



Bergvesenet

Postboks 3021, 7002 Trondheim

Rapportarkivet

Bergvesenet rapport nr BV 2141	Intern Journal nr	Internt arkiv nr	Rapport lokalisering	Gradering Fortrolig
Kommer fra ..arkiv Sulitjelma Bergverk A/S	Ekstern rapport nr "532100003"	Oversendt fra	Fortrolig pga	Fortrolig fra dato:
Tittel Halo-geochemistry project report. May 1984. Halo geokjemi				
Forfatter COOK N		Dato 1984	Bedrift Sulitjelma Gruber A/S	
Kommune	Fylke	Bergdistrikt	1: 50 000 kartblad	1: 250 000 kartblad
Fagområde	Dokument type	Forekomster		
Råstofftype	Emneord			
Sammendrag Progress report on halo-geochemistry project. Topics covered indude; sulphide separate analysis, sphalerite geobarometry,feeder-zones, active hydrothermal systems, probe work, anhydrite, sulphide metamorphism, chemical exchange. Report is largely based on work carried out in London Spring 1984 and does not constitute a final report. Halo geokjemi Anhydritt. Geobarometri. Feedersone.				

SULITJELMA BERGVERK AS

Tlf: (081) 40500

Telex: 64065 SUA-N

Ref.nr: 532.100.	Krt.nr:	Prj.nr: 141	År: 1984
------------------	---------	-------------	----------

Forfatter: NIGEL COOK

Ant:

Tittel: HALO GEOCHEMISTRY PROJECT
REPORT. MAY 1984Fordeling
Sulitjelma:

Nga.koord:

X1: Y1: Z:

X2: Y2:

Sulis koord:

X3: Y3: Z:

X4: Y4:

Resyme:

Progress report on halo geochemistry project. Topics covered include; Sulphide separate analysis, sphalerite geobarometry, feeder zones, active hydrothermal systems, probe work, anhydrite, sulphide metamorphism, chemical exchange. Report is largely based on work carried out in London Spring 1984 and does not constitute a final report.

Andre:

Kommentar:

P. Kaspasen

REPORT
TO A/S SULITJELMA BERGVERK

20 MAY 1984

NIGEL JOHN COOK

Introduction

This report represents an overview of progress so far, on various topics currently being considered, and on subjects advanced upon during recent months in London. Most of this work is aimed at understanding more about the processes governing trace element distributions which have been found in preceding studies. The trace element patterns around the Giken deposit can soon be presented in their final form as contour maps and profile diagrams, together with interpretations and guidelines as to the applicability of exploration-viable models. The techniques can now be applied to other areas like the South Mine Area where interpretations as to hidden ore bodies can be made, although this cannot be completed until the end of the Summer. The data from Sagmo is presently not sufficient to allow modelling of distributions, but can provide valuable information on this petrogenetically different deposit and its genesis. Sampling is now planned to take place on two fronts: Firstly, core material from the Mons Petter drilling programme, and secondly, mine sampling of Palmberg and associated horizons. This is to be carried out in conjunction with mineralogy and other studies to consider further if it represents a feeder zone.

The work done in London has been useful in opening up new concepts for appraisal and to clarify some misconceptions about genetic aspects of massive sulphide deposit research. In many ways, the broad picture is becoming more complicated rather than simpler. The next couple of months work will mainly deal with the above sampling. Further underground work in Giken will be required. Some interpretive work also needs to be carried out. Much of the work planned for the Summer depends on the drilling programme. A regional orientation is being considered. In the following review, selected topics are discussed in the light of recent observation. All of these topics are treated as of integral importance to the present project, and none constitutes a final assessment. Much work remains to be done in the course of the next 18 months.

Boron (B)

Boron is a moderately mobile rare element which occurs in trace quantities in most rocks. In metamorphic rocks, Boron occurs as tourmaline (Na-Al boro-silicate) and also substituting into muscovite, which can be a major host for the element. Boron can be introduced into a rock during metasomatic processes and hydrothermal waters frequently contain high concentrations of B. The element has been considered as potentially useful in exploration for mineral deposits, although more suited to vein type deposits and Cu-porphyry type systems. However, the levels of B in the 15 rocks analysed from Sulitjelma are very low (≤ 10 ppm.) This means that the element is not enriched to be of sufficient use in exploration. No boron-bearing minerals have been seen in strata related to the sulphide deposits, although tourmaline has been recorded from the Baldoive granite which may have played a role as a heat source during ore formation. It is possible that a B halo might exist in the associated mica-schists. The Boron content of a rock is normally thought to decrease with increasing metamorphism. Ref: Wedepohl.

Thallium(Tl)

Thallium is generally present in most rocks in very low quantities. The element is generally enriched in rocks which have been affected by metasomatic processes and those associated with K enrichment. Enrichment around hydrothermal mineral deposits is commonplace (e.g. Kuroko). Tl is incorporated mainly in pyrite and sphalerite (although galena is the best host of all). The element is also highly mobile during metamorphism due to its high volatility. Thus, Tl should be a highly suitable element in exploration for hydrothermal mineral deposits. (See Ikramuddin et al (1983)) Tl correlates well with K and Rb and it is suggested that Tl was concentrated in hydrothermal fluids and may have been supplied by acid intrusions (e.g. Baradov and Rabinovitch)

The Tl data for the Sulitjelma rocks (15 analyses) do indicate that they are generally enriched in that element. There is a broad correlation between Tl and the principal ore components Cu, Zn and S. However, the high mobility of Tl infers that metamorphism has probably obliterated the primary Tl halos about individual deposits and that the Tl enrichment is probably a regional feature of the Sulitjelma area and that Tl is probably not suitable for exploration on the local scale. Further interpretive work on the data is required to evaluate the element properly. Refs.: Ikramuddin et al (1983), DeAlbuquerque and Shaw (1972) and Voskrenskaya and Karpova(1958).

Tellurium (Te)

The abundance of the element Te in the Sulitjelma ores shows enrichment (1-4 ppm) and the element correlates well with both Se and Cu. Te occurs mostly as tellurides, with a very high affinity to form gold tellurides. There is no apparent correlation between Te and Au in the analysed samples. Te has been demonstrated to be an efficient exploration tool for porphyry copper deposits with large (greater than 5km halos). It seems reasonable that Te halos should also exist around massive sulphide deposits. The Te minerals are often present within chalcopyrite crystals as inclusions or exsolutions. None were seen during microscopy due to the very limited occurrence of the minerals. It is also suggested that Te substitutes for Se (and correspondingly S) particular in pyrite. Te appears to be a good indicator element although the analytical method used would have to be sufficiently accurate and sensitive to make use of Te as an exploration tool practical. Refs.: Czamanske and Hall (1975), Shcherbina and Lebedev(1966), Watterson (1977) and Oftedal (1959)

Further interpretive work needs to be done especially as concerns the mobility of the element and its role in metasomatic and hydrothermal processes.

Separation and Analysis of Individual Sulphides

A selection of sulphide minerals were prepared and analysed to establish patterns of trace element distribution among the main sulphide minerals, and to view the variation in trace element content in minerals from different occurrences. Most were collected by differential magnetic separation. Over 50 samples were eventually prepared for analysis. Each was analysed for Ti, V, Cr, Mo, Mn, Co, Ni, Cu, Ag, Zn, Cd and Pb at I.C. (Also some work on Sb, Bi and As, although the methodology needs to be refined)

The resulting data has been inspected for trends. Below is a table which shows the degrees of enrichment for trace elements in different sulphide minerals:

As	Py > Cpy > Po > Sph	Mo	Cpy > Py > Po > Sph
Mn	Sph > Cpy > Po > Py	Co	Py > Po > Cpy > Sph
Ni	Po >> Py > Cpy > Sph	Ag	Cpy > Gal > Sph > Po, Py
Cd	Sph > Gal >> Cpy > Po, Py	Pb	Sph >> Cpy, Py > Po
Bi, Sb	Gal >> Others		

MEAN ABUNDANCES (PPM)

	Ti	V	Cr	Mo	Mn	Co	Ni	Cu	Ag	Zn	Cd	Pb	As
Pyrite	36	4	7	20	20	722	55	5427	4.6	2205	4	121	125
Pyrrhotite	68	18	26	18	70	297	198	2585	4.2	558	2	7	1
Chalcopyrite	tr	21	19	36	152	98	34	-	26	7025	24	82	17
Sphalerite	tr	1	1	20	445	62	17	7300	17	-	2000	1600	3

The presence of some of these elements in the sulphides (Cu, Zn, Pb) indicates that there are impurities and inclusions present. Pyrites, for example, may contain several per cent Cu. A number of minor phases were seen during microscopy of ore samples. There follows a brief review of the main points in the above study.

Chalcopyrites from massive ores are richer in Zn, Sb, Bi and As than cpy from disseminated ores. Otherwise, uniform trace element contents are recorded.

Sphalerites High Cd, Mn and Pb. Often intergrown with chalcopyrite.

Pyrrhotites Generally, a poor host for trace elements. The Co, Ni and Co/Ni ratios are of interest. The pyrrhotites from the Sagmo "Quartz Ores" are very high in Co and Co/Ni is greater than 2. These ores

might be interpreted as "remobilised" or "relocated" ores. The high Co/Ni ratio may be attributed to the lack of re-equilibration between pyrite and pyrrhotite. (There is no pyrite present in this occurrence with which to re-equilibrate) It has been established that, during metamorphism, ores containing the two minerals will re-equilibrate, causing Co to become concentrated in the pyrite, and Ni in the pyrrhotite. (Co/Ni of pyrrhotites will decrease). In the Banded Ores, where there are both minerals present Co, Ni and Co/Ni are 44,234 and 0.19 respectively, suggesting substantial re-equilibration.

Pyrites from massive ores are richer in As, Bi, Cu, Zn, Cd and Pb, whilst those from disseminated ores are clearly enriched in Ti, Mn and Ni. The low Ni content can be explained by lack of pyrrhotite in the disseminated ores of Giken. The Mn and Ti are probably present in included in silicates. Silicate inclusions are common in pyrites from the disseminated ores. The following Co/Ni ratios are seen in pyrites: 51.0 (Sagmo Ores), 23 (Giken massive ores) and 5.6 (Giken disseminated ores). This is again attributable to relative amounts of Po-Py re-equilibration.

Sagmo pyrites are noticeably richer in Mo, which cannot readily be explained. The presence of As, Bi, Cu, Zn, Cd and Pb concentrated in the massive ores could be due to the high mobility of these elements being concentrated higher in the system.

Various workers have attempted to relate the Co and Ni contents of sulphide minerals to the temperature of metamorphism and also the environment of formation of the ore body. However, other workers, notably Gavelin and Gabrielson (1947) suggest that the Co and Ni contents of sulphides in metamorphosed deposits is far more dependant upon the presence of other sulphide minerals, a concept which the present study would tend to support.

Refs: Bjørlykke and Jarp (1950), Hegemann (1943) Temperature dependance of Co/Ni.

Cambel and Jarkovsky (1967), Loftus-Hills and Solomon (1967) Co/Ni and formational environment

Ryall (1977) and Roberts (1982) Trace elements in pyrite in exploration

The Pyrrhotite in the Sulitjelma Deposits

In a textural sense, the pyrrhotite from certain of the deposits is metamorphic, yet it is highly uncertain that the pyrrhotite may be primary in a mineralogical sense. That the pyrrhotite is primary (or metaprimary) can be argued from studies of the widespread occurrence of pyrrhotite in active hydrothermal systems and an understanding of phase relationships. A tentative model can be put forward as to the origin of the Sagmo deposit which requires further study and mapping. The metamorphic conditions operating at Sulitjelma would be sufficient to have produced pyrrhotite from pyrite, but it is significant that, in deposits other than Sagmo, the occurrence of pyrrhotite is not widespread. It is suggested that different physico-chemical conditions were operating for the pyrrhotite-rich deposit during formation. It is implied that pyrrhotite would be precipitated preferentially to pyrite in a stringer zone at a relatively higher temperature and lower pH, f_{O_2} and f_{S_2} compared to the sulphides ejected onto the sea-floor, at substantially higher f_{O_2} and slightly lower temperatures. An alternative suggestion is that different sulphur/metal ratio is a function of the distance between thermal centre and place of deposition. This also offers a plausible explanation as does the concept of the occurrence of pyrrhotite being controlled by depth and sea-floor topography.

Further work needs to be carried out on the textures of the Sagmo ores, looking for evidence to support a pre-metamorphic origin for the pyrrhotite. Geochemically, the Sagmo ores are poor in elements like Pb, As, Au, Ag, Sb, and Bi compared to the Giken pyritic ores, as would be predicted for a feeder-zone. However, this is merely a function of mineralogy (pyrrhotite is a poor host for most trace elements) and is not conclusive in itself. Refs.: Sundblad (1981), Plimer and Finlow-Bates (1978), Sangster and Scott (1976), Mallio and Gheth (1972), Large (1977) and Finlow-Bates (1977)

Sphalerite Geobarometry

The concepts of, and the theoretical background to, the Sphalerite Geobarometer have been investigated. The FeS content of sphalerite varies as a function of pressure and is completely independent of temperature over a great range 100-700° C. Conditions for the successful application of the geobarometer are the presence of pyrite and hexagonal pyrrhotite in equilibrium with the sphalerite. If this condition is met, then a reliable estimation of the maximum pressure during metamorphism can be attained. Key references are Scott (1976), Wiggins and Craig (1980) and Tornroos (1982).

A number of sphalerites from Sulitjelma were analysed using the probe. The mean FeS content of the sphalerites was found to be 13%, there being little variation from this. Application of the geobarometer implies a pressure of about 6.5 to 7 kBar, agreeing well with other estimates of pressure for the regional metamorphism of the Sulitjelma Amphibolites. More sphalerites need to be analysed before the final conclusions can be drawn, and additionally, a greater control of the phase relationships within the Fe-Zn-S system needs to be gained.

The application of certain sulphide phase geothermometers has been considered but none of these are entirely suitable and can only offer a broad 450-700° C. estimation of temperature during metamorphism, corresponding to lower amphibolite grade.

Tectonic Environment

The present study is concerned with assigning a tectonic environment of formation to the Sulitjelma ore bodies. Geochemistry can be of considerable help in this respect, although the relatively simplistic concepts of a decade ago are now much under review. Various rocks from the Sulitjelma amphibolites were analysed for major and trace elements, including the so called "immobile" elements (Zr, Y, Ti, Nb) which have been demonstrated as being useful in the classification of rock suites into different tectonic environments (island arc, mid-ocean ridge e.t.c.) Initial results indicate that there is a strong possibility that the Sulitjelma rocks originated in a mid-ocean ridge environment. My recent literature studies have concentrated upon the following points:

1. How immobile are the above elements? Do they, under certain circumstances behave more mobile than previously thought?
2. Are the classifications too rigidly defined? For example, How does marginal sea basalt geochemistry compare with mid-ocean ridge?
3. How would the syngenetic and metamorphic processes affect concentrations of the "immobile" elements?
4. The origin of ophiolite suites. Are they restricted to the traditional MORB environment?
5. How does the proposed tectonic environment fit in with that suggested for other massive sulphide deposits in Scandinavia?

Various studies have been made to assess the mobilities of the "immobile" elements. These generally indicate that the elements Y, Zr and Ti are immobile during hydrothermal alteration (spilitization) and during metamorphism to greenschist facies. It appears that apparent changes may be more related to volume changes during the alteration process. Hence these elements may be considered suitable as indicators of tectonic environment for greenstone belts. Spilites which have been dredged from the oceans generally have similar abundances of the "immobile" elements when compared to fresh rocks of the same type. It is an established fact that the changes make a rock appear a little less tholeiitic.

There exists in the literature, a great range of trace element abundances for the different tectonic environments. Indeed, many environments are now subdivided: MORB can be N type (normal) or P (plume type) and geochemically, these are supposed to be detectably distinct. Much work has been carried out to define these types using trace-element geochemistry and stable isotope data. All basalts are thought to have originated from an essentially similar mantle source and each derived through varying degrees of partial melting. An additional complicating factor is that the mantle source in oceanic regions is itself locally chemically heterogenous.

Back-arc basins are similar to MORB geochemically with their immobile element abundances and ratios, REE patterns and isotope abundances falling within the broad MORB category. The current thinking is that it is unlikely that geochemical criteria could be erected to unequivocally separate MSB-BAB from MORB. Thus it is possible that the Sulitjelma data which appears to indicate a MORB environment could equally be a marginal sea-back-arc basin environment.

More data is required, enabling me to construct trace element and REE spidergrams for comparison purposes, since the aims of this part of the project is to be able to suggest a possible tectonic environment and to try and assess the changes which might have been induced by syngenetic alteration and later metamorphism. The current data also requires more detailed interpretation. It is envisaged that the analysis of a small number of samples for REE and possibly some Sr isotope determinations might be very useful in this respect.

Similar studies at other massive sulphide deposits in the Norwegian greenstone belts have shown that the rocks have been classified in many different ways....as spreading centres, island arcs, and also, some within plate settings, whilst others, e.g. Løkken is interpreted as a marginal sea basin.

It has been suggested that parts of the (opening) Iapetus Ocean may have been rapidly spreading and fringed by arc-basin systems. Rocks from each of those environments can be found in the Norwegian Caladonides and this is a suitable working model. It is further suggested that rates of spread were slower in the north and that immobile trace elements may be able to quantify the spreading rates. Initial work on these important concepts presented in a recent paper by Gale and Pearce indicates that my data would support this theory well, although this would need to be verified before any conclusions could be drawn.

References: Sun et al (1979) Saunders and Tarney (1979)
Gale and Pearce (1982) Humphris and Thompson (1978)
Karig (1978) Jakes and White (1972)
Furnes et al (1980) Finlow-Bates and Stumpfl (1981)
Pearce and Cann (1973)

Feeder Pipes and Exhalite Horizons

The concept of feeder pipes is very much part of the integral genetic model for massive sulphide deposits. Literature has been reviewed on this topic covering the mineralogical and physico-chemical environment of a feeder zone. (e.g. Franklin et al (1981) Hall (1982)). Feeder-zone like lithologies occur widely in the Sulitjelma ore area but it is often difficult to relate these to being the feeder zones of distinct ore zones. The chemical manifestation of feeder zones demands further study with respect to the application of lithogeochemistry to feeder zone systems (e.g. Løkken). Sampling of the "palmberg" horizon is required and the analytical data to be put into perspective alongside expected trends. A structural approach might also be made as to the recognition of the link between deposits and corresponding feeder zones. Mineralogical studies of samples collected from the supposed feeder zones can be applied as to the physico-chemical conditions operating. This can provide information which can be compared to other deposits. However, a very major study of the tectonics would be required before total comprehension could be attained. This is well beyond the scope of the present project.

The ore zones are also being considered, in terms of their genesis as tuffaceous exhalites. Their pre-metamorphic mineralogy and geochemistry is appraised with respect to certain distinct exhalite facies, notably the more felsic "pseudo-keratophyre" horizons. Interpretations shall eventually be drawn as to the processes involved in the production of these horizons and the subsequent development of them as lithological units. Comparisons can be made with equivalent horizons in other types of massive sulphide deposits, notably the "tetsusekei" of the Japanese Kuroko deposits. Attention can also be drawn to the apparent lack of hematite-chert horizons at Sulitjelma. The recent paper of Scott et al (1983) suggests several geochemical concepts for possible application at Sulitjelma, although it is to be noted that the above writers are not optimistic about the role of trace element distributions in exhalite horizons as a useful exploration tool.

Active Hydrothermal Systems

The concepts of active hydrothermal systems (e.g. The East Pacific Rise) as present-day analogues of massive sulphide deposits during formational processes has been investigated using the recent literature on this subject.

Particular attention has been paid to the size and scale of these systems and the physico-chemical environment and processes attributed to them. Understanding of the role of "smokers" (Hydrothermal vents) is of key importance in the derivation of a model for massive sulphide deposit formation. The production of different base metal sulphides and other minerals (including anhydrite) from different types of smokers has been noted, as has the control placed on the systems by factors such as the water depth and the local sea-floor topography. A genetic model for the Sulitjelma deposits should include references to active smoker systems as the analogues of the systems which produced the Sulitjelma massive sulphide deposits and the majority of all the volcanic-assisted exhalative-hydrothermal deposits.

Special note has been made of the temperatures and pressures operating in hydrothermal vents and the chronological pattern of vent evolution. Physical and chemical limits can be placed upon the nature of the ejected fluids.

Key references are: Sloer et al (1982), Hekinian et al (1980), Speiss et al (1980), Oudin et al (1981), Finlow-Bates and Large (1978), Haymon (1983), Haymon and Kastner (1981), Edmond (1979) and Solomon and Walshe (1979).

The tectonic environment of the above smokers have been considered along with local structural features and concepts of hydrothermal circulation argued from a theoretical point of view. (Finlow-Bates (1979) and Strens and Cann (1982, 1983). Other studies of related interest include the origin

of the sulphur in hydrothermal systems (Skirrow and Coleman (1982)) and in sulphates (Sasaki (1970))

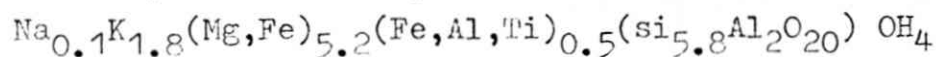
Some features of the Sulitjelma deposits could be attributed to primary processes of smoker evolution (e.g. certain zonation patterns implying chemical gradients) as well as using smoker models to define more accurately the physico-chemical environments for each deposit. (e.g. the temperature control of Cu/Zn and primary pyrrhotite formation). Black smokers may also be used to construct primary sulphide parageneses. Many important revelations concerning hydrothermal vents have yet to be published in the literature.

Probe Work

Probe work has concentrated on the study of 1) silicate mineralogy of rocks of exhalite and stringer origin in the association of the Giken ore body, and 2) sulphide assemblages from different types of ores.

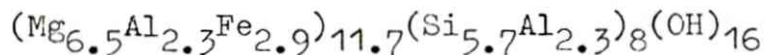
A total of 108 satisfactory analyses have been made, some findings are detailed below, but the work is ongoing and numerous relevant samples have yet to be worked on.

Plagioclase feldspar In all samples (from various types), the composition is $Ab_{99}An_1$, indicating extensive albitization.
Biotite Samples from Giken footwall contain large biotites, these have been analysed to correspond to the formula:



This is an Al poor biotite (i.e. NOT a phlogopite) with an Mg/Fe ratio of about 0.33 and having an appreciable Ti content. (av. 1.5% TiO_2)

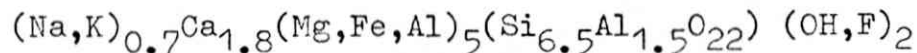
Chlorite Fe/Mg is about 0.45 (pycnoclrite)



Serisites Generally low K with some Ti content

Anhydrites 1.5% SrO

Amphiboles Hornblende Mg/Fe 1.5



Pyrrhotite Fe_8S_9 by stoichiometry

Sphalerite about 8% FeS

Analyses of minerals in different samples agreed well with each other.

Microscope work has been carried out on the above silicate assemblages with respect to mineral relationships, metamorphic recrystallization, silicate-sulphide relationships and the

textures of metamorphism, deformation and brecciation, and this has been extensively investigated along with the calculation of modal mineralogies.

Reflected light microscopy has been carried out to reach an understanding of sulphide mineral parageneses with respect for governing processes and the extent of metamorphism and alteration of the assemblage. Minor phases have been identified and micro-textural features interpreted.

Work is ongoing to explain the observed features relative to the phase relationships in the relevant parageneses. a further selection of samples has been prepared for future ore microscopy, including a selection from Sagmo.

The Significance of anhydrite

The anhydrite occurring in the Sulitjelma deposits, mostly in vein-like features at the top of the impregnation ores is typified by a violet colour. Chemical analyses indicate that the mineral is rich in Sr (SrO about 1.2%) but with only trace Mn and Ba. It can be proposed that the mineral anhydrite controls the distribution of Sr around the ore bodies, and explains the apparently random distribution of Sr.

The occurrence of anhydrite in volcanogenic sulphide deposits has been investigated, together with the physical conditions of anhydrite formation. The only type of massive sulphide deposit where anhydrite is commonly encountered are the Kuroko deposits of Japan. Studies made upon the anhydrite of these deposits indicate that it was formed by precipitation from heated seawater at 100-200° C. Sulphur isotope data for Kuroko deposits show that the sulphates have ratios very similar to miocene oceanic sulphate. The temperature estimation is made on the basis of experimental work on anhydrite solubility in saline solutions. The solubility of anhydrite is very low at temperatures above 150° C.

Anhydrite has been recorded from most active hydrothermal systems. At Reykjanes (Iceland), anhydrite is seen to precipitate when cold water invades the hot hydrothermal reservoir and that such invasions of cold seawater occur frequently during tectonic disturbances, producing anhydrite in fracture filling. Other studies indicate that as seawater is progressively heated, as much as 67% of the sulphate, and 90% of Ca in that seawater will precipitate to anhydrite between 150 and 200° C. Anhydrite can be reduced to sulphide but experimental studies indicate that this is unlikely because of the very large amount of free Fe which would be required to balance the sulphate. The presence of anhydrite in preference to gypsum at Sulitjelma is interesting. Certainly, anhydrite is easier to form at higher temperatures than

gypsum, but if gypsum had initially been formed, the released water could have played a major role in the transportation of mobile constituents. The Sulitjelma anhydrite is certainly metamorphic in a textural sense, but it may be proposed that this secondary anhydrite recrystallized from primary anhydrite precipitating from seawater during ore genesis. It is anticipated that a short study can be made of the sulphur isotope abundances in the anhydrite to determine the origin, and also to assess the effects of equilibration with the co-existing pyrite porphyroblasts. -possibly these represent a limited amount of reduced reaction product and this will be indicated by distinct geochemical and isotopic differences between the pyrite associated with the anhydrite and regular pyrite porphyroblasts in the massive ore.

A further point of significance is that anhydrite is very rare in other massive sulphide ore bodies in Scandinavia. This could be related to metamorphic temperatures or the speed of retrograde metamorphic processes and demands further investigation. Certainly, the question of the anhydrite in the Sulitjelma deposits is an interesting, yet complex topic, and in addition to techniques outlined above, a more detailed study of anhydrite occurrences in situ, is required to relate the sulphate bodies into the genetic and evolutionary models for the deposits.

Refs.: Björnsson et al (1978) (Reykjanes)

Blount and Dickson (1969) Solubility Studies

Sakai et al (1970) Kuroko isotope studies

Mottl and Holland (1978) Anhydrite from hydrothermal alteration of oceanic basalt (also Bischoff et al (1975))

Bischoff and Seyfried (1978), Holser (1978),

Lambert and Sato (1973) and Sasaki (1970)

Metamorphism of sulphides

Any interpretation of sulphide mineralogy and petrology should take account of the change induced by metamorphism. These changes can be divided into the following groups:

1. Changes in mineralogy
2. Changes in the form of the minerals (fabric)
3. Deformation features
4. Mobilization of minerals and elements
5. Features of retrograde metamorphism

Some or all of these can be seen in sulphide bearing rocks from Sulitjelma and it is necessary to be able to explain features as resulting from metamorphism. A study of the literature concerning the metamorphism of sulphides has been carried out in conjunction with macroscopic and microscopic studies of relevant samples.

Many metamorphism-induced features are seen. Notable are the large rounded pyrite crystals which may represent metablastic growth during metamorphism. These are typically structurally deformed and contain large amounts of included material. Understanding of phase equilibria must be used in conjunction with data on metamorphic environment to suggest changes in mineralogy which may have occurred. In the Sulitjelma deposits, the possible metamorphic recrystallization of pyrrhotite is of particular interest (see elsewhere) and the presence of unmixing textures are seen between various pairs of sulphide minerals. Work has been done to interpret the significance of such features and to infer conditions. Application of geothermometers and geobarometers can help in this aspect.

The metamorphically-influenced fabric of sulphides is noted in the Sulitjelma ores. Metacrysts of pyrite predominating over matrix sulphides. (sph, cpy, po) as is the orientation and shape of inclusions within the pyrite metablasts. Recrystallization textures such as 120° triple junctions between pyrites have been seen in thin section and these can be attributed to metamorphism, as can the apparent increase in grain size at the

expense of silicates. Similarly, the common features of pyrites from disseminated ores (greater size) can be attributed to nucleic recrystallization. These are often well formed as they have been able to grow relatively free of competing pyrites.

The deformation features (often cataclastic deformation) can be studied with regard to the relative plasticity of different sulphide minerals and the timing of deformational events with respect to metamorphic recrystallization. The fabric of the Sulitjelma ores is very complex due to possible repetition of crystallization and deformational processes and it is very difficult to devise a chronological model of these processes, especially since much of the sulphide has been extensively brecciated.

Deformation features of pyrite are typified by elongation of large crystals in the less massive parts of the ore body and may be intensely physically distorted. Other sulphide minerals may also show such features, pyrrhotite for example often occurs parallel to the schistosity of the rock. The softest minerals (cpy, sph) show fewer deformation features since they behave more plastic. It is a characteristic of the Sulitjelma deposits that along with the highly deformed pyrite crystals, there occurs idiomorphic, undeformed pyrite porphyroblasts, and these may be attributed to mineral growth following the termination of the deformational stresses.

Another feature of the Sulitjelma ores is the lack of banding structures in some of the ores, the original banded structure having been completely destroyed. Many relict fabrics have disappeared during the metamorphism (e.g. fibroblastic textures) but others such as mineral banding is still largely present, although it might be questioned that mineral banding is implicitly primary in origin, or not? It is possibly a favoured replacement of a banded or schistose rock during post-formational processes.

Mobilization is seen in the Sulitjelma ores and may be ascribed to plastic flow within the body of the sulphides. The softer sulphides are seen to migrate around silicate "boudins" and are clearly concentrated in the pressure shadows of porphyroblasts. Thickening and thinning due to folding is seen and mobilization into cross fractures. Relative mobility increases in the sequence: pyrite-sphalerite-pyrrhotite-chalcopyrite-galena, and it follows that structurally induced mobilization of chalcopyrite plays a significant role in the distribution of copper on the local scale. The distances over which certain components of sulphide bodies may be transported is however poorly quantified. Generally, these distances are considered to be small, occasionally many metres. Certain rare minerals can be selectively remobilized (notably Pb,As,Sb and Au-Ag components) and these may be found in veins, lenses and other masses, sometimes called sulphide "pegmatites" with much vein quartz, which appears to be the first of the non-sulphide minerals to be mobilized. A more detailed study of such structures in the Sulitjelma ores is required. Certainly, there is a quartz vein in Giken which contains appreciable galena and certain Bi minerals. Other such occurrences are recorded (e.g. Ramdohr 1938). Also of significance in this respect are the occurrences of zeolites as vein filling (e.g. Vogt 1926). An understanding of the physico-chemical conditions of emplacement of such bodies needs to be reached, as does the mechanisms of these processes. A genetic model for these deposits should account for these late-stage features.

The possible migration of ore-forming elements under regional metamorphism must also be considered such that the influence of metamorphism upon primary geochemical patterns be understood.. Metamorphism may also induce certain trace elements to migrate relative to (host) major elements. Of note, and highly relevant to the present study, is the apparent tendency for Ag to concentrate relative to Pb, and Cd relative to Zn in zones of stress-relief within areas of high intensity

deformation. This warrants further investigation to see if the same follows in the Sulitjelma deposits. If these deformationally-influenced trace-element migrations are significant enough then this holds severe implications for halo sampling programmes.

Retrograde features are somewhat harder to identify. There is evidence for re-equilibration between pyrite and pyrrhotite, possibly occurring at low temperatures under retrograde conditions.

Further study on the subject of the metamorphism of sulphides should concern experimental simulation of metamorphism of sulphide ores and also on the interpretation of features at other mineral deposits. The observed features can then be interpreted with regard to metamorphic environment.

References: Vokes (1969), Gill (1969), MacDonald (1967), Mookerjee (1976) and Graf and Skinner (1970)

Chemical Exchange

Assessment of data concerning chemical exchange during hydrothermal alteration of the host rock has been carried out. This is a complex topic and initial data needed considerable reworking. The aim of this exercise is to establish patterns of geochemical exchange during the processes of hydrothermal convective flow through the spilite pile. This involves comparison of geochemical analyses of altered rock with published data on unaltered rock of the same type and must be applied with great caution, involving models of "immobile" element conservation and correspondingly implied volume changes. Initial work implies net real gain of alkalis and the removal of Ca and base metals, although actual figures have yet to be computed. This is an attempt to support the concept that the sulphide deposits could have been formed by the convective circulation of seawater through a basic rock pile. Estimations can be made as to the total volume of base metals leached, and correspondingly available for sulphide deposit formation from the Sulitjelma amphibolites, and at a later date, this may be linked into a grand model.

It is further anticipated that the same techniques could be applied to element exchange in the feeder pipe, which is characteristically enriched in elements leached from enclosing spilites and is very highly enriched in the K family of elements. Information on temperature conditions can be sought from this type of work. This topic must be treated with considerable care since there are so many uncertainties involved, but it may help to explain certain observed trends.

It has also been attempted to show evidence of geochemical zonation within the ore body. Extensive tectonic deformation has destroyed much of the original zonation pattern, but there is a general pattern of Cu/Zn from top to base which can be used to interpret way-up criteria for an ore deposit. The Giken ore body appears the right way up, whilst Sagmo indicates both inversion and non-inversion (Could this be related to folding features?) Techniques applied will require further investigation to give a fuller understanding of operating functions. The technique is of great use to apply way-up criteria to ore profiles in exploration areas, where local tectonic influences have not caused disruption or repetition of the definitive zonation sequence. Similarly, such geochemical patterns can be used to understand

the nature of the tectonic disturbances in conjunction with the tectonic mapping of the ore horizon.

Much work has been carried out to reproduce experimentally basalt alteration by seawater at elevated temperatures. It has been demonstrated that ions such as Na^+ and Sr^+ and SO_4^{2-} are removed from seawater. Ca, K and Ba are leached from basalt and that heavy elements can be transported in saline solutions at higher temperatures. Maximum concentrations of deposit-forming elements in the heated solutions have been calculated. Additionally, the typical alteration mineral assemblage observed in nature is very similar to that produced experimentally. Such experiments hold important implications for genetic aspects of massive sulphide deposit study.

Refs: Hajash (1975) Mottl and Holland (1977) Bischoff and Dickson (1975)
Bischoff and Seyfried (1978) Seyfried and Bischoff (1977)
Hart et al (1974)

Rare Earth Elements as a tool in exploration

The application of REE geochemistry to exploration has been investigated with respect to available information on the behaviour of REE during hydrothermal processes in an attempt to adequately interpret the first batch of REE data which seemingly show interesting patterns. Work is recorded in the literature that uses REE to differentiate between ore-bearing felsic volcanics of the Canadian Archean belt and those which are barren. Similarly; studies as to the effects of spilitization and other sea floor hydrothermal processes on REE abundances have been made by various workers. There are no references in the available literature concerning the application of REE to local scale lithogeochemistry or REE behaviour in exhalite horizons. It has been established that REE in hydrothermally "formed" rocks will have a very similar pattern to the solutions from which they were derived, and that the REE abundances will be substantially influenced by alteration processes, principally involving light REE (LREE) enrichment, although it is by no means certain that other types of REE movement will not occur. Metamorphism can also cause selective REE mobilization and will generally occur systematically with other more immobile elements (Zr,Y,Ti). The REE distribution may be controlled by minerals such as zircon and sphene, although feldspar also plays a role. Spilitization is generally associated with increasing LREE/HREE ratios (e.g. La/Yb)

The samples which have been analysed for REE were collected from the Giken Footwall horizon, a SW-NE profile. Extreme Σ REE depletion is recorded at the centre of this profile with high Σ REE and very high Σ LREE at the margins, relative to Σ HREE (i.e. La/Yb increases outwards away from the centre.) The model proposed suggests that there is extensive leaching of LREE in the central area (the area with the highest hydrothermal activity) and the distribution is controlled by the

recrystallization of REE bearing phases (sphene obviously of great importance in Sulitjelma) at a distance from the centre of hydrothermal activity. Much more work needs to be done to clarify the picture. This should include:

1. Identification of what the sampled lithologies represent.
2. Mineralogical controls of REE distribution, possibly involving analysis of sphene.
3. Studies of the relative mobilities of REE.
4. REE patterns for related amphibolite rocks, rather than purely exhalite horizons.

Key references are: Graf (1977), Robertson and Fleet (1976), Kay and Senechal (1976), Ludden and Thompson (1978, 1979), Floyd (1977), Hellman and Henderson (1977), Humphris et al (1978), Campbell et al (1980), Hellman et al (1979), Cordie and Baragar (1974) and Su-Sun and Nesbitt (1978).