore Deposits (IAGOD) this year will arrange its 7th symposium in Scandinavia. The symposium, which is held in Luleå, Sweden, is arranged by the Geological Surveys of Sweden, Finland and Norway and the Luleå University of Technology. As an important part of the symposium programme, nine pre- and post-symposium excursions covering most of the important mining districts in Norway, Sweden and Finland are arranged (see overleaf). For these excursions, guide books have been written and are now available amongst the publications of the Geological Survey of Sweden (SGU Ca 59–67). The Swedish part of excursion no 6 was prepared in 1980 and was published by the Geological Survey of Finland. To all who have been involved in planning and organizing the excursions as well as writing the guide books I would like to express my sincere thanks.

Krister Sundblad, Geological Survey of Sweden
coordinator of the IAGOD-excursions 1986



1. Metallogeny associated with the Oslo Paleorift
Guide book: SGU Ca 59.
Excursion leader: S. Olerud.
Topic: Porphyry molybdenum mineralizations (Nordli, Hurdal and Bordvika, Drammen). Native silver-bearing veins at Kongsberg. Mineralizations associated with the Drammen granite; contact metasomatic Zn-Pb deposits (Konnerudkollen), intramagmatic Mo deposits.

2. Stratabound sulphide mineralizations in the central Scandinavian Caledonides
Guide book: SGU Ca 60.
Excursion leaders: M.B. Stephens and A. Reinsbakken.
Topic: Early Palaeozoic, massive Cu-Zn sulphide mineralizations in both volcanic (Gjersvik, Joma, Løkken and Stekenjokk) and sedimentary (Ankarvattnet) environments. The Laisvall sandstone-hosted, disseminated Pb-Zn deposit.

3. Mineral deposits of southwestern Finland and the Bergslagen province, Sweden
Guide book: SGU Ca 61.
Excursion leaders: H. Papunen and I. Lundström.
Topic: Proterozoic Zn-Cu-Pb deposits in volcanosedimentary environments including the mined-out Orijärvi and Aijala deposits in Finland, and the Garpenberg and Åmmeberg deposits in Sweden; the iron ore deposit of Dannemora in Sweden. Deposits associated with intrusive rocks include the Vammala Ni-Cu mine in Finland and the Wigström W deposit in Sweden.

4. Massive sulphide deposits in the Skellefte district
Guide book: SGU Ca 62.
Excursion leader: D. Rickard.
Topic: Proterozoic Cu-Zn-(Pb-As-Au) mineralizations in volcanosedimentary environments, including the Boliden, Långsele, Näsliden and Kristineberg deposits.

5. Proterozoic mineral deposits in central Finland
Guide book: SGU Ca 63.
Excursion leader: G. Gaál.
Topic: Early Proterozoic mineralizations including the Kemi Cr mine, PGE mineralization in the Penikat layered intrusion, Pyhäsalmi Cu-Zn deposit, Outukumpu Cu-Co-Zn mine and the Enonkoski Ni-Cu deposit.

6. Precambrian mineral deposits in northernmost Scandinavia
Guide books: SGU Ca 64 (Norwegian part)
Geol. Surv. Finland (1980), Guide 078 A+C, part 1 (Swedish part)
Excursion leaders: J.S. Sandstad and H. Lindroos.
Topic: Precambrian copper and iron ore deposits including visits to two of the largest mines in northern Europe: Kiirunavaara underground mine (Fe) and Aitik open pit operation (Cu, Au). In addition, the Raipas, Repparfjord, Bidjovagge and Viscaria Cu deposits and Au prospects in the Gällivare area will be shown.

7. Proterozoic mineralizations associated with granitoids
Guide book: SGU Ca 65.
Excursion leader: B. Öhlander.
Topic: Mineralizations associated with Proterozoic granitoid intrusions including the Pleutajokk, Rävaberget and Björklund U deposits, the Allebouda and Kåtaberget Mo deposits, the Storuman W mineralization and Tallberget Cu-Mo deposit.

8. Archaean and Proterozoic geology in northern Finland, Norway and Sweden
Guide book: SGU Ca 66
Excursion leaders: T. Sjöstrand, M. Often and V. Perttunen.
Topic: Archaean and Proterozoic geological environments in the ore-bearing Nordkalott area, including greenstone belts and granulites.

9/10. Enåsen Au deposit and Alnö alkaline complex
Guide book: SGU Ca 67.
Excursion leaders: T. Lundqvist, S. Sundberg and P. Kresten.
Topic: Geology at and around the Proterozoic Enåsen Au deposit and the Alnö alkaline complex.

STRATABOUND SULPHIDE DEPOSITS IN THE CENTRAL SCANDINAVIAN CALEDONIDES

CONTENTS

METALLOGENY OF STRATABOUND SULPHIDE DEPOSITS IN THE CENTRAL SCANDINAVIAN CALEDONIDES

M. B. Stephens

GENERAL TECTONIC SETTING AND CLASSIFICATION OF STRATABOUND SULPHIDE DEPOSITS

Thrust-emplaced terranes dominate the structure of the central Scandinavian Caledonides (Stephens & Gee 1985, and Fig. 1). Platformal and miogeoclinal components of the Baltoscandian margin to the late Proterozoic-Silurian continent Baltica (Ziegler 1982) occur within the autochthonous cover sediments and the thrust sheets represented in the Lower and Middle Allochthons. These allochthonous units comprise transported slabs of Proterozoic crystalline basement and Upper Proterozoic to Silurian sedimentary cover rocks. The overlying Seve Nappes (Upper Allochthon) are thought to have been derived from the rifted edge of Baltica and represent a continent-ocean transition zone. The passive continental margin to Baltica extended during the Cambrian at least 500 km west of the present thrust front, i.e. far west of the present Norwegian coastline. The higher thrust sheets, occurring in the Köli Nappes (Upper Allochthon) and Uppermost Allochthon, are far-transported slices of volcanic, intrusive and sedimentary rocks of ocean-floor, rifted arc, outer-arc basin, and back-arc marginal basin infill association, as well as ensialic fragments with abundant Lower Palaeozoic intrusions. Although several models assume Baltoscandian affinities for even these terranes (see, for example, Roberts *et al.* 1985), there is sufficient evidence for an early history unrelated to Baltica (Stephens & Gee

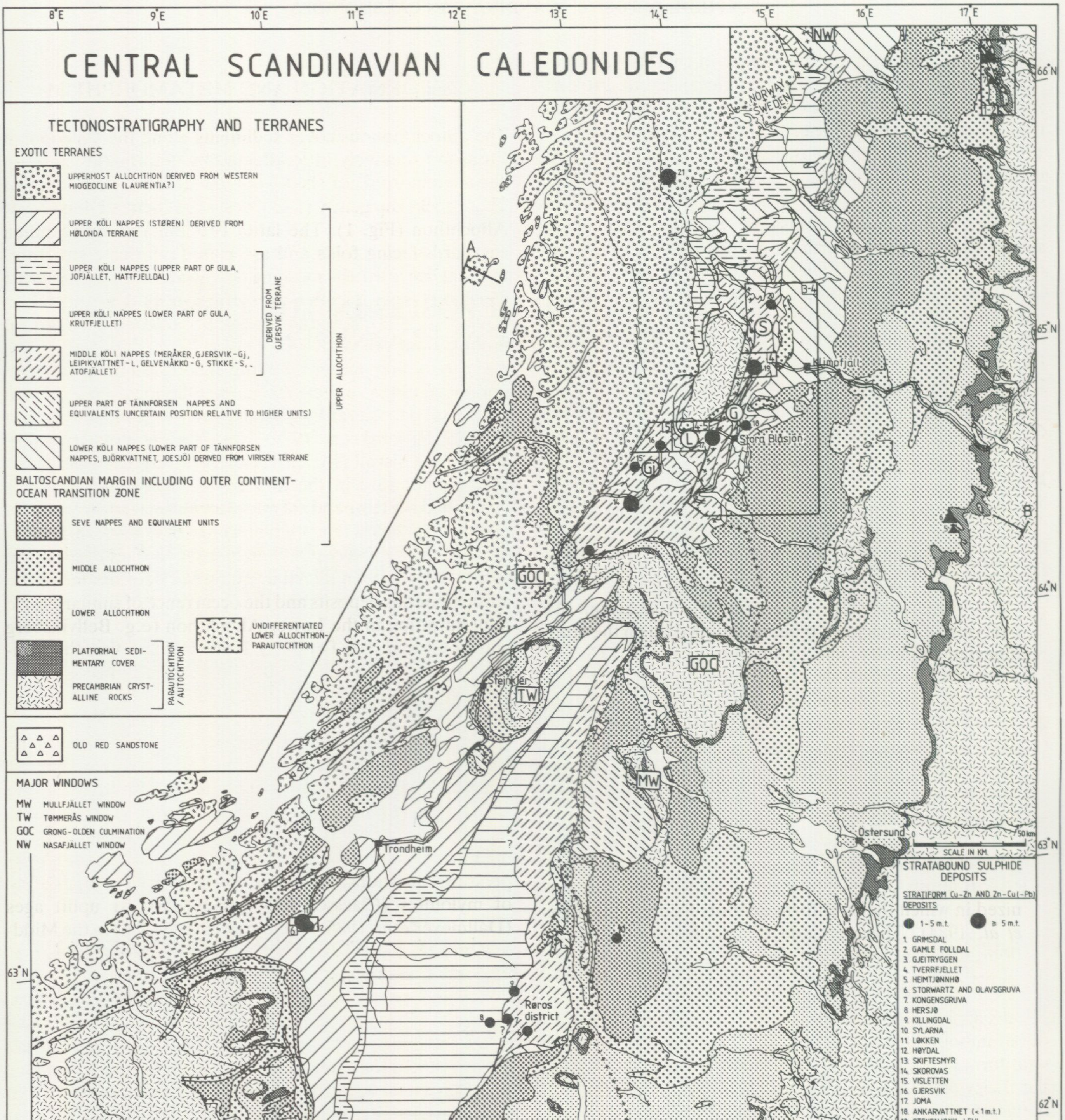


Fig. 1. Tectonostratigraphic, terrane and stratabound sulphide distribution map of the central Scandinavian Caledonides (base geology after Stephens & Gee 1985, W.K. Dallmann, pers. comm., 1985).

1985). These terranes are thus exotic in character.

Following opening of the Iapetus Ocean in late Proterozoic to Cambrian time (c. 600 Ma) and spreading during the Cambrian, plate convergence occurred over a period of c. 130 Ma from late Cambrian to Silurian-Devonian time. Convergence involved B-subduction, early continent-arc collisions, marginal basin opening, and ultimately continent-continent collision. The collisional episodes involved A-subduction, complex deformation, and locally development of zones of high-pressure metamorphism. In northernmost Scandinavia, early (Cambrian and early Ordovician) deformational pulses are referred to as the Finnmarkian orogenic episode (Sturt *et al.* 1978) while the ubiquitous Silurian-Devonian deformation, involving final elimination of Iapetus, is referred to as Scandian (Gee 1975).

Stratabound sulphide deposits in the Scandinavian Caledonides are of two distinctive types occurring at different levels in the tectonostratigraphy (Zachrisson 1980, Bjørlykke *et al.* 1980 and Fig. 1):

1. Non-stratiform, disseminated Pb-Zn deposits hosted by platformal Upper Proterozoic to Cambrian sandstones (quartz arenites). These occur in the autochthonous sedimentary cover to the Proterozoic basement and in transported correlatives in the Lower Allochthon. An overview of this deposit type, including data on the Scandinavian examples, and its relation to red-bed Cu and carbonate-hosted Pb-Zn deposits has been presented by Bjørlykke and Sangster (1981).
2. Stratiform, polymetallic, massive to disseminated sulphide deposits hosted by Upper Proterozoic (?) and Lower Palaeozoic volcano-sedimentary rocks. Although smaller deposits are known from the Seve Nappes, the more important deposits occur in the far-transported exotic terranes of the Köli Nappes and Uppermost Allochthon. Based on the nature of the host rocks, several different palaeotectonic settings have been recognized in which the stratiform deposits formed (Stephens *et al.* 1984). These include ensialic intra-plate, ocean floor, rifted arc, and post-arc marginal basin environments.

It is the aim of this excursion to study examples of both types of stratabound sulphide deposits. As far as the non-stratiform group is concerned, attention will be focused on the Laisvall Pb-Zn deposit. In the stratiform group, a metasediment-hosted deposit formed in a post-arc marginal basin infill environment (Ankarvattnet) and several metavolcanite-hosted deposits will be examined. The latter were deposited either in a rifted arc setting (Stekenjokk and Gjersvik) or along (Løkken and Høydal) and possibly off (Joma) one or more oceanic ridge axes. In all examples, close attention will be focused on the unmineralized host-rocks to the sulphide deposits prior to a detailed underground and/or surface study of the individual deposits. Emphasis will also be placed on the host-rock alteration associated with the stratiform deposits and the use made of the sulphide deposits for a closer understanding of the general geology.

DEFORMATION AND METAMORPHISM

The autochthonous cover sediments along the Caledonian Front are relatively little affected by deformation and are non-metamorphic or show very low grade metamorphism. These rocks dip gently (1–2°) westwards beneath the Lower Allochthon (Fig. 1). The latter is dominated by Scandian eastwards-facing folds and associated imbricate structure, internal listric thrusts merging downwards into a sole thrust which serves as a décollement surface above the Autochthon (Gee *et al.* 1978); low grade metamorphic conditions prevail in the Lower Allochthon.

Open folding, minor thrusting and occasional high-angle normal faulting affect the autochthonous Pb-Zn non-stratiform deposits at Vassbo and Laisvall (Christofferson *et al.* 1979, Rickard *et al.* 1979). Nevertheless, illite crystallinity data at Laisvall (Rickard *et al.* 1979) suggest a metamorphic temperature in the mineralized sandstones which is lower than the temperature of ore formation (approximately 150° C, see below); a metamorphic overprint related to thrusting down to a depth of no more than 20 m beneath the sole thrust has been inferred. The weak deformation in the autochthonous deposits and the occurrence of similar Pb-Zn mineralization in the Lower Allochthon (e.g. Bellviksberg and Lövstrand, see Du Rietz 1960) indicate that this non-stratiform sulphide mineralization occurred prior to Scandian deformation and metamorphism.

Markedly increased complexity and intensity of both deformation and metamorphic grade are conspicuous in the higher allochthons which thin down and mostly wedge out westwards (Fig. 1). This is especially conspicuous in the transported continent-ocean transition zone represented in the Seve Nappes which show polyphase deformation and medium- to high-grade metamorphism, locally under high-pressure conditions. Thin-slab, whole-rock Rb-Sr age dating of mylonites (Claesson 1980) and ^{40}Ar-^{39}Ar uplift ages (Dallmeyer *et al.* 1985, Dallmeyer & Gee 1986) in the Middle Allochthon and Seve Nappes, respectively, demonstrate an early Caledonian (Finnmarkian equivalent?) deformational and metamorphic history with a late Caledonian (Scandian) overprint. At higher tectonostratigraphic levels (Gula and Krutfjellet Nappes of the Upper Köli, and Uppermost Allochthon, see Fig. 1), complex deformation-metamorphism-intrusion relationships and whole-rock age dating results also indicate a pre-Scandian, in part Ordovician, deformational and medium- to high-grade metamorphic history, overprinted by Scandian events (note reviews by Gee *et al.* 1985 and Stephens *et al.* 1985a). However, polyphase deformation and metamorphism in most of the exotic terranes represented in the Köli Nappes are related solely to Scandian movements (Stephens *et al.* 1985a).

Four phases of ductile deformation and low-grade metamorphism dominate the Middle Köli Nappes (Fig. 1) which are of particular interest on this excursion. The stratiform sulphide deposits are affected by all these phases of deformation and metamorphism recognized in the host rocks, thus supporting the interpretation that they represent

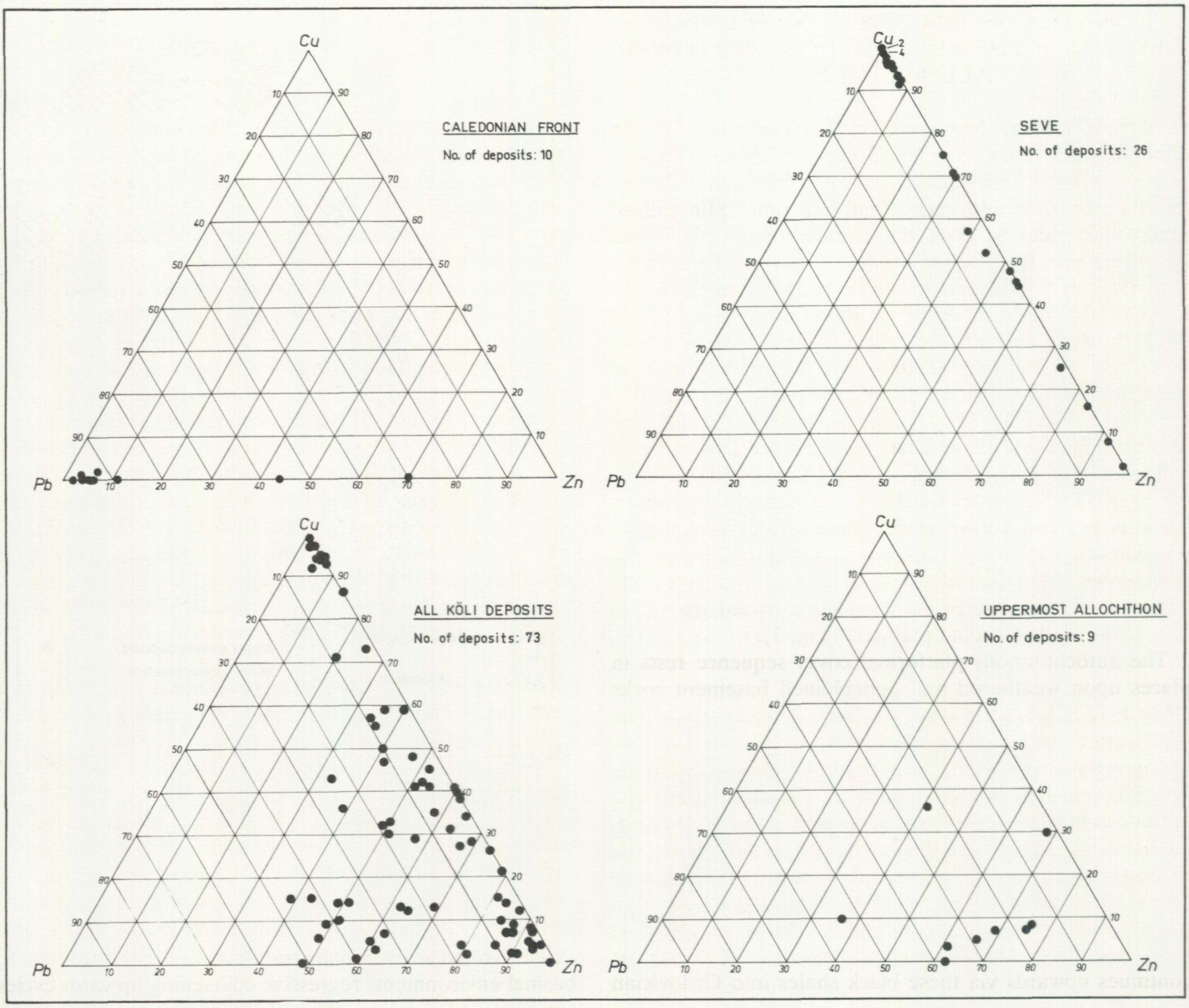


Fig. 2. Base metal proportions (weight %) of Caledonian Front (Autochthon and Lower Allochthon), Seve (Upper Allochthon), Köli (Upper Allochthon), and Uppermost Allochthon stratabound sulphide deposits (after Zachrisson 1977 and complementary data from Bjørlykke *et al.* 1980 for the Uppermost Allochthon).

chemical sediments within the volcano-sedimentary sequence. The D_1 and D_2 phases account for much of the strain and are pre- or syn-thrusting at this tectonostratigraphic level. The regional foliation is subparallel to bedding and the overall structural style is flat-lying (Fig. 1) with a significant progressive simple shear strain component (Roberts & Gee 1985). Studies of metal zoning and distribution of alteration zones within stratiform sulphide deposits have established the dominance of inverted stratigraphies in the various thrust sheets within the Middle Köli Nappes. The thrusts at this tectonostratigraphic level appear to be slides which have cut out the right way up limbs of megascopic, eastward-facing, overturned folds formed during the Scandian collisional tectonic regime (note especially Stekenjokk deposit on Day 4). The peak of metamorphism was established prior to thrusting. Application of sphalerite geobarometry (pyrite-encapsulated sphalerite grains) and arsenopyrite geothermometry on stratiform sulphide deposits in the Middle Köli indicate peak metamorphic pressures in the range 3–5 kb (Hutchison & Scott 1980, Sundblad *et al.* 1984) and metamorphic temperatures of c. 370° C and c. 420° C in chlorite- and biotite-zone deposits, respectively (Sundblad *et al.* 1984).

The D_3 and D_4 phases formed after establishment of the tectonostratigraphic pile at the Köli tectonostratigraphic level. The D_3 structures account for the megascopic, often upright antiforms and synforms which dominate the outcrop pattern (Fig. 1). Although often related to late-stage gravity disturbance following thrust nappe emplacement (e.g. Williams & Zwart 1977), an alternative hypothesis relates these structures to the folded roofs of duplexes of varying thickness which developed during the propagation of thrusting at lower tectonostratigraphic levels (for model see Elliott & Johnson 1980).

NON-STRATIFORM DISSEMINATED Pb-Zn DEPOSITS IN THE AUTOCHTHON AND LOWER ALLOCHTHON

Geological setting. Non-stratiform, disseminated Pb-Zn mineralization (Fig. 2) is hosted by quartz arenitic sandstones which represent a marine transgression during latest Proterozoic and early Cambrian time. Mineralized sandstones occur in both the autochthonous platformal cover sequence lying on top of the peneplained Fennoscandian (Baltic) Shield and in allochthonous equivalents in immediately overlying thrust nappes (Lower Allochthon). All of the major and most of the minor deposits occur where these tectonostratigraphic units are situated along the Caledonian Front, a strike distance of approximately 2000 km (Figs. 1 and 3). Major deposits include Laisvall and Vassbo in the autochthonous sequence, of which the former will be studied on this excursion, and Lövstrand and Bellviksberg (Dorotea district) in the Lower Allochthon. Minor deposits are also known at the same tectonostratigraphic position and in the same transgressive sandstones westwards in windows within the Caledonides and notably over 500 km east of the Caledonian Front along the eastwards continuation of the Baltoscandian platform (Fig. 3).

The autochthonous platformal cover sequence rests in places upon weathered and peneplained basement rocks (Høy 1977, Christofferson *et al.* 1979, Willdén 1980). The basal conglomerate, arkose and feldspathic sandstone, locally interpreted to be of glacial origin (Willdén 1980), pass upwards into a few tens of metres (maximum) of quartz arenitic sandstone, siltstone, shale and phosphorite conglomerate. Disseminated Pb-Zn mineralization is hosted by the sandstone. The sequence is either capped by Middle and Upper Cambrian black alum shales, with conspicuously high contents of organic matter and various trace elements including U, V, Mo and Ni (Andersson *et al.* 1985), or continues upwards via these black shales into Ordovician limestones (Fig. 4). Various sedimentological studies have demonstrated an essentially transgressive shallow marine to basinal environment, regressive coarsening upwards cycles

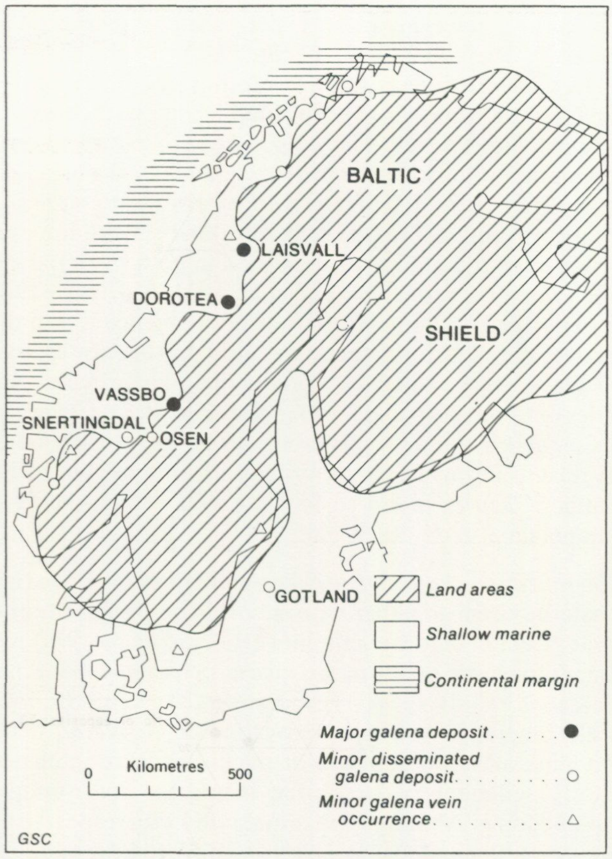


Fig. 3. Schematic picture showing the position of non-stratiform, sandstone-hosted Pb-Zn deposits in relation to major palaeogeographic features during latest Proterozoic and early Cambrian time (after Bjørlykke & Sangster 1981).

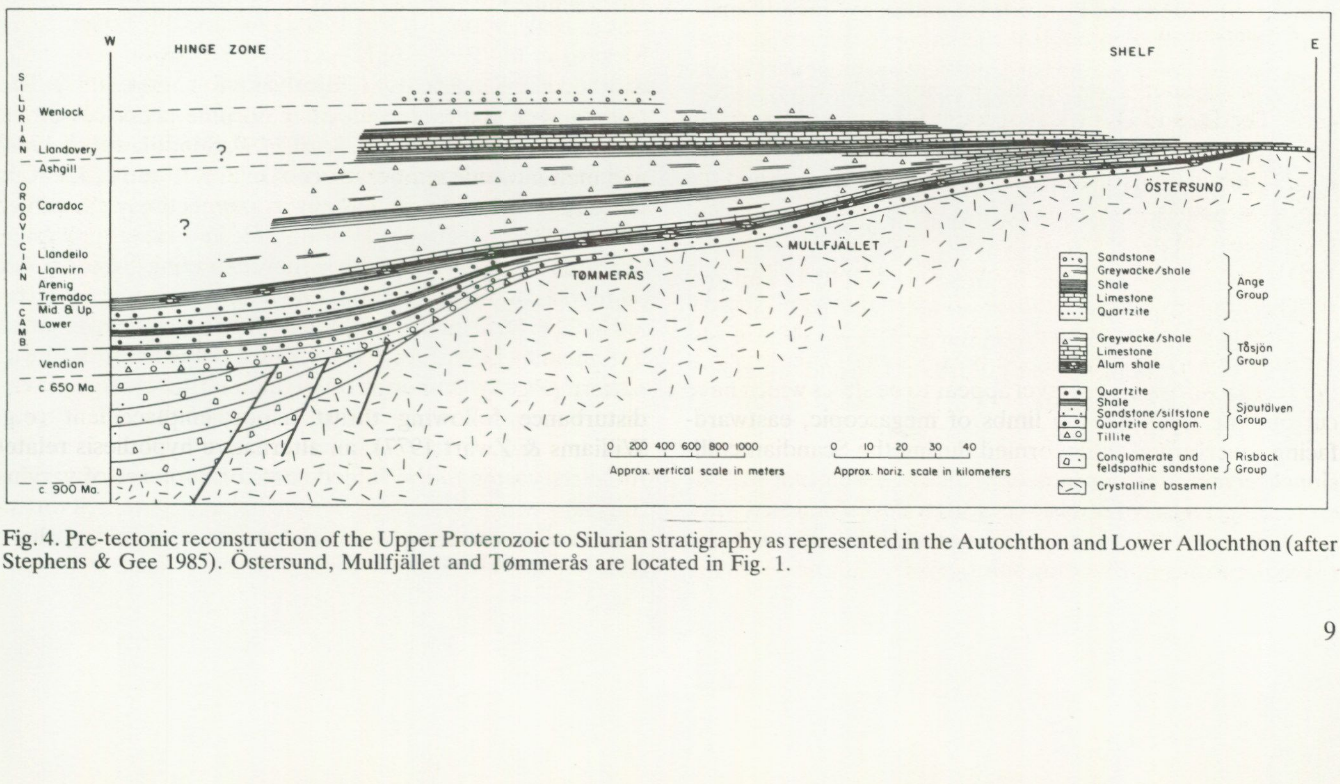


Fig. 4. Pre-tectonic reconstruction of the Upper Proterozoic to Silurian stratigraphy as represented in the Autochthon and Lower Allochthon (after Stephens & Gee 1985). Östersund, Mullfjället and Tømmerås are located in Fig. 1.

dominating, however, the pre-alum shale sequence (Willdén 1980, Thelander 1982, Wallin 1982).

The allochthonous correlatives to this platformal succession (Gee 1975 and Fig. 4) deposited further to the west are conspicuously thicker. The Upper Proterozoic and Lower Cambrian sandstone-dominated and locally Pb-Zn-mineralized part of the sequence passes stratigraphically downwards into tillite and dolomite, and several hundred metres of clastic sediments deposited in both subaerial and submarine environments (Gee *et al.* 1974, Bjørlykke 1978, Nystuen 1982). The upper part of the sequence is also distinctive, the sandstone-dominated unit passing upwards via the black alum shales into predominantly turbidites and shales of Ordovician and Silurian age (Fig. 4). Deposition of this sequence either strictly along, or in one or more failed rift-related intracratonic basins close to the margin of the continent Baltica is envisaged (Gee 1975, Bjørlykke 1978, Kumpulainen & Nystuen 1985).

Mineralization characteristics. Disseminations of galena and sphalerite occur together with subordinate pyrite, fluorite, barite, calcite, chlorite and illite (Rickard *et al.* 1979) as a cement to clastic grains in the quartz-rich sandstone. Silver content is relatively low (generally ≤20 gm/metric ton), locally ranging up to 56 gm/metric ton (Stephens *et al.* 1979). The mineralization occurs as distinctive spots or intimately follows sedimentary structures including, for example, cross-bedding. Although it is stratabound with respect to the sandstone-dominated unit, sharp and discordant mineralization contacts on both mesoscopic and megascopic scales (see, for example, Grip 1973, Rickard *et al.* 1979) demonstrate its non-stratiform character and a timing of mineralization after sandstone deposition. As argued earlier, deformational relationships indicate that the mineralization was also pre-thrusting. Various controls of mineralization related to basement topography have been suggested. At Laisvall, coarser grained, more porous sandstones close to basement highs (Barkey 1964, Carlson 1970) and, at Vassbo, thicker sandstones deposited in basement depressions along intensely eroded Proterozoic diabases (Christofferson *et al.* 1979) appear to control the siting of mineralization. Lead isotope compositions are markedly radiogenic (Wickman *et al.* 1964, summary of modern data in Johansson and Rickard 1983 and Fig. 5) and sulphur isotope compositions at Laisvall for sulphur in sulphides and sulphate are distinct from each other (Richard *et al.* 1979). Illite crystallinity, the presence of hydrocarbons, and fluid inclusion data from sphalerite in the Laisvall deposit suggest that the temperature of ore deposition was approximately 150° C and the metal-bearing fluid was a concentrated Na-Ca-Cl oil-field brine (Rickard *et al.* 1975, Lindblom & Rickard 1978, Rickard *et al.* 1979, Lindblom 1986). Further data and discussion of the detailed studies carried out at the Laisvall deposit are presented later in the Day 1–2 description.

Genetical considerations – state of the art. Two general models for the genesis of sandstone-hosted Pb-Zn deposits were summarized by Bjørlykke and Sangster (1981) based on the nature of the metal-bearing solution:

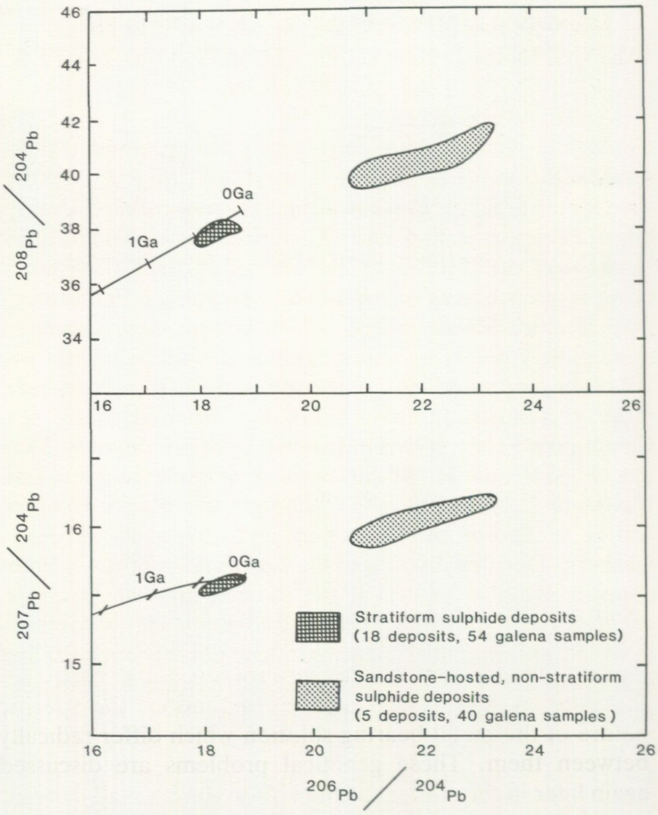


Fig. 5. Pb isotope compositional fields for sandstone-hosted, non-stratiform sulphide deposits along the Caledonian Front and stratiform sulphide deposits within the Swedish Caledonides. The primary growth curve of Stacey & Kramers (1975) has been drawn on both diagrams. Data from Johansson & Rickard (1984) for the non-stratiform, and Sundblad & Stephens (1983) for the stratiform deposits.

1. A hydrothermal or basin-brine model.
2. A ground water or meteoric model.

The Scandinavian deposits have been discussed in the context of both model 1 (Grip 1960, 1967 and 1973, Gee 1972, Rickard *et al.* 1979, 1981) and model 2 (Bjørlykke 1977, Bjørlykke & Sangster 1981, Bjørlykke & Thorpe 1982). The essential features of the model 1 variants, as discussed by Grip (1960, 1967) and Rickard *et al.* (1979), are basinal sediment dewatering, transport of material through porous sandstone to the basin margin in connection with either compaction or tectonic deformation, and metal precipitation probably by mixing with sulphide-bearing ground water (Bjørlykke & Sangster 1981). The alternative model, preferred by Bjørlykke and Sangster (1981) and described in detail by Samama (1969, 1976), involves prolonged weathering of a basement area and/or its overlying detritus, metal enrichment during percolation of ground water through a broad pediment, and metal precipitation in a coastal environment with a sufficiently high H_2S content to precipitate sulphides (Fig. 6).

Several features, including the mixing of different fluids (sulphur isotope compositions), the importance of a base-

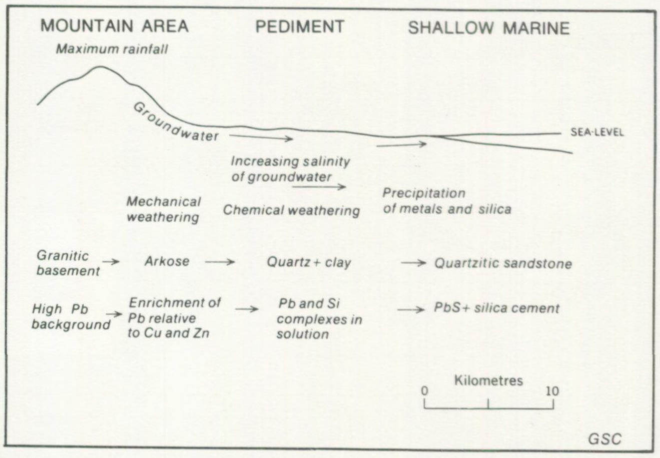


Fig. 6. Schematic representation of the main features of the groundwater transport model for non-stratiform Pb-Zn deposits (after Bjørlykke & Sangster 1981).

ment and/or overlying detritus source (lead isotope compositions), and sandstone porosity, are compatible in both models. It is the timing of mineralization, the dynamics of the solution flow system and, by definition, the specific nature of the metal-bearing solution which differ radically between them. These genetical problems are discussed again later in the context of the visit to the Laisvall deposit. It is particularly the fluid inclusion data and the inferred timing of mineralization which led Rickard *et al.* (1979) to favour the basin-brine model for Laisvall and, following Grip (1960, 1967), to invoke easterly metal-bearing fluid migration related to deformation of the outer basin. Nevertheless, the importance of release of Pb and Zn during deep weathering of basement rocks and subsequent groundwater transport towards the westerly marine environment was emphasized by Grip (1973) as a *precursor* to the easterly fluid migration and final precipitation of the Pb and Zn in ore deposit concentrations.

STRATIFORM SEDIMENTARY-EXHALATIVE DEPOSITS IN THE UPPER AND UPPERMOST ALLOCHTHONS

Although, for a considerable time, a centre of controversy (see, for example, review in Vokes 1976), the type of mineralization represented by the stratiform sulphide deposits in the higher nappes of the Scandinavian Caledonides is now generally accepted to represent a chemical sediment deposited from hydrothermal metal-bearing solutions on and immediately beneath the palaeo-seafloor (see, for example, Carstens 1955, Oftedahl 1958a, Stanton 1959). Individual deposit studies of the Scandinavian deposits, emphasizing critical genetic aspects including predeformational base metal sulphide deposition, metal zoning, predominantly unilateral host-rock alteration etc., support application of this genetic model to these deposits. Reference below to particular deposits is focused on those to be visited during this excursion (Ankarvattnet, Stekenjokk, Joma, Gjersvik, Løkken and Høydal), relevant literature for which is concentrated in the day descriptions of the individual deposits.

Cu-Zn deposits in the Seve Nappes, Upper Allochthon

Quartzo-feldspathic and mica schists, gneisses, subordinate marbles, and prolific quantities of rift-related (Solyom *et al.* 1979, Hill 1980) metabasites and solitary ultramafites comprise the Seve Nappes. These rocks predominantly show medium- to high-grade metamorphism and locally mineral assemblages related to high-pressure metamorphism (van Roermund & Bakker 1983, Stephens & van Roermund 1984, Nicholson 1984, Andréasson *et al.* 1985). Although Middle Proterozoic protoliths have been identified in some of the higher grade rocks (Reymer *et al.* 1980, Claesson 1982), the schists and metabasites have been compared with Upper Proterozoic lower grade lithologies in the Middle Allochthon (Gee 1975, Solyom *et al.* 1979). On this basis, they are inferred to be late Proterozoic in age and to have formed the continent-ocean transition zone at the western edge of the continent Baltica (Gee 1975).

Stratiform, predominantly disseminated sulphide deposits occur within both metabasites and metasediments. The mineralogy is dominated by either pyrite or pyrrhotite with chalcopyrite, sphalerite and magnetite as well as occasional bornite (Zachrisson 1980). Although the host rocks contain a conspicuous quartzo-feldspathic metasedimentary component, the mineralization is Cu-Zn with extremely low Pb contents (Zachrisson 1977 and Fig. 2). All occurrences of these poorly understood deposits are small, the largest occurrence being Sylarna (3.8 million metric tons of 0.72 % Cu) south of the Grong-Olden Culmination (Fig. 1). None of these deposits will be visited on this excursion.

Massive sulphide deposits in the Köli Nappes, Upper Allochthon

Geological setting – sulphide-bearing terranes and their accretionary history. Stratiform massive sulphide deposits occur in three separate outboard terranes within the Köli Nappes of the Upper Allochthon, referred to as the Virisen, Gjersvik and Hølonda terranes (Stephens & Gee 1985 and Fig. 1). These terranes are located in distinctive groups of thrust nappes referred to as the Lower Köli, the Middle and Upper Köli, and the Støren Nappe in the Upper Köli, respectively (Gale & Roberts 1974, Stephens 1980a, and Fig. 1). Stratigraphic sequences and Ti-Zr-Y-Cr-Si discriminant diagrams for metavolcanites and high-level intrusions in the Gjersvik and Hølonda terranes, which host all the major sulphide deposits (Fig. 1), are shown in Figs. 7 to 9. Igneous activity related to an active rifting component is a common feature in *all* the massive sulphide-bearing sequ-

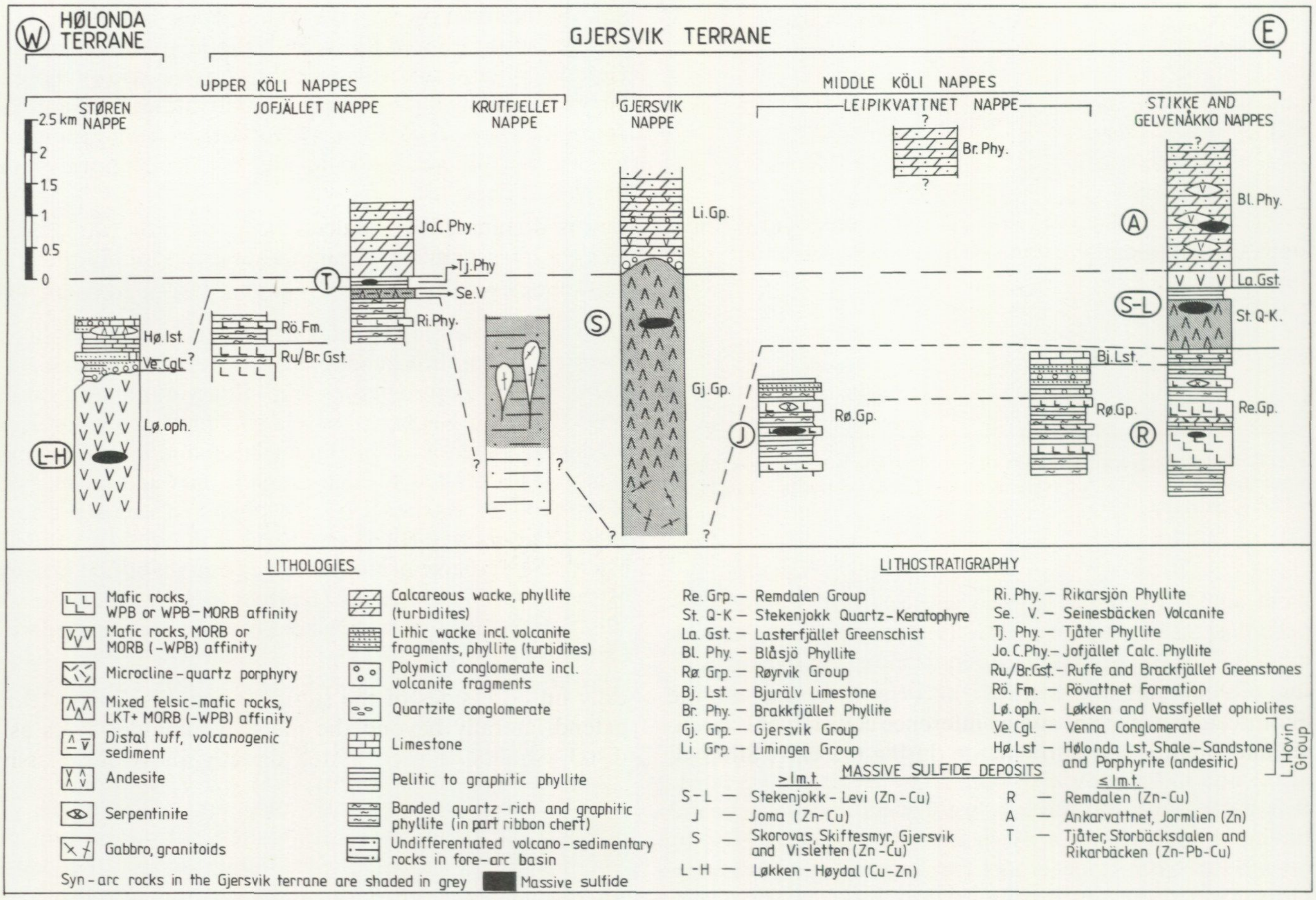


Fig. 7. Summary of stratigraphic relationships and massive sulphide deposits in the Gjersvik and Hølonda terranes, Köli Nappes (after Stephens *et al.*, 1984).

ences. This component is considered to be of extreme importance for both the spatial distribution and timing of mineralization, the latter being related to a major thermal input (Stephens 1980b, 1982a).

Both the Virisen and eastern part (Middle Köli Nappes) of the Gjersvik terrane contain early Ordovician (Claesson *et al.* 1983, in prep.) bimodal metavolcanic and high-level intrusive rocks related to rifted arc development (Stephens 1977a, 1982b, Stephens *et al.* 1985b, and Figs. 7 to 9). The widespread occurrence of solitary as well as detrital ultramafites in the Virisen terrane and the contrasting character of Ordovician turbidite sequences overlying the rifted arc complexes in both terranes (Fig. 7) distinguish them from each other (Stephens & Gee 1985). The western part of the Gjersvik terrane (Upper Köli Nappes excluding Støren Nappe) includes metavolcanites and volcaniclastic metasediments of probable outer-arc basin affinity (Stephens & Senior 1981). Tentative stratigraphic correlation of successions in these Middle and Upper Köli Nappes (Fig. 7) suggests that the Gjersvik terrane represents a single disrupted early Ordovician rifted arc complex with subduction polarity to the east (Stephens & Gee 1985).

The Hølonda terrane, in the structurally highest part of the Köli nappe sequence, is characterized by a variety of thrust sheets containing ophiolites (Furnes *et al.* 1980, 1985, Grenne *et al.* 1980), at least in part of pre-late Arenig age (Figs. 7 and 9). They are overlain by volcaniclastic conglomerates, volcaniclastic and calcareous turbidites, black shale, limestone, and andesitic to rhyolitic volcanites (Fig. 7). The post-ophiolite sequence is Arenig to Caradoc and possibly even Ashgill in age, and the Arenig-Llanvirn faunas show an unequivocal North American platformal affinity (see summary of data in Bruton and Bockelie 1980). This sequence is thought to have been deposited in a marginal basin environment which lay east of an Arenig-Llanvirn calc-alkaline mature arc (Roberts 1980, Grenne & Roberts 1980), the faunal evidence suggesting that this arc-basin couple developed along the Laurentian margin (Bruton & Bockelie 1980, Stephens & Gee 1985). Considerable discussion prevails whether the ophiolites in the Hølonda terrane represent a pre-late Arenig obducted relic of the Iapetus ocean floor, the oceanic basement to the Ordovician marginal basin, or both of these possibilities (see, for example, Sturt *et al.* 1984 and discussion in Stephens & Gee 1985).

The nature of the Ordovician clastic sequences in the Gjersvik and Hølonda terranes suggests proximity of these terranes by the mid Ordovician (Stephens & Gee 1985). However, an early obduction hypothesis for at least some of the ophiolites in the Hølonda terrane (Furnes *et al.* 1980) and isotopic age dating of trondhjemites in the Upper Köli (Klingspor & Gee 1981) allow amalgamation of these terranes both to each other and the Laurentian margin by the early Ordovician (Stephens & Gee 1985). Such an accretionary history suggests that the Arenig and younger units in the Hølonda terrane were deposited in an inter-arc basin between an active calc-alkaline arc to the west and a remnant rifted arc in the Gjersvik terrane to the east (Stephens *et al.* 1985b). Thus, the close association of both the Gjersvik and Hølonda terranes to the Laurentian margin during the early and mid Ordovician is inferred.

The post-arc turbidites in the Virisen terrane regress upwards into quartzite conglomerate, quartzite and Ashgill limestone (Fig. 7). This shallow marine sequence deepens upwards into Llandovery black shales and a younger coarsening-upwards turbidite succession. The Silurian part of this sequence is conspicuous not only in the Virisen but also locally in the Gjersvik terrane, and along the Baltoscandian margin as represented in the Lower Allochthon (Fig. 4). Thus, evidence for amalgamation of the outboard Gjersvik and Hølonda terranes both to the Virisen terrane and the Baltoscandian margin, and by inference collision of Laurentia and Baltica, starts to emerge during the early Silurian.

Mineralization characteristics and associated chemical sediments. Although several minor stratiform sulphide deposits occur in the rifted arc metavolcanites of the Virisen terrane and the presumed outer-arc basinal sequence in the Gjersvik terrane, major deposits are restricted to the pre-, syn- and post-rifted arc complex of the Gjersvik terrane (Middle Köli Nappes) and the ophiolites of the Hølonda terrane (Støren Nappe, Upper Köli). Most of these deposits are hosted by metavolcanic rocks although some occur along metavolcanite-metasediment contacts (e.g. Stekenjokk-Levi) and a significant group occurs within the post-arc clastic metasediments (e.g. deposits in the Røros district, Ankarvattnet). Deposits in the Gjersvik terrane display a predominant Cu-, Zn- or Cu-Zn-rich character and a higher Pb content relative to the stratiform deposits in the Seve Nappes (Zachrisson 1977 and Fig. 2). Au and Ag contents are generally quite low (0.1–0.3 and 5–50 gm/metric ton, respectively), although higher values (1–2 and 100–400 gm/metric ton, respectively) together with high As contents are known in some minor deposits (Stephens *et al.* 1979). The deposits in the Hølonda terrane are of Cu-Zn type with negligible Pb content but with Au and Ag values similar to those recorded in the Gjersvik terrane deposits (Bjørlykke *et al.* 1980). Most of the deposits in both terranes are small, the tonnage distribution being totally dominated by a limited number of large ($\geqslant$5 million metric tons) deposits (Fig. 1).

The review papers by Bjørlykke *et al.* (1980) and Zachrisson (1980) summarize the principal features of the deposits. Both massive and disseminated ore types are prevalent. The main iron sulphide, both in massive and disseminated types, is either pyrite or pyrrhotite. Some deposits (e.g. Løkken, Skorovas) are virtually devoid of pyrrhotite while, in others (e.g. Stekenjokk-Levi, Joma, Ankarvattnet), pyrrhotite occurs together with chalcopyrite in a massive breccia ore type ("durchbewegt") separated from, but in direct contact with, the massive pyrite ore; the latter occurs predominantly with sphalerite. Magnetite occurs in minor amounts in several deposits. The base metal mineralogy is dominated by chalcopyrite, sphalerite and galena while a large number of minor and accessory ore minerals (e.g. in Stekenjokk about 20, see Juve 1974) are present. Deposit shapes are either extremely elongate (e.g. Løkken, Stekenjokk-Levi) or more or less plate-shaped and equidimensional (e.g. Joma, Ankarvattnet).

In mafic-dominated metavolcanites hosting massive sulphide deposits in both the Gjersvik and Hølonda terranes (e.g. Gjersvik Group and Løkken ophiolite, see Fig. 7), extensive horizons of chemical sediments other than the base metal sulphides, including layered iron-rich rocks and jasper, are prominent. The former comprise alternating layers rich in pyrite and/or pyrrhotite, magnetite, iron-rich silicate and subordinate carbonate minerals, and quartz, and are referred to as "vasskis" (Carstens 1955, Sand 1986). Although these chemical sediments may occur stratigraphically on both sides of the sulphide deposits, some clearly extend laterally beyond the massive sulphide layers as a distal exhalite or precipitated directly above the massive sulphides (Grenne *et al.* 1980, Reinsbakken 1980). A close genetic link between these chemical sediments and the basal sulphide deposits is suggested.

Host-rock alteration. Following the pioneering work of Gjelsvik (1968) at the Skorovas deposit, several studies of massive sulphide deposits, hosted by both metavolcanites and metasediments, have demonstrated an intense local (ten to a maximum of a few hundred metres from the massive sulphide layer) alteration of the host rock in association with a sulphide dissemination. These zones are generally interpreted as sub-seafloor feeder zones to the sedimentary-exhalative mineralization. This alteration is often concentrated on one side of the massive sulphide layer, inferred to be the stratigraphic footwall, but in some instances extends into the other side of the sulphide mineralization (e.g. Ankarvattnet, Løkken); some massive sulphides are actually enclosed within the altered host rocks (e.g. Killingdal, see Rui 1973).

Significant variations in host-rock alteration between different deposits are apparent. For example, whereas a conspicuous quartz-chlorite-white mica alteration is prevalent in the Stekenjokk-Levi mineralization hosted by felsic-dominated metavolcanites (Zachrisson 1982a, 1984), a more albitic alteration occurs within several of the deposits hosted by mafic-dominated metavolcanites including Skorovas, Løkken and Joma (Reinsbakken 1980 and this volume, Grenne 1981 and this volume). Furthermore, a clear zoning is apparent within individual deposits. For example, at Løkken, a chlorite-albite alteration lies peripheral to a chlorite-quartz alteration, both types increasing in white mica content towards the massive sulphide layer (Grenne, this

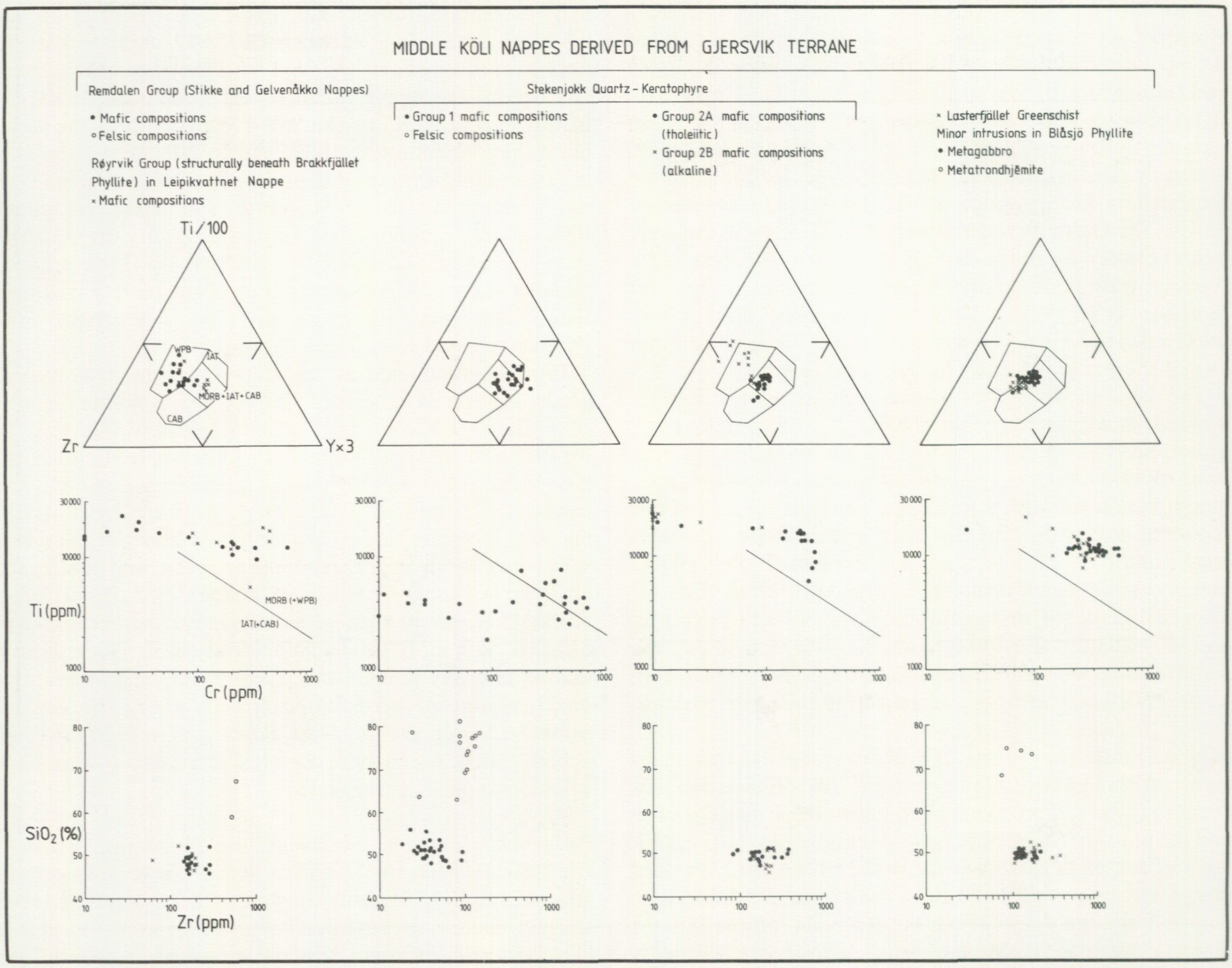


Fig. 8. Chemical variation diagrams (analyses on volatile-free basis) for metavolcanites and high-level intrusions in the Middle Köli Stikke, Gelvenåkko and Leipikvattnet (lower part) Nappes derived from the Gjersvik terrane. Data sources are Stephens (1982b and unpublished data) and Stephens *et al.* (1985b). MORB = Mid-ocean ridge basalt, IAT = Island arc tholeiite, CAB = Calc-alkaline basalt, WPB = Within-plate basalt (after Pearce & Cann 1973, Pearce 1975).

volume). In the metasediment-hosted Ankarvattnet deposit, a conspicuous dolomitic alteration is peripheral to the chlorite-white mica-quartz alteration, white mica again increasing towards the massive sulphide layer (Sundblad 1981a). These local alteration zones are generally concordant with the massive sulphide mineralization. However, they extend laterally at one side beyond the massive mineralization in a conspicuous overlapping geometry. At the Ankarvattnet deposit, this geometry has been explained in terms of deformation of the theoretical high-angle relationship between discordant feeder zone and stratiform exhalative layer, a critical simple shear component forming part of the total finite strain (Sundblad 1980). Several studies have compared the geochemistries of these feeder zone alteration rocks and the host rocks, thus permitting apparent chemical changes to be defined. Only a limited number of studies have attempted to take into account volume-change corrections and thus assess more accurately actual chemical additions and subtractions during alteration. More detailed discussions of the chemical changes in connection with this local alteration can be found below in connection with the individual deposit excursion descriptions. At Stekenjokk-Levi, for example, marked addition of K, Mg and base metals, and depletion of Na and Ca are apparent (Zachrisson 1982a).

It is considered vital from a prospecting point of view to distinguish this *local alteration* from the *regional alteration* (Stephens 1982a) which is prevalent in at least the metavolcanic host rocks in both the Gjersvik and Hølonda terranes. This regional alteration is inferred to be pre-deformational and is associated with the development of Na-enriched spilites (mafic rocks) and quartz keratophyres (felsic rocks). In the case of the Stekenjokk metavolcanites in the Gjersvik terrane (Fig. 7), depletion of several elements from the volcanic pile, including in particular total Fe, Mg, Ca, K, Cu and Zn, is also apparent during the spilitization process

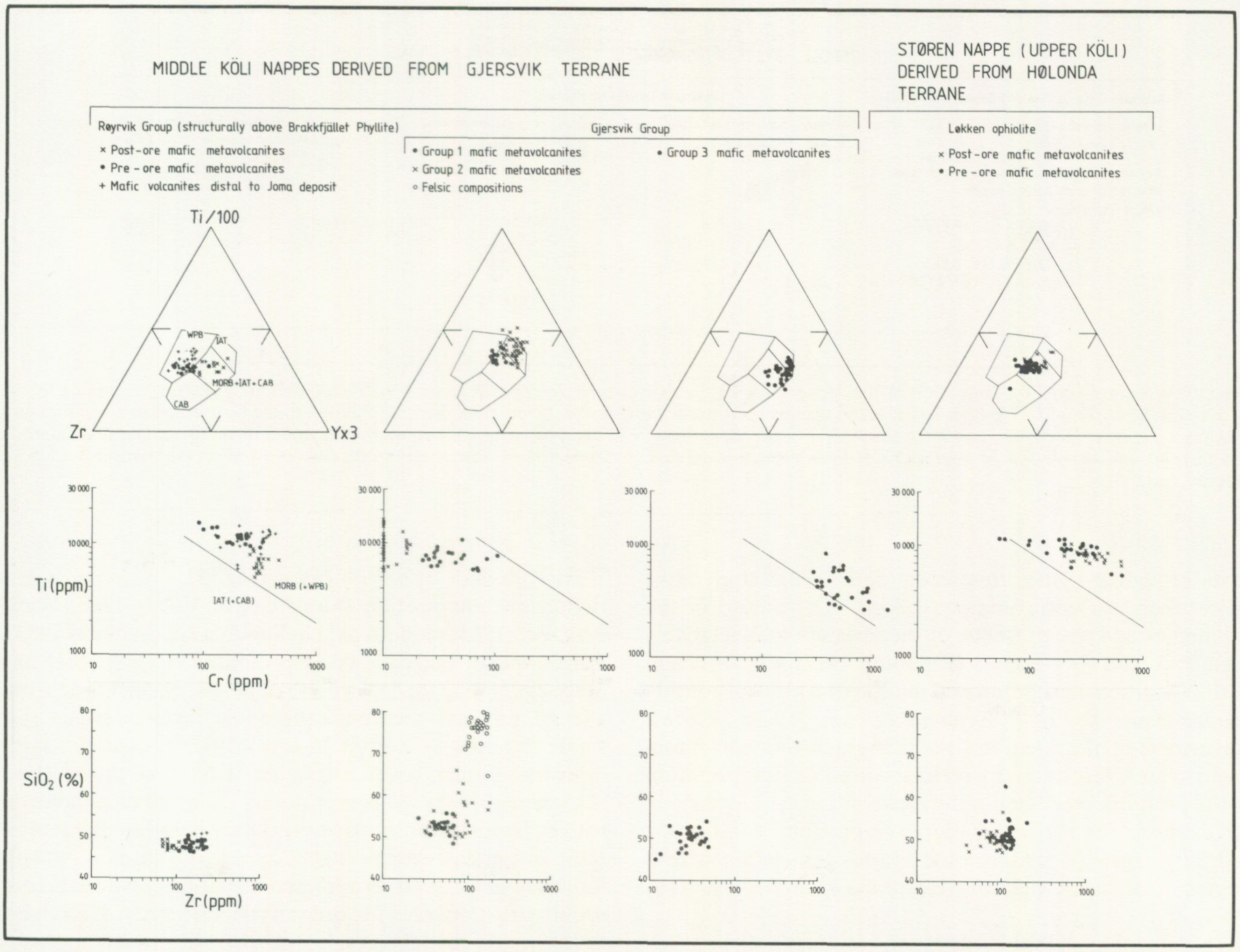


Fig. 9. Chemical variation diagrams (analyses recalculated to 100 % without L.O.I.) for metavolcanites and high-level intrusions in the Middle Köli Leipikvattnet (upper part) and Gjersvik Nappes derived from the Gjersvik terrane, and the Løkken ophiolite in the Upper Köli Støren Nappe derived from the Hølonda terrane. Data sources are A. Reinsbakken (pers. comm., 1986), Grenne *et al.* (1980) and T. Grenne (pers. comm., 1986). Discriminant fields as in Fig. 8.

(Stephens 1980b). A genetic link between the regional scale spilitization process, and the local alteration and exhalative processes associated with base metal sulphide deposition was inferred, i.e. these different types of alteration were regarded as complementary end-members of essentially the same hydrothermal system (Stephens 1980b, 1982a). This model is in many respects similar to that described by MacGeehan (1978) and expanded upon by Parry and Hutchinson (1981). The Na-enriched spilites and quartz keratophyres were regarded as residual products of early stage, seawater-rock interaction, while derivative products were thought to be epidotite and calcite nodules/veinlets and massive sulphide deposits with their associated K- and Mg-enriched local alteration haloes and carbonate+chlorite +quartz gangue (Fig. 10). Since the post-ore rocks at Stekenjokk are also spilitized, it is clear that the regional alteration persisted after deposition of Stekenjokk-Levi and associated massive sulphide deposits, albeit without apparent effect on the local alteration.

Pb-Zn SEDEX DEPOSITS IN THE UPPERMOST ALLOCHTHON

The nappes of the Uppermost Allochthon are dominated by gneisses, in part migmatitic, a variety of psammitic, pelitic and calcareous schists with strongly subordinate metabasites, and thick dolomite and calcite marbles, in part conglomeratic (Stephens *et al.* 1985a). Abundant granitoid batholiths and dykes, some at least of which have provided Ordovician-Silurian whole-rock Rb-Sr ages (e.g. Priem *et al.* 1975, Claesson 1979, Cribb 1981, Tørudbakken & Brattli 1985), and conspicuous stratiform, metasediment-hosted, magnetite-hematite and Pb-Zn massive sulphide deposits (Figs. 1 and 2) distinguish this exotic ensialic terrane (Stephens & Gee 1985). Protolith rock ages and much of the deformation and metamorphism in the Uppermost Allochthon are pre-mid Ordovician in age; mid Proterozoic whole-rock Rb-Sr ages have been inferred for some units (Cribb 1981, Brattli *et al.* 1982). Thrust transport onto underlying units occurred during the Scandian deformational episode.

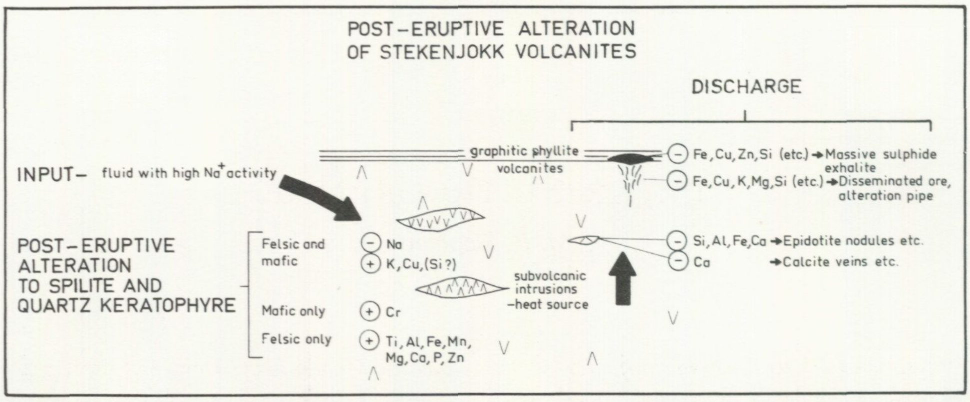


Fig. 10. Working model for formation of the Stekenjokk-Levi massive sulphide deposit, central Swedish Caledonides (after Stephens 1980b). Movement of different elements is indicated as occurring from the input and evolved metal-bearing fluid (-) in the post-eruptive alteration and discharge areas, respectively, and from the rock into the input fluid (+). The post-eruptive alteration is regional in character (input fluid–rock interaction) and the discharge area includes local alteration related to deposition of base metal sulphides (evolved metal-bearing fluid–rock interaction).

Data providing tighter time constraints in the Uppermost Allochthon are unfortunately lacking. The nature of the lithologies and the presence of metabasites with relatively high TiO_2 and Zr contents (Ramberg 1967) are consistent with deposition at a continental margin or within an entirely intracratonic setting (Stephens *et al.* 1984, 1985a). Nevertheless, the medium- to high-grade metamorphism and complex deformation preclude confident interpretation of the protolith character of the rocks within the Uppermost Allochthon. The tectonostratigraphic position of this exotic terrane suggests a pre-tectonic spatial association with a western continent, possibly Laurentia (Stephens & Gee 1985).

The massive sulphide deposits, including the major deposits at Bleikvassli and Mofjellet (see review in Bjørlykke *et al.* 1980), are hosted by either psammitic to pelitic schists and gneisses, or marbles; metabasites comprise only a very minor component in the host-rock sequence. The nature of the host rocks, chemical composition of the mineralization, and occurrence of gahnite (Vokes 1962 and review of occurrences in Sundblad 1982) distinguish these deposits from other stratiform sulphides at lower tectonostratigraphic levels. Other properties, including ore types, base metal and iron sulphide mineralogy, and deposit size and shape, are similar to the deposits in the tectonostratigraphically lower units. Stratiform sulphide mineralization at this tectonostratigraphic level and of this specific type will not be studied during this excursion.

Lead isotope systematics of stratiform sulphide deposits

In distinct contrast to the non-stratiform sulphide deposits in the Autochthon and Lower Allochthon, the lead in the stratiform polymetallic deposits shows lower $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios (Fig. 5), i.e. a clearly less radiogenic composition (Moorbath & Vokes 1963, Wickman *et al.* 1963, modern data in Sundblad & Stephens 1983). Furthermore, the data bank presented by Sundblad and Stephens (1983) for 18 Swedish deposits, occurring at virtually all relevant tectonostratigraphic levels, reveals that single deposits as well as groups of deposits at the same lithostratigraphic level within an individual thrust sheet show similar isotopic compositions. The principal contrast within these stratiform deposits occurs between metavolcanite- and metasediment-hosted types, the former showing less radiogenic lead isotopic compositions. Nevertheless, use of growth curves for ordinary lead (Stacey & Kramers 1975) yields model ages for all deposits which are only slightly younger than the independently established or inferred deposit ages.

Application of the plumbotectonics model (Zartman & Doe 1981) to the lead isotope data (Sundblad & Stephens 1983) suggests that the metavolcanite-hosted deposits show the most significant influence of a mantle-related source. Various models were discussed by these authors to explain the radiogenic component. A contribution from a continental source remains just one possibility. Processes which cause an increase in $^{238}U/^{204}Pb$ and/or $^{232}Th/^{204}Pb$ in an ultimately mantle-derived source rock relative to normal mantle compositions will, after sufficient time, provide an increase in the radiogenic lead component. For the metavolcanite-hosted deposits, the influence of magmatic differentiation, sub-seafloor alteration, and mantle heterogeneity were discussed as possible alternatives. For different groups of metasediment-hosted deposits, the influence of pelagic sediments and erosion of an island arc complex, where $^{238}U/^{204}Pb$ was sufficiently high in the igneous source rocks, were proposed as possible alternatives to the influence of detrital components from a continental source.

EXCURSION PROGRAMME

M. B. Stephens

The excursion route aims firstly to study the non-stratiform Pb-Zn sulphide deposit at Laisvall along the Caledonian Front (Fig. 1). The first day will focus on a critical profile through the Proterozoic basement rocks and the unconformably overlying autochthonous cover sequence prior to an underground visit to the mine on the second day. The remainder of the second day will be spent travelling southwards to Stora Blåsjön (Fig. 1). Days 3, 4 and 5 will focus our attention on the host-rock geology and massive sulphide deposits of Ankarvattnet, Stekenjokk, Joma and Gjersvik in the exotic Gjersvik terrane. Ankarvattnet is hosted by metasediments (post-arc marginal basin), Stekenjokk by felsic metavolcanites stratigraphically beneath graphitic phyllite (rifted arc), Joma by mafic metavolcanites (ocean floor, off ridge axis?) and Gjersvik by felsic stratigraphically beneath mafic metavolcanites (rifted arc). The remainder of Day 5 will be spent travelling further southwards to Trondheim (Fig. 1). Finally, on Day 6, we will visit the Løkken and Høydal ophiolite-hosted deposits in the Hølonda terrane (ocean floor, along ridge axis). The excursion will finish on our return to Trondheim. A programme summary and the various leaders are shown in Table 1. The excursion stops are located by reference to a 1:100 000 (Sweden) or 1:50 000 (Norway) map-sheet and the coordinates in the respective National Grid Systems.

TABLE 1. Summary of excursion programme, Laisvall-Trondheim.

DAY	PROGRAMME	LEADER(S)	OVERNIGHT STOP
1.	Travel from Luleå to Laisvall, surface geology at Laisvall	Omari Mwinyihamisi, Arne Bjørlykke and Michael B. Stephens	Arjeplog
2.	Underground visit to Laisvall, travel from Laisvall to Stora Blåsjön	Omari Mwinyihamisi, Arne Bjørlykke and Michael B. Stephens	Stora Blåsjön
3.	Surface geology southwest of Stora Blåsjön (Kvarnbergsvattnet), Ankarvattnet deposit	Michael B. Stephens, Krister Sundblad	Stora Blåsjön
4.	Open pit and underground visit at Stekenjokk, surface geology west of Stora Blåsjön (Røyrvik)	Ebbe Zachrisson, Arne Reinsbakken and Michael B. Stephens	Stora Blåsjön
5.	Underground and open pit visit at Joma, Gjersvik deposit, travel to Trondheim	Arne Reinsbakken	Trondheim
6.	Løkken and Høydal deposits	Tor Grenne	

DAYS 1 AND 2
THE LAISVALL DISSEMINATED NON-STRATIFORM SULPHIDE DEPOSIT

M. Y. Willdén and O. Mwinyihamisi

INTRODUCTION

M.Y. Willdén

Discovery and mining operations. The Laisvall Pb-Zn, disseminated, non-stratiform, sulphide deposit, located along the Caledonian Front just south of the Arctic Circle in northern Sweden, is an underground mining operation run by Boliden Mineral AB. The ore deposit was discovered in 1939 and development of the mine started in 1941 (Grip 1954). Original ore reserves were estimated to approximately 80 million metric tons containing 4 % combined Pb and Zn. Present production (1985) is 1.45 million metric tons of ore per year. The deposit is mined using the room-and pillar-method and the ore is milled and concentrated at Laisvall. Separate Pb and Zn concentrates are produced.

Stratigraphy and palaeoenvironmental interpretation. The host rock of the Laisvall deposit forms part of an extensive autochthonous platformal sequence of sedimentary rocks developed approximately 2000 km along the eastern border of the Caledonian mountain belt. This sequence, which is late Proterozoic-Ordovician in age, was deposited unconformably on an eroded and levelled surface of Proterozoic and Archaean rocks belonging to the Fennoscandian Shield and is essentially transgressive in character. The transgression corresponds in time with the spreading phase of the Iapetus Ocean and establishment of a passive margin to the ancient continent Baltica (Gee 1975, Stephens & Gee 1985). The Autochthon is overlain by various nappe complexes transported eastwards during Silurian to Devonian time in connection with the climactic phases of the Caledonian orogeny and final closure of the Iapetus Ocean.

The stratigraphy of the autochthonous cover sequence at Laisvall was established by Lilljequist (1973). This classification was modified slightly by Willdén (1980) who also presented a palaeoenvironmental interpretation of the autochthonous sequence. A geological map of the Laisvall area and the stratigraphy of the Autochthon are shown in Figs. 11 and 12.

The Proterozoic basement consists of granite and syenite dated (Rb-Sr whole rock) at 1625±45 Ma (Welin 1970). The upper surface of the Proterozoic basement is a peneplain with isolated hills rising up to 50 m above the surroundings. The thickness of overlying sedimentary layers diminishes gradually towards the basement hills. The autochthonous sediments are initiated by about 10 m of various feldspathic sandstones (Ackerselet Formation) which are interpreted to be glaciofluvial in origin. These sandstones are followed upwards by the ore-bearing Såvvovare Formation, consisting of shale and quartzitic sandstones with a thin phosphorite conglomerate in its uppermost part.

The pebbly shale with outsized clasts (Saivatj Member) that initiates the Såvvovare Formation was probably deposited in a glaciomarine environment. This development was succeeded by various shallow marine environments (tidal influenced beaches, sand flats and channel-bar complexes), in which mainly arenaceous sediments were deposited for a considerable period of time. Three sandstone units are distinguished. The lower sandstone (Kautsky Ore Member), measuring about 25 m in thickness, is a white, medium-grained sandstone with continuous layers of green shale and clayey sandstone at some levels. The middle sandstone (Tjalek Member) is about 6–8 m thick. It consists of a thin quartz conglomerate overlain by clayey, medium-grained sandstones of a greyish to black colour. The upper sandstone (Nadok Ore Member), measuring about 6–11 m in thickness, is dominated by cross-bedded, fine- to coarse-grained sandstones of a white to greyish black colour. Ore grade mineralization is confined almost exclusively to the lower and upper sandstone units. The phosphorite conglomerate on the top surface of the upper sandstone unit constitutes a marker bed that is present all over the area. The conglomerate is believed to have formed by reworking of sediments deposited in shallow shore lagoons in which phosphoritic and calcareous matter had accumulated.

The Såvvovare Formation is overlain by a 40 m thick sequence, mainly of shale and siltstone, which is referred to as the Grammajukku Formation. During the period of time representing the deposition of this unit, the Laisvall area is likely to have occupied the central part of a gulf, extending E–W towards the interior of the Fennoscandian Shield (Willdén 1980). The occurrence of shelly fossils near the top surface of the Grammajukku Formation (Kautsky 1945) indicates an age of this part of the Autochthon corresponding to the uppermost stage of the Lower Cambrian (i.e. the Strenuella linnarssoni stage).

The Autochthon is terminated upwards by the Alum Shale Formation, an organic-rich black shale which over vast areas along the platform contains anomalous concentrations of a variety of trace elements including U, V, Mo and Ni (Andersson *et al.* 1985). In the Laisvall area, the Alum Shale Formation constitutes the principle sole of the thrust nappe sheets.

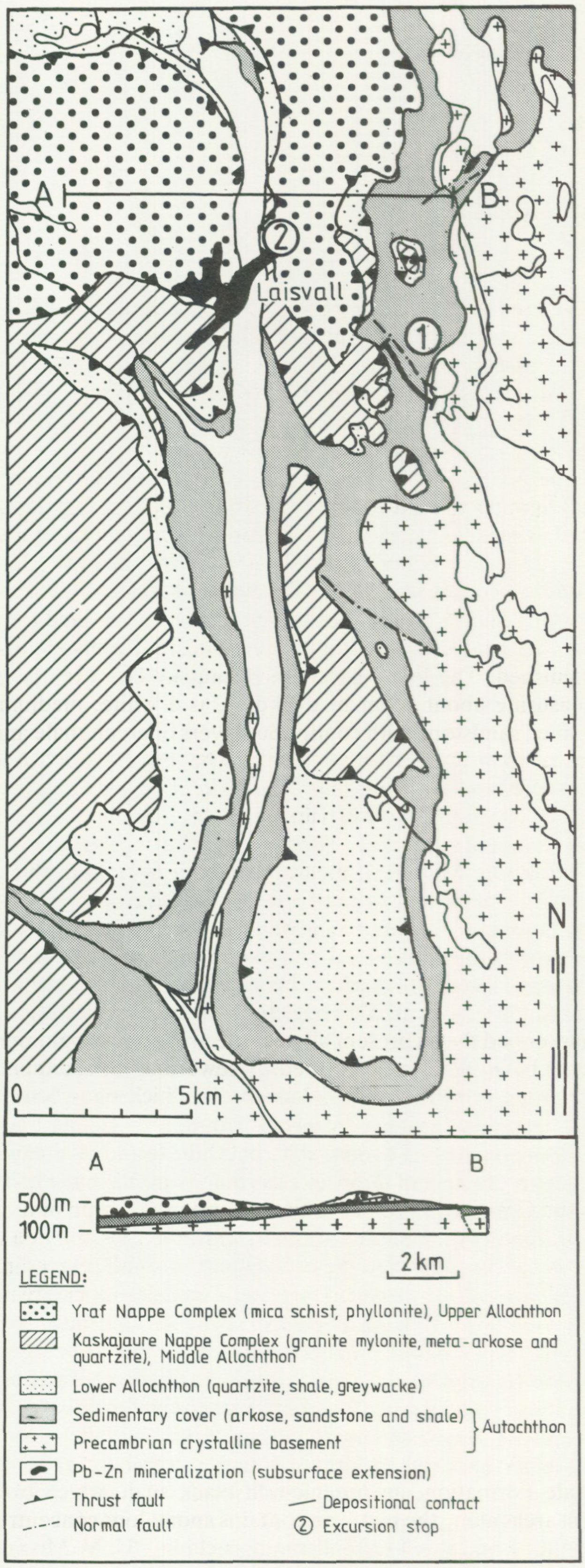


Fig. 11. Geology of the Laisvall area with excursion stops (Days 1 and 2) indicated (modified after Lilljequist 1973).

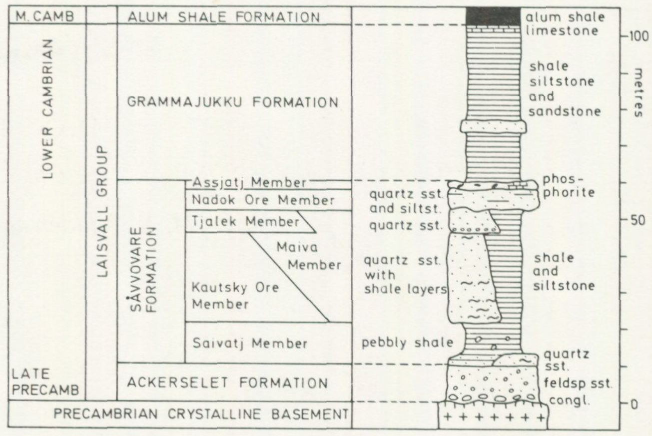


Fig. 12. Stratigraphy of the Autochthon in the Laisvall area (after Willdén 1980).

Structure of the Autochthon. The Autochthon shows a regional dip of a few degrees to the west. The ore-bearing sandstones are virtually undeformed. Faults and folds recognized in the mine area are shown in Fig. 13. The Kautsky disturbance is a thrust fault with a vertical throw of about 30 m and a lateral displacement of 200 m. The frequency of joints increases towards the Kautsky disturbance. The Nadok disturbance is a normal fault with a vertical throw of about 15 m (Fig. 13).

In the central part of the mine area, there is a system of broad anticlinal fold structures (Fig. 13). Along the crests of these structures, the sandstones are uplifted 5–10 m compared to the elevation of surrounding sandstones directly bordering the anticlines. Where exposed, the rocks within the anticlinal structures may be gently folded and/or disturbed along low-angle thrust planes. As a result of the deformation, joints and fissures were formed, some of which have remained open and function as principle water courses today.

The mine area is limited to the east by a basement hill elongated north-south. A similar yet smaller hill occurs in the northern part of the Laisvall area. Probably as a result of differential compaction caused by variations in thickness and lithology, the overlying sedimentary layers are deformed parallel to the basement topography close to and above the hills (Fig. 14).

Characteristics of the mineralization. The Laisvall deposit is sheet-shaped and elongated along a NE–SW direction (Fig. 13). The length of the deposit is 5 km and the width 3 km. Maximum thickness amounts to 24 m. Although the deposit is continuous, four ore bodies are distinguished and referred to as the Kautsky, Strand, Central and Nadok ore bodies (Fig. 13).

The Laisvall deposit comprises varying Pb and Zn contents in alternating thin sandstone layers. As mentioned above, ore grade mineralization occurs in the lower and upper sandstone units. The base of the mineralization

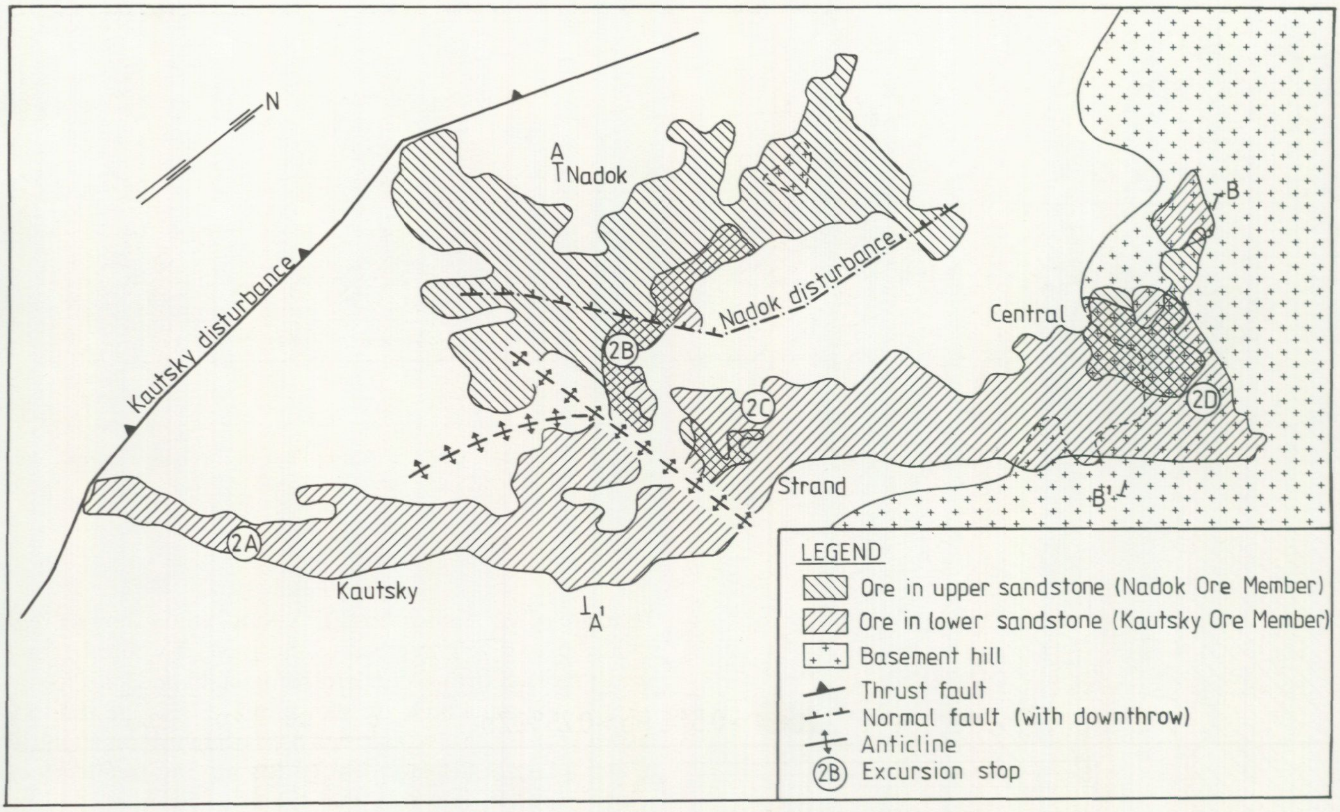


Fig. 13. Structure of the Autochthon and excursion stops in the Laisvall mine.

defines an approximately horizontal plane that cuts the sandstones by a few degrees such that mineralization lies at a higher stratigraphic level to the northwest (Fig. 14). At the intersection between ore units in the lower and upper sandstones, ore grade mineralization may occur in the middle sandstone. The ore boundary is distinct to the southeast, the grade diminishing from about 15 % to less than 1 % within a lateral distance of a few decimetres. To the northwest, the ore grade decreases gradually.

The ore minerals occur as characteristic spots in massive sandstone. The spots, which are 1 cm or less in size, are mostly randomly distributed, but may be accumulated along bedding surfaces. A concentration of ore minerals at the contact between sandstone and interbedded layers of shale is commonly observed in the lower sandstone. In the upper sandstone, where cross-bedded sequences of alternating fine- and coarse-grained sandstone are frequent, the mineralization is often clearly regulated by bedding. A negative correlation between ore grade and clay content of the host rocks has been observed, especially in the lower sandstone. In this unit, ore grade mineralization is restricted to layers of white, pure sandstone.

The principal minerals were deposited in the order calcite, barite, fluorite, sphalerite, and galena. This process was repeated several times and sulphide deposition was accompanied by calcite dissolution (Lindblom 1986). The minerals infill pore spaces in the sandstones. To a limited extent mineralized joints also occur. The regional distribution of galena and sphalerite displays a zoned pattern which essentially follows the northwesterly climb of the mineralization to higher stratigraphic levels. Thus, Zn-rich ore is concentrated down-dip in the upper sandstone, i.e. in the northwestern part of the Nadok ore body. There seems to be no close relationship between the distribution of galena and sphalerite on the one hand and barite, fluorite and calcite on the other. Barite and fluorite occur mainly in the lower half of the lower sandstone. Calcite is distributed evenly in the lower and upper sandstone units.

Ore genesis considerations. The genetic models proposed for sandstone-hosted Pb-Zn deposits can be divided into two essential types based on the nature of the metal-bearing solution (Bjørlykke & Sangster 1981): (1) hydrothermal or basin- brine model and (2) ground-water or meteoric model. Recently, a number of investigations of the Laisvall deposit have been undertaken aimed at tackling the ore genesis problem. The investigations include studies of (1) the spatial relationships of the ore, (2) the illite crystallinity of shales, (3) fluid inclusions in the disseminated ore, (4) hydrocarbons, (5) the isotopic compositions of calcite carbon and oxygen, (6) the sulphur isotopic compositions of sulphide and sulphate constituents, and (7) the lead isotopic composi-

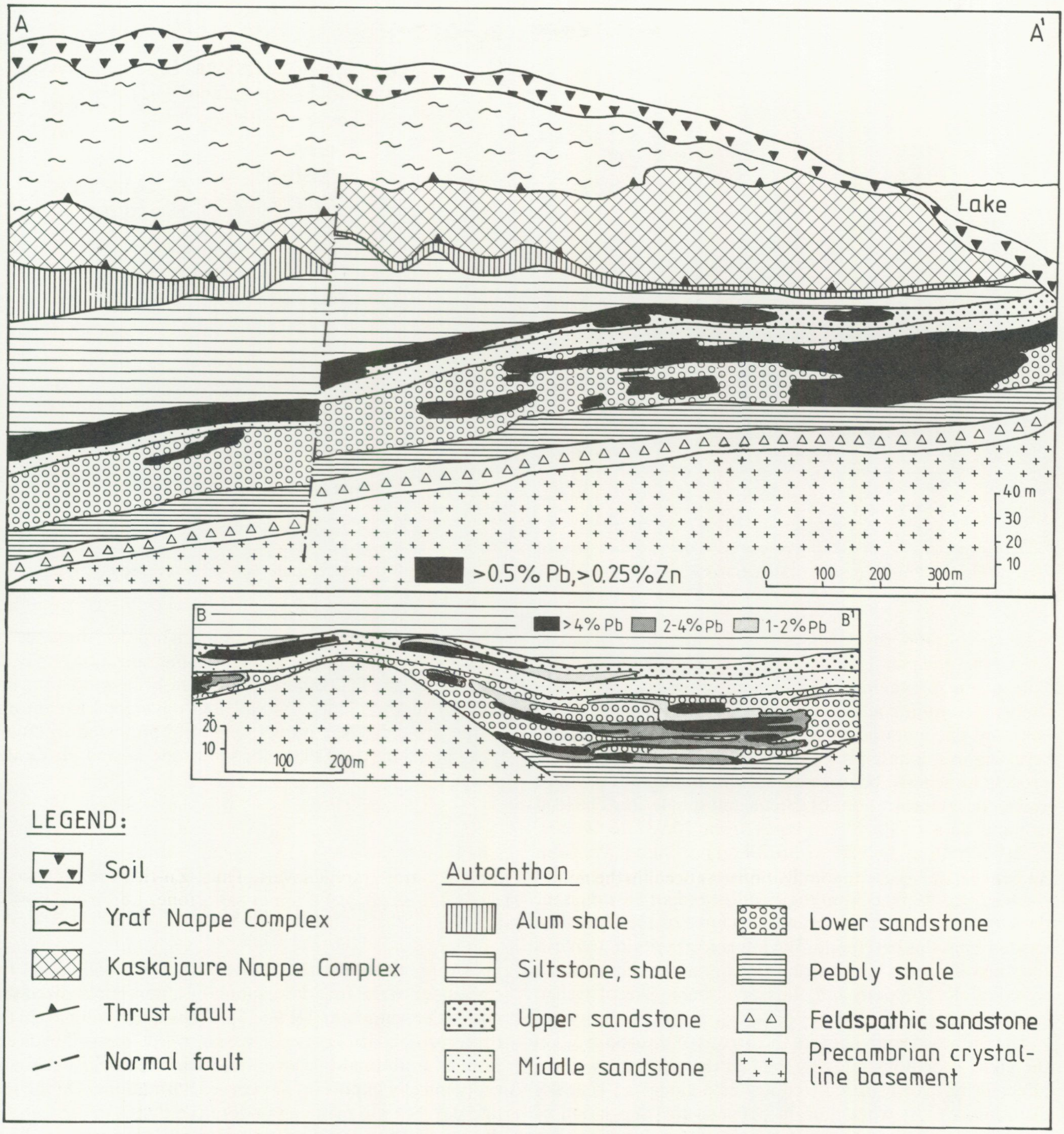


Fig. 14. NW–SE cross-sections through the Laisvall Pb-Zn deposit (section lines are shown on Fig. 13).

tion of galena. A summary of the results of these investigations, which are reported in detail by Rickard *et al.* (1979, 1981) and Lindblom (1986), is given below.

The ore-forming environment was an unsealed sandstone aquifer overlain by argillaceous layers measuring some hundreds of metres in thickness. Fluid inclusion data and the presence of hydrocarbons show that the ore minerals precipitated from a concentrated Na-Ca-Cl oil-field brine at a temperature of about 150°C. Homogenization and melting temperatures obtained from fluid inclusions in sphalerite occurring along joints (Roedder 1968, Larsson *et al.* 1973) are similar to the disseminated ore. The fact that the sulphide sulphur was found to be isotopically heavier (+24.1‰$\delta^{34}S$) than the sulphate sulphur (+14.9‰$\delta^{34}S$) suggests the presence of two solutions during the ore precipitation, one of which was a sulphide solution and the other a

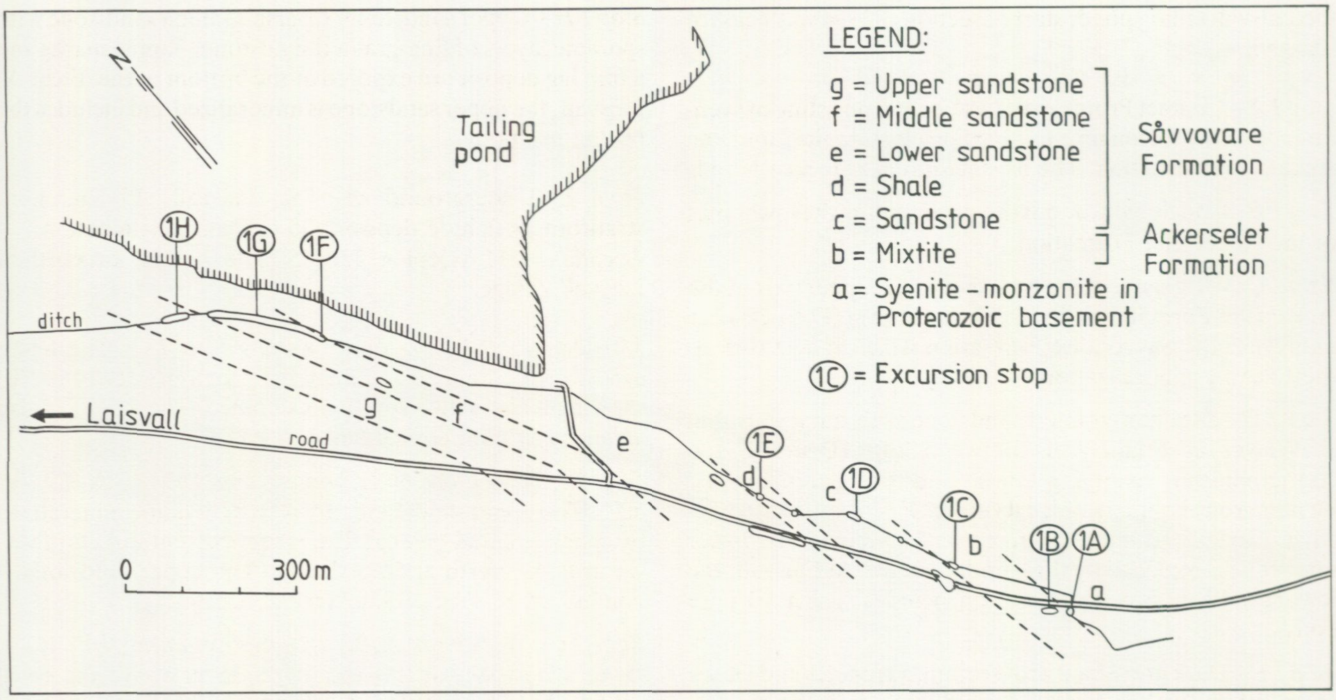


Fig. 15. Profile at Stop 1 through the Autochthon near Såvvovare, southeast of Laisvall (for location of profile, see Fig. 11).

sulphate solution. Based on various considerations, it can be shown that the metals were carried in the sulphate solution. Due to the prevailing hydrodynamic flow pattern in the sandstone aquifer at the time of mineralization, sulphate solutions encountered sulphide solutions in certain places, resulting in sulphide precipitation. At Laisvall, this mixing process must have been going on long enough to produce economic concentrations of galena and sphalerite. The lead isotopic data ($^{206}Pb/^{204}Pb$ ranges from 20.937 to 23.220, $^{207}Pb/^{204}Pb$ from 15.926 to 16.208, and $^{208}Pb/^{204}Pb$ from 39.621 to 41.563) are markedly radiogenic and suggest that the lead was derived from the Fennoscandian Shield either directly from a basement granitoid source or the sediments eroded from this basement. The inferred granitoid source in the Laisvall area is late-orogenic in character relative to the Svecokarelian orogeny and, thus, an ultimate Svecokarelian lead source is suggested.

The ore was formed before the arrival of thrust nappes in the area, as demonstrated by the fact that the ore itself was affected by overthrusting (for instance along the Kautsky disturbance). At what time in between the deposition of overlying, capping shales and the overthrusting the mineralization took place is still an unsettled question. Some indications such as similarities in fluid inclusion and isotopic compositions between the disseminated type of mineralization and joint mineralization may suggest that the ore formed after the onset of Caledonian deformation, since the jointing seems to be related to processes connected with this deformation.

Although certain data (e.g. sulphur isotopic compositions, source of lead) are compatible with both models summarized by Bjørlykke and Sangster (1981) in their overview paper, other data (e.g. fluid inclusions, presence of hydrocarbons, tentative timing of mineralization) provide support for the hydrothermal or basin-brine model for the Laisvall deposit. Thus, Laisvall does not appear to conform to the ground-water model generally preferred by Bjørlykke and Sangster (1981) for sandstone-hosted Pb-Zn deposits.

STOP DESCRIPTIONS

M.Y. Willdén (Stop 1) and O. Mwinyihamisi (Stop 2)

Following arrival in the Laisvall area, we will spend the remainder of the first day examining a non-mineralized section in the Autochthon (Fig. 15). This section will start in the Proterozoic basement rocks, pass upwards across the unconformity and finally concentrate on the Ackerselet and economically important Såvvovare Formations. On the second day, we will make an underground visit to the Laisvall deposit and pay particular attention to the mineralization of primary sedimentary structures. We will also examine representative drillcore material through the deposit. The remainder of the second day will be spent driving from Laisvall to Stora Blåsjön.

Stop 1: Old tailing pond section through Proterozoic basement rocks unconformably overlain by Vendian to Lower Cambrian Ackerselet and Såvvovare Formations (Fig. 15). *Location:* 25H Arjeplog, 156570/733590 to 156440/733735. c. 2 km section along stream flowing to southeast parallel to the Laisvall tailing pond; start of section c. 5 km southeast of Laisvall.

Stop 1 A – Contact Proterozoic basement, consisting of syenite-monzonite belonging to the Sorsele Granite, and the Ackerselet Formation. The basement rocks are weathered.

Stop 1 B – Conglomeratic mixtite representing the lower part of the Ackerselet Formation.

Stop 1 C – Silty sandstone representing the upper part of the Ackerselet Formation. The following stops (1D to 1H) are entirely in the Såvvojaure Formation which is host rock to the Laisvall mineralization.

Stop 1 D – Medium-grained sandstone with numerous thin shale layers at certain levels. Between Stops 1D and 1E, the stratigraphically overlying lower sandstone is represented by numerous boulders of local origin. It is frequently somewhat clayey. To the north, towards Maiva, the lower sandstone is replaced by shale and siltstone. At Laisvall, the lower sandstone is mineralized and includes the Kautsky ore body.

Stop 1 E – Dark grey shale with scattered granules and lenses of sandstone.

Stop 1 F – Contact lower sandstone/middle sandstone. The uppermost part of the lower sandstone is represented by a sequence of alternating shale and siltstone. The lowermost part of the middle sandstone consists of a sandstone layer, several decimetres thick, containing scattered granules of quartz. This layer is overlain by 2–3 m of white sandstone, followed by dark sandstone.

Stop 1 G – Cross-bedding in middle sandstone.

Stop 1 H – Upper sandstone. Coarse-grained sandstone with sporadic layers of fine-grained sandstone. Ripple marks and a thin lag deposit are exposed at the bottom of the ditch. At Laisvall, the upper sandstone is mineralized and includes the Nadok ore body.

Stop 2: Underground visit to Laisvall, Pb-Zn, non-stratiform, sulphide deposit and drillcore examination.
Location: 25H Arjeplog, 156145/733960. c. 1.5 km north of Laisvall village.

Stop 2A, Kautsky ore body, mining area 13 – The lower sandstone contains disseminated Pb-rich ore (5–10 % Pb) showing a distinctive spotty appearance. The galena is also arranged in thin, concordant layers.

Stop 2B, Nadok ore body, mining area 800, drifts 802 and 807 – The upper sandstone shows cross bedding mineralized by sphalerite and galena. The palaeocurrent direction was towards the north and northwest. The upper sandstone is dominated by such sedimentary structures.

Stop 2 C, Strand ore body, "Gamla restaurangen" – The lower sandstone, at this locality c. 15 m above the basal pebbly shale member of the Såvvovare Formation, shows mineralized convolute bedding. Galena has only impregnated the clean sandstone material; the greenish, clay-rich sandstone lacks galena mineralization.

Stop 2 D, Central ore body – Interlayered galena-mineralized upper sandstone and shale are deformed in a weak anticlinal fold structure. This deformation is related to the tectonic emplacement of thrust sheets above the autochthonous sequence at Laisvall.

DAY 3

A. STRATIGRAPHY AND DEFORMATION IN THE MASSIVE SULPHIDE-BEARING STIKKE NAPPE, UPPER ALLOCHTHON

M. B. Stephens

INTRODUCTION

Stratigraphy and palaeotectonic setting. The Stor-Blåsjön – Kvarnbergsvattnet area in northern Jämtland, Sweden (Figs. 1 and 16) provides an excellent illustration of the stratigraphy and deformational features in the massive sulphide-bearing Stikke Nappe in the Middle Köli complex of nappes (Upper Allochthon). The rocks in this area dip regularly to the northwest and increase in dip across the strike from southeast to northwest. The stratigraphy within the Stikke Nappe can be continuously mapped from the Grong-Olden Culmination, in the south, to north of Remdalen (see Figs. 1 and 16), a strike length of over 100 km. The stratigraphic sequence is exposed in the core or on the southeastern limb of the Western Synform, one of four major post-thrusting and post-regional foliation fold structures with NE–SW trend in the Köli Nappes of northern Jämtland and southern Västerbotten (Zachrisson 1969). The basis for the stratigraphy was established by Zachrisson (1964a) from the Remdalen area and by Nilsson (1964) from the Stor-Blåsjön area. Sjöstrand (1978) has studied the same sequence in the Kvarnbergsvattnet area.

Calcareous phyllites with metagabbroic and occasional metatrondhjemitic intrusions (Blåsjö Phyllite) lie structurally above (Fig. 17) shallow-water quartzites and limestones (Bellovare Formation), and a metamorphosed volcano-sedimentary complex (Tjopasi Group). The upper part of the calcareous phyllite sequence, containing graphitic phyllite intercalations, was treated by Sjöstrand (1978) as a separate formation (Haraön Phyllites). The calcareous phyllites are overlain (Fig. 17) north of Stor-Blåsjön by mafic metavolcanites and high-level intrusions (Lasterfjället Greenschist) and then by phyllites, metatuffites and bimodal, yet predominantly felsic, metavolcanic and high-level intrusive rocks (Stekenjokk Quartz-Keratophyre). The sequence is structurally capped (Fig. 17) by quartzite, quartzite conglomerate and locally fossil-bearing (pelmatozoa) limestone, a variety of fine-grained often graphitic phyllites, and mafic metavolcanites (Remdalen Group). Trace element geochemistry of mafic rocks in this sequence (Table 2) indicates that rift-related igneous activity was prevalent during deposition of the Blåsjö Phyllite and Lasterfjället Greenschist, that the Tjopasi metavolcanites and Stekenjokk Quartz-Keratophyre extruded in rifted tholeiitic arc systems, and that the mafic metavolcanites of the Remdalen Group are tholeiitic to alkaline with E-MORB or WPB affinity (Stephens 1977a, 1980a, 1982b, Stephens *et al.* 1985b; see also Fig. 8). Zn-Cu (-Pb) massive sulphide deposits occur in the Tjopasi Group, Blåsjö Phyllite, Stekenjokk Quartz-Keratophyre and mafic metavolcanites of the Remdalen Group. However, it is the Stekenjokk Quartz-Keratophyre which contains the single major deposit (>25 m.t) at Stekenjokk-Levi. This deposit as well as the metasediment-hosted Ankarvattnet deposit (0.75 m.t.) in the Blåsjö Phyllite will be visited on Days 3 and 4 of this excursion.

Zachrisson (1964a, 1969) considered the stratigraphy described above to be continuous, the lower part of the Blåsjö Phyllite being correlated with the Lövfjäll Formation in the Eastern Synform (Fig. 17). On this basis, the Blåsjö Phyllite, Stekenjokk Quartz-Keratophyre and Remdalen Group were all considered to be post-mid or even post-earliest late Llandovery in age (Fig. 17). Sjöstrand (1978) was the first to point out problems with this model, based on the extremely short time interval available for the deposition of these rocks prior to late Silurian deformation and metamorphism. On the basis of regional correlation with rocks south of the Grong-Olden Culmination and supported by the results of Juve (1977), who suggested that the Stekenjokk-Levi massive sulphide deposit lay in an inverted position, Sjöstrand (1978) proposed a major inversion of the stratigraphy, the Blåsjö Phyllite being the youngest unit and the Remdalen Group the oldest. Sjöstrand favoured a fold nappe model. He continued to correlate the Blåsjö Phyllite with the Lövfjäll Formation and the Stekenjok Quartz-Keratophyre with the pre-Ashgill metavolcanites of the Tjopasi Group. He placed the 'inversion line' in the central part of the Blåsjö Phyllite.

Recent work at the Ankarvattnet (Sundblad 1980) and Stekenjokk-Levi (Zachrisson 1982a, 1984) massive sulphide deposits, summarized below in this guide, has added further support to the inversion hypothesis. However, on the basis of (1) the restriction of metagabbro intrusions to the *overlying* Blåsjö Phyllite and their absence in the Lövfjäll Formation, and (2) the local identification of phyllonites and mylonites at or near the base of the Blåsjö Phyllite and, in particular, the recognition of a thrust contact between metagabbro-intruded calcareous phyllite and the underlying Lövfjäll Formation in the area north of Remdalen (Stephens 1977b, Häggbom 1978), Stephens (1980a, 1982b) suggested that the inverted Blåsjö Phyllite – Stekenjokk Quartz-Keratophyre – Remdalen Group stratigraphy lies in a separate tectonic unit (Stikke Nappe) relative to the underlying sequence, including the Lövfjäll and Bellovare Formations and Tjopasi Group (Björkvattnet Nappe), (Fig. 17). It is suggested that the thrust at the base of the Stikke Nappe is a slide

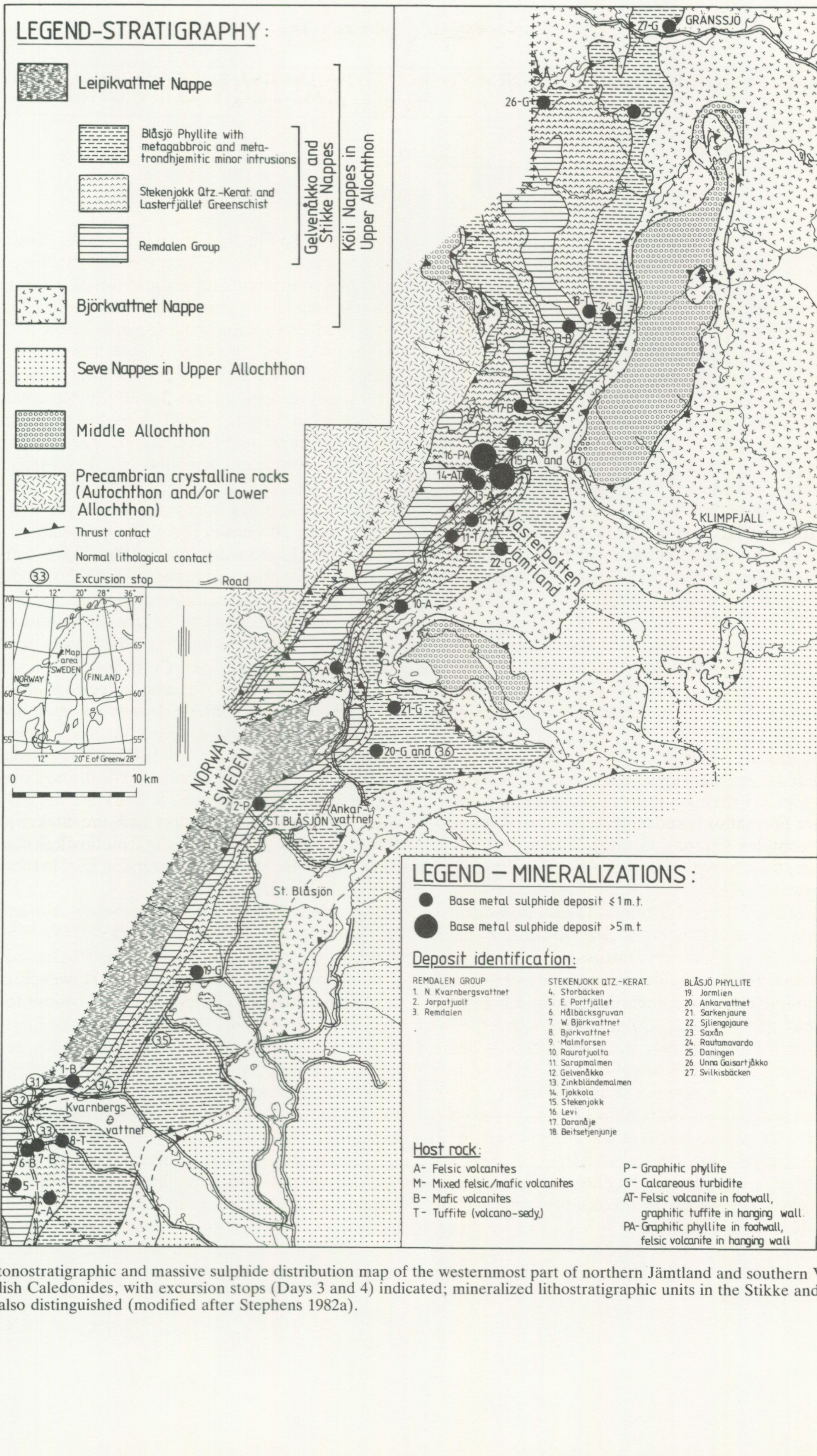


Fig. 16. Tectonostratigraphic and massive sulphide distribution map of the westernmost part of northern Jämtland and southern Västerbotten, central Swedish Caledonides, with excursion stops (Days 3 and 4) indicated; mineralized lithostratigraphic units in the Stikke and Gelvenåkko Nappes are also distinguished (modified after Stephens 1982a).

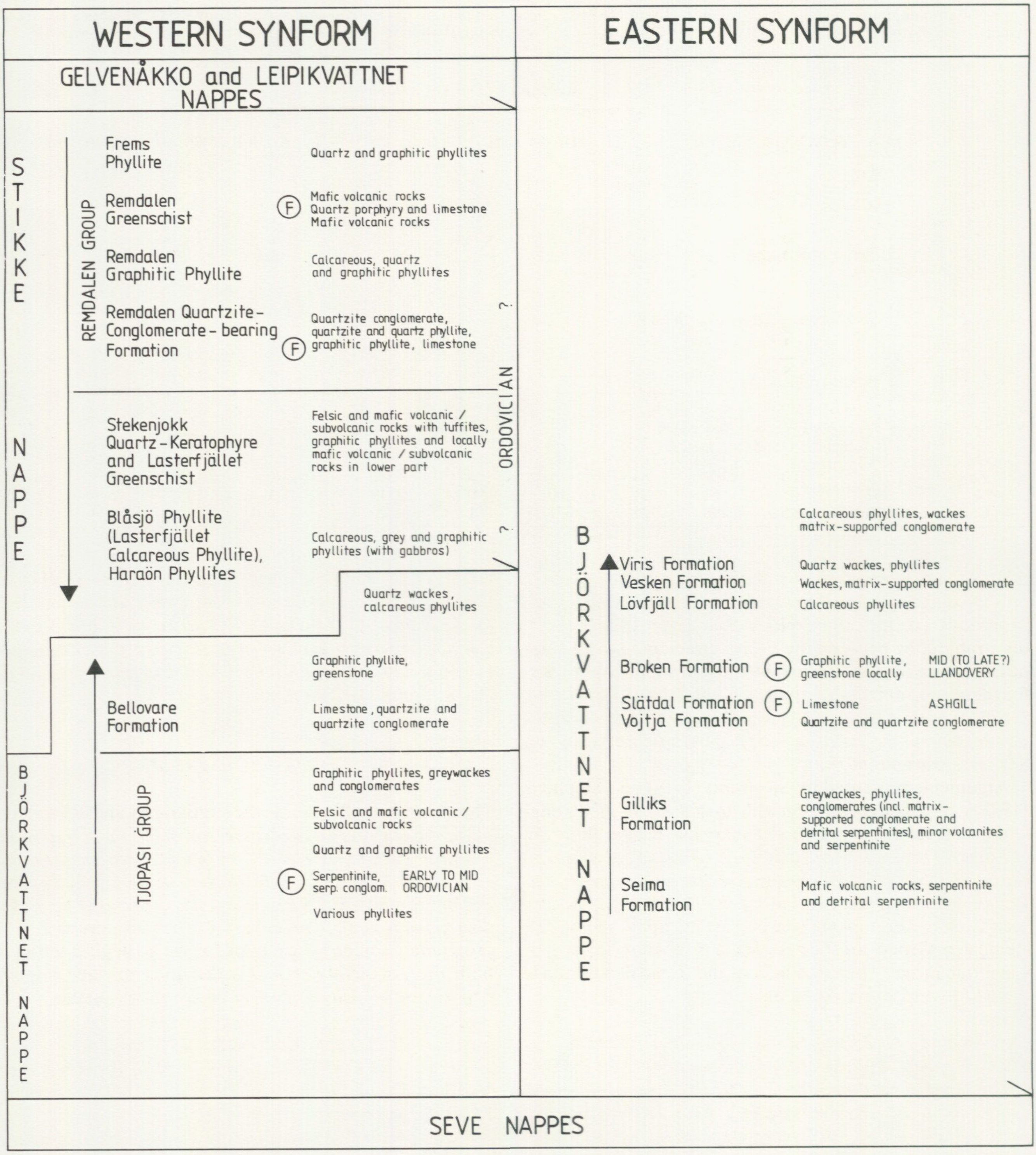


Fig. 17. Stratigraphy within the Björkvattnet and Stikke Nappes (after Stephens 1982b). Vertical arrows indicate way up of the different successions. F indicates macrofossil occurrences.

TABLE 2. Representative analyses of metavolcanic and high-level intrusive rocks in the Stikke Nappe. 1 = mafic metavolcanite in Remdalen Group; 2 = Microcline porphyry in Remdalen Group; 3 = mafic metavolcanite in Røyrvik Group beneath Brakkfjället Phyllite; 4–7 = mafic metavolcanites in Stekenjokk Quartz-Keratophyre, compositions 1A, 1B, 2A and 2B, respectively; 8 = Metatrondhjemitic high-level intrusion in Stekenjokk Quartz-Keratophyre; 9 = mafic metavolcanite in Lasterfjället Greenschist; 10 = Metagabbroic high-level intrusion in Blåsjö Phyllite; 11 = Metatrondhjemitic high-level intrusion in Blåsjö Phyllite. Major elements by optical emission spectroscopy using prefabricated, fused, synthetic standards (Danielsson 1967), AAS (Na_2O and K_2O) and wet chemical methods; trace elements by XRF (see also Stephens 1982b).

		Remdalen and Røyrvik Gps.			Stekenjokk Quartz-Keratophyre					Last. Gschist.	Blåsjö Phyllite	
		1	2	3	4	5	6	7	8	9	10	11
		M76–139	M76–140	M77–17	M77–11	M76–94	BH 70710-S	BH 69118-R	BH 69118-R	M76–66	M76–104	M76–41
%	SiO_2	46.9	65.1	50.5	49.4	47.5	47.6	47.1	74.0	45.4	48.6	73.4
	TiO_2	2.06	0.53	1.83	0.64	0.96	2.20	3.00	0.18	1.76	1.85	0.16
	Al_2O_3	14.5	12.7	13.4	16.2	14.5	12.7	14.3	11.7	17.3	15.8	13.8
	FeO (tot)	13.1	6.0	11.8	10.4	11.2	11.2	13.2	1.9	10.7	10.3	1.8
	MnO	0.15	0.14	0.22	0.18	0.16	0.20	0.22	0.08	0.14	0.16	0.01
	MgO	7.4	0.47	6.2	5.6	8.1	6.4	4.6	0.70	8.1	6.7	0.48
	CaO	5.8	3.2	9.4	5.9	9.4	11.6	6.6	2.7	7.4	9.8	2.0
	Na_2O	4.7	4.9	4.2	5.7	2.8	2.3	3.4	6.5	3.7	3.6	5.5
	K_2O	0.2	2.3	<0.1	0.1	0.2	0.1	0.5	0.2	<0.1	0.4	0.6
	P_2O_5	0.20	0.09	0.16	0.06	0.08	0.23	0.46	<0.01	0.23	0.24	0.06
	Volatiles	5.1	3.5	3.4	4.4	6.3	4.1	4.6	2.0	5.0	3.1	1.1
	Total	100.1	98.9	101.2	98.6	101.2	98.6	97.9	100.0	100.1	100.6	98.9
%	S	0.04	<0.02	<0.02	0.04	<0.02	0.13	0.15	0.33	<0.02	0.04	<0.02
ppm	Zr	150	583	122	39	93	141	153	131	178	211	126
	Y	27	74	46	16	29	43	33	51	38	37	13
	Cu	40	<5	6	36	47	56	45	7	38	25	<5
	Zn	80	100	102	84	61	106	107	40	84	75	13
	Ni	67	<5	63	21	160	90	19	1	101	76	<5
	Cr	210	<5	198	25	331	201	26	n.d.	289	228	<5

related to an overturned fold, the inverted limb of which is preserved and the right way up limb cut out. A thrust nappe hypothesis satisfactorily explains the major differences in the stratigraphy between the Björkvattnet and Stikke Nappes, a feature which is ignored by the fold nappe hypothesis. Furthermore, detailed mapping in the Blåsjö Phyllite by Sundblad (pers.comm., 1981), who recognized several different members, has failed to reveal the proposed 'inversion line' of Sjöstrand (1978).

Arguments presented by Sjöstrand (1978) and Stephens (1982b), based on correlation with areas south of the Grong-Olden Culmination and recent mapping results there by Hardenby (1982), as well as the occurrence of pelmatozoa-bearing limestone in the stratigraphically upper part of the Remdalen Group suggest that the Blåsjö Phyllite, Stekenjokk Quartz-Keratophyre and at least the upper part of the Remdalen Group are Ordovician and possibly even late Cambrian in age. The remainder of the Remdalen Group is thought to be Ordovician or older.

Deformation. A deformational sequence relevant to the Stikke Nappe was proposed by Zachrisson (1969). Sjöstrand (1978) subsequently presented a detailed study of deformation–metamorphism relationships in the Kvarnbergsvattnet area. Sjöstrand's pre- and syn-metamorphic deformational phases correspond to the D_1 structures now generally recognized in the Köli Nappes, his late-metamorphic folding, in particular the overturned and reclined Portfjället folds, to D_2 structures, and his post-metamorphic deformation to D_3 and D_4 structures, respectively. Bedding and regional foliation, the latter complex and established during D_1 and D_2, are mostly subparallel. Thrusting at this tectonic level in the Upper Allochthon was completed prior to development of D_3 structures. D_3 folding gave rise to the major NE–SW trending antiforms and synforms recognized by Zachrisson (1969) and may well be a reflection of continued thrusting at deeper tectonostratigraphic levels.

STOP DESCRIPTIONS

The excursion will examine the stratigraphy and deformational features in the Stikke Nappe traversing stratigraphically upwards (structurally downwards) through the inverted sequence from the Remdalen Group to the Blåsjö Phyllite. Mesoscopic structures examined are dominated by F_2 folding as well as S_{1+2} regional foliation development. This programme will provide a basis for the geological setting of both the Ankarvattnet and Stekenjokk massive sulphide deposits to be visited later on during the excursion.

Stop 3.1: Phyllites of the Remdalen Group.
Location: 22D Portfjället, 139990/717270. Roadside exposure at Vallmon on the Sweden-Norway border, north of Kvarnbergsvattnet.

Graphitic phyllite with thin laminae and lenses of quartz-rich phyllite lie above quartzite conglomerate (Portfjället Conglomerate). Structurally higher in the sequence (not seen at this locality) greenstones of probable extrusive character are interlayered within these phyllites. These rocks form the structurally highest and presumed stratigraphically lowest units within the Stikke Nappe.

Stop 3.2: Stekenjokk Quartz-Keratophyre underlying limestone and quartzite conglomerate at the structural base of the Remdalen Group.
Location: 22D Portfjället, 139950/717215. Roadside exposure c. 150 m west of the northern bay at the western end of Kvarnbergsvattnet.

Foliated, epidote-rich greenstone with hornblende phenocrysts is overlain sharply by limestone with interbedded calcareous chloritic phyllite. This boundary marks the contact between the Stekenjokk Quartz-Keratophyre and the Remdalen Group.

After a small gap in exposure, there follows a quartzite conglomerate (Portfjället Conglomerate). This conglomerate consists of clean quartzite fragments in a dark grey, quartz-mica matrix. The fragments are flat and slightly elongate (30° to the north) in the main foliation. Towards Nordli to the south, Kollung (1979) reports that the conglomerate passes laterally into quartzite. To the north, this conglomeratic unit is represented by phyllite with scattered quartzite pebbles interlayered with thin banks of quartzite conglomerate. c. 500 m to the northwest in Havdalselven, a limestone lens within phyllite contains pelmatozoa (Sjöstrand 1978).

Limestone, phyllite, quartzite and quartzite conglomerate are a conspicuous association at the structural base of the Remdalen Group (Zachrisson 1964a, 1969). Bearing in mind the stratigraphic inversion in the Stikke Nappe (Fig. 17) and assuming a depositional contact relationship between the Stekenjokk Quartz-Keratophyre and Remdalen Group, these rocks may be interpreted as an indication of shoaling *prior to* eruption of the Stekenjokk metavolcanites. Reworking of quartzitic rocks within the stratigraphically older Remdalen Group may be the source of the abundant quartz and quartzite debris at the Portfjället Conglomerate level. The fossil occurrence indicates the late Cambrian or younger age of the metasediments at the stratigraphic top of the Remdalen Group.

Stop 3.3: Stekenjokk Quartz-Keratophyre in the hinge of F_2 Portfjället folds.
General location: Scattered outcrops along the road and in the wood west of Björkvattnet, near the intersection between the road going south from Kvarnbergsvattnet towards Nordli (Norway) and the road going eastwards to Björkvattnet and Gäddede. It is important to note that the outcrops at this stop are strongly disturbed by F_2 folding. The sheet-dip of the rocks is considered to be steep to the west; the axial surface of the F_2 folds dips northwards.

Stop 3.3 A – 22 D Portfjället, 139955/716865. Outcrops in the wood just south of the Björkvattnet-Gäddede road, c. 250 m east of the road intersection referred to above.

A coarse pyroclastic rock (volcanic breccia) is exposed in the wood near the Björkvattnet-Gäddede road. Intensely epidotized felsic rock fragments (10–15 cm by a few cm) occur flattened in the main foliation; a single coarser mafic fragment with epidote clots has also been recorded. In several fragments, the cores appear particularly epidotized. The matrix to this breccia is mafic and also contains abundant epidote clots (epidotized lapilli?).

The volcanic breccia described above passes under to banks of massive quartz keratophyre with only minor intercalations of a pale, calcareous greenschist. The quartz keratophyre banks are homogeneous and up to several metres thick, consisting of a fine-grained albite-quartz (-chlorite) groundmass containing megacrysts (phenocrysts?) of albite and bluish quartz, and abundant quartz (-chlorite) veinlets. The texture, homogeneity and thickness of such felsic units led Stephens (1982b) to suggest that they represent ash-flow, vitric-crystal tuffs.

The matrix minerals in the quartz keratophyres are aligned in a foliation which is folded by F_2 mesoscopic folds plunging c. 20° to the NNE. The quartz(-chlorite) veinlets are intensely drawn out and deformed on the limbs of these folds, the rock showing a layered structure, while, in the hinge zones, they show a more irregular network structure subparallel to the early foliation. It is concluded that these veinlets formed prior to the F_2 folds. A few metres to the west, in finer layered mafic and felsic tuffs, spectacular F_2 mesoscopic folds can be seen. A differentiated crenulation cleavage subparallel to the axial surface of these folds is developed in the thinner mafic units, while no significant realignment of minerals parallel to the axial surface is noted in the thicker felsic layers. Fold shapes, with alternating broad, rounded and tight, pinched hinges, reflect the highly contrasting physical characteristics of the mafic and felsic layers.

Stop 3.3 B – 22 D Portfjället, 139980/716865. Return to the Björkvattnet-Gäddede road from Stop 3.3 A. Walk c. 400 m eastwards along the road to the beginning of the next stop. Examine roadside exposures along the Björkvattnet-Gäddede road (north side), between 650 m and 250 m east of its intersection with the Kvarnbergsvattnet-Nordli road. Walk the section from east to west.

Quartz keratophyre similar to that seen at the previous stop (3.3A) is interlayered with a pale, calcareous greenschist, c. 1–1.5 m thick, and, at the eastern end of the exposure, a darker, more massive and coarser grained greenstone. All rocks are deformed by F_2, reclined folds plunging NNE, a weak axial surface cleavage being developed even in the felsic rocks. The darker greenstone at this locality is similar to other 'grainy' mafic rocks in the Stekenjokk Quartz-Keratophyre, interpreted, on the basis of their texture and occasional chilled margin relationships, as minor intrusions and belonging to either the 1B-2A (Ti-rich, tholeiitic) or 2B (alkaline) fractionation series of Stephens (1982b).

Walk along the road to the west to the next group of exposures, passing probably up the sheet-dip.

A greenschist unit with thin, dark limey layers is deformed in F_2 mesoscopic folds together with graphitic and rusty-weathered (sulphide-bearing?) phyllite. At the western end of the exposure, graphitic phyllite and calcareous, chloritic phyllite (fine-grained, reworked tuff?) occur by the road. These metasediments pass up the slope into layered felsic and mafic metatuffs with abundant crystal fragments. The pyroclastic debris is deformed in both the earlier foliation and later F_2 mesoscopic folds. The metasediments in these outcrops interlayered within the Stekenjokk Quartz-Keratophyre suggest that the volcanism was submarine, occurring in a calm, basinal situation away from the influence of a terrigenous source; some reworking of the volcanic material appears to have occurred.

Continue along the road to the west to the final group of exposures.

Epidote-carbonate-rich greenschist is interlayered here with graphitic phyllite. This unit probably lies above the fragmental metatuffs and mixed volcanic-sedimentary rocks of the immediately preceding exposures.

Stop 3.3 C–22 D Portfjället, 139915/716890. Walk westwards from Stop 3.3B to the road intersection. Head northwards to the next intersection, then turn westwards along the minor road running on the south side of the small lake (Holmtjärnen). c. 100 m from the intersection, examine outcrops along and just away from the south side of the road.

Several outcrops of a homogeneous, massive, granular-textured felsic body are exposed at this locality, being tentatively interpreted by Sjöstrand (1978) and Stephens (1982b) as a high-level intrusion. Particularly fresh samples may be studied in a recently blasted exposure where a large sample was taken for a U-Pb (zircon fractions) whole-rock isotopic dating study.

Although referred to by both Sjöstrand and Stephens as "quartz keratophyre", it is considered that this term should be reserved for the extrusive felsic rocks. In other places in the Stekenjokk Quartz-Keratophyre (Zachrisson, pers. comm., 1981), such massive, probably intrusive felsic rocks have been referred to as "albite granite". This term is, however, also unsatisfactory as these intrusive rocks have a similar high Na_2O and low K_2O chemistry as the extrusive quartz keratophyres. The term albite metatrondhjemite (Barker 1979) is, thus, preferred.

Stop 3.4: Minor metagabbro intrusions within the Blåsjö Phyllite.
Location: 22 E Frostviken, 140445/717225. Roadside exposure c. 2.5 km west of the intersection (Viken) between the road running along the north shore of Kvarnbergsvattnet and the road from Viken to Jormlien.

At this locality, two minor metagabbro sheets, the easterly one up to 2–3 m thick and the westerly one some tens of metres thick, intrude calcareous phyllite. The metagabbro-phyllite contacts are sharp and are parallel with the main foliation in the phyllite. The metagabbros are foliated, particularly near their margins, and show chilled contact relations. The phyllite at the western end of the exposure shows a complex foliation, the main foliation being a crenulation cleavage dipping more steeply to the northwest than an earlier, penetrative surface (mica-chlorite alignment). The 2 m thick zone of phyllite between the metagabbro sheets near the eastern end of the exposure is non-calcareous, a contact phenomenon which may be related to the intrusion of the metagabbros.

Stop 3.5: Minor albite metatrondhjemite intrusion within the Blåsjö Phyllite.
Location: 22E Frostviken, 140885/717690. Roadside exposure on the road between Jormlien and Viken, c. 7 km south from the Jormlien hotel.

At least 3 m of massive to slightly foliated albite metatrondhjemite (albite-quartz-epidote-mica rock) is in sharp contact above calcareous phyllite belonging to the Blåsjö Phyllite. The contact and foliation in the phyllite dip c. 40° to the NNW. The margin of this felsic body appears finer than the interior and an intrusive origin is suggested. The outcrop has recently been blasted and a large sample taken for a U-Pb (zircon fractions) whole-rock isotopic dating study.

Sjöstrand (1978) reported several bodies of similar type in the Blåsjö Phyllite south from Jormlien; they vary up to several hundred metres thick and are conformable with the main foliation. However, such felsic bodies are strongly subordinate to minor metagabbro intrusions in the Blåsjö Phyllite (see Stop 3.4).

DAY 3

B. THE METASEDIMENT-HOSTED ANKARVATTNET MASSIVE SULPHIDE DEPOSIT

K. Sundblad

INTRODUCTION

Location and geological setting. The Ankarvattnet deposit is situated in northern Jämtland, 2.5 km northeast of the village Ankarvattnet which lies along the northeastern shore of the lake with the same name (Fig. 16). A path leads from the second farm in the Ankarvattnet village up to the deposit which is situated some 350 m above the lake level.

The deposit lies in calcareous phyllites referred to by Nilsson (1964) as the Blåsjö Phyllite and interpreted by Sjöstrand (1978) to be a metamorphosed turbiditic, shale-greywacke sequence. Elongate metagabbroic bodies occur frequently adjacent to the mineralization. However, they are never in direct contact to the sulphide deposit. The metagabbros have a high-Ti basalt composition and have been interpreted by Stephens (1980a, 1982b) to be shallow intrusions related to post-arc rifting and marginal basin opening. The sulphide deposit has been drilled by the Geological Survey of Sweden (SGU) and an ore calculation has yielded 750 000 metric tons of ore at a grade of 18.4 % S, 5.5 % Zn, 0.45 % Cu, 0.37 % Pb, 0.2 ppm Au and 17 ppm Ag (Zachrisson 1964b). The deposit has a sheet-like morphology of about 2–5 m thickness and a diameter of 500 m. It lies parallel to subparallel to the main foliation in the surrounding calcareous phyllites and dips about 30–40° to the northwest (Fig. 18).

Mineralization types and spatial relationships. The deposit consists of iron sulphide-dominated massive (>50 vol.% sulphides) mineralization types lying in host rocks of more dispersely disseminated mineralization types. Two massive and four disseminated types have been distinguished:

1. Massive mineralizations
a) Pyrite type
b) Pyrrhotite type

2. Disseminated mineralizations
a) Sericite quartzite
b) Sericite-chlorite quartzite
c) Chlorite quartzite
d) Dolomitic phyllite

The *pyrite type* is dominated by pyrite and sphalerite while other sulphides, such as arsenopyrite, chalcopyrite, galena and pyrrhotite, occur more sporadically. Layering on a cm-scale between sphalerite- and pyrite-rich units is sometimes observed. The *pyrrhotite type* is dominated by pyrrhotite and sphalerite. Chalcopyrite and sometimes also pyrite occur more sporadically while other sulphides are very rarely observed. The *sericite quartzite* consists mostly of quartz and phengite with minor ankerite and disseminations of pyrite, sphalerite, pyrrhotite and arsenopyrite. The *sericite-chlorite quartzite* has a mineralogical composition consisting of quartz and ripidolite with minor ankerite and

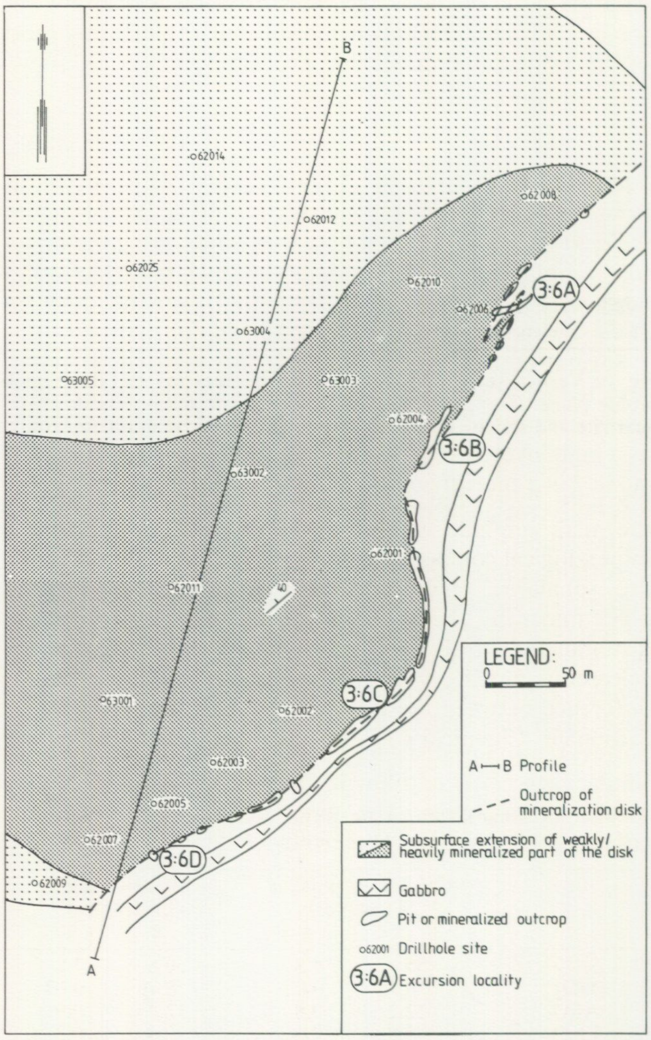


Fig. 18. Subsurface extension of the Ankarvattnet deposit projected to the horizontal plane (modified after Sundblad 1981b). Individual excursion stops are indicated. Unshaded area is calcareous phyllite.

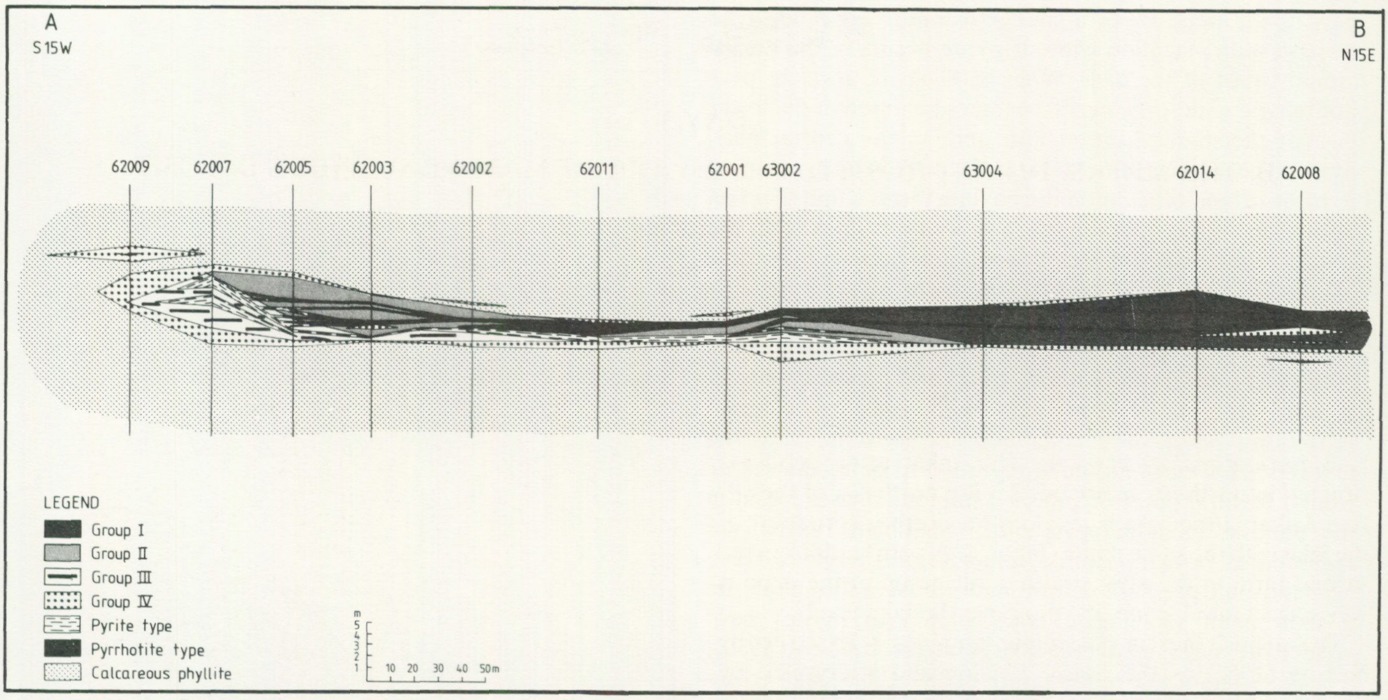


Fig. 19. Vertical section through the Ankarvattnet deposit (after Sundblad 1981b). Drillhole information has been projected perpendicular to the profile plane. Group I = chlorite quartzite with minor sericite-chlorite quartzite; Group II = interlayered chlorite quartzite, sericite-chlorite quartzite and sericite quartzite; Group III = sericite quartzite with minor sericite-chlorite-quartzite; Group IV = dolomitic phyllite.

phengite. Pyrrhotite, sphalerite, chalcopyrite and pyrite are the main sulphide minerals. The *chlorite quartzite* has a mineralogical composition of quartz and ripidolite. Pyrrhotite, sphalerite, chalcopyrite and pyrite are the main sulphide minerals. The *dolomitic phyllite* is the least sulphide-disseminated of all host rocks and is very similar to the calcareous phyllite forming the country rock. The major difference between these two rocks is the character of the carbonate. Chemical variations between the silicate-dominated mineralization types and the host calcareous phyllite are shown in Table 3.

The different mineralization types in the Ankarvattnet deposit display a characteristic overlapping geometry within the mineralized disk (Fig. 19). Thus, the chlorite quartzite is the dominating host rock in the northern part and overlies the sericite-chlorite quartzite in the central part of the disk. Furthermore, the sericite quartzite underlies the sericite-chlorite quartzite and is the host rock in the southernmost

TABLE 3. Chemical data for the silicate-dominated rocks at Ankarvattnet (Sundblad 1981a). $\bar{x}$ = mean value and s = standard deviation. Total Fe is shown as Fe_2O_3. Major (wt.%) and trace (ppm) elements by plasma spectroscopy (Burman *et al.* 1977).

		Calcareous phyllite (4 samples)		Dolomitic phyllite (3 samples)		Chlorite quartzite (5 samples)		Sericite-chlorite quartzite (3 samples)		Sericite quartzite (4 samples)	
		$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
%	SiO_2	55.9	4.8	50.6	7.0	68.3	1.8	72.0	0.8	81.9	2.2
	TiO_2	0.75	0.03	0.79	0.03	0.47	0.06	0.39	0.01	0.35	0.6
	Al_2O_3	12.2	0.8	12.4	0.9	6.7	0.9	5.8	0.3	5.2	0.9
	Fe_2O_3	5.8	0.6	5.8	0.3	11.3	2.3	8.5	0.5	4.6	1.1
	MnO	0.08	0.01	0.15	0.09	0.2	0.1	0.15	0.02	0.03	0.01
	MgO	4.0	0.7	9.6	1.8	5.9	1.0	4.0	0.8	0.7	0.4
	CaO	7.4	2.5	5.9	2.5	0.5	0.2	0.5	0.2	0.4	0.4
	Na_2O	1.8	0.4	1.2	1.8	0.1	0.1	0.6	0.2	0.4	0.6
	K_2O	2.3	0.2	1.9	0.1	0.05	0.02	0.4	0.2	1.3	0.5
	H_2O^+	2.5	0.4	3.8	1.3	3.6	0.6	2.2	0.3	0.9	0.3
	H_2O^-	0.4	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1
	CO_2	6.6	2.6	8.3	3.7	0.6	0.4	0.7	0.3	0.6	0.7
	S	0.05	0.02	0.3	0.2	1.6	0.7	3.7	1.0	3.0	1.6
ppm	Cu	15	4	49	61	368	170	663	255	317	342
	Zn	64	9	172	93	7300	2500	10170	4350	4140	4900
	Pb	37	4	71	26	106	126	367	240	935	213
	Zr	170	18	197	64	124	32	107	21	92	21
	Y	22	2	21	3	11	4	8	2	9	2

part of the deposit. In a similar manner, pyrrhotite-type massive mineralization without pyrite occurs in the northernmost part of the disk. When moving southwards, pyrr hotite type with some pyrite becomes common in the lower part of the mineralization disk and, in the central part, pyrite-type massive mineralization is overlain by pyrite-rich, pyrrhotite type. The dolomitic phyllite forms a thin sheet on both sides of the mineralization disk and is thickest in the southern part where it wraps around the sericite quartzite.

Metamorphism and deformation. The Ankarvattnet deposit and the surrounding country rocks were subject to low-grade metamorphism (chlorite zone) and polyphase deformation during the late Silurian. As a consequence, all mineralization types have recrystallized and show metamorphic textures. However, although regarded to be metamorphic from a textural point of view, all sulphide phases found in the deposit, including pyrrhotite (Sundblad 1981b), are regarded as primary from a mineralogical point of view. Metamorphic pressure determinations using the sphalerite geobarometer (sphalerite encapsulated in pyrite) have yielded pressures of 5.0±0.6 kbar (Hutchison & Scott 1980); a peak metamorphic temperature of 380° C has been estimated using the As content in arsenopyrite in mutual contact with both pyrite and pyrrhotite (Sundblad *et al.* 1984).

In a regional synthesis of northern Jämtland and southern Västerbotten, Zachrisson (1969) established a structural sequence built up of three deformation phases corresponding, respectively, to the D_1+D_2, D_3 and D_4 structures now generally recognized in the Middle Köli. All these deformation phases have been observed within the Ankarvattnet deposit which, thus, emphasizes its pre-deformational origin. The D_2 and D_4 structures are best seen in outcrop scale (see Stops 3.6A and 3.6C, respectively). The D_3 phase forms an open, flexure-like fold which is responsible for the S-shaped outcrop pattern seen in Fig. 18. This fold possesses a weak axial surface foliation which is nearly vertical and strikes N 50°E.

Genetic model. The present distribution pattern of mineralization types in an overlapping pattern within a disk-shaped exterior was shown by Sundblad (1980) to be a result of combined pure and simple shear of an originally T-shaped deposit, together with inversion of the whole deposit. The intense modification of the original geometry to produce the present, apparently concordant shape is considered to have occurred during the D_1 and/or D_2 phases of deformation. It is, thus, suggested that the deposit was originally built up with a discordant stringer zone, composed of pyrrhotite-type massive mineralization in chlorite quartzite and sericite-chlorite quartzite, underlying horizontal, exhalative layers of pyrite-type massive mineralization and sericite quartzite (Fig. 20). The stringer zone acted as a feeder system for ascending ore fluids, the country rocks in this way becoming highly altered and mineralized. The pyrite-type mineralization and sericite quartzite were formed when these ore fluids reached the sea floor and finally precipitated their solute to form chemical exhalites. The dolomitic phyllite formed at the very last stage of the hydrothermal activity and formed minor alteration effects at the outer edges of the stringer zone and also in the sediments already formed on top of the sericite quartzite.

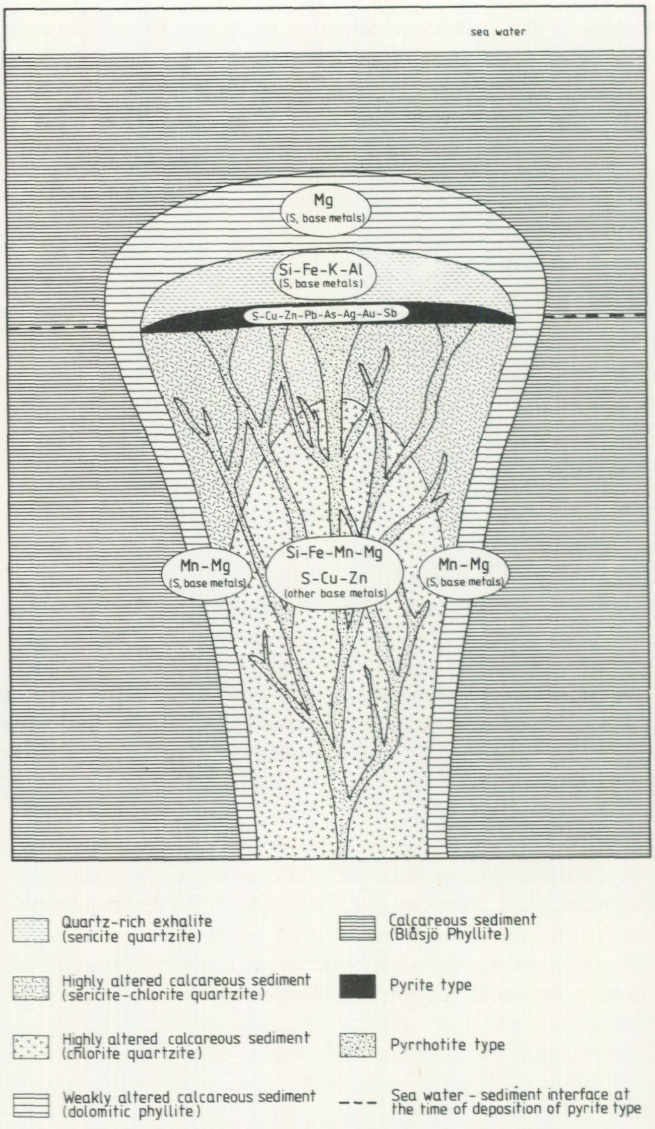


Fig. 20. Inferred pre-deformational geometrical relationships and most important chemical characteristics of each zone at the Ankarvattnet massive sulphide deposit (modified after Sundblad 1981a).

The dolomitic phyllite, chlorite quartzite and sericite-chlorite quartzite, in the presumed stringer zone, were formed by addition of Si, Fe, Mn, Mg, S and base metals to, and depletion of Ca, Na, K and CO_2 from the host calcareous sediments during ore fluid-host sediment interaction (Sundblad 1981a). Depletion of Na and K decreases stratigraphically upwards towards the layers believed to have been deposited on the sea floor. The presumably exhalative sericite quartzite was formed by precipitation of mainly Si, Fe, K and Al together with S and base metals. Nevertheless, the most conspicuous expression of chemical exchange during the mineralization process is the addition of Fe, S and base metals to the system which thus gave rise to the massive mineralization types. Lead isotopic analysis of galena from the pyrite-type massive mineralization has yielded $^{206}Pb/^{204}Pb$ = 18.133, $^{207}Pb/^{204}Pb$ = 15.544 and $^{208}Pb/^{204}Pb$ = 37.922 (Sundblad and Stephens 1983). This isotopic composition is only slightly more radiogenic than lead from the Stekenjokk deposit and a similar kind of source rock for these deposits is, therefore, envisaged.

STOP DESCRIPTIONS

Stop 3.6A: Tightly to isoclinally folded pyrrhotite-type layer in chlorite quartzite.
Location: 23E Sipmeke, 142710/720025. Outcrops and small pits 280 m NNE of main adit, 35 m east of drillhole 62006.

In these outcrops and pits, thin layers of pyrrhotite-type massive mineralization occur in chlorite quartzite. The pyrite content in the pyrrhotite type is very low in the northern part of these outcrops but increases when moving towards the south. Tight to isoclinal F_2 folds deform the mineralized layer and the earliest foliation (mica-chlorite alignment) in the adjacent silicate-rich rocks. The S_2 axial surface foliation forms the main foliation and the fold axes trend N70°W/40°. This fold phase is the earliest recognized in the area.

Stop 3.6B: Pyrrhotite-type massive mineralization in chlorite quartzite and sericite-chlorite quartzite.
Location: 23E Sipmeke, 142710/720020. Pit 200 m north of main adit, 30 m southeast of drillhole 62004.

Several pyrrhotite-layers occur in an irregular, anastomosing network pattern in chlorite quartzite and sericite-chlorite quartzite. The uppermost layers are very poor in pyrite while an increasing pyrite content is noted in pyrrhotite-type layers lower down. In the southern part of the pit, pyrite-type mineralization is seen lying under the pyrrhotite-type layers. This is the northernmost point where pyrite type has been observed in the deposit.

Stop 3.6C: Pyrite-type massive mineralization overlain by pyrrhotite type.
Location: 23E Sipmeke, 142700/720000. Pit and outcrops 60 m east of drillhole 62002, near the major adit.

In these exposures, pyrite-type massive mineralization is overlain by sericite-chlorite quartzite and pyrrhotite-type layers. A thin horizon of sericite quartzite underlying the pyrite type can be seen in the pit. No direct contact between pyrrhotite and pyrite types is present at this locality but has been observed in drillhole 62002. In the pit, 15 m north of the small entrance to the stope, all these mineralization types are folded by F_4 structures with flat-lying axial surfaces and fold axes plunging N40°E. This fold phase is the latest recognized in the area. 10 m to the north of these folds, boudinage structure may be observed in the pyrite type with thicknesses varying between 20 and 50 cm.

Stop 3.6D: Sericite quartzite.
Location: 22E Frostviken, 142690/719990. Outcrops in a partly covered trench, 150 m south of major adit, 40 m east of drillhole 62007, 30 m south of drillhole 62005.

Sericite quartzite is here up to 5 m in thickness and is underlain by dolomitic phyllite. No massive mineralization types can be observed at this locality but pyrite type has been observed overlying the sericite quartzite in drillholes 62005 and 62007.

DAY 4

A. THE STEKENJOKK Zn-Cu(-Pb) MASSIVE SULPHIDE DEPOSIT IN A BIMODAL METAVOLCANIC SEQUENCE

E. Zachrisson

INTRODUCTION

Discovery and investigations. The Stekenjokk Zn-Cu(-Pb) massive sulphide deposit (Figs. 16 and 21) was discovered in 1918 due to a large number of ore blocks in a heavily moraine-covered area. During the same year, a tiny outcrop of compact pyrite ore was located in a small stream. First investigations, including 11 diamond drillholes, were carried out in 1918–1921 (Högbom 1925). The main period of investigations, with more than 60 000 metres of drilling, extended over the time period 1952–1963. An underground survey was handled by the Boliden Company, 1963–1966. The mill and mine were built in 1973–1976 and production started late in 1975. It is the only producing deposit in the Swedish part of the Caledonian allochthons, being run for the government by Boliden Mineral AB. Two major ore bodies exist, Stekenjokk and Levi, with the following grades and tonnages (Zachrisson 1982b, 1984):

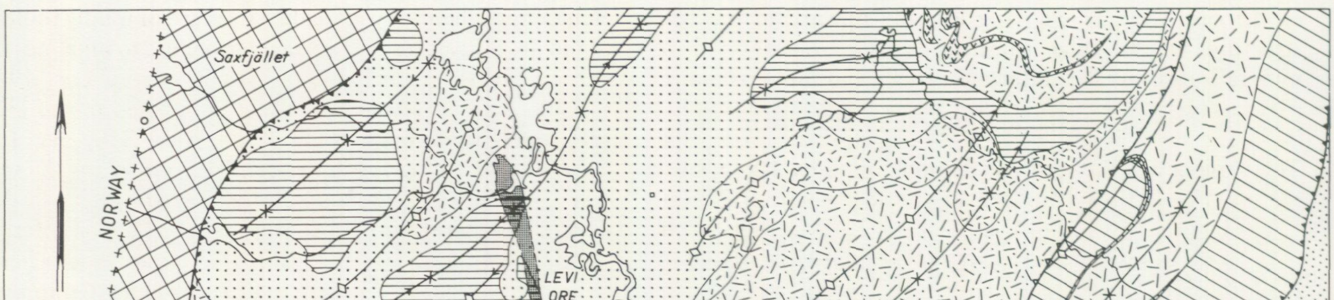


Fig. 21. Geological map of the Stekenjokk area.

	Tonnage (metric tons)	Cu %	Zn %	Pb %	S %	Au g/t	Ag g/t
Levi	5 260 368	1.33	1.78	0.10	15.4	0.15	26
Stekenjokk	20 453 170	1.35	3.22	0.36	18.76	0.30	54
Total	25 713 538	1.35	2.93	0.31	18.1	0.27	48

The Stekenjokk mine operates at a rate of 600 000 metric tons/year. At present, c. 6 million metric tons of ore have been mined out. Due to low metal prices and high production costs, ore reserves have been reduced; at the same time, Levi has become subeconomic.

Structure. In a horizontal projection (Fig. 22), the Stekenjokk-Levi ore bodies are extremely elongate (Zachrisson 1971). Together they cover a total length of more than 9 km, 1.5 km being eroded away over the Stekenjokk culmination. The average width varies between 100 and 300 m. In cross-section, Levi forms, as far as is known, a single, flat-lying layer. The Stekenjokk ore horizon, generally 2–10 m thick, occurs in complex isoclinal, eastwards-facing F_2 fold structures. A consecutive suite of cross sections is shown in Fig. 23. The long axis of the ruler-shaped ore layer is slightly oblique to the generally NNW axial direction of the F_2 folds. As a result, the sulphide ores, representing the thickest parts of the ore layer, move progressively upward in the fold structure when going southwards. The distribution of mineralization-related alteration rocks and metal zonation patterns (Juve 1977; Zachrisson 1982a, 1984 and see below) indicate a major inversion of the stratigraphy at Stekenjokk. The vergency of the folds, as demonstrated by a composite section (Fig. 24), gives further support to this interpretation.

The inverted Stekenjokk sequence, with its internal isoclinal F_2 folds described above, was subsequently deformed by NNE–SSW F_3 folds with a subvertical, axial surface crenulation cleavage. The resulting major structures include the Stekenjokk Antiform (Figs. 21 and 22) and the adjacent synforms in the Levi and Gelvenåkko areas, the latter containing the infolded Gelvenåkko Nappe (Fig. 21). The southern extension of the Stekenjokk ore body can be traced beneath the sole thrust of the Gelvenåkko Nappe.

An attempt to unfold the isoclinal F_2 fold stack into an inverted position (Zachrisson 1984) reveals a pre-F_2, perhaps primary elongate ore sheet, present over a length of more than 10 km and with a width varying between 100 to 700 m (Fig. 25).

Lithology and stratigraphy. The Stekenjokk Quartz-Keratophyre, hosting the Stekenjokk and Levi ore bodies, forms an important and persistent bimodal metavolcanic formation stratigraphically beneath (structurally above) mafic metavolcanites (Lasterfjället Greenschist) and calcareous metagreywackes (Blåsjö-Lasterfjället Phyllite), (Figs. 16 and 21). It has a major lateral extension (150 km) and shows marked variations in thickness (0–1 km). The mafic metavolcanites are often spilitic (Stephens 1980b). Chemical changes of felsic rocks during this process involved addition of Na, net losses of Fe, Mg, Ca and K, and, of special interest in this context, extraction of Cu and Zn (see Table 4, pre-alteration and altered composition estimates, Stephens 1980b). Major and especially less mobile trace element geochemistry indicate a mixture of mildly tholeiitic island arc volcanites and strongly tholeiitic to alkaline, probably intrusive, rifting-type basalts (Stephens 1977a, 1982b). Apart from pelmatozoan fragments in the stratigraphically underlying Remdalen Group (Högbom 1925, Sjöstrand 1978), no fossils are available for dating the sequence. The Stekenjokk metavolcanites are probably Ordovician in age (Sjöstrand 1978, Stephens 1982b), an inference strongly supported by the specific trace element geochemistry of a graphitic phyllite (see below), lying stratigraphically immediately above the Stekenjokk-Levi stratabound sulphide horizon (Sundblad & Gee 1984).

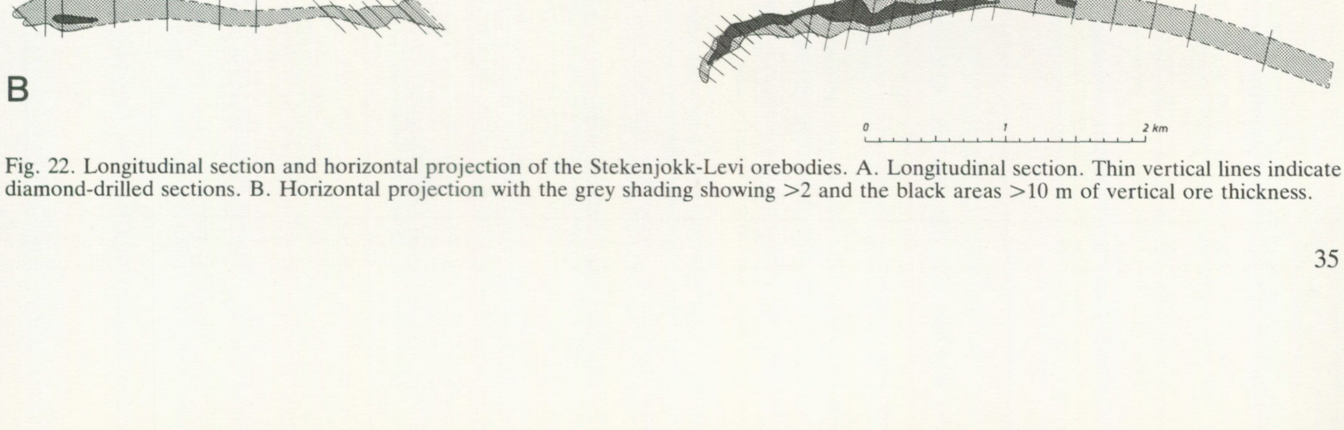


Fig. 22. Longitudinal section and horizontal projection of the Stekenjokk-Levi orebodies. A. Longitudinal section. Thin vertical lines indicate diamond-drilled sections. B. Horizontal projection with the grey shading showing >2 and the black areas >10 m of vertical ore thickness.

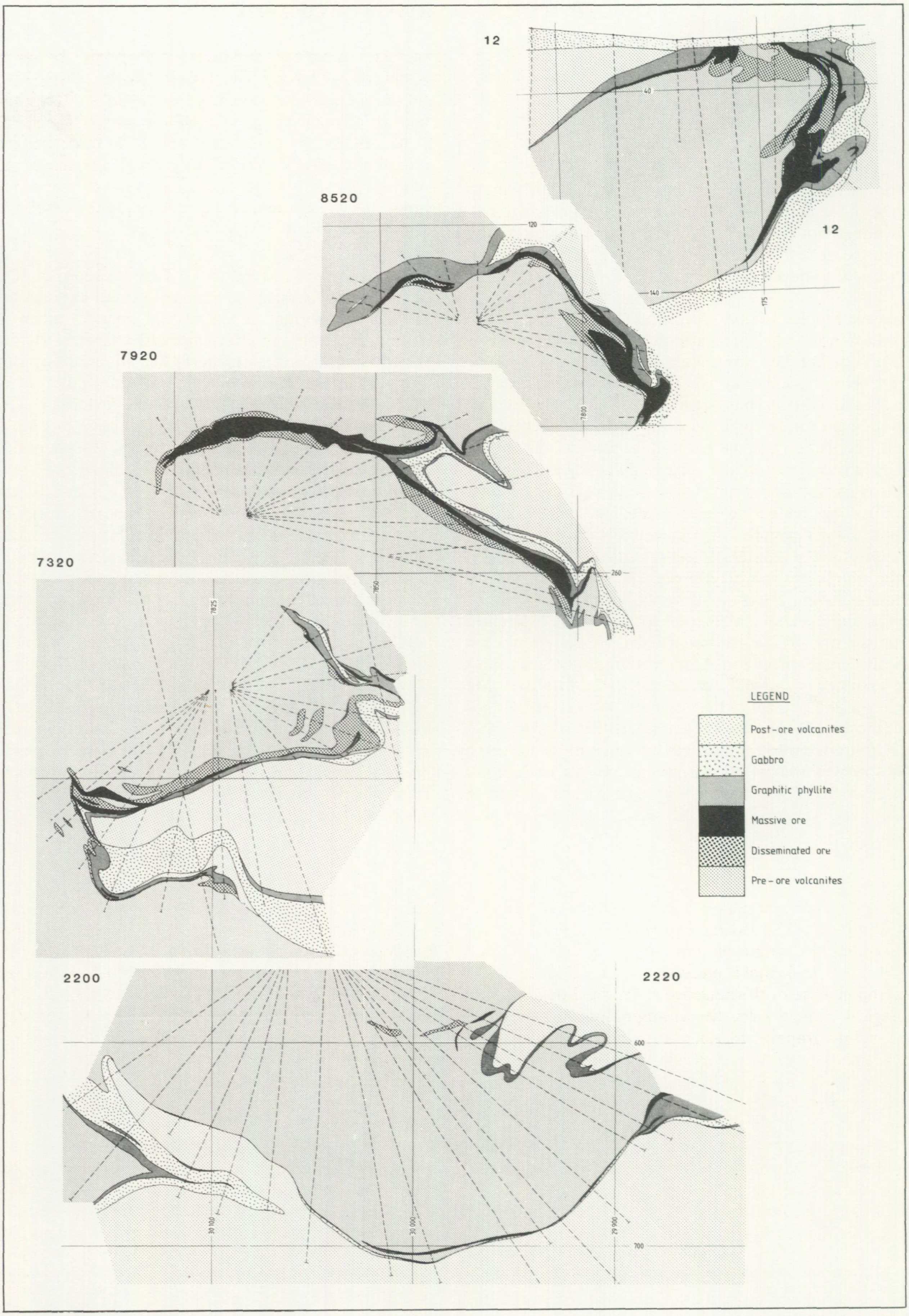


Fig. 23. Cross sections of the northern and central parts of the Stekenjokk orebody, looking north. Locations shown in Fig. 25. The profiles are based on extensive tunneling and mining operations by Boliden Mineral AB combined with surface and underground drilling. All grid figures in metres, depth below surface.

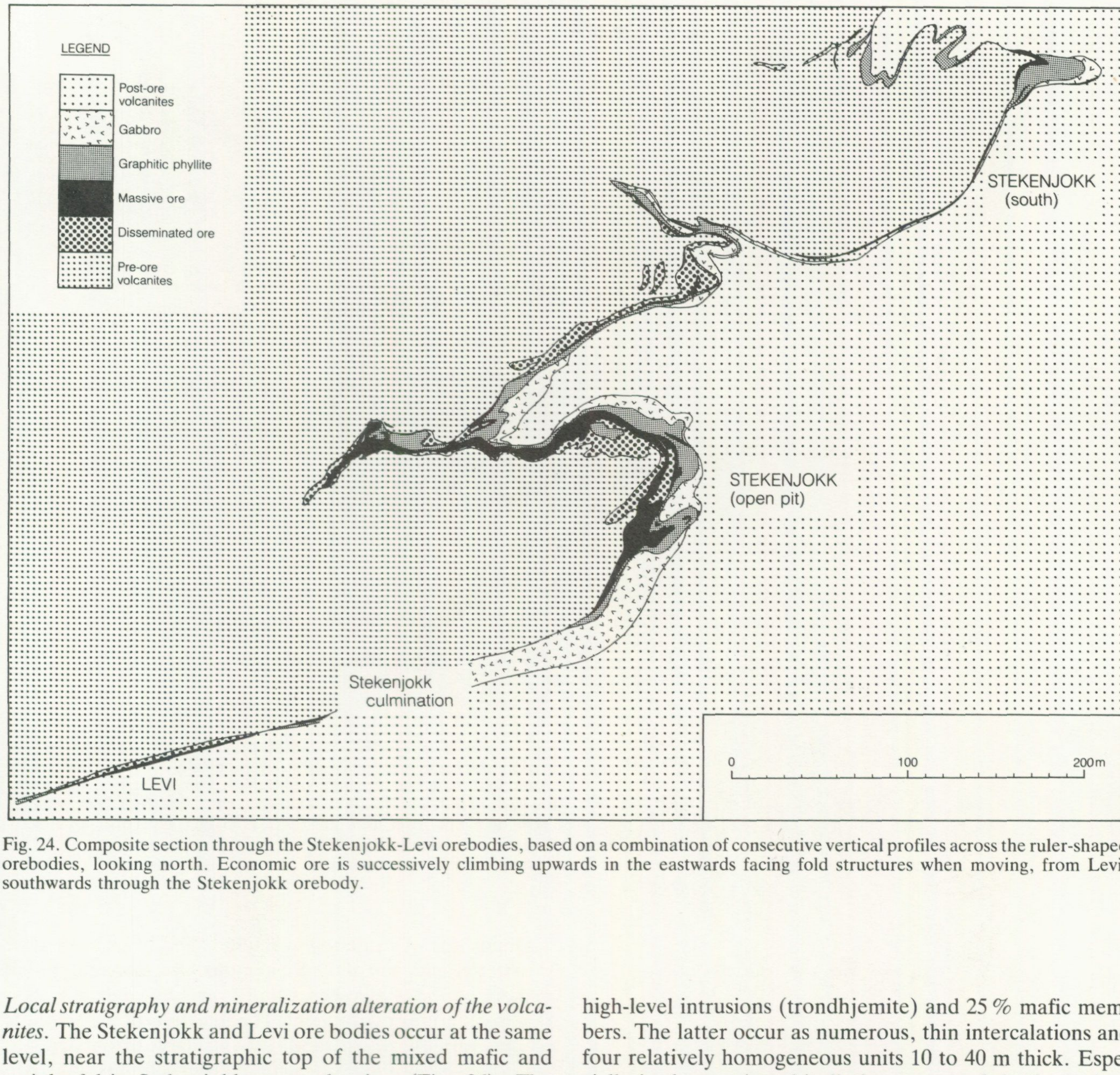
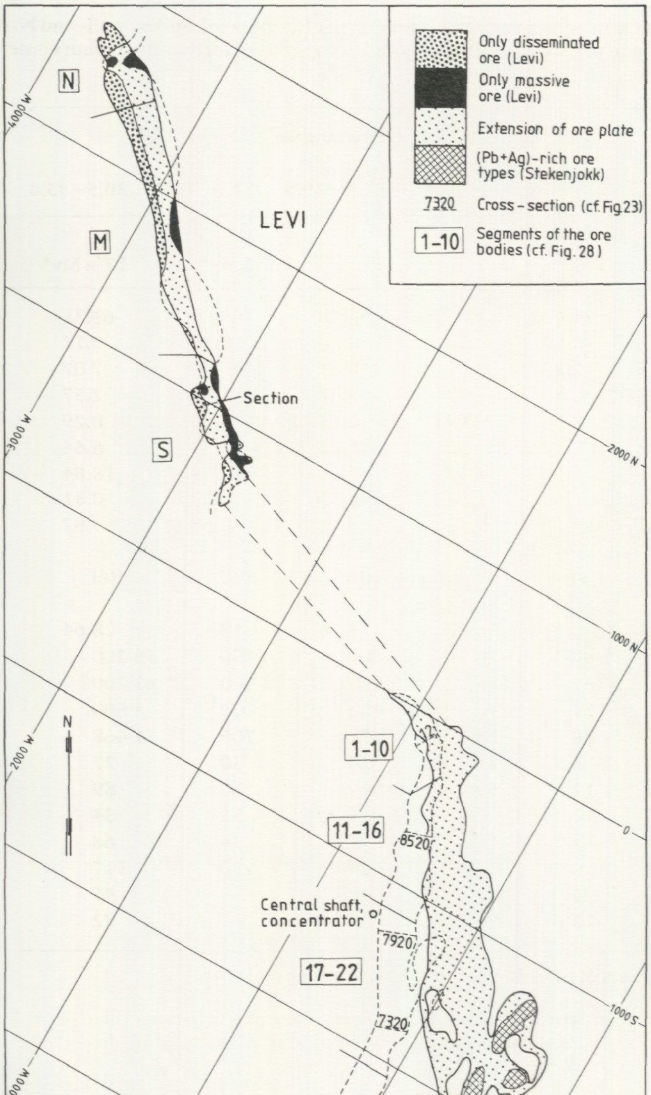


Fig. 24. Composite section through the Stekenjokk-Levi orebodies, based on a combination of consecutive vertical profiles across the ruler-shaped orebodies, looking north. Economic ore is successively climbing upwards in the eastwards facing fold structures when moving, from Levi, southwards through the Stekenjokk orebody.

Local stratigraphy and mineralization alteration of the volcanites. The Stekenjokk and Levi ore bodies occur at the same level, near the stratigraphic top of the mixed mafic and mainly felsic Stekenjokk metavolcanites (Fig. 26). The stratigraphic base of this sequence is marked by an abrupt lithological change from the stratigraphically underlying grey, slightly graphitic phyllites into the felsic metavolcanites (quartz keratophyres). North and south of the Stekenjokk area (Zachrisson 1969), this transition is marked by a quartzite conglomerate or pseudoconglomerate, which is thicker to the south (Portfjället Conglomerate of Sjöstrand 1978). The top of the Stekenjokk Quartz-Keratophyre is defined by the cessation of felsic members. In the Stekenjokk area, the Lasterfjället Greenschist rests directly on top of the Stekenjokk Quartz-Keratophyre, without intervening metasedimentary members.

The total stratigraphic thickness of the Stekenjokk metavolcanites is c. 650 m. The formation is composed of approximately 75 % comagmatic felsic metavolcanites and high-level intrusions (trondhjemite) and 25 % mafic members. The latter occur as numerous, thin intercalations and four relatively homogeneous units 10 to 40 m thick. Especially in the stratigraphically lower part of the formation, where pre-deformational felsic, high-level intrusions are common, there are centimetre- to metre-thick intercalations of a homogenous, typically plagioclase-phyric greenstone or greenschist. Chilled margins, indicated by the reduced size and content of the phenocrysts, can often be observed and these mafic rocks are also interpreted as high-level intrusions. Their apparently concordant geometry is caused, at least in part, by intense deformation. Metagabbro intrusions occurring within graphitic phyllites immediately above the ore also have mineralogical and chemical compositions similar to the plagioclase-phyric greenstones and the mafic rocks of the overlying Lasterfjället Greenschist (Stephens 1980a). These are generally high-Ti basaltic rocks showing MORB and WPB affinity and are related to the later rifting stage of arc development (Stephens 1980a, 1982b).



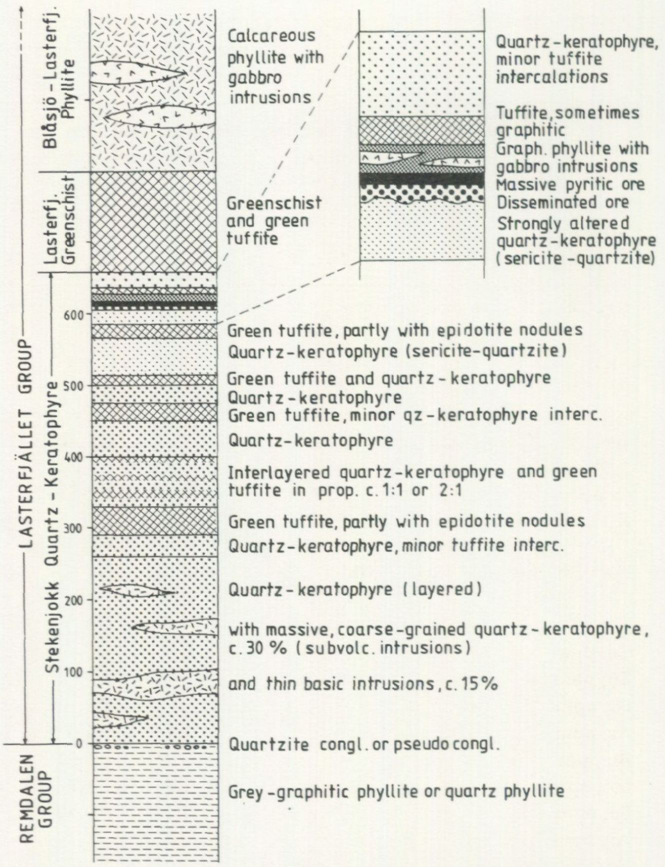


Fig. 26. Schematic section of the Stekenjokk Quartz-Keratophyre Formation (thickness in metres) and stratigraphically over- and underlying formations, based on borehole information from the central and northern parts of the Levi area. The sequence, which is regionally inverted, is shown in the diagram according to the inferred correct order of deposition.

Deposition of stratabound sulphide and black shale near the stratigraphic top of the Stekenjokk Quartz-Keratophyre marks a period of quiescence and a very slow sedimentation rate in a marine environment. The thickness of the graphitic phyllite varies between 0 and 10 m, to a large extent depending on the degree of deformation. High contents of U, Mo and V led to the conclusion (Sundblad & Gee 1984) that the graphitic phyllite at Stekenjokk might be related in time to the Alum Shale Formation, which on the Baltoscandian Platform is of late Cambrian-early Ordovician age. The graphitic phyllite is often intruded by sill-like, metagabbro bodies.

Fig. 25. Shape of the unfolded Stekenjokk-Levi ore layer in horizontal projection. The more regular, flat-lying Levi orebody is kept in its inverted position and the Stekenjokk part is unfolded into a similar inverted position. Distribution is shown of areas at Levi with only disseminated stringer ore and only massive pyrite ore, and at Stekenjokk of ore types with high Pb + Ag-contents. Unit area of grid equals 1 km^2; position of cross sections presented in Fig. 23 are shown with dashed lines and small figures; framed letters and figures indicate segments referred to in Fig. 28.

TABLE 4. Major elements in silicate fraction (recalculated to 100%) and base- and trace-metal contents of felsic metavolcanites, wall- and host-rock quartz keratophyres (quartz-sericite rocks), and heavily disseminated and massive ores at Stekenjokk, according to increasing sulphur content (after Zachrisson 1982a).

	Felsic rocks Pre-alteration	Altered	Quartz–keratophyre Sulphur content, % 0–0.5	0.5–1.0	1.0–2.5	2.5–5.0	5.0–10.0	Ore samples 10.0–20.5	17.0–20.5	20.5–35.8
No. of samples	2–9	6–16	72	26	14	3	3	9	2 Mv*	17 + Mv*
SiO_2, %	69.96	78.51	73.12	74.92	74.85	76.40	82.05	64.78	63.00	63.31
TiO_2, %	0.55	0.18	0.26	0.22	0.25	0.13	0.19	0.08	0.16	0.15
Al_2O_3, %	13.14	11.65	13.66	13.33	13.92	12.24	8.34	10.85	10.60	7.07
FeO, %	4.45	1.93	2.74	2.07	1.36	2.55	1.27	2.81	1.75	2.57
MnO, %	0.08	0.03	0.06	0.09	0.06	0.06	0.09	0.13	0.19	0.29
MgO, %	2.22	0.81	3.18	3.40	4.02	3.79	4.20	15.72	12.54	6.64
CaO, %	3.24	1.01	1.83	1.64	1.50	1.12	1.53	5.21	10.89	18.84
Na_2O, %	5.05	5.57	3.70	2.62	2.14	1.41	1.62	0.31	0.29	0.31
K_2O, %	1.31	0.31	1.45	1.71	1.90	2.30	0.71	0.11	0.58	0.82
Total, %	100	100	100	100	100	100	100	100	100	100
S, %	–	–	0.19	0.71	1.54	3.27	6.25	13.16	18.65	28.64
Cu, ppm	28	5	28	69	221	1 080	6 970	21 000	16 100	18 200
Zn, ppm	91	30	87	147	720	2 467	6 175	5 800	25 200	41 200
Pb, ppm	–	–	8	28	71	127	70	400	2 000	4 500
As, ppm	–	–	2.1	6.0	16	28	58	278	700	1 468
Bi, ppm	–	–	0.26	0.61	1.3	3.5	21	20	30	27
Mo, ppm	–	–	2.0	3.7	8.2	12	50	49	50	89
Sn, ppm	–	–	0.54	0.50	1.7	10	5.0	15	35	34
Ag, ppm	–	–	0.13	0.27	1.3	2.7	7.3	33	34	68
Co, ppm	–	–	4.2	5.7	7.7	10	22	58	160	117
Ni, ppm	–	–	13	17	24	25	42	28	–	47
V, ppm	–	–	36	44	66	25	90	37	–	92

*Mv indicates bulk ore analysis of drilled cross-section, including all drill cores (25–40 m) that penetrate economic ore.

The stratabound ore – graphitic phyllite horizon is overlain by a 20–200 (?) m thick sequence of post-ore metavolcanites. These rocks are more clearly banded due to a better colour-preservation of light (quartz keratophyre) and green (tuffite, greenschist) layers, generally with an intimate alternation of the two components. By contrast, the immediate pre-ore felsic volcanites have been altered to a quartz-sericite rock while the mafic members have been strongly bleached and converted to chlorite or chlorite-sericite rocks (Juve 1980). However, such clear differences between pre- and post-ore metavolcanites occur only where the stratigraphically upper part of the pre-ore sequence has been strongly affected by alteration close to exhalative centres.

Geochemically, the already spilitized pre-ore volcanic pile was altered during mineralization, close to discharge areas, involving loss of Na and a marked enrichment in K and Mg (Zachrisson 1982a, 1984; cf. Table 4). The thinner post-ore sequence of felsic and mafic metavolcanites lacks the mineralization alteration described above and is of the normal spilitic type, similar to the pre-ore metavolcanites away from the mineralization.

Ore-types. The Stekenjokk-Levi ore deposit principally contains two different types of ore with pyrite, pyrrhotite, chalcopyrite, sphalerite and galena in various proportions. These are composed of (1) massive stratabound pyritic ore with Cu $<$ Zn and (2) irregularly disseminated, generally pyrrhotitic ore, often with Cu $>$ Zn. The latter contains higher (although subeconomic) contents of Bi, Mo and Sn and has been interpreted as representing the stringer ore system (Zachrisson 1982a) whereas the massive ore type shows higher metal/sulfur ratios for Pb, As, Sb, and Ag and comprises the exhalative stage of mineralization. An illustration of the geometrical distribution of the two ore types is given in Fig. 23.

The lead isotope composition of galena-lead from five samples of Stekenjokk-Levi pyrite ore is very homogeneous and is on average $^{206}Pb/^{204}Pb = 18.025$, $^{207}Pb/^{204}Pb = 15.536$ and $^{208}Pb/^{204}Pb = 37.699$ (Sundblad & Stephens 1983). These data plot between the mantle and orogene curves of Zartman and Doe (1981).

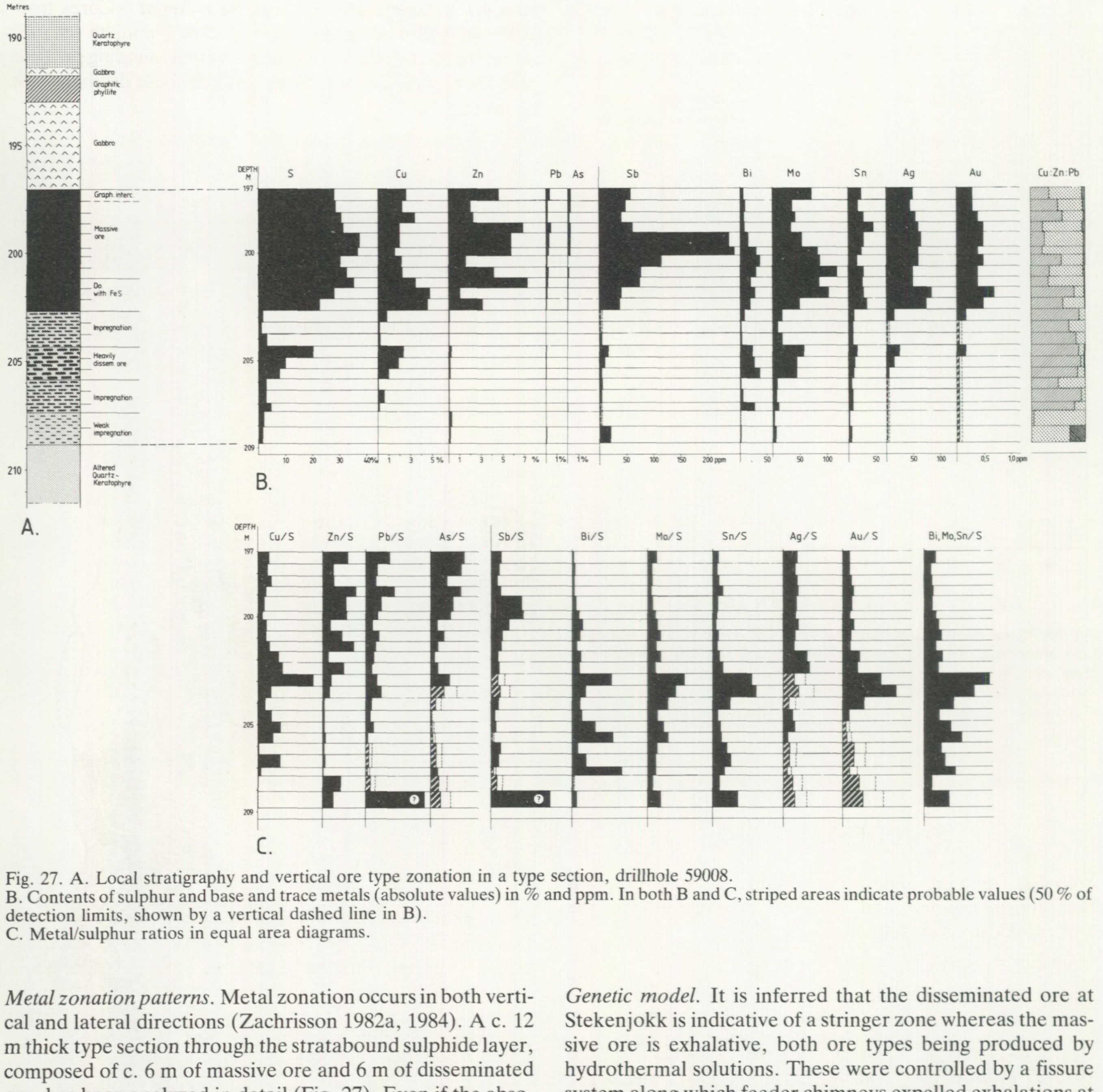


Fig. 27. A. Local stratigraphy and vertical ore type zonation in a type section, drillhole 59008.
B. Contents of sulphur and base and trace metals (absolute values) in % and ppm. In both B and C, striped areas indicate probable values (50 % of detection limits, shown by a vertical dashed line in B).
C. Metal/sulphur ratios in equal area diagrams.

Metal zonation patterns. Metal zonation occurs in both vertical and lateral directions (Zachrisson 1982a, 1984). A c. 12 m thick type section through the stratabound sulphide layer, composed of c. 6 m of massive ore and 6 m of disseminated ore, has been analyzed in detail (Fig. 27). Even if the absolute contents of S and nearly all base and trace metals are higher in the massive ore layer, the sulphide phase itself is enriched (higher metal/S ratios) in Cu, Bi, Mo and Sn in the stringer zone and in Zn, Pb, As, Sb and Ag in the exhalative massive ore. Au analyses are not conclusive. It is furthermore evident that enrichment of Pb, As and possibly also Zn occurs toward the top of the massive ore layer. The distribution and proportions of different ore types give rise to systematic lateral variations in the metal contents (Fig. 28). The overall pattern indicates decreasing Cu and increasing Pb proportions toward the south. This is even more accentuated when the Pb/Cu ratio is considered. The Ag-content has a strong positive correlation with Pb.

Genetic model. It is inferred that the disseminated ore at Stekenjokk is indicative of a stringer zone whereas the massive ore is exhalative, both ore types being produced by hydrothermal solutions. These were controlled by a fissure system along which feeder chimneys expelled exhalations at several locations (Zachrisson 1984). The fissure zone also controlled the bottom topography, creating local troughs in which the brines deposited their Fe and base metal sulphides, metals being extracted from the volcanites during the spilitization process (Stephens 1980b). The period of sulphide deposition occurred at a late stage of the arc development, during an extensional régime related to the incipient intra-arc rifting (Stephens 1980b, 1982a). The lateral metal zonation indicates a general southward migration of the expelled brines. Even if most of the mineralization indicates proximal conditions, the southernmost, Pb- and Ag-rich parts probably represent more distal deposition.

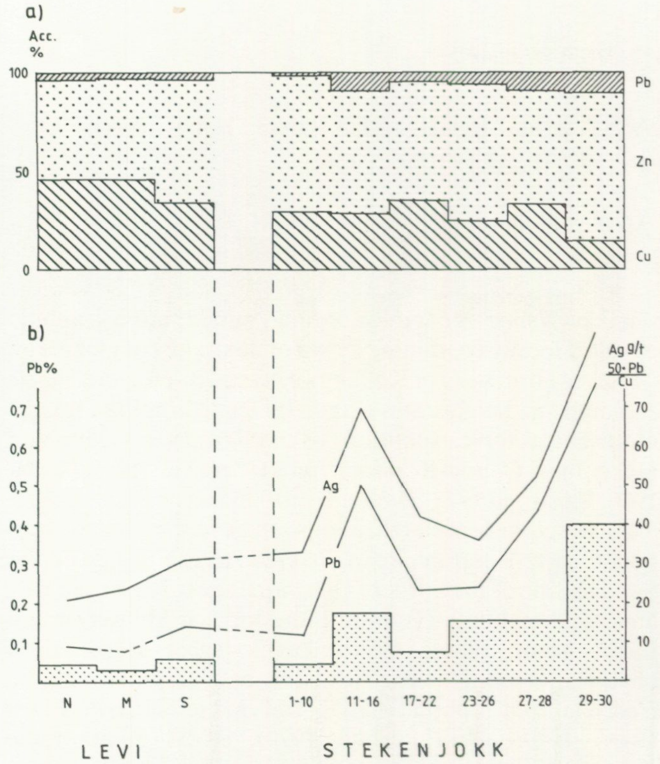


Fig. 28. Metal distribution patterns along the combined Stekenjokk-Levi orebodies. (a) Base metal proportions. (b) Pb/Cu ratios (histogram) and Pb- and Ag-contents. N, M, S, and the numbers 1–30 refer to various segments of the Levi and Stekenjokk orebodies, respectively, as indicated in Fig. 25.

STOP DESCRIPTIONS

Stop 4.1: Open pit, underground (subject to mining operation considerations) and drillcore examination of the Stekenjokk massive sulphide deposit.
Location: 23E Sipmeke, 143680/722150. Stekenjokk office site, c. 20 km west of the Klimpfjäll village, along the Saxnäs – Stora Blåsjön road.

Stop 4.1A, open pit – During the summer-autumn seasons 1975–77 (with minor clearing operations 1981), the upper part of the Stekenjokk ore was mined in an open pit (Fig. 29), taking out the lower limb, the fold hinge and minor parts of the upper limb of the isoclinal ore fold down to a depth of c. 50 m. It is intended to walk down the ramp, descending to the bottom of the quarry. Most of the ore has been mined out but some is to be seen as well as the various host and wall rocks. Early isoclinal folds with axial surfaces subparallel to the regional foliation and superimposed F_3 folds with axial surface crenulation cleavage will be studied.

Stop 4.1B, underground mining operation – A visit will be made to the underground mining operation to demonstrate ore sections, ore types and wall rocks at a few places. Relevant material will be distributed during the mine visit.

Stop 4.1C, examination of drillcore material – Cores from drillholes will be demonstrated to show complete sections across the stratabound ore horizon and surrounding pre- and post-ore metavolcanites. Samples from these drillholes can be taken.

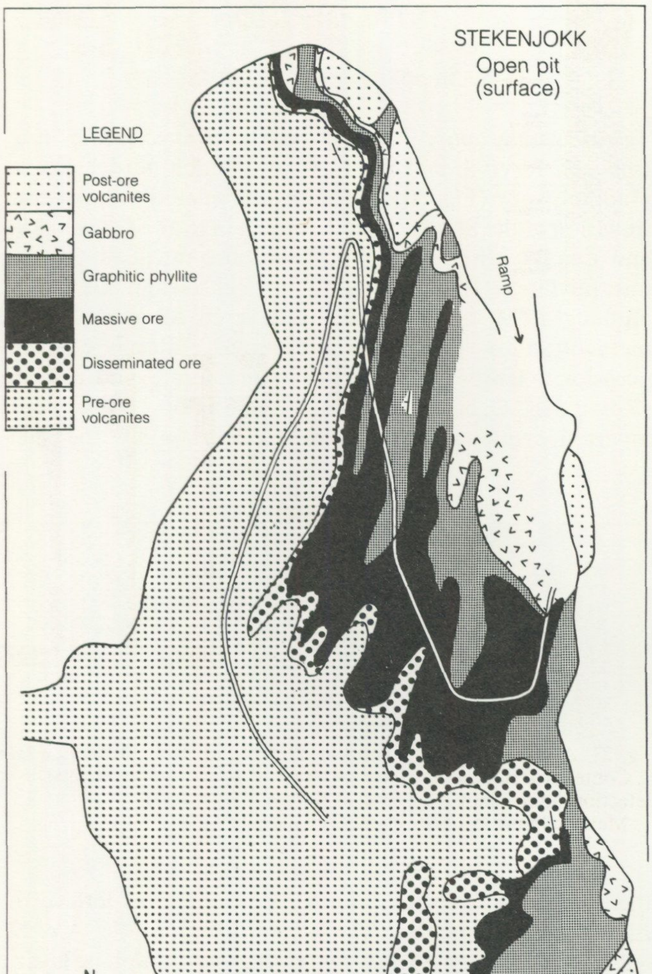


Fig. 29. Outcrop map of the open pit area at Stekenjokk as observed when the Quaternary cover was stripped off. The position of the "road" leading to the bottom of the excavation is also projected onto this surface and thus does not always give a correct position in relation to the geology shown on the map.

DAY 4

B. LITHOLOGY AND DEFORMATION IN THE MASSIVE SULPHIDE-BEARING GELVENÅKKO AND LEIPIKVATTNET NAPPES, UPPER ALLOCHTHON

A. Reinsbakken and M.B. Stephens

INTRODUCTION

M.B. Stephens and A. Reinsbakken

Tectonostratigraphy, lithology and palaeotectonic setting. Between Røyrvik and the Norway-Sweden border east of Huddingsvann (Fig. 30), the highly attenuated westerly continuation of the Stikke Nappe is overlain by the Gelvenåkko and Leipikvattnet Nappes. Metagabbro-intruded calcareous phyllites (Blåsjö Phyllite or Renselvann Group of Kollung 1979) overlain by interlayered felsic and mafic metavolcanites (Stekenjokk Quartz-Keratophyre), and occasional lenses of quartzite conglomerate and phyllite (Remdalen Group) comprise the Stikke Nappe. This inverted sequence is tectonically overlain by the Gelvenåkko Nappe, a complex of fine-grained, often graphitic phyllites locally containing lenses of quartzite conglomerate (Rantser Formation of Kollung 1979) and interlayered felsic and mafic metavolcanites (Fig. 30). These lithological units represent tectonic repetitions of the Remdalen Group and Stekenjokk Quartz-Keratophyre, respectively (Zachrisson 1969, Sjöstrand 1978). Minor (<50 000 metric tons), Cu-Zn massive sulphide mineralizations are hosted by the Stekenjokk Quartz-Keratophyre in the Gelvenåkko Nappe on the Swedish side of the border. This thrust sheet is overlain by a limestone mylonite (Bjurälv Limestone or Huddingsvann Limestone of Kollung 1979) and a thick succession of mixed phyllites, layered quartz-rich rock and graphitic phyllite (recrystallized ribbon chert), and mafic metavolcanites (Røyrvik Group of Kollung 1979), all lying within the Leipikvattnet Nappe (Fig. 30). This sequence has been cor-

Fig. 30. Geological map of the Huddingsvann-Røyrvik area and location of stops on Days 4 and 5. Geology based on Kollung (1979).

related with the Remdalen Group (Sjöstrand 1978, Kollung 1979) and the geochemistry of the mafic metavolcanites in both units, indicating a tholeiitic to alkaline character and N-MORB as well as E-MORB or WPB affinity (Olsen 1980, Stephens *et al.* 1985b, Reinsbakken, unpublished data, 1986 and Fig. 9), provides support for this hypothesis. Whereas Olsen (1980) suggested a back-arc basinal environment for the sequence in the Leipikvattnet Nappe, Stephens and Gee (1985), on the basis of the regional geological setting and the metavolcanite geochemistry, proposed that these rocks represent the upper and probably off-axis segment of the ocean floor to a rifted arc complex. Disrupted pieces of this rifted arc and the post-arc marginal basin infill occur in adjacent thrust sheets, i.e. the underlying Stikke and Gelvenåkko, and overlying Gjersvik Nappes (Stephens & Gee 1985).

Deformation. The sequence described above occurs on the northwestern limb of a late upright synform (Joma Synform, Fig. 30). The axial surface trace of this synform trends northeastwards from Limingen to Leipikvattnet where it merges into the post-thrusting F_3 Western Synform (Zachrisson 1969). In the thickened hinge zone of this synform southwest of Huddingsvann, three levels of mafic metavolcanites have been recognized within the Leipikvattnet Nappe. The middle metavolcanic unit hosts the major Cu-Zn massive sulphide deposit at Joma. Ongoing work (Odling, pers. comm., 1985) suggests that these three levels represent imbricate thrust sheet repetitions of the same metavolcanic horizon and that the thrust at the base of the middle unit is a slide related to an overturned, earlier F_2 fold. Thus, it is apparent that the Leipikvattnet Nappe is a complex of thrust sheets.

Four mesoscopic deformation phases are recognized (Odling, pers. comm., 1985) in agreement with the structural sequence in the underlying Köli units. D_1 and D_2 account for early strains associated with regional schistosity development. Post-thrusting D_3 structures are parasitic to the major Joma Synform and D_4 includes late folds with flat-lying axial surfaces.

STOP DESCRIPTIONS

A. Reinsbakken

The excursion will examine the lithologies and deformational features in both the Gelvenåkko and Leipikvattnet Nappes. This will provide a basis for the geological setting of the Joma Cu-Zn deposit which will be visited on Day 5 of the excursion.

Stop 4.2: Contact between Gelvenåkko and Leipikvattnet Nappes.
Location: Map-sheet M711/1924 I Huddingsvatnet, VM 4525/9580. North side of Stora Blåsjön-Røyrvik road at junction with access road to the Joma mine.

Gently northerly dipping, grey to white, layered limestone mylonite lies with sharp contact beneath a sequence of layered dark greenschist, consisting of chlorite, epidote, actinolite and carbonate, and paler quartz keratophyre. The compositional layering in both limestone and metavolcanites is a metamorphic layering (S_2). Much calcite and epidote are concentrated along the S_2 surfaces. Late (F_4), minor, open folds and crenulations with near-horizontal axial surfaces are conspicuous in the layered metavolcanites. This contact represents the tectonic surface between the Bjurälv (Huddingsvann) Limestone at the base of the Leipikvattnet Nappe and the Stekenjokk Quartz-Keratophyre in the upper part of the Gelvenåkko Nappe. The contact is here locally overturned by the later, post-thrusting, F_3 structures which cause significant variations in dip of the S_2 surfaces in the Huddingsvann area.

Stop 4.3: Polyphase deformed layered metavolcanites (Stekenjokk Quartz-Keratophyre) in the Gelvenåkko Nappe.
Location: Map-sheet M711/1924 IV Røyrvik, VM 3700/9720. Small stream crossing the Stora Blåsjön-Røyrvik road, immediately west of the Myrmo farm; north side of road.

This stop is situated in the well-layered metavolcanites (Stekenjokk Quartz-Keratophyre) of the Gelvenåkko Nappe, just beneath the contact to the Leipikvattnet Nappe. The metavolcanites are represented by paler quartz keratophyre and darker biotitized greenschist rich in chlorite, actinolite and subordinate plagioclase and biotite; the compositional layering is of cm to dm thickness.

This locality demonstrates the complex polyphase deformation in the area. Westward-trending, tight to isoclinal folds (F_2), deforming an earlier compositional layering and showing an intense axial surface foliation, are refolded by upright, open, F_3 structures plunging gently westward and having a steeply NW-dipping axial surface. The steeply-dipping S_2 surfaces also show a flat-lying crenulation folding (F_4) with flat-lying axial surfaces.

Stop 4.4A: Layered metavolcanite-phyllite repetitions (Gelvenåkko Nappe) beneath Bjurälv (Huddingsvann) Limestone and Røyrvik Group in the Leipikvattnet Nappe.
Location: Map-sheet M711/1924 IV Røyrvik, VM 3215/9786. A 650 m road section along the Stora Blåsjön-Røyrvik road, starting 250 m east of the larger and ending 350 m west of the smaller Vekteren bridge. The section shown in Figure 31 illustrates the southern side of the road. The section description proceeds from east to west, up the structural dip.

The eastern end of the section is composed of well-layered quartz keratophyre and greenschist, correlated with the Stekenjokk Quartz-Keratophyre. The main foliation (S_2) dips steeply to the southwest and is deformed by later (F_4) minor folds with flat-lying axial surfaces. A tectonic contact (30 m) marks the upper boundary of these metavolcanites, separating them from overlying dark graphitic phyllite with a quartzite conglomerate or pseudoconglomerate layer and a thin (c. 1 m) greenstone horizon (Remdalen Group or Rantser Formation). The tectonic boundary is itself deformated by the F_4 structures. The graphitic phyllites are overlain (150 m) by more greenschist and quartz keratophyre,

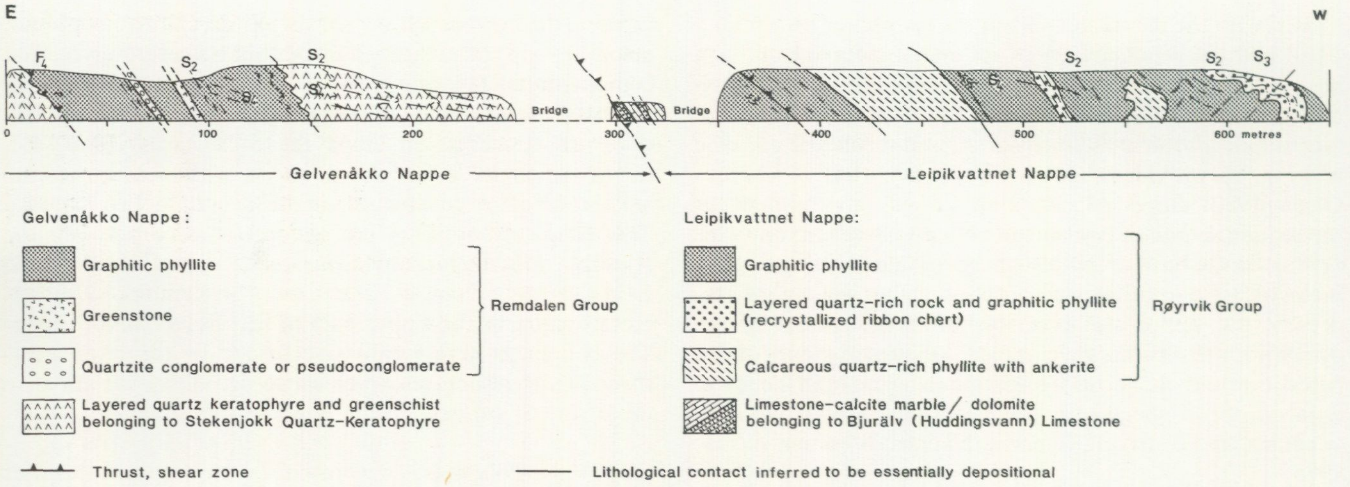


Fig. 31. Road section (southern side) at Stop 4.4A, near Røyrvik.

likewise correlated with the Stekenjokk Quartz-Keratophyre. At the western end of the larger bridge, a sharp tectonic boundary separates layered dark greenschist (Stekenjokk Quartz-Keratophyre) from a c. 15 m thick section of mylonitic carbonate-rich rocks. A 1 m thick buff-coloured dolomite containing conspicuous white mica and secondary quartz segregations lies in tectonic contact with the underlying mafic metavolcanites. The dolomite is overlain by a white mylonitic marble which grades upwards into a slightly impure greyish limestone (Bjurälv or Huddingsvann Limestone). The tectonic contact between the metavolcanites and carbonate sequences marks the boundary between the Gelvenåkko and Leipikvattnet Nappes (Fig. 31).

At the western end of the smaller bridge (350 m), graphitic phyllite belonging to the Røyrvik Group is crenulated by flat-lying F_4 structures. This phyllite lies beneath (420 m) calcareous quartz-rich phyllites, pelitic phyllites, and layered quartz-rich rock and graphitic phyllite tectonically repeated several times in what is thought to be a complex series of D_2 high-angle slides. Quartz veins are concordant with the S_2 foliation which is crenulated by F_4 folds with flat-lying axial surfaces. At 620 m, layered quartz-rich rock and graphitic phyllite (recrystallized ribbon chert) dominates. Quartz-ankerite segregations lying within the S_2 foliation are transposed into an upright S_3 crenulation cleavage with steep southeasterly dips. F_4 angular kink-like structures with a flat-lying axial surface cleavage dipping to the northwest are probably conjugate to the southwest-trending F_3 structures.

Stop 4.4B: Recrystallized ribbon chert within the Røyrvik Group.
Location: Map-sheet M711/1924 IV Røyrvik, VM 3140/9770. Small outcrop on eastern side of Stora Blåsjön–Røyrvik road, c. 350 m west of Stop 4.4A.

In the vicinity of Røyrvik village (Fig. 30), a thick sequence of layered quartz-rich rock and graphitic phyllite, interpreted as recrystallized ribbon chert, comprises the dominant part of the Røyrvik Group and forms more resistant outcrops in this area. These lithologies are well represented at this stop. A fine dissemination of graphitic material gives the grey to bluish-grey colour to the 'cherty' layers. The compositional layering and mica foliation in the phyllites (S_1) are tightly folded by F_2 structures trending NW–SE. These folds are themselves deformed by flat-lying F_3 and F_4 structures which form box-fold conjugate sets.

Stop 4.4C: Polyphase deformed graphitic phyllite and greenschist in the Røyrvik Group.
Location: Map-sheet M711/1924 IV Røyrvik, VM 3137/9715. Road section on western side of Stora Blåsjön-Røyrvik road, c. 100 m north of the road sign at the Røyrvik village road junction.

Somewhat rusty, graphitic and quartz-rich phyllites lie beneath and are folded (F_3) together with a pale, laminated greenschist interpreted as a mafic tuff. The latter is dominated by layers of albite + chlorite (Mg-rich) + white mica + sphene + carbonate; pelitic and graphitic phyllite interlayers occur close to the contact with the underlying phyllites. A minor rust zone with pyrrhotite dissemination occurs south of an E–W trending, nearly vertical fault and is best studied on the opposite (eastern) side of the road. The pyrrhotite dissemination is associated with layers of quartz, pink garnet (spessartine?) and carbonate. White mica porphyroblasts are also typical for this rock. Similar lithologies have been observed at the ore level distal to the Joma ore body.

The F_3 folds plunge 20° to 35° to the northwest and contain an intense axial surface crenulation cleavage (S_3) which trends approximately N–S and dips 35° to the southwest. Quartz and ankerite veins and segregations are conspicuous along the S_3 cleavage while earlier quartz segregations, related to D_{1+2} deformation phases, are deformed by the D_3 structures. A later upright crenulation cleavage with steep dip to the southwest occurs at the northern end of the section.

Stop 4.4D: Greenstone and greenschist in the Røyrvik Group.

Location: Map-sheet M711/1924 IV Røyrvik, VM 3133/9697. Western road section starting c. 60 m south of the sign at the junction between the Røyrvik village and Stora Blåsjön-Røyrvik roads.

Strongly foliated pale greenschist grades southwards into a greenstone with flattened and elongate pillow-like structures. The pillows display dark rims rich in Fe-chlorite and sphene, and calcite is concentrated in pillow centres and the interstitial areas. Minor biotite porphyroblasts occur within the pillows while occasional recrystallized chert and pelitic phyllite can be found within the pillow interstices. Pyrrhotite is concentrated along thin rust zones associated with S_2 shears. The greenstones from this locality are typical for the Røyrvik Group mafic metavolcanites distal to the Joma ore body.

The main foliation (S_2) in the strongly flattened pillowed greenstones strikes N-S and dips 45° to the west. Later F_3 folds with Z-shaped asymmetry, parasitic to the Joma Synform, display an axial surface crenulation cleavage. Thin quartz veins often lie along the S_3 cleavage. At the northern part of the outcrop, the F_3 folds plunge 5° to the NNW. To the south, the D_3 structures are warped by F_4 folds. The latter show a chevron style, an S-shaped asymmetry, a variable plunge both to north and south, and a flat-lying axial surface cleavage.

DAY 5

A. THE JOMA Cu-Zn MASSIVE SULPHIDE DEPOSIT HOSTED BY MAFIC METAVOLCANITES

A. Reinsbakken

INTRODUCTION

General. The Joma stratiform massive sulphide deposit (Figs. 30 and 32) lies within the Røyrvik Group (Leipikvattnet Nappe), and outcrops some 2 km south of the mine entrance at Ornes. From its surface exposure in the river flowing into the eastern end of Huddingsvann, the double arc-formed, dish-shaped orebody dips steeply to the southwest and west, levelling off to nearly horizontal at c. 200 m depth, and has a 1200–1500 m lateral extension.

History, grade and tonnage. The deposit was first discovered in 1911. Apart from substantial drilling by the Germans during the 2nd World War, very little activity took place until the 1950's. Modern exploration culminated around 1963–64 and the present operator, Grong Gruber A/S, acquired mining rights in 1969. When production started in 1972, the total reserves were calculated at c. 20 million metric tons of massive and disseminated ore containing 32 % S, 1.30 % Cu, 1.70 % Zn and with only minor amounts of Pb and recoverable Ag and Au. However, since pyrite is of no economic interest and is not recovered, production was based on 6.8 million metric tons averaging 1.70 % Cu and 1.11 % Zn. The annual production is now 400 000 metric tons/year.

Structure. The Joma deposit is hosted by the middle of three distinct greenstone units within the Røyrvik Group, contained in the late (D_3) Joma Synform which trends from Limingen to Leipikvattnet (Fig. 30). Structural studies (Odling & Reinsbakken, in prep.), both on a regional scale and within the mine, have shown that the host-rock lithologies to the Joma ore horizon lie in an inverted position. Two major phases of deformation control the geometry. The earlier phase, related to the D_2 structures, is represented by isoclinal folds trending roughly NNW–SSE and plunging gently to the NW. These deform wallrocks as well as ore layers, and mesoscale F_2 folds are probably parasitic to much larger isoclinal fold structures. They are responsible together with associated thrusts for repetitions of the greenstone horizons found within the late F_3 Joma Synform. The most spectacular deformation of the orebody occurred during D_3, leading to open, asymmetrical crenulation folds (F_3) at right angles to F_2 and with fold axes plunging moderately to the southwest. Late F_4 folds, showing opposite vergence and flat-lying axial surfaces, are only slightly developed at Joma.

Lithology. The greenstones show a variety of textures and structures. Remnants of pillows, pillow breccias and hyaloclastites occur, indicating deposition in a submarine environment. A detailed investigation of the three greenstone units indicates that the lower and middle greenstones (Orklumpen and Joma, respectively) are similar in their distribution of massive, pillowed lava and volcaniclastic sequences; they are interpreted as belonging to the same metavolcanite complex, repeated by isoclinal folding and thrusting. Thus, the Joma horizon lies in an overturned limb of a major F_2 isoclinal fold structure and is probably cut out at depth by a major thrust which separates these two greenstones.

The Joma deposit itself occurs within the middle greenstone, at the interface between two local metavolcanic units. The older (structural hanging wall), pre-ore metavolcanites comprise a sequence of massive flows and high-level intrusions, enveloped in a laterally extensive pillow lava and pillow breccia sequence. The younger metavolcanites (structural footwall) consist of a thinner pillow lava and

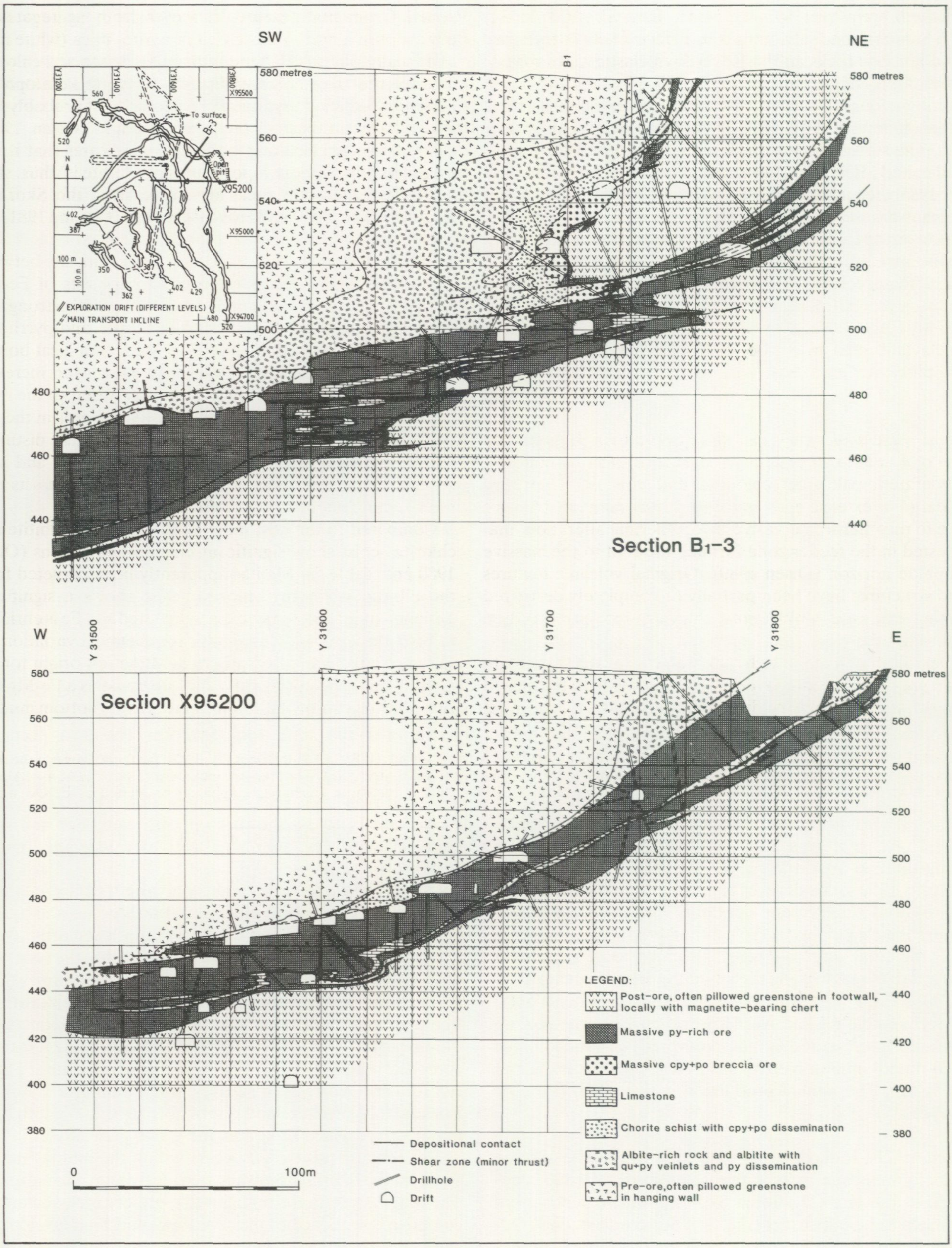


Fig. 32. Cross sections through the Joma ore deposit.

pillow breccia unit which grades, both stratigraphically upwards and laterally, into a sequence of well-laminated volcaniclastic rocks and tuffs. The pyroclastic rocks contain minor layers of grey and dark graphitic phyllites and carbonates, grading upwards into layered quartz-rich rocks and graphitic phyllites (recrystallized ribbon chert). The Røyrvik greenstones show a metabasaltic composition (spilites) and mixed MORB-WPB affinities (Olsen 1980, Stephens et al. 1985b, Reinsbakken, unpublished data, 1986). A significant difference between the pre- and post-ore lavas is, however, apparent (Table 5). For example, the post-ore lavas show distinctly lower contents of TiO_2 and Zr at similar Cr contents relative to the pre-ore lavas, the former thus showing a N-MORB and the latter an E-MORB or WPB affinity (Fig. 9). The Røyrvik Group metavolcanites appear to have formed in an oceanic, probably off-axis setting (Stephens & Gee 1985).

Pre-ore metavolcanites and their alteration. The pre-ore metavolcanites in the vicinity of the ore horizon are uniform, moderate to pale green coloured, and schistose. They have undergone extensive chemical and mineralogical changes due to the intense, pervasive, hydrothermal alteration, manifested in the feeder zone forming the root to the massive sulphide horizon (Olsen 1980). Original volcanic textures and structures have been partially or completely destroyed during extensive albitization, chloritization, sericitization and sulphidization.

The albitite or albite-rich rock is characterized by white to pale grey colouration, layering and veining with pyrite and quartz, an extremely fine dissemination of pyrite, and a local zoned fragmental texture. It varies from aggregates of almost pure albite to those rich in pyrite, mica (white mica and locally biotite), sphene, albite, actinolite and chlorite. The albitite shows a resemblance to quartz keratophyre. However, detailed investigations show that it probably represents a hydrothermal alteration product (Olsen 1980), since the trace element geochemistry indicates that it was originally of basaltic composition. The albitite is, thus, similar to the alteration rocks described from the Skorovas (Reinsbakken 1980) and Høydal-Løkken (Grenne 1981) deposits.

The dark chlorite schist occurs stratigraphically between the albitite and the massive ores and consists of Fe-rich chlorite, albite, biotite and sphene often with strong disseminations and thin layers of chalcopyrite and pyrrhotite which appear to be concordant to the lithological boundaries. The density of these Cu-rich sulphide layers increases upwards towards the massive sulphides. Distal to the main hydrothermal vent and stratigraphically upwards in the sulphide-silicate pile, the chlorite schist becomes distinctly pyrite- and carbonate-bearing as disseminations and individual layers. This unit is enriched in Zn and contrasts with the Cu enrichment stratigraphically below.

Compared to the host metabasalts, both the albitite and chlorite schist show significant chemical variations (Olsen 1980 and Table 5). Mg has apparently been depleted from the albitite while the chlorite schist shows a significant enrichment in this element; Ca is depleted and Fe is enriched in both these units. This significant chemical variation led Olsen to advocate a hydrothermal alteration origin for the albitite and deposition of the chlorite schist as a Fe-Mg-Cu-rich, syn-depositional layer of tuffaceous (?) bottom mud. In

TABLE 5. Representative analyses of pillowed metabasalts from the Røyrvik Group (1–3) and altered metabasalts in the feeder zone to the Joma deposit (4–5). 1 = Metabasalt distal to Joma, Stop 4.4D; 2 = Pre-ore metabasalt, Stop 5.2D; 3 = Post-ore metabasalt, Stop 5.2A; 4 = Albitite containing quartz-pyrite veins, Stop 5.2C; 5 = chlorite schist. Fe_2O_3 (tot) is total iron (including sulphides) calculated as Fe_2O_3. n.a. = not analyzed.

		1	2	3	4	5
%	SiO_2	46.27	46.65	45.75	54.28	29.17
	TiO_2	2.04	1.35	0.96	1.69	2.00
	Al_2O_3	14.79	15.25	16.15	16.01	16.92
	Fe_2O_3 (tot.)	10.62	10.51	10.30	6.79	31.00
	MnO	0.16	0.13	0.14	0.04	0.14
	MgO	7.58	6.75	10.26	0.17	9.85
	CaO	10.02	10.99	9.96	6.43	3.50
	Na_2O	3.03	3.67	2.27	8.11	1.65
	K_2O	0.58	0.08	0.55	0.55	0.01
	P_2O_5	0.35	0.17	0.11	0.82	0.05
	L.O.I.	3.23	1.49	2.87	7.33	5.64
	Total	98.67	97.03	99.32	102.22	99.93
%	S	0.12	0.03	0.07	4.43	4.46
ppm	Zr	200	150	80	440	180
	Y	28	30	20	60	10
	Sr	250	170	120	70	160
	Rb	10	n.a.	5	0	0
	Cu	20	30	90	110	3260
	Zn	70	90	80	1450	120
	Pb	10	10	10	30	0
	Ni	180	60	150	0	20
	Cr	370	200	440	10	200
	Ba	150	10	40	20	20
	V	330	310	220	120	440

part, the chlorite schist represents an intensely altered hyaloclastite on top of or adjacent to the main fumarolic vent. The Ca leached from the lavas below could have been held in solution and later deposited as extensive, concordant limestone layers within the Zn-rich pyritic ore of the upper parts of the sulphide stratigraphy.

Ore types, vertical zonation and ore mineralogy. A palinspastic reconstruction, based on the distribution of ore types in relation to host rock lithologies and hydrothermal alteration in the feeder zone, has led to establishment of the following stratigraphic succession surrounding the orebody:

Top

1. Pale, epidote- and calcite-bearing post-ore greenstones and minor magnetite-rich, dark quartz-rich rocks (recrystallized chert) and limestone.
2. Massive, generally, pyritic ore with interlayers and lenses of limestone and chlorite schist. The following ore types can be recognized, probably in a vertical sequence:
   a) Medium- to coarse-grained pyritic ore, with carbonate and chlorite as both matrix and individual layers; rich in Zn and generally devoid of Cu.
   b) Fine-grained to flinty pyritic ore; minor to medium contents of both Cu and Zn.
   c) Fine- to medium-grained, Cu-rich pyrite-pyrrhotite-chalcopyrite ore with layers of disseminated amphibole needles, chlorite schist, magnetite ore and dark quartz-rich rock (chert).
3. Cu-rich chalcopyrite-pyrrhotite breccia ore containing fragments of chlorite schist, limestone, magnetite ore and fine-grained pyritic ore.
4. Dark, Fe-chlorite schist, rich in disseminations and layers of chalcopyrite-pyrrhotite.
5. Albitite rich in pyrite-quartz-calcite veins and disseminations, often rich in Zn and having minor contents of Pb; this rock grades laterally under the ore zone into pale Mg-rich schist (albite + Mg-chlorite + actinolite + white mica).
6. Moderate green chloritic greenstones with epidote knots and pyrrhotite disseminations; minor pyrite veining.

Base

The following ore minerals have been recognized in the Joma deposit (Olsen 1980, Eidsmo *et al.* 1984, Leissmann, pers. comm., 1985). Major components are pyrite, pyrrhotite, chalcopyrite, sphalerite and magnetite. Minor and trace components include cubanite, tetrahedrite, mackinawite, galena, arsenopyrite, cobaltite, ilmenite, rutile, valleriite, amalgam, electrum, native Ag, argentite and pyrargyrite. A primary FeS phase was suggested by Olsen (1980).

'Durchbewegt' ore. The chalcopyrite-pyrrhotite breccia ore is a characteristic and interesting ore type at Joma. It often occurs as distinct layers following minor thrusts (shear zones) that cut the massive Cu-rich ores and adjacent host rocks. Numerous angular to subrounded fragments of chlorite schists, white limestone and amphibole schist, magnetite, and fine-grained pyritic ores attest to derivation of the breccia ore from the adjacent host rock and ore lithologies. Isoclinal fold hinges of an early compositional layering within the fragments and rounded hydrothermal glassy quartz fragments indicate an early tectonic (D_1–D_2) derivation (cf. Olsen, 1980, who favoured a primary sedimentary-exhalative origin). The fragments become notably smaller and more rounded the further they occur along the thrust away from their source rock. This breccia ore may be classified as a 'durchbewegt' ore type and can be traced several hundred metres along minor thrust surfaces. The chalcopyrite-pyrrhotite breccia ore can locally form distinct layers containing impressive thicknesses (>2 m) rich in chalcopyrite, with ore grades up to 20 % Cu. The competency contrasts between the silicate and sulphide layering, and the presence of large quantities of both chalcopyrite and pyrrhotite in these layers have probably been the governing factors in the formation of this tectonic breccia ore. Pyrrhotite and chalcopyrite, and for that matter also sphalerite, are minerals which, due to their internal structures (cleavage planes along which gliding can occur), are readily mobilized and redistributed by tectonic shearing movements associated with the 'durchbewegt' phenomena. Chalcopyrite, pyrrhotite, sphalerite and quartz-calcite are also typically mobilized along D_3 piercement structures and late cross-cutting fracture fillings, adjacent to the Cu-rich massive sulphide ores at Joma.

Summary. Considerable evidence has accumulated to indicate that all the lithologies except the breccia ore formed prior to D_1–D_2 and are, therefore, probably syn-depositional in origin. Consequently, Olsen (1980) concluded that the Joma stratiform massive sulphide deposit formed by exhalative processes, the sequence of events being:

1. Formation of a feeder zone with associated hydrothermal alteration phenomena, including depletion of Mg and Ca and formation of pyrite-bearing albitites. The feeder zone forms the roots to the massive ores and the channels through which the metal-bearing fluids have ascended on their way to the seafloor.
2. Deposition of a Fe-Mg-Cu-rich tuffaceous (?) mud immediately overlying and adjacent to the feeder zone.
3. Deposition of massive Fe sulphides at the seawater-pillow lava interface immediately above and adjacent to the feeder zone. The sulphide ores grade from an early Cu-rich layer, represented by the present layered Cu-rich sulphide-, silicate- and magnetite-rich ore, into a more Zn-rich and Cu-poor, pyritic top layer. The occurrence of limestone and chlorite schist layers within the ore shows that the deposition of sulphides was not continuous.
4. Relative position and bulk chemistries of these layers were maintained during the subsequent deformation and metamorphism except for the tectonic origin of the chalcopyrite-pyrrhotite breccia ore and the minor chalcopyrite-pyrrhotite concentrations in later veins and fracture fillings.

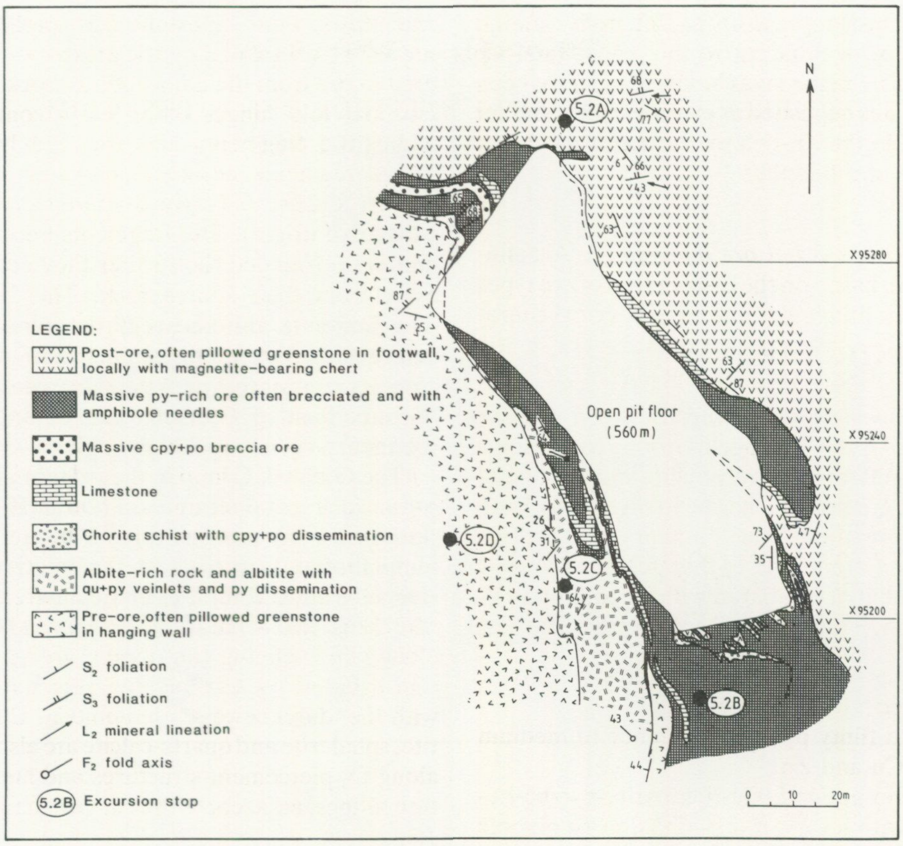


Fig. 33. Sketch map of the open pit at Joma.

STOP DESCRIPTIONS

Stop 5.1: Joma underground mining operation.
Location: Map-sheet M711/1924 I Huddingsvatnet, VM 4575/9450.

A visit will be made to various levels in the underground mining operation at the Joma deposit. Emphasis will be placed on (1) the chlorite schist and various massive sulphide ore types at the 375 m level, (2) hydrothermally altered pre-ore metavolcanites and the chalcopyrite-pyrrhotite breccia ore at the 387 m level, (3) D_2 and D_3 structures at the 385 m level and (4) the Zn-rich massive pyrite ore and limestone layers which dominate at the 416–429 m levels. Relevant material will be distributed during the mine visit.

Stop 5.2: Joma open pit area.
Location: Map-sheet M711/1924 I Huddingsvatnet, VM 4720/9275.

Close to the northeastern edge of the open pit (5.2A, Fig. 33), massive, well preserved, post-ore (structural footwall) metabasalts are folded together with the massive sulphides in a large F_3 structure. The typical close-packed pillow structures are characterized by their dark (Fe-chlorite-rich) pillows rims and pale centres. Large, pale epidote + calcite knots are found near the pillow centres. A prominent S_3 crenulation cleavage dips steeply to the northwest and cuts the main S_2 trend.

At the southwestern edge of the open pit (5.2B, Fig. 33), fine grained, flinty, Cu- and Zn-bearing massive pyritic ore is tectonically brecciated and fractured, and infilled with quartz. A Cu-rich sulphide facies, containing pyritic fragments, dark amphibole needles and chlorite-rich layering, occurs near the western contact of the massive ore. A Zn-rich, carbonate ore horizon, rich in minor pyrite fragments (slump?), occurs between the Cu-rich ore and the silicate-dominated rocks to the west.

Approximately 40 m to the north (5.2C, Fig. 33) in the structural hanging wall to the massive sulphide layers, albitite containing a network of pyrite and quartz veins demonstrates the central part of the hydrothermally altered feeder zone at this level. It grades rapidly into an albite + white mica + Mg-chlorite and actinolite-bearing schist, also rich in pyrite veining and minor calcite. Further north, pillow-like structures are found, set in a strongly pyritized chlorite schist.

Finally, along the western side of the road leading northwestwards and upwards from the open pit area (5.2D, Fig. 33), pre-ore (structural hanging wall) metavolcanites considerably less altered and sulphidized relative to 5.2C can be studied. Pillow breccias and hyaloclastites are present. The isolated, pale, albite-rich pillow fragments, with conspicuous epidote knots, occur in a dark green (Fe-chlorite) altered hyaloclastite matrix. The only sulphides present at this locality are disseminations of pyrrhotite ± chalcopyrite, generally concentrated within the dark chlorite schist.

DAY 5

B. THE GJERSVIK Cu-Zn MASSIVE SULPHIDE DEPOSIT IN A BIMODAL METAVOLCANIC SEQUENCE

A. Reinsbakken

INTRODUCTION

Stratigraphy and palaeotectonic setting. Between Gjersvik and Røyrvik (Fig. 34), the Limingen Group, consisting of various calcareous metasandstones, phyllite and conglomerate as well as minor greenstone, has been divided by Lutro (1979) into three formations, the Finnbursvika, Litlfjelltangen and Vektaren Formations. In this area, the Limingen Group is more attenuated compared with its outcrop in the type-area to the south; it thins rapidly northwards. The basal conglomerate unit occurs further south along the western shore of the lake Limingen, in direct erosional and inverted contact relationship with the metavolcanites of the Gjersvik Group. East of Gjersvik, the Limingen-Gjersvik Group boundary lies along a high-angle, N–S-trending fault.

The Gjersvik Group in the present area (Fig. 34) consists of various metavolcanic units. The Kleiva and Bjørkvassklumpen Formations (Lutro 1979) are layered and massive amphibolites occurring at the westernmost levels of the metavolcanite complex, immediately east of and beneath the thrust that separates the Gjersvik Nappe from the high-

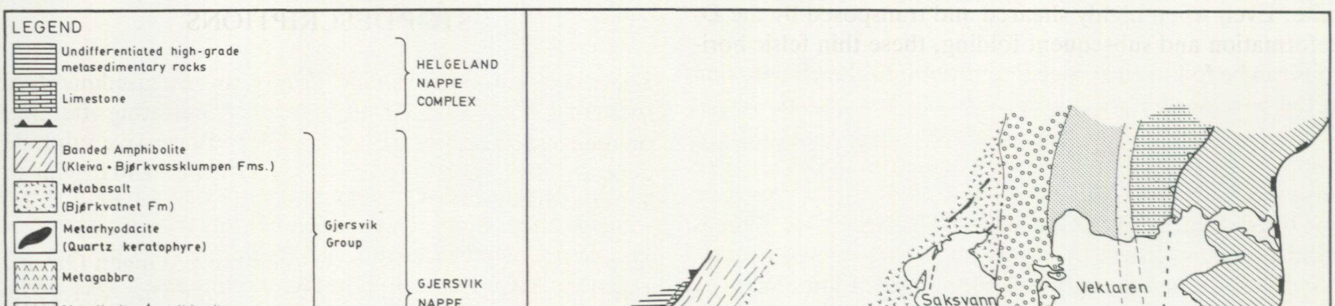


Fig. 34. Geological map of the Gjersvik-Bjørkvatnet area and location of stops on Day 5. Geology based partly on Kollung (1979) and Lutro (1979).

grade rocks of the Helgeland Nappe Complex to the west. Some of these amphibolites are tholeiitic in character and show MORB affinity (data by A. Reinsbakken in Stephens *et al.* 1985b).

The amphibolites lie with a minor tectonic break above and to the west of the Bjørkvatnet Formation (Lutro 1979), consisting predominantly of lower grade mafic metavolcanites of three distinct types (Fig. 9). Detailed stratigraphic and structural investigations have shown that this thick sequence of tholeiitic metavolcanites is lying in an inverted position. In the Bjørkvatnet area (Fig. 34), the stratigraphically older, more primitive tholeiites (Group 1) lie to the west of and structurally above more evolved tholeiites (Group 2), and a conspicuous unit of high-Mg and high-Cr tholeiites (Group 3). These units are dominated by thick sequences of massive flows, pillow lavas and associated pyroclastic rocks, all indicating a submarine mode of formation. The Group 1 mafic rocks are low-K tholeiitic basalts and subordinate basaltic andesites thought to represent an immature ensimatic arc complex (Fig. 9 and see also Halls *et al.* 1977, Lutro 1979). The Group 2 mafic rocks are evolved Fe-rich basalts and andesites (Fig. 9). They are intimately associated with felsic metavolcanites (metarhyodacite or quartz keratophyre) with which they comprise a distinctive bimodal suite. Even when highly sheared and transposed by the D_2 deformation and subsequent folding, these thin felsic horizons can be followed at specific stratigraphic levels near and at the base of, and at the top of the Group 2 mafic rocks. Feldspar porphyry (F) and quartz porphyry (Q) varieties comprise these slightly different stratigraphic levels. The felsic metavolcanites are dominantly pyroclastic in character and often occur as thin impersistent horizons between areas of felsic dyke swarms and related thicker felsic 'lava domes'. The felsic rocks are suggested to have been generated by partial melting of a mafic source rock at the base of the arc, similar to that suggested for the Stekenjokk metavolcanites (Stephens 1982b), in connection with the incipient stages of arc rifting. The Group 3 mafic rocks are best developed north of Gjersvik. South of Gjersvik, they occur at the stratigraphic top of the Gjersvik metavolcanic sequence and in direct erosional contact with the Limingen Group. The Group 3 rocks comprise Mg-rich basalts and basaltic andesites (tendency towards boninitic compositions?), show characteristically high Cr (400–500 ppm) and low Ti (c. 5000 ppm) contents (Fig. 9) and are often pyroxene phyric in flows. A trend towards MORB affinity may reflect the initial stages of marginal basin development during uplift and rifting of the arc.

The plutonic infrastructure of the Gjersvik rifted arc, which forms the root to the consanguineous submarine volcanic complex (Halls *et al.* 1977), is represented in this area by metagabbro, metadiorite to trondhjemite, and granodiorite intrusions. The metagabbro/serpentinite complex found within the Kleiva Formation amphibolites is similar to the large layered gabbro complex found to the southwest of Skorovas.

Massive sulphide deposits. The felsic 'lava domes' are intimately associated with the volcanogenic stratiform massive sulphides (e.g. Skorovas and Gjersvik) and related distal exhalative mineralizations or 'vasskis' (sedimentary banded pyrite, magnetite and chert) within the metavolcanic sequence. The major volcanogenic massive sulphide deposits in the Gjersvik Group are in the order of 1.5–3.5 million metric tons with the exception of Skorovas (10 million metric tons). These deformed stratiform, Cu-Zn, massive sulphide deposits are more Zn-rich than the Joma deposit and are fine-grained massive pyritic ores, with the exception of the Gjersvik deposit which also contains a pyrrhotite-rich ore facies. The deposits are generally lensoid and plate-like massive sulphide bodies which are found directly overlying a zone of intense hydrothermal wall-rock alteration and associated interconnected network of sulphide veining (feeder zone) that cuts through the felsic pyroclastics and 'lava dome' below the massive ore. Certain ore facies are of distinctly chemical sedimentary origin. The Cu-Zn zonation patterns found within the ore zone, the occurrence of hydrothermal alteration and a feeder zone beneath the massive ores, and the intimate relations of these ores to the distal exhalative mineralization facies suggest a synvolcanic exhalative origin for these deposits.

STOP DESCRIPTIONS

The excursion will examine briefly the metasedimentary rocks of the Limingen Group before concentrating attention on the roadside exposures of the Gjersvik massive sulphide deposit. The remaining part of Day 5 will be spent driving to Trondheim.

Stop 5.3: Metasedimentary rocks of the Limingen Group. *Location:* Map-sheet M711/1924 IV Røyrvik, VM 2775/9453. On the main Gjersvik-Røyrvik road (764), c. 5.3 km southwest from the cross-roads to the Røyrvik village and c. 650 m southwest of Litlfjelltangen.

This locality occurs in a conglomeratic calcareous metasandstone with thin darker green interbeds rich in chlorite and white mica. The polymict conglomerate layers vary widely in their grain size and relative proportion of component clasts. The pebble material is very poorly sorted, subangular to subrounded and highly flattened, with a maximum grain size between 0.5 and 10 cm. Quartzite, ferroan calcite limestone, trondhjemite, metadacite and occasionally chloritic greenstone are the major pebble constituents. The matrix is here dominantly fine-grained and schistose, composed of chlorite, white mica, quartz, carbonate and subhedral pyrite. Fuchsite has been observed in the matrix at one locality (A. Mellin, pers. comm., 1979).

The rock shows a well-developed, penetrative foliation and metamorphic layering dipping moderately to the northwest (N15°E/35°NW) and lying at a slight angle to the bedding. The individual pebbles are completely transposed into this pre-D_3 foliation and flattened. Some of the pebbles show extension fractures and redistribution of quartz and calcite in the pressure shadows, while some clasts are rotated showing pressure shadow tails. Pre-D_3 fold axial trends in the vicinity plunge c. 5–10° to the north, the axial surface orientation to these folds lying parallel to the penetrative foliation in the area. Pebble elongation is here sometimes at a high angle to the early fold axes (Lutro 1979) and roughly parallel to a weak stretching lineation. Tectonic segregations of ferroan calcite and quartz parallel to the foliation are refolded and boudinaged by F_3 and F_4 folding.

Stop 5.4: Gjersvik massive sulphide deposit and host rock metavolcanites.
Location: Map-sheet M711/1924 IV Røyrvik, VM 2590/9350. c. 900 m east of the cross-roads at Gjersvik, along the Gjersvik-Røyrvik road. Examine the deposit by walking along the road from east to west. The deposit is repeated on the two limbs of a southerly plunging, late, open, F_3 synform (Fig. 35).

Introduction. The Gjersvik pyritic deposit forms one of the major volcanogenic stratiform massive sulphide ore bodies within the Gjersvik rifted arc. It was discovered early in this century and was already planned for production as early as 1920. However, because of disputes between the foreign shareholders and the Norwegian government, it was never set into production. Remnants of the early erected workshops and offices can be seen along the Limingen lake shore, near the entrance to the main exploration adit beneath the western limb of the ore horizon.

The present geometry of the Gjersvik orebody consists of an asymmetrical, spoon-shaped, synformal structure (F_3) which plunges southerly, the new road section cutting through both limbs of this structure. Pre-D_3 structures are also present. The ore reserves at Gjersvik have been calculated at c. 1.6 million metric tons of ore (massive and disseminated) with an average of 31 % S, 1.6 % Cu and 0.9 % Zn with only trace amounts of Pb and precious metals (Oftedahl 1958b). The dominant mineralogy is pyrite, pyrrhotite, magnetite and chalcopyrite, with subordinate sphalerite in a carbonate plus chert and minor chlorite gangue.

Two distinct facies are present:

1. A pyritic facies consisting of >95 % compact pyrite and minor chalcopyrite (grain size c. 50 μm), and containing a carbonate and chlorite matrix.
2. A pyrrhotite facies rich in pyrite and magnetite, containing c. ≤50 % pyrite showing euhedral to subhedral grains (0.5–1.5 mm), pyrrhotite and magnetite porphyroblasts and minor chalcopyrite, set in a matrix of c. 10–15 % carbonate.

The nature and distribution of these sulphide facies suggests that they are two distinct primary ore facies and probably represent a primary physico-chemical variation occurring at the time of deposition. A more siliceous facies occurs in the lateral extension of the ore horizon (i.e. the western limb of the ore zone along the road cut) which is often notably layered. The layers consist of a varying proportion of fine-grained pyrite, magnetite and fine-grained recrystallized chert, with carbonate in the matrix. Although these layers are now tectonically modified, they probably represent original stratification. Other distal exhalite facies such as banded magnetite-chert and minor carbonate-rich facies have been found to the north and east.

TABLE 6. Representative analyses of 1. Group 2 metabasalt, 2. feldspar porphyritic dyke and 3. strongly altered metarhyodacite with pyrite dissemination, all at the Gjersvik mineralization. Fe_2O_3 (tot) is total iron (including sulphides) calculated as Fe_2O_3. n.a. = not analyzed.

		1	2	3
%	SiO_2	50.30	75.20	73.40
	TiO_2	1.57	0.17	0.19
	Al_2O_3	15.92	11.90	11.62
	Fe_2O_3 (tot.)	15.67	4.05	5.18
	MnO	0.24	0.02	0.06
	MgO	6.35	0.42	0.39
	CaO	2.52	0.31	0.18
	Na_2O	4.13	5.98	4.26
	K_2O	0.05	0.02	1.07
	P_2O_5	0.14	0.04	0.05
	L.O.I.	4.43	0.49	2.86
	Total	101.32	98.60	99.26
ppm	Zr	36	107	98
	Y	22	40	46
	Sr	76	49	26
	Rb	0	n.a.	n.a.
	Cu	0	4	29
	Zn	125	2	1068
	Pb	n.a.	33	27
	Ni	4	23	23
	Cr	0	71	62
	Ba	7	110	320
	V	340	58	0

The footwall rocks of the Gjersvik massive pyritic horizon consist of Group 2 massive, dark, chloritic metabasalts and the hanging wall rocks consist of an intensely hydrothermally-altered and pyrite-veined metarhyodacite complex (Table 6). Stratigraphic and structural investigations indicate that the hanging wall altered and pyrite-veined metarhyodacite complex represents an inverted 'felsic lava dome' containing feeder zone sulphide ore which grades up into massive ore, a succession similar to that at Skorovas (Reinsbakken 1980) and other volcanogenic sulphide deposits related to acid volcanism (e.g. the Kuroko type deposits).

The present elliptical configuration and inverted nature of the Gjersvik orebody shows that much of the older, originally underlying lithologies have now been eroded away, except for the immediately underlying 'felsic lava dome' and feeder zone pyrite ore. This causes some difficulties in comparing the Gjersvik deposit with other deposits in the Gjersvik sequence. However, distal exhalites ('vasskis') related to the Gjersvik mineralization suggest that the Gjersvik orebody is associated with an episode of explosive felsic volcanism which occurred between deposition of the Group 1 (pale, Ti-poor) and Group 2 (dark, Fe-rich) mafic metavolcanites.

Stop description. The steeply plunging massive sulphide horizon is underlain to the east (Fig. 35) by a dark greenish chloritic metabasalt (Group 2 Fe-rich basalt, Table 6). This unit is massive and fine-grained, containing numerous small concentrations of pyrite and locally quartz-carbonate-stilp-

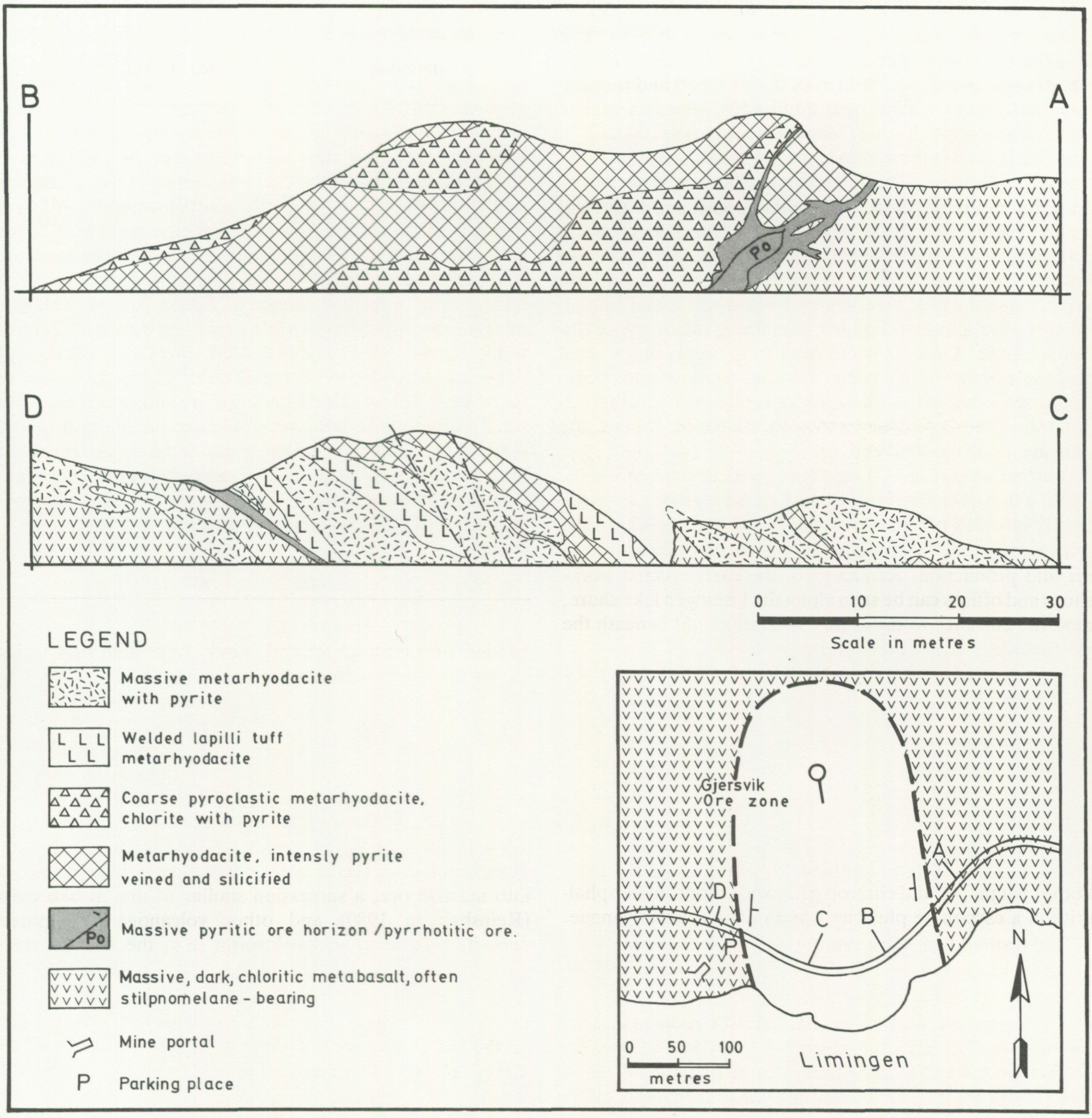


Fig. 35. Detailed sketch map of the Gjersvik mineralization (modified after A. Mellin, pers. comm., 1979).

nomelane-epidote knots. Minor pillow breccias have been observed further to the northeast. A thin, dark green magnetite-bearing chlorite schist occurs directly beneath the massive ore.

The massive sulphide ore horizon (Fig. 35) occurs as an irregular, 1–5 m thick, steeply SW-dipping band of massive pyrite- and massive pyrrhotite-rich ore facies. An extremely fine-grained, flinty, massive pyrite ore facies forms both the footwall and hanging wall of the ore zone and shows irregular fold-like protrusions out into the metabasalts. A coarser grained pyrrhotite-magnetite ore facies occurs within the massive pyritic ore. This coarser-grained ore facies contains much more visible carbonate in the matrix.

The massive sulphide ore horizon is overlain by a pale weathered, massive metarhyodacite complex (Fig. 35). Immediately adjacent to the massive ore, there occurs a darker, chloritic pyroclastic metarhyodacite unit. The felsic pyroclasts consist of flattened, angular, pale metarhyodacite fragments set in a darker, greenish, quartz-albite-chlorite-calcite matrix containing much pyrite dissemination. The angular or lensoid fragments vary in size from 1–5 cm (maximum dimensions) and consist of a very fine grained, equigranular, holocrystalline quartz and albite, with subordinate epidote and some chlorite. Magnetite and pyrite, up to 2 %, are nearly always present in fragments along with accessory apatite and sphene. This felsic pyroclastic unit is overlain by and partly interlayered with a paler, more massive and dense, highly siliceous metarhyodacite which is probably extrusive in origin. This unit is in places highly veined by an interconnected network of pyrite veinlets and the adjacent rock consists of a pale-white 'albite-rock' consisting of almost pure albite and quartz containing minor pyrite disseminations. A quartz-white mica rock occurs in the most intensely pyrite-veined parts. Textural relations and chemical analyses show that these rocks represent hydrothermal alteration products associated with the feeder zone to the massive ores above (Table 6).

Further west (Fig. 35), near the creek at the bend in the road, a thin dyke-like body of dark metabasalt occurs, apparently infolded within the metarhyodacite complex; it may represent a deformed feeder dyke to the younger metabasalts. Between this metabasaltic dyke and the western limb of the orebody, several southeast-dipping parallel zones of metarhyodacite breccia and pyrite-cemented ore-veined areas (1–2 m wide) are found within the otherwise massive, dense, silicified metarhyodacite. Parts of the massive unit show visible grains of welded pyroclastic texture which appears most clearly on weathered joint surfaces.

The western limb of the Gjersvik orebody (Fig. 35) occurs as a thin (<1 m), more gently southeast-dipping massive pyritic horizon carrying visible magnetite and chert bands and tectonic lenses. This unit appears more sheared and the wall rocks are strongly schistose. The western ore horizon is underlain by a thick sequence of Group 2, dark, chloritic metabasalts, which have visible pyrite and quartz concentrations. Further west, highly folded (pre-D_3) sills/dykes of dense metarhyodacite (Table 6) occur within the vesicular metabasalt. These felsic intrusions are subporphyritic with small visible albite laths set in a mixed albite and quartz matrix. The dark grey colour is due to finely disseminated magnetite in the matrix. Quartz segregations occur as tension gash fillings related to the folding of the more competent felsic dykes; mullion structures are also observed.

DAY 6

OPHIOLITE-HOSTED Cu-Zn DEPOSITS AT LØKKEN AND HØYDAL, TRONDHEIM NAPPE COMPLEX, UPPER ALLOCHTHON

T. Grenne

INTRODUCTION

Regional setting and deformation. The geology of the Løkken area (Fig. 36) has received considerable attention on account of the presence of massive sulphide deposits. The first brief descriptions of the greenstones and the mineralizations were provided by Carstens (1919, 1935, 1951), and more recently by Rutter *et al.* (1967) and Grenne *et al.* (1980). The geology of the sedimentary and volcanic rocks stratigraphically overlying the greenstones has been studied by Vogt (1945), Chadwick *et al.* (1962), Chaloupsky (1970), Bruton & Bockelie (1980) and Ryan *et al.* (1980).

At Løkken, the greenstones are deformed in a fairly open, asymmetric synform trending approximately E–W, with near vertical dips along the strongly attenuated northern limb and more moderate, northerly dips in the little deformed southern parts. At least one earlier phase of deformation can be recognized with formation of overturned folds with strongly attenuated middle limbs and development of local shear zones along favourable lithological units or boundaries. This is thought to be responsible also for the regional inversion of the greenstone sequence; younger sediments – conglomerates, metagreywackes, siltstones and shales – occur structurally below the basaltic greenstone pile while the stratigraphically lower parts of the sequence are found within the core of the major synformal structure (Fig. 36). In southern-central areas, a series of low-angle thrusts (Fig. 36) with minor southerly movements cross-cut the early regional schistosity. The greenstone complex has been further dissected by a series of faults, of which the most conspicuous is a set of ESE–WNW and SW–NE trending faults (Fig. 36) which can be followed along the entire central and eastern part of the Løkken synform, south of its hinge zone. The rocks are regionally metamorphosed in the lower greenschist facies, with formation of albite, epidote, chlorite, actinolite, sericite and locally stilpnomelane as characteristic minerals in the metabasalts and metagabbros.

The Løkken greenstones are stratigraphically overlain by the mainly sedimentary Lower Hovin, Upper Hovin and Horg Groups. The sedimentary rocks include a mainly volcanic-derived conglomerate or breccia considered by Vogt (1945) to be the basal conglomerate of the Lower Hovin Group. The overlying sequence of metagreywackes, siltstones, green and black shales, limestones, and calcareous sandstones is characterized by marked facies changes. Fossils have provided ages ranging from Caradoc, down to mid or late Arenig for the oldest sediments, and the Arenig-Llanvirn faunas show Laurentian affinities (Bruton & Bockelie 1980). A variety of subvolcanic, volcanic and volcaniclastic rocks are also included in the thick sedimentary cover to the greenstones. Ranging from calc-alkaline andesites ('Hølonda porphyrites') at lower levels to dacitic and rhyolitic tuffites and welded tuffs higher up, these rocks bear no resemblance to the underlying ophiolitic assemblage of tholeiitic greenstones and gabbros (see below). The whole volcanic-sedimentary sequence was interpreted by Roberts *et al.* (1984) as having formed in a marginal basin environment. Together with other ophiolite fragments in the western Trondheim district (Vassfjell, Grefstadfjell–see inset map, Fig. 36), the Løkken greenstones were considered to represent phases of extensive crustal thinning and oceanic lithosphere accretion within the basin, with formation of the overlying conglomerates and breccias during subsequent intra-basinal movements or abortive displacement of the newly-formed oceanic crust during late Arenig time. All these greenstone sequences have generally been regarded as equivalents to the thick and extensive Støren Group greenstones to the southeast (inset map, Fig. 36 and Vogt 1945, Chaloupsky 1970). The Støren Group *sensu stricto,* together with its substrate, the Gula Complex, upon which it was tectonically emplaced (Gale & Roberts 1974), was considered to have been initially deformed, metamorphosed, uplifted and eroded in earliest Ordovician time (Furnes *et al.* 1980), following earlier suggestions by Vogt (1945). This prominent stratigraphic break was termed the 'Trondheim Disturbance' by Holtedahl (1920). The deformed Støren and Gula sequences were cut by trondhjemites of early to mid Ordovician age (Klingspor & Gee 1981) and, since Tremadoc slates are found within the Gula (Vogt 1940), the early deformation of the Støren greenstones (and the Gula Complex) may be broadly coeval with the later stages of the Finnmarkian orogenic event (Roberts & Sturt 1980), which corresponds to the Grampian deformation of the British Caledonides. The Lower Hovin, Upper Hovin and Horg Groups were unconformably deposited upon the trondhjemite-intruded Støren and Gula sequences and were deformed, metamorphosed and transported together with these previously deformed rocks as one nappe complex (the Trondheim Nappe Complex) during the later, Silurian-Devonian, Scandian orogenic event. The frequently used term 'Støren Nappe' for the Støren, Lower/Upper Hovin and Horg Groups, introduced by Gale and Roberts (1974)

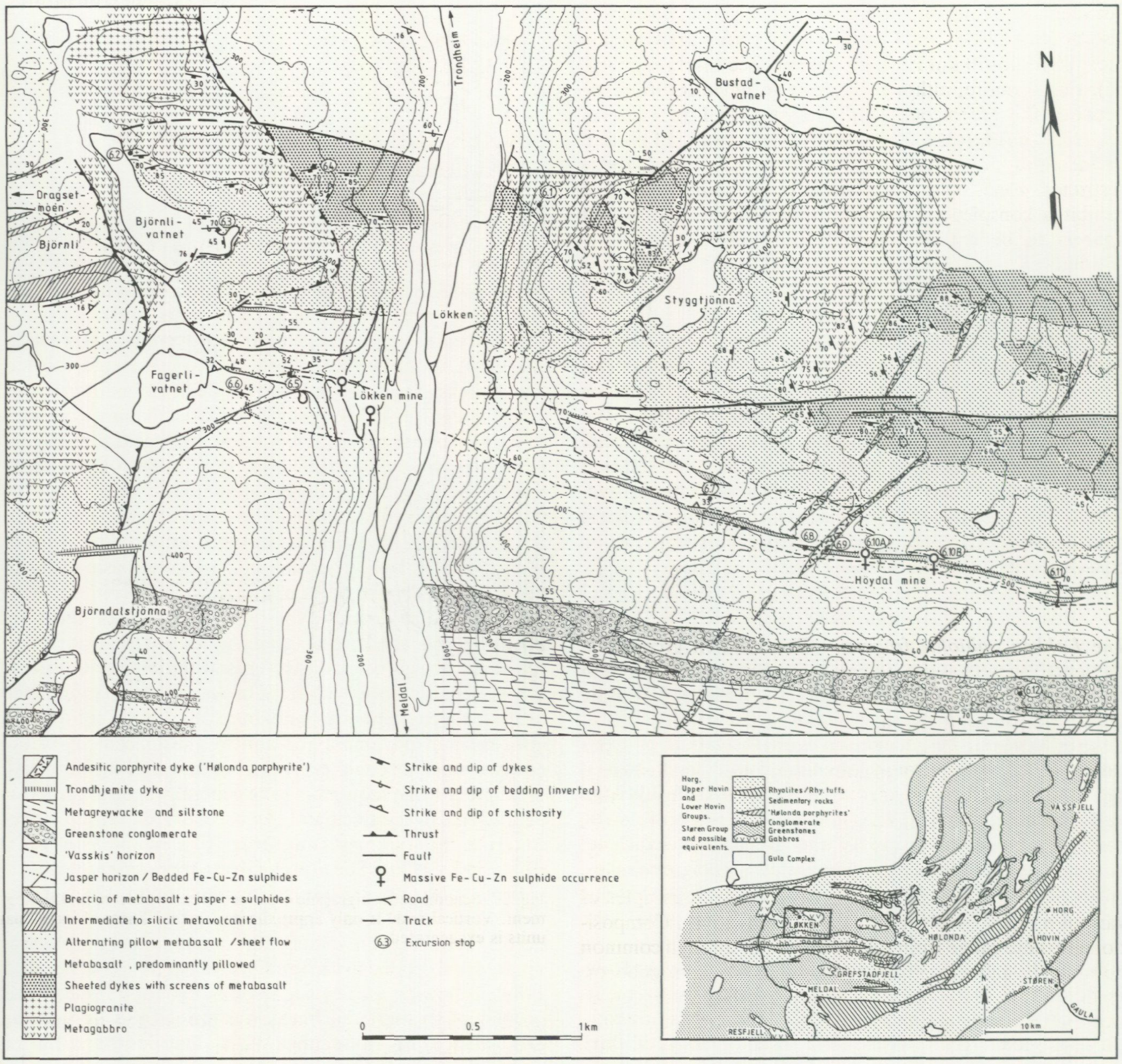


Fig. 36. Geological map of the Løkken area, with excursion stops indicated for Day 6. Contour interval 25 m.

based on the assumption that these units were tectonically emplaced *together* on the Gula Complex, is thus somewhat misleading.

The traditionally accepted correlation of the Løkken, Grefstadfjell and Vassfjell ophiolite fragments with the Støren Group *sensu stricto* is presently somewhat ambiguous. Mapping in the Meldal area, some 10 km south of Løkken (Fig. 36), led Ryan *et al.* (1980) to suggest that the thick greenstones in the Grefstadfjell area actually occur *within* the Lower Hovin Group. This was based on observations of apparently interfingering relationships between the fossiliferous, uppermost Arenig, Lower Hovin sediments and pillow lavas at the top of the Grefstadfjell lava pile. Ryan *et al.* thus inferred that the Grefstadfjell complex and the Løkken greenstones are younger than the Støren Group, and that the overlying breccias and conglomerates here are not the product of a tectonic disturbance as suggested by Vogt (1945). The situation at Løkken is similar to that in the Grefstadfjell area, in as much as the uppermost lavas interdigitate with Lower Hovin sedimentary rocks. Here, however, in view of the deformation style in the Løkken area, with early overturned tight to isoclinal folds with strongly attenuated middle limbs passing into imbricate structures, it is quite possible to interpret the interfingering relationships as tectonic repetition of parts of the sequence. The ambiguous nature of the apparently interfingering relationships between the greenstones and Lower Hovin rocks was noted also by Vogt (1945) and Carstens (1951) from the Hølonda area, some 15–20 km ENE of Løkken (see inset map, Fig. 36). Furthermore, although there is no *obvious* difference between the greenstones and the younger Lower Hovin sequence, either with respect to the deformational pattern or metamorphic grade, it has been noted that relatively restricted zones within the Løkken ophiolite fragment exhibit a conspicuously strong deformational fabric that *appears* to be cut by obliquely intruding dykes of the Hølonda porphyrites of early Ordovician, probably Llanvirnian age (Grenne & Roberts 1981). It should also be noted that Vogt (1945) described fragments of crystalline marble and metamorphosed calciferous sandstones in the conglomerate resting on top of the greenstones in the area northwest of Løkken (along strike), while adjacent overlying Hølonda limestones are apparently unmetamorphosed. The question whether there is an important stratigraphic break between the greenstones and the younger Lower Hovin sequence must, therefore, await further studies. In the present author's opinion, the mid-late Arenig age of the oldest recorded fossiliferous Lower Hovin sediments still must be considered as a minimum age.

The Løkken ophiolite fragment. The Løkken greenstone sequence, as well as the neighbouring thick greenstones in the Western Trondheim district, does not contain the fully developed pseudostratigraphy of a typical ophiolite assemblage (Coleman 1977). Due to the tectonic contact relationship with the substrata or an unexposed base (as at Løkken), and the presumed eroded upper contacts with younger sediments (see above), the sequence is lacking the ultramafic plutonic parts as well as any evidence of possible overlying, pelagic sediments. The lowermost exposed parts of the sequence (Figs. 36 and 37) comprise a 1–2 km thick complex of various metagabbros with associated derivatives. Compositionally these range from relatively mafic, through common hornblende gabbros into magnetite-bearing ferrogabbros. Highly differentiated, intermediate to plagiogranitic derivatives occur as small or locally larger (Fig. 36) bodies within the uppermost parts of the gabbro complex. The metagabbros have intruded relatively high up in the sequence, generally into overlying pillow lavas. A thick complex of 100 % sheeted basic dykes, which in the neighbouring ophiolite fragments can be found with decreasing dyke density downwards into metagabbros and upwards into pillow lavas (Grenne 1980, Grenne *et al.* 1980, Ryan *et al.* 1980, Heim *et al.*, in prep), is preserved only locally in the Løkken area. These dykes are subparallel and generally strike in an ESE–WNW direction. Some dykes extend downwards into the upper parts of the metagabbros and are likely to be derived from the intruding gabbroic magma, while a few dykes cut through the whole plutonic complex and are obviously derived from deeper sources. Geochemical studies (see below), as well as field relationships, suggest that all these dykes are feeders to various parts of the overlying volcanic sequence, although a few dykes with distinctly different compositions are obviously not related to, and are younger than, the ophiolite complex.

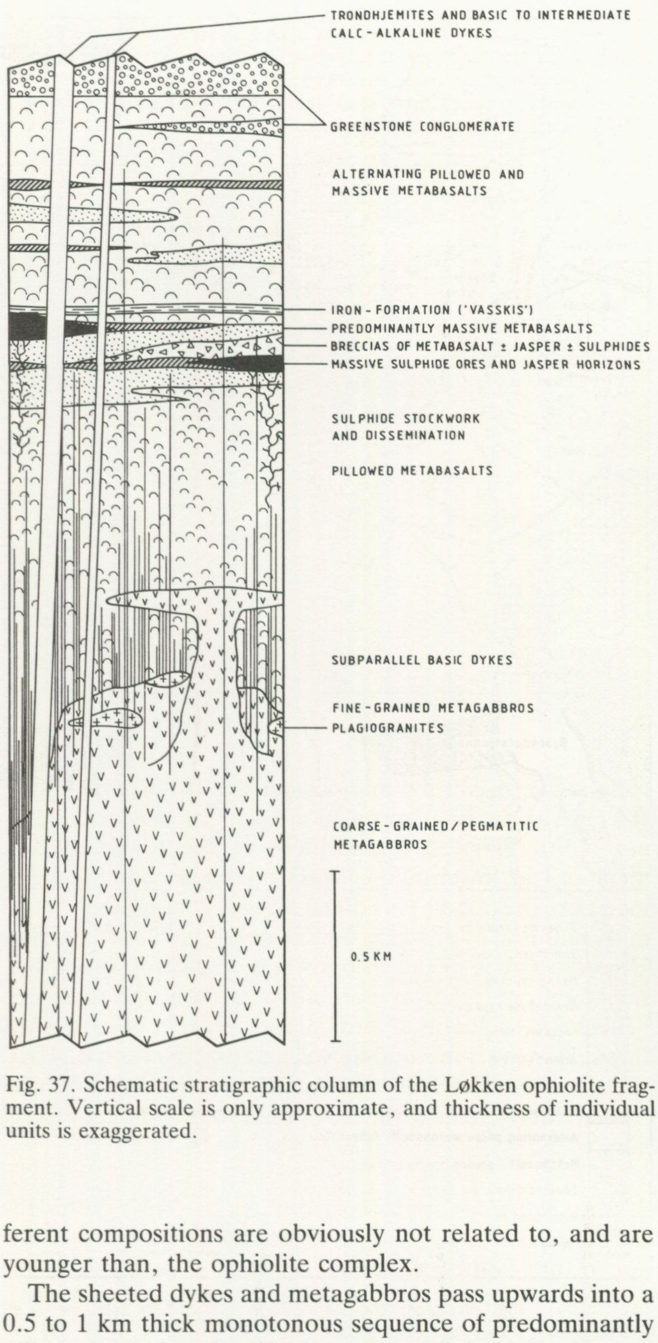


Fig. 37. Schematic stratigraphic column of the Løkken ophiolite fragment. Vertical scale is only approximate, and thickness of individual units is exaggerated.

The sheeted dykes and metagabbros pass upwards into a 0.5 to 1 km thick monotonous sequence of predominantly pillowed metabasalts. The lower part of the volcanic complex is characterized by relatively thick-rimmed, non-vesicular to only slightly vesicular pillows and abundant hyaloclastite breccias. The lower pillow lava member is overlain by a variably thick (near Løkken approximately 0.5 km) pile of vesicular, generally close-packed and thin-rimmed pillowed metabasalts alternating with sheet flows, locally with interlayered jasper horizons. In the lower parts of this sequence, here termed the middle volcanic member, thick sheet flows often predominate over pillowed flows, suggesting very high flow rates of large volumes of fluid lava at that level.

The chemical composition (Table 7A) of the various volcanic rocks of the ophiolite sequence, particularly with respect to the more stable elements (Grenne *et al.* 1980), is

TABLE 7. Representative analyses of metabasalts from the Løkken ophiolite fragment (A) and altered metabasalts in the feeder zones to the Løkken and Høydal deposits (B). 1 = Chlorite-quartz-sulphide rock, central part of the Løkken feeder zone; 2 = Chlorite-albite-epidote rock, peripheral part of the Løkken feeder zone; 3 = Quartz-sericite-pyrite rock, central upper part of the Høydal feeder zone; 4 = Albite-sericite-pyrite rock, peripheral upper part of Høydal feeder zone. Fe_2O_3 (tot) is total iron (including sulphides) calculated as Fe_2O_3. Major and trace elements by XRF, except Na_2O which is analyzed by AAS or flame photometry (see also Grenne *et al.* 1980). n.a. = not analyzed.

A.	Lower volcanic member	Middle volcanic member		Upper volcanic member	B. 1	2	3	4
SiO_2%	46.46	50.88	45.49	46.00	43.11	44.57	62.69	58.38
Al_2O_3%	13.76	13.16	15.92	14.96	13.36	15.81	9.72	15.61
P_2O_5%	0.13	0.34	0.07	0.10	0.11	0.10	0.11	0.14
TiO_2%	1.67	2.33	1.09	1.26	1.54	1.31	1.47	1.24
Fe_2O_3 (tot)%	12.30	11.42	8.99	10.37	24.11	12.77	13.67	9.31
MnO%	0.20	0.20	0.17	0.16	0.16	0.43	<0.01	<0.01
MgO%	6.76	3.45	8.10	6.73	8.50	10.14	0.66	0.33
CaO%	11.53	7.34	12.92	9.59	0.37	4.26	0.22	1.19
Na_2O%	3.21	6.03	2.28	4.19	0.30	3.28	0.35	6.98
K_2O%	0.15	0.19	0.11	0.25	0.07	0.63	2.31	1.02
S%	n.a.	n.a.	n.a.	n.a.	3.18	0.67	9.80	7.10
Zr ppm	119	191	74	78	94	90	95	70
Y ppm	37	55	23	27	26	27	22	27
Sr ppm	216	63	192	134	7	33	24	68
Ba ppm	23	80	15	48	14	109	91	21
Cr ppm	166	32	562	274	351	385	16	<5
Ni ppm	49	21	234	106	47	98	15	11
Cu ppm	84	31	101	45	3200	51	158	40
Zn ppm	86	114	103	95	73	333	107	268

comparable to normal mid-ocean ridge (MOR) tholeiites. Recent studies have revealed a tendency towards slightly more differentiated compositions in the lower volcanic member (the lower pillow lavas) as compared to the upper member. The middle part of the sequence, by contrast to the fairly uniform lower and upper members, is characterized by large diversities in the composition of the volcanic rocks, ranging from relatively primitive to very differentiated (Table 7A, columns 2 and 3) and, locally, intermediate flows. However, this middle volcanic unit shares the MOR-tholeiite characteristics (with respect to, for instance, incompatible-element ratios) of the lower and upper members.

Massive sulphides, jasper horizons and 'vasskis'. Within the middle part of the volcanic sequence, at least two of the known ore bodies within the Løkken greenstones – the Løkken and the Høydal deposits – are found (Fig. 36). Abundant breccias composed of angular fragments of metabasalts and jasper occur at the same general level and are interpreted to represent debris accumulations adjacent to steep escarpments on the seafloor (Grenne *et al.* 1980), reflecting probably also an increased faulting activity at the time of their formation. Within the same stratigraphic interval, jasper horizons play a prominent role. They appear to be intimately associated with the stratiform ore bodies, some of them extending laterally from the massive sulphides as a more distal expression of the hydrothermal activity which led to the sulphide formation. Slightly above the massive sulphides, or locally resting directly upon them, conspicuously extensive iron-rich banded sediments have precipitated. These horizons, which are called 'vasskis' in traditional Norwegian mining terminology (possibly derived from the German term 'weiss-kies', meaning white sulphide as opposed to the yellowish Cu-bearing sulphides), comprise alternating layers rich in very fine-grained pyrite and/or pyrrhotite, magnetite, iron-rich chlorite or stilpnomelane, and subordinate iron carbonates together with varying proportions of quartz (Sand 1984). Sand (1986) interprets these horizons, with very low base metal values (Table 8) and $\delta^{34}S$ between −20 and −25‰, to represent precipitation from hydrothermal, seawater-derived solutions. The metalliferous massive sulphide ore bodies of indisputable hydrothermal origin, by contrast, have $\delta^{34}S$ values of +1.5 to +5‰ (Grenne, in prep.). The latter values are comparable to those found in, for instance, the East Pacific Rise hydrothermal sulphides (Arnold & Sheppard 1981, Styrt *et al.* 1981, Kerridge *et al.* 1983). It is also noteworthy that the metabasalts directly underlying the 'vasskis' horizons often show evidence of a conspicuous seafloor weathering, including strong oxidation of some of the basalts. This alteration is distinctly different from that of the hydrothermal feeder zones to the massive ore bodies in the area (see below). The question whether the 'vasskis' horizons have a hydrothermal origin (Sand 1986), or if other seafloor, possibly weathering, processes were involved, is thus still a matter of dispute.

The massive sulphide occurrences in the Løkken area, among which only the Løkken mine is still operating (1986), contain predominantly pyrite with more or less chalcopyrite and sphalerite; pyrrhotite is abundant only in one of the deposits (Dragset, some 8 km WNW of Løkken). Galena, magnetite or hematite are local minor constituents, while tetrahedrite-tennantite occurs only as an accessory mineral. The main gangue mineral is quartz, constituting 12–14 % of the ore (Grenne *et al.* 1980). The ores display a massive to banded structure, or they may show irregular patches or

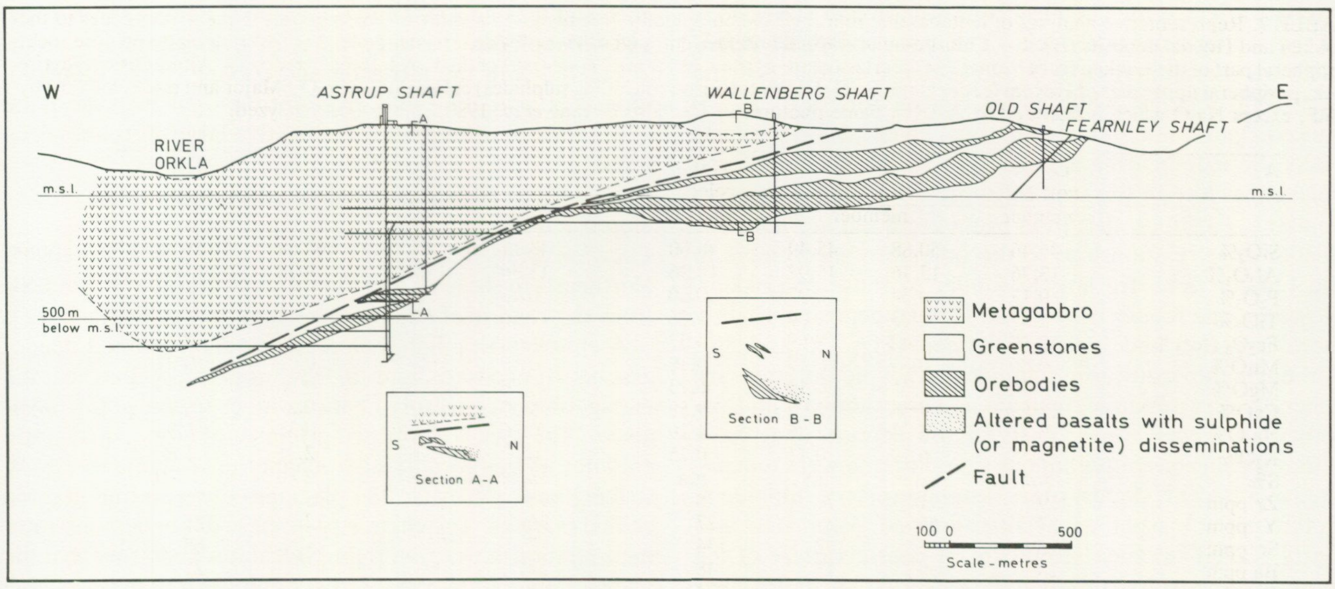


Fig. 38. Vertical longitudinal and cross-sections of the Løkken massive sulphide deposit (after Grenne *et al.* 1980).

bands enriched in chalcopyrite or sphalerite. The texture is very fine-grained, commonly with porous or colloform pyrite aggregates with gangue or base metal sulphides in the interstices. Several generations of sulphides can often be distinguished (Grenne & Vokes 1986). Average metal contents of stratiform ore in three of the deposits (Løkken, Høydal and Dragset) are provided in Table 8. The size of most of these massive ore bodies can be estimated to less than 100 000 metric tons. The Løkken deposit, which was discovered in 1654 where the ore outcrops in the western hillside of the valley at Løkken, is the outstanding exception, having originally more than 25 million metric tons of ore contained mainly in one large body. If the several separate ore bodies in the Løkken mine were part of the same horizon of sulphide deposition, as suggested by Grenne *et al.* (1980) and confirmed by later work (R. Juhava and G. Grammeltvedt, pers. comm.), the ore body had a primary very elongate morphology (Fig. 38); total length exceeds 4 km with a maximum width and thickness of c. 400 and 60 m, respectively. The shape was largely controlled by the sheet-like feeder zone which underlies the central part of the stratiform sulphide body along its entire length.

The feeder zone cross-cuts obliquely the volcanic stratigraphy and is well-defined down to more than 300 m below the contemporaneous palaeo-seafloor. Sulphide stockworks and disseminations constitute the most conspicuous parts of the feeder zone, in a width of c. 100 m, increasing in density towards the most central parts and particularly towards the stratiform ore level. Different sulphide facies can be distinguished within the zone, commonly forming cross-cutting or composite veins, or veins cutting earlier disseminations (Grenne 1986 and in prep.). Hydrothermal alteration has

TABLE 8. Mean compositions of massive, stratiform sulphide ores and 'vasskis' sulphides from the Løkken area. Løkken mine data are on a continuous mill head sample (1982 production). Høydal data are based on 63 representative samples, and the 'vasskis' figures are averages of 11 samples of sulphide layers from 'vasskis' horizons in various parts of the Løkken area. Dragset data (19 samples) from McQueen (1985). Analyses by AAS, except Au, As, Sb and Se, which are done by instrumental neutron activation (20 selected samples from Høydal). 'Vasskis' Au is analyzed by fire assay-AAS. n.a. = not analyzed.

	Løkken	Høydal	Dragset	Vasskis
Cu	2.2%	1.7%	2.2%	220 ppm
Zn	2.4%	7.1%	2.7%	450 ppm
Pb	330 ppm	840 ppm	100 ppm	170 ppm
Ag	18 ppm	36 ppm	18 ppm	1 ppm
Co	450 ppm	250 ppm	210 ppm	30 ppm
Ni	30 ppm	40 ppm	50 ppm	120 ppm
Cd	70 ppm	210 ppm	90 ppm	2 ppm
Mn	190 ppm	120 ppm	170 ppm	530 ppm
Mo	50 ppm	20 ppm	n.a.	n.a.
Au	200 ppb	270 ppb	n.a.	<20 ppb
As	330 ppm	500 ppm	n.a.	n.a.
Sb	5 ppm	12 ppm	n.a.	n.a.
Se	70 ppm	70 ppm	n.a.	10 ppm

strongly affected the chemical composition and mineralogy of the feeder-zone wall-rocks. The most conspicuous features are alteration to chlorite-albite-rich assemblages in the peripheral regions, while in the central zone a more advanced, pervasive, alteration has given chlorite-quartz rocks. Sericite-bearing assemblages appear in the altered volcanites close to the stratiform ore level. Representative analyses of various alteration rocks are listed in Table 7B. Feeder-zone relationships in the other ore occurrences in the Løkken area are largely similar to those at Løkken. However, the feeder zone at the Høydal deposit is slightly more irregular and less well-defined (Figs. 36 and 39). Although the stratiform sulphide bodies in the area are generally very proximal, lying immediately above their hydrothermal feeder zones, parts of the deposits may have suffered penecontemporaneous slumping and were redeposited as adjacent, slightly more distal breccias of sulphide ± metabasalt ± jasper or as finer-grained, laminated and partly graded sulphide sediments. A coarse variety of the former type is well exposed in the eastern mine in the Høydal deposit (Fig. 39), where it constitutes a major part of the total stratiform sulphides. These breccias are considered as equivalents to the above-mentioned greenstone ± jasper talus breccias (Grenne 1981).

STOP DESCRIPTIONS

The excursion localities are concentrated to the vicinity of Løkken and the area around the Høydal mine (Fig. 36). Starting with the stratigraphic lower parts of the ophiolite pseudostratigraphy, the excursion will successively move to higher levels until the overlying conglomerate is reached in the southern part of the excursion area. Emphasis is placed on the middle part of the volcanic sequence, including the massive sulphides, which are easily accessible and well exposed in the open-pits of the abandoned Høydal mine. Most of the localities are off the road, and Stops 6.7 to 6.12 are along a 4 to 5 km walking traverse over the hill Høydalskammen.

Stop 6.1: Metagabbro with dykes.
Location: Map-sheet M711/1521 III Løkken, NR 3620/0040. c. 300 m along a steep track off the road through Langenglia, c. 300 m ESE of football ground.

The uppermost parts of the metagabbro can be seen on small exposures on and near the track. The metagabbro, which is medium-grained and isotropic, is cut by several basic dykes trending c. NW–SE, with fairly steep dips to the southwest. The dykes range from 0.5 m in thickness to thin off-shoots a few centimetres across. Flow-banding is prominent along the fine-grained dyke margins, which were obviously chilled against an already cooled part of the gabbro. Angular bends in margins suggest that the dykes intruded along cracks and joints in the chilled metagabbro. Irregular veins of epidote (occasionally with an adjacent alteration rim) often cut both metagabbro and dykes. This type of veining is abundant in the lower parts of the ophiolite sequence and may be related to interactions between wall-rocks and solutions in the deep parts of hydrothermal systems associated with the intrusion and cooling of the metagabbros. c. 50 m to the south, dyke-intruded pillow lavas of the lower volcanic member are exposed in large cliffs above the track.

Stop 6.2: Plagiogranite.
Location: Map-sheet M711/1521 III Løkken, NR 3430/0075. Northeastern shore of the lake Bjørnlivatnet, c. 400 m ESE from the road near the northwestern end of the lake.

A characteristic light-coloured, medium grained plagiogranite is exposed here in the uppermost part of the metagabbro or possibly at the contact to the pillow lavas above. The rock is composed primarily of albite, quartz and epidote; at this locality also magnetite is abundant. E–W striking basic dykes cut the plagiogranite with fine-grained chilled margins. The chemistry of these dykes demonstrates their relationships to overlying volcanites and hence that the plagiogranite is a part of the ophiolite. Numerous N–S oriented quartz veins occur in the plagiogranite at this locality; these veins also post-date and cut the basic dykes.

c. 100 m east of the locality, we can see a relatively dark, magnetite-bearing, somewhat fractionated metagabbro with basic dykes, whereas the first, relatively poor exposures southeast from the plagiogranite apparently show abundant basic dykes in pillow lava. A few, thin silicic dykes have the same general orientation as the basic dykes in this area.

Stop 6.3: Pillow lavas of the lower volcanic member.
Location: Map-sheet M711/1521 III Løkken, NR 3460/0045. Northeastern shore of the lake Bjørnlivatnet, 400–500 m southeast of Stop 6.2.

Along the shore and in a cliff on the southwestern side of a small promontory, there are several good exposures of the pillow lavas characteristic of the lower volcanic member. The pillows range from more than 2 m to small pillows a few centimetres across. At this locality, the pillows have relatively regular, bun-shaped morphologies; the larger ones are slightly flattened. Inversion with steep northerly dip and way up to the south is clearly demonstrated. Radial and concentric cooling joints can be seen occasionally. Small spherulitic varioles are found especially along pillow margins, while vesicles are absent or scarce. A prominent and characteristic feature is the thick, originally glassy pillow rims surrounding the individual pillows. The basaltic glass is altered to mainly chlorite, with epidote along thin joints. The original glassy nature is clearly shown by the very well-preserved conchoidal jointing, leaving a more than 2 cm thick shell of small, sharp-edged and smoothly curved 'glass' shards around each pillow. The shards may be in situ, or glass fragments may have spalled off the pillow rims, forming thicker 'pockets' of hyaloclastite between pillows.

Stop 6.4: Sheeted dykes.
Location: Map-sheet M711/1521 III Løkken, NR 3510/0065. Southeastern side of small hill-top, 350 m northeast of the dam of lake Bjørnlivatnet.

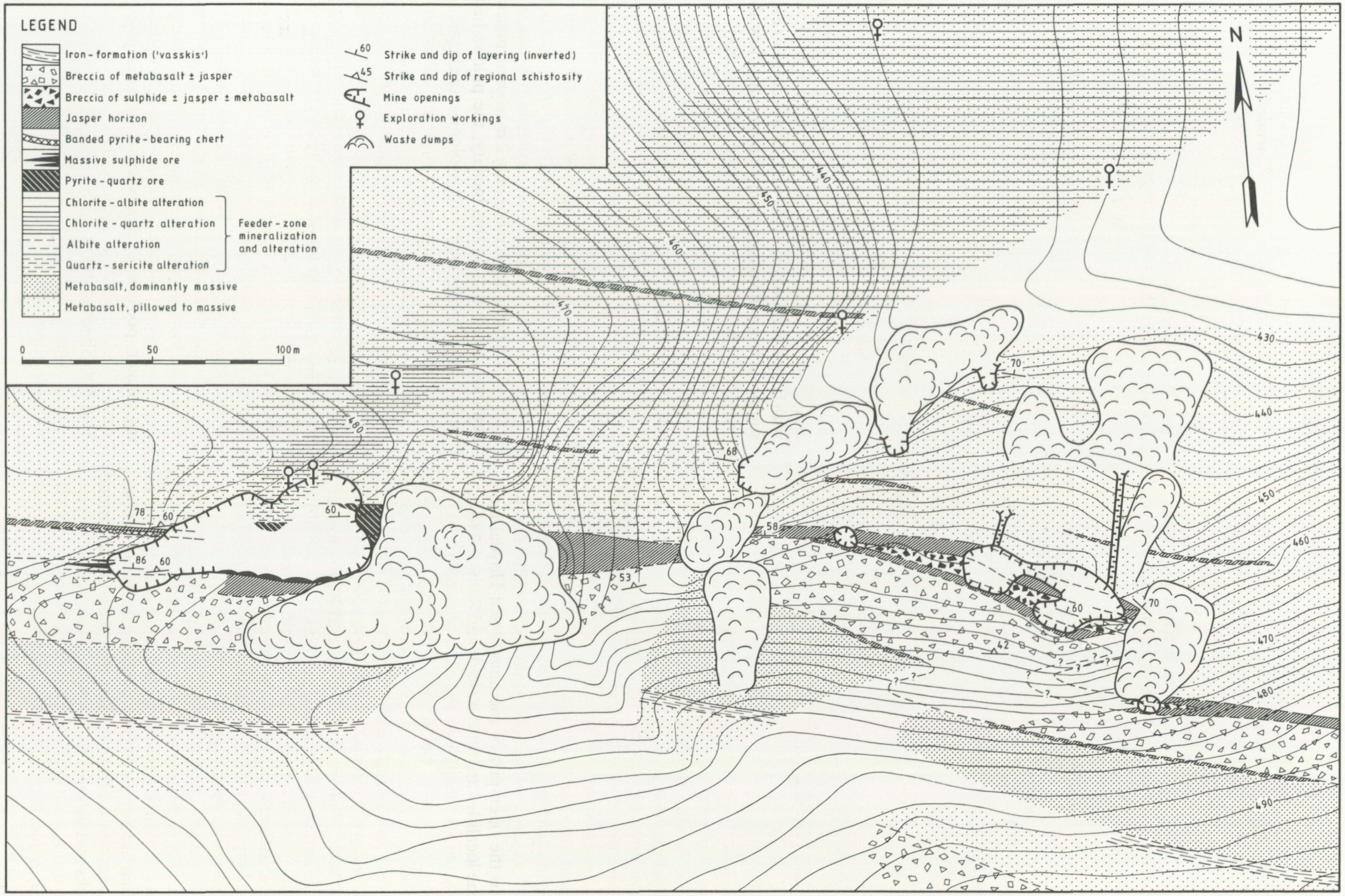


Fig. 39. Geological map of the Høydal mine area. Stippled boundaries are inferred from drillhole data. Contour interval 2 m.

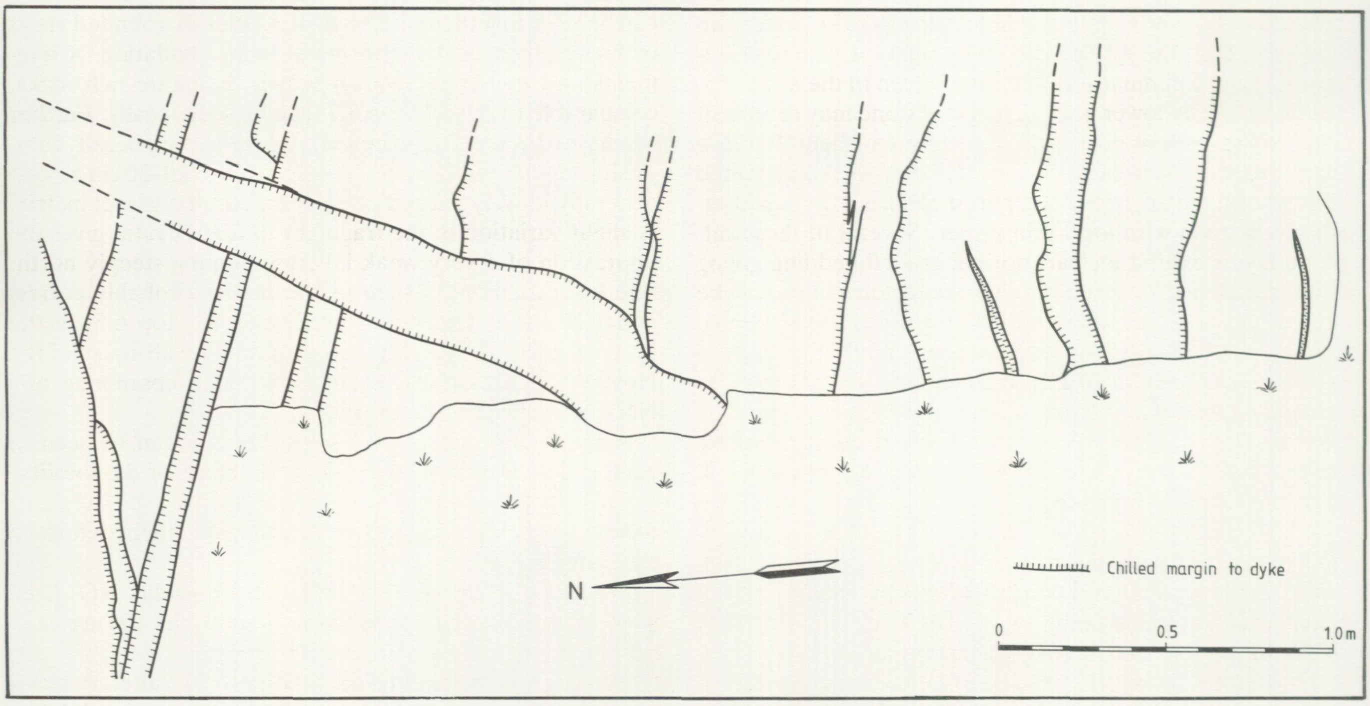


Fig. 40. Sketch from Stop 6.4 showing multiple metadolerite dykes.

In this area, basic dykes predominate, with only a few screens of pillow lava occasionally preserved between the dykes. The locality displays a section with 100 % dykes intruded subparallel, as multiple dykes, along earlier dyke margins, or with cross-cutting relationships (Fig. 40). Dyke width ranges from more than 1 m down to 10 cm, although thinner off-shoots can also be seen. Their margins are fine-grained and may show a vague flow-banding, while the interior parts pass into more medium grained metadolerite depending on dyke thickness. One set of dykes strikes approximately WNW–ESE with southerly dips. A later generation intruded in a more E–W direction, while the latest dyke at this locality cuts the older ones with a NE–SW strike and moderate dip to the northwest. The latter intruded along a fracture or minor fault with some 30 cm displacement of the early dyke contacts (see Fig. 40). All these dykes have tholeiitic compositions which are compatible with their origin as a part of the ophiolite.

Stop 6.5: Distal part of the Løkken ore body.
Location: Map-sheet M711/1521 III Løkken, NQ 3505/9975. Cliffs above old road, 80–100 m south of main road from Løkken to Bjørnli, just above old adit.

This locality is thought to be the place of discovery of the Løkken ore in 1654. Assuming that the separation of the ores in the Løkken mine into different bodies is due to a tectonic repetition of essentially one elongate lensoid ore layer (see introduction), this most distal part of the sulphide layer must originally have been 200 m or more from the feeder zone, measured perpendicular to the feeder zone/massive sulphide intersection line.

The sulphides are resting, in inverted position, on a sheet flow which can be seen to the north. This metabasalt is plagioclase-phyric and generally, although variably, vesicular. Highly vesicular varieties with fairly large vesicles can be seen a few metres to the north, as well as some 100 m to the east, along strike. Transitions into irregular thin-rimmed pillow-like structures are found locally within the upper few metres of the generally massive flow. The flow-top surface, which is very well exposed, displays ropy to lobate pahoehoe structures, now oriented horizontally along strike. Shape and curvature of these structures may suggest a flow direction towards the south (in the present inverted position) which is away from, and roughly perpendicular to, the longitudinal axis of the proximal parts of the Løkken ore body.

The lowermost part of the c. 90 cm thick distal ore horizon, resting directly on the pahoehoe flow top, comprises 5–10 cm of finely laminated, fine-grained sulphides alternating with greenish bands and occasional jasper lenses. The top of this bed shows ripple-like structures oriented horizontally along strike, and it is overlain by a 40 cm thick unit of coarse clastic breccia ore. In addition to sulphides, this unit contains large and smaller fragments of fine-grained greenstone, minor jasper, and irregular chlorite-rich 'flakes' in a sulphide matrix which shows a vague grading towards more sandy sulphide along the stratigraphic top. The upper 40 cm of the ore zone comprise thin, fine-grained sulphide (pyrite-chalcopyrite-sphalerite-pyrrhotite-magnetite) layers alternating with reddish to greenish fine-grained, finely laminated, silicate-oxide sedimentary layers. Structures which can be interpreted as representing soft-sediment deformation are abundant.

A 10–15 m thick massive, plagioclase-phyric greenstone concordantly overlies the sulphide horizon. The lower and upper contacts are fine-grained but apparently non-vesicular. A vague columnar jointing can be seen in the northern, stratigraphically lower parts. The greenstone may represent a subvolcanic sill or possibly a non-vesicular sheet flow. To the south, this is overlain by a new, c. 70 cm thick, laminated sulphide (mainly pyrite-chalcopyrite-sphalerite)-magnetite-silicate horizon with local thin jasper. Several of these sulphide layers exhibit a clear, normal graded bedding giving further evidence for inversion. A weak tectonic fabric can be seen along both the southern and northern ore horizons, striking c. WSW–ENE with a more gentle NNW dip than the layering, and, in the southern zone, minor folds may be related to this fabric. The southern ore horizon is covered by a close-packed pillow lava with a fairly primitive basaltic composition (Table 7A, column 3); this is exposed some 40 m to the west along strike.

Stop 6.6: 'Vasskis' horizon.
Location: Map sheet M711/1521 III Løkken, NQ 3475/9965. Small exploration workings near old railway line, 50 m WSW of tunnel. East of lake Fagerlivatnet.

The locality shows a more than 1 m thick, typical 'vasskis' horizon, striking WNW–ESE with 45° dip to the north. Very fine-grained Fe-sulphides (here pyrite) alternate with thick, dark, silicate-magnetite layers. The three pyrite layers exposed here are 1 to 3 cm thick and display a very fine regular internal lamination. A similar fine lamination is seen also in the dark silicate-oxide interlayers. Contrary to the banded sulphides at Stop 6.5, these 'vasskis' sulphide layers are nearly devoid of base metal sulphides. The horizon apparently occurs 50–100 m stratigraphically above the massive ore level. Comparable 'vasskis' layers are found also immediately or a few metres above the massive ore in the Løkken mine. Thus, it is likely that there are several of these horizons, although they are confined to a very restricted stratigraphic interval above the massive sulphides.

Stop 6.7: Hematite-rich altered pillow lava.
Location: Map-sheet M711/1521 II Hølonda, NQ 3695/9905. 10 m above the track, 30–40 m east of small stream.

In a small outcrop, we can see pillow lava or pillow breccia, more or less altered to hematite-rich, purplish rocks which grade into more normal, greyish-green metabasalt. Oxidation has partly occurred along a network of thin veins. This kind of alteration is common throughout the whole area, down to a few tens of metres stratigraphically below 'vasskis' horizons. It possibly reflects a period (or periods) of more pervasive weathering of the uppermost parts of the oceanic crust by oxidizing seawater.

Stop 6.8: Greenstone ± jasper breccia.
Location: Map-sheet M711/1521 II Hølonda, NQ 3735/9885. A 15 m long N-S cliff, 300 m WNW of the western open-pit of the Høydal mine.

Greenstone breccias of this type, with or without jasper clasts, are characteristic of the middle volcanic unit. In the north, a few angular jasper fragments up to 20–30 cm across can be seen together with angular to slightly rounded clasts of fine-grained or doleritic metabasalt. Oxidation of fragments and matrix to reddish-brown, hematite-rich rocks, comparable to that at Stop 6.7, can be seen locally. Further south, the breccia is composed entirely of metabasalt, comprising angular blocks a few centimetres to 20–30 cm across, generally loosely packed in a green, basaltic gravel matrix. A slight variation in the fragment to matrix ratio gives the impression of a very weak layering dipping steeply north. The weak schistosity seen in the matrix probably corresponds to the deformation fabric seen at Stop 6.5, in the breccias at Stops 6.9 and 6.11, and in the wall-rocks of the Høydal ore. At all localities, this schistosity dips more gently NNW than the bedding surfaces.

A poor exposure of a 'vasskis' horizon can be seen in exploration workings some 30 m southeast of the locality.

Stop 6.9: Hølonda porphyrite cutting through deformed greenstones.
Location: Map-sheet M711/1521 II Hølonda, NQ 3745/9880. Small exposures on the top of a small hill, 100 m east of Stop 6.8.

Bluish-grey, magnetite-rich pillow lava (altered metabasalt) and greenstone breccia exhibit a pronounced deformational fabric with a schistose matrix and strongly deformed fragments. A dyke of Hølonda porphyrite (of early Ordovician, probably Llanvirnian age) with northeastern strike cuts obliquely through the deformed greenstones, apparently without any significant deformation of the porphyrite. The thickness of the dyke is approximately 50 m. Near the margin, 1–2 cm tabular plagioclase phenocrysts are generally arranged subparallel to the somewhat irregular contact to the deformed greenstones. The orientation of the phenocrysts behind larger irregularities may also suggest turbulent flow along the dyke margin.

Stop 6.10A: Massive sulphide deposit and related feeder-zone mineralization.
Location: Map-sheet M711/1521 II Hølonda, NQ 3765/9875. Høydal mine, western open-pit, 2 km ESE of Løkken.

The ore at Høydal was discovered in 1659. Mining operations took place at intervals until 1911 on two separate ore bodies, in underground workings, and later in small open-pits. The mine is small. Total production has been of the order of 100 000 metric tons averaging 45 % S, 1.5 % Cu and some zinc, contained in pyrite, chalcopyrite and sphalerite (Grenne *et al.* 1980). Galena is a minor constituent but is more abundant than in the Løkken deposit where also the Zn/Cu ratio is considerably lower (Table 8).

In the western open-pit, there appears to be two different levels of stratiform sulphides, separated by a 10 m thick lava (Fig. 39). The lower horizon is seen in the western part of the pit, as finely laminated pyrite-chert overlying a jasper bed. To the east, along strike, apparently the same level comprises more massive or vaguely banded pyrite-quartz mineralization. However, here the relationships to the upper ore horizon are somewhat unclear due to poor exposure. The upper ore horizon is exposed along the southern wall of the open-pit, as well as in the extreme west where the massive pyrite-sphalerite-chalcopyrite ore fingers out into metabasalt breccias. Locally, these are strongly albitized but grade into recognizable greenstone (± jasper) breccias both upwards and along strike. A few metres east along the south wall of the pit, one can see more normal greenstone breccias directly overlying the sulphides. Further east, however, the ore is overlain by a more than 5 m thick jasper, with local sulphide-jasper breccias along the contact.

The stratiform sulphides are underlain by a deep, fairly well-defined feeder zone which is, however, more irregular than the Løkken feeder zone. It comprises sulphide disseminations and veining (Grenne 1981 and in prep.). The feeder zone can be followed continuously in drillholes and exploration workings, more than 300 m into the stratigraphically underlying greenstones, trending NE–SW (Fig. 39) with a gentle dip to the northwest. The feeder zone was partly worked in the western Høydal mine and is, thus, very well exposed in the northern wall of the open pit. Typically it contains relatively coarse-grained pyrite occurring as disseminations and networks of veins up to a few centimetres across or as individual thicker veins and irregular lenses. The veins sometimes follow primary volcanic structures in the wall-rocks, like pillow rims, pillow cooling joints etc. Vesicles are filled with pyrite and quartz. The feeder zone is clearly cutting through the lower horizon of jasper and banded pyrite-chert, as well as the overlying intra-sulphide metabasalt, and the jasper is almost completely bleached with only a few small, red hematite-bearing patches preserved. Pyrite-quartz vein networks also cross-cut parts of the upper ore horizon, to which they are genetically related, as seen in the extreme west of the pit. In the north wall, we can also see that the feeder zone is actually separated into several, thinner and parallel, more strongly mineralized zones, the intersections between these and the bedding plunging to the WNW, similar to the plunge of the Løkken ore body.

The basaltic lavas in and around the feeder zone are variably altered. Chlorite-albite-rich assemblages predominate with chlorite-quartz alteration occurring only locally in the central parts. In the upper 30–50 m, these rocks grade into albite-sericite and quartz-sericite-rich rocks, respectively (Table 7B). Metabasalt breccias immediately overlying the stratiform sulphides are locally affected by albite alteration.

Stop 6.10B: Sedimentary breccia of sulphide-jasper-metabasalt.
Location: Map-sheet M711/1521 II Hølonda, NQ 3795/9875. Eastern Høydal mine, 300 m east of Stop 6.10A, and waste dumps below the mine.

In small open-pits (Fig. 39), we can see a sedimentary breccia ore composed of sulphides similar to those found in the western Høydal mine, together with angular to rounded clasts of red jasper, greyish chert and variably altered metabasalt. The matrix is mainly sulphide, sometimes with some sand-sized jasper fragments, and the larger sulphide clasts are recognizable only where they are more fine-grained and massive than the matrix. The size of the clasts is variable, the largest, quite angular jasper blocks being more than 1 m across. Sorting or size grading is not observed in the deposit, although finer-grained banded sulphides, more like those seen in the distal parts of the Løkken ore (Stop 6.5), can occasionally be found on the waste dumps.

The breccia ore is both underlain and overlain by fairly thick jasper beds; these often exhibit a fine lamination more or less disturbed by soft-sediment deformation. Pillow lavas, which are found below the lower of these jasper horizons in the open pit, show no significant feeder-zone mineralization or alteration. 20–30 m south of the mine, the thick metabasalt breccia overlying the sulphides and jaspers are exposed in a cliff; it can also be seen in blocks in the waste dumps below the mine.

Stop 6.11: Oxidized metabasalt-jasper breccia, at or close to the Høydal ore level, and overlying metabasalts and 'vasskis' horizons.
Location: Map-sheet M711/1521 II Hølonda, NQ 3840/9865 to 3845/9855. A 120 m traverse from north to south, across a hill 450 m SSE of the small lake Gruvtjønna, and 500 m ESE of the last stop.

Starting at a small cliff down the hillside north of the peak, we observe a vesicular metabasalt just below (stratigraphically) the metabasalt-jasper breccia. The rock is oxidized (similar to that seen at Stop 6.7) and is rich in hematite, particularly along and outwards from a network of 1–3 cm thick bluish-grey veins. The breccia overlying this altered metabasalt is exposed in a large block and a cliff some metres higher up. At this locality, the breccia has suffered strong oxidation similar to the underlying rocks, and the matrix is stained dark greyish by the high content of hematite. Also the metabasalt clasts are oxidized, although to a variable degree.

The contact between the breccia and the overlying metabasalt is exposed in the cliff to the south. The contact is sharp, with the oxidized breccia apparently being squeezed up between pillow-like structures in the base of the flow. The metabasalt shows no sign of strong oxidation which thus must have taken place prior to the eruption of the basalt, while the breccia was exposed on the seafloor. On several exposures at the top of the hill, the basaltic flow is developed as a slightly vesicular, close-packed and fairly thin-rimmed pillow lava. Pillow shapes confirm the inversion of the rocks. An unusually strong accentuation of the radial and concentric jointing of the pillows gives the rock a breccia-like appearance.

Overlying the pillow lava, on the southeastern slope of the hill, is another metabasalt breccia, here composed of loosely packed bluish-grey to greenish-grey fragments in a more normal greenish matrix. The fragments were probably derived from the oxidized metabasalts lower down. The rock displays a marked tectonic fabric similar to that seen at Stop 6.9. Two thin 'vasskis' horizons separated by a 3 m thick massive flow occur stratigraphically above the breccia. These are seen in small workings on the southern steep slope of the hill, and comprise centimetre-thick pyrite layers along with thin jasper and black magnetite-rich layers.

Stop 6.12: Greenstone-jasper conglomerate overlying the ophiolite sequence.
Location: Map-sheet M711/1521 II Hølonda, NQ 3830/9815. Just northeast of the small hill Brandan on Høydalskammen, 400 m SSW of Stop 6.11.

On large hill-top exposures, we can see the basal Lower Hovin greenstone-jasper conglomerate, here with a mixture of large angular to slightly rounded fragments, some of them more than one metre across. The clasts are mainly derived from the upper part of the underlying complex, with slightly vesicular, sometimes almost whole pillows, angular doleritic greenstone fragments, jasper and pink chert; a block of banded jasper together with 'vasskis' is also present. At this locality, the conglomerate also contains a high proportion of angular, white felsite fragments, as well as blocks of calcite-rich, volcanite- and jasper-derived sedimentary rocks. The very irregular structure of some thin, green siltstone and sandstone layers within the conglomerate may have been caused by a syn-depositional soft-sediment deformation.

100 m to the south, the conglomerate contains a more than 15 m thick greenstone. Pillow structures suggest that it is situated in the normal inverted position, showing way up to the south. It is not clear whether this greenstone represents a basalt flow within the period of conglomerate deposition, or if it is a large slide-block in the conglomerate; the latter interpretation is considered more likely. An E–W striking trondhjemite dyke cuts the conglomerate just south of the greenstone; such rocks have not been observed higher up in the Lower Hovin sedimentary sequence.

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NGU = Norges geologiske undersøkelse
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