A

THESIS

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"GEOCHEMICAL DISPERSION FROM BASE METAL MINERALISATION, CENTRAL NORWAY"

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Abstract.

Geochemical investigations have been carried out over a number of cupriferous pyrite mineralisations occurring within the Cambro-Silurian rocks in the Hjerkinn-Folldal area of south central Norway. The distribution of base metals and Fe was studied in rocks, glacial overburden, soils and in the components of the drainage, including bogs.

The primary dispersion patterns of ore elements in the wall rocks of economic mineralisation were found to be of limited extent and restricted to Fe and Zn. Cu, Pb and As are enriched only within the ore.

The data concerning the distribution and mode of occurrence of metals in siliceous overburden overlying mineralisation indicates that ore elements are dominantly dispersed via the agency of groundwater and to a lesser extent, the biochemical cycle. Syngenetic metal anomalies in the moraine appear to be only weakly developed.

The drainage dispersion from sub-outcropping ore is closely related to groundwater movements. Anomalous concentrations of ore elements are present in the stream waters and sediment for several kilometers down-drainage from the Tverrefjellet orebody but the highest metal concentrations are observed some distance from the sub-outcrop where maximum addition of groundwater to the surface drainage occurs. The soils, and particularly the alluvial soils, for several tens of meters on either side of the streams contain abnormal concentrations of metals. Furthermore where there is a hydrostatic head of anomalous water the barren underflow along the major river is deflected and anomalous concentrations of metal are detectable in both banks of the river despite the absence of a stream water anomaly.

Precipitation of the ore metals from the ground and surface waters is closely related to changes in pH. However, co-precipitation of the base metals with Fe is considered also to be an important mechanism.

The results of limited comparative drainage studies in the vicinity of other deposits in the area are consistent with those from Tverrefjellet.

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INTRODUCTION

The first applied geochemical studies to be undertaken in Norway were those of Vogt and co-workers (1939-1948) in the Röros district. They studied the distribution of ore elements in soils, plants and stream waters from mineralised and barren areas. The field and laboratory studies indicated the possibility of the successful application of soil and stream water sampling to ore prospecting. The preliminary results of the geobotanical studies however had no apparant significance in the search for ore.

In 1954 the Geochemical Division (formerly known as the Statens Råstoff Laboratorium) of the Norwegian Geological Survey started geochemical prospecting. The results demonstrated the general applicability of stream sediment sampling to delineating areas of mineral potential in Norway. In addition the sampling of the Ao soil horizon in forrested areas gave encouraging results (Heltzen, 1956).

In 1962 the Norwegian Geological Survey invited the Applied Geochemistry Research Group (A.G.R.G.), of the Imperial College, London, to undertake a detailed research investigation into the problems of using geochemical methods in Norway. The research project was initiated by

Professor J.S. Webb, and forms an integral part of the overall programme of the A.G.R.G. The study was aimed at obtaining a thorough understanding of the mode of dispersion of base metals from a bedrock source beneath transported overburden. The results of such an orientation survey, it was hoped, would provide the necessary basis for improving prospecting procedure and the interpretation of geochemical data in glaciated terrain.

The detailed study was centred on the massive pyrite orebody at Tverrefjellet, near Hjerkinn in C. Norway. The investigation was divided into four inter-related stages:

(1) A study of the distribution of ore elements in the country rock.

(2) A study of the nature and extent of the weathering zones above the ore.

(3) A study of the distribution and dispersion of ore elements in the overburden and in plants in the vicinity of the mineralisation.

(4) An investigation into the distribution and dispersion of ore elements in ground waters, stream waters, stream sediments, banks and bogs down drainage from the orebody.

Concurrent investigations were undertaken in barren areas to study the background distribution of the ore elements in the various media.

In order to test the applicability of the results of the detailed study to a wider area, limited comparative investigations were undertaken over cupriferous pyrite mineralisation in the Folldal area, 35 km. south east of Hjerkinn. The practical applications of the research study are given at the end of this report.

PREVIOUS WORK

The only previous geochemical work in the area surrounding the Tverrefjellet orebody was that of the Norwegian Geological Survey (Bölviken, 1959). The survey showed that the anomalous dispersion train in the stream sediments extended for 2.5 km. down drainage from the Tverrefjellet orebody. In particular the stream sediments in the immediate vicinity of the sub-outcropping mineralisation were found to contain background concentrations of cold extractable Cu. However, at greater distances from the ore the cold extractable Cu content of the active stream sediments increased to strongly anomalous values. It was also observed that in the major stream near the junction with the anomalous tributary a significant difference in metal concentration occurred on opposite sides of the stream.

In contrast with the geochemical drainage data, soil samples taken over the known sub-outcrop of the Tverrefjellet orebody were found to contain background metal concentrations.

In other recently glaciated regions it has been shown that in the vicinity of ore, macro- amd micro-boulder (indicator) trains are often present in deposits of ground moraine. For example, indicator trains have been detected in Sweden (Grip, 1953), in Finland (Hyvärinen, 1958; Kauranne, 1959), in Canada (Dreimanis, 1958) and in Ireland (Donovan, 1965). In addition where conditions are favourable ore elements may be dispersed in ground waters leading to the development of hydromorphic patterns in the overburden above and downslope of sub-outcropping mineralisation (Dreimanis, 1960; Yardley, 1958). The distance over which anomalous metal dispersion trains can be detected is dependant on many factors, such as: degree of oxidation (Hawkes and Webb, 1962), the pH of the environment (Dreimanis, 1960), the permeability of the moraine (Bischoff, 1954), the level of the groundwater table and the present day climatic conditions. Biogenic anomalies have also been recognised over mineralisation in glaciated terrain, for example at the Van Stone orebody in eastern Washington (Cox and Hollister, 1955, as interpreted in Hawkes and Webb, 1962).

The present study area was ideally suited to testing the conclusions of these earlier workers under the relatively arid conditions pertaining in Central Norway above the tree line.

ACKNOWLEDGEMENTS

The present work forms part of the general programme of the Applied Geochemistry Research Group at the Imperial College, London, directed by Professor J.S. Webb.

Sincere appreciation is expressed to the Science Research Council for providing personal financial assistance for the duration of the study, and to the Norwegian Geological Survey in Trondheim who financed the field work. The writer wishes to record his gratitude to the staff of the Geochemical Division of the Norwegian Geological Survey; in particular to the Director, Dr. Kvalheim, and also to Mr. Bölviken and Mr. Krog for help and advice during the course of the field programme.

The field work was carried out in areas where the mineral rights are held by Folldal Verk A/S. The co-operation of this Company in the loan of their reports, maps and aerial photographs, together with help received from Mr. Loevold, the Director and from Mr. Husum, the Mine Manager is gratefully acknowledged.

The writer is indebted to Professor J.S. Webb for proposing the problem and to Dr. J.S. Tooms for his supervision and invaluable advice throughout the study.

The help given to the writer by members of the staff at Imperial College is also gratefully acknowledged.

PART I

DESCRIPTION OF THE FIELD AREAS

The main research studies were carried out at Hjerkinn in central southern Norway and less detailed comparative studies were made in the vicinity of a number of mineralisations in the Folldal area, 35 km. east south east of Hjerkinn.

Hjerkinn is the geographical centre of southern Norway being located on latitude 62° 15'N and longitude 9°30'E (Fig.1). It lies at the highest point (1017 m. above sea level) on the rail connection between Oslo and Trondheim, and is situated 156 km (100 miles) south of Trondheim.

Until recently Hjerkinn has consisted of the railway station and the military artillery range. However, since 1958 when the 8-10 million ton Cu-Zn pyritic orebody was discovered in the hillside (Tverrefjellet) north west of the railway station a fairly considerable mining industry has been established.

Mining has till now been limited to exploration and underground development of the orebody. These activities have not resulted in any significant surface contamination.

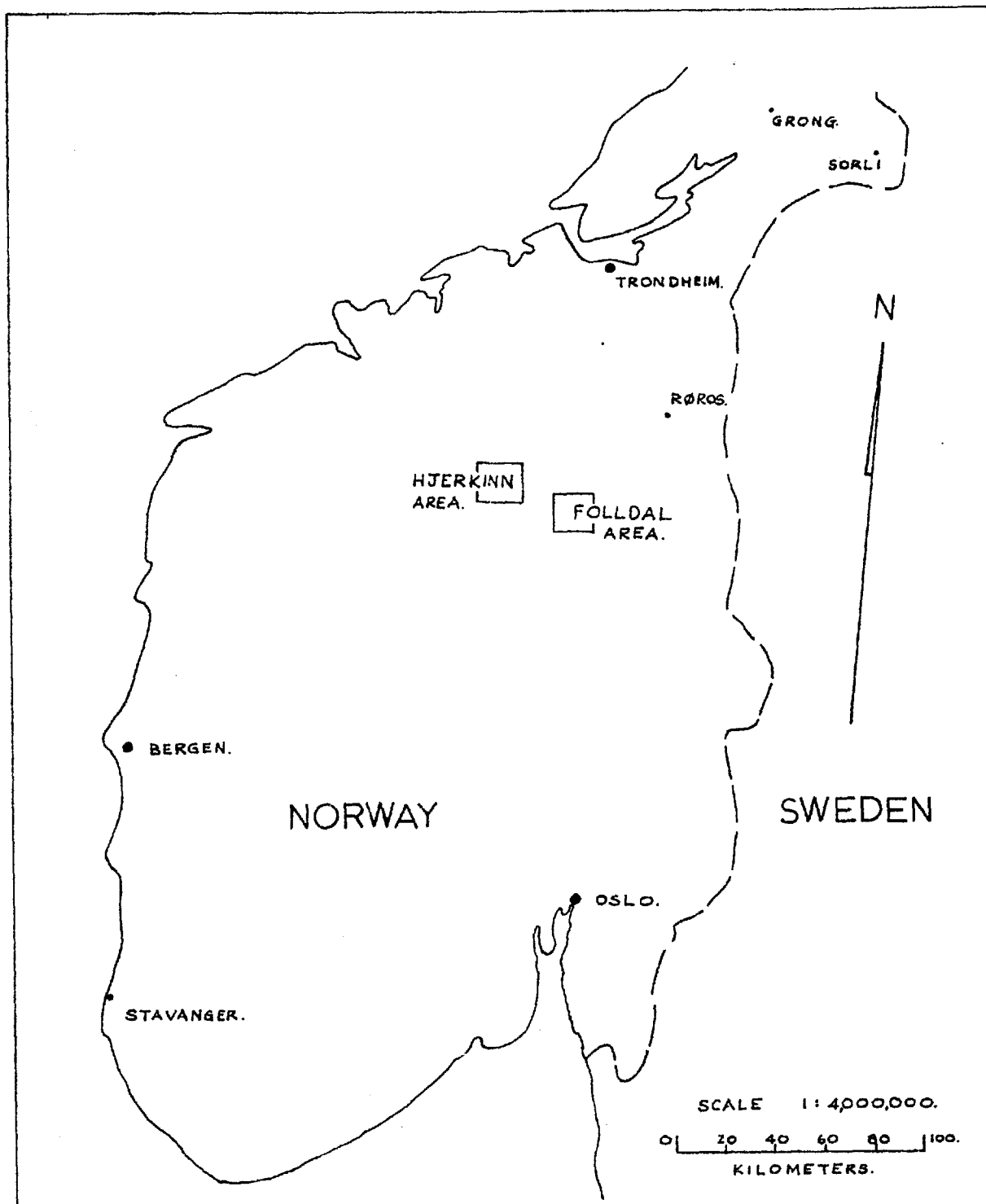


Fig. 1. Location of field areas.

GEOLOGY

The following outline of the pre-Quarternary geology has been taken largely from the publications of Vogt (1945) and Holtedahl (1960). This information is supplemented by personal observation made by the writer in the course of the field work.

(1) Regional pre-Quarternary Geology.

Rocks of pre-Cambrian to Permian age have been recognised in Norway. However, Cambro-Silurian rocks which have been highly folded and metamorphosed during the Caledonian oregeny underlie much of the country and contain a large proportion of the mineralisation. They can be sub-divided into three distinct facies which are characteristic of the different parts of the Caledonian geosyncline (Fig.2). The eastern facies is developed around Oslo and extends into Sweden and is composed mainly of gently folded shales with subordinate limestones.

Sediments typical of the eugeosynclinal environment are found in a south west - north east belt between Bergen and Trondheim. In this area vast thicknesses of pelitic and terriginous material occur which rarely contain recognisable fossil remains. The large volume of basic effusive rocks and their associated tuffaceous sediments constitute a distinctive feature of this part of the geosyncline.

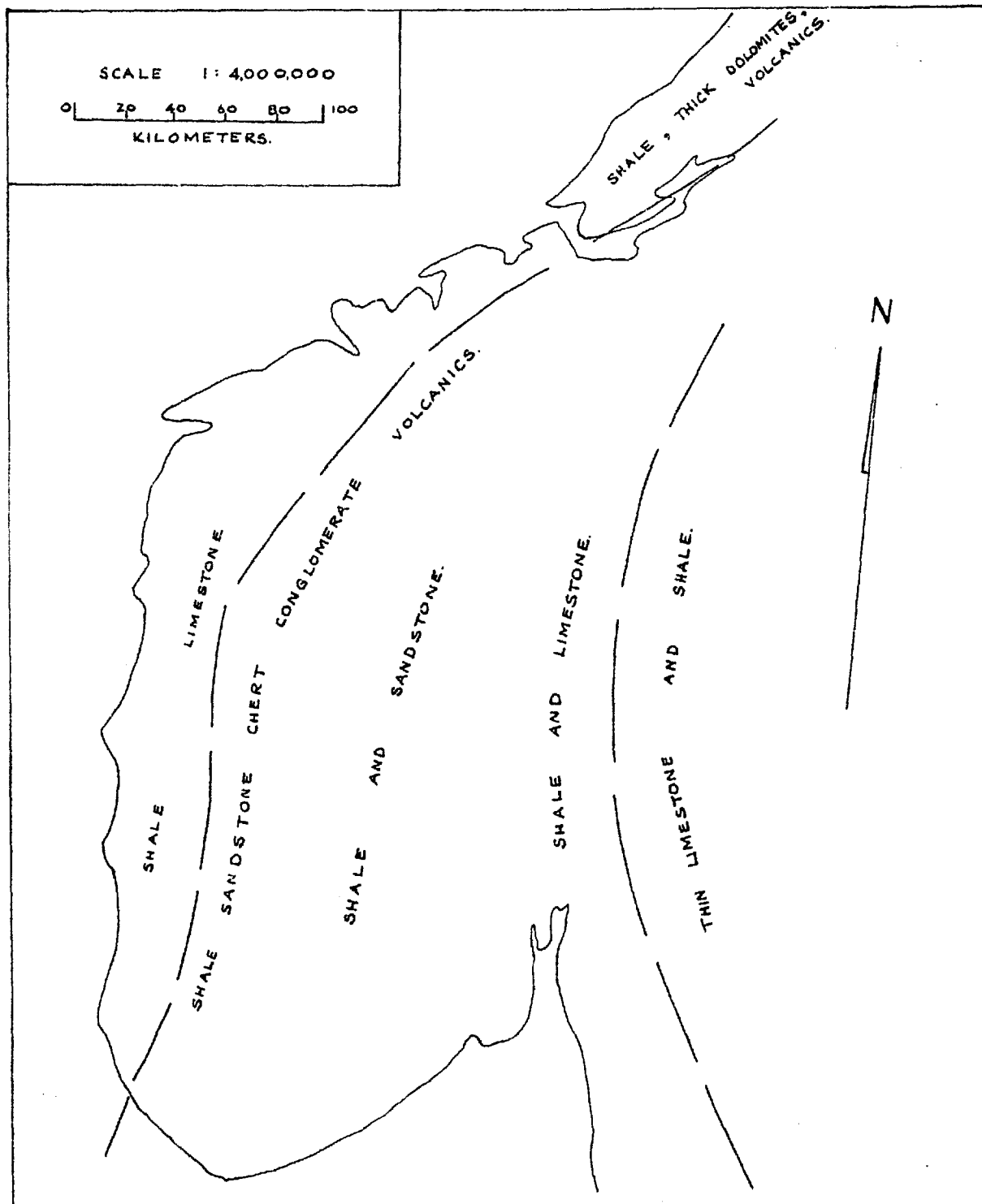


Fig.2. Map to show the distribution of the different facies of the L.Ordovician rocks in Scandanavia (After O. Holtedahl, 1938).

Further to the west lies a third belt also of eugeosynclinal type, but which contains less volcanic material. These rocks are in the main pelitic and calcareous and underlie the Nordland and Troms districts of northern Norway.

(ii) Pre-Quarternary Geology of the Hjerkinn-Folldal District

The Trondheim basin of which the Hjerkinn-Folldal district is a part is a broadly synclinal depression in which metamorphosed Cambro-Silurian rocks have been preserved from erosion (Strand, 1960). In general the deposits conformably overlie the eo-Cambrian Sparagmites, although there are thrust contacts with pre-Cambrian gneiss in some places.

In the vicinity of Hjerkinn the Trondheim Syncline is constricted (Fig.3). This is accompanied by a change in strike from the normal caledenoid northwest-southwest trend, to one which is oriented more east-west. Dips are generally between 30° and 90° to the south on the northern margin of the basin, and between 30° and 50° to the north on the southern side around Folldal.

The main rock types are mica schists, greenstones and quartz mica schists of which the detailed stratigraphy is not known. The rocks have been generally folded on east-west axes which plunge to the east at angles of up to 50°.

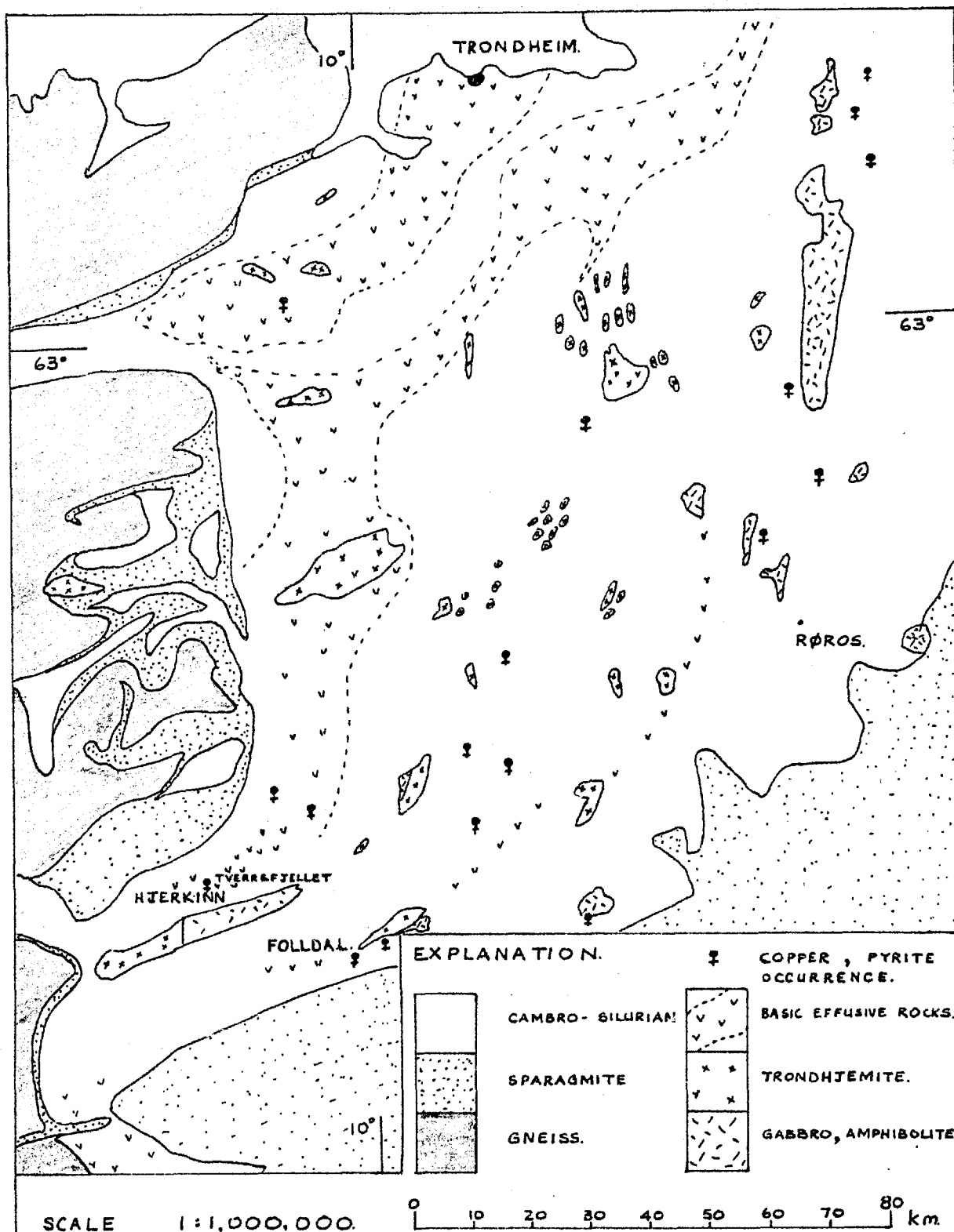


Fig. 3.
Geological map of the Trondheim Cambro-Silurian basin. (After O. Holtedahl and J.A. Dons, 1953).

The metamorphic grade increases slightly from south to north, but consistently within the high epidote-amphibolite facies.

The central part of the Hjerkinn-Folldal area is occupied by a large intrusive complex consisting of trondhjemite in the western part and gabbro in the east. At the contact the trondhjemite has intruded the gabbro.

Late stage fracturing has affected the area and generally seems to have taken place along northwest-southeast lines (Geis, 1960).

(iii) Mineralisation of the Hjerkinn-Folldal area.

On the north side of the basin a mineralised horizon intercalated in the greenschist belt can be traced over a strike length of 10 km. This horizon has an average thickness of 0.5 m. and consists of pyrite and pyrrhotite containing trace amounts of Cu and Zn. The field evidence indicates that this horizon is stratigraphically controlled and occurs in association with a thin magnetite bearing quartzite. A similar horizon is present on the south margin of the basin passing through the village of Folldal and running along the line of the Grimsa valley. This horizon also occurs within the greenschist belt and may be correlated with its Hjerkinn counterpart.

Massive pyritic ore deposits occur at places along the strike of the mineralised horizons both in Hjerkinn and Folldal, but whereas the uneconomic mineralisation is stratigraphically controlled, the massive deposits are essentially controlled by the structure which may or may not parallel the strike.

The Tverrefjellet Orebody

During the course of the field work the ore at Tverrefjellet was briefly studied at its sub-outcrop and in underground exposures.

The ore occurs in a zone 1000 m. in length which is orientated east-west in conformity with the country rocks (Fig.4.). In this zone there are two offset orebodies which have an average thickness of 10 m. The bulk of the ore is contained in the south body which dips at high angles to the north whilst the country rock dips at 85° to the south. It is cut by a zone of north-south trending fractures which throw to the east.

The north orebody which appears to be fully concordant with the country rocks is situated directly on strike of the uneconomic mineralised horizon (Fig.4). It may be significant that this body contains ore of lower grade than the south body (Table 1). Both deposits plunge to the east at angles of 45° to 50° which coincides with the fold axes.

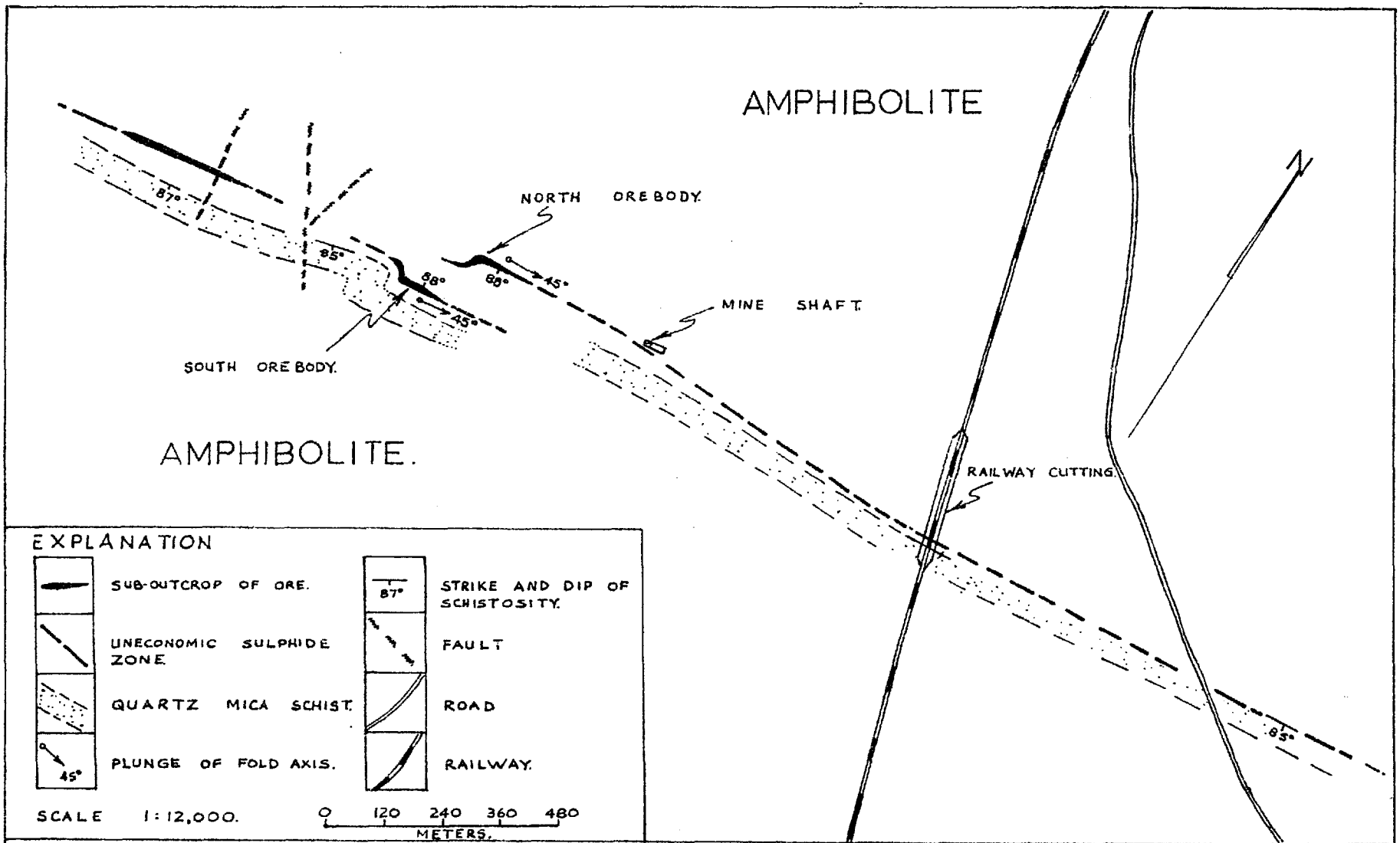


Fig. 4. Plan showing the Tverrefjellet orebody and uneconomic sulphide zone at Hjerkinn.

TABLE 1.

Comparative Analyses of the Two Ore Bodies at Tverrefjellet
(Data of the Folldal Verk A/S)

Element	South Body	North Body
Cu	1.4%	0.3%
Zn	1.3%	1.0%
S	34.7%	42.4%
	Arith. mean values of 33 samples.	Arith. mean values of 10 samples.

Mineralogy

Both orebodies consist predominantly of massive pyrite with rare pyrrhotite. The minor constituents are chalcopyrite, sphalerite and occasionally galena. In hand specimen the ore has an even texture and the average grain size of the sub-euhedral pyrite is around 1 mm. Strongly banded ore is a distinctive feature of the south body and is due to alternating layers of magnetite and pyrite. The banded ore seems to have a very restricted occurrence.

Folldal Ore

In the Folldal area five major orebodies are known, viz: the old Folldal mine, the Nordre and Sondre Gjeiteryggen mines, the Nygruven mine and the Grimsdal deposit. The general character of the mineralisation is very similar to Tverrefjellet, although none have been studies in detail by the writer. Surface geochemical studies were carried out in the vicinity of the two Gjeiteryggen mines and around the Grimsdal orebody, and mention of these will be made in the appropriate place.

(iv) Quarternary Geology of the Hjerkinn-Folldal Area

The information given in this section has been obtained from an unpublished report by Holmsen (1963) supplemented by the writer's observations.

The drift cover consists of ground moraine, eskers and gravel deposits of late glacial and post glacial rivers.

(a) Glacial Deposits

Ground and Ablation Moraine

The greater part of the area is covered by glacial deposits which may be termed ground moraine. This term is applied to material within the bottom strata of the ice which was deposited directly on bedrock. The moraine which is

grey in colour is dominated by local material, but it is frequently noted that the surface layers are thick with boulders of more distant origin. These layers may derive from material carried on or within the ice and deposited during the phase of stagnation and melting of the ice sheet. This material, "ablation moraine" is often difficult to distinguish from ground moraine. Ablation moraine occasionally takes the form of small hillocks which may represent bodies of moraine debris which occupied cavities in the ice surface. Because of the difficuly in differentiating ablation moraine from ground moraine, the general term "moraine" is used in referring to these deposits.

Thickness of the Moraine

Evidence of drill holes and trench sections indicates that in normal terrain exposed to the ice flow the moraine has an average thickness of 3 m. In Lee positions the moraine can be of considerably greater thickness. For example, at Tverrefjellet it was found to be 20 m. thick in the ground below the mine shaft which stands on a north-easterly facing hillside.

Eskers

Small eskers are occasionally found along valley sides and consist of layered sand and gravel of local origin. Taken as a group they show no preferred orientation,

but locally sub-parallel sets of small eskers are not uncommon. For example, five closely spaced eskers all orientated roughly northeast-southwest are located 700 m. north-east of the Tverrefjellet orebody (Fig.5). The eskers are normally 3 to 7 m. high and have a length up to 500 m.

Evidence of the Latest Dominant Direction of Ice Transport.

Crag and tail features indicate that the ice has moved from south to north across the area. This is supported by the mapping of distinctive erratic boulders and by the occurrence of occasional ore boulders and fragments of oxidised ore material in the moraine at Hjerkinn, to the northeast of the Tverrefjellet orebody (Fig.5).

Ice striae provided additional evidence on the movement of the ice. In the Hjerkinn area three systems of ice striae are recorded. The oldest set orientad southeast-northwest is cut by a second system of intermediate age which records movement to the northeast. A third set of striations indicate that the ice finally moved to the north and northeast (Fig.5).

As mentioned above the deposits of ground moraine, at least in the vicinity of the Tverrefjellet orebody seem to

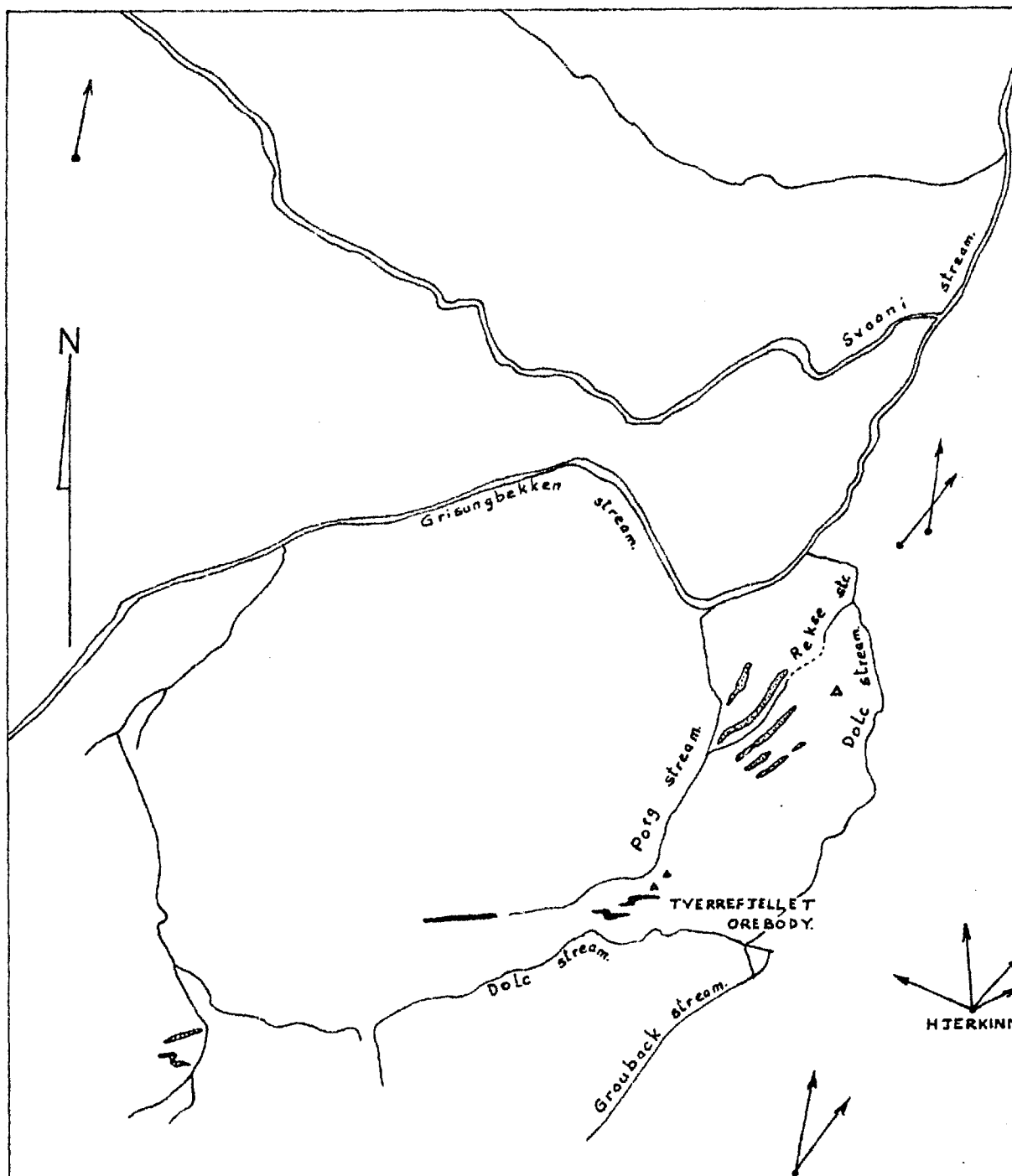


Fig.5. Map of the area around the Tverrefjellet orebody to show some of the glacial features. (Measurements of ice striae after Holmsen 1963)

be related to the intermediate system of striae orientated in a north easterly direction.

The significance of the youngest set of ice striae is not clear, but they have only been recorded in a very few localities, and possibly represent local variations in direction of ice movements in the latter stages of glaciation.

Age of the Glacial Deposits

No deposits have been recognised that pre-date the last glaciation, (variously known as Würm, Weichsel, Wisconsin). Furthermore, the ground and ablation moraine in the Hjerkinn-Folldal area is almost certainly a product of the final glacial episode of the last glacial period. This period ended about 11,000 years ago.

(b) Late-glacial and Post-glacial Deposits

Two main types of deposit are recognised, viz: (1) fluvio-glacial sand and gravel deposits, and (2) organic-rich deposits (bogs).

Fluvio-glacial Deposits

In the vicinity of Hjerkinn the Grisungbekken and Svaani rivers run through a large plain-like area covered with thick deposits of sand and gravel. On the aerial photographs these materials show "braided" forms and are thought to have been deposited by a large drainage system

which functioned at a late stage in the glacial history of the area (Holmsen).

Piedmont-type sand and gravel deposits are more typical of the Folldal area which is situated to the north of a massive range of mountains (the Rondane Range). Late glacial drainage from the high ground deposited thick masses of sand and gravel in the valleys. At Grimsdal all the ground lying below and to the north of the orebody is covered with this kind of deposit.

In some areas, thin sheets of sand and gravel overlie the eroded surface of the moraine. These deposits are more commonly found in the sloping ground below eskers and are generally about 50cm. thick. The location and form of occurrence of these deposits indicates that they may derive from a redistribution of material by sheet-wash during the period of stagnation and melting of the ice sheet.

Organic-rich Deposits

Small local depressions are commonly the site for accumulation of organic material. The thickness of the organic layer rarely exceeds 1 m. and is composed of partially decomposed humus. There are three distinct types of bog occurring in the area, viz:

(1) valley bogs, which form along the margins of streams in sections where the drainage is impeded,

(2) hill bogs, filling local depressions,

(3) solifluxion terrace bogs, which form mainly on gentle hill slopes.

The degree of humification is generally low, and peats have not been observed in the area.

(c) Solifluxion and Patterned Ground

Above the tree line the depth to which the frost penetrates the overburden is governed largely by the depth of snow cover during the winter. In many places exposed to the wind, snow cover can be completely removed, and in the Hjerkinn-Folldal area which has a dry climate receiving less than 40% of its precipitation during the winter, frost may deeply penetrate the overburden. Conditions of perma-frost may prevail in some places in the study area, but it is improbable that this condition is widespread. However, in many places in the overburden and in bogs, frozen layers persist well into the summer and it was the writer's experience that these deeper layers did not thaw at least until September.

In the overburden several conditions are developed by frost action:-

Solifluxion. This is a widespread condition in the Hjerkinn area and is most commonly developed on ground moraine (Holmsen, 1963). The lower slopes of hillsides are frequently a complex of arcuate solifluxion fronts, the one overriding the other. The lateral movement is probably short, not more than 10 m. (Holmsen 1963). The mechanism involves the saturation of the surface layers of the overburden with water, which may be accomplished by melting snow patches. In addition water is probably drawn from deeper layers in the overburden by capillary forces induced by the formation of ice nearer surface. The formation of ice at fairly shallow depths in the overburden continues by this process. During the summer this water is released to the upper layers having been drawn largely from below (Tabor, 1930).

Williams (1959) showed that the process of solifluxion is one of turbulent mixing in which the organic layer formed at the surface is incorporated within a mass of morainic debris.

Patterned Ground. The term "patterned" ground may be used to describe a variety of earthy structures which form on different types of overburden under the influence of frost action. Of these the frost tussocks and stony polygons are the most widespread. In Norway these structures are

most commonly found at elevations between 1000 and 1250 m. above sea level (Holtedahl, 1960).

Frost tussocks form in certain bogs and are composed of fine to medium grained silty material with a high organic carbon content and may be up to 2 m. in diameter and 50 cm. high.

Stony polygons are commonly found in relatively flat sandy ground where the water table is near surface, and in these areas circular structures have developed which have a bouldery core surrounded by a raised ring of finer grained material. These structures are usually 1-2 m. in diameter and when in close juxta position have polygonal boundaries.

Both polygons and tussocks are presumed to develop as a result of alternate freezing and thawing. The exact mechanism is not fully understood. However, during the formation of stony polygons, material may be raised from deeper layers in the overburden to the surface by frost heaving.

SOILS

In the study area soil forming processes have given rise to thin soils with poorly differentiated horizons (Fig. 6). The profile when characteristically developed consists of a surface layer of partially decomposed humus

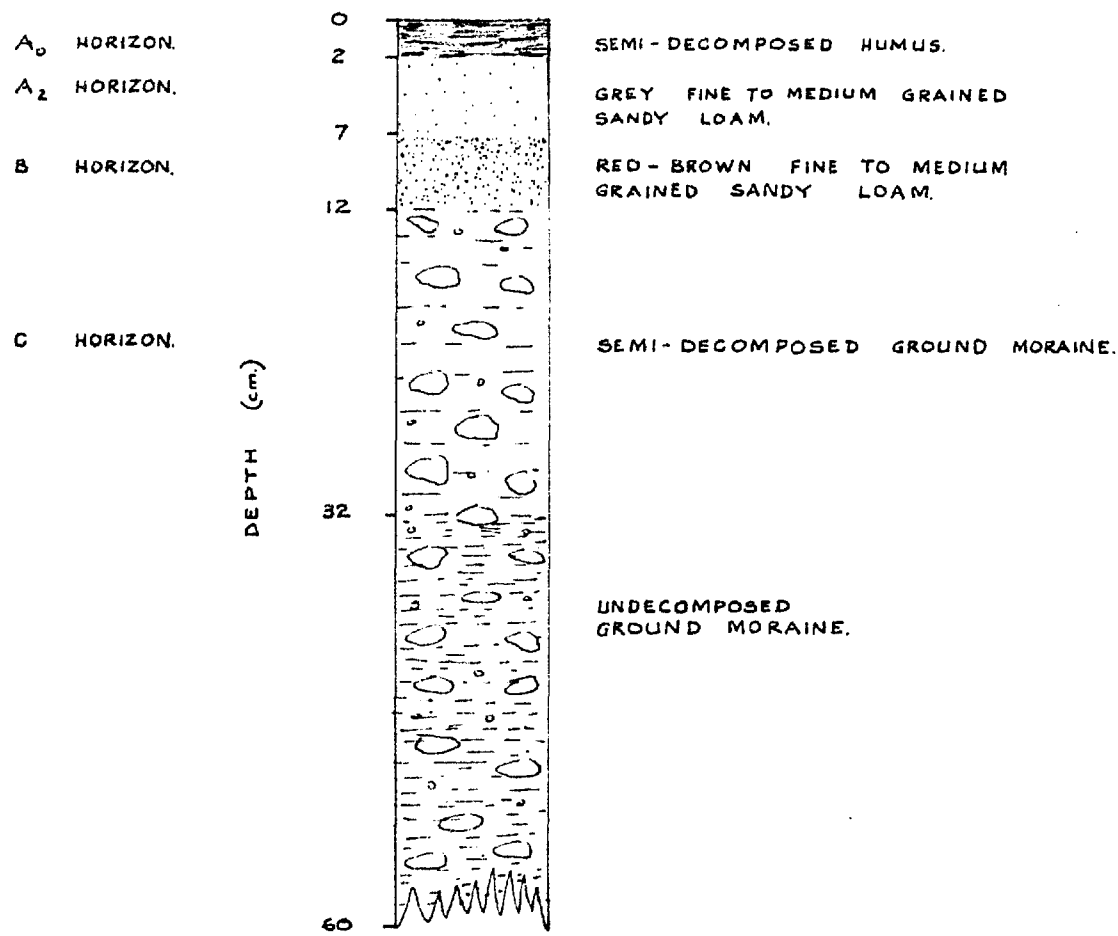


Fig.6.
Generalised soil profile, Hjerkinn-Folldal area, C. Norway.

which is underlain by a grey leached horizon 5 to 10cm. thick. At the base a red-brown layer may be developed, and this horizon grades down into semi-decomposed parent material. The total thickness of the soil is never more than 50 cm..

The cold dry climate is probably of fundamental importance in giving rise to a poorly illuviated A horizon and a correspondingly ill-developed B horizon. In addition to the climate, the parent material seems to have been a major factor affecting soil development in this area. For example, soils are characteristically developed on ground and ablation moraine but are absent or very thin on well drained fluvio-glacial sand and gravel deposits. This is perhaps due to the permeable nature of the fluvio-glacial sand and gravels which favours the removal of the fine grained fraction in ground waters. Consequently a loose rubbly surface layer develops which is unsuitable for soil formation. Fluvio-glacial sand and gravels occurring in poorly drained low-lying areas gives rise to conditions suitable to the formation of bogs.

The factors affecting soil formation, namely, parent material, relief, climate, biological activity, and time, all militate against the formation of a well-developed soil in this area. The soil that has formed is considered to

belong to the Tundra group being characterised by an indistinct profile similar to podzols.

TOPOGRAPHY

Hjerkinn lies on the topographic culmination of Central Norway where the elevation varies between 900 and 1,400 m. The hills generally have smooth south facing slopes, rounded tops, but craggy ice-plucked northeast faces. Valleys are broad and little modified from the U-shaped forms inherited from glacial occupation.

The hill country gives way to a very broad flat bottomed valley, 2.5 km. north of Hjerkinn, which is surrounded by hills, and floored by fluvio-glacial deposits. The enclosing ring of hills is breached in the northwest (in the vicinity of Kongsvoll) by a norrow and deep gorge. This broad valley with its deep outlet gorge was probably cut by melt waters of the Quarternary ice sheet (Holmsen, 1963) and is a major geomorphological feature of the Hjerkinn area.

In passing from Hjerkinn to Folldal the elevation decreases to 700 m. in the vicinity of the village, which lies in a broad valley occupied by the river Folla. Above the valley the hill country is very similar to that of Hjerkinn.

The topographic grain of the country is broadly coincident with the geological trend, indicating that glacial erosion has been controlled to a large extent by bedrock geology. However, some valleys, notably the Kvitdalen and Folldalen cut across the strike of the underlying bedrock, and in the case of Kvitdalen is controlled by a northwest - southeast trending fault zone. Folldalen which is a major valley in the Hjerkinn-Folldal area is not controlled by any known structural line. It is possible that this valley which runs roughly northwest - southeast may have developed during an interglacial period when other outlets were blocked. There is certainly evidence of it being ice-scoured during the last glaciation.

DRAINAGE.

Hjerkinn lies on the water divide between north western and south eastern Norway. The Grisungbekken and Svaani streams rise in the area to the northwest of Hjerkinn and are tributaries of the River Driva. This major river flows out of the area via the deep gorge, which is presumed of late glacial origin, and thence to the west coast.

To the south of Hjerkinn all drainage flows to the south east via the river Folla which joins the Glomma, Norway's longest river.

The flow of water to the streams is regulated in the summer by the many small lakes and boggy areas, but in spring, snow melt leads to a seasonal influx of large volumes of water.

A detailed description of the drainage which was sampled during the course of the field work will be given in succeeding parts of this report.

CLIMATE

The mean annual temperature at Hjerkinn is -0.8°C with extremes of -9.5°C in January and + 10.3°C in July, (readings at 8.00 hours). Precipitation is low with 60-70% occurring during the months of May to September (Table 2).

TABLE 2.

Mean Monthly and Annual Amounts of Precipitation for the Period 1900-1940.

(data of the Norske Meterologiske Institut)

Station	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Folldal	20	11	12	12	15	43	61	72	28	23	27	17	341
Hjer-kinn	12	7	7	9	15	29	50	35	22	11	16	14	227

(precipitation in mm).

VEGETATION AND AGRICULTURE.

Vegetation

The vegetation occurs in zones which are controlled to a large degree by the elevation. Thus below the 800 m. contour conifer forests are predominent, giving way above 800 m. to a zone of birch woodland. At elevations in excess of 1050 m. the flora is entirely of sub-arctic type consisting of Batula nana (dwarf birch), Salix sp. (dwarf willow), grass, heather and moss. The dwarf birch and willow rarely exceed 50cm. in height, and the flora has a distinctive "scrub-like" appearance. The moss is mainly the lichen Cladonia rangiferina (or reindeer moss), and in places where reindeer are plentiful (i.e. in the area west of the railway line at Hjerkinn) over-grazing has led to a stripping of the moss cover which elsewhere forms a thick protective matte.

Agriculture

Mixed farming constitutes the major industry of the area, but is largely restricted to the valley of the River Folla. Summer grazing of cattle and sheep in the hilly districts is a practice which is falling away, and in the Hjerkinn area only three hill farms (setters) remain, now largely disused. The geochemical investigations carried out during the course of the present study, were made largely in areas too barren for farming.

MINING AND MILITARY ACTIVITIES.

Mining

In the Folldal area the mining of cupriferous pyrite commenced in 1748, but large scale production only began in 1907, and at the present time the industry in Folldal is producing 45,000 tons of pyrite and 3,600 tons of Cu concentrate annually. Production is from one mine only (the Nordre mine), and of the four other known orebodies in the Folldal area, two are exhausted (i.e. the old Folldal mine and the Sondra mine), whilst the Nygruve mine and the Grimsdal orebody were abandoned after proving to be sub-economic.

The geochemical investigations in the vicinity of the Nordre and Sondre mines, and at Grimsdal, were carried out in selected localities where contamination from mining operations was at a minimum. Frequently this entailed sampling over sub-economic mineralisation on strike of the ore.

At Hjerkinn mining is at an early stage of development having commenced in 1958 and has so far not led to any significant surface contamination. The area of sub-outcrop of the orebody occurs on the other side of the hill on which the mine shaft is located, so that in this main study area the question of contamination does not arise.

Military Activities

The area to the west of the railway line at Hjerkinn is given over to the military authorities, and is used as an artillery range. The effects of the artillery barrages seems to have been slight from a contamination point of view, but the main target areas were avoided as much as possible during the sampling.

PART II

TECHNIQUES

SAMPLE COLLECTION AND STORAGE

Samples were collected in pre-numbered kraft paper envelopes. The envelopes for collection of routine samples measured 3 inches by 5 inches, whilst the larger envelopes measuring 5 inches by 9 inches were employed for bulk samples.

(i) Rocks

Outcrop: Rock samples collected from outcrop were retained only if they were more or less unweathered. Fresh outcrop is not uncommon in Norway although some rock types, notably quartz mica schists are usually weathered, and in these cases greater efforts had to be made in obtaining suitable samples. Systematic sampling of outcrop was not possible for several reasons, of which the most important are the low outcrop density and the tendancy for only resistant rock types to be exposed.

Artificial exposures such as road and railway cuttings and trench sections were systematically chip sampled at intervals varying between o.5 to 5 m. In these cuttings less resistant rock types were frequently not exposed and this has placed limitations on the primary dispersion study.

Drill Core: All the holes drilled into the ore zone at Tverrefjellet were kindly made available to the writer by Folldal Verk A/S. Selected holes were sampled by taking chip samples at intervals of between 0.5 and 1 m. in the ore zone and its wall rocks, and at 5 m. intervals in the country rocks. It was not possible to obtain continuous sampling along the core. This is particularly unfortunate where the metal distribution appears to be erratic.

(ii) Moraine and Soil

Trenching: Over the orebody at Tverrefjellet, the overburden was exposed by digging trenches to bedrock. Because of a layer of frozen ground occurring at a depth of between 1 - 2 m. below the surface the overburden was stripped to this depth with bulldozers. After allowing two weeks to thaw the sections were then able to be sunk to bedrock with the aid of a small excavator.

Channel samples were taken from the trenches along vertical lines 0.5 - 1 m. apart taking 20 cm. lengths per sample except in soil horizons where sample intervals conformed to the natural boundaries. These samples were collected with a trowel and each section was cleaned off before sampling commenced, starting at the base of the profile and working up to avoid unnecessary contamination.

Routine sampling: Sampling of the overburden in background locations and in the Folldal area was accomplished by digging shallow pits through the soil horizons and into the moraine. These pits were never deeper than 50 cm. and the profiles were sampled with a trowel, taking individual samples of each horizon. "Deep" samples down to a depth of 1 m. were obtained using a hand auger. It was often necessary to drill a hole with a length of steel and a sledge hammer before a sample of moraine could be obtained at this depth. In one locality the moraine was successfully sampled down to a depth of 2 m. using a hand auger but this was exceptional. In many places the moraine at this depth was dry and friable. Accordingly it was not possible to collect a representative sample with a spiral auger. New sampling techniques and equipment need to be developed before it will be possible to obtain reasonably deep samples in the very bouldery and dry moraine occurring in this part of Norway.

(iii) Bogs

Bogs were sampled along traverse lines oriented at right angles to the drainage direction. A hiller peat auger was used to obtain samples at 0-20, 20-50 and 50-100 cm. in the profile at each sampling site, which were spaced

at intervals varying between 5 and 10 m. along the traverse line. This pattern of sampling was not always adhered to because of bouldery or frozen ground occurring in the bog.

(iv) Stream Sediment and Banks

In small streams, samples of the active stream sediments were taken from the middle of the stream. In the larger streams and rivers sediment samples were taken from both sides of the stream, sufficiently far away from the banks so as to avoid collection of material deriving from bank collapse, and where possible a third sample was taken from the middle of the stream.

Bank samples were taken from the material occurring at a depth of 10-30 cm. That is, the material below the organic layer, and above the gritty zone which in many streams occurs near to the water line and consists of bank material contaminated with stream sediment. Bank profile samples were collected at certain localities.

(v) Stream Waters and Ground Waters

Stream waters: One liter samples were collected in acid scrubbed polythene bottles provided with a screw cap. The bottles were washed out thoroughly at the sample site before taking the sample. pH, Eh, $CO_3^{=}$ and $HCO_3^{=}$ were determined on site, and $SO_4^{=}$ was measured in the field laboratory.

Ground Waters: These samples were collected from pits sunk to the ground water table which was frequently very shallow. The water was allowed to stand in the pit before collection to eliminate unnecessary volumes of sediment being included with the water sample. Groundwater was transferred from pit to bottle by scooping.

The waters collected during the summer field season of 1964 were acidified with 2ml. of conc. hydrochloric acid before shipment to London. Waters collected on the second field trip of the following year were not acidified.

Acidification of Water Samples

The disparity in treatment of waters collected on the successive occasions with respect to acidification has led to differences in the analytical results. Table 3 compares non-acidified and acidified samples collected from the same site at an interval of one year.

TABLE 3.

Comparison of the Analytical Results for Acidified and Non-acidified Waters Collected at the Same Site.

	Acidified Sample ppb			Non-acidified Sample ppb		
	Cu	Pb	Zn	Cu	Pb	Zn
Ionic Metal	550	8.4	1100	190	4.0	840
Total Metal	520	10.0	880	600	14.0	920
Date Collected	July 1964			July 1965		

At the precision of the methods the differences between the individual total metal values of the two samples are probably not significant. However, the content of all the metals is recorded as somewhat higher in 1965 than in 1964. There is no evidence from the control samples that there was an overall bias between 1964 and 1965. Therefore, the fact that all total metal values are recorded as being higher in the non-acidified waters of 1965 probably reflect an actual difference between these two years.

The major difference is seen in the data on ionic Cu which indicates that in non-acidified samples, part of the ionic Cu is brought into complex form, possibly by organic matter in solution or through the agency of

bacteria. Zn is lower in the non-acidified sample, but considering the precision of the analytical method it is possible that Zn is not involved in these processes. Pb however, shows a tendency similar to Cu. It follows that in non-acidified samples the results for ionic Cu and Pb are invalid and therefore these figures will not be presented in the succeeding parts of this report.

Solvent Extraction of Metals from Water in the Field

A proportion of the water samples were treated in the field; ionic Cu, Pb and Zn being extracted by shaking the buffered water with successive 10 ml. portions of 0.15% dithizone in carbon tetrachloride. This treatment was continued until there was no further reaction with the dithizone solution. The organic metal concentrates were stored in 50 ml. capacity polythene containers provided with airtight screw caps. The concentrates were subsequently analysed in the London laboratory, each sample being treated as follows:-

The organic metal concentrate was transferred from its container to a 100 ml. capacity beaker. The polythene bottle was then scrubbed with 10 ml. of hot acid mixture to recover any metal that may have adhered to the walls of the vessel. (The acid mixture being prepared by mixing 3 parts of concentrated nitric acid with 1 part

of 60% perchloric acid.) The acid washings were combined with the organic metal concentrate and 2 ml. of concentrated sulphuric acid added. The contents of the beaker were then digested under a watch glass until all the organic matter had been destroyed. The clear solution was evaporated to dryness and the residue taken up in 10 ml. of 0.5M. hydrochloric acid. At this stage aliquots were taken for the colorimetric determination of Cu, Pb and Zn.

Duplicate water samples which were acidified in the field and shipped to London were also analysed for ionic metal. The method of analysis was the same as that described above, the only difference being that there was no storage of the organic metal concentrates in polythene containers. The two sets of results are compared in Table 4 and show that the solvent extracts stored in polythene containers loose a large proportion of their metal content.

TABLE 4.

Ionic Metal Results of Duplicate Water Samples showing the Affects of Storage of the Organic Metal Concentrates in Polythene Containers. Waters in the Strongly Anomalous Range

Organic Metal Concentrates Stored in Polythene Containers (Metals Separated in the Field) ppb			Analysis of Acidified Waters for Ionic Metal without Storage of the Solvent Extracts ppb			Percent Difference		
Cu	Pb	Zn	Cu	Pb	Zn	Cu	Pb	Zn
118	0	1120	3400	115	7000	97	100	84
41	0	598	750	34	1400	94	100	57
20	0	650	1700	55	2800	99	100	77
				Average Loss		97	100	73

Table 5 gives the results for waters in the background-threshold range. In this case the duplicate water samples were not acidified and therefore only the Zn values are given. Ionic Cu and Pb being adversely affected in waters stored without the addition of hydrochloric acid (Table 3).

TABLE 5 As for Table 4 - Waters in the Background-Threshold Range

Organic Metal Concentrates Stored in Polythene Zn ppb	Solvent Extracts Analysed without Storage Zn ppb	Percent Difference
4.5	12.0	60
5.1	7.0	28
2.1	12.0	83
6.5	11.0	40
8.5	9.0	6
Samples collected at the same site: July 1964 July 1965		Average Loss 40%

In waters in the background-threshold range, the average loss of Zn is 40% (Table 5), whilst in the strongly anomalous waters Zn values show an average loss of 73% (Table 4). This may be explained in three ways, viz:-

(1) A small amount of metal on or within the walls of the polythene containers may have been available to the hot oxidising acids used in scrubbing the vessels. This would have a more significant effect on the low order values.

(2) Contamination from mineral acids may have affected the results and would have a more marked effect in the low range.

(3) Waters in the background-threshold range contain metal concentrations near to the lower limit of the analytical

methods (metals being extracted from 1 liter sample volumes). At this level the precision may fall outside ± 25% at the 95% confidence level.

As far as possible these various hypotheses have been investigated and it was found that in testing the analytical technique using samples of known Zn content the precision of the results in the concentration range of 1 to 12 ppb is within ± 35% at the 95% confidence level. In addition, blank determinations on the $HCLO_4/HNO_3$ mixture which was used in scrubbing the polythene vessels indicated that 10 ml. of the acid mixture would contain no more than 0.2 µg. of Zn. These results would imply that (a) the difference in the Zn values in the background-threshold range (Table 5) is probably not due to analytical error, and (b) contamination from the $HCLO_4/HNO_3$ mixture has not had any significant affect on the Zn values. It is, therefore, tentatively concluded that a small proportion of the Zn on or within the walls of the polythene containers used in storing the organic metal concentrates was available to the hot oxidising acids used in scrubbing the vessels.

The loss of metals from solvent extracts stored in polythene may occur as the carbon tetrachloride diffuses through the walls of the container. During this process

Cu, Pb and Zn could be lodged in the pore spaces of the polythene. The attempt to recover the metals failed which possibly indicates that they are largely firmly held in the polythene.

Collection and analysis of waters during the course of the study has shown that the use of polythene containers for storage of solvent extracts is not satisfactory. In view of the complicated analytical procedures it is recommended that acidified water samples should be transported to a well equiped laboratory before the determination of their metal content is undertaken, if precise results are required.

In the present work, the samples that were lost by the deterioration of the organic metal concentrates were replaced during the second field trip.

(vi) Vegetation

Because of the widespread occurrence of Betula nana (dwarf birch) this species was sampled in preference to the other vegetation. Each vegetation sample consisted of a collection of twigs taken from around the periphery of one individual. This was done in order to minimise sampling error that may arise from variations in metal content on different sides of the plant, as reported by Cannon (1957). Note was also taken of the dimensions of each plant that was sampled.

SAMPLE PREPARATION

(i) Drying

Samples were dried in an air current of about 80°C whilst still in their unopened envelopes. The drying equipment designed and built by the Norwegian Geological Survey, consisted of an electrical heating element in the base, with an exhaust fan placed vertically above it. The trays carrying the samples were provided with perforated aluminium base plates to allow free passage of air and several of these could be stacked one above the other in between the heating element and the exhaust fan. The equipment operated on a 24-hour basis when necessary, without overheating or any other serious defects.

(ii) Rocks

Each sample was crushed to a 2 mm. aggregate in a jaw crusher and then ground to -80 mesh in an agate mortar. Samples of ore were held over till the end of these operations to avoid contamination of unmineralised rock samples. After passing each sample through the jaw crusher the working parts in contact with the sample were cleaned down with a brush, and these precautions were also observed after grinding the samples in the mortar.

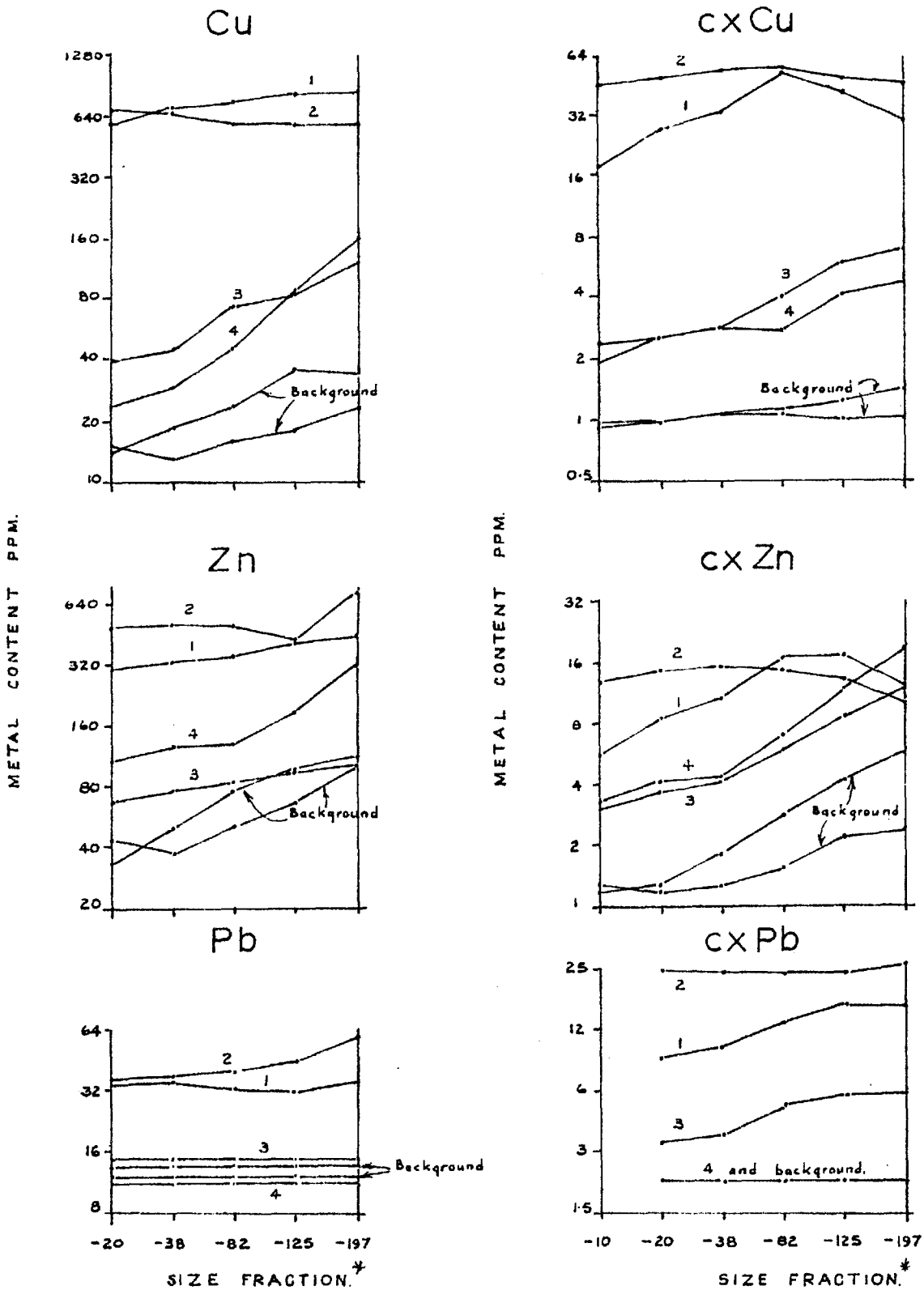
(iii) Bog Samples

Bog samples were found to contain up to 10% of organic carbon. These samples are largely composed of fine grained sand and silt together with decomposed plant material. In order to obtain a representative sieved fraction, the samples were lightly pulverised in a porcelain pestle and mortar to break down the aggregated organic material. When sieved to -80 mesh all the material passed the screen except for the occasional coarse mineral grain, and some undecomposed plant parts. The small amount of material remaining in the sieve was discarded.

(iv) Stream Sediment and Overburden (excluding bog samples)

The samples, which were completely friable when dry, were sieved to the -80 mesh fraction through nylon bolting cloth set in a perspex frame. After each sieving the screen was cleaned with a brush to avoid contamination between samples.

The selection of the -80 mesh fraction was based on the results of size analysis carried out prior to the commencement of the systematic laboratory work. The results presented graphically in Fig.7 refer to four samples of stream sediment taken from the anomalous drainage at increasing distances from the Tverrefjellet orebody, and are compared with two samples from a stream draining essentially



EXPLANATION	
Sample Nº	Distance downdrainage from the Tverrefjellet orebody (metere)
1	50
2	700
3	1200
4	2500

Fig.7.

Size analysis, active stream sediments.

* B.S.S mesh size.

unmineralised ground. In Fig.8, the results of size analysis of selected overburden samples are shown. The samples were taken from a profile overlying the Tverrefjellet orebody, and from a profile overlying barren bedrock.

These studies show that the contrast between anomalous and background material is very similar in all the under-size fractions in both stream sediment and overburden samples (Figs.7 and 8). The -80 mesh fraction was selected (i) to allow comparison with the results of other workers (ii) because a 0.1g sample would be representative of the whole, and (iii) because this fraction consistently provided sufficient material for all analytical purposes.

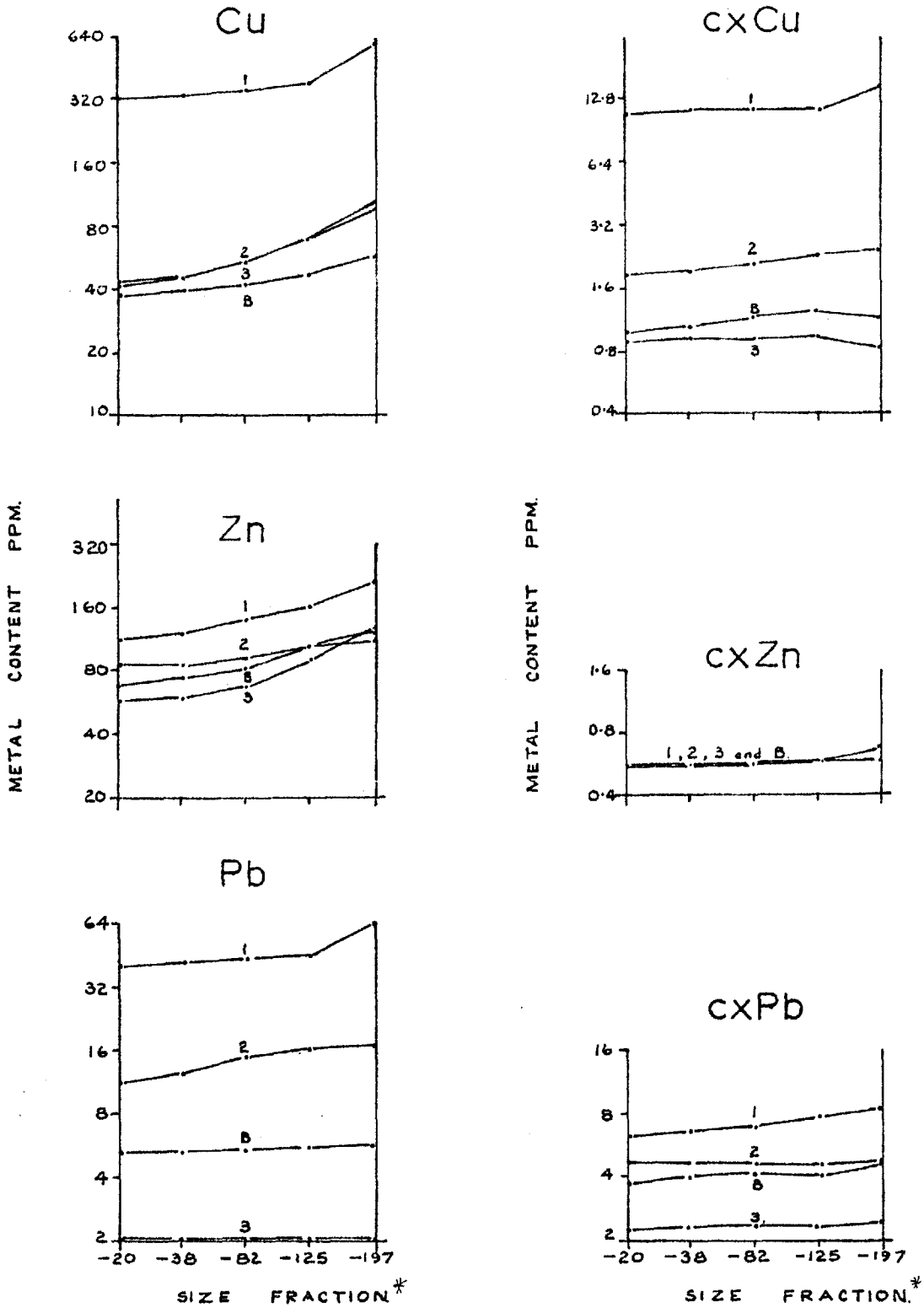
(v) Vegetation

Twig samples were ashed over night in silica crucibles in a muffle furnace. Considerations on the temperature of volatilisation of Cu, Pb, Zn and Fe coupled with the need to effect a complete ashing decided the selection of 450°C as the ashing temperature.

ANALYTICAL TECHNIQUES

(i) Sample Attack (rocks, stream sediments, overburden)

A variety of sample attack has been employed varying from a complete attack using hydrofluoric and perchloric



EXPLANATION	
Sample	Depth below surface in profile over the Tverrefjellet orebody (cm).
1	320 - 340
2	280 - 320
3	60 - 120
B	Background; at depth 60-80 cm.

Fig.8. Size analysis, glacial overburden.

* B.S.S mesh size.

acids, through to the measurement of exchangeable metal by shaking the sample with IM. neutral ammonium acetate in the cold. Between these extremes fusion with potassium bisulphate, digestion with IM. hydrochloric acid, and cold extraction with acidic reagents have been employed. Unless otherwise stated the data refers to results obtained after fusion with potassium bisulphate.

In this sub-section the different sample attacks are briefly described and discussed in terms of the kind of metal that is being determined.

(a) Hydrofluoric-perchloric Acid ($HF-HCLO_4$) Attack

(Modification of the procedure described by R.E.Stanton, A.J. Macdonald and I. Carmichael, 1962).

In this procedure 0.25 to 0.5g of the sample is digested with hydrofluoric acid, perchloric acid and nitric acid in a platinum dish. After the acids have been completely driven off, the residue is taken up in 15 ml. of IM. hydrochloric acid and this solution transferred to a 150 ml. separating funnel, containing 25 ml. of sodium citrate buffer solution. Reacting metals are extracted with successive 5 ml. portions of 0.015% dithizone in CCL_4 until there is no further reaction. The organic phase is collected in a second separating funnel. The aqueous solution is discarded and the organic phase

placed in a 100 ml. beaker and evaporated to dryness. Small quantities of concentrated sulphuric acid, nitric acid and 60% perchloric acid are then added and refluxed under a watch glass until all the organic residue has been destroyed. The contents of the beaker after fuming to dryness are taken up in 0.5M.. hydrochloric acid and transferred to a test-tube diluting to 10 ml. with 0.5.M. hydrochloric acid. Aliquots are then taken for colorimetric determination of the metals.

This procedure was applied to the determination of the trace element content of the standard rocks G-1 and W-1 by Carmichael and Macdonald (1961) whose results correspond closely with those obtained by other workers using radiochemical methods. More recently Harden and Tooms (1964) used this procedure as a standard to compare the efficiency of the potassium bisulphate attack on rocks, minerals, soils and stream sediments.

(b) Potassium Bisulphate ($KHSO_4$) Attack

0.1 gm. of sample sieved or ground to -80 mesh, is fused with 0.5 gm. of potassium bisulphate in a pyrex test-tube to a red quiescent melt. The cooled fused cake is leached with 5 ml. of IM-hydrochloric acid on a sand tray and diluted to 10 ml. with water. From the leachate aliquots are taken for the colorimetric determination of the metals.

This method has been extensively employed in the present study and is particularly convenient since Cu, Pb, Sn, Fe and As may be determined from the one attack. The method yields results that are commonly referred to as "total" metal but the efficiency of this attack has been shown to vary considerably from mineral to mineral and between different sample materials (Harden and Tooms 1964). However, comparison of these results with values obtained after a complete ($HF-HCLO_4$) attack on samples of moraine from the Hjerkinn area shows that on this sample material the potassium bisulphate fusion is very nearly 100% efficient (Table 6).

TABLE 6

The Efficiency of the Potassium Bisulphate Fusion on Samples of Moraine from the Hjerkinn Area

(data on the -80 mesh fraction)

Sample No.	Cu ppm		Zn ppm		Pb ppm	
	$HF/HCLO_4$	$KHSO_4$	$HF/HCLO_4$	$KHSO_4$	$HF/HCLO_4$	$KHSO_4$
3203	62	42	104	60	22	20
3213	1020	1150	368	340	24	20
4153	50	37	84	80	12	5
5401	82	70	168	160	16	5

(c) Perchloric Acid - Nitric Acid ($HCLO_4$-HNO_3) Attack

5 mls. of acid mixture (prepared by mixing 1 part of 60% perchloric acid with 3 parts of concentrated nitric acid) is added to 100 mg. of sieved sample contained in a pyrex test-tube. The acidified sample is placed in an oven and evaporated to dryness at a temperature of 200°C. The residue is leached with 5 mls. of 1M-hydrochloric acid and diluted to 10 ml. with water. Aliquots are then taken for the colorimetric determination of the metals.

This form of sample attack has been used as an alternative to fusion with potassium bisulphate for treating organic-rich samples which are incompletely attacked by potassium bisulphate. The method proposed by R.E.Stanton (1964), was applied to samples from Ireland by P. Donovan (1965). Donovan found that in some organic-rich samples anomalous concentrations of Cu were liberated after $HCLO_4$-HNO_3 attack but not when fused with $KHSO_4$. Suppression of $KHSO_4$ metal values by organic material had previously been reported by Smith (1963) on material from New Brunswick. The important question that should be evaluated is whether the nature of this suppression is erratic or not. A batch of bog samples from the Hjerkinn area was therefore analysed for Cu after fusion with $KHSO_4$

and again after $HCLO_4$-HNO_3 attack. The results presented graphically in Fig.9 show that (within the precision of the analytical methods) the extraction of Cu from organic-rich samples when fused with $KHSO_4$ is not erratic but bears a constant relationship to the $HCLO_4$-HNO_3 Cu. It is, therefore, valid to apply the $KHSO_4$ attack to organic-rich samples from the Hjerkinn area.

(d) IM. Hydrochloric Acid Digestion

0.2 gm. of sieved sample is weighed into a pyrex test-tube and 5 ml. of IM. hydrochloric acid added. The sample is digested for 30 min. on a sand tray and then diluted to 10 ml. with water. At this stage aliquots can be taken for the colorimetric determination of Cu.

In the estimation of sulphate in soil and sediment samples a similar acid digestion is employed. In this case 1 g. of sieved sample is weighed into a pyrex test-tube and digested for 1 hour with 5 ml. of IM. hydrochloric acid. The solution after being allowed to settle may be tested for sulphate.

(e) Cold Extraction Techniques
cx Cu and cx Zn.

The cold extractable forms of both metals are conveniently determined separately, by shaking 0.2 gm. of sieved

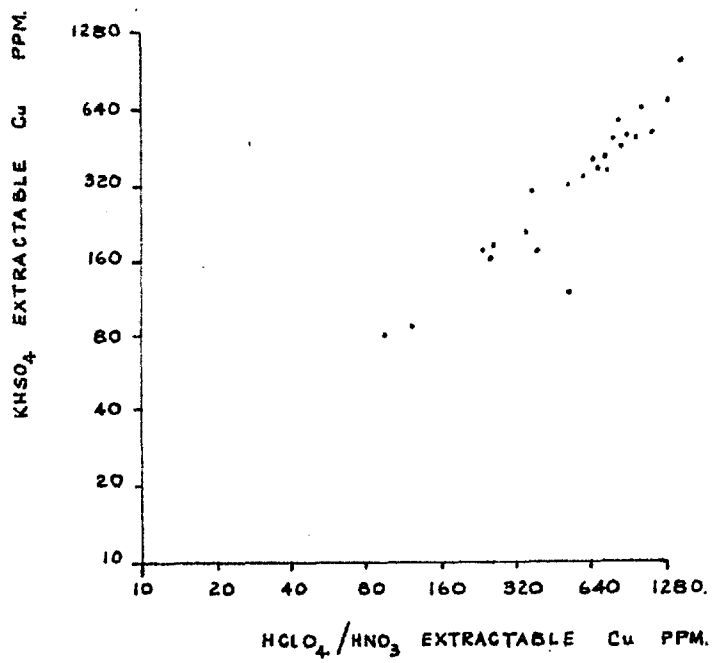


Fig.9. Comparison of the $KHSO_4$ and $HClO_4/HNO_3$ attacks on the extraction of Cu from the samples rich in organic carbon. (Data on the -80 mesh fraction).

sample with 5 ml. of the appropriate buffer solution in the presence of 2 ml. of 0.001% dithizone in benzene. The amount of cx Me is estimated visually by comparing the colour of the organic layer with standards. If the metal content of the test is above the range of the standards the sample is shaken with additional volumes of dithizone solution until the colour of the organic layer is within the range of the standards.

The buffer for the determination of cx Cu is made by dissolving 100 gm. of ammonium citrate and 100 gm. of hydroxylamine hydrochloride in about 500 ml. of water. This solution is scrubbed with 0.01% dithizone in carbon tetrachloride to remove traces of Cu and the excess dithizone is removed by washing with carbon tetrachloride. The buffer solution is then made up to 1000 ml. with water.

cx Zn buffer is made by dissolving 500 gm. of sodium acetate, 5 gm. of sodium fluoride and 125 gm. of sodium thiosulphate in about 1500 ml. of water. 15 ml. of acetate acid is added, and the solution made free of Zn by scrubbing with 0.01% dithizone in carbon tetrachloride (as for cx Cu buffer). The solution is then made up to 2000 ml. with water.

Determination of cx Me in the field.

The methods for the determination of cx Zn and cx Cu have been well tried over a period of years at the A.G.R.G. without encountering any major difficulties. Rapid on-the-spot determination of cx Cu in the field has been extensively used in controlling sampling and following-up anomalies in many parts of the world. Application of this technique in Norway has met with difficulty. During fieldwork it was observed that samples known to contain high cx Cu yielded none of this metal when analysed at the sample site. This occurred most noticeably when the temperature was on or around $0^{\circ}C$, (which was commonly the case). The reason for this was not investigated but may be due to a combination of a slow reaction time under the low temperature conditions, and incipient crystallisation of the benzene which would lead to dithizone solutions of increased concentration. The result is a complete breakdown of the method. Even shaking of the sample for extended periods produces no result.

(f) 0.5 M-Hydrochloric Acid Soluble Metal

This attach was developed originally by Ledward (1960) for the estimation of weakly held Pb. The procedure involves shaking 0.2 gm. of sieved sample with 10 ml. of 0.5M-hydrochloric acid for 30 sec. Aliquots can then be taken for the determination of Cu, Pb, Zn and Fe.

(g) Neutral IM-Ammonium Acetate Soluble Metal (Exchangeable metal)

A known weight of sieved sample is shaken for 1 hour with a measured volume of neutral IM-ammonium acetate solution. After shaking, the suspension is allowed to settle and the aqueous phase decanted off. A complete separation is achieved by centrifuging for 10 min. at 2000 r.p.m. The resultant solution can then be tested for its metal content.

The metal determined in this way is said to relate specifically to that which is held in exchange positions. Certain factors may to some extent invalidate this assumption, for example pH variations due to the sample material having an acid reaction, or to the presence of calcium carbonate in the sample which would give rise to an alkaline solution. These factors have been investigated, and the relevant information will be presented with data on exchangeable metal.

(ii) Physical Properties (stream sediment and overburden)

(a) Base Exchange Capacity (B.E.C.) and Total Exchangeable Bases (T.E.B.) (Bray and Willhite 1929)

A known weight of sieved sample is shaken for 1 hour with a measured volume of IM. neutral ammonium acetate. After shaking the suspension is allowed to settle and the

aqueous phase decanted. A complete separation is achieved by centrifuging for 10 minutes at 2000 r.p.m.

Base Exchange Capacity (B.E.C.)

The pre-treated sample material is transferred to a filter paper and washed free of ammonium acetate with an 85% solution of ethyl alcohol in water. The filter paper containing the washed sample is then placed in a retort with 10 ml. of 2 N. sodium hydroxide solution and 100 ml. of water.

The ammonium ions occupying the available exchange positions in the sample are driven off and distilled into 20 ml. of standardised 0.1 M hydrochloric acid. The concentration of ammonium ions is determined after titration of the un-neutralised acid with standardised 0.1 M sodium hydroxide solution. The base exchange capacity is reported as millie-equivalent per 100 gm. (m.e./100 gm.).

To check the reproducibility of the method several samples were analysed in duplicate (Table 7).

TABLE 7.

Date Concerning the Reproducibility of the Method for Determining the Base Exchange Capacity

Sample No.	Base Exchange Capacity M.E./100 gm.	
	1st Determination	2nd Determination
2117	33.0	31.0
2118	21.0	22.0
2119	24.5	27.0
4003	28.6	28.5

Total Exchangeable Bases (T.E.B.)

The total exchangeable bases are measured on the ammonium acetate solution after it has been separated from the sample material. This solution is evaporated to dryness in a silica basin and the acetates in the residue are converted to carbonates and oxides by igniting in a muffle furnace overnight. When the basin is cool the residue is neutralised with excess 0.1M hydrochloric acid, and the excess acid titrated with standard alkali using methyl red as an indicator. The results are reported as millie-equivalent/100 gm.

(b) pH of Sample Material

The available hydrogen ion content of stream sediment and overburden samples was determined on the minus-80-mesh fraction by testing the pH of a 1:5 solid/water suspension

equilibrated by shaking for 1 hour on an automatic shaking machine. The water used in these experiments was normal de-ionised water boiled to eliminate dissolved carbon dioxide.

(iii) Partial Size Analysis

50 or 100 gm. of sample sieved to -5 mesh was dispersed in de-ionised water by subjecting it to ultrasonic vibration for 30 mins. The resultant slurry was washed with de-ionised water through perspex framed non-contaminating sieves of the following sizes:-

10, 20, 38, 82, 125 and 197 mesh (B.S.S.), corresponding to 1.651, 1.150, 0.545, 0.204, 0.107 and 0.054 mm.

Each fraction after complete separation was dried at a temperature of approximately 80°C.

(iv) Analytical Treatment of Water Samples

During the analysis of water the following were determined: Cu, Pb, Zn, Fe, Al, Si, $SO_4^{=}$, $CO_3^{=}$, HCO_3^{-}, pH and Eh. Of these, the last four were measured on site, whilst $SO_4^{=}$ was determined in the field laboratory shortly after collection. Supplementary $SO_4^{=}$ determinations were made in London on samples collected during the second field trip. The metals were determined in London, although some field data was obtained using abbreviated methods of analysis.

Metals in water were determined in essentially two different ways:-

(1) The use of complexing agents in the extraction, or direct estimation of predominantly ionic metal. The elements determined in this way were: Cu, Pb, Zn, Fe, Al and Si.

(2) Total metal by evaporation. The elements measured being Cu, Pb, Zn and Fe.

(a) Ionic Metal

Cu, Pb and Zn were extracted from water by repeated shaking with successive portions of 0.015% dithizone in carbon tetrachloride in the presence of sodium citrate buffer.

Fe was extracted with 8-hydroxyquinaline (dissolved in ethyl alcohol) by repeated shaking with successive portions of chloroform in the presence of a sodium acetate buffer.

Al was determined by means of aurin tricarboxylate, and Si by means of the yellow ammonium silico-molybdate complex (British Standards Institution, B.S.2690 : 1956 P.106 and P.43).

The metal determined by these methods would be unlikely to include that in non-ionic form, for example: metal

firmly held in organic complexes. However, some metal loosely held in complexes of this sort may be available to these reagents.

(b) Total Metal

500 ml. of water are evaporated in the presence of 30 ml. of acid mixture (prepared by mixing 1 part of 60% perchloric acid with 3 parts of conc. nitric acid) under a watch glass. The amount of acid mixture is calculated to just cover the bottom of the beaker when all the water has been evaporated. This procedure eliminates deposits on the walls of the vessel, and when the small volume of acid mixture remaining in the beaker is transferred to a container of more suitable size, no deposit is left on the base of the original beaker. The remaining solution is fumed to dryness and the residue taken up in 10 ml. of 0.5M. hydrochloric acid. Cu, Pb, Zn and Fe can then be determined on this solution.

(v) Methods of Estimation

The analytical techniques used in this study have been described in a number of publications and will, therefore, not be reproduced in this report. The elements and other properties that have been determined, together with the principles employed in their estimation are given in Table 8 with appropriate references.

The analytical work has been controlled by using a set of samples made up from a high and a low component. The mean precision of the results can be obtained by applying the statistical treatment proposed by Craven (1953-54). The results of analysis for Cu, Pb and Zn after fusion with potassium bisulphate, and for cx Cu constitute the basis data for this thesis. Accordingly the data referring to the precision and level of these results are given in Fig.10. The data (Fig.10) shows that the potassium bisulphate extractable metal results have a variation of less than $\pm$ 25% at the 95% confidence level (which are the accepted precision limits of the methods). Pb, however, at the lower limit of the method, in the range of 10-20 ppm has yielded results that lie outside the $\pm$ 25% limits. The precision of the cx Cu results fall well within the accepted limits of $\pm$ 30% at the 95% confidence level. Furthermore, even at the lower limit of the cx Cu method in the range of 0.5 to 2.5 ppm this precision has been maintained.

TABLE 8

List of Elements and Properties Determined, the Principles of their Estimation and Precision of the results, with appropriate references

TABLE 8 (Contd.)

Element of Property Determined	Principle of Estimation	Reference	Precision at the 95% confidence level
Cu	Colorimetric : 2.2' diquinolyl in anyl alcohol	A.G.R.G. Tet.Comm.23 (After H.Almond 1955)	± 25%
cx Cu	Colorimetric : Dithizone in Benzene	A.G.R.G. Tet.Comm.23 (After R.H.C.Holman 1956-57)	± 30%
Zn	Colorimetric : Dithizone in Benzene	A.G.R.G. Tet.Comm.30 (After R.E.Stanton 1962)	± 25%
cx Zn	Colorimetric : Dithizone in Benzene	A.G.R.G. Tet.Comm.31 (After R.H.C.Holman 1956-57)	± 30%
Pb	Colorimetric : Dithizone in Benzene	A.G.R.G. Tet.Comm.16 (After Geophysiques et Minieres 1957)	± 25%
Fe	Colorimetric : Thyoglycollic Acid	A.G.R.G. Tet.Comm. 40 (After E.B.Sandell 1959)	± 25%
As	Gutzeit method using mercuric chloride papers	A.G.R.G. Tet.Comm.49 (After R.E.Stanton 1964)	± 25%
Al	Colorimetric : Aurin Tricarboxylate	A.G.R.G. Provisional method (Brit.Stand.Inst.B.S. 2690 1956)	
Si	Colorimetric : Ammonium silicomolybdate	A.G.R.G. Provisional method (Brit.Stand.Inst.B.S. 2690 1956)	
Organic Carbon	Wet combustion method	A.G.R.G. Tet.Comm.32 (After C.J.Schollenberger 1927)	± 25%
Carbonate in Soil	Titration method	A.G.R.G. Provisional method (After C.S.Piper 1950)	
$SO_4^=$ in soil & water	Turbidometric estimation as barium sulphate	A.G.R.G. Tet.Comm.27 & 33 (After N.W.Scott 1955)	± 25%
CO_3 and HCO_3	Titration method	A.G.R.G. Tet.Comm.26 (After N.W.Scott 1955)	± 25%
pH and Eh	Analytical pH meter		

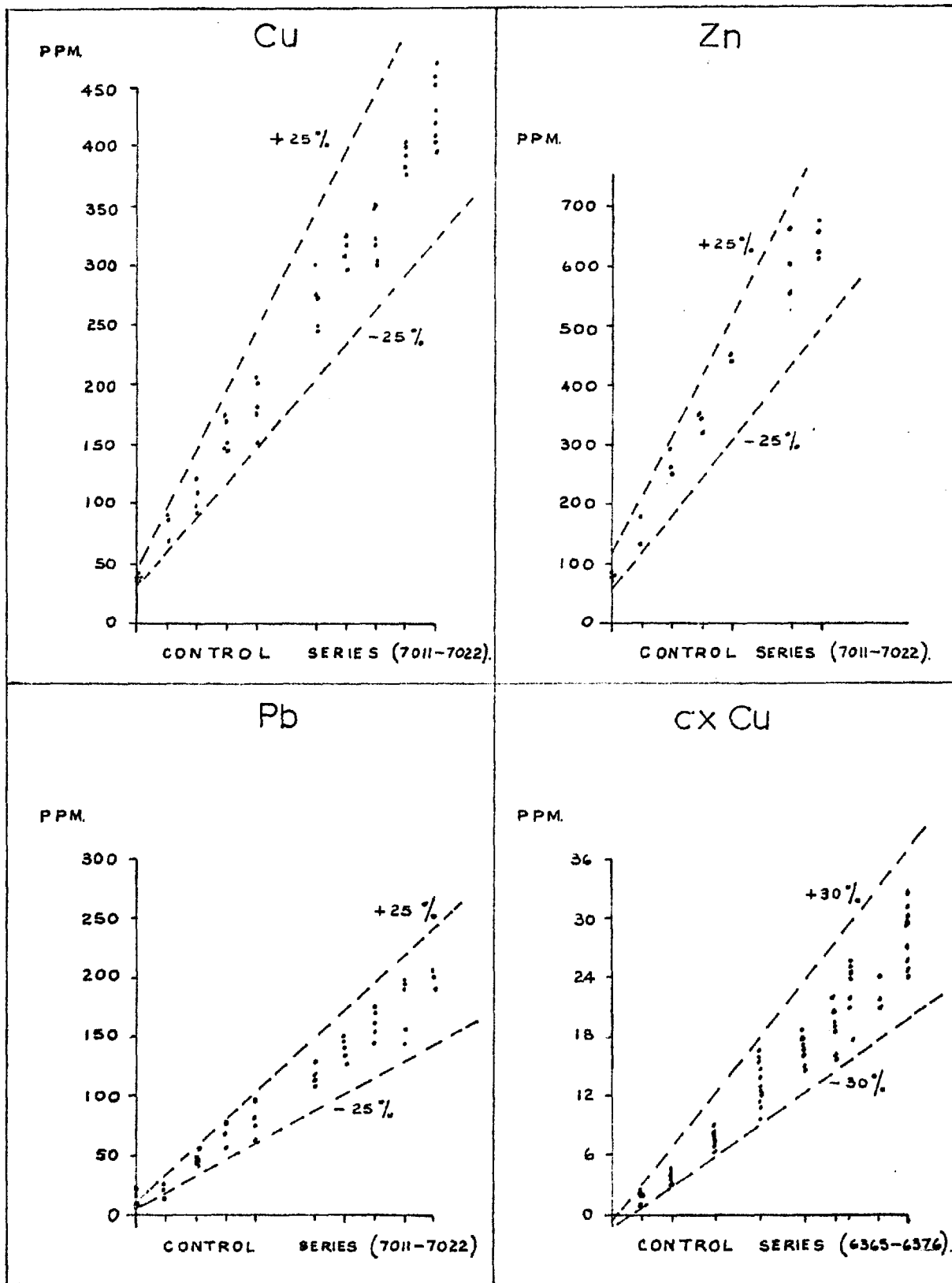


Fig.10. Graphical presentation of the precision obtained in the analysis of $KHSO_4$ extractable Cu, Zn, Pb and cold extractable Cu, during the course of the project.

PART III

GEOCHEMICAL RESULTS

SECTION A - PRIMARY DISPERSION

The primary dispersion study was centred on the Tverrefjellet orebody at Hjerkinn. The aims of the investigation may be summarised as follows:-

(1) To determine the nature and extent of the wall rock aureole around the ore.

(2) To obtain an understanding of the relationship between the ore and the zone of uneconomic mineralisation,
and -

(3) On the basis of (1) and (2), to investigate whether bedrock patterns have any application in prospecting for ore of Hjerkinn type.

The scope of the study was limited by the scarcity of outcrop and lack of suitable underground exposure. This was offset to some extent by the number of drill holes located in the ore zone. The data is exclusively derived from potassium bisulphate fusion of rock samples.

(i) Dispersion of Ore Elements in Rocks from Unmineralised (background) Areas.

A selection of 15 rock samples from unmineralised ground were analysed to evaluate the background ranges of Cu, Pb, Zn, Fe and As (Table 9). These samples include representatives of all major rock types occurring within the Hjerkinn area. Information obtained from diamond drill hole intersections in the ore zone at Hjerkinn indicates that there is a wide variety of gradational rock types within the amphibolite group. However, a low outcrop density in many unmineralised areas has limited the number of rock types available for sampling. Because of this it is not possible to give due consideration to all the lithological variations in the background range.

TABLE 9.

Background Variations in Rocks from the Hjerkinn Area
(Data on samples ground to -80 mesh)

Rock Type	No. of Samples	ppm				%
		Cu	Pb	Zn	As	Fe
Massive fine gr. amphibolite	4	10-120	10-30	100-170	5-12	2.9-5.0
Massive crse.gr. amphibolite	2	25-130	5	100-180	5	2.9-3.3
Amphibolite Schist	4	10-135	5-10	100-170	10	2.7-5.0
Quartz mica Schist	2	10-190	5-12	160-180	12	4.8-5.0
White Quartzite	3	0-20	5-10	80-180	5	1.7-5.5
Arithmetic mean values of 15 samples		50	10	140	8	4.5

Several types of amphibolite have been sampled which are distinguished by their texture (Table 9). These rocks have very similar contents of Pb, Zn, Fe and As which vary between narrow limits. There are large variations in the Cu content of these rocks however. The causes of these variations were not investigated but a number of untested explanations can be put forward. In particular, the amphibolites may be derived from the regional metamorphism of a number of rocks of differing composition including basic lava flows, argillaceous dolomitic beds and possibly marls.

In view of the lithological gradations that are known to be present, the mean values for the metals (Table 9), may be most representative of the regional background level. The validity of this concept was tested by comparing the mean values with the average base metal content of ground moraine from unmineralised localities in the Hjerkinn area (Table 10). The ground moraine provides an almost ideal bulk sample of the rocks from which it was derived and as demonstrated later, there is little weathering of the deeper moraine. Goldschmidt (1954) has demonstrated the applicability of this principle in southern Norway.

TABLE 10

Comparison of the Average Base Metal Content of Ground Moraine from the Hjerkinn Area With the Mean Values of the Unmineralised Bedrock from which it was derived.

(Material sieved or ground to -80 mesh, and analysis after $KHSO_4$ fusion.)

	ppm			No. of Samples
	Cu	Pb	Zn	
Mean values for unmineralised bedrock	50	10	140	15
Average values in background ground moraine	60	10	150	66

The agreement between the two sets of data suggests that for a first approximation the mean values for the base metals may be regarded as the regional background levels for rocks in the Hjerkinn area.

(ii) Geochemical Patterns within the Mineralized zone at Tverrefjellet

The mineralised zone at Tverrefjellet has been described in part I of this report. A summary of the salient features is given below.

The ore has an average thickness of 10m. and occurs within a zone 1,000m. long oriented east-west in conformity with the enclosing greenstones. This zone contains two offset steeply dipping ore bodies which plunge at 45° to 50° east (Fig.16). The north body lies directly on strike of the uneconomic mineralised horizon and contains ore of lower grade than that of the south body (Table 1). The uneconomic mineralised horizon which is 0.5m thick is intercalated in rocks of the greenstone group and can be traced over a strike length of 10 Km.

(a). Wallrock Dispersion Patterns.

The ore zone was examined along its strike in the cores of five drill holes which were collared at surface and inclined at 45°. In the south ore body the drill holes selected were, from west to east, 21, 4, 3, and 2 (Fig.16). Drill hole 21 is located on the western

extension of the body where the mineralisation is thin and uneconomic. Bore holes 4 and 3 intersect the western part of the ore which occurs below a conspicuous surface cavity; the result of oxidation and collapse of the leached ore near surface. Drill hole 2 is located near the eastern termination of the ore at sub-outcrop.

The dispersion patterns in the wall rocks around the north orebody were examined in drill hole 5 (Fig.16).

The intersections show that the contact between the ore and the wall rocks is generally well defined, and there are no macroscopic features indicative of wall rock alteration. Insignificant mineralised sections occur in the country rock at variable distances from the ore.

Diamond drill hole sections 21, 4, 3, 2 and 5 showing the geochemical dispersion patterns of Cu, Pb, Zn and Fe appear in Figs. 11, 12, 13, 14 and 15. In order to comment on the data, arbitary upper background levels for the metals have been selected (Table 11), based on the data of the background study.

Table 11. Arbitary Upper Background Levels of Cu, Pb, Zn, Fe and As in Rocks of the Hjerkinn Area. (Data on rocks ground to - 80 mesh.).

Metal	Arbitary Upper Background Level.
Cu	150 ppm.
Pb	25 ppm
Zn	200 ppm
As	12 ppm
Fe	5.5 %

The main geological and geochemical features noted in the borehole sections are as follows:-

(i) Wall rock Dispersion Patterns on the Western Extension of the Ore Zone.

On the western extension of the ore, sub-economic mineralisation 0.5 m. thick is intersected in borehole 21 (Fig.11). The mineralisation is contained within a series of amphibolites which tend to be more siliceous in the north wall of the mineralised zone than in the south wall. In the south quartz mica schists are intersected near to the collar of the hole. In these wall rocks Fe and Zn form broadly coincident aureoles which are characterised by homogeneous values. The Fe

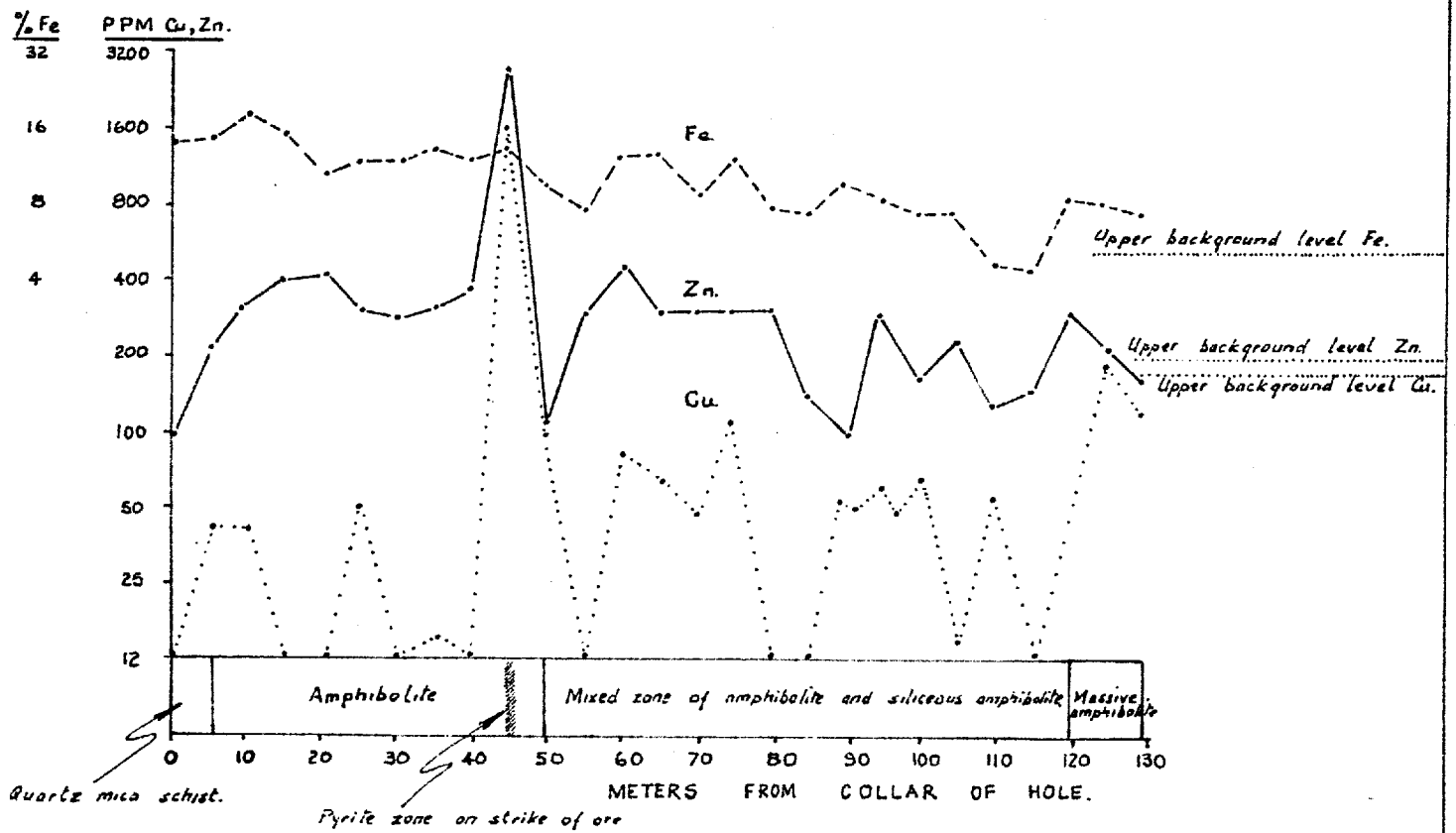


Fig.11. Wall rock dispersion patterns, around the uneconomic mineralisation on the western extension of the Tverrefjellet South orebody—diamond drill hole 21. (Data on rocks crushed and ground to -80 mesh).

values vary between 1.5 and 3 times the upper background level, and decrease towards the north. There are no peak Fe values coinciding with the mineralised horizon, and the characteristic feature of the Fe enrichment is its pervasive nature. The elevated Fe values occur over a width of 100 m. and the highest values are recorded in the quartz mica schist.

Zn is concentrated in the mineralised zone to 3,000 ppm, and forms an aureole 30 m. wide on either side of this horizon. Within the aureole Zn values vary between 300 and 500 ppm (1.5 to 2 times the upper background level). In the south wall of the mineralisation the Zn values decrease to background at the contact with the quartz mica schist. In the north wall Zn is more erratic especially beyond the limits of the aureole, where the values approach background.

In contrast to the dispersion patterns of Fe and Zn, Cu is enriched only within the sulphide zone (1800 ppm), and outside this zone the Cu values are in the background range (10 - 180 ppm). Pb and As have no anomalous pattern either in the mineralised horizon or its wall rocks.

(2) Wallrock Dispersion Patterns about the Ore.

In the west, the south ore body is enclosed by amphibolites (borehole 4 and 3, Figs. 12 and 13). Towards

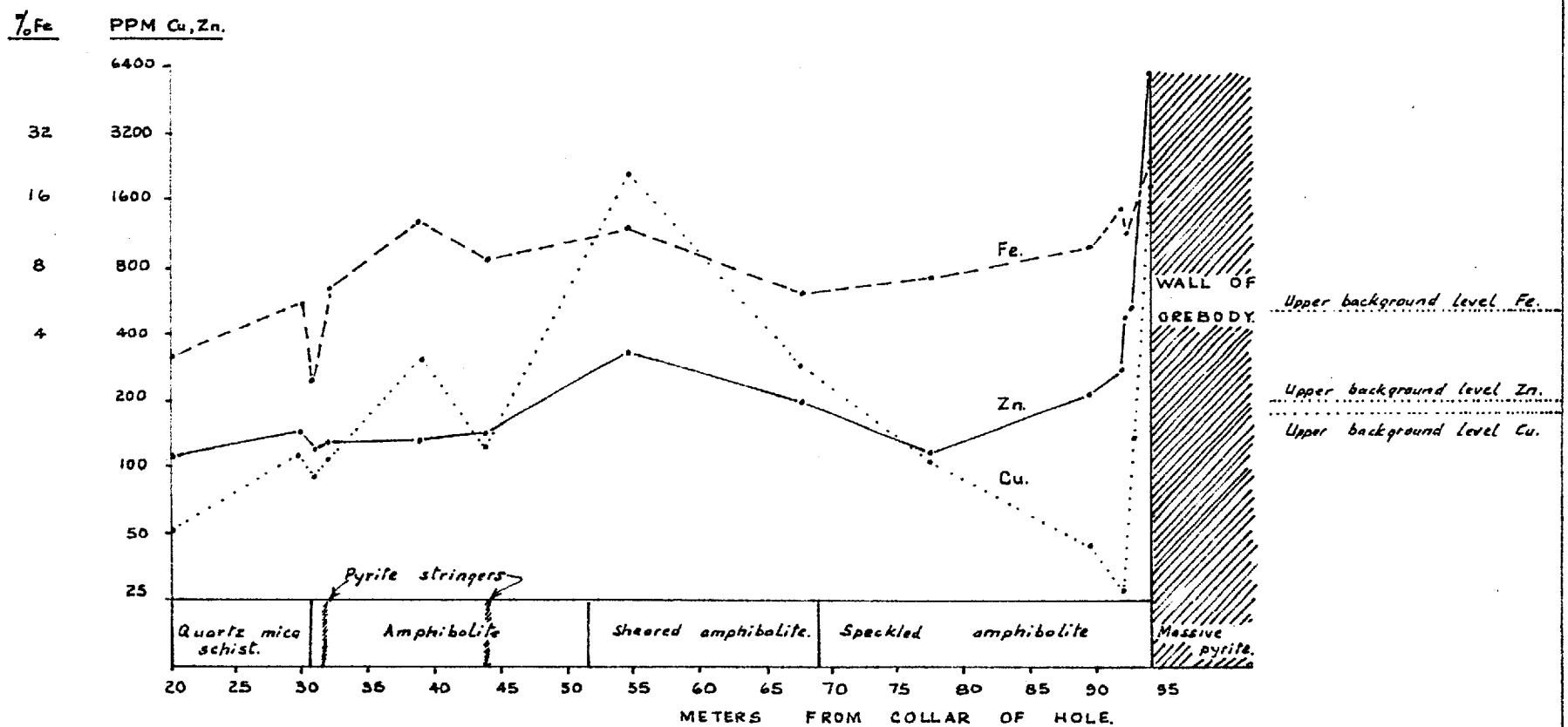


Fig.12. Wall rock dispersion patterns, diamond drill hole 4, Tverrefjellet mine. (Data on rock crushed and ground to -80 mesh).

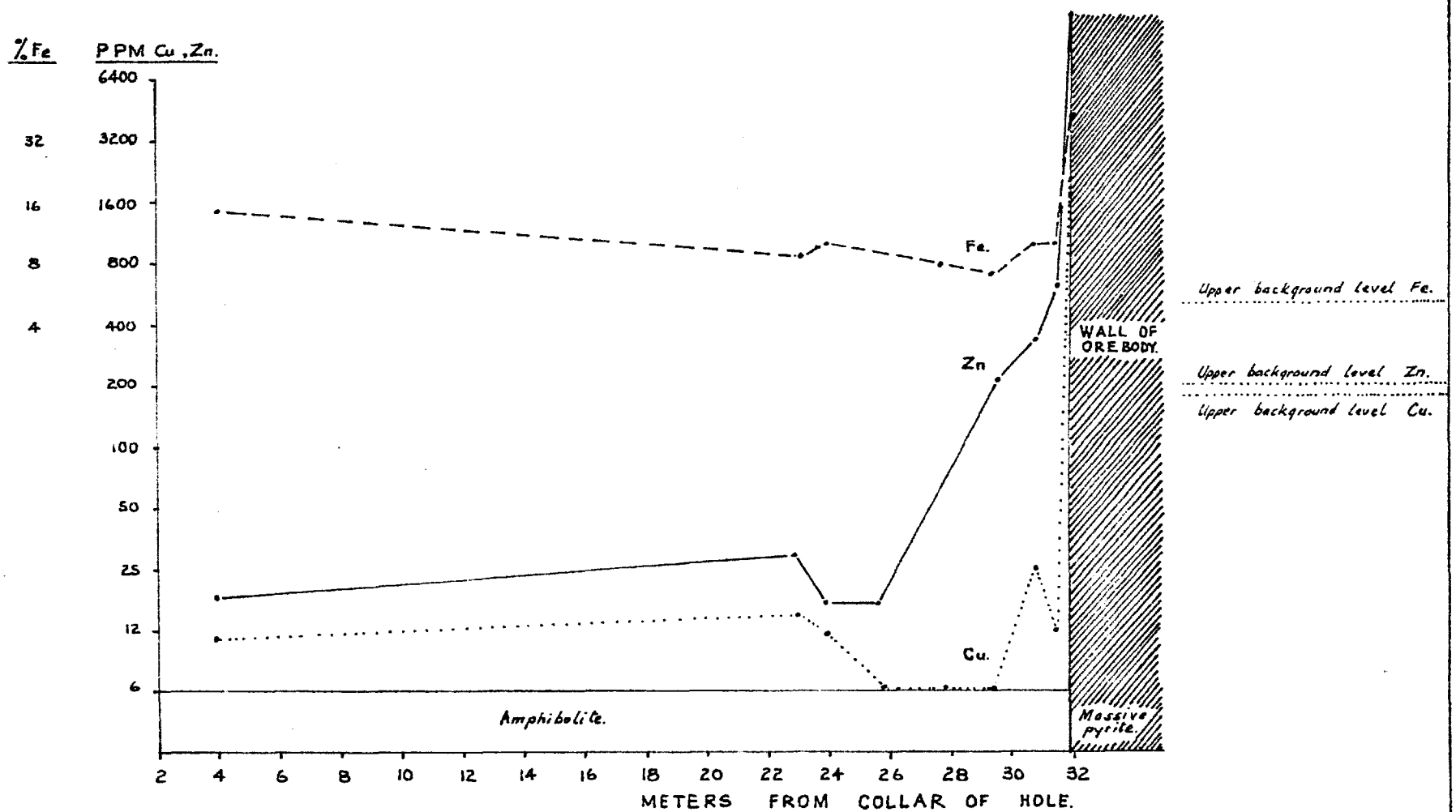


Fig. 13. Wall rock dispersion patterns, diamond drill hole 3., Tverrefjellet mine. (Data on rock crushed and ground to -80 mesh).

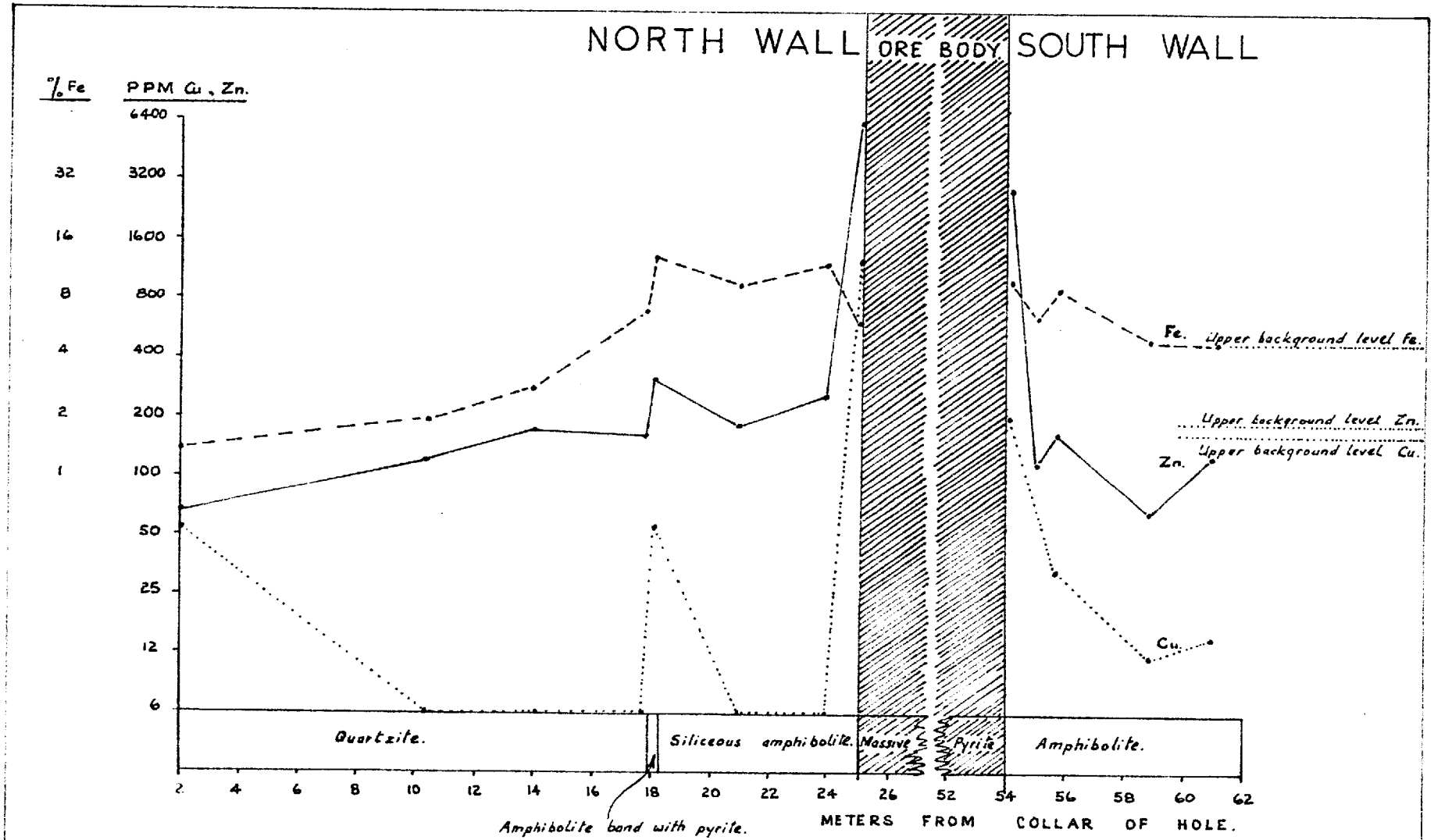


Fig. 14. Wall rock dispersion patterns, diamond drill hole 2, Tverrefjellet mine. (Data on rock crushed and ground to -80 mesh).

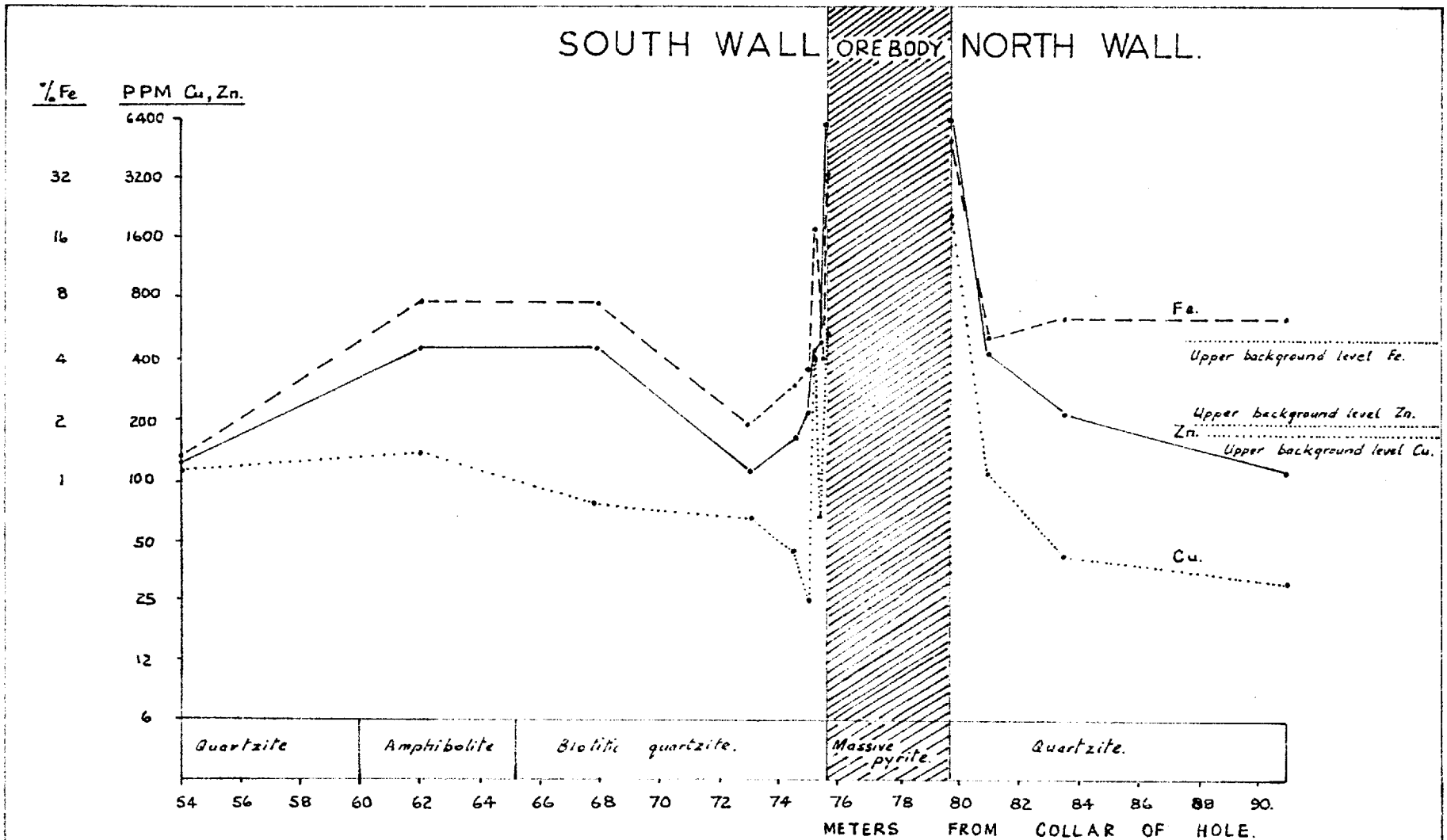


Fig.I5. Wall rock dispersion patterns, diamond drill hole 5, Tverreffellet Mine. (Data on rock crushed and ground to -80 mesh.)

the east quartzite horizons are prominently developed in the north wall of the ore body (borehole 2, Fig.14). Further to the east, the north orebody is confined within rocks predominantly consisting of quartzite, with subordinate amphibolite bands (borehole 5, Fig.15). The wall rocks of this ore zone therefore become more siliceous towards the east.

The aureoles developed about the ore contain Fe and Zn. Cu, Pb and As are generally enriched only within the ore, and in the wall rocks these elements are usually present in concentrations characteristic of the background range.

The Zn aureole was never found to be greater than 7m. in width, and in general is approximately 2m. wide. The values decrease sharply with distance from the ore, and in borehole 4 (Fig.12) Zn values follow a logarithmic decay curve.

Fe tends to behave like Zn (borehole 2, Fig.14), but in the amphibolitic rocks cut by boreholes 3 and 4 an extensive Fe anomaly has developed independantly of the base metals (Figs. 12 and 13). The Fe values vary between 1.5 and 3 times the upper background level. A similar

pattern is developed in the siliceous rocks in the north wall of the north ore body cut by borehole 5 (Fig. 15). However, in the south wall of the ore intersected in this borehole, Fe and Zn vary sympathetically and form an anomalous pattern 7m. wide. In this section the Fe and Zn values rise to 1.5 and 2 times the upper background level respectively. The elevated values are separated from the ore by a zone of background values 3m. in width. The high values are associated with a greenstone horizon which passes into biotitic quartzite and finally to quartzite towards the ore. The weakly anomalous dispersion of Fe and Zn over this section, may therefore be related to the lithology.

In the wall rocks intersected in borehole 4 (Fig. 12) two thin zones of disseminated pyrite occur in the amphibolites. The disseminated mineralisation is located in the south wall, 60 m. away from the ore, and is characterised by background values of the base metals. In the same wall rock section the amphibolites are strongly sheared at a point 40 m. from the ore. The sheared amphibolites were found to be enriched in Cu to

a maximum of 2400 ppm, and in Zn to 340 ppm (12 and 1.7 times the upper background level, respectively).

Analysis of Ore Samples after Fusion with Potassium Bisulphate.

The assay data of the Folldal Verk A/S provides the basis for comparison of the two ore bodies (Table 1), and shows that the south body contains the highest grade ore. Table 12 gives some additional information on the metal content of the ore after fusion with potassium bisulphate.

TABLE 12

Analysis of Ore after Fusion with Potassium Bisulphate

Number of Samples 30.	F. P. M.				%
	Cu	Zn	Pb	As	Fe
Minimum	105		45	65	16
Average	2,400	+10,000	500	150	32
Maximum	20,000		2,500	240	40

The orebodies plunge to the east, but the mineralisation at sub-outcrop continues for at least 10 Km. in this direction as a layer of uneconomic sulphides 0.5 m. thick. In this connection it should be

noted that the uneconomic sulphides lie directly on strike of the north ore body. Furthermore, the south body which contains the highest grade ore occurs at the western end of the ore zone. The mineralisation therefore tends to increase in grade towards the west.

Bedrock patterns around the uneconomic sulphide layer were examined to obtain an understanding of its relationship to the ore.

(b) Bedrock Patterns Associated with the Zone of Uneconomic Mineralisation.

The uneconomic sulphide zone was examined over a strike length of 2 Km. from the vicinity of the road and railway cuttings in the east, to the point where the north ore body occurs at sub-outcrop in the west (Fig. 16).

The road cutting exposes a series of amphibolites with intercated bands of quartzite and quartz mica schist. The sulphide mineralisation is restricted to a narrow zone 0.5 m. wide and is associated with a thin magnetite bearing quartzite. The analysis of rock chips taken across the strike reveals a pattern of metal distribution in which Fe and Zn occur slightly in excess of the upper background levels, (i.e. 5.5% Fe and 200 ppm Zn). The northern limit of the aureole was not detected because of

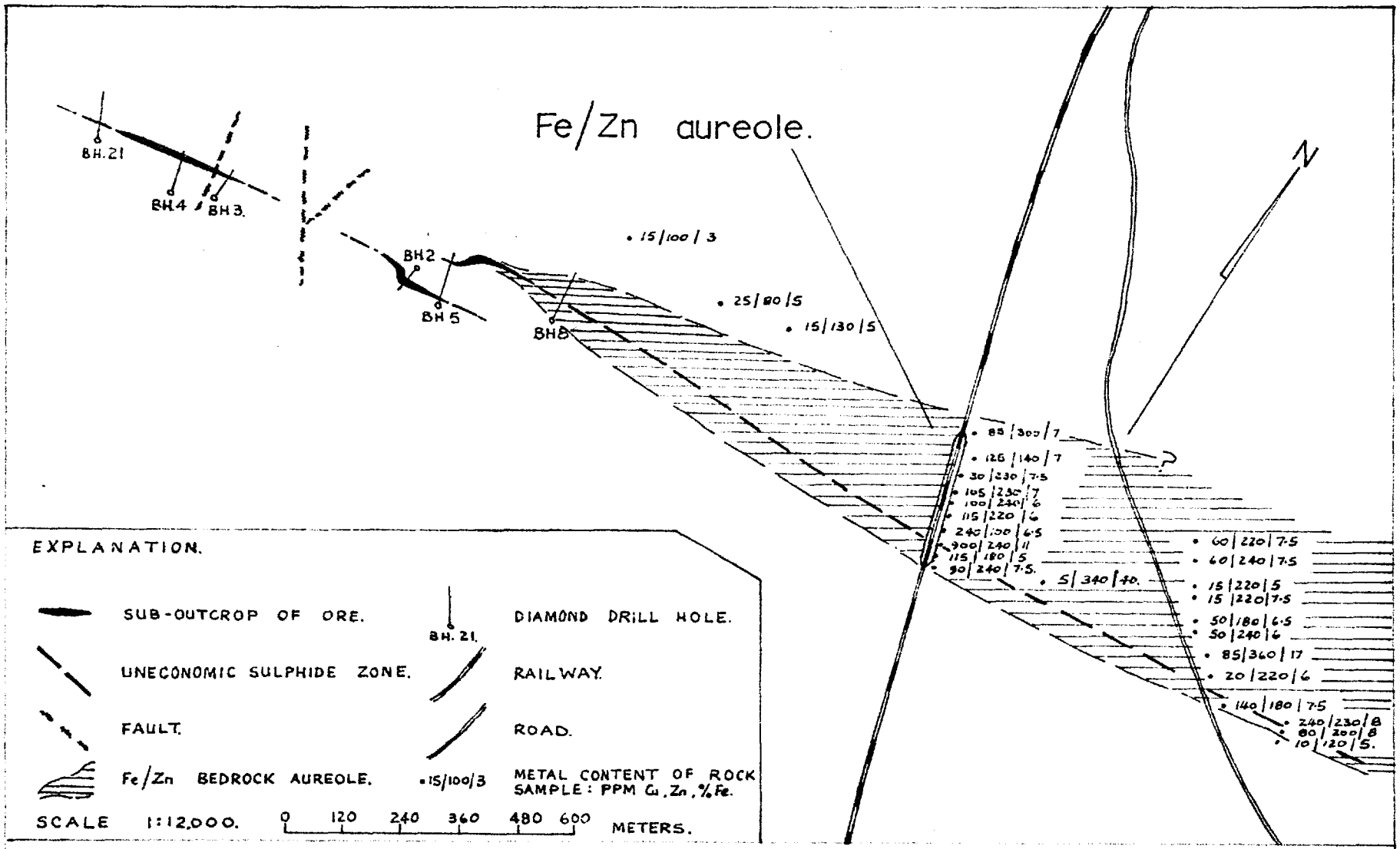


Fig.16. Plan showing the Fe/Zn aureole in the bedrock surrounding the uneconomic sulphide zone, and the location of the drill holes studied. (Data on rocks crushed and ground to -80 mesh.)

lack of outcrop. Elevated Cu values are present only within the narrow sulphide zone which occurs near to the southern margin of the Fe - Zn aureole. The maximum Cu value in this zone is 240 ppm which is 1.7 times the upper background level.

In the railway cutting which exposes the same rocks some 650m. west of the road cutting, a similar pattern is present. In this locality the Fe - Zn aureole is 350m. wide and is again defined by values that are just above the upper background level. Anomalous Cu values are restricted to the sulphide zone where values reach a maximum of 900 ppm. It is of interest to note that Pb and As are essentially absent from the sulphide zone and from the surrounding Fe - Zn aureole.

Further west, borehole 8 intersects the rocks lying above the north ore body which at this position is plunging at 45° to the east. The hole intersects a series of sheared amphibolites which contain thin bands of quartzite. Within this sequence are two narrow zones of disseminated pyrite (Fig.17). Fe, Zn and Cu values are very erratic with peak values varying between 1.5 and 3 times the upper background level. In general the Fe

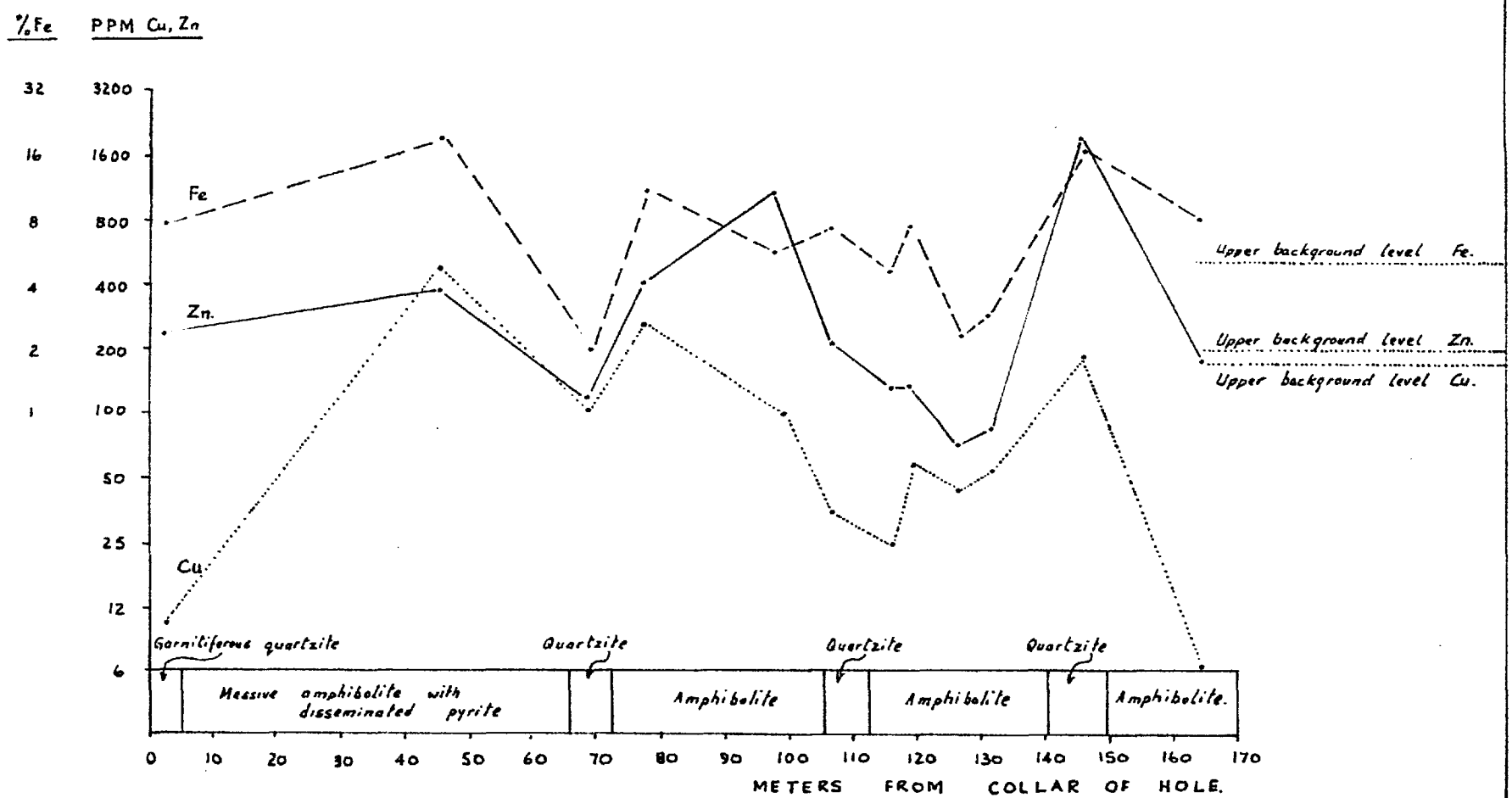


Fig.I7. Bedrock dispersion patterns, diamond drill hole 8, Tverrefjellet Mine.
(Data on rocks crushed and ground to -80 mesh.)

and Zn values are erratically anomalous over the 160 m. section, whilst elevated Cu values are of more restricted occurrence being concentrated in the rocks immediately above the ore.

(iii) Discussion

In the wall rocks of the ore, one section showed Zn to decrease logarithmically. Patterns of this type are thought to indicate a diffusion mechanism (Lovering and Morris et al). In the Tintic district, Utah, Morris (1952) showed that Cu, Pb and Zn decrease logarithmically in the wall rocks of certain hydrothermal deposits. Morris found that significant wall rock dispersions of the base metals were present in both siliceous and dolomitic environments, but were more restricted in dolomites, being confined to within 10 feet of the ore. Cu and Pb appear to have been largely immobile in the siliceous environment of the primary zone at Hjerkinn. However, Zn forms are aureole which is generally confined to within 2 m. of the ore, and Fe tends to be associated with it. In this connection it is of interest to note that the more extensive Fe anomaly which is present in the rocks cut by bore holes 3 and 4 may not be a primary feature. As previously mentioned, these drill holes interesect the ore which, nearer to surface, is strongly

oxidised. It is, therefore, possible that much of the Fe in the rocks below this zone is of secondary origin. The base metals, however, show no apparent secondary enrichment.

Outside the ore zone where the mineralisation is thin and uneconomic, the aureoles in the bedrock are again confined to low order dispersions of Zn and Fe. However, these aureoles are much more extensive than the patterns developed about the ore. In the rocks surrounding the uneconomic zone along strike of the ore to the east the Fe - Zn aureole increases in width and decreases in intensity with distance from the ore. The introduction of the Cu into this zone which increases on approach to the ore, must rank as major features of the metallisation.

The uneconomic zone along strike of the ore to the east is bedded with the amphibolites and is associated with a magnetite bearing quartzite. Similar uneconomic horizons are of frequent occurrence within the greenstone rocks of the Trondheim basin, and are generally held to be of sedimentary origin (Carstens, Vokes, Vogt and others). It is probable, therefore, that this zone at Hjerkinn is also a sedimentary feature.

The geochemical patterns suggest that the ore and the uneconomic sulphide zone are inter-related. This may be

regarded as evidence that they have a common origin. Equally, it can be postulated that the Fe/Zn aureoles developed during metamorphism after emplacement of the ore. The fact that the ore is structurally controlled indicates a third factor which may have been important in the development of the bedrock dispersion patterns. Clearly there is a need for more data before any well founded conclusions can be made regarding the origin of the ore and its relationship with the uneconomic bedded sulphide zone.

(iv) Practical Applications of the Primary Dispersion Study

Of practical importance to the present study are the narrow limits to which the ore and dispersed ore elements in the wall rocks surrounding the ore, are confined. This has important implications when considering the secondary dispersion of ore elements in the glacial overburden.

The uneconomic sulphide zones at Hjerkinn and Folldal are intimately associated with economic accumulations of sulphide ore. There is no obvious pattern of occurrence of the orebodies which appear apparently at random along these zones. At Hjerkinn it has been shown that bedrock aureoles containing Fe and Zn are developed about the uneconomic sulphides. The aureole increases in intensity

and decreases in width towards the ore. In addition the bedded uneconomic pyrite contains Pb and As in the background concentration range. If these patterns are general then a study of bedrock geochemical patterns around similar zones elsewhere in the area may constitute a valuable ancillary guide to ore.

SECTION B SECONDARY DISPERSION

In strongly glaciated terrain such as Norway the dispersion of ore elements in the zone of oxidation and weathering may take place as a result of three major processes, namely:

(1) mechanical dispersion of ice eroded ore minerals,

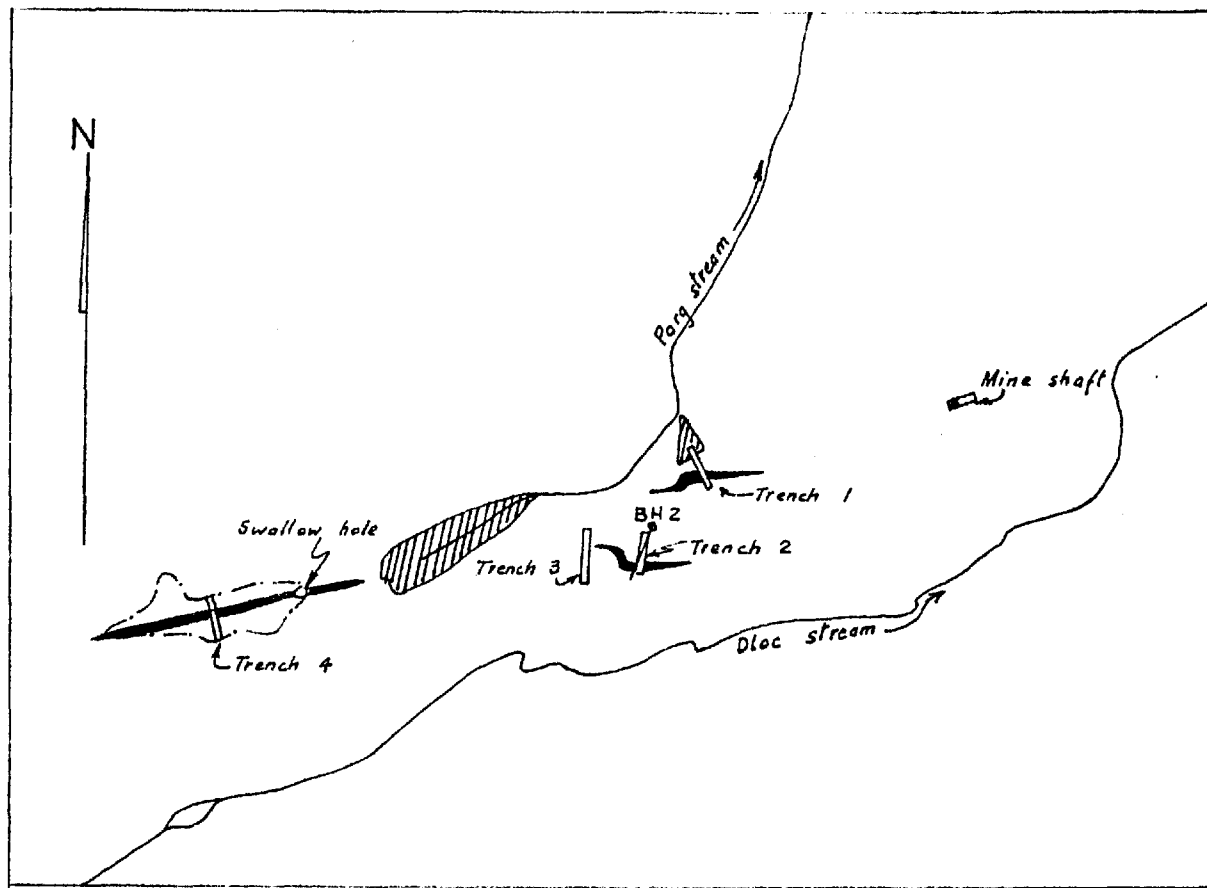
(2) hydrogeochemical dispersion following chemical decomposition of sub-outcropping mineralisation,

and

(3) biogeochemical dispersion.

In the following pages data is presented on the secondary dispersion of ore elements in the overburden, vegetation, groundwaters, stream waters and stream sediments. This data is discussed in terms of the mechanisms controlling the dispersion patterns in the various media investigated.

The Tverrefjellet orebody and surrounding district was selected as a type area for a detailed study. Less detailed comparative studies were undertaken around



EXPLANATION.

SUB-OUTCROP OF ORE.

COLLAPSED STRUCTURE OVER OXIDISED ORE.

SECONDARY IRON OXIDES CEMENTING THE MORAINE.

BH.2 DIAMOND DRILL HOLE 2.

TRENCH SITE.

SCALE 1: 10,000.

0 100 200 300 400 500 METERS.

Fig.18. Plan showing some surface features and the location of trenches at Tverrefjellet.

occurrences of cupriferous sulphide mineralisation in the Folldal area. The location of these areas is shown in Fig. 1, and detailed maps of the individual areas appear as Figs. 18, 34, 36 and 38.

Evidence for Post-glacial Oxidation of the Sub-outcropping Ore

At Tverrefjellet drill hole intersections show that the ore is strongly oxidised to a depth of 10 metres below its sub-outcrop. In the western part of the ore zone a conspicuous topographic depression coincides with the sub-outcrop of the ore (Fig.18). At the lowest point of the depression which occurs at the eastern end, there is a swallow hole. The swallow hole at about 10 metres below the surface leads to a slope-like opening which is inclined dipping at 35° to the east, and striking approximately north-south. This plane when extended to lower levels joins a fracture zone exposed in the underground workings. The underground cavity, therefore, appears to be a solution fissure along a fault plane. There is no evidence that the topographic depression is the result of ancient mining activities, and indeed the occurrence of a considerable thickness of moraine within the depression (trench 4) makes this extremely improbable.

Immediately downslope of the depression there is a mass of secondary iron oxides in the moraine (Fig.18). The oxides cement the overburden and the resultant product resembles a ferruginous conglomerate which grades into normal moraine on its boundaries. The source of the Fe must be the oxidising orebody, and since the mass is clearly in situ it indicates that the orebody has undergone significant oxidation in post-glacial times.

At Tverrefjellet the depression with its swallow hole overlies ore which is open to rapid oxidation. It is possible that these conditions are not typical of pyrite orebodies elsewhere in the area. In order to obtain more specific information on this point, the Grimsdal orebody in the Folldal area was visited.

The Grimsdal deposit sub-outcrops below a thin cover of moraine and has been exposed in several places by mining activities. In a mine shaft which has been in existence for only two years the ore is seen to be strongly oxidised for at least 5 metres below its sub-outcrop. Evidence for the usual low rate of oxidation is provided by blocks of fresh ore brought from the underground workings and dumped in the stream at Grimsdal which show only slight traces of "rusty" weathering.

Also at Grimsdal, where the orebody sub-outcrops on a hill side there is a secondary iron oxide deposit occurring above the orebody and extending downslope. Of particular significance is the fact that the secondary iron oxides cement the moraine which overlies the orebody.

In connection with the oxidation of the Hjerkinn - Folldal orebodies, ice transported ore boulders found in the moraine are composed of essentially fresh sulphides except for a film of "rusty" weathering. The stability of sulphide ore in the zone of weathering and oxidation, therefore, seems to be related partly to local variations in the environment. In particular it is probable that the extent of oxidation is largely controlled by the ability of aerated groundwaters to come into contact with the sulphides. In other words, it appears probable that despite the argillaceous nature of the overburden, aerated groundwaters are able to penetrate to the bedrock-moraine interface in significant volumes.

There is some evidence to suggest that the degree of oxidation of sulphide ore is related to the occurrence of the bacteria Thiobacillus ferro-oxidans (Lyalikova,1962) Groundwaters may or may not be suitable for this bacteria, and is a further factor warranting consideration.

Dating of the Weathering Zones

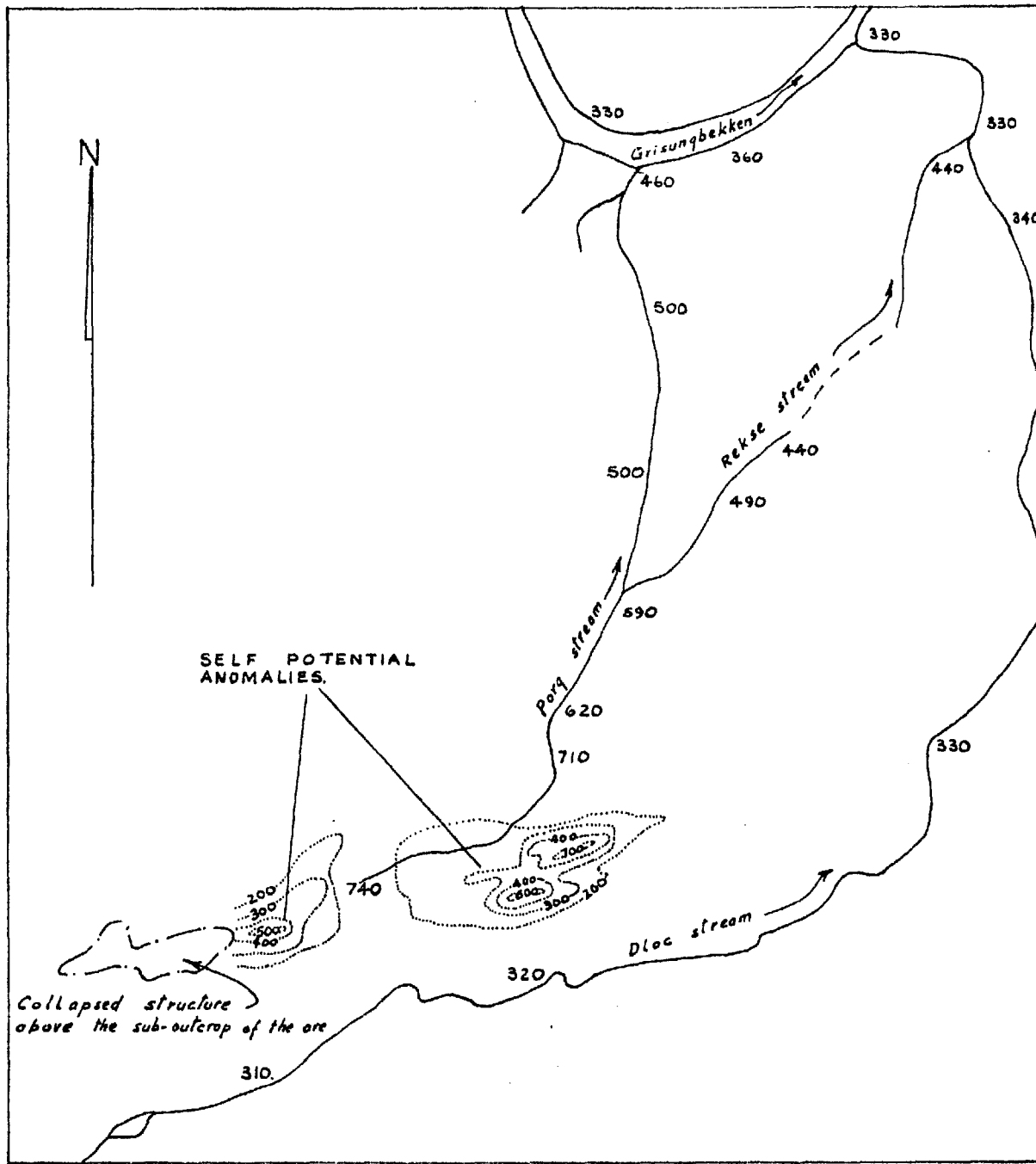
The Tverrefjellet and Grimsdal orebodies may have been oxidised in pre-glacial times, but such products of weathering would be readily removed by the ice. That the orebodies have undergone significant oxidation in post-glacial times is clearly indicated by the secondary iron oxides which cement the moraine in the vicinity of sub-outcropping ore. However, at Tverrefjellet it is possible to show that the ore is presently undergoing oxidation from two lines of investigation:-

(a) self potential survey done by the Norges Geologiske Undersökelse (N.G.U.)

and

(b) Eh measurements in groundwaters obtained by the writer.

The self potential anomalies defined by the N.G.U. indicate that the ore is undergoing oxidation at three centres (Fig.19). In groundwaters rising downslope of the orebody, Eh measurements of 740 mv were recorded in waters having a pH of 2.7. The Eh measurements possibly reflect the oxidation of Fe^{2+} to Fe^{3+}. At a pH of 3.0 the Eh of the reaction: $Fe^{2+} + OH \rightleftharpoons Fe(OH)^{2+} - e$ can be calculated on thermodynamic principles to be 732 mv. This supports the view that the Eh is a result of the oxidation of divalent Fe deriving from the breakdown of pyrite.



EXPLANATION.

540 Eh OF STREAM WATER (m.v.).

400 SELF POTENTIAL (m.v.). (Measured by the Norge Geologiske Undersøkelse).

SCALE 1 : 10,000.

0 100 200 300 400 500 METERS.

Fig.19. Plan showing the self potential anomalies over the sub-outcrop of the orebody at Tverrefjellet, and the Eh values in the stream waters.

Chemical Changes due to Oxidation and Weathering of Sub-outcropping Ore

In a series of trenches that were excavated to bedrock over the orezone at Tverrefjellet (Fig.18), trench 2 was the only transect in which a reasonable exposure of the bedrock was achieved. This trench is in a location which is devoid of the features which characterise the depression area where the ore is open to rapid oxidation. It is probable that the conditions found in trench 2 are more typical of oxidising pyritic orebodies elsewhere in the area. This transect is especially valuable because it is possible to make a direct comparison between fresh ore and rock in borehole 2, with the same material in the zone of weathering and oxidation exposed in the trench immediately above the line of the drill hole.

This trench exposed a material having a sponge-like appearance and consisting of a skeletal mass of quartz heavily charged with brown secondary iron oxide. Analysis of this material shows high concentrations of Cu, Pb, Zn and Fe indicating that it is oxidised ore in which primary sulphide minerals appear to be totally lacking. Comparison with the fresh ore in borehole 2 shows it to be impoverished in base metals, except Pb, probably as a result of extensive but incomplete leaching. Wallrock in the zone of weathering which was exposed downslope of the orebody

contains background concentrations of Pb whilst the same rocks are heavily impregnated with Zn, and to a lesser extent Fe and Cu as compared to the wallrocks in drill hole 2 (Figs. 20, 21 and Table 13).

TABLE 13.

Comparison of the Metal Content of Fresh Ore and Rock in Drill Hole 2, with the same Material in the Zone of Oxidation and Weathering in Trench 2. (Data on rock material ground to -80 mesh, and analysis after $KHSO_4$ fusion).

Metal	Average val. Fresh Ore (Borehole 2) ppm	Max. Value of Oxidised Ore (Trench 2) ppm	Average Content Fresh Wall Rock (Borehole 2) ppm	Average Content of Wallrock from Zone of Weathering Down-slope of Ore (Trench 2) ppm
Zn	+ 10,000	1,400	150	1,600
Cu	6,500	3,200	15	100
Pb	1,600	1,500	6	6
Fe	400,000	320,000	100,000	100,000

The secondary enrichment in base metals of the sub-outcropping wallrocks downslope of the orebody, is most probably due to groundwaters percolating through the weathered rock surface.

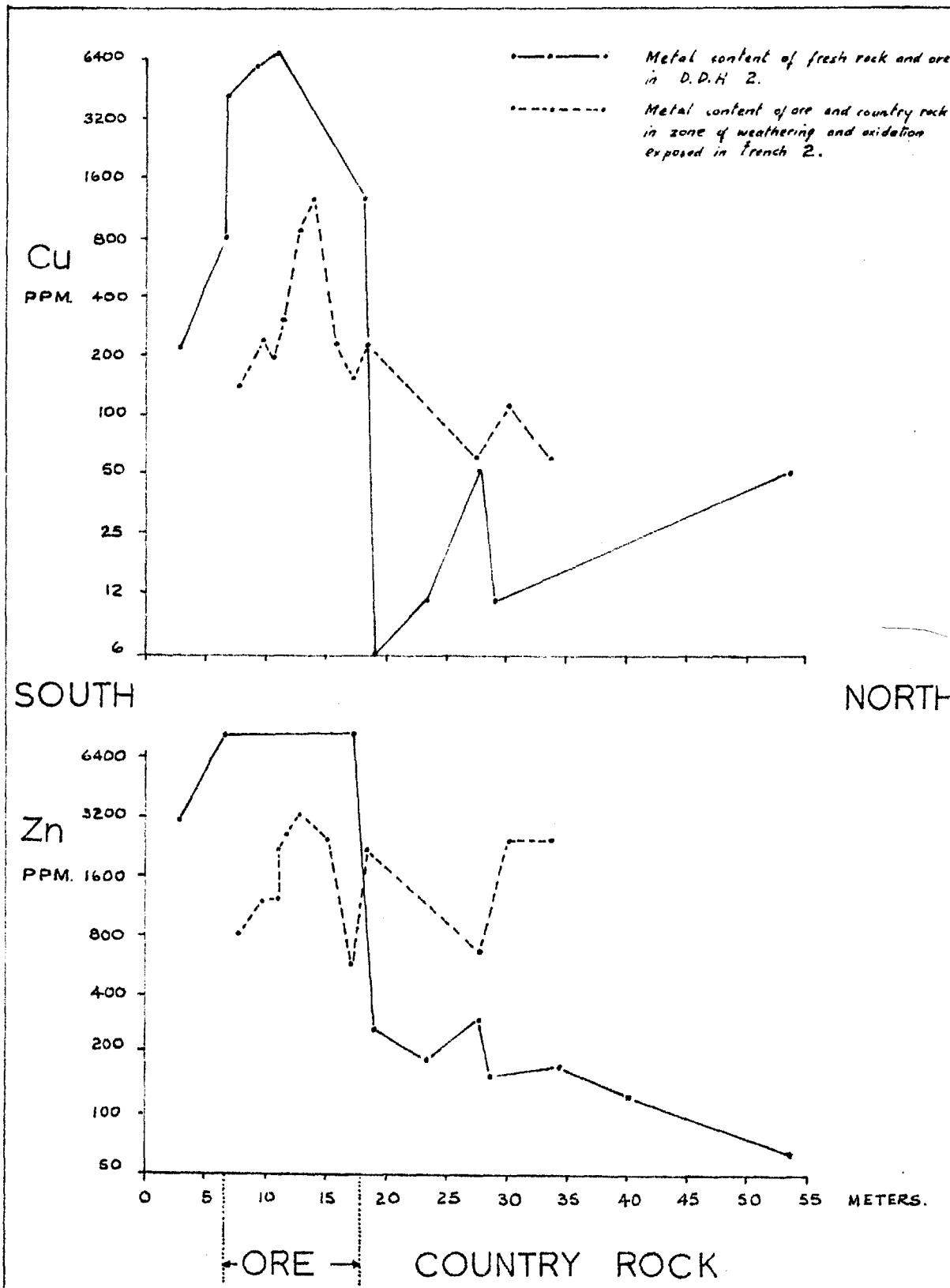


Fig.20. Graphs comparing the Cu and Zn contents of the fresh ore and country rock in diamond drill hole 2 with the corresponding material in the zone of oxidation exposed in trench 2, Tverrefjellet. (Data on rocks ground to -80 mesh.)

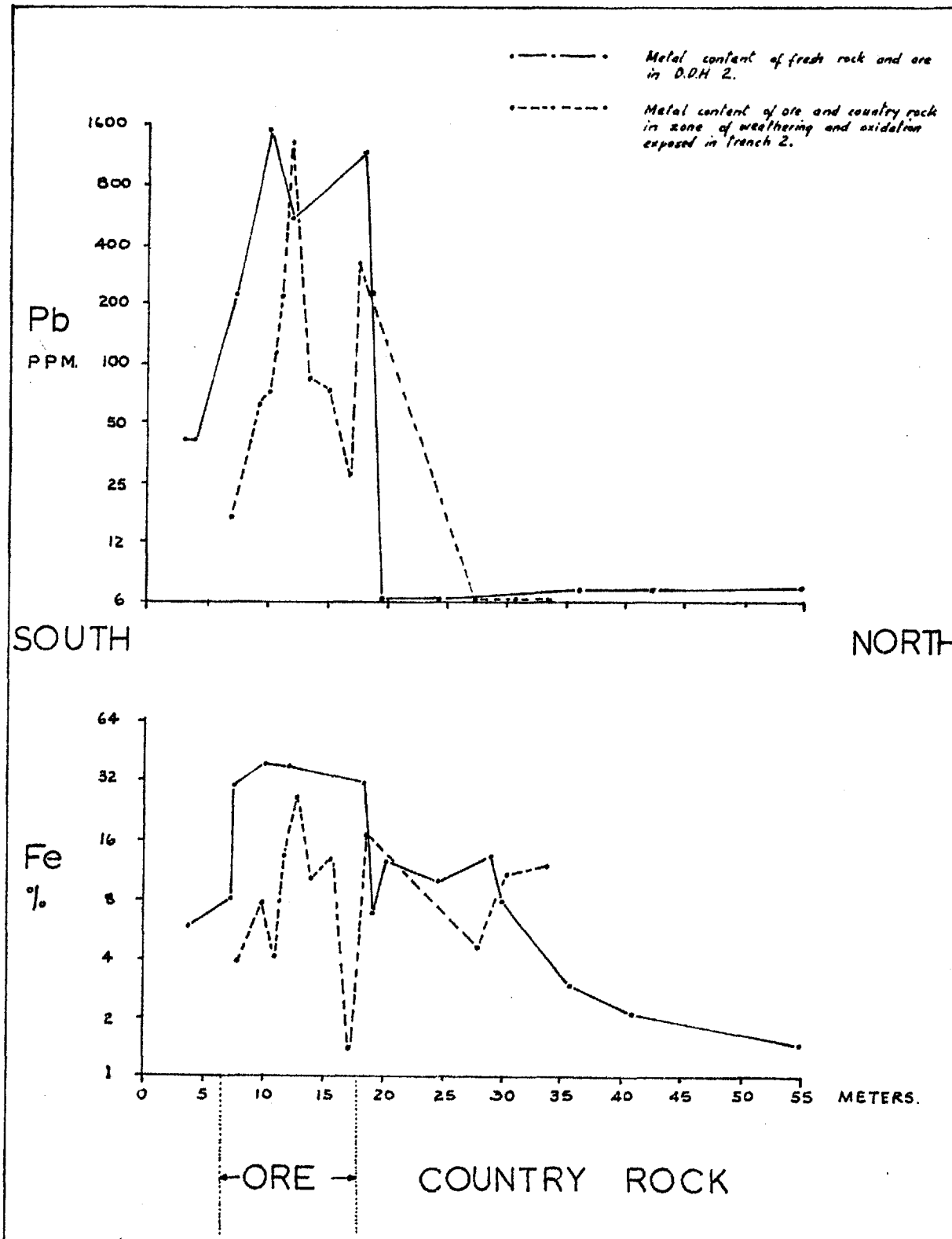


Fig.2I. Graphs comparing the Pb and Fe contents of the fresh ore and country rock in diamond drill hole 3 with the corresponding material in the zone of oxidation exposed in trench 3, Tverrefjellet.
(Data on rocks ground to -80 mesh.)

OBSERVED DISPERSION OF ORE ELEMENTS IN THE OVERBURDEN (excluding bogs) IN UNMINERALISED (BACKGROUND) AREAS

A detailed account of the moraine has been given in Part I of this report. In summary, the main types of glacial deposit are:-

(a) ground moraine: average 3 m. thick, of widespread occurrence.

(b) Ablation moraine: occurring as mounds and sheets on top of the ground moraine.

(c) Glacio-fluvial deposits: of restricted occurrence.

The ground and ablation moraine are the most widespread and overlie all the orebodies that were examined. Accordingly, these materials have received the most detailed study.

In the Hjerkinn area two locations underlain by barren rocks of the greenstone group, were selected for a background study of the geochemistry of the overburden. The background locations designated "A" and "B" (Fig.22) are both freely drained and are situated on gentle hill slopes above the tree line. The vegetation is restricted to the sub-artic assemblage: Betula nana, Salix sp, grass, heather and moss. The geochemical results of the background study are summarised in Table 14.

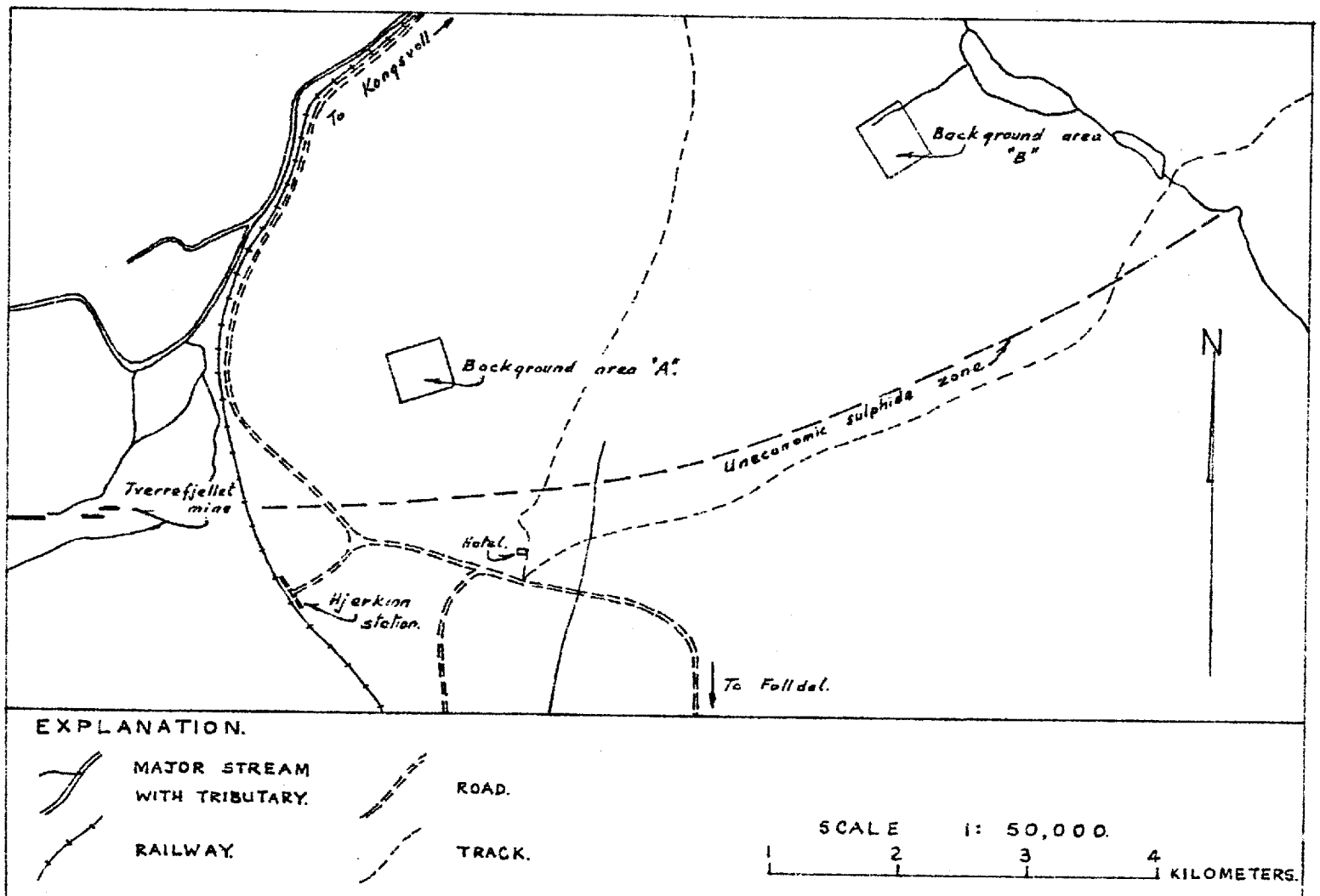


Fig.22. Plan showing the location of Background areas A and B.

TABLE 14

Geochemical Values in the Moraine and Overlying Soil Horizon in Profiles from Background Areas "A" and "B" (Data on the -80 mesh fraction)

Depth cm.	Description	$KHSO_4$ Me. ppm			ppm ex cu	B.E.C. m.eq/100g	pH	% Carbonate	ppm Exchangeable	
		Cu	Zn	Pb					Cu	Zn
0-5	bl/br organic	5	70	10	0.2	10	4.3	0.1		
5-15	Grey leached loam	10	60	10	0.5	8.0	4.6	0.1	0.02	0.3
15-25	br.med.gr.loam	20	100	10	0.7	6.0	4.2		0.02	0.3
25-30	Semi-decomp.moraine	20	100	10	0.6	6.0	4.8		0.02	0.3
30-50	Grey moraine	30	100	10	0.6	6.0	5.1		0.02	0.3
50-90	"	50	150	10	1.0	4.3	6.0	0.2	0.02	0.1
90-120	"	60	160	10	1.1					
120-150	"	60	140	10	1.2					
150-180	"	65	160	10	1.2					
170-180	"	65	160	10	1.2					
180-200	Grey moraine	70	160	10	1.2	4.0	6.3	0.2	0.02	0.2
Mean values of 66 samples from 10 profiles						Data from 1 profile				

From a study of the overburden in background profiles two important observations can be made:-

(1) There is no concentration of ore elements in any of the soil horizons, compared with metal values in the parent material.

(2) Base metal values (except Pb) increase to a depth of 1 m., beyond which the metal concentrations do not increase significantly.

The increase in metal content with depth is accompanied by a rise in the pH. In the moraine just below the soil horizons the pH increases rather abruptly and contrasts with the very acid environment in the soil.

These observations are consistent with a leaching of the overburden. This process has affected the development of the profile to a depth of 1 m. and is particularly pronounced in the soil horizons which is most probably a reflection of the more acid conditions at this level in the profile. The Cu/Zn ratios (Table 15) indicate that Cu is more severely leached than Zn.(The Pb values are in the range where significant differences are not detected by the method.).

TABLE 15.

Mean Cu/Zn Ratios in Freely Drained Background Profiles
(Based on data of TABLE 14)

Depth cm	Description	Cu/Zn Ratio	Soil Horizon
0-5	Bl/br.organic layer	1:12	A^{o} Horizon
5-15	Grey Leached horizon	1: 6	A^{2} Horizon
15-25	Br. med.gr. Loam	1: 5	B Horizon
25-30	Semi-decomp.moraine	1: 5	
30-50	Grey moraine	1: 3	
50-90	"	1: 3	C Horizon
90-120	"	1:2.6	
180-200	"	1:2.3	

Of particular significance is the fact that the ratio is lowest in the organic layer. This is consistent with biochemical activity and possibly correlates with the presence of Betula nana. This species is known to be an accumulator plant with respect to Zn (Vogt et al 1943).

Moraine samples from widely scattered localities within the Hjerkinn-Folldal area were compared on the basis of their physical properties (Table 16). This was done to assess the applicability of the background data to the Hjerkinn-Folldal area as a whole. The samples were taken at a depth of 1m. so that the affects of leaching would be approximately equal in all cases.

TABLE 16.

Some Physical Properties of Moraine Samples from the Hjerkinn-Folldal Area.

(Data on the -80 mesh fraction of samples taken at depths of 1 m.)

Sample Number	Location	B.E.C. m.eq/ 100g.	pH	Exchangeable Metal ppm		% Carbonate
				Cu	Zn	
43/4032	Background Location 'A'	2.2	5.5	0.02	0.3	0.1
43/4364	Background Location 'B'	4.3	6.0	0.02	0.1	0.2
43/3213	Hjerkinn-near the mine	2.4	5.9	0.08	0.3	0.1
43/4750	Folldal-Nordre mine	4.6	5.7	0.02	0.3	0.2
43/5035	Folldal-Grimsdal orebody	6.0	5.7	0.08	0.3	0.1

The salient features deriving from this study of the general properties of the moraine are:-

(1) The moraine is siliceous over the Hjerkinn-Folldal area.

(2) At a depth of 1 m. the moraine in the areas studied is essentially similar with respect to pH, exchangeable metal, and carbonate content.

(3) The base-exchange capacity is subject to local variations which appear to have had little affect on the amount of exchangeable metal.

The reasons for the variation in base exchange capacity were not investigated but may be due to a number of factors. For example, local variations in grain size of the till particles due to (a) differences in the degree of grinding by the glaciers, and (b) elutriation of fines by melt waters. In addition a limited amount of weathering may have occurred in some areas at a depth of 1 m. resulting in an increased exchange capacity.

The calculation of metal anomaly threshold values for the overburden is complicated by the effects of leaching. Threshold values were calculated for the soil horizons taken as a group (the solum), and for the moraine below the soil horizons to a depth of 1 m. (Table 17). The threshold values were estimated as that value which is exceeded by no more than $2\frac{1}{2}\%$ of the total number of observations, excluding erratic high values not belonging to the population for barren rocks. These threshold values are somewhat arbitary and were used only as guides in the interpretation of the data.

TABLE 17.

Calculated Background and Threshold Values for the Solum and the Moraine in the Hjerkinn-Folldal area, with the Range of Metal Values

(Data on the -80 mesh fraction)

	ppm Cu		ppm Zn		ppm cx Cu	
	Mean	Threshold	Mean	Threshold	Mean	Threshold
SOLUM (50 samples)	15	30	70	140	0.5	1.0
Range	2 - 35		30 - 155		0.2 - 1.1	
MORAINE (70 samples) to a depth of 1 m.	40	80	80	180	0.6	1.4
Range	10 - 90		20 - 230		0.2 - 1.6	

Pb in background samples of soil and moraine was found to vary between 5 and 20 ppm. At this concentration near the analytical detection limit the variations can not be considered significant. Accordingly, an arbitary upper background level of 20 ppm Pb for all levels of the overburden is used in this report in order to comment on the data.

OBSERVED DISPERSION OF ORE ELEMENTS IN THE OVERBURDEN (excluding bogs) IN THE VICINITY OF MINERALISATION

The Tverrefjellet orebody and surrounding area was selected for a detailed study, and less detailed comparative studies were carried out over cupriferous pyrite mineralisation in the Folldal district.

The ground containing the Tverrefjellet orebody, is drained by the Porg stream which rises in the secondary iron oxide body downslope of the collapse structure and swallow hole. These features mark the western extremity of the ore. At the eastern end of the ore sub-outcrop, and near to the Porg stream there is a second iron oxide body in the moraine. This is very much smaller than the one occurring downslope of the swallow hole. The strike of the ore and the course of the stream diverge towards the east so that the sub-outcrop of the ore occurs at increasing distances to the south of the stream (Fig.18). The conditions are such that the ground underlain by the ore is freely drained.

The surface of the overburden overlying ore is even, apparently unaffected by frost heaving, whereas in the ground close to the stream, stoney polygons and frost tussocks have developed.

(i) Evidence of a Boulder Train at Tverrefjellet

Two sulphide ore boulders were discovered in the moraine at Tverrefjellet, 20 m. and 100 m. northeast of the ore. In addition on the low ground 1 km. northeast of the orebody a fragment of till cemented by secondary iron oxides was observed. This provides evidence of ore oxidation prior to the last glaciation.

These boulders were discovered by the writer, but a fourth ore boulder found by residents of the Hjerkinn district was located on the northern slopes of Hjerkinn HÖ, approximately 5 km. northeast of its supposed origin (Fig.23). This boulder was of considerable size being about 1 m. in diameter, whereas the three others were of hand specimen size.

Continued search failed to bring to light further ore boulders which suggests that the boulder train at Hjerkinn is not well developed. The very restricted sub-exposure of the ore, and the lack of wallrock alteration have probably been major factors limiting the development of the boulder train.

(ii) Distribution of Ore Elements in the Overburden in the Vicinity of the Tverrefjellet Orebody

The dispersion patterns in the overburden were investigated in four trenches cut across the strike of the

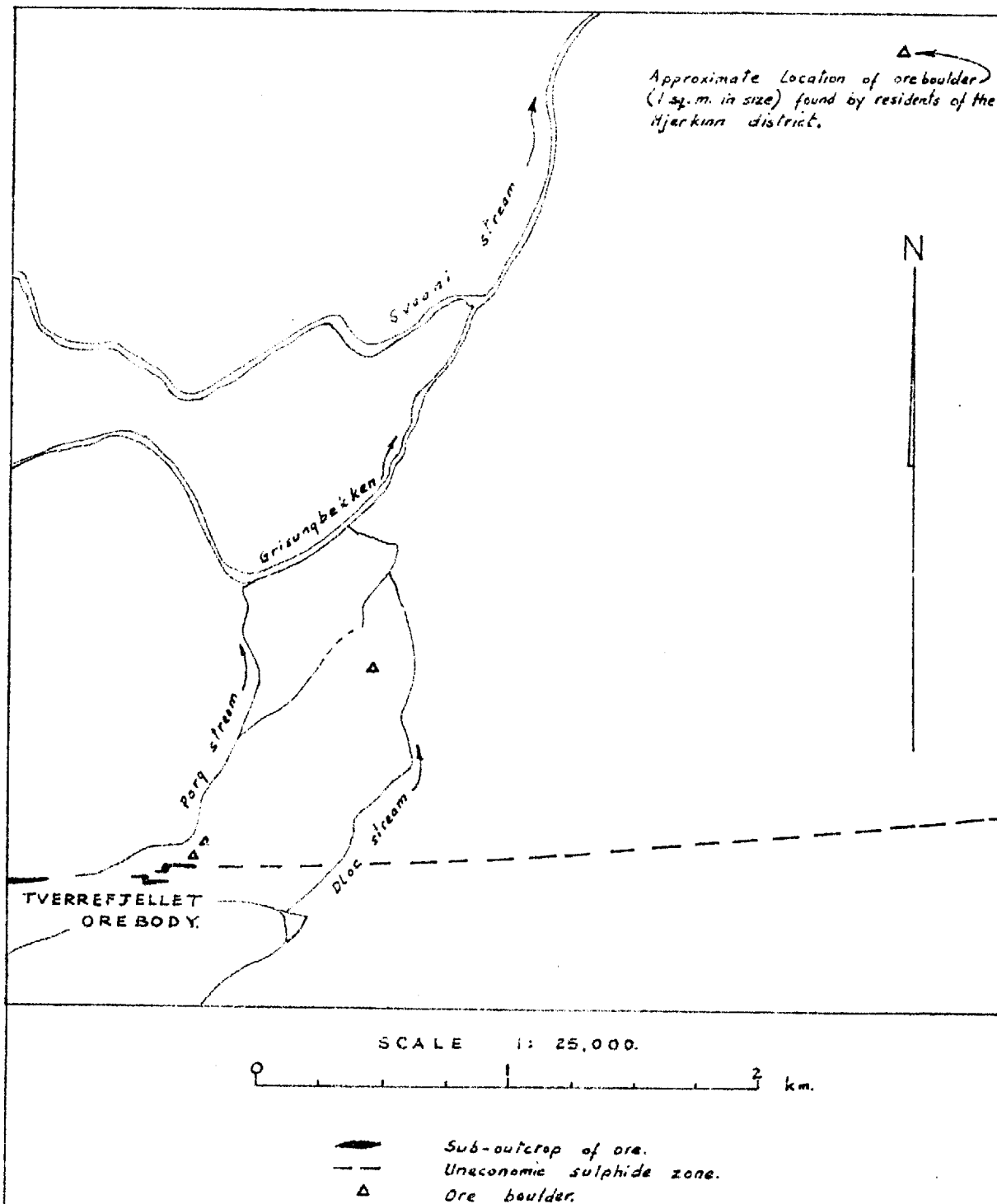


Fig.23. Plan showing the location of ore boulders in the vicinity of the Tverrefjellet orebody, Hjerkinn.

ore (Fig.18). The trench sites were selected to allow the study of different environments. Thus trench 1 exposes ore where the water table is normally well below the rock surface. Trench 2 also intersects the ore, but where the groundwater table is at or just above the rock/moraine interface. In trench 3, the ore zone is crossed where the bedrock contains only minor mineralisation. The fourth trench was sited to study dispersion where oxidation is at a maximum, i.e.: within the collapsed structure. Unfortunately, trench 4 did not reach bedrock because of an excessive thickness of moraine. Seismic reflection readings indicate that here, the overburden is 12 m. thick (Data of the Geophysical Dept. of the N.G.U.).

The major features of the overburden and bedrock surface exposed in the trenches are illustrated in Figs.24 and 25. Attention should be drawn to the following:

(i) Soil Development: In trench 2 the soil horizons are absent, and the grey moraine is overlain by a thin layer of undecomposed humus. In trenches 1 and 3 the soil, when present consists of 20 cm. of light brown sandy loam overlain by a thin layer of raw humus.

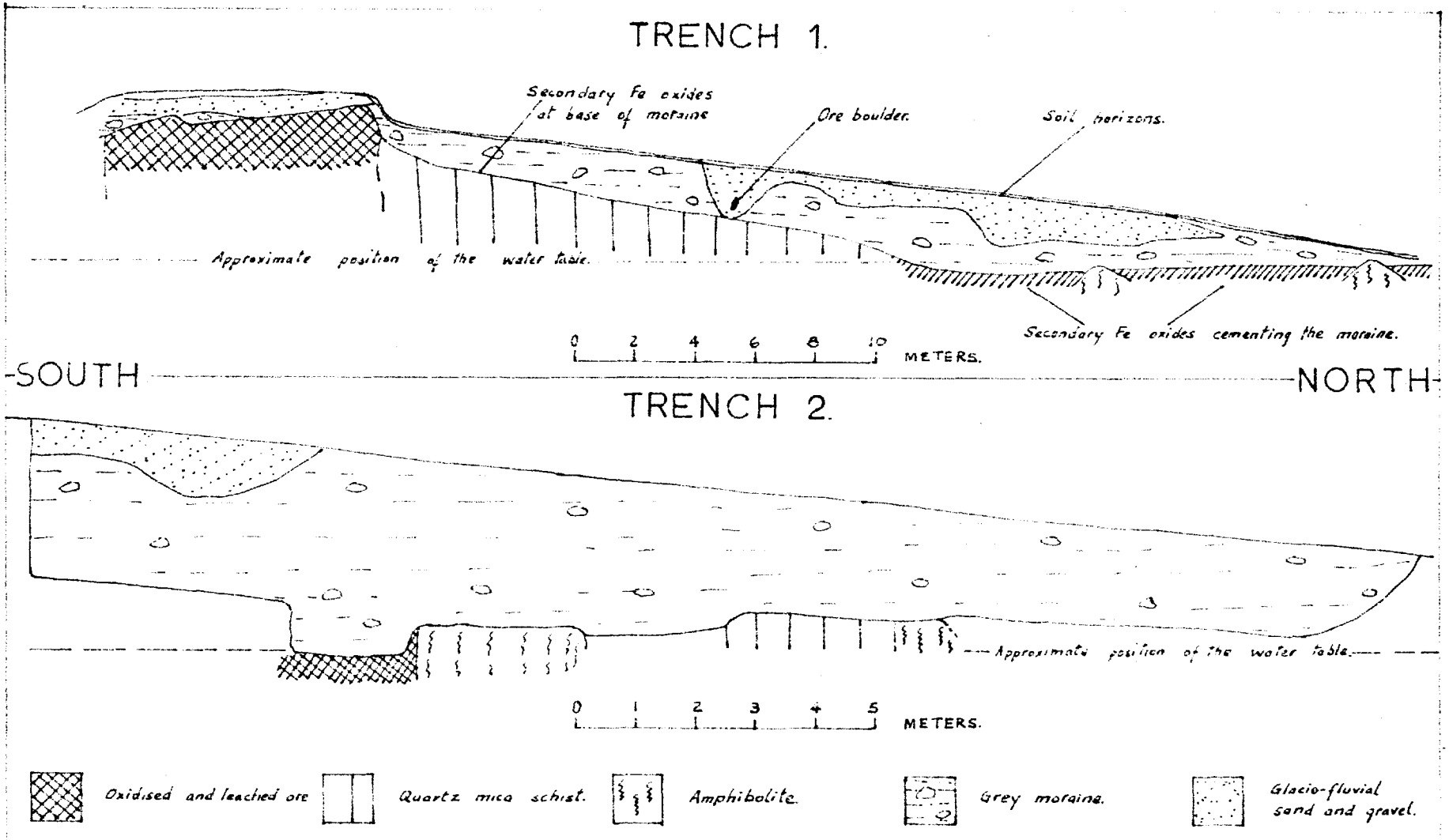


Fig.24. Plan showing the geology of trenches 1 and 2 located over the sub-outcrop of the ore at Tverrefjellet. (For location see Fig.18).

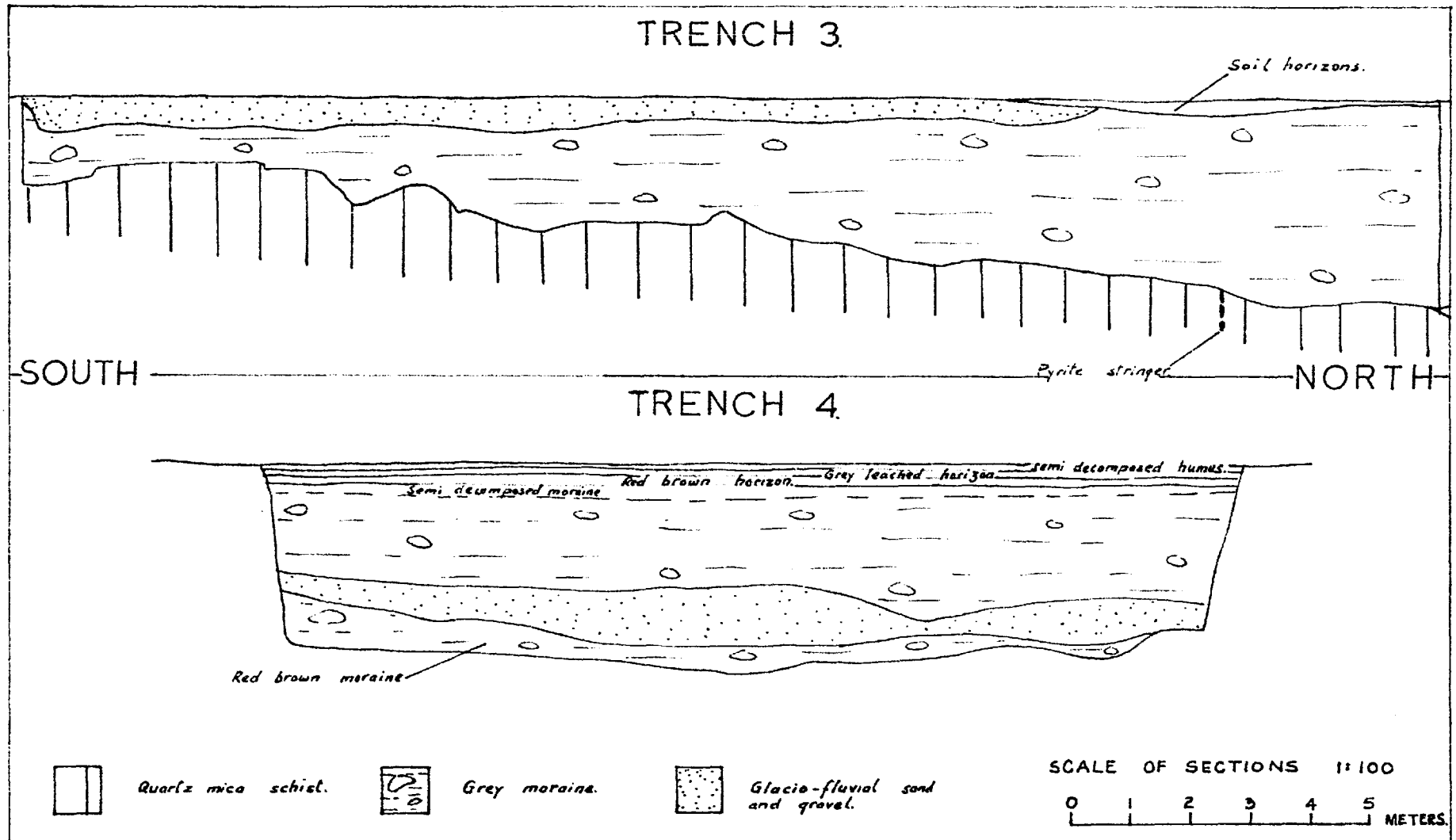


Fig.25. Plan showing the geology of trenches 3 and 4 located over the ore zone at Tverrefjellet. (For location see Fig.18).

However, in the fourth trench the soil horizons are well developed and up to 50 cm. in thickness.

(2) Glacial deposits: The overburden consists of grey bouldery moraine which is overlain in trenches: 1, 2 and 3 by glacia-fluvial sand and gravels. The sand and gravels have an irregular distribution and in trench 1 were found to contain a sulphide ore fragment. In trench 4 a lens of finely laminated sand and silt is contained within the grey moraine.

(3) In all the trenches exposing ore, the basal 10 cm. of the moraine overlying the mineralisation and downslope of it is cemented by secondary iron oxides.

As previously mentioned one wall of each trench was sampled along vertical channels and the profiles were analysed for cx Cu, Cu, Zn and Pb (Figs.26-31).

In trenches 1, 2 and 3 the anomalies occur downslope of the ore, that is to say, in the direction of latest ice transport. In the distribution of the anomalous metal the two most striking features are:-

(1) the very much greater extent of the cx Cu values compared with Cu or Zn,

and

(2) the rare occurrence of Pb.

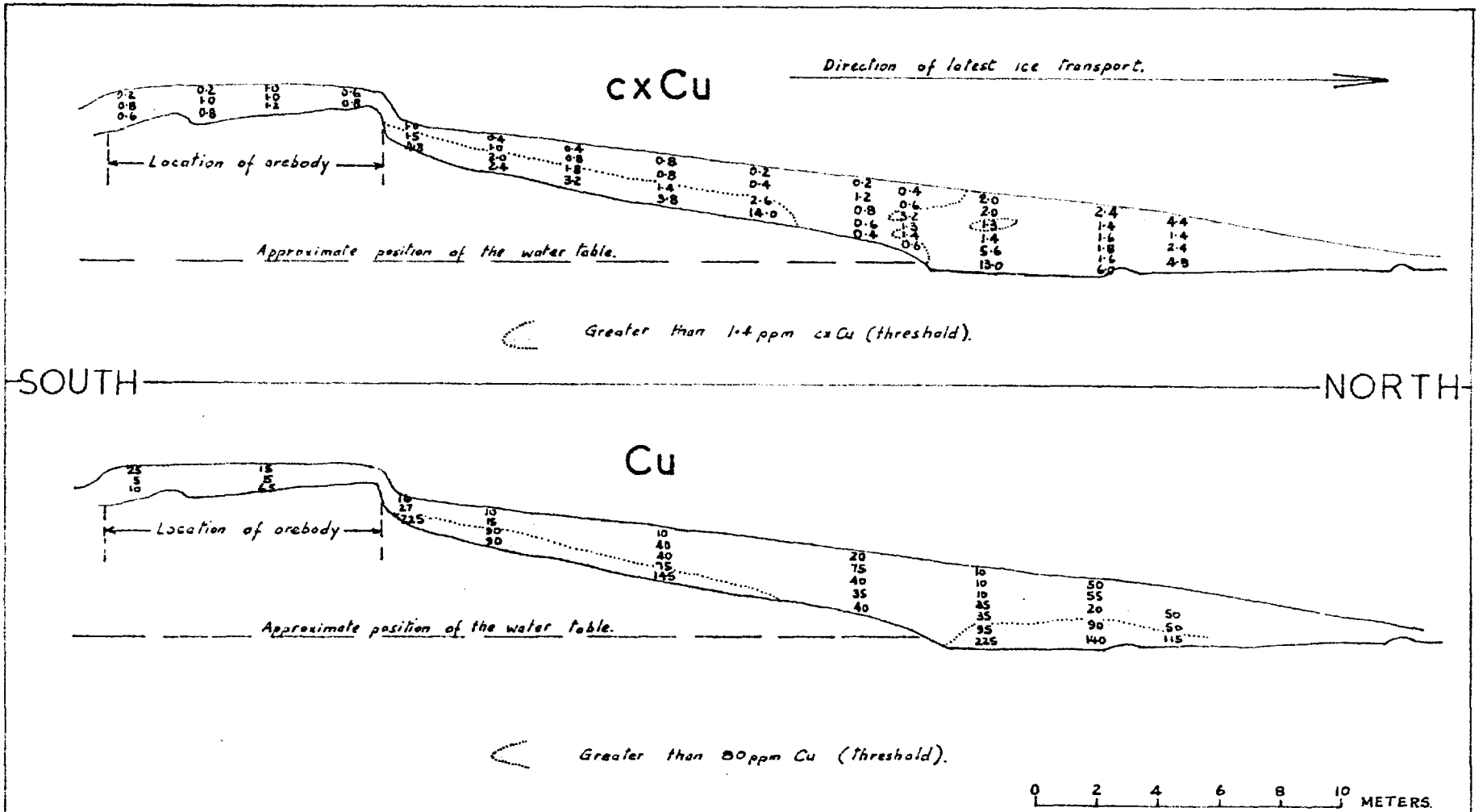


Fig.26. Sections showing the distribution of cxCu and Cu in the overburden — Trench I, Tverrefjellet. (data on the -80 mesh fraction).

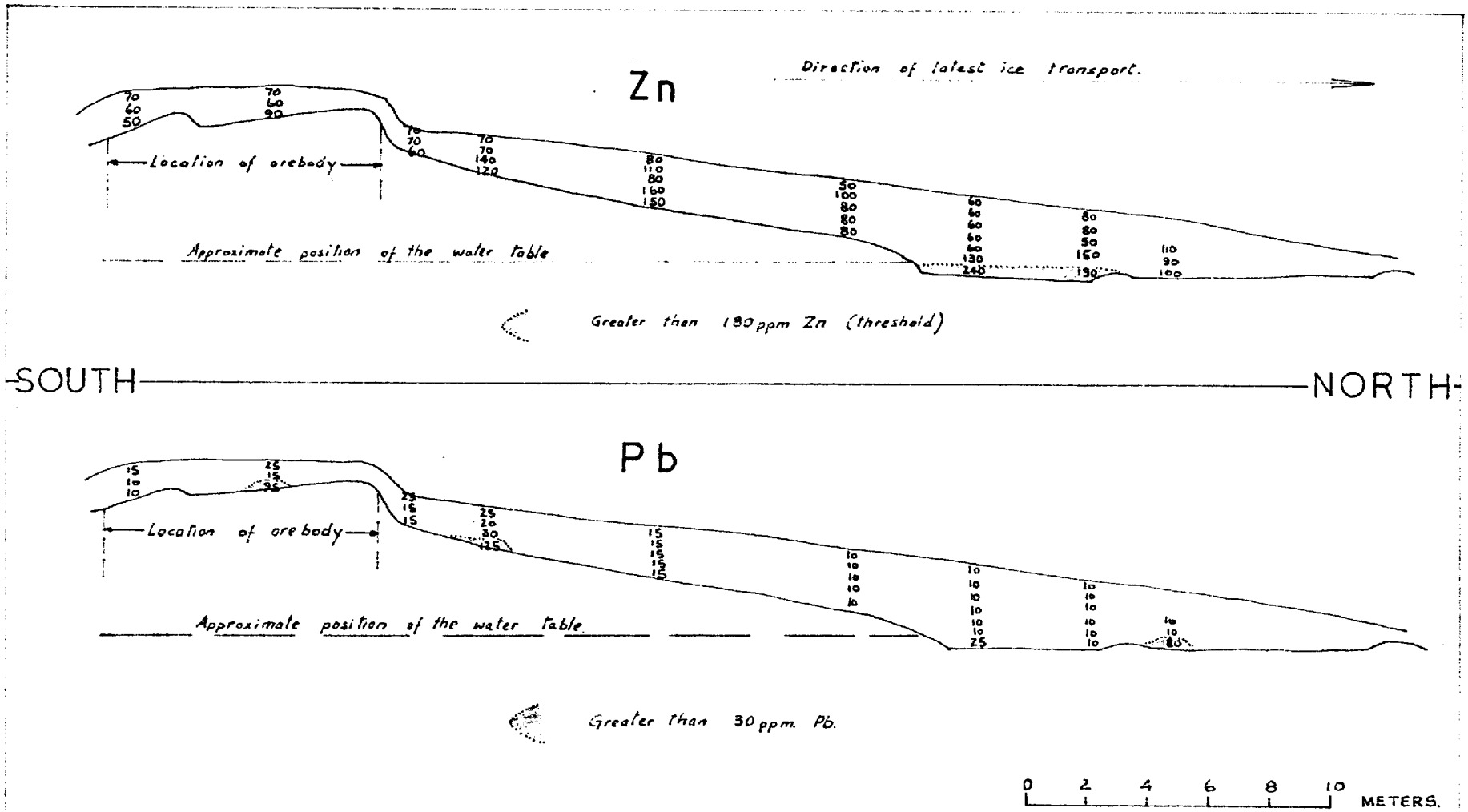


Fig.27. Sections showing the distribution of Zn and Pb in the overburden—Trench I. Tverrefjellet. (data on the -80 mesh fraction).

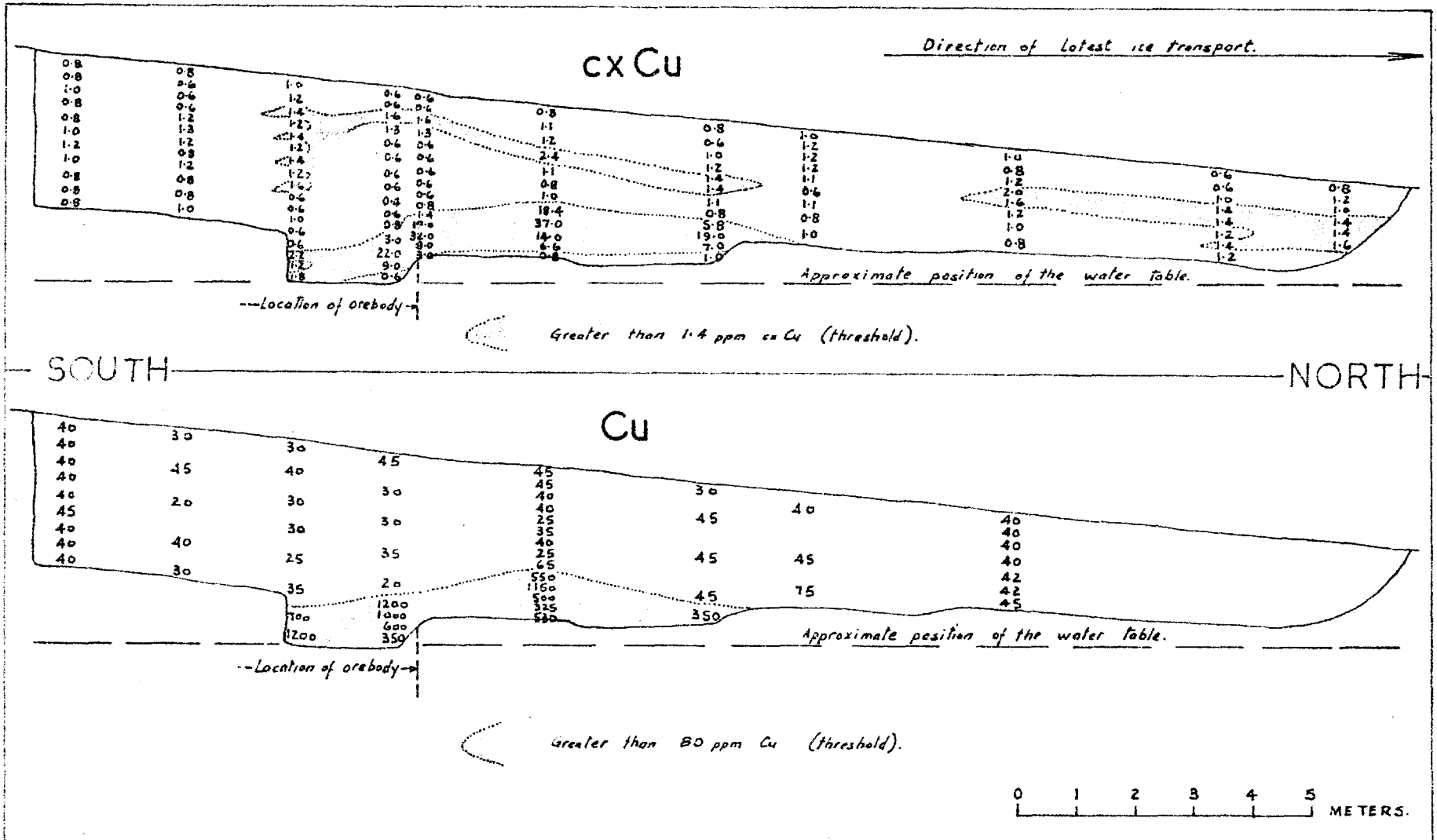


Fig.28. Sections showing the distribution of cxCu and Cu the overburden— Trench 2, Tverrefjellet. (data on the -80 mesh fraction).

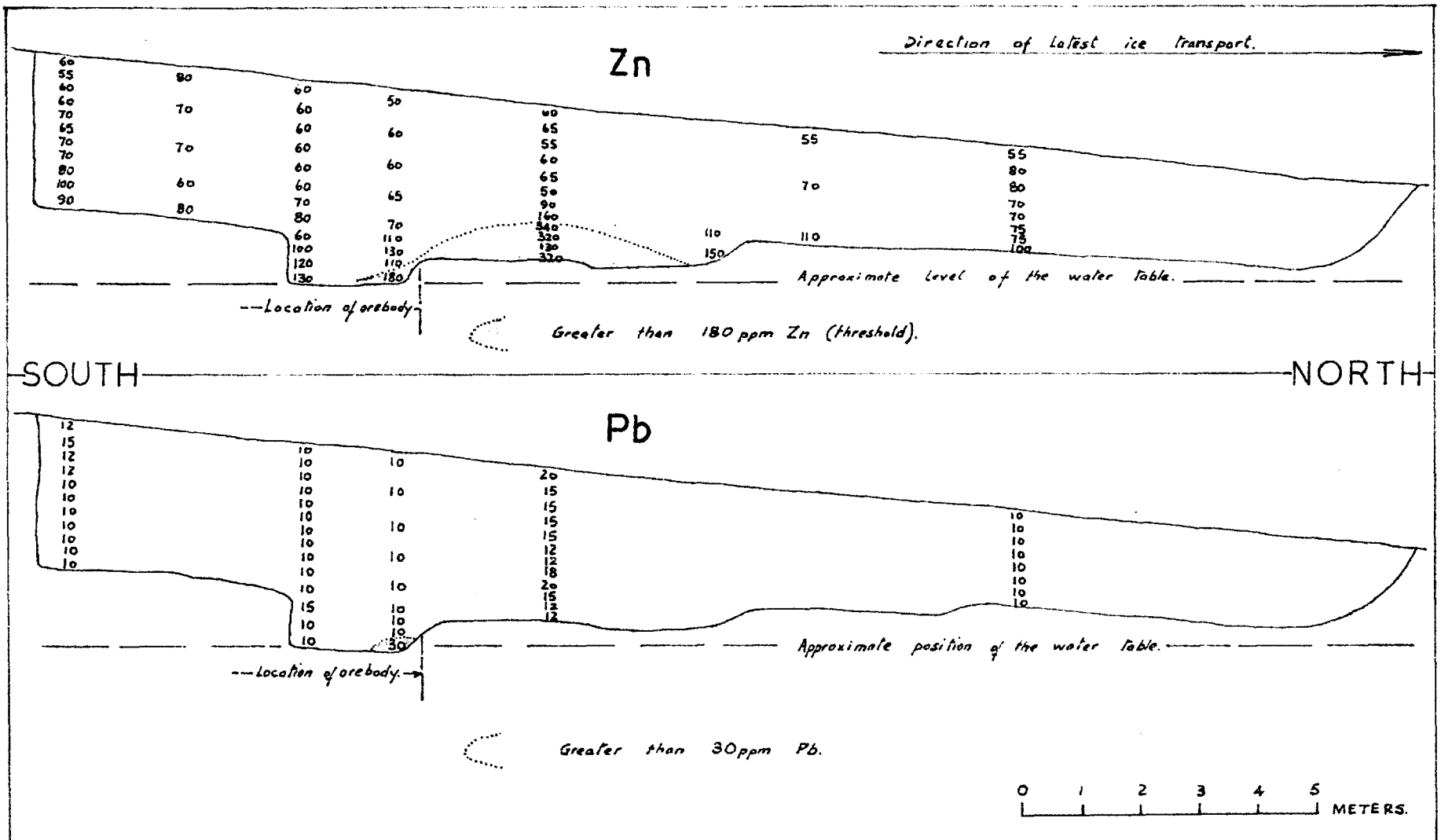


Fig.29. Sections showing the distribution of Zn andPb in the overburden— Trench 2, Tverrefjellet. (Data on the -80 mesh fraction).

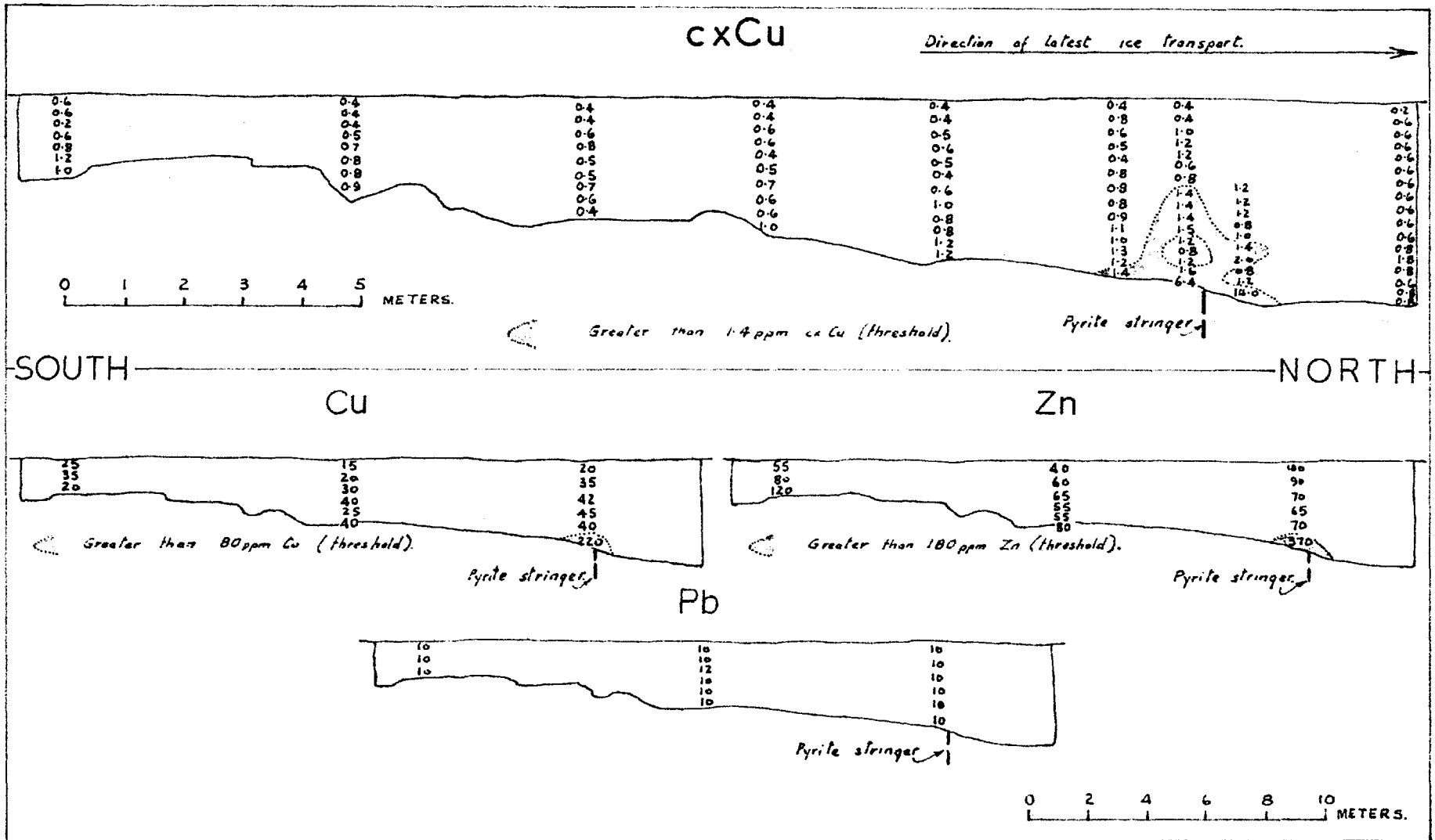


Fig.3o. Sections showing the distribution of cxCu, Cu, Zn and Pb in the overburden-Trench 3, Tverrefjellet. (Data on the -8o mesh fraction).

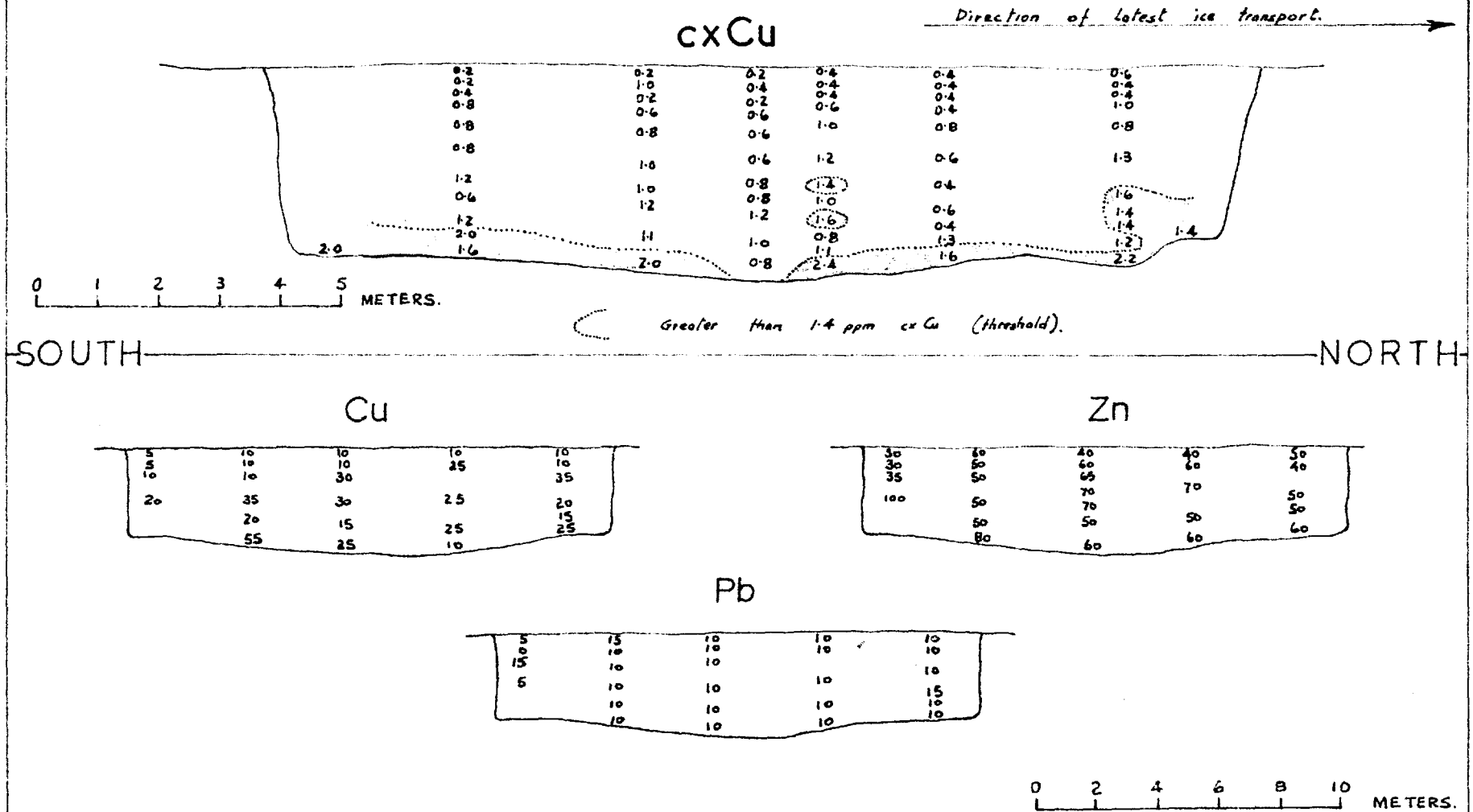


Fig.3I. Sections showing the distribution of cxCu,Cu,Zn and Pb in the overburden — Trench 4,Tverrefjellet. Data on the -80 mesh fration).

In general the basal 50 to 100 cm. of the moraine downslope from the ore contains the anomalous base metal values, which decrease in intensity upwards. In trench 2 however, the highest cx Cu and Cu values (up to 26 and 15 times threshold respectively) occur in the upper layer of the strongly anomalous zone which has a sharp upper cut-off. The zone is underlain by 10 cm. of ferruginous moraine which is in contact with bedrock. The ferruginous layer is characterised by background cx Cu values, whilst containing anomalous amounts of cu and Zn.

Weakly anomalous patterns of cx Cu are not reflected by the Cu, Zn or Pb data. For example, in trench 2 a thin irregular layer 1 to 2 m. above the bedrock surface contains cx Cu values up to 1.7 times threshold (2.4 ppm), which is not reflected by the other data. Attention is drawn to the fact that the weakly anomalous zone is surrounded entirely by barren moraine.

In trench 1 the strongly leached ore is located well above the normal level of the water table. The material overlying the ore contains background metal values except for one erratically high Pb value. However, 20 m. downslope from the ore the basal layer of the moraine is anomalous for all metals except Pb. The upper part of the profile, however, is anomalous only with respect to

cx Cu. It is perhaps significant that the anomaly coincides with the sub-outcrop of the water table i.e.: from bedrock into the moraine.

The overburden in the fourth trench is excessively thick and well drained and is generally found to contain metal values in the background range. In the moraine exposed in the base of the excavation, however, the cx Cu values are weakly anomalous, up to twice the threshold value (3.2 ppm).

(iii) Discussion of the Dispersion of Ore Elements into the Overburden at Tverrefjellet.

(a) Correlation of the metal content of the ore and the moraine.

Data concerning the distribution of the ore elements in the primary and secondary environments of the ore zone has previously been presented (Table 13). The results of the study showed that substantial quantities of Cu, Zn and Fe have been leached from the ore in the zone of oxidation and weathering. By contrast, Pb was found to be relatively immobile in the secondary environment.

The ratios of Cu : Zn : Pb in the primary ore, the gossan and the anomalous basal part of the moraine (Table 18) refers to material from trench 2 and diamond drill hole 2.

TABLE 18.

Cu : Zn : Pb : Ratios in the Primary Ore, the Gossan and the Anomalous Basal part of the Moraine. (Data from Trench 2 and Borehole 2 on material crushed or sieved to - 80 mesh).

Material.	Ratios of Base Metal Content		
	Cu	Zn	Pb
Primary ore.	4	6	1
Gossan	2.3	1	1
Anomalous basal moraine.	40	25	1

The ratios (Table 18) indicate that the metal content of the anomalous moraine does not bear any direct relationship to the primary ore, or to the gossan. Of particular significance are the low Pb values of the anomalous moraine. This applies equally to the anomalous till samples from all the trenches, whether heavily charged with secondary iron oxides or not.

The incorporation of sulphide ore particles or gossanous material into the moraine would have resulted in the secondary dispersion of Pb as well

as the other ore elements. Since Pb is relatively immobile in the zone of weathering the concept of syngenetic (i.e. mechanical) dispersion is inconsistent with the data. In other words it appears probable that chemical rather than mechanical processes have been important in the secondary dispersion of the ore elements into the overburden.

(b). Mode of occurrence of the ore elements in the overburden.

In trench 2 some of the possibly more significant chemical and physical characteristics of the strongly anomalous zone were measured (Table 19). Included in the table are data for moraine lying above the anomalous zone.

There seems to be no correlation between pH and the observed metal concentrations. The B.E.C. shows an increase at depth, but is accompanied by a decrease in the exchangeable Cu content. This may be due to a saturation of the exchange position with Fe, particularly since the sample (43/3216) is ferruginous. The high Fe content of the sample (43/3216) may be the reason for the low cx Cu content of the basal ferruginous layer. The proportion of cx Me / Me is dependant to some extent on

the nature of the bonding of the metal in the sample material. It has been observed that crystallisation of iron hydroxides may result in the fixation of Cu in a form not readily extractable (Tooms 1965). The data supports this concept in as much as within the strongly anomalous zone the cx Cu values increase as the Fe concentration decreases.

Table 19 Overleaf.

TABLE 19.

Some Chemical and Physical Properties concerning a Profile Overlying the Mineralised Bedrock in Trench 2.

(Data on the - 80 mesh fraction).

Sample No.	Depth cm.	Description.	Cu ppm	cx Cu ppm	ex Cu ppm	Fe %	pH	BEC m.eq	TEB 100g	$CO_3^{=}$ %
		TRENCH 2.								
43/3206	60- 80	Grey moraine	42	2.4	0.01	3.5	5.4	2.4	1.2	0.1
43/3208	100-120	Grey moraine	35	0.8	0.08	3.3	6.8	2.3		
43/3213	200-220	Grey moraine	1150	32.0	6.5	4.0	5.9	2.4		0.25
43/3215	230-240	Grey-Yellow moraine	325	6.6	0.3	7.5	6.0	3.0	0.8	
43/3216	240-250	Red Brown moraine	500	0.8	0.005	10.0	5.9	5.0	8.2	0.1

The availability of Cu to different reagents may be significant of its mode of occurrence. Accordingly selected anomalous samples were treated with extractants of differing strengths (Table 20). The results are compared with similar data relating to moraine overlying unmineralised bedrock.

TABLE 20

The Extraction of Cu from Samples of Moraine by Different Reagents

(Data on the -80 mesh fraction)

Sample Attack		HF/HCLO4 extraction	KHSO4 fusion	IM.HCL digestion	IM.neutral Amm. Acetate
Sample No.	Depth (cm).	Cu ppm	Cu ppm	Cu ppm	cx Cu ppm
OVERLYING CRE					
43/3203	0-15	62	42	27	0.3
43/3213	200-220	1020	1150	1100	6.5
43/3216	240-250	N.D.	500	222	0.005
OVERLYING BARREN BEDROCK					
43/4153	40-50	50	37	22	0.02
43/5401	180-200	82	70	47	0.02

(N.D. = Not Determined)

In the strongly anomalous horizon (Sample 43/3213) Cu is totally extracted by digestion with IM. hydrochloric acid (Table 20). In the background samples this attack released only 50% of the Cu when compared with the total $HF/HCLO_4$ extraction. The anomalous Cu is, therefore, relatively weakly bonded. By the same criteria the anomalous metal in the ferruginous horizon overlying the ore (Sample 43/3216) is comparatively strongly bonded.

The data indicates that anomalous Cu is held by secondary iron oxide minerals in ferruginous moraine. In the non-ferruginous moraine the anomalous Cu is held in some other more soluble mineral species.

(c) Mode of Dispersion of the Ore Elements

The distribution of the ore elements in an anomalous profile in trench 2 (Table 21) shows a vertical partition of the metals and $SO_4^=$.

TABLE 21.

Vertical Distribution of the Ore Elements in the Moraine Overlying the Mineralised Zone in Trench 2.

(Data on the -80 mesh fraction)

Sample No.	Depth cm.	Description	cxCu ppm	Cu ppm	Zn ppm	Fe %	Pb ppm	SO4 ppm
43/3209	120-140	Grey Moraine	0.2	40	65	3.4	15	-
43/3210	140-160	" "	0.4	25	50	2.0	12	-
43/3211	160-180	" "	1.0	65	90	3.7	12	-
43/3212	180-200	" "	18.4	550	160	3.6	18	-
43/3213	200-220	" "	37.0	1150	340	4.0	20	-
43/3214	220-230	" "	14.0	525	320	5.0	15	25
43/3215	230-240	Grey-Yellow Moraine	6.6	325	130	7.5	12	4250
43/3216	240-250	Red Brown Moraine	0.8	500	320	10.0	12	250

(- = Not Detectable)

Pb is demonstrably stable in the secondary environment and therefore the observed distribution (Table 21) is unlikely to have resulted by the leaching of syngenetic metal derived from mineralisation. The evidence is consistent with the ore elements having been introduced into the moraine via the groundwaters. In particular the sharp upper cut-off of the anomalous metal in the moraine indicates precipitation along well defined fronts.

In addition, the moraine in trench 2 nontains weakly anomalous cx Cu values in a zone approximately 1 m. below the surface of the overburden (i.e.: 1 to 2 m. above the

bedrock surface). The moraine both immediately above and below contains only background concentrations of cx Cu (Fig.28). It is improbable that the anomaly is due to biogeochemical dispersion since the plant rootlets were observed to penetrate to depths not greater than 50 cm. However, the weakly anomalous zone coincides with the level at which the moraine was found to be frozen. It is possible that during the freezing procees small quantities of groundwater are raised by capillary forces to higher levels in the profile (Tabor, 1930). The small quantities of translocated groundwater derived from underlying mineralisation may be concentrated in the moraine at the level at which freezing occurs. During the thaw the anomalous metal contained in the groundwater would be available to the moraine.

In the other trenches (1, 3 and 4), the dispersion patterns are unlike those in trench 2, inasmuch as the maximum values occur at the base of the moraine and in general, decrease in intensity upwards. However, the position of the groundwater table and the rate of flow are possibly important factors in the development of the dispersion patterns. For example, in trench 1, the major anomaly is coincident with the sub-outcrop of the water table (i.e.: from bedrock into the moraine). In contrast

in trench 2, the groundwater table and the bedrock surface are approximately at the same level.

Attention is directed to the occurrence in trench 1 of slightly higher cx Cu values in the surface layers of the overburden compared with the immediately underlying material (Fig.26). The surface enrichment in cx Cu may be due to biogeochemical processes.

In trench 3 the anomalous metal values in the moraine are restricted to the base of the profile immediately overlying the weak mineralisation in the bedrock (Fig.30). In particular, the anomalous cx Cu values occur both up and down slope of the primary mineralisation which may imply (a) that the metal has been introduced into the moraine after its deposition, and (b) that the anomalous metal has possibly been secondarily dispersed in the groundwater where it occurs above the bedrock/moraine interface. The very small width of the bedrock mineralisation (i.e.: 5 cm.) exposed in the trench militates against the development of a syngenetic dispersion pattern in the moraine.

In the fourth trench neither the bedrock nor the groundwater table where intersected. The anomalous metal in the overburden occurs at the base of the exposed section (approximately 3 m. below the surface) and is restricted to weakly anomalous cx Cu values. The lack of Cu, Zn or Pb

anomalies tends to confirm the results of the seismic reflection survey of the Norges Geologiske Undersökelse (1964) which indicated that here the moraine is 12 m. thick. The very well drained profile is thought to be the reason for the lack of any well developed anomalous distribution of the ore elements in the moraine. There is certainly no evidence to indicate that anomalous metal has been incorporated in the moraine as a result of glaciation.

(d) Size Distribution of Cu and Zn in the Moraine

Most of the data on the till relates to analysis of the -80 mesh fraction. The distribution of the metals in other size fractions was investigated in only a limited number of samples (Fig.32).

The salient features of this data are:-

(1) The metal is predominantly held in the fine fractions of the moraine.

(2) Up to 120 cm. above mineralisation the -20 +38 mesh fraction contains significantly more Cu (and to a lesser extent Zn) than the corresponding fraction of background moraine. Above this level there is no contrast with background in any of the size fractions examined.

In the samples studied the maximum Cu content of the -20 +38 mesh fraction was 250 ppm in the moraine at the

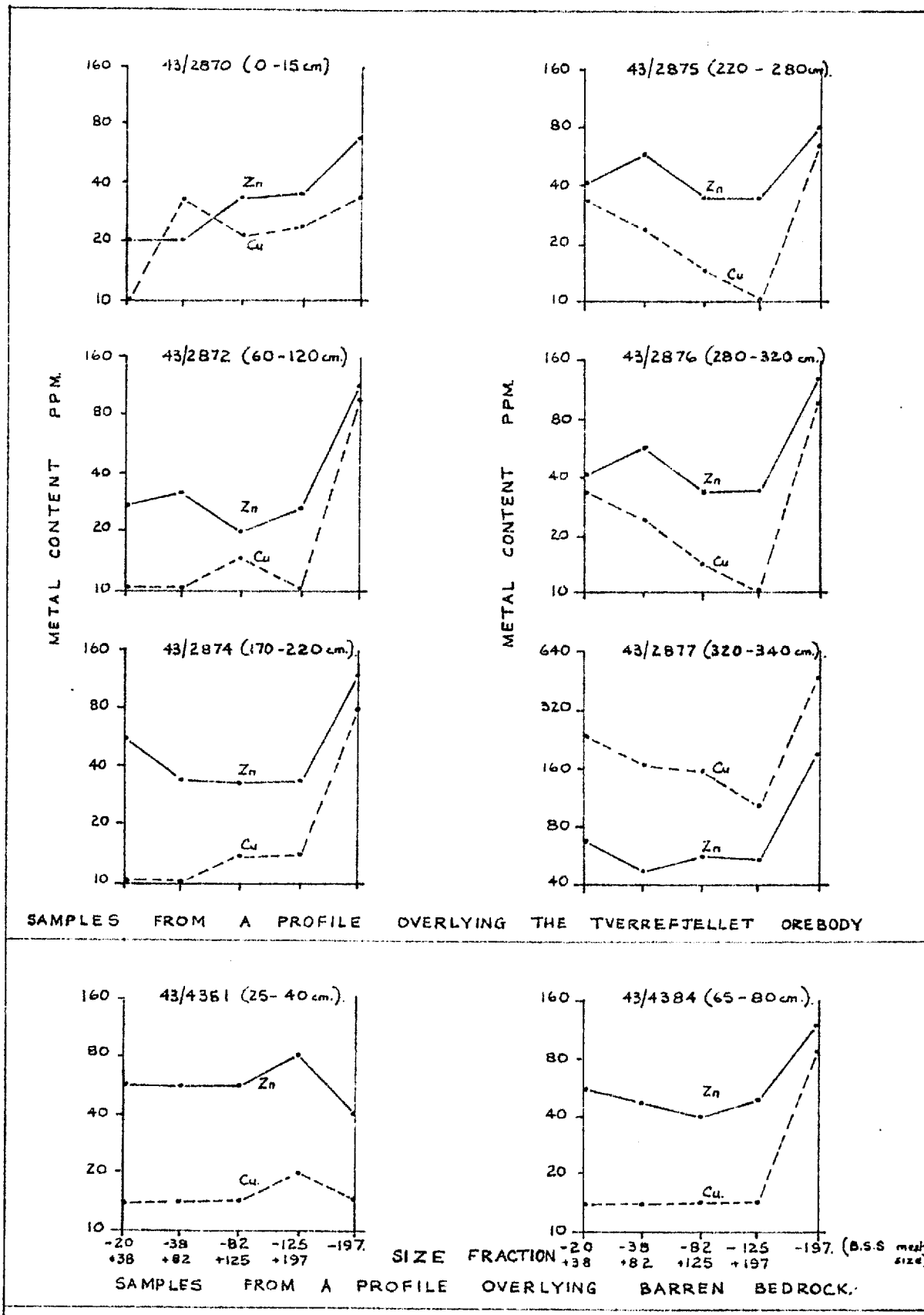


Fig.32. Size distribution of Cu and Zn in moraine overlying mineralised and barren bedrock.

base of the profile overlying ore. Cu decreases to 35 ppm in the moraine 20 cm. above the base. An examination of the size fractions for primary ore grains obtained negative results. It is, therefore, probable that the dispersion of metals in the coarse size fractions has resulted from the same process controlling the dispersion patterns in the -80 mesh fraction.

In summary, the distribution of the ore elements in the moraine at Tverrefjellet shows many features indicative of hydromorphic dispersion. In particular the anomalies are located in the lower 50-100 cm. of the moraine. A characteristic feature is the strongly anomalous cold extractable Cu values. Similar patterns were found by Dreimanis (1960) in non-calcareous moraine at the Nigadoo mine, New Brunswick. He attributed the dispersion to upward migration of ore elements in low pH groundwaters. Yardley, at Ely Minnesota came to somewhat similar conclusions for the dispersion of Cu and Ni from sulphide mineralisation into siliceous moraine (Yardley 1958).

The ore boulder train extends from Tverrefjellet to 5 km. down-ice and consists of four known boulders. A micro-boulder (indicator) train has not been detected, probably because of massive dilution with barren moraine.

In this connection it should be noted that the bedrock source is of small dimensions. In particular the ore is enclosed by tough siliceous wallrocks.

(iv) Dispersion of Ore Elements in the Overburden (excluding bogs) over Cupriferous Pyrite Mineralisation in the Folldal Area.

The distribution of ore elements in the overburden at Tverrefjellet was compared with the patterns developed in the moraine over cupriferous pyrite mineralisation in the Folldal area.

The location of the three ore bodies studied in the Folldal area are shown in Fig.33. In these locations the pyritic ore strikes east-north-east, west-south-west, and the dip of the individual ore bodies varies between 30° and 60° to the north-north-east. The entire area has been glaciated by ice which moved to the north and north-east during the last glacial episode. The vegetation is in general, restricted to the sub-arctic assemblage : Betula nana, Salix sp, grass, heather and moss.

In the following pages the dispersion of ore elements in the overburden is described, and where appropriate specific mention is made of the local secondary environment.

(a) Nordre Gjeiteryggen

Mining activities have resulted in the contamination of a wide area around the mine shafts. Consequently, the

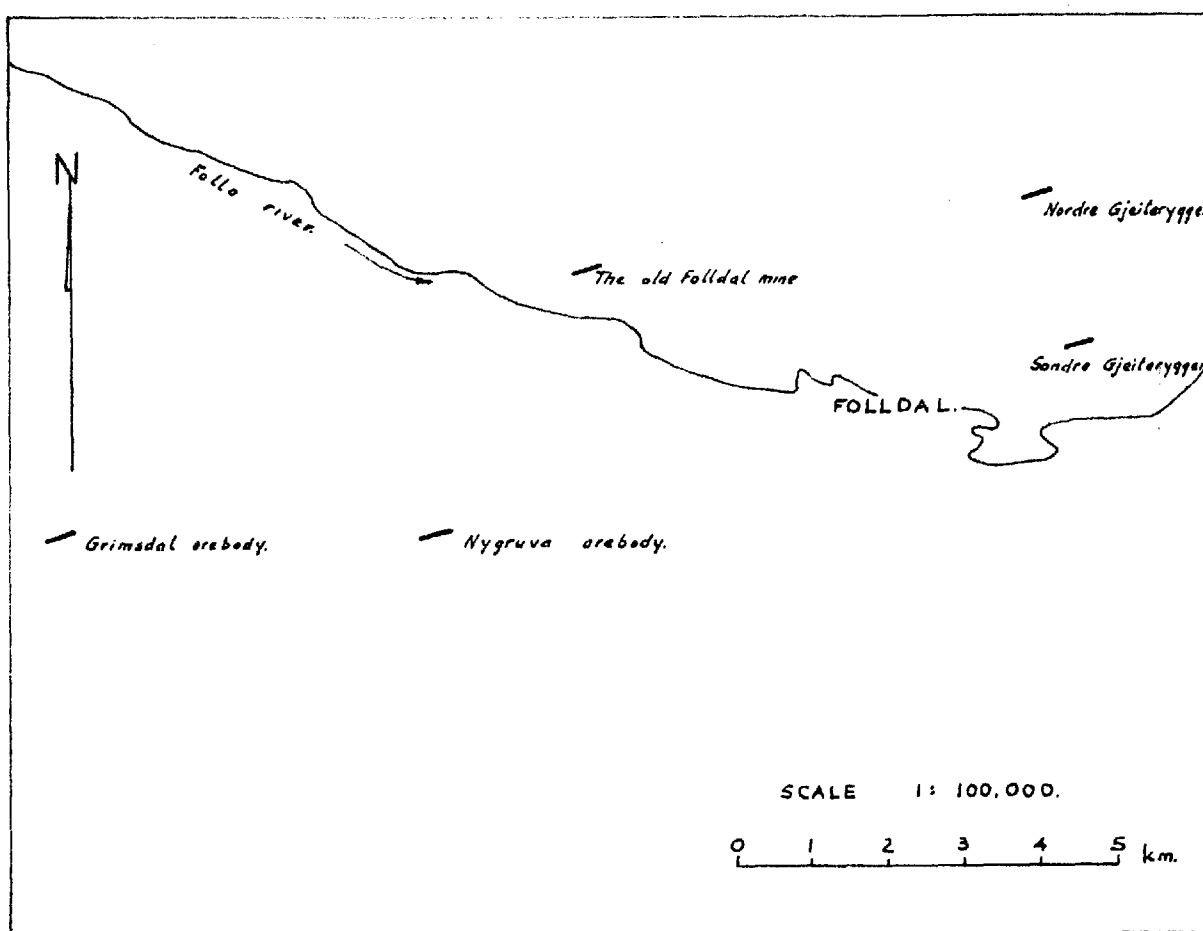


Fig.33. Plan showing the location of pyritic ore in the Folldal area.

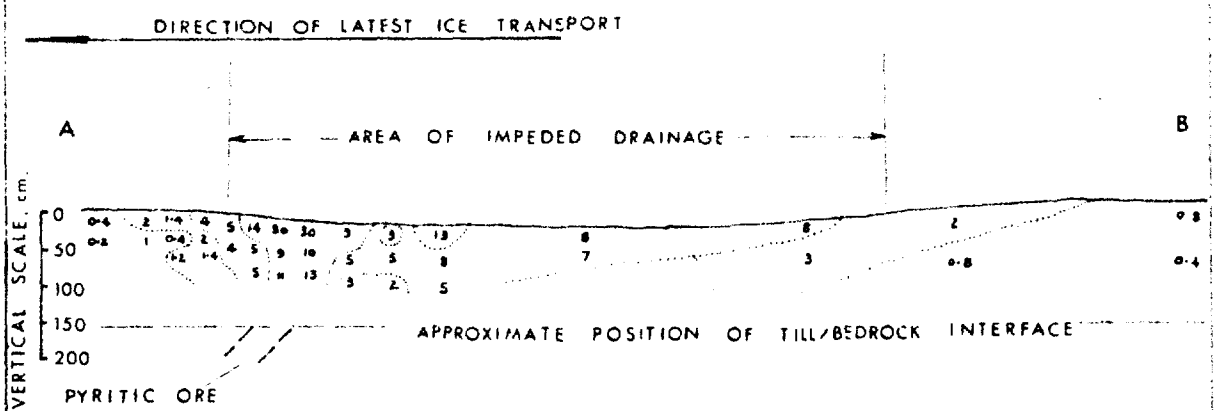
sample traverse was located outside the contaminated area, along strike of the ore to the east, where the ore grade is reported to be low. The traverse, at right angles to the ore, is located in an area of impeded drainage, where the groundwater flows to the south-west (Fig.34). At both ends of the traverse the overburden is freely drained and was found to consist of grey ground moraine overlain by 20 cm. of light brown sandy loam. At the surface there is a layer of undecomposed humus. Within the area of impeded drainage, which is characterised by abundant frost tussocks, the waterlogged grey moraine is overlain by moraine with admixed organic material. The organic rich layer did not exceed 20 cm. in thickness.

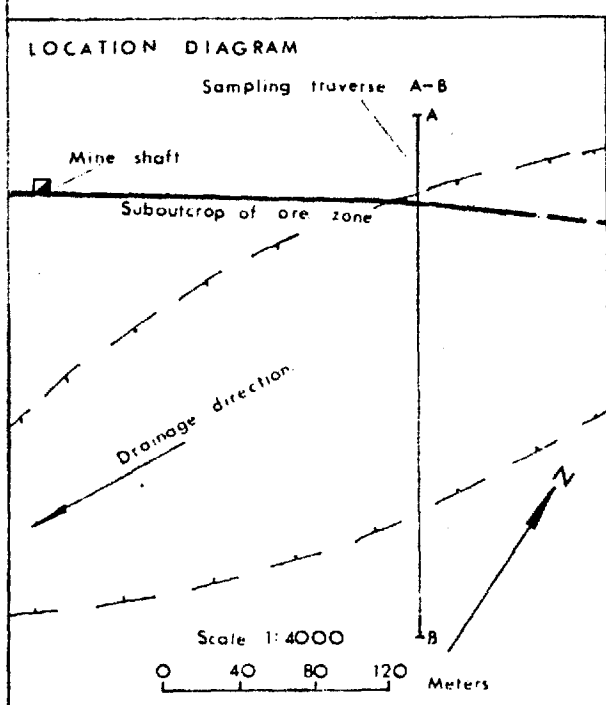
The dispersion patterns of cx Cu, Cu, Zn and Pb are shown in Figs.34 and 35. The principle features of this data are:-

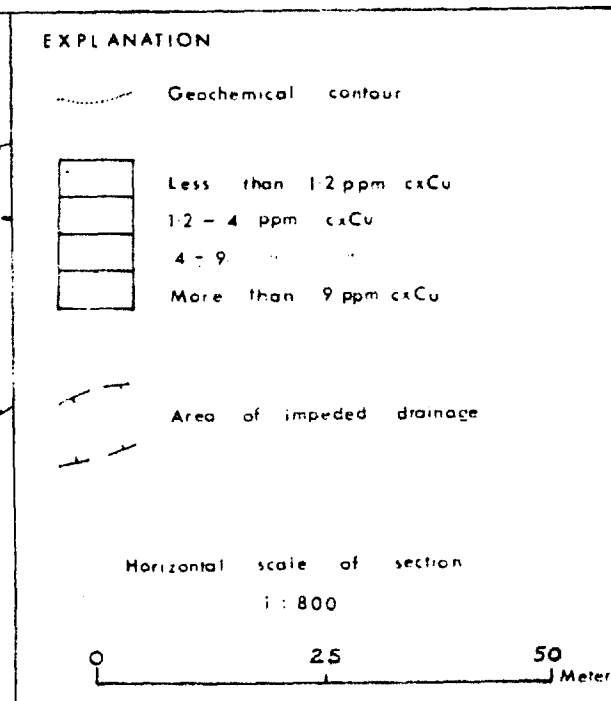
1. The cx Cu values in the moraine immediately overlying the ore are strongly anomalous being in the range of 9-40 ppm (6-28 times threshold). The cx Cu content in this zone increase towards the surface where the maximum value of 40 ppm is recorded. On the north side of the ore zone cx Cu values decrease to background over a distance of 16 m. South of the ore the values are anomalously high over a distance of 105 m. It is

FIG. 34.

PROFILE THROUGH THE OVERBURDEN ALONG TRAVERSE A–B SHOWING THE DISTRIBUTION OF cxCu IN THE TILL AT THE NORDRE GJEITERYGGEN MINE. DATA ON THE MINUS-80-MESH FRACTION.







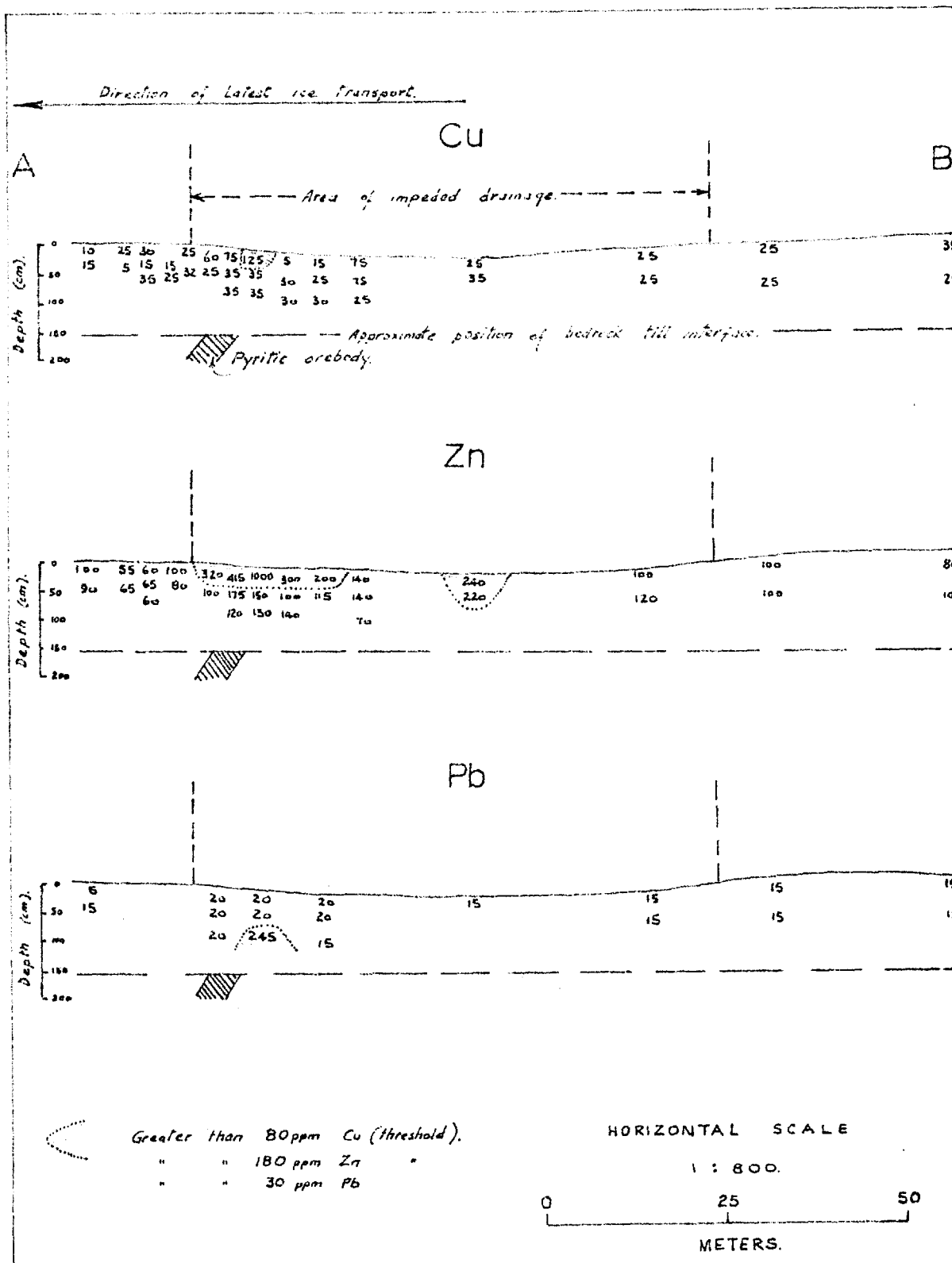


Fig.35 Sections showing the distribution of Cu, Zn and Pb in the overburden, along traverse A-B at the Nordre Gjeiteryggen mine. (Data on the -80 mesh fraction).

significant that the anomaly is most extensive downslope of the ore, i.e.: in the direction from which the latest ice moved.

2. In contrast to the dispersion of cx Cu, the Cu values are anomalous only in one sample which occurs in the organic rich horizon at the top of the profile immediately overlying the ore. However, elsewhere in the immediate vicinity near threshold values are characteristic of this organic horizon, i.e.: in the range of 60-75 ppm as compared to 5-35 ppm at greater distances from the source.

3. The distribution of Zn has a pattern very similar to Cu, being anomalous only in the organic rich horizon overlying the ore. In this layer the values vary between 202 and 1100 ppm (up to 5 times threshold). The water-logged moraine occurring below the organic horizon, and above the ore contains background quantities of Zn.

4. Pb is entirely at background concentration (0-20 ppm) through the section studied, except for one sample at the base of the profile overlying ore. This sample contains 245 ppm Pb (20 times the upper limit of background). It may be significant that the moraine overlying the ore is found to consistently contain 20 ppm Pb. Away from the vicinity of the ore the values in the moraine are normally 15 ppm or less.

Discussion

In one major respect the dispersion patterns of the ore elements at Nordre Gjeiteryggen are similar to Tverrefjellet. Namely, in the very much greater extent of the anomalous cx Cu values compared with those for Cu, Zn or Pb. In addition, it is a matter of observation that the cx Cu anomaly is related to the groundwater being dispersed down-slope. However, the cx Cu values over the ore increase upwards to maximum in the organic rich surface layer, which is also the location of the very restricted anomalous Cu and Zn values. These features were not observed at Tverrefjellet. The accumulation of metal in the organic rich horizon may be due to biogeochemical processes. It is important to note that the moraine is waterlogged and the drainage impeded. Under these conditions it is probable that metal rich groundwater will be available to the shallow rooted plants. The absence of anomalous Pb values from the surface layer of the overburden above the ore tends to confirm that groundwater is the medium by which the ore elements are dispersed. However, the limited solubility of Pb is indicated by the very slight enrichment of the moraine immediately above the ore.

General observation has shown that the orebodies are frequently leached at sub-outcrop. The porous capping thus provided, is an excellent aquifer for the free

circulation of shallow groundwaters. It is therefore probable that substantial volumes of groundwaters are channeled through the leached ore. At Nordre Gjeiteryggen, these groundwaters would rise in the area of impeded drainage in which the sampling traverse is located. These special geomorphological features are considered to have had an important influence on the development of the dispersion patterns in the overburden at this locality.

(b). Sondre Gjeiteryggen.

The orebody is located on the brow of a hill. In the vicinity of the ore the ground slopes to the south at between 2° and 3°, but the gradient increases to 9° 30m. south of the ore. Over the mineralisation the soil horizons are fairly well developed and consist of 20 cm. of organic rich loam underlain by 20 cm. of grey leached material. This grades down into grey moraine at the top of which there is very occassionally developed an intermediate red brown B horizon. On the steep lower slope a soil profile is absent, and the surface layer is composed of grey moraine with admixed organic material.

Sondre Gjeiteryggen is different from the other mineralised localities that were studied in being located within the coniferous belt. The conifer forest over the ore has been cut back, but 30m. downslope there is a dense population of coniferous trees. It will be noted that the overburden is very freely drained, and that the movement of groundwater is in a direction opposite that of the latest ice transport (Fig.36). The dispersion of metals in the overburden was investigated in an area away from the contaminated environs of the mine shaft.

The dispersion patterns of the metals in the overburden appear in Figs. 36 and 37. The main features shown by these results are:-

(1). In the overburden north of the mineralisation, and also in profiles above the ore, the concentration of cx Cu is in the low background range (0.2 - 0.8 ppm). In the profile located 7m. south of the ore anomalous values are only detected in the soil horizons, being at maximum concentration in the surface organic layer. In the underlying moraine the cx Cu values are within the background range. At the next sample point and for

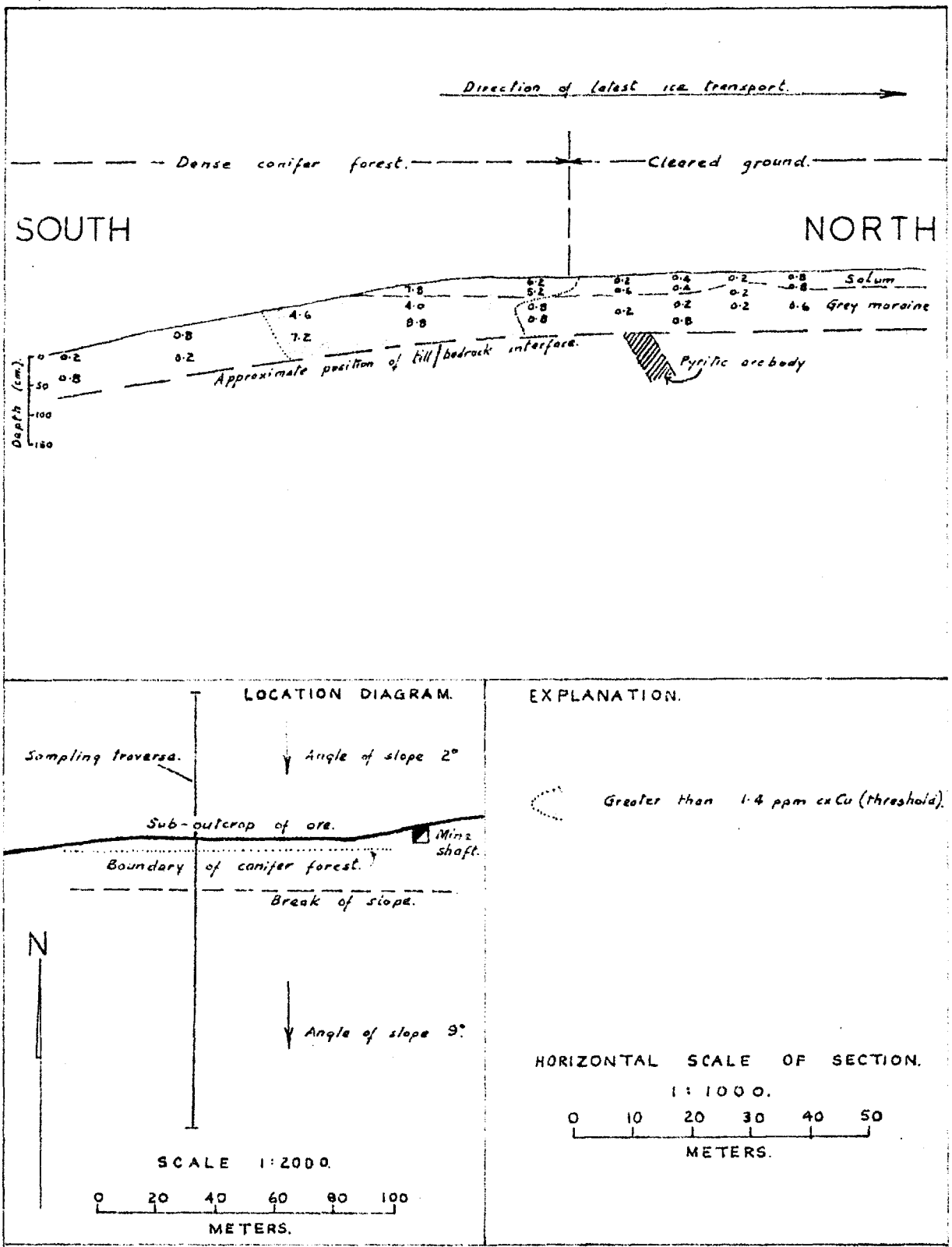


Fig.36. Location of the sampling traverse at the Sondre Gjeiteryggen mine and a section showing the distribution of exCu in the overburden. (Data on the -80 mesh fraction).

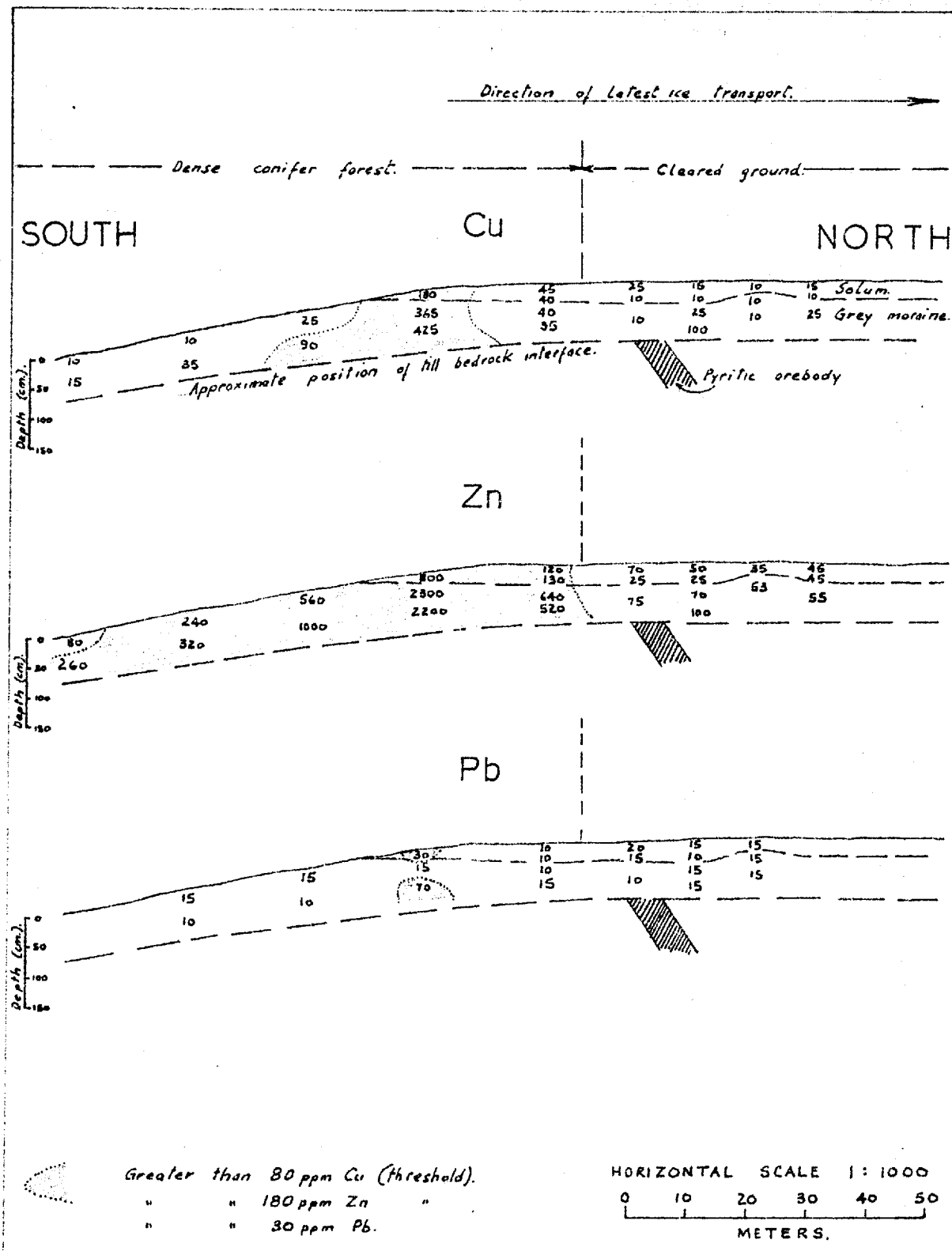


Fig.37. Sections showing the distribution of Cu, Zn and Pb in the overburden— Sondre Gjeiteryggen mine (Data on the -80 mesh fraction).

50m. downslope anomalous concentrations of cx Cu were found in both the till and soil. Within the anomaly the deeper parts of the till contain between 7 and 9 ppm cx Cu which is overlain by morphologically similar moraine containing 4 to 5 ppm. The concentrations of cx Cu is greater (5 to 8 ppm) in the soil horizons than the immediately underlying parent material.

(2). By contrast with the cx Cu results an erratically high value of 100 ppm Cu was recorded in the bottom sample of a profile located 5m. down ice movement (north) from the ore. However, the main Cu anomaly starts 30 m. south of the ore and persists downslope for a further 20 m. Maximum Cu concentrations are found in the basal part of the moraine, the values decreasing upwards with no increase in Cu content in the soils. A maximum contrast of 6 times threshold characterises the anomaly both in the moraine and in the soil. Outside the anomalous zone the Cu values are in the background range.

(3). The Zn anomaly extends for 90 m. south and downslope from the ore, being first detected in the profile located 5 m. south of the ore. The maximum Zn

values (up to 12 times threshold) occur within the first 50 m. of the anomalous zone. In any one profile the Zn values decrease in intensity towards the surface being lowest in the soil horizons. Above the ore, and upslope from it the overburden contains background quantities of Zn.

(4). The Pb results are in the background range (0 - 20 ppm) throughout the section studied except for two erratically high values. These high values occur in the same profile in which maximum values of Cu and Zn are recorded, which is located 40 m. south of the ore. At this position the overburden at a depth of 1 m. contains 75 ppm Pb, and is overlain by moraine containing 15 ppm. The attenuated soil horizon at the top of the profile is characterised by a Pb value of 30 ppm.

Discussion

The base metal anomalies are developed downslope of the ore, that is to say in the direction from which the latest ice moved. The secondary dispersion of the ore elements has therefore taken place predominently by epigenetic processes. An exception is the erratically high Cu value 5 m. north of the ore which may be evidence for ice transported ore material. The

observation however is not substantiated by the Zn or Pb data.

The major base metal anomalies located downslope of the ore are separated from the bedrock source by moraine containing base metal values in the background concentration range. Within the anomalous zones the maximum values occur at the change from the gently inclined to the strongly sloping ground. In addition the values generally decrease upwards, although the cx Cu results indicate a weak enrichment in the soil horizons compared with the immediately underlying moraine.

The anomalous metal patterns in the moraine may be related to the migration of mineralised groundwaters which at the break in slope possibly have a strong horizontal component of movement. It is also possible that downslope creep of the overburden has contributed to the anomalous patterns. However, the deeply rooted coniferous forest growth is a factor which has probably, (a) minimised the extent of gravity movements, and (b) assisted in the upward migration of anomalous groundwater.

A "barren gap" separating the bedrock source from the anomalies in the overburden has also developed at Tverrefjellet, for example in trench 1. However, the

very much greater extent of the anomalous Zn values compared with those of Cu or cx Cu is a distinctive feature characteristic of Sondre Gjeiteryggen. The significance of the very well developed Zn anomaly is not understood, although it may be due, in part at least, to the high Zn tenor of the Sondre Gjeiteryggen ore (i.e. 4.35% Zn, as compared to 1.5% Zn in the Tverrefjellet ore and 3.08% in the ore at Nordre Gjeiteryggen).

(c). The Grimsdal orebody.

At Grimsdal the ground is rather flat lying, and the local topography is dominated by a small, almost conical hill at an elevation of 1112 m. above sea level. The area is drained by the Veslgaasaai which flows to the north. Widespread deposits of glacio-fluvial sand and gravel overlie ground moraine which is exposed only on the more elevated ground. The ore sub-outcrops in the hill below 1 to 2 m. of ground moraine and also occurs across the valley to the east where it is overlain by a variable thickness of sand, gravel and moraine (Fig.38). On the west side of the hill, at least the basal ground moraine above and downslope of the ore is

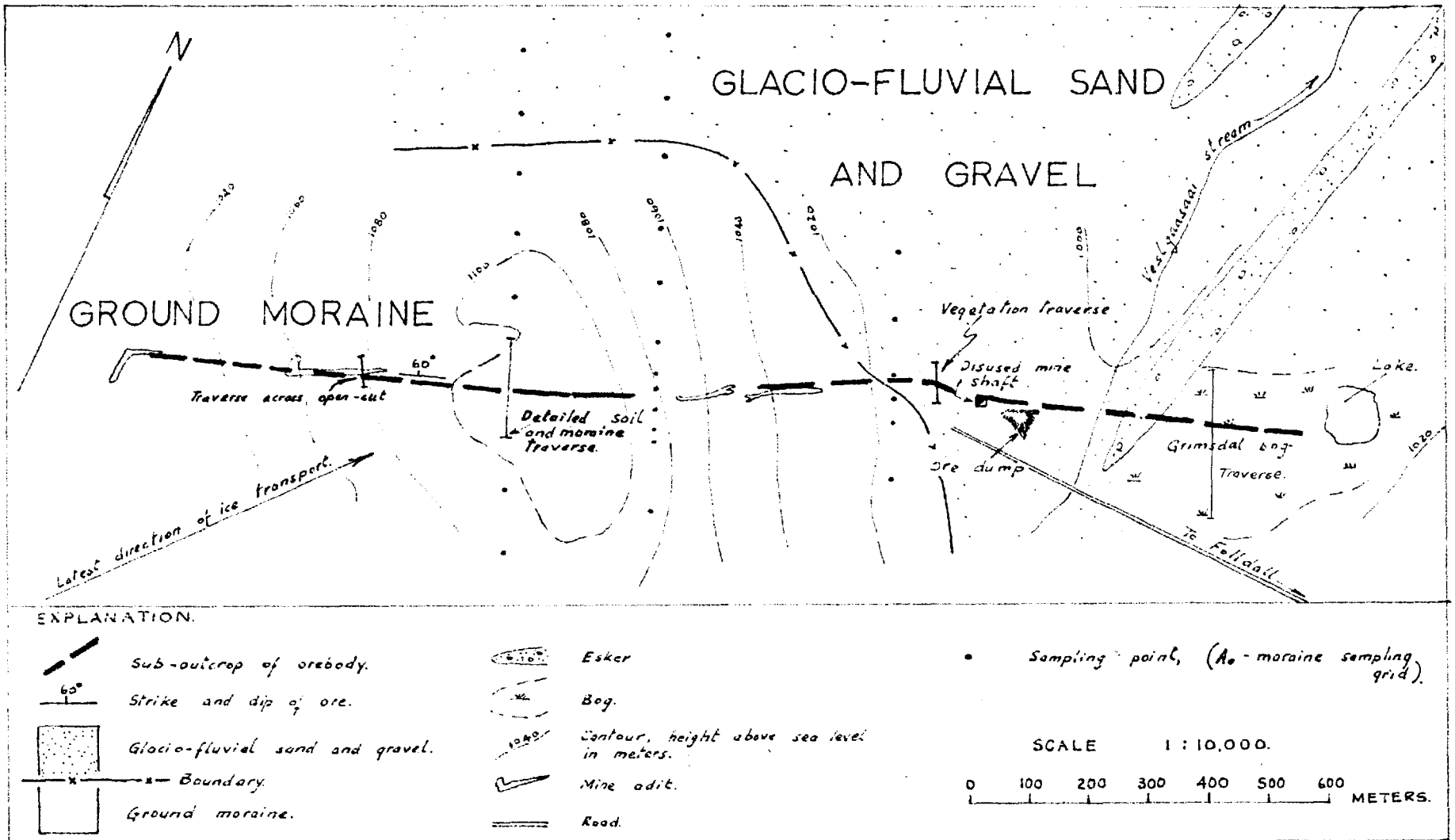


Fig.38. Plan showing the geology and physical features of the area surrounding the Grimsdal orebody, and the location of sampling traverses.

cemented by secondary iron oxides. In this vicinity the ore has been exposed in a series of old adits with consequent contamination of the surface. The ore on the east side of the hill has also been exposed in a number of places in more recent times. Accordingly the geochemical studies were largely confined to the top of the hill where the sub-outcrop of the ore has not been disturbed by mining, and where contamination does not appear to be an important factor. It should be mentioned that the old mine workers restricted their activities to the western side of the hill where there are surface indications of underlying ore. Mining from adits and open-cuts was mainly practised and the ore was hand picked. A reduction in the grade of the ore seems to have influenced the life of the old mining operations which ceased without prospecting for ore on the top or eastern side of the hill.

The weathered ore, its wall rocks and the secondary iron oxides were sampled in the old exposures. In the weathered ore the Zn content was found to be in excess of 1%, Pb up to 3200 ppm and Cu at a maximum of 1500 ppm (Fig. 39). The

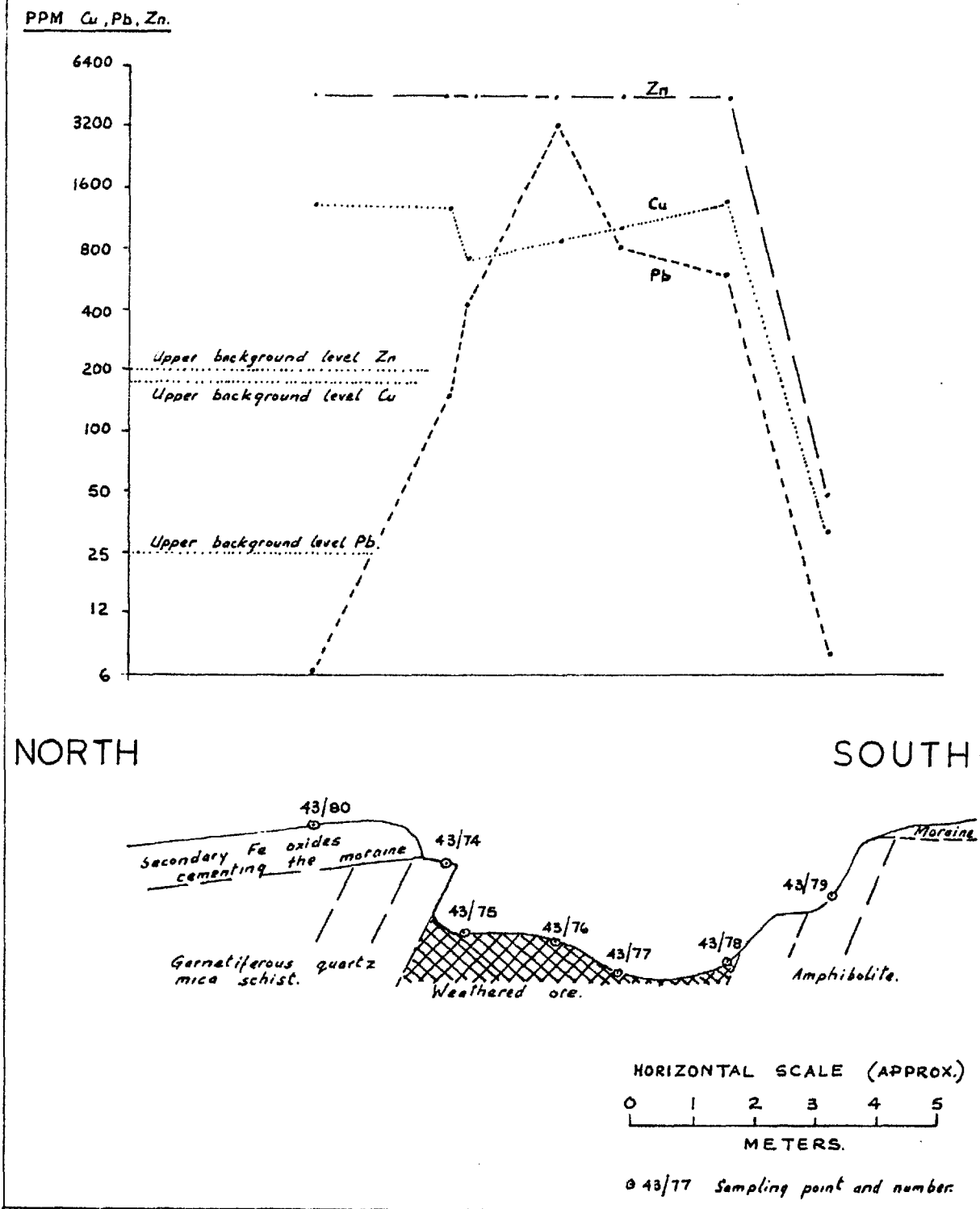


Fig.39. Transverse section of an open cut in the ore at Grimsdal showing the variation in metal content of the weathered ore, wallrocks and secondary iron oxides. For location of traverse see Fig.38. (Data on the rocks ground to -80 mesh).

wallrocks upslope of the ore contain background concentrations of the base metals. Downslope of the mineralisation the wallrocks are overlain by secondary iron oxides which cement the basal part of the ground moraine. At this location both the wallrocks and the secondary iron oxides contain Cu and Zn of the same tenor as in the weathered ore. However, the Pb content of the wallrocks is up to 150 ppm, whilst extremely low Pb values (7 ppm) are characteristic of the ferruginous moraine.

Detailed sampling has shown that in the study area the soil overlying ground moraine is composed of two horizons with a total thickness of 30 cm. The surface layer, 10 cm. thick consists of grey semi-organic loam, and is underlain by a red brown sandy loam which grades down into the moraine.

The dispersion patterns of the ore elements in the overburden were investigated by a detailed auger traverse and a Ao soil and morane sample grid (Fig.38). The analytical data is shown in Figs. 40, 41 and 42. Pb is omitted from the diagrams since it has no anomalous dispersion pattern within the area sampled; the maximum Pb value being 7 ppm.

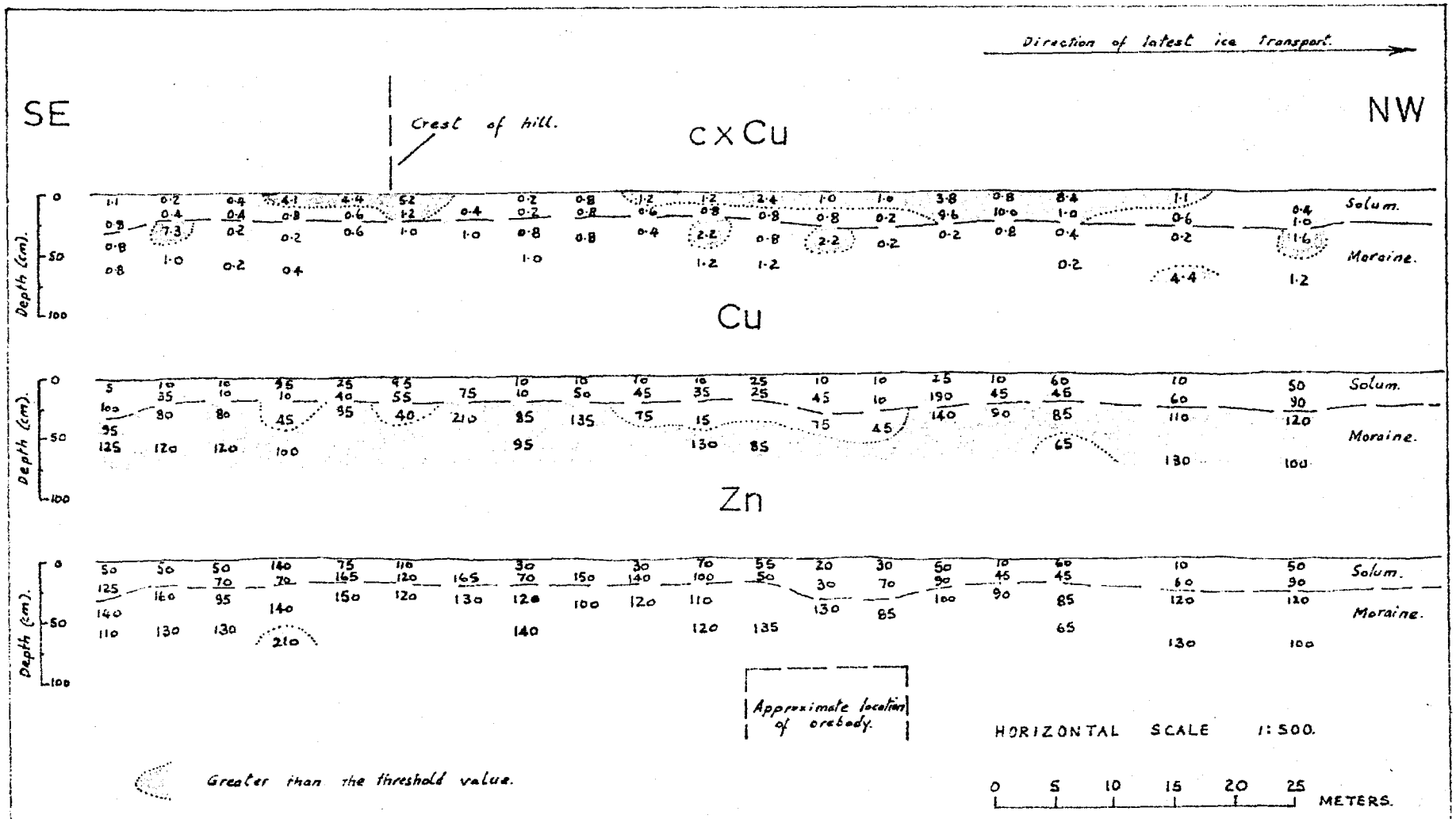


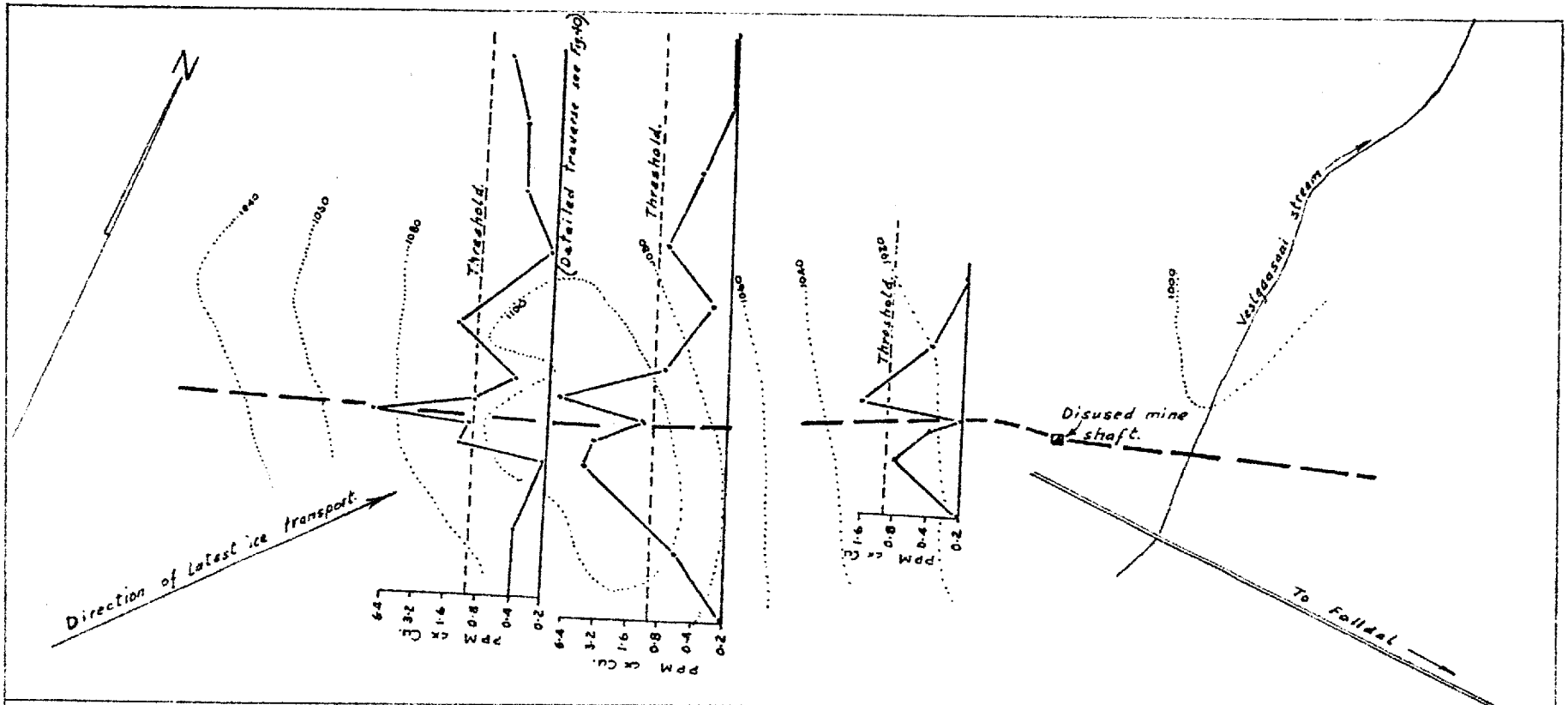
Fig.40. Sections showing the distribution of cxCu, Cu and Zn in the overburden in a detailed traverse over the sub-outcrop of the Grimsdal orebody. For location see Fig.38. (Data on the -80 mesh fraction).

From the analytical data the following features are noted:-

(1) In the detailed traverse the soil horizons contain a cx Cu anomaly which overlies the ore and extends for 20 m. downslope to the north. A second soil anomaly separated from the first by background values occurs some 25 m. downslope of the ore to the south. The anomalous values are contained largely in the upper grey semi-organic layer where the cx Cu content varies erratically up to 18 ppm. The high values in certain places persist into the red brown loam at the base of the soil.

Anomalous cx Cu values of low order (2.2 ppm) occur in the moraine immediately over the ore. A separate zone 15 m. to the north and downslope of the mineralisation, contains anomalous values up to 5 ppm (3.5 times threshold). Elsewhere in the moraine the cx Cu values are in the low background concentration range (0.2 to 1.0 ppm).

(2) The areal distribution of cx Cu as illustrated by the grid samples in the semi-organic top soil shows the anomaly to be superimposed above the sub-outcrop of the ore (Fig.41). The anomaly is up to 150 m. in width, and was traced over a strike length of 250 m. Three salient features characterise the anomaly:-



EXPLANATION

Sub-outcrop of orebody.

1100 Contour height above sea level in meters.

Road.

Graphical presentation of the cxCu content of the A_o soil horizon.

Line of traverse.

SCALE 1:10,000.

0 100 200 300 400 500 600 METERS.

Fig.4I. Plan showing the cxCu content of the A_o soil horizon over the sub-outcrop of the Grimsdal orebody. (Data on the -80 mesh fraction).

(a) the apparent random distribution of erratically high values,
(b) the increase in the anomaly width down the eastern flanks of the hill, and
(c) the disruption of the anomaly into two segments over the ore on the crest of the hill.

(3) In the detailed traverse the Cu contents of the moraine were predominantly above the threshold level of 80 ppm with values up to 200 ppm (2.5 times threshold). However, erratic zones containing less than 80 ppm occur within the section. In the soil horizons the basal layer over the greater length of the traverse is weakly anomalous with respect to Cu. The values decrease upwards and in the semi-organic layer at the surface the Cu content is predominantly within the background range (5-30 ppm).

(4) The distribution of Cu in the moraine grid at a depth of 1 m. (Fig.42) shows the 80 ppm isopleth to outline an area of anomalous values over an extensive area about the sub-outcrop of the ore. The low order anomaly extends downslope to the east, spreading north and south down the flanks of the hill.

(5) In the moraine investigated in the detailed traverse Zn occurs predominantly within the background concentration

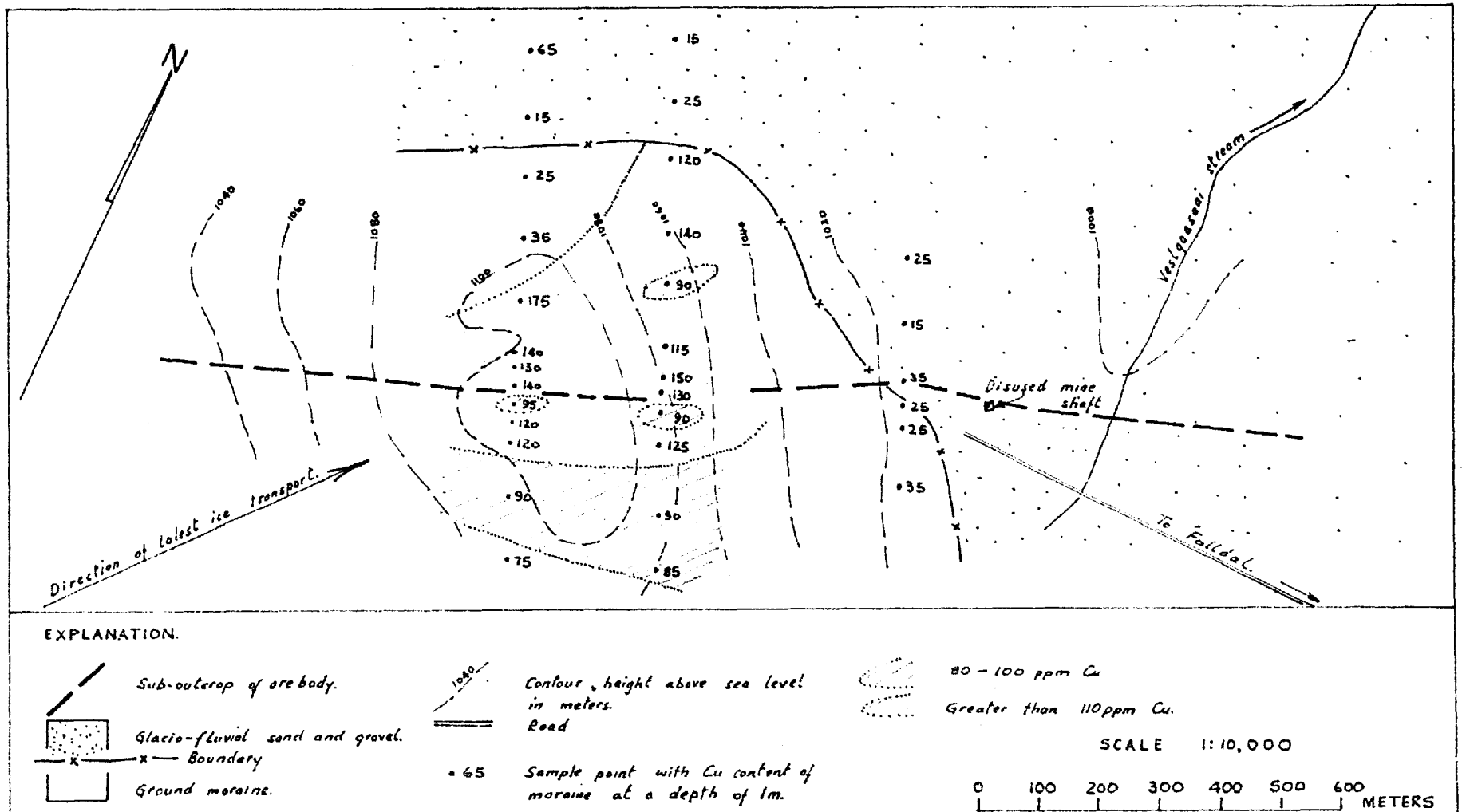


Fig.42. Plan showing the distribution of Cu in the moraine at a depth of Im. (below the surface), over the sub-outcrop of the Grimsdal orebody. (Data on the -80 mesh fraction).

range (0-180 ppm). In the soil, the values vary between 10 and 90 ppm, but erratically high values are noted, particularly in the red brown loam to the south of the ore (Fig.40).

Discussion

The observations on the moraine recorded above, cannot be readily explained on the basis of either a syngenetic or epigenetic theory.

If the dispersion is syngenetic it would be expected that Pb and Zn would be associated with the Cu anomaly if the weathered ore was the source. Even if the dispersion was from an earlier till cemented with iron oxide, Zn and Cu anomalies would be expected to be co-extensive. Nevertheless, the shape and orientation of the low order Cu anomaly suggests a relationship to the movement of the latest ice, subsequently modified by gravity creep. If these criteria of origin are valid it may be suggested that the pre-glaciation products of ore oxidation were rich in Cu but low in Zn and Pb. It is equally possible that Zn has been subsequently leached from the moraine.

Additional field and laboratory studies are required to determine the origin of the Cu anomaly. This was not possible in the time available to the writer.

The cx Cu anomaly in the Ao horizon of the soil profile outlines an extensive area around the sub-outcrop of the ore. As the secondary enrichment of cx Cu has taken place in the organic rich surface layer, it is probable that the dispersion is controlled in part at least by biogeochemical processes. Of particular significance is the fact that the high cx Cu values have an apparent random distribution. The mechanical disruption of the Ao horizon would not be inconsistent with the geochemical data, and solufluxion movement may be an important factor in the development of the anomaly.

One of the pre-requisite conditions necessary for solifluxion to take place is an alternate freeze-thaw process in the overburden. In the exposed position of the hill top this condition will almost certainly be met.

An additional factor is the upward migration of groundwaters during freezing of the overburden. For example, at Tverrefjellet the study has indicated the probability that groundwater may be raised through the overburden by the formation of ice in the profile. Consequently at Grimsdal where the overburden on the hilltop appears to be no thicker than 2 m. (as compared to 3m. at Tverrefjellet) it is possible that small quantities of

metal rich groundwaters would be available to the shallow rooted plants. However, the depth to the water table on the hilltop at Grimsdal is not known.

BIOGEOCHEMICAL DISPERSION OF ORE ELEMENTS

In certain parts of the study area, it appears that biogeochemical processes are of some importance in the secondary dispersion of ore elements. For example, at Nordre Gjeiteryggen over the ore, the organic rich top soil contains higher concentrations of the ore elements than the underlying moraine. For this reason, the metal content of plant material was investigated, the study being limited to the twigs of Betula nana. This plant was sampled in preference to other species because of its tolerance to a wide range of conditions. In this connection it is of interest to note that Betula nana is found even in the highly toxic environments of ferruginous moraine, intolerable to many other species.

The metal content of Betula nana twigs from unmineralised areas (Table 22) shows that even in this environment the species characteristically contains very high concentrations of Zn (and to a lesser extent Fe). This agrees with the results of other workers (Vogt et al 1943), and confirms that in the Hjerkinn-Fǿlldal area the dwarf birch is an accumulator plant with respect to Zn. This may be partly the reason for the very wide range in the Zn content (Table 22). However Cu and Pb are not en-

riched to any appreciable extent in the plant material from unmineralised areas.

TABLE 22. Metal Content of Betula nana Twigs from Unmineralised Localities (Background areas 'A' & 'B')

No. of Samples 20	Metal Content of Dried Plant Material ppm			
	Cu	Pb	Zn	Fe
Minimum	3.5	0.3	220	100
Average (arithmetic mean)	4.5	0.5	400	150
Maximum	5.3	0.7	720	240

In order to comment on the data the maximum values (Table 22) have been arbitarily selected as the upper background levels for the metals.

Metal Content of Betula nana Twigs over Mineralisation in the Hjerkinn-Fǿlldal area

(a) Hjerkinn

At Hjerkinn the dispersion of ore elements in the twigs of Betula nana was investigated over transects land 2 (Figs.43 and 44). Transect 1 was extended to the north to include vegetation occuring over the secondary iron oxide body in the moraine.

Transect 1.

Over the ore zone the concentrations of the base metals and Fe in the plant material corresponds to the upper background levels. The values decrease downslope to the north.

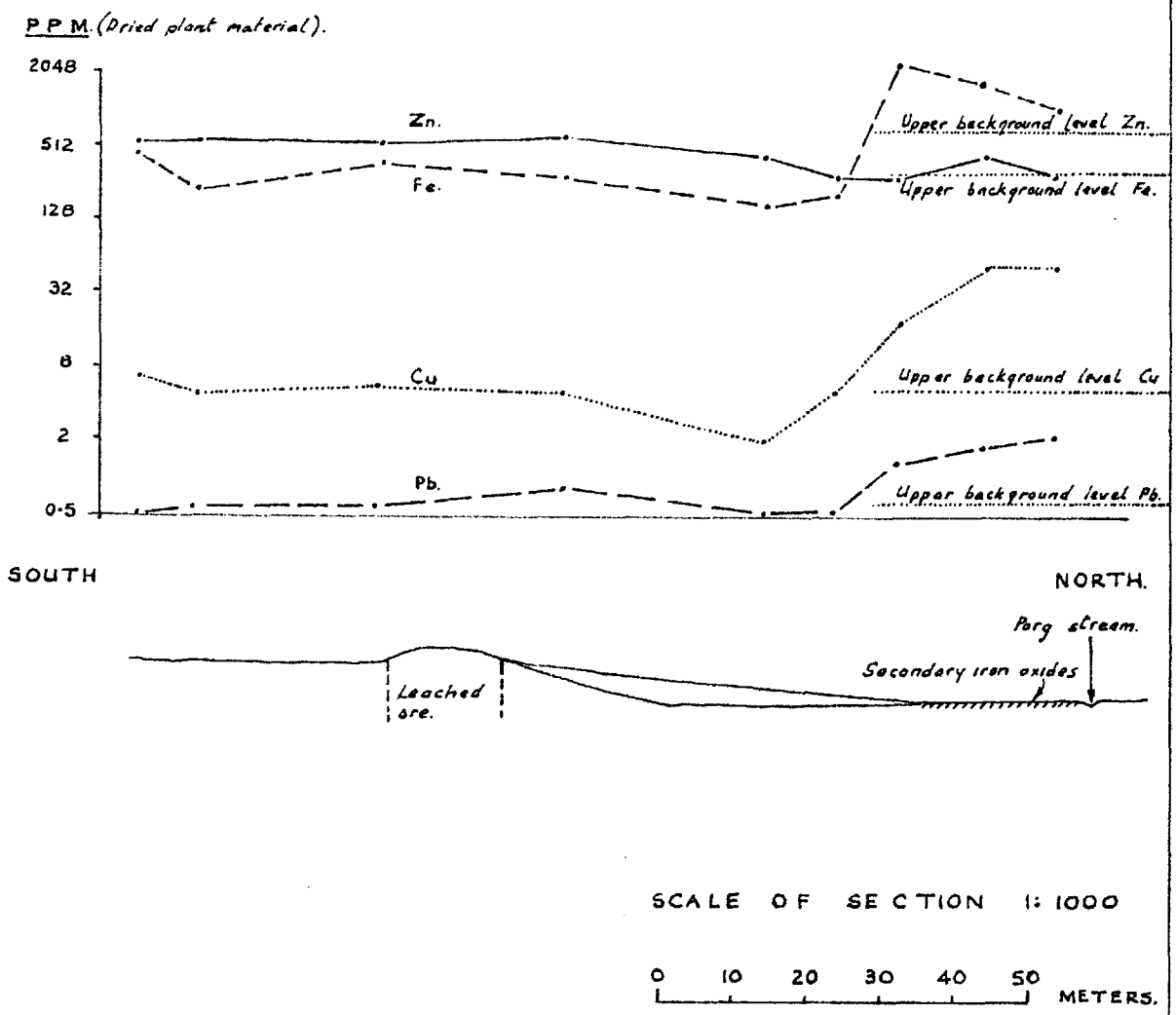


Fig.43. Variation in the metal content of Betula nana twigs taken from the line of Trench I, Tverrefjellet. (data reported as ppm of dried plant material).

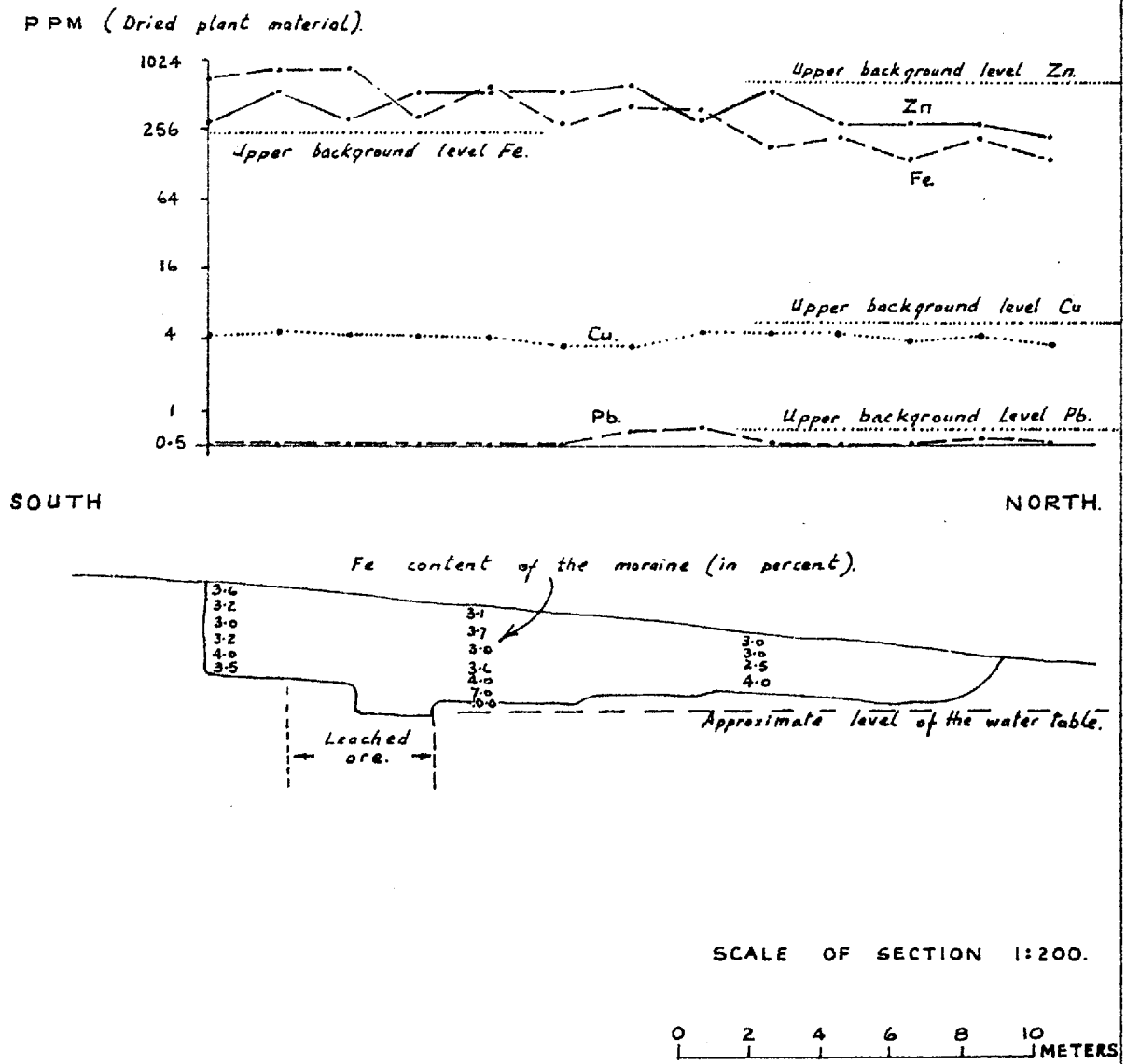


Fig.44. Graphical presentation of the metal content of Betula nana twigs taken from the line of Trench 2, Tverrefjellet, (data reported as ppm of dried plant material). The Fe content (in percent) of the overburden in Trench 2 is shown in the section. (Data on the -80 mesh fraction).

However, in the plants growing on the iron oxide body 55 m. north of the ore the Pb, Cu and Fe contents are respectively 3, 8 and 11 times the upper background levels. By contrast Zn is in the background range.

Transect 2.

Analysis of Betula nana twigs from this transect shows that Cu, Pb and Zn are within the background range (Fig.44). The base metal values show small variations which do not appear to have any significance. However, the Fe concentration increases steadily from north to south reaching a maximum of 800 ppm (3 times the upper background level) over the sub-outcrop of the ore. At this point the overburden is freely drained and is 3.5 m. thick. In addition there is no evidence of Fe enrichment in the surface layers of the overburden (Fig.44). However, the steady increase in the Fe content of the Betula nana twigs upslope, to maximum values over the ore does not appear to be consistent with contamination.

(b) Nordre Gjeiteryggen

Over this transect the metal content of the twigs of Betula nana growing in boggy conditions is erratic, particularly in Pb (Fig.45). For example immediately over the ore one plant specimen contained background concentrations. In general, however, the Pb content in

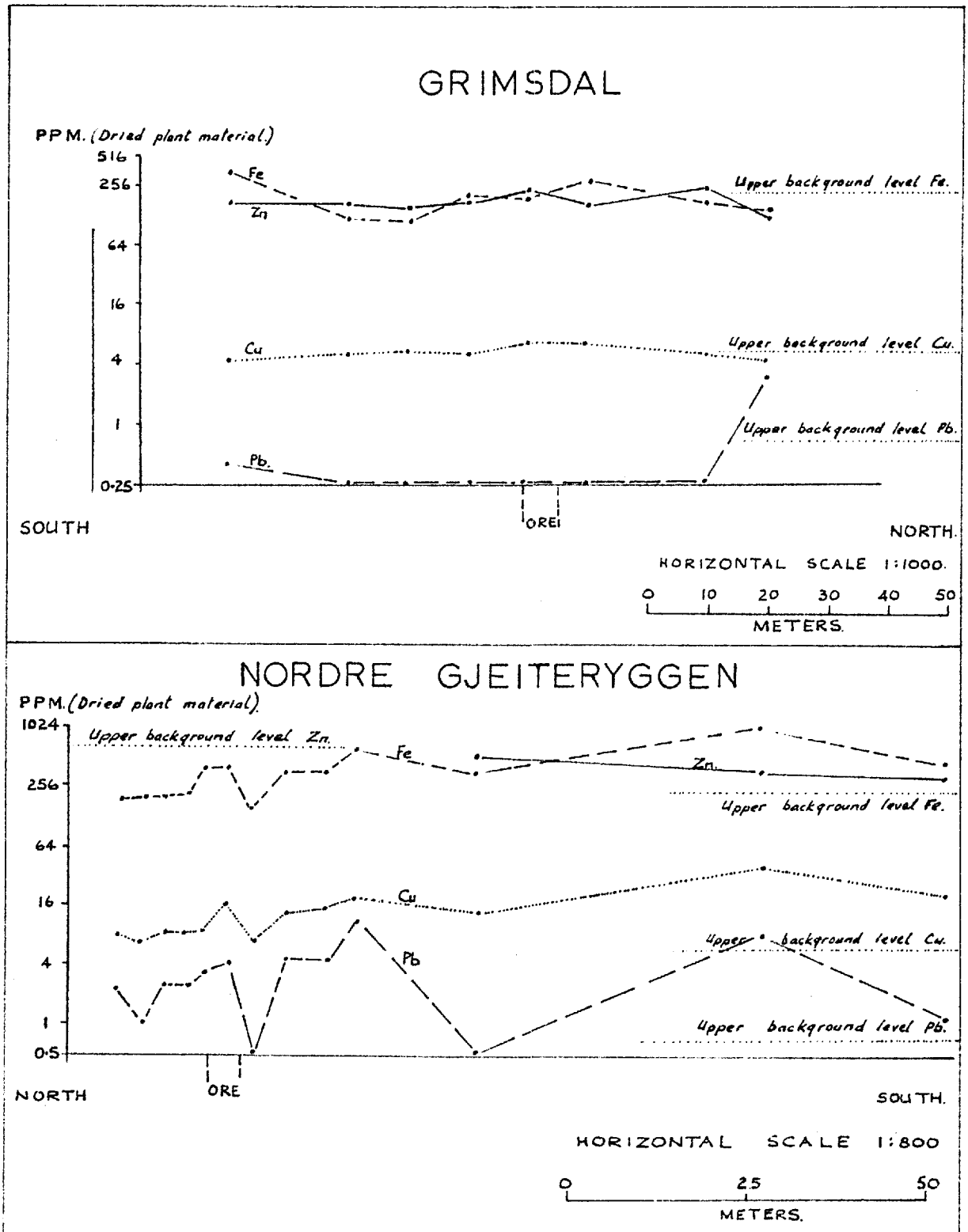


Fig.45. Graphs showing the metal content of Betula nana twigs from the vicinity of sub-outcropping ore at Nordre Gjeiteryggen and at Grimsdal. Data reported as ppm of dried plant material.
(The location of the Nordre Gjeiteryggen traverse is shown in Fig.34, and the Grimsdal traverse in Fig.38.)

the vicinity of the ore varies between 3 and 15 times the upper background level. The values approach background on both sides of the ore zone, but are again erratically high 100 m. south of the ore. Cu and Fe are just above the upper background levels over the mineralisation but the concentrations increase away from the ore to the south, to 6 and 4 times the upper background levels respectively. In the samples analysed for Zn the values are within the background range.

The variation in the metal content of the Betula nana twigs does not appear to bear any relationship to the distribution of metals in the overburden (compare Figs. 34 and 35).

(c) Grimsdal

The main geochemical studies were largely carried out on the top of the hill away from the contaminated areas. However, in this exposed position Betula nana was absent and a transect was sampled at the foot of the hill. The results of analysis are shown in Fig.45.

The Pb and Zn content of the plant material are within the background range except for one erratically high Pb value at the northern end of the transect. Cu and Fe concentrations are at the upper background level.

Discussion

Many plants can take up metals that are in groundwater solution. In addition elements not originally in solution may be dissolved by processes taking place at the tips of plant rootlets (Keller and Frederickson, 1952). The elements taken up are transported to the plants aerial parts to be returned to the surface soil on the death and decay of the leaves and other vegetal matter (Tooms 1965).

The twigs of Betula nana were found to contain anomalous concentrations of Cu, Pb and Fe only in the mineralised areas where the water table was near the surface, For example, at Tverrefjellet in transect 1, and also at Nordre Gjeiteryggen. In other localities underlain by ore, but where the water table was deep, Betula nana twigs were not enriched in metal. However, an exception was found at Tverrefjellet in transect 2 where an Fe anomaly occurs in Betula nana twigs growing over the ore. The anomaly in this location is not understood since the groundwater table is 3.5 m. below the surface, and the plants are rooted in material containing background quantities of Fe. Even in the mineralised areas where the water table is near surface, the plant anomalies tend to be very erratic and show little

comparison with the distribution of ore elements in the overburden. Nevertheless at Grimsdal and Nordre Gjeiteryggen well developed anomalies in the Ao soil horizon occur above the sub-outcrop of the ore. In view of the lack of correlation between the metal content of Batula nana twigs and the soil anomalies, it is possible that other plant species are more important to the biogeochemical process in these areas.

From a practical point of view, the shallow rooted tundra vegetation in the Hjerkinn-Folldal area is not a suitable medium for prospecting through deep transported overburden. Observations on the depth to which the rootlets penetrate suggests that groundwaters deeper than 50 cm. below the surface could not be available to the plants. Vogt (1943) investigated the metal content of various plants of the tundra flora in the Röros district of Norway. He concluded that "the determination of Cu and Zn in plants does not seem to be very useful as an ore prospecting method", in the Röros district.

Unfortunately the coniferous trees occurring at Sondre Gjeiteryggen which may tap the deep groundwaters, were not sampled. However, despite the deeply rooted vegetation the Ao soil horizon is only weakly enriched in cx Cu when compared to the accumulation of metal in the organic rich layer at Nordre Gjeiteryggen, or at Grimsdal.

SUMMARY OF CONCLUSIONS ON THE DISPERSION OF ORE ELEMENTS IN THE OVERBURDEN (excluding bogs) IN THE HJERKINN-FOLLDAL AREA

1. The overburden in unmineralised areas is leached to a depth of 1 m. In particular the removal of Cu is noted, whilst Zn tends to be the least affected. The evidence indicates that Zn is to some extent retained in the soil horizons in organic complexes, being first enriched in Zn accumulator plants.

2. The moraine occurring in the Hjerkinn-Folldal area is siliceous. In the area studied the moraine is essentially uniform with respect to some physical properties, for example, pH, exchangeable metal and carbonate content.

3. In the vicinity of mineralisation syngenetic (i.e. mechanical) dispersion is apparently of minor importance. At Tverrefjellet an ore boulder train consisting of four known boulders extends over a distance of 5 km. down-ice from the ore. Evidence for a micro-boulder train in the moraine near the orebody is lacking. At Nordre and Sondre Gjeiteryggen the geochemical data is inconsistent with syngenetic dispersion. At these localities there are no ice-transported ore boulders known to the writer.

4. At Grimsdal, the low order Cu anomaly in the moraine has a shape and orientation which suggests a relationship

to the latest ice movement. The anomalous Cu is relatively strongly bonded, but coincident Pb and Zn anomalies are lacking. The evidence is inconclusively in favour of syngenetic dispersion of the pene-ultimate products of ore oxidation and weathering.

5. The distribution patterns of the ore elements in the moraine at Tverrefjellet, Sondre and Nordre Gjeiteryggen are indicative of epigenetic (i.e. hydromorphic) dispersion. The evidence for this process is particularly striking at Sondre and Nordre Gjeiteryggen where the base metals are dispersed downslope. That is to say, in the direction from which the latest ice moved.

6. At Tverrefjellet, the slope and latest ice transport direction coincide. The striking features of the dispersion of the anomalous metal is the much greater extent of the cx Cu values compared with those of Cu or Zn. In addition anomalous Pb values are generally absent. The ratios of Cu : Zn : Pb in the primary ore, the gossan and the anomalous moraine indicate the importance of chemical rather than mechanical processes in the secondary dispersion of the ore elements.

7. The local conditions which determine the movement of groundwaters appears to have had an important influence

on the mode of dispersion of the ore elements in the overburden. For example, at Tverrefjellet in trench 2 the bedrock surface and groundwater table approximately coincide. In the moraine Cu, Zn, Fe and $SO_4^{=}$ show a vertical partition, the Cu values increasing upwards to a sharp cutoff. In trenches 1 and 3 the metal values decrease upwards. In these localities the bedrock surface dips at fairly steep angles and the profiles are relatively well drained.

At Nordre Gjeiteryggen anomalous concentrations of metal are dispersed downslope, a considerable distance from the source in an area of impeded drainage.

8. There is some evidence to suggest that the formation of ice at fairly shallow depths in the overburden induces the upward migration of small quantities of groundwater. This process may explain the weak cx Cu anomaly in the moraine at Tverrefjellet (trench 2) which is surrounded by moraine containing background concentrations of the base metals.

9. The Ao soil horizon has been enriched in metals where it occurs above mineralisation at Nordre Geiteryggen and Grimsdal. To a lesser extent a surface enrichment has occurred at Sondre Gjeiteryggen and also at Tverrefjellet in trench 1. In particular cx Cu has

accumulated in the organic rich surface layer, although at Nordre Gjeiteryggen substantial quantities of Zn are also present. The metals are thought to have accumulated in the surface layer of the soil profile by biogeochemical processes. The flora is of the shallow rooted variety (except at Sondre Gjeiteryggen), and at Nordre Gjeiteryggen the plant rootlets are in contact with the near surface groundwaters. At Grimsdal the moraine is thin (i.e. 1 to 2 m.) and mineralised groundwaters are thought to have been transferred to the soil horizons from the deeper parts of the overburden by ice formation, (although the position of the groundwater table is not know). The freeze-thaw process is the basic mechanism for the solifluxion movement of surface materials which may explain the distribution of the erratic high cx Cu values in the Ao soil horizon at Grimsdal.

10. The tundra flora is composed of shallow rooted species which in general do not provide a suitable medium for prospecting through deep transported overburden. In particular, the metal content of the twigs of Betula nana do not show any consistent relationship to sub-outcropping ore, or to the Ao soil anomalies. An understanding of the biogeochemical process would require the careful study of all plant species within the area.

DISTRIBUTION OF ORE ELEMENTS IN THE COMPONENTS OF THE DRAINAGE AND BOGS

In the following pages data are presented on the distribution of ore elements in groundwaters, surface waters, stream sediments, banks and bogs at Tverrefjellet. The secondary dispersion processes in the groundwaters are discussed after presentation of the relevant data. However, the full discussion of the correlations between the various media is deferred until all the data has been presented. After the discussion of the Tverrefjellet drainage data, there is a section dealing with the distribution and dispersion of ore elements in the drainage and in a bog in the vicinity of the Grimsdal orebody. A summary of conclusions on the dispersion processes of ore elements in the components of the drainage completes the section.

The official maps of the Hjerkinn area leave many of the streams un-named. Accordingly the four small streams draining the area surrounding the Tverrefjellet orebody have been named by the writer: the Porg, Rekse, Dloc and Grouback (Fig.46).

The sub-outcrop of the Tverrefjellet orebody is located on the north side of the broad open Tverrefjellet

valley. The valley floor slopes to the north east at between 5 and 8° and abuts onto low, rather flat lying ground. In the valley the drainage is carried by three streams the Porg, Dloc and Grouback which are tributaries of the Grisungbekken (Fig.46). The Dloc and its southern tributary, the Grouback drain the south part of the valley which is underlain by essentially unmineralised rocks. A low divide separates the Dloc-Grouback system from the catchment area of the Porg stream. The Porg stream rises in the secondary iron oxide mass located downslope from the swallow hole in the orebody. Some 800 m. from its source the Porg stream flows over a steeply sloping outcrop and at high water it divides into two distributors. The eastern flowing distributor, the Rekse stream is an overspill channel, the greater part of the drainage being carried by the parent Porg stream flowing to the north.

On the low ground impeded drainage has given rise to boggy conditions around all the streams, which give their names to the individual bogs (Porg bog, Rekse bog and Dloc bog). All the streams mentioned flow over glacial deposits, only rarely exposing bedrock.

DISPERSION OF ORE ELEMENTS IN GROUNDWATERS

(i) Background

A regional study of the characteristics of near surface groundwaters at a distance of several kilometers from unmineralised ground was not undertaken. The assessment of the variations in the properties of background groundwaters (Table 23) is based on three samples from the immediate vicinity of Hjerkinn. The figures are, therefore, of a provisional nature.

TABLE 23

Properties of Near Surface Groundwaters from Barren Ground

	Total Metal ppb		Ionic Metal ppb	
No. of Samples : 3	Cu	3-9	Cu	c.8
pH 6.8 - 7.3	Zn	18-30	Zn	13-40
$SO_4^{=}$ 2.5-5 ppm.	Pb	c.3	Pb	c.2
	Fe	188-260		

The data (Table 23) suggests that the metal is to a large extent in an ionic state. This possibly reflects a lack of dissolved organic matter possessing chelating properties and may correlate with the general observation that the organic layer of the soil is in an undecomposed condition.

(ii) Properties of Groundwaters in, and Deriving from the Tverrefjellet Orebody

(a) Deep Groundwaters

The pH and metal content of groundwaters taken from the underground workings of the Tverrefjellet mine, over the sub-outcrop of the ore and from sites immediately adjacent to the Porg-Grisungbekken drainage system are compared in Table 24. The location of the sample sites is indicated in Fig.46.

In the mine, deep groundwaters drainage through fractures in the orebody were collected on level 1, 60-80 m. below the sub-outcrop of the ore (Sample 43/5393 and 43/5395) and on level 2, 160 m. below the surface (Sample 43/4575). This latter sample location is vertically beneath the oxidised and collapsed section of the orebody. However, the sample site is located in barren rock exposed on the western side of a fault zone which throws to the east. The ore although located immediately above (as evidenced by surface drill holes) pinches out at a fairly shallow depth below the surface. The groundwaters represented by sample 43/4575 may not be related to the groundwaters passing through the ore.

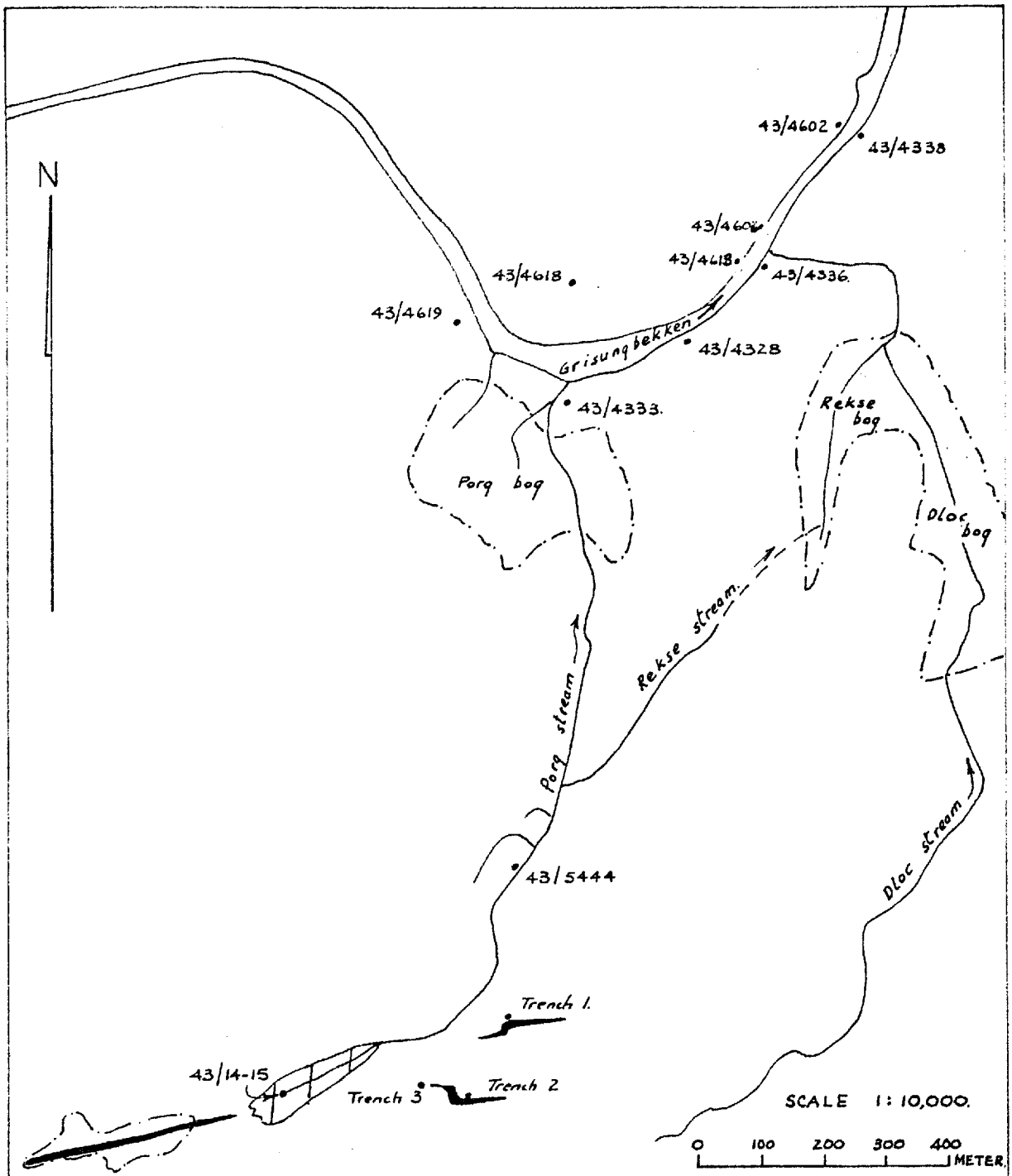


Fig.46. Plan showing the loction of near surface groundwater samples taken adjacent to the Porg-Grisungbekken drainage system.

TABLE 24

Properties of Groundwaters in, and Down-drainage of the Tverrefjellet Orebody

A. - Deep groundwaters from underground workings of the Tverrefjellet mine.

B. - Shallow groundwaters from sub-outcrop of the ore.

C. - Near surface groundwaters from sites immediately adjacent to the Porg-Grisungbekken drainage system.

Sample No.	Location	pH	METAL CONTENT ppb				Distance down drainage from head Porg stream (Meters)
			Cu	Zn	Pb	Fe	
A..							
43/4575	Level 2	8.0	15*	5*	1.5*	600*	
43/5393	Level 1	6.4	7	24	6	60	
43/5395	Level 1	5.9	15	18	3	48	
B.							
Trench 1	Sub-outcrop of ore	3.8	69*	214*	6.8*	18000	
" 2	Sub-outcrop of ore	6.3	8.6*	6.0*	1.4*	1000	
" 3	Sub-outcrop of ore	5.5	92*	90*	2.0*	18500	
C.							
43/14-15	Top Porg Stream	2.5	18400*	23000*	640*	360000*	0
43/5444	Middle Porg Stream	4.6	460	1520	2	120	700
43/4333	Lower Porg Stream	5.7	110*	1300*	4*	N.D.	1400
43/4328	Grisungbekken	N.D.	85*	650*	3*	N.D.	1600
43/4613	"	6.0	70	720	3	188	1750
43/4606	"	6.3	78	300	6	840	1800
43/4602	"	6.4	25	60	8	260	2000

N.B. Results are for total metals except where indicated by asterisk when ionic metal values given.

N.D. - Not Determined.

The groundwater on level 1 has a pH in the range 5.9-6.4 and contains low concentrations of the base metals and Fe. Whilst Cu and Pb are slightly higher than the normal background, Zn and Fe are in the background range. Attention is drawn to the fact that the underground development had been in existence for only one year prior to the sampling. During this interval the extent of ore oxidation appears to have been insignificant in view of the relatively high pH and low metal content of waters draining through fractures in the ore.

In comparison with the analysis of groundwater from level 1, the water obtained on the second and deeper level (43/4575) has a much higher pH (i.e. pH 8.0) and contains 10 times more Fe. The base metal contents of the groundwater from both levels are, however, essentially of the same order (Table 24). Of possible significance is the fact that the level 2 sample site is located vertically below the oxidised and collapsed ore. In this vicinity the country rocks contain anomalous amounts of Fe but background concentrations of the base metals (as previously mentioned in Part III of this report). The trace element content of the level 2 groundwater and of the rocks through

which it passes suggests a relationship between the two media. The anomalous Fe may have been derived from groundwaters descending from the oxidised ore nearer surface. However, a concomitant enrichment in base metals would be expected, which is not observed.

(b) Groundwaters at the Sub-outcrop of the Ore

Comparison of the deep groundwaters with groundwaters obtained over the sub-outcrop of the ore shows in general that in the latter environment the pH is lower and the metal concentrations higher. In trenches 1 and 3, Cu, Zn and Fe are strongly anomalous whilst Pb does not enter the composition of the groundwaters to the same extent. Trench 2 however contains groundwater of pH 6.3 with background metal concentrations. In trench 2 the groundwater was observed to be dominantly issuing from the leached gossanous capping of the ore. The analysis of the gossan (Table 13) shows it to contain high metal values which suggests that the secondary ore minerals of the gossan are essentially insoluble in water of pH 6.3. In addition it should be noted that the rock/till interface and groundwater table approximately coincide in trench 2, whilst in trench 1 the ore is well above the normal groundwater table. Under these conditions the

ore would continue to oxidise in trench 1 long after the process had been completed in the second trench.

A sample (43/14-15) was also collected of groundwater reaching surface via a series of seepages in the iron oxide mass downslope of the swallow hole in the orebody. The groundwater in these seepages very probably represents surface waters channeled through the swallow hole into the oxidising sections of the ore. The sample contains extremely high concentrations of the base metals and Fe and has a pH of 2.5 (Table 24). This confirms that the ore in this vicinity is undergoing rapid oxidation compared with the sections exposed in trenches 1, 2 and 3.

The disparity in the metal contents of the near surface and deep groundwaters within the ore zone raises the problem of the nature of the groundwater circulation. Primarily the deep groundwaters move along fractures in otherwise impermeable rocks. The primary dispersion study has not produced any evidence to show that base metals are secondarily enriched in the host rocks of the ore. The data are consistent with the view that the near surface groundwaters which have passed through the oxidised ore do not enter the deep groundwater

circulation. This would imply that the fractures in the rocks below the swallow hole are two tight for the waters to enter. In addition it is probable that the deep groundwaters within the ore zone are supplied from unmineralised, possibly distant sources. It is possible, for example, that open fractures may be sealed by ground moraine over large areas, except where the glacial deposits are permeable, or absent.

(c) Near Surface Groundwaters Immediately Adjacent to the Porg-Grisungbekken Drainage System.

A series of near surface groundwater samples were obtained from sites immediately adjacent to the Porg-Grisungbekken drainage system. The samples were taken at intervals over a distance of 2000 m. down drainage from the orebody. The results of analysis are given under section C of Table 24. The data shows that the pH rises down drainage from 2.5 to 6.4 which is accompanied in general by a decrease in the metal content. The concentrations of Fe and Pb decrease drastically over the first 700 m. Thereafter, the values show small increases down drainage which in the case of Pb is possibly due to analytical error (being at very low concentrations). The increase in Fe however is greater than the analytical

error, but the fluctuation is within the background range, except in sample 43/4606. The high Fe value of 840 ppb in this sample is not understood, but may be due to contamination. The decrease in the Cu and Zn values down-drainage however, are of a more significant nature (Fig.47).

The Cu content of the groundwaters diminish log linearly down drainage, the decrease being particularly pronounced over the first 700 m, beyond which the values decrease at a reduced rate. Zn follows Cu over the first 700 m. but between 700 and 1400 m. the Zn values remain essentially constant at approximately 1400 ppb. Between 1200 m. and 2000 m. down-drainage from the sub-outcrop of the ore the Zn values decrease to 60 ppb whilst the pH increases from 5.7 to 6.4.

The lateral spread of mineralised near surface groundwaters of the Porg-Grisungbekken drainage system was investigated at 2 locations (Fig.48 and Table 25). On the Porg stream the sampling location was 700 m. from the source where the stream is flowing through a well defined and open valley. The valley of the Grisungbekken is very open, particularly on the north bank where the ground is low lying and boggy. Samples of groundwater were taken at critical locations on the north and south

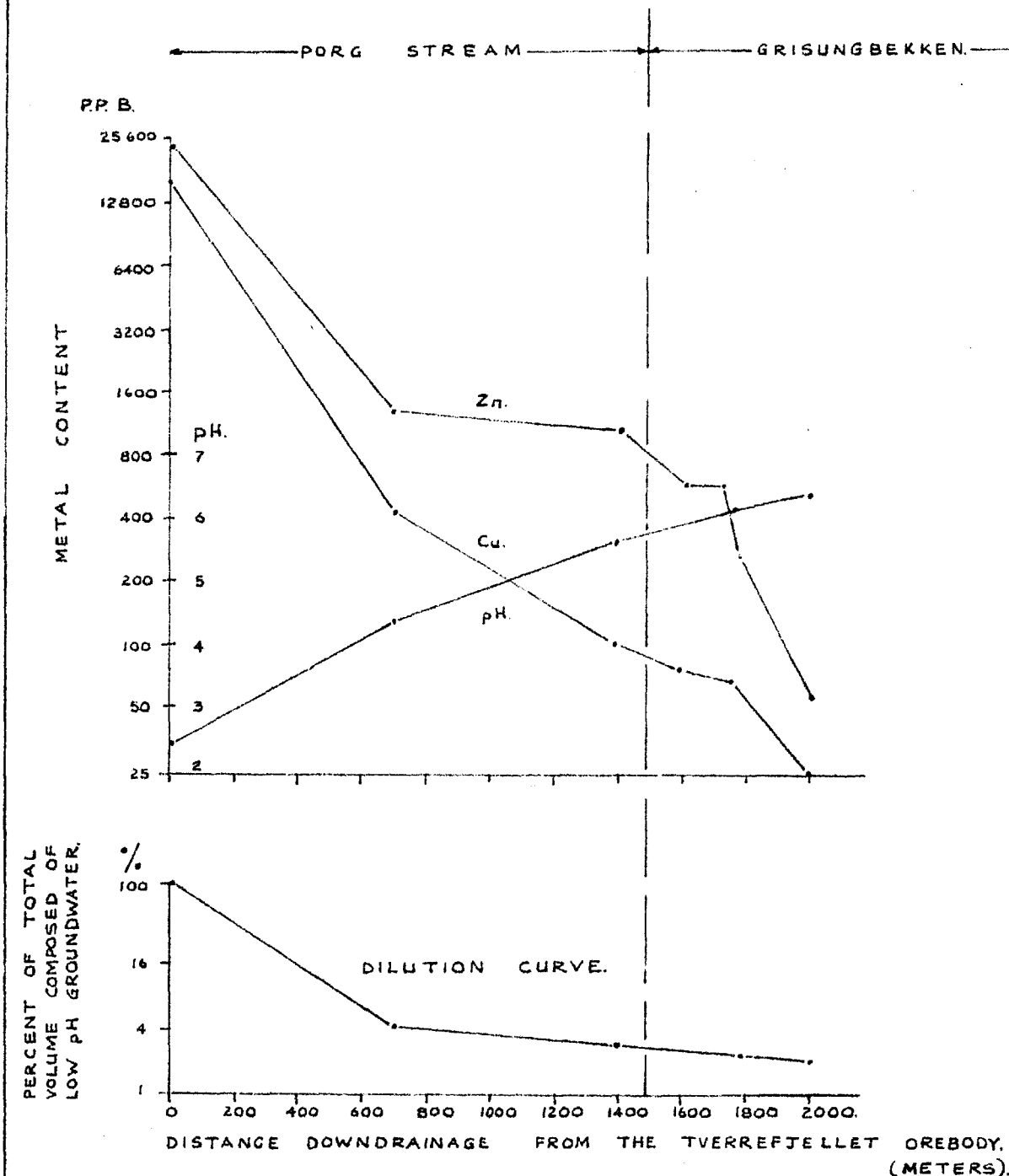


Fig.47. Variation in the Cu and Zn contents of groundwater in the Porg-Grisungbekken drainage system, and the estimated dilution of the mineralised by barren groundwaters as indicated by the pH.

banks of the Grisungbekken, the lateral spread of the mineralised groundwater being determined in a series of samples 1800 m. down-drainage from the orebody.

The cut-off between the mineralised and barren groundwaters on the north side of the Porg drainage channel was found to be located between 20 and 30 m. from the stream (Table 25). The proportionately similar decrease in the Cu and Zn content of the groundwaters with distance from the stream suggests that dilution by barren water is more important than precipitation. Sampling of the south bank was not undertaken because of elevated bouldery ground.

TABLE 25

Decrease of Metal Values in Near Surface Groundwaters taken at Right Angles to the Porg Stream on the North Bank

Sample No.	Location	Distance at right angles to Porg Stream	pH	ppb			
				Cu	Zn	Pb	Fe
		(Meters)					
43/5444	700 m. down drainage from head Porg stream	3	4.6	460	1520	2	120
43/5442	" " "	18	6.4	18	68	2	52
43/1507	" " "	32	7.0	8*	13*	2	N.D.

N.B.: Results are for total metals except where indicated by asterisk, when ionic metal values given.
N.D. = Not Determined.

In the Grisungbekken the groundwaters were sampled on both sides of the stream (Fig.48). Groundwaters taken at 50 and 100 m. away from the stream contain background metal values (43/4618 and 43/4619). Detailed sampling shows that the anomalous near surface groundwaters are restricted to within 20 m. of the Grisungbekken on the north side (samples 43/4613, 43/B, 43/4606 and 43/D). On the south bank anomalous groundwaters were confined to the vicinity of the Porg stream (i.e.43/4328). Elsewhere on the south bank all samples contained background metal values, (samples 43/4336 and 43/4338).

These data from the Grisungbekken can only be considered in relation to other data on the metal content of the stream sediment, alluvium and till. Accordingly, discussion is postponed until after presentation of the drainage results.

A knowledge of the proportions of mineralised and barren waters entering a given drainage system is essential to the interpretation of geochemical water data. In the Porg stream the volume of water was not measured at different points down-drainage mainly because the stream has a poorly defined course, especially in the lower reaches where the drainage is braided. In addition such

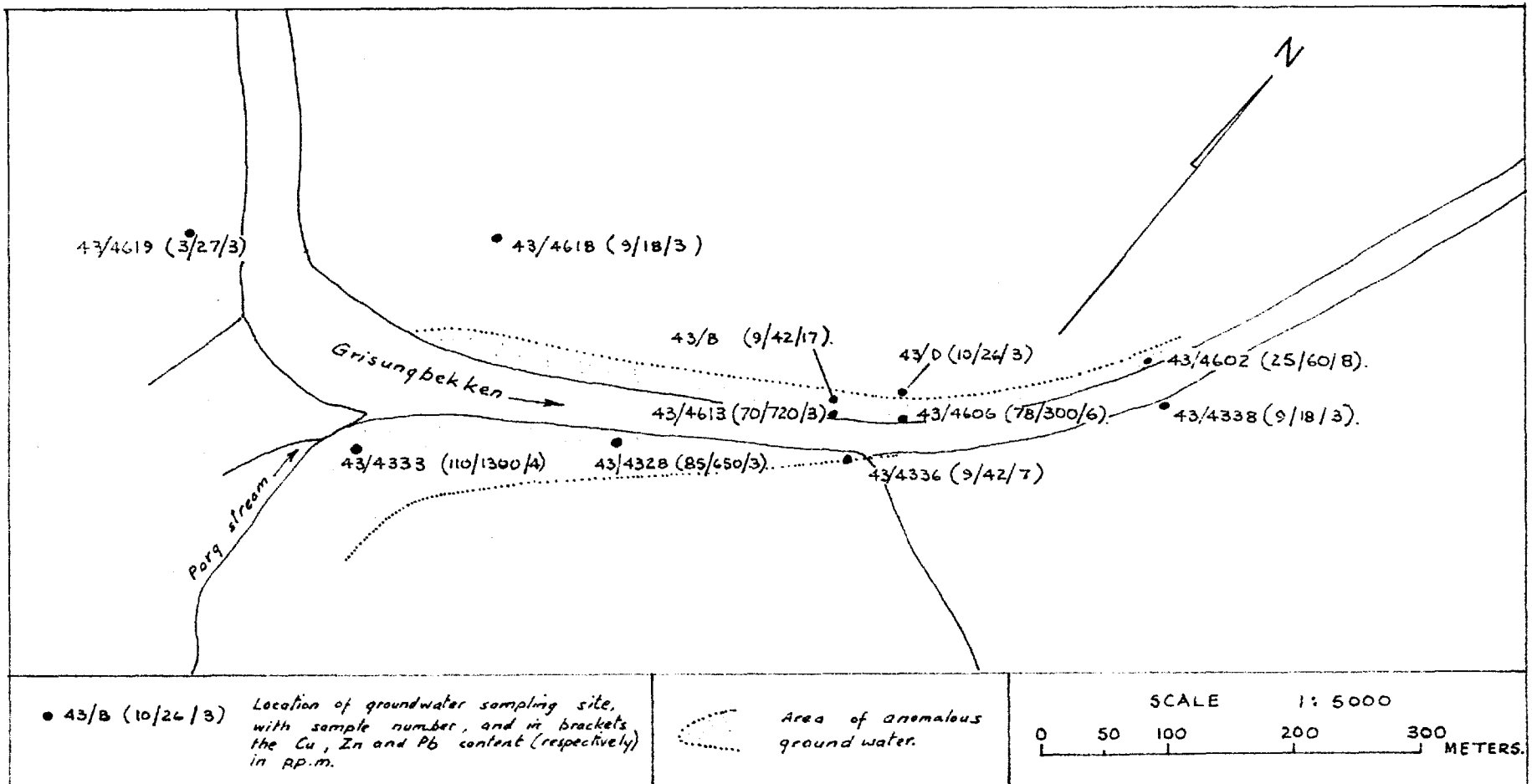


Fig.48. Plan showing the distribution of Cu,Zn and Pb in the near surface groundwaters in the vicinity of the Grisungbekken.

measurements take no account of the water travelling as underflow. However, the dilution of mineralised (low pH) by barren (high pH) waters may be estimated from the variation of pH, assuming that the increase of pH is due solely to dilution. It is appreciated that certain factors may upset this simple concept, for example, the absorption of CO_2 from the atmosphere, or the introduction of humic acids derived from decaying organic material. Nevertheless the dilution as indicated by the variation of pH is a first approximation to the actual amount of dilution taking place. Accordingly, a barren water sample (43/5861) having a pH of 6.8 (collected from a barren source entering the Porg stream) was added from a burette to a known volume of mineralised water (sample 43/14-15) of pH 2.5. The increase in pH as the mineralised low pH water is diluted by barren high pH water is not a simple straight line (Fig.49). There is a slight buffering capacity in the pH range of 3.1 to 3.7 and again in the pH range 5.7 to 6.8. The buffering affect in the pH range 5.7 to 6.8 may be due to the absorption of CO_2 by the system resulting in the following reactions: $CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$ (de Grys, 1959; Hem, 1960). The reason for the buffering capacity

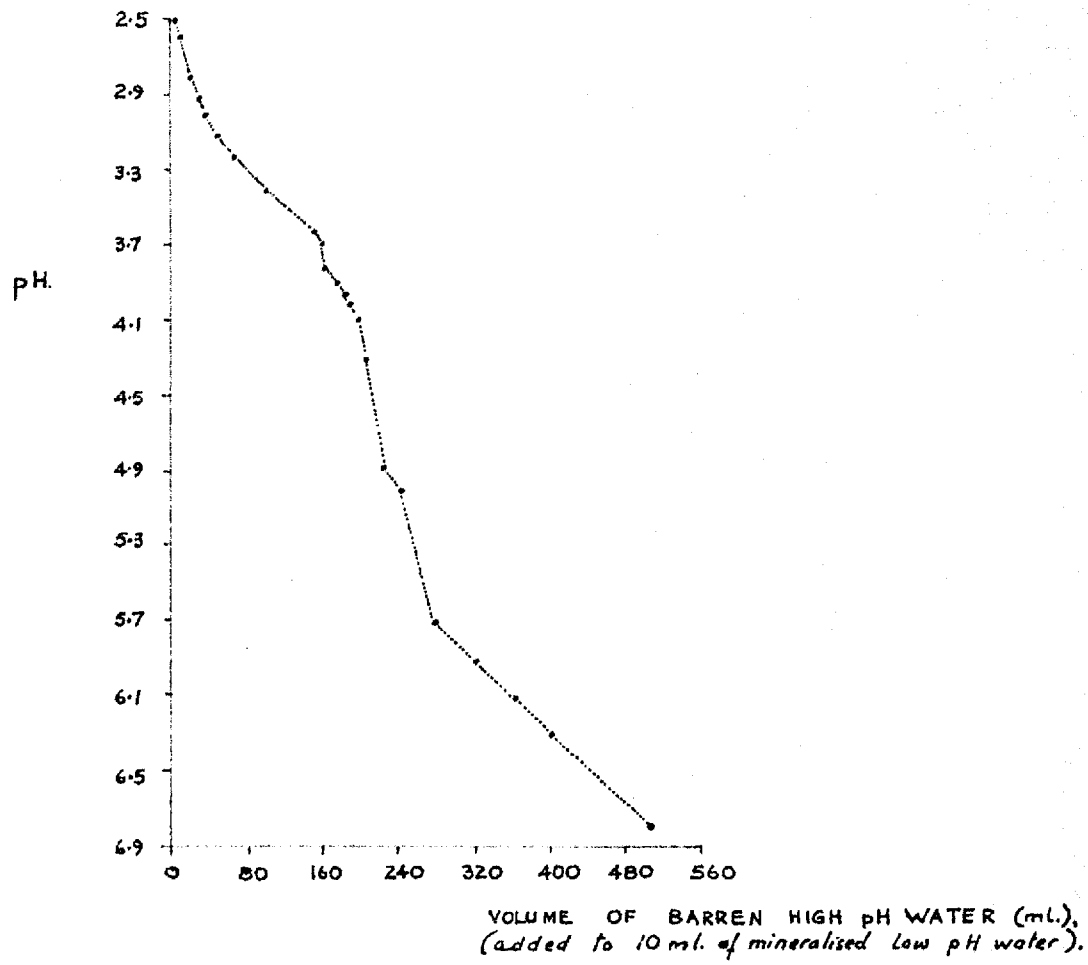


Fig.49. Graph showing the change in pH when 10 ml of mineralised low pH water (pH 2·5, sample 43/I4-I5) is diluted by barren high pH water (pH 6·8, sample 43/586I).

of the water in the pH range 3.1 to 3.7 was not investigated.

The proportion of mineralised and barren water (as indicated by the pH), at various points along the Porg - Grisungbekken drainage system, can be calculated from the experimental data (Fig.49). The line joining the calculated values is referred to as the "dilution curve" for the purposes of discussion.

The "dilution curve" for the groundwaters of the Porg-Grisungbekken system (Fig.47) indicates:-

(a) a massive dilution of the mineralised groundwaters by barren water over the first 700 m. down-drainage from the ore,

(b) beyond the first 700 m. the dilution decreases significantly.

(iii) Discussion

In the groundwaters of the Porg-Grisungbekken system the reduction in the base metal and Fe values over the first 700 m. are too great to be explained entirely by dilution. That is to say, the rate at which the pH increases is less than the rate of decrease of the metal concentrations. This would imply that the metals are being precipitated; Fe and Pb being almost completely removed from solution. Beyond 700 m. the groundwaters still contain anomalous amounts of Cu and Zn, but whereas

the Cu values decrease, the Zn content remains approximately constant over the remaining 700 m. of the Porg stream. These changes are accompanied by an increase in the pH from 4.6 to 5.7, which suggests that (a) there are no additions of low pH (mineralised) groundwaters to the system, and (b) that whilst Cu is apparantly unstable in solution and is being precipitated, the solubility of the dissolved Zn is unaffected by the change in pH.

In the groundwaters of the Grisungbekken the pH increases from 5.7 to 6.4 over a distance of 600 m. down-drainage from the Porg stream.

In this section of the drainage both Cu and Zn contents of the groundwaters decrease, the reduction in the Zn values being more pronounced than for Cu.

In terms of saturation concentrations the solubility of trivalent Fe is a function of the pH (Hem, 1960). The solubility of Cu is dependant not only on pH, but also on the total dissolved carbonate species and sulphate (Sillman, 1958). The data required for computing the saturation concentrations of Cu are not available for the Porg stream groundwaters. However, the saturation concentrations of Cu in the Porg stream surface waters are

known and may be used as guides in the interpretation of the groundwater data (Table 26). Data for the calculation of saturation concentrations of Pb and Zn are not available.

TABLE 26

Observed Concentrations of Cu and Fe in Groundwater Compared to the Calculated Saturation Concentrations.

pH	Calculated Saturation Concentration of Cu in Porg Stream Surface Waters ppm	Observed Cu ppm Groundwaters	Calculated Saturation Concentration Fe^{3+} ppm	Observed Fe ppm Groundwaters
2.5	63500 +	18	8325	360
4.5	635	0.46	0.016	0.120
6.5	0.06	0.025	Less than 10 ppb	0.260

($SO_4^{=}$ = 10^{-3} ; $\leq CO_2$ = 10^{-5})
(where a = activity)

The data (Table 26) suggests that the groundwaters are unsaturated with respect to Cu, whilst being saturated with Fe (except at the head of the Porg stream where the observed Fe concentration is below the theoretical value). In addition the hydrolysis of Zn takes place in the pH range of 5.3 - 6.8 and Pb at a pH of 6.8 (Morris and Lovering, 1952). However, the field data is consistent

with the precipitation of base metals and Fe from the groundwaters over the first 700 m, in the pH range 2.5 - 4.6. Therefore it is tentatively concluded that the base metals are co-precipitated with Fe. Beyond 700 m. Fe and Pb are almost totally removed from groundwater solution, whilst Cu continues to precipitate down-drainage but Zn does not. The renewed precipitation of Zn takes place only in the Grisungbekken groundwaters where the pH is in the range of 5.7 - 6.4. The precipitation of Cu but not of Zn from the groundwaters in the lower reaches of the Porg stream is consistent with the pH conditions. However, the presence of Zn as well as Cu in the Porg stream sediments would imply that there are other processes operating, for example, sorption onto clays and sesquioxides.

DISTRIBUTION OF ORE ELEMENTS IN SURFACE WATERS

(a) Properties of Surface Waters Draining Unmineralised (background) Areas

The data for surface waters in barren areas (Table 27) refers to samples from the Dloc stream, the upper Grisungbekken, and the stream draining background area "B". The upper limit of the variation for the various elements and properties measured is taken as the upper background level.

TABLE 27.

Properties of Stream Waters Draining Unmineralised Ground in the Hjerkinn Area.

Element	Total Metal ppb	Ionic Metal ppb	Other Properties	
Cu	3-10	6-13	pH	6.4 - 7.2
Zn	8-12	1.4-13	Eh	+0.13-+0.35 v.
Pb	2-6	1-1.8	HCO_3^-	24-48 ppm
Fe	30-100	N.D.	$CO_3^=$	Nil
Si	N.D.	3600-7000	$SO_4^=$	2.5 - 10 ppm
Al	N.D.	280-300		

(Number of samples 7)
(N.D. = Not Determined)

The close correspondence in the total and ionic Cu and Zn data suggests that the metals are in a predominantly readily available form. The Pb results however indicate that rather more metal is obtained by a total attack on the

sample. This may indicate that some of the Pb is occurring in the stream waters in association with complexing agents, for example, organic material. Variations in metal content which may correlate with environmental conditions were not noted. However, such variations would be expected and may be detected by a more extensive study of surface waters draining from barren areas.

Distribution of Ore Elements in the Grouback Stream Waters

The Grouback stream which drains the southern part of the Tverrefjellet valley was originally selected for a background study. The stream is particularly appropriate since its thalweg closely resembles that for the Porg stream which drains the ground underlain by ore. However, it was found that the Grouback stream waters and sediments contain higher than average contents of Pb and Zn. This feature limits the usefulness of this stream as an example of background. Accordingly, the results obtained from it have not been included in the background data on water (Table 25).

The Grouback originates in a col between high rocky ground where the drainage is impeded. It flows to the north east over glacial moraine and crosses a geological

boundary half way down its course. Quartz mica schists occur to the south of the contact and rocks of the greenstone group to the north. The high metal values appear to originate from this contact indicating the possibility of weak mineralisation in the bedrock in this vicinity. Small solifluxion fronts have closed in on the stream all the way along its course, and in places form a bridge above the stream.

The analysis of the Grouback stream waters (Table 28) shows an abnormally low HCO_3^- content. In addition, a large proportion of the weakly anomalous total Pb and Zn content of stream waters is in a form not readily available to solvent extraction. In constrast Cu is apparently dispersed in the stream waters in ionic form, but at background levels.

TABLE 28.

Properties of the Grouback Stream Waters

Element	Total Metal ppb	Ionic Metal ppb	Other Properties	
Cu	12	12	pH	6.5
Zn	120	2	Eh	+ 0.36
Pb	13	2	HCO_3^-	10 ppm
Fe	72	N.D.	$CO_3^=$	Nil

(No. of Samples 2)
(N.D. = Not Determined)

(ii) Distribution of Ore Elements in Surface Waters of Streams Draining from the Tverrefjellet Orebody

(a) The Porg-Grisungbekken System

The Porg stream rises in the secondary iron oxide body downslope of the oxidised and collapsed part of the orebody and flows to the north. The stream is approximately 1400 m. in length and the fall in height from its source to the junction with the Grisungbekken is 150 m. Barren waters enter the stream all along its course from seepages and surface run-off. The stream thalweg (Fig.50) shows it to have a 6° gradient over the first 900 m. of its course, which decreases to 2.5° in the lower reaches. The thalweg also shows three small steps in the stream bed which represent a series of small solifluxion benches crossing the stream about half way down. Also, as previously mentioned, the stream flows over a steeply sloping outcrop which occurs at the foot of the second solifluxion bench. The benches mainly consist of bouldery moraine which have not been cut down by the stream to any extent, and the waters flow both over and through them. Near its source the stream flows in a channel 1 m. wide and 20 cm. deep, but becomes less well defined downstream where the drainage is braided. This is especially marked in the low lying ground where the stream flows through the Porg bog. The bog covers a wide

area to the west of the stream, the boggy conditions extending to the foot of a range of hills. Substantial volumes of barren water flow into the bog from the hill-sides largely as surface run-off. On the eastern side of the stream the ground is better drained. In this vicinity the area around the stream has been intensely disturbed by frost heaving.

Ferruginous material and iron staining occur over the entire course of the Porg stream being most prominent in its upper reaches. Of particular interest is the sporadic occurrence of white flocculent material lying as a thin veneer on the sediments of the stream. This occurs mainly in the vicinity of the solifluxion benches but is again conspicuous at the mouth of the Porg stream where the waters flow into the Grisungbekken.

The Grisungbekken in contrast to the Porg stream has a "clean" appearance and is between 50 and 75 m. wide, and up to 1 m. in depth. This major stream flows to the east and north-east out of Grisungdalen taking a wide bend to the south around the obstructing hills in the vicinity of Tverrefjellet. The confluence with the Porg stream occurs to the east of the bend where the Grisungbekken returns to its north easterly course. At this point a number of small

islands occur in the Grisungbekken and appear to have been incorporated by channel erosion of the south bank. The area through which the Grisungbekken flows is low lying and has a gradient of between 1 and 1.5°. The banks are generally well drained, but sporadic boggy areas occur, particularly downstream from the junction with the Porg stream.

Surface waters down-drainage from the sub-outcrop of the ore were sampled in the Porg-Grisungbekken system, and the following properties measured: Cu, Zn, Pb, Fe, Si, $SO_4^{=}$, HCO_3^{-}, $CO_3^{=}$, Ph and Eh. In the Porg stream the metal content of the acidified waters were obtained by solvent extraction techniques, whilst the Grisungbekken waters were analysed for total metals. The use of different analytical methods was necessitated by a disparity in the field treatment and storage of samples which has previously been described in Part II of this report.

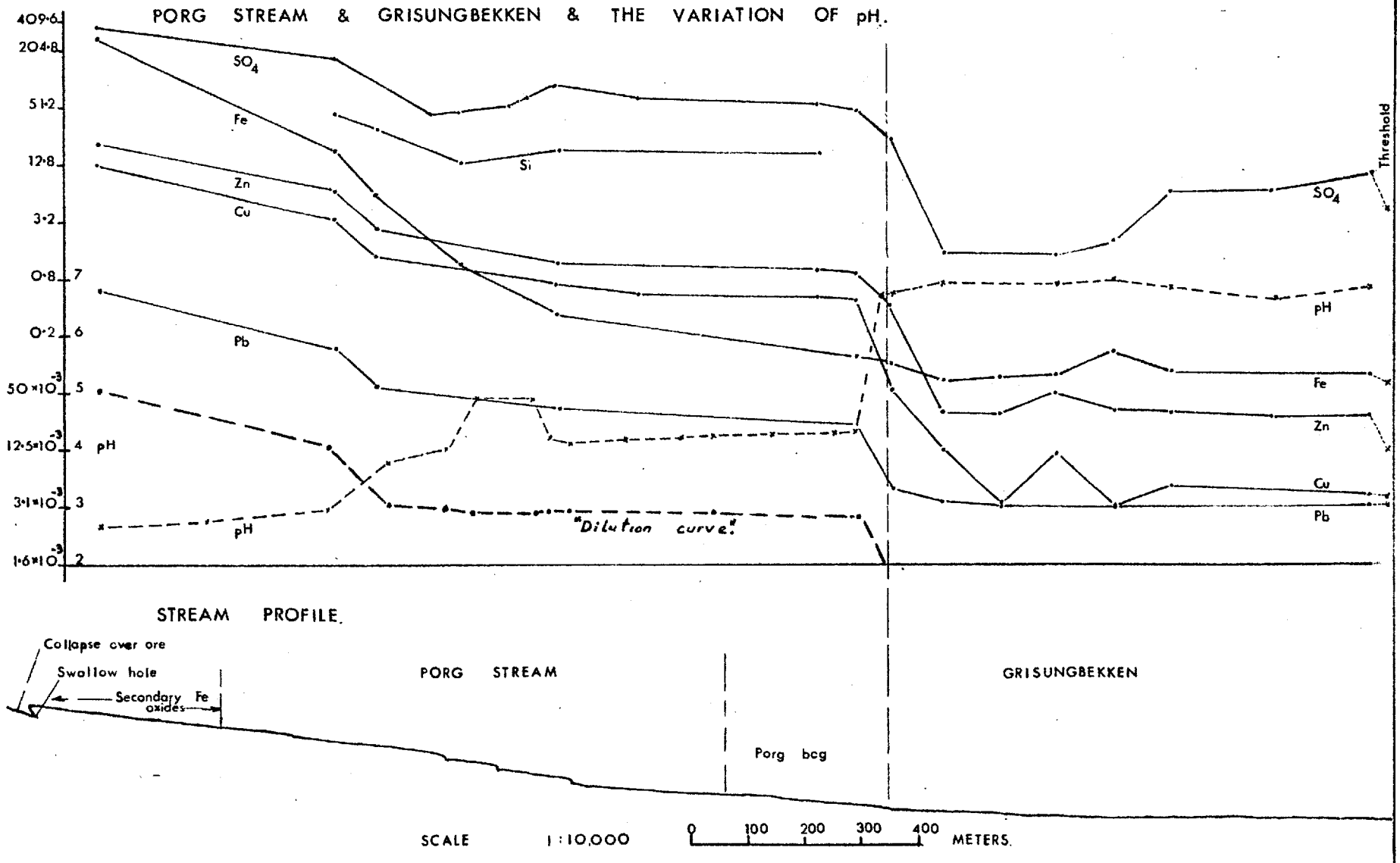
The variation in the properties of the surface waters in the Porg-Grisungbekken system is illustrated in Fig.50. The following characteristics of the dispersion patterns are noted.

(1) pH

In the Porg stream the pH increases from 2.5 to 3.0

FIG. 50.

GRAPH SHOWING THE CONCENTRATIONS OF Cu, Zn, Pb, Fe, Si, & SO_4 IN THE WATERS OF THE PORG STREAM & GRISUNGBEKKEN & THE VARIATION OF pH.



over a distance of 300 m. from the source. Over the next 400 m. the pH rises to 4.9 in the vicinity of the solifluxion benches. At the base of the last prominent bench, the pH decreases to 4.1 and is maintained at between 4.1 and 4.3 over the lower reaches of the Porg stream, a distance of 500 m. At the junction with the Grisungbekken the pH increases abruptly to 6.8. In the Grisungbekken the pH varies between 6.8 and 7.2.

On the assumption that the pH variation reflects solely the effect of the mixing of low and high pH waters, there is a major dilution by barren waters between 400 and 500 m. from the head of the Porg stream. At the junction with the Grisungbekken there is a massive dilution of the low pH water. The so-called "dilution curve" for the Porg stream surface waters calculated from the pH data is illustrated in Fig.50.

(2) The Base Metals

Cu decreases from a maximum concentration of 18,400 ppb at the head of the Porg stream to 500 ppb at a point 60 m. from the junction with the Grisungbekken. Over the same distance Zn decreases from 23,000 ppb to 1,200 ppb, and Pb from 640 ppb to 14 ppb. It will be noted that the

plotted values for Cu and Zn parallel almost exactly the "dilution Curve". The decrease in the Pb values is slightly greater than can be explained by dilution alone. In all cases the metal values follow log linear decay curves. At the junction with the Grisungbekken the metal values decrease abruptly in sympathy with the dilution curve.

In the Grisungbekken Pb is at background (2-6 ppb) at the point of entry of the Porg stream, whilst the Cu value decrease to background (3-10 ppb) within 200 m. of the confluence. Zn however decreases to 30 ppb (2.6 times the upper background level) within 100 m. of the confluence, but remains at that level for a further 800 m. downstream. At this point the sampling of the Grisungbekken waters was discontinued.

(3) Fe

In the Porg stream the Fe values decrease from 360,000 ppb at the head of the stream to 100 ppb at the junction with the Grisungbekken. Within the Grisungbekken the Fe values are essentially constant at the upper background level of 100 ppb.

(4) $SO_4^{=}$, HCO_3^{-} and $CO_3^{=}$

$SO_4^{=}$ decreases from a maximum value of 375 ppm at the

head of the Porg stream to 20 ppm at the junction with the Grisungbekken. The decrease in the $SO_4^{=}$ content of the Porg stream waters is approximately similar to the "dilution curve", but an addition of $SO_4^{=}$ is noted just below the last prominent solifluxion bench. In the Grisungbekken $SO_4^{=}$ decreases to 2 ppm within 100 m. of the confluence. However, downstream the $SO_4^{=}$ content of the Grisungbekken increases to 12 ppm (the upper background level).

HCO_3^{-} is absent from the Porg stream waters. In the Grisungbekken the bicarbonate content increases to 18 ppm 100m. downstream from the confluence, and finally to 24 ppm. Above the confluence the bicarbonate content of the Grisungbekken is 28 ppm.

$CO_3^{=}$ is absent from both the Porg stream and the Grisungbekken waters.

(5) Lateral Distribution of Ore Elements in the Surface Waters of the Porg - Grisungbekken System

In the lower reaches of the Porg stream a wide area on the west of the channel lies under water. Much of this area (the Porg bog) is inundated by barren waters running off the hill sides. However, in the vicinity of the stream the mineralised waters are able to disperse laterally since there are no well defined banks. The extent of the lateral dispersion was determined by taking surface water samples at increasing distances to the west of the Porg stream (Table 29). During the field work an attempt was made to obtain shallow ground waters along the same traverse. This proved to be impossible because the ground was frozen.

TABLE 29. Properties of Surface Waters in the Porg Bog at increasing Distances to the West of the Porg Stream.

Sample No.	Distance West at Porg Stream (Meters)	pH	ppm HCO_3^-	TOTAL METALS ppb			
				Cu	Zn	Pb	Fe
43/5492	0	4.2	Nil	500	1160	12	60
43/5494	2	5.7	6	300	920	14	130
43/5496	10	6.2	18	34	180	6	52
43/5392	30	6.2	N.D.	11	430	5	N.D.
43/5390	60	6.5	29	12	250	6	N.D.

(N.D. = Not Determined Nil = Not detectable)

The data (Table 29) shows that the ore elements are dispersed laterally into the Porg bog to different limits. Pb and Fe decrease to the upper background level within 10 m. and Cu within 30 m. In contrast, Zn is strongly anomalous even at 60 m. from the Porg stream. This suggests that the decrease in the metal values is not entirely governed by dilution. Of particular significance is the fact that Zn is the only metal to remain at anomalous concentration in water having a pH of 6.5. Theoretically Zn precipitates between pH 5.3 and 6.8, Cu^{2+} at pH 5.3 and Pb at pH 6.8 (Morris and Lovering). The data is not inconsistent with the view that the lateral dispersion of Cu and Zn is controlled largely by the pH gradient.

Lateral Distribution of Ore Elements in the Grisungbekken

The Grisungbekken is 50 m. wide at the point of entry of the Porg stream. The lateral dispersion of the ore elements was investigated in a series of samples taken across the full width of the major stream (Table 30). It will be noted that the pH of the Grisungbekken waters varies between 6.5 and 6.9 (discounting the low pH at the mouth of the Porg stream). These measurements were made in 1965 when the pH was found to be somewhat lower than in 1964 (6.8 - 7.2). The difference is possibly due to a seasonal variation in the snow cover and rate of melting.

TABLE 30. Distribution of Ore Elements in the Grisungbekken Stream Waters

Sample No.	Distance from Junction with Porg Stream (Meters)	Location in Grisungbekken	pH	ppm HCO_3^-	TOTAL METALS ppb			
					Cu	Zn	Pb	Fe
43/5419	30m Upstream	Middle stream	6.6	28	3	18	3	60
43/5422	At Porg entry	N. bank	6.5	28	3	38	7	N.D.
43/5423	" " "	Middle stream	6.3	5.5	12	60	6	100
43/5424	" " "	S. bank	5.7	Nil	48	480	5	100
43/5428	250m Downstream	N. bank	6.8	24	12	46	7	80
43/5429	" "	S. bank	6.8	24	19	64	6	90
43/5430	400m "	N. bank	6.9	24	3	18	7	80
43/5436	" "	S. bank	6.8	24	3	32	6	150
43/5431	550m "	N. bank	6.8	24	3	28	6	120
43/5435	" "	S. bank	6.5	24	5	34	6	88
43/5432	700m "	N. bank	6.6	24	5	30	7	200
43/5433	" "	S. bank	6.5	24	3	28	7	80

(N.D. = Not Determined)
(Nil = Not detectable)

The data (Table 30) shows that Cu is homogeneously distributed across the full width of the Grisungbekken within 400 m. of the Porg stream confluence. The Zn values however are consistently higher in waters near the south bank compared with those on the north side. It is only a point 700 m. downstream of the Porg entry that the Zn values are essentially the same on both sides of the Grisungbekken. Even here, Zn is at a level 2.5 times higher than the upper background value of 12 ppb. At 400 m. downstream the anomalous Cu is removed whilst Zn is not,which is possibly indicative of the higher solubility of Zn under the prevailing pH conditions. The low Pb concentrations precludes the detection of significant variations. However, the possibility that metal is being introduced into the Grisungbekken from anomalous groundwaters cannot be excluded. The possible affects of the anomalous groundwaters on the surface waters is discussed after presentation of the stream sediment data.

(b) The Rekse - Dloc System

As mentioned earlier, the Rekse stream originates as an overspill channel of the Porg stream. From the divergence it flows to the north east between two prominent esker ridges. For most of the year the Rekse carries only

small volumes of surface waters. The original course of the stream has been diverted by recent earth moving operations of the military authorities. A distance of 350 m. from its source the waters sink into the sands and gravels of the esker which originally bounded the stream on the north. The Rekse bog which is located downslope of the esker almost certainly still receives a large proportion of the Rekse waters, but now a result of seepage instead of surface flow.

The bog is elongated north east, south west and joins with the Dloc bog containing the Dloc stream in the north east. The combined waters then flow out of a common exit from the bogs to a junction with the Grisungbekken (Fig.46).

The Dloc stream derives from a catchment area within the Terrefjellet valley where it is underlain by unmineralised bedrock. Accordingly these waters have a high pH and contain background concentrations of the ore elements (Table 31).

TABLE 31.

Properties of the Dloc Stream Waters

Sample No.	Location	pH	HCO_3^- ppm	$SO_4^=$	IONIC METAL ppb		
					Cu	Zn	Pb
43/1249	Upper Dloc	7.1	31	N.D.	9	1.4	1.8
43/1264	Middle Dloc	7.3	36	5	13	3.0	1.8
43/3987	Lower Dloc	7.1	N.D.	N.D.	6	2.0	1.3

(N.D. = Not Determined)

In contrast the waters of the Rekse stream and the Rekse bog contain anomalous concentrations of the ore elements (Table 32).

TABLE 32.

Properties of the Rekse Stream and Rekse Bog Waters

Sample No.	Location	pH	HCO_3^- ppm	$SO_4^=$ ppm	TOTAL METAL ppb			
					Cu	Zn	Pb	Fe
43/5474	Rekse Stream	4.1	Nil	58	560	1440	11	148
43/5343	Rekse Bog	5.3	38	20	300	440	7	160

The common ground between the Rekse and Dloc bogs allows the mineralised and barren waters to mix over a fairly wide front. The surface waters leaving the bog and draining into the Grisungbekken contain near background concentrations of the ore elements (Table 33). Zn however is

an exception in being 2.5 times above the upper background level in this stretch of the drainage. The upper background levels for the metals being: Cu 10 ppb, Pb 6 ppb, Zn 12 ppb and Fe 100 ppb (by total methods of analysis).

TABLE 33.

Properties of Surface Waters Draining out of the Rekse Bog

Sample No.	Location	pH	HCO_3^- ppm	$SO_4^=$ ppm	TOTAL METAL ppb			
					Cu	Zn	Pb	Fe
43/5440	At bog exit	6.4	38	12	2	34	6	80
43/5437	At junction with Grisungbekken	6.8	24	12	3	32	8	150

In the surface waters of the Rekse bog the variation in metal content is not known. This lack of data is due to loss during analysis.

DISTRIBUTION OF ORE ELEMENTS IN ACTIVE STREAM SEDIMENTS

(i) Distribution of Ore Elements in Active Sediments of Streams draining Unmineralised Ground

The Dloc and Grouback are taken as type examples of streams draining essentially unmineralised ground within the Tverrefjellet valley. However the sediments from the upper part of the Grouback stream contain high Pb and Zn values. In addition the Pb and Zn contents of the Grouback stream water are above the upper background levels (Table 28). The stream passes over a geological contact between quartz mica schist to the south and greenstone to the north. As previously mentioned, the rocks on the contact may be weakly mineralised. Accordingly, metal contents of the upper Grouback stream sediments are omitted from the calculation of mean and threshold values for stream sediments.

TABLE 34.

Background and Threshold Values for Stream Sediments Calculated from Samples Collected from the Dloc and Grouback Streams

(Data on -80 mesh)

Cu ppm		cxCu ppm		Zn ppm		cxZn ppm		Pb ppm		cxPb ppm	
M	T	M	T	M	T	M	T	M	T	M	T
15	30	1.6	3.0	50	120	3.0	7.0	16	30	1.3	4.5
Number of Samples											
33		37		38		21		10		22	

(M = arithmetic mean. T = threshold, calculated as mean plus two standard deviations.)

With the exception of Pb, the mean and threshold values of $KHSO_4$ extractable metal for the active stream sediments are substantially lower than those calculated for the overburden. Since the streams do not expose bedrock, but are actively eroding the moraine, it could be expected that values in the moraine would be reflected in the stream sediments. The sediments however consist predominantly of medium to fine grained sand and silt. Much of the fine fraction of the moraine which enters the

streams must be removed in suspension in the swiftly flowing waters. The moraine investigation showed that a large proportion of the metal is held by the fine fraction. The $KHSO_4$ extractable metal content of the active stream sediments is therefore consistent with the elutriation of the fine fraction of the eroded moraine.

In contrast, the cold extractable metal content of the stream sediments is significantly higher than that of the moraine. It is possible that metal leached from the overburden (see P.83) enters the drainage and is reprecipitated. Deep samples of groundwater from the moraine would be required to substantiate this suggestion, and it was not possible to collect such samples. However, the shallow groundwaters from background areas do contain more Zn than unmineralised surface waters, (i.e. groundwater 18-30 ppb Zn, surface water 8-12 ppb Zn). There is therefore some evidence (at least in the case of Zn) to suggest that metal leached from the barren overburden

enters the drainage and is incorporated in the sediments in a readily extractable form.

(ii) Distribution of the Ore Elements in the Active Sediments of Streams Draining from the Tverrefjellet Orebody.

(a) Porg - Grisungbekken System

The sediments were examined for Cu, cx Cu, Zn, cx Zn, Pb and cx Pb. The length of the respective anomalous drainage trains were found to vary. The cx Cu train is particularly well developed being detected as far as 2.5 km. down-drainage from the ore (Fig.51). In contrast the anomalous Pb values (including cx Pb) are confined to the Porg stream sediments (Fig.52).

The detailed distribution of the base metals in the sediments of the Porg stream and Grisungbekken are shown in Figs. 53, 54 and 55. In these diagrams the values in the Grisungbekken refer to sediments on the south side of the stream. The salient features shown by these data are as follows:

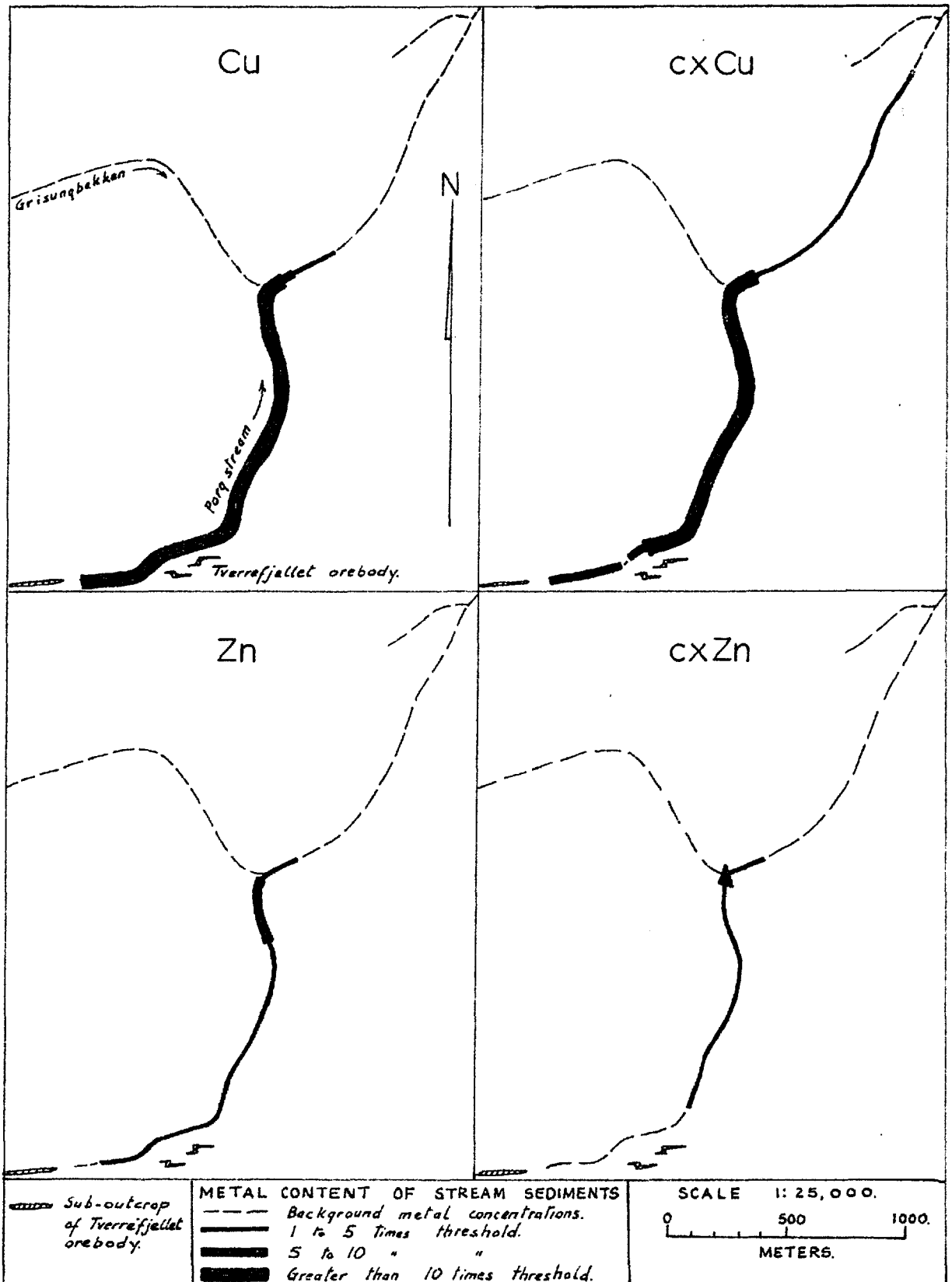
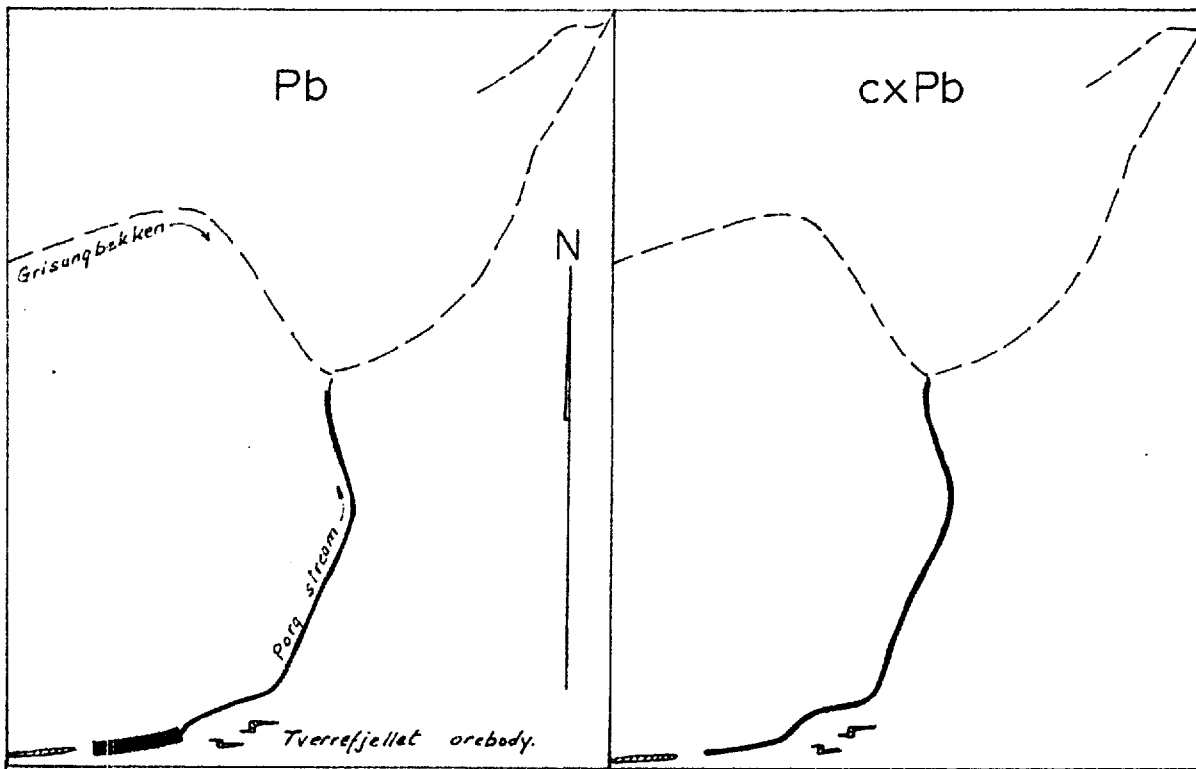


Fig.5I. Drainage trains of Cu, cxCu, Zn and cxZn in the active stream sediments of the Porg-Grisungbekken system. (Data on the -80 mesh fraction)



SCALE 1:25,000.

0 500 1000 1500 2000.

METERS.

Sub-outcrop of Tverrefjellet orebody.

METAL CONTENT OF STREAM SEDIMENTS

- Background metal concentrations.
- 1 to 5 times threshold.
- 5 to 10 " "

Fig.52. Drainage trains of Pb and cxPb in the active stream sediments of the Porg-Grisungbekken system.
(Data on the -80 mesh fraction).

(1) Cu

In the Porg stream Cu varies between 400 and 800 ppm and increases in concentration down-drainage. Modal values of 480 and 600 ppm are characteristic of the sediments in the upper and lower halfs of the stream respectively. In the Grisungbekken the values decrease abruptly, and are at the threshold level (30 ppm) within 400 m. of the Porg confluence.

(2) cx Cu

Cold extractable Cu in the Porg stream sediments is more erratic than $KHSO_4$ extractable Cu, but in general the values increase downstream. At the head of the stream the cx Cu content of the very ferruginous sediments varies between 2.5 and 20 ppm. The values increase to 300 ppm at a point 60 m. from the Grisungbekken. In this major stream the values decrease proportionately to $KHSO_4$ extractable Cu over the first 200 m. but remain above the threshold level of 3.0 ppm.

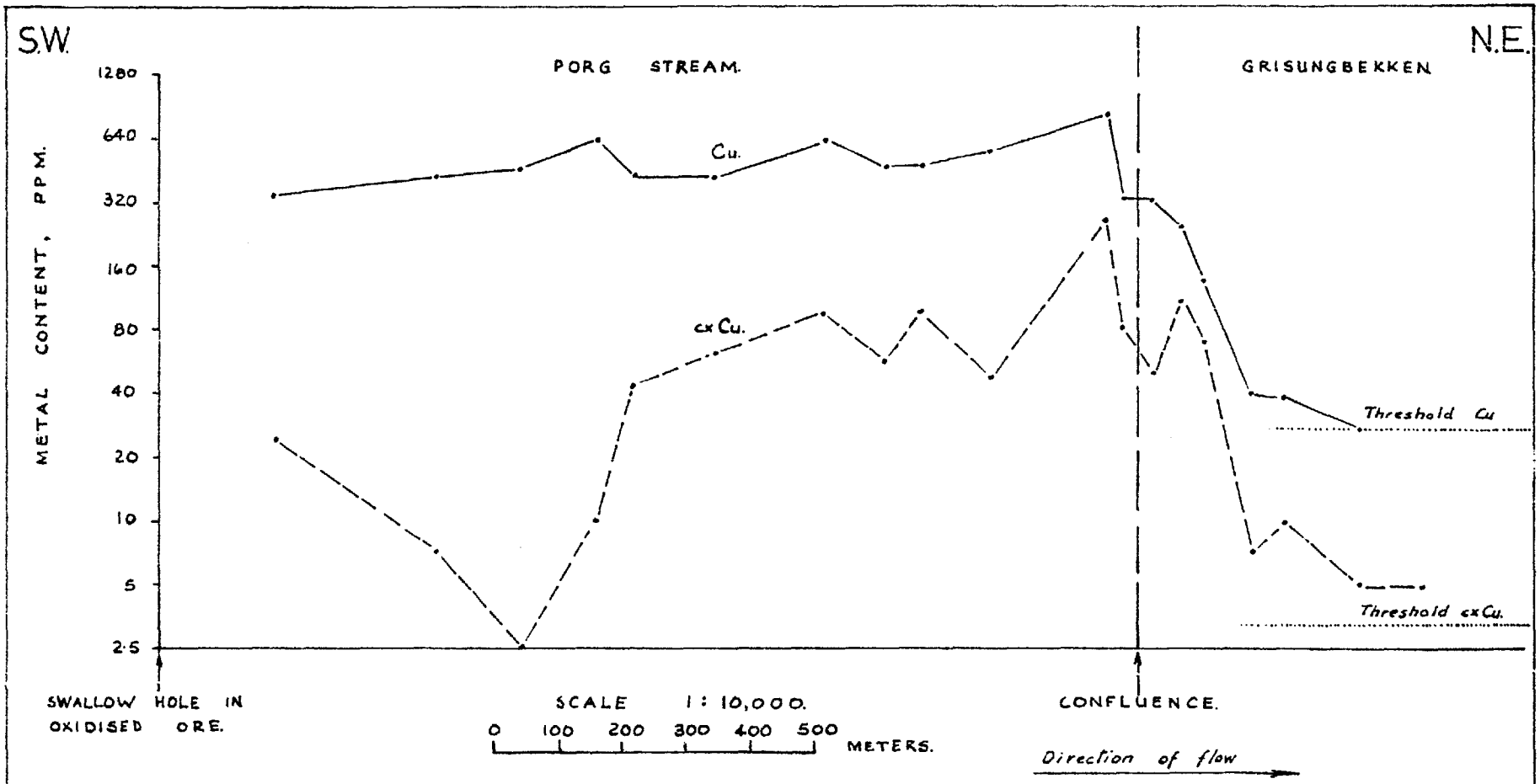


Fig.53. Graph showing the Cu and cxCu contents of the active stream sediments in the Porg-Grisungbekken drainage system. (Data on the -80 mesh fraction).

(3) Zn

Zn shows a steady increase in concentration down the Porg stream from 120 ppm at the source to 640 ppm near the junction with the Grisungbekken. The values decrease in the Grisungbekken to below the threshold level, of 120 ppm, within 200 m. of the Porg entry.

(4) cx Zn

cx Zn over the first 600 m. of the Porg stream is below the threshold level of 7.0 ppm. Beyond this point the values increase at remarkably steady rate to a maximum value of 60 ppm in the Grisungbekken at the mouth of the Porg stream. Within the Grisungbekken the values decrease abruptly to below threshold within 200 m. of the Porg confluence.

(5) Pb

Pb has a very erratic distribution in the Porg stream sediments. In general, the values decrease downstream from 300 ppm at the source, to 30 ppm (threshold) at the mouth. In the Grisungbekken Pb is essentially within the

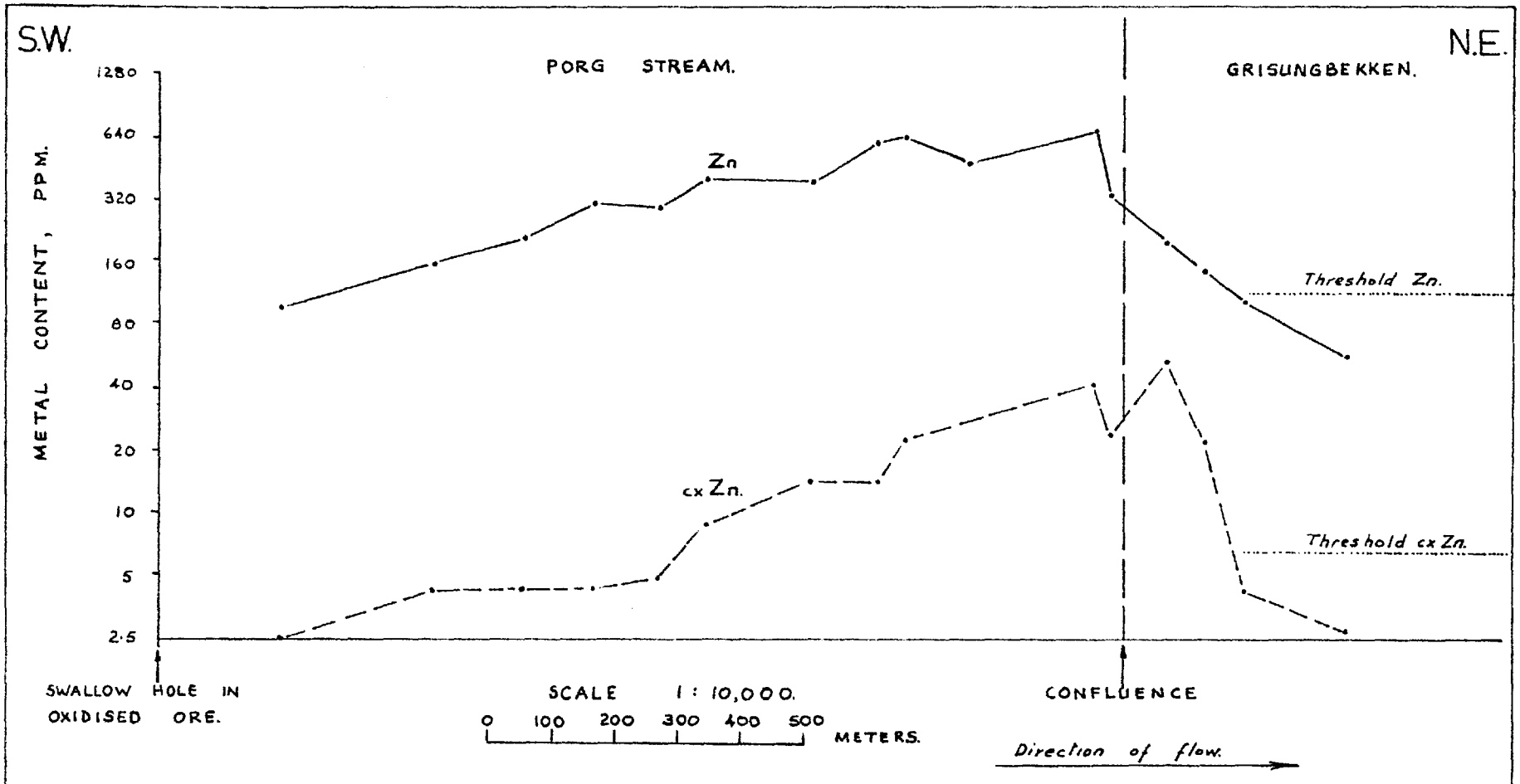


Fig.54. Graph showing the Zn and cxZn contents of the stream sediments in the Porg-Grisungbekken drainage system.
(Data on the -80 mesh fraction).

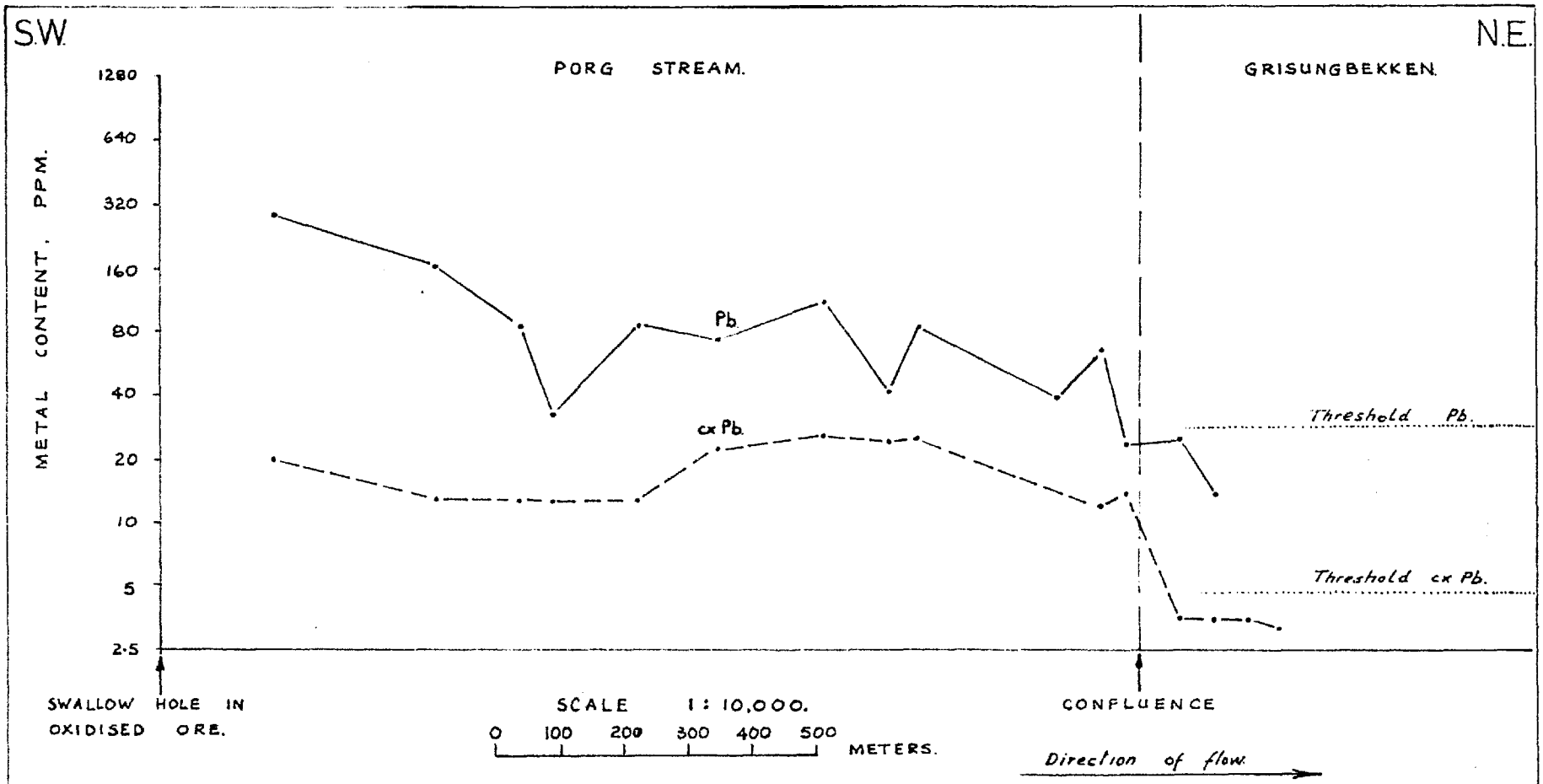


Fig.55. Graph showing the Pb and cxPb contents of the active stream sediments in the Porg-Grisungbekken drainage system. (Data on the -80 mesh fraction).

background range of 5-30 ppm.

(6) cx Pb

Cold extractable Pb is rather evenly distributed in the Porg stream sediments, varying between 12 and 30 ppm. In the upper part of the stream cx Pb is at a level of approximately 15 ppm. The concentration increases in the lower half of the stream to peak values, 450 m. from the Grisungbekken. From this point the values decrease and are in the background range of 0.5-4.5 ppm in the sediments of the major stream.

A distinctive feature of the base metal dispersion in the Porg stream sediments is the relationship between the cx Me/Me ratios (Fig.56). In particular it is noted that the ratios for Cu, Zn and Pb increase downstream at somewhat similar rates. This is indicative of an increasing proportion of readily available metal, and has an important bearing on the "form" of the metals. These aspects are discussed in a later section.

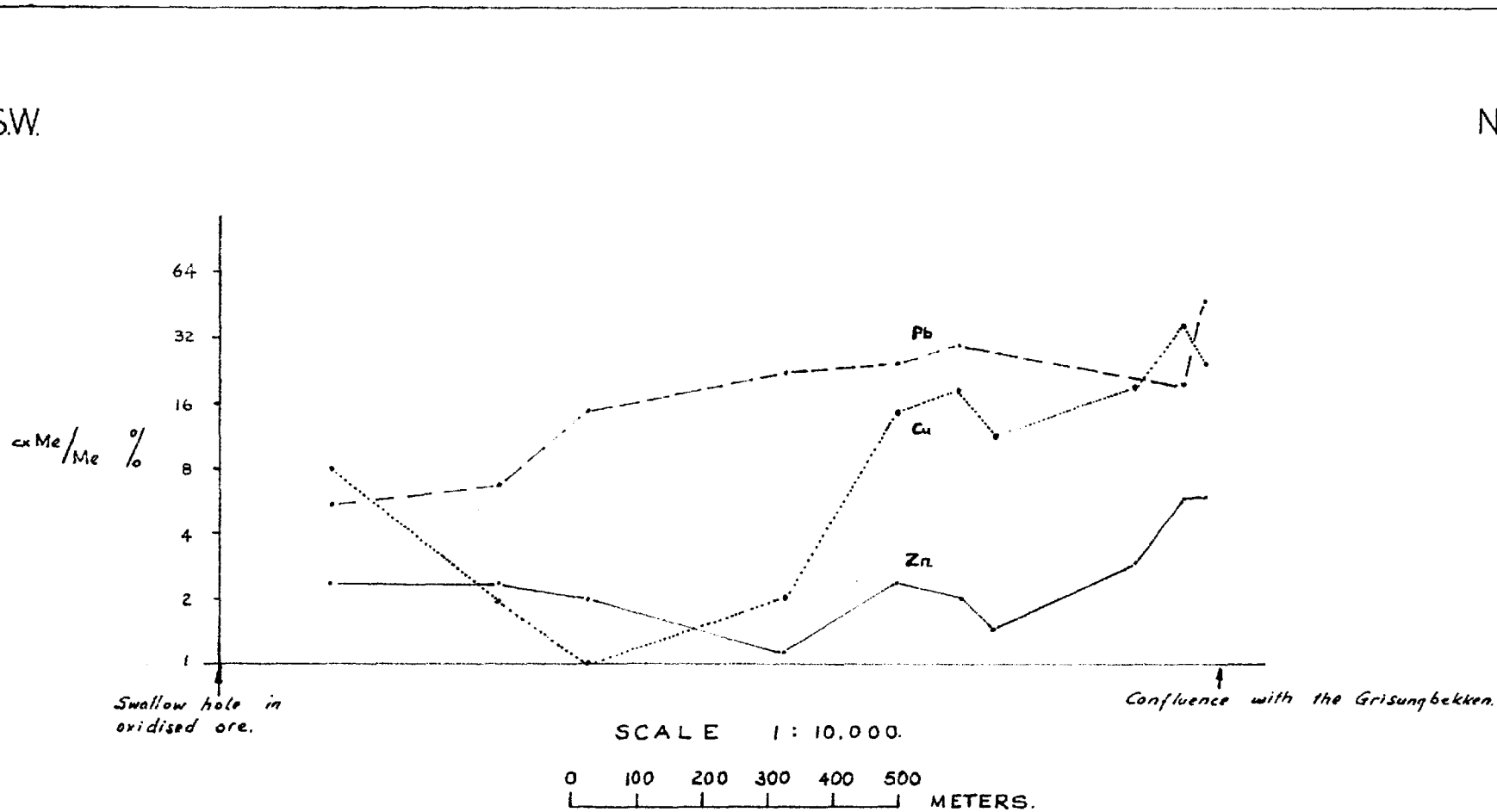


Fig.56. Graph showing the variation in the ratios of the cold extractable to bisulphate extractable metal (Cu,Zn and Pb) in the active sediments of the Porg stream.
(Data on the -80 mesh fraction).

(7) Affect of Sediment Type on the Drainage Anomaly

In general the sediments of streams within the Hjerkinn area are fairly well sorted and consist of coarse to medium grained sand and silt. However, the sediments of the Porg stream are much more variable in mechanical composition as well as metal content (Table 35).

TABLE 35.

Base Metal Content of Different Sediment Types Occurring in the Porg Stream

(data on the -80 mesh fraction)

Sample No.	Distance from Source (Meters)	Description of Sample	$KHSO_4$ extractable metal ppm		
			Cu	Zn	Pb
43/1058	450	Ferruginous coarse grained sand and silt	340	320	35
43/1059	"	Ferruginous red ooze	475	340	60
43/1063	600	Ferruginous coarse grained sand and silt	590	480	85
43/1066	"	Ferruginous red ooze	725	460	85
43/1067	"	Fine grained grey silt	490	460	50
43/1033	650	White flocculent material	450	440	75
43/1036	"	Ferruginous red ooze	440	480	75
43/1037	"	Brown medium to coarse grained sand and silt	590	420	110

The variation in the metal content of the sediment types is within the range of analytical error and may not be significant. Of practical importance however is the fact that all the sediments within the Porg stream contain anomalous metal.

(8) Variations in Metal Content Across the Width of the Grisungbekken

In the Grisungbekken the metal content of the stream sediment varies markedly across the width of the stream, down-drainage from the mouth of the Porg (Fig. 57). On the south side the sediments are strongly anomalous with respect to Cu and Zn, whilst those on the north contain background concentrations of the metals. This condition persists for 200 m. down stream in the case of Cu, and for 350 m. for Zn, after which the values are homogeneously distributed across the width of the stream.

(b) Rekse - Dloc system.

As previously described this drainage system

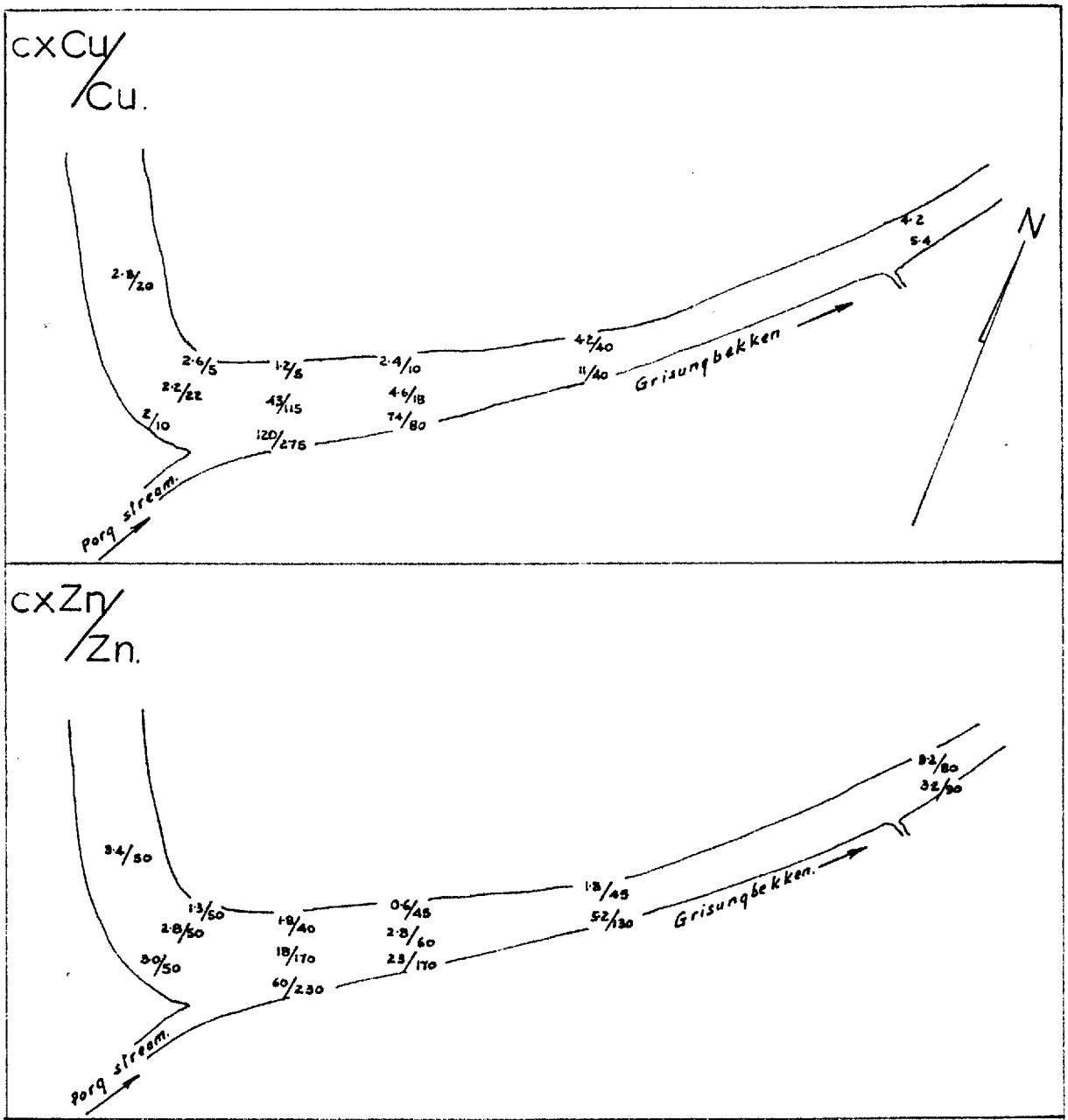


Fig.57. Plan showing the variation in the Cu and Zn contents of the Grisungbekken sediments, downdrainage from the confluence with the Porg stream.
(Data on the -80 mesh fraction).

consists of three parts, namely: the Rekse stream, the Rekse bog and the outlet from the bog draining into the Grisungbekken. The latter is the channel for the combined Rekse and Dloc stream waters. The distribution of the base metals in the stream sediments is shown in Fig.58.

At the point of departure of the Rekse from the Porg stream the sediments contain equal amounts of Cu and Zn (500 ppm) and 80 ppm Pb. The base metal values decrease down-drainage to the edge of the Rekse bog where Zn is at 240 ppm, Cu at 100 ppm, and Pb at the threshold level of 30 ppm. Within the bog Cu and Zn values increase to maxima of approximately 1,000 ppm, but Pb remains at the threshold level. In the drainage out of the bog the sediments contain Cu and Zn up to twice the threshold value and background amounts of Pb (0 - 30 ppm). Cold extractable Cu varies sympathetically with $KHSO_4$ extractable Cu throughout.

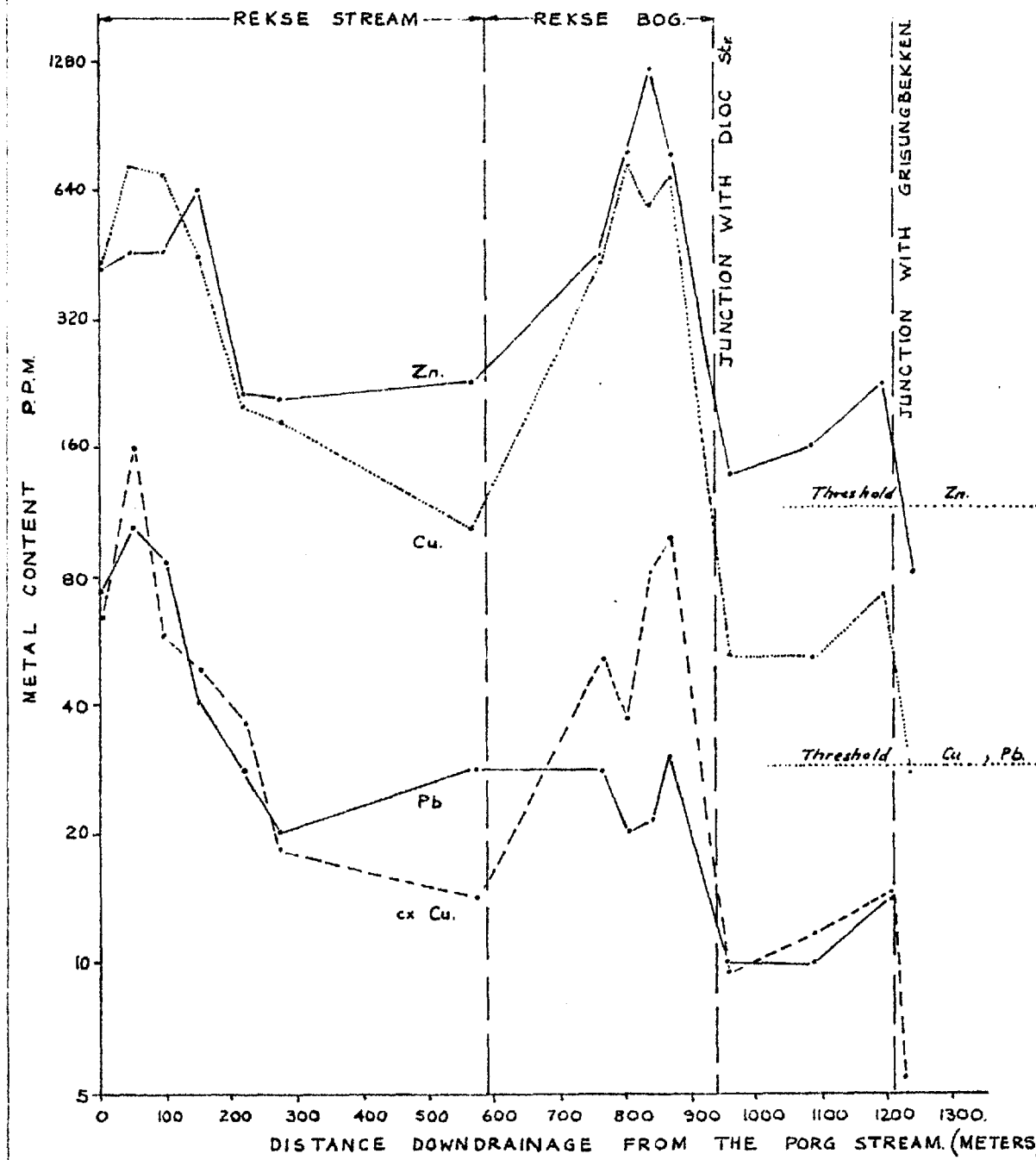


Fig.58. Graph showing the base metal contents of the stream sediments in the Rekse-Dloc drainage system.
(Data on the -80 mesh fraction).

The data indicates that the Rekse bog is acting as a geochemical barrier to the continued dispersion of the base metals. The distribution of the metals in the bog is the subject of a later section.

DISTRIBUTION OF ORE ELEMENTS IN STREAM BANKS AND IN BOGS

(i) Distribution of Ore Elements in Freely Drained Banks of Barren Streams

The banks of the Dloc and Grouback streams provide the background data (Table 36) for this environment. Since these streams have fairly steep gradients (of the order of 5°), the banks are predominantly well drained. The threshold values derived from this study were not found to be fully applicable to the banks of certain streams draining from mineralisation. In particular some areas surrounding the Grisungbekken are boggy and in these places it was necessary to apply the background data pertaining to bogs.

TABLE 36.

Background and Threshold Values for Freely Drained Banks (of material at a depth of 10 - 20 cm), calculated from samples collected from the Dloc and Grouback Streams.
(Data on the -80 mesh fraction).

cx Cu ppm		Cu ppm		Zn ppm		Pb ppm	
M	T	M	T	M	T	M	T
1.5	3.0	15	30	75	150	15	30
Number of Samples							
46		47		41		9	

(M = arithmetic mean T = threshold, calculated as mean plus two standard deviations.)

(ii) Distribution of Ore Elements in Bogs Overlying Unmineralised Bedrock and Receiving Drainage from Barren Streams

The concentration of the ore elements in barren bogs was studied in the Dloc bog upstream from the Rekse bog, and in a small solifluxion terrace bog located on high ground above the Grouback stream (Fig.59).

The distribution of the base metals in bog profiles (Fig.60) shows a surface enrichment of Zn and cx Cu. A second and similar enrichment is noted at a depth of 1 m. In both cases the metal values within these horizons are somewhat erratically distributed. In general however, other data on the distribution of metal in Norwegian bogs

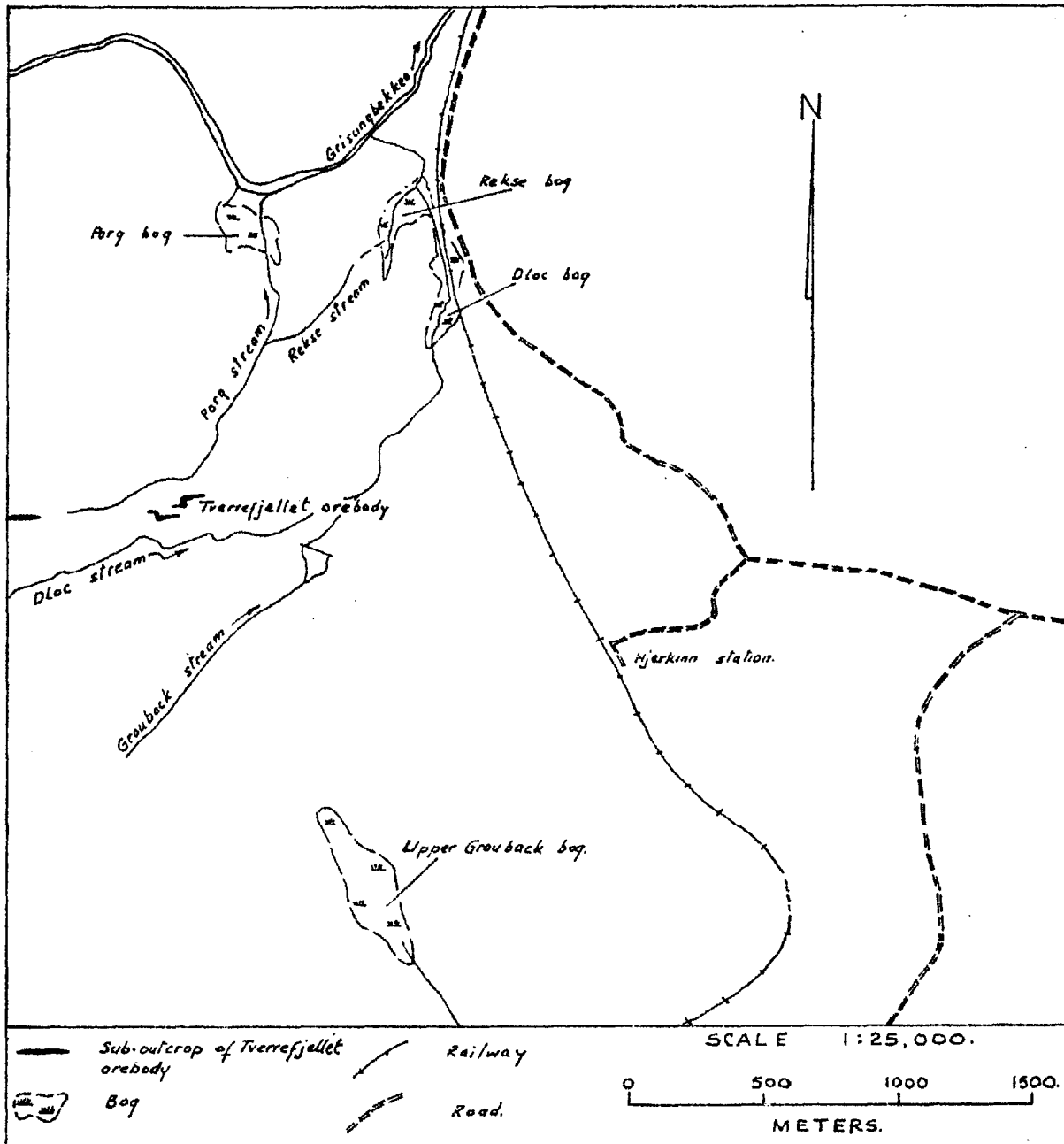


Fig.59. Plan showing the location of bogs studied in the Hjerkinn area.

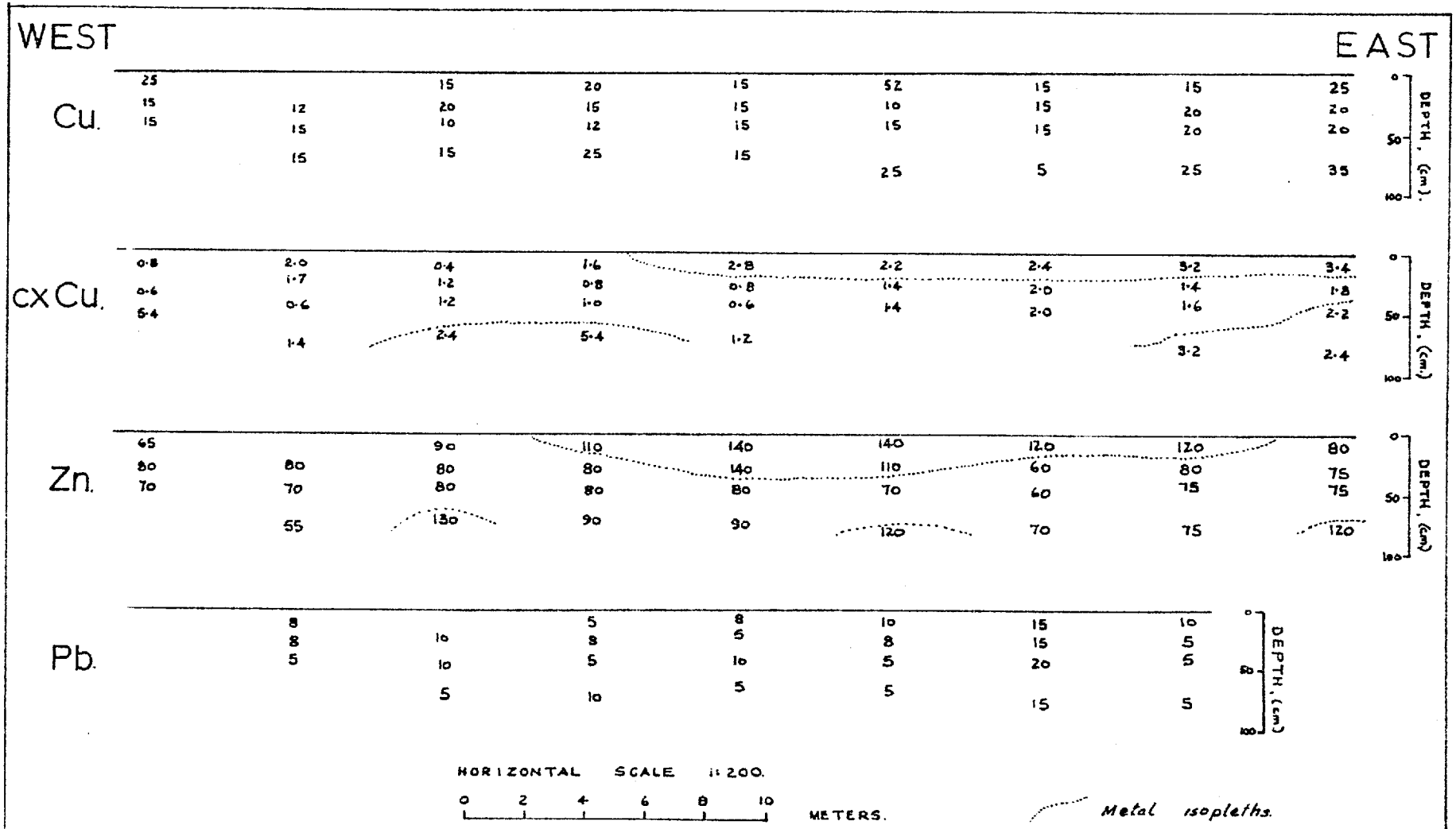


Fig.60. Sections showing the distribution of base metals in the Dloc bog. (Data on the -80 mesh fraction).

(Hvatum, 1964) suggests that Zn accumulates only in the surface layers. The reason for this is not understood.

In view of the rather erratic distribution of the base metals in bog profiles the results were not treated statistically. The upper background levels (Table 37) are considered to represent an approximation to the threshold levels.

TABLE 37.

Properties of Bog Material in Unmineralised Areas
(Data on the -80 mesh fraction)

Element	Range ppm	Miscellaneous Parameters
cx Cu	0.6 - 5.5	pH of slurries, 4.7 - 5.7
Cu	15 - 50	pH of groundwaters, 6.5 - 7.3
Zn	55 - 200	Base exchange capacity (BEC), 11.3 - 28.6 m.eq/100 g. % Fe 1.0 - 3.5.
Pb	5 - 30	% Organic Carbon, 4.2 - 10.5

Number of Samples 68

(iii) Distribution of Ore Elements in the Stream Banks of the Porg-Rekse-Grisungbekken Triangle down-drainage from the Tverrefjellet Orebody

An area of approximately 1 sq. km. surrounding the Porg, Rekse, Dloc and Grisungbekken streams was sampled on a grid system. The samples were taken at a depth of 10 - 20 cm. and analysed for cx Cu, Cu and Zn. As

previously mentioned much of the area surrounding the streams is waterlogged and boggy. Accordingly, as a first step in the interpretation of the data the upper background levels for bog material were used in defining the anomalous dispersion patterns (Figs.61 and 62).

The anomalously high values occur in broad dispersion haloes around the courses of the Porg, Rekse and Grisungbekken streams down-drainage from the orebody. The halo width varies between 25 and 100 m. being at the maximum in the boggy ground surrounding the lower reaches of the Porg stream. In the more elevated parts of the drainage (i.e. the upper reaches of the Porg and Rekse streams) the haloes are less extensive and vary between 25 and 50 m. in width. In this connection it is of some interest to note that the old course of the Rekse stream before diversion shows up as an anomalous track, whereas its present course does not.

The cx Cu, Cu and Zn anomalies are broadly co-extensive, and the dispersion patterns decrease in intensity down-drainage after reaching maxima in the Porg and Rekse bogs. In the banks of the Grisungbekken 2.0 km. from the orebody, cx Cu, Cu and Zn are 3, 2 and 1.1 times the upper background levels (for bog material) respectively. However, in the

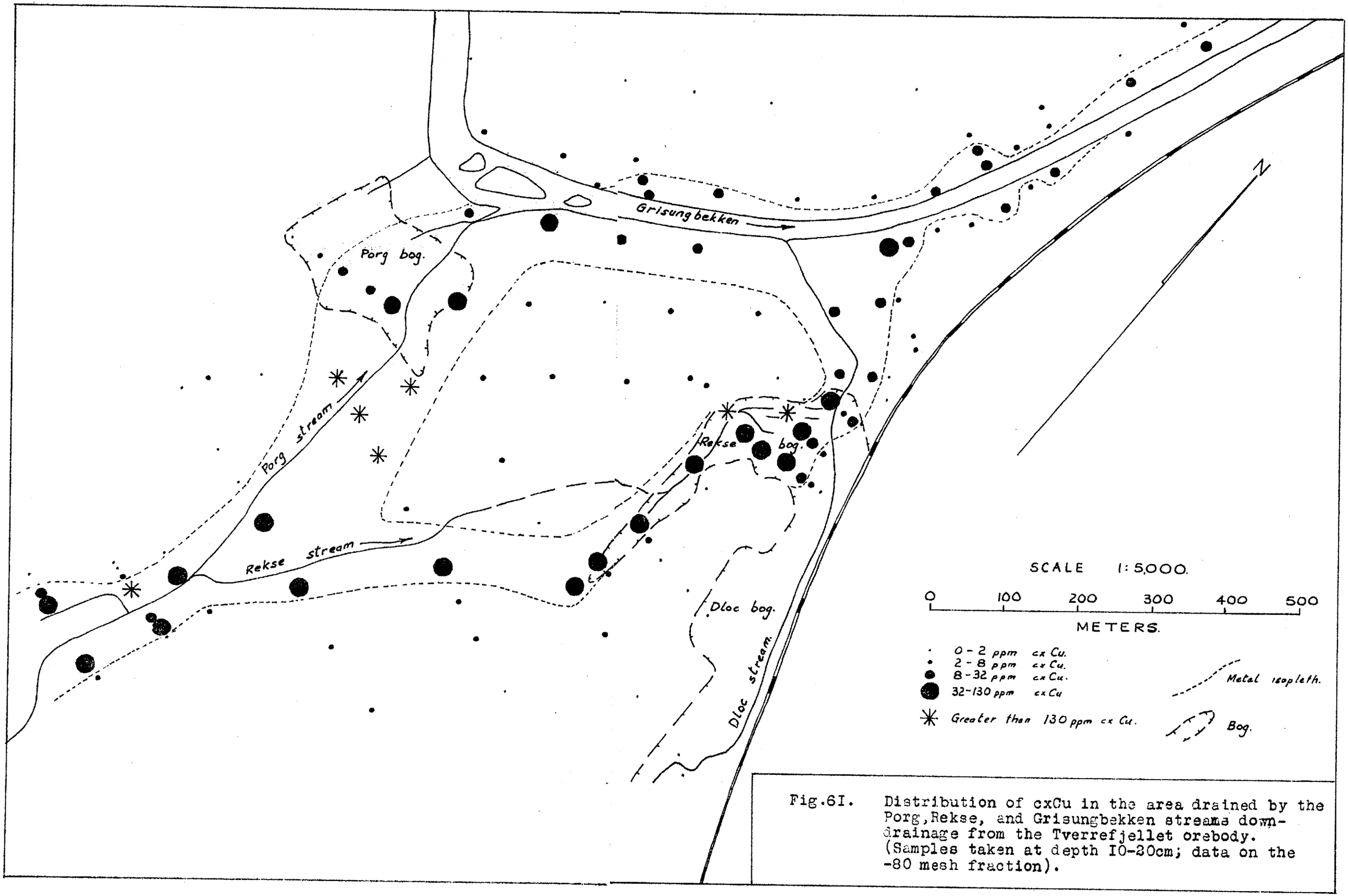


Fig.6I. Distribution of cxCu in the area drained by the Porg, Rekse, and Grisungbekken streams down-drainage from the Tverrefjellet orebody. (Samples taken at depth 10-30cm; data on the -80 mesh fraction).

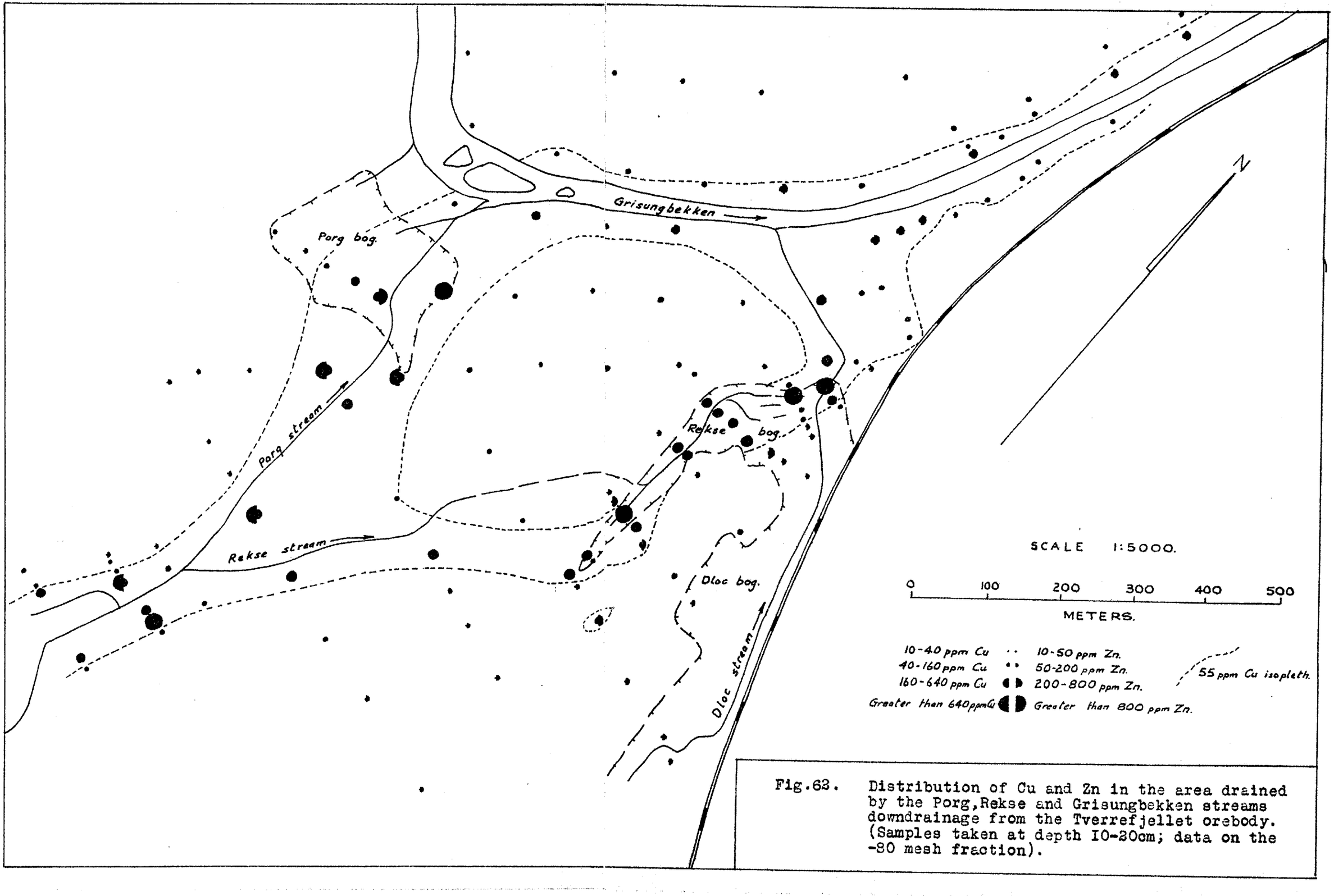


Fig.63. Distribution of Cu and Zn in the area drained by the Porg, Rekse and Grisungbekken streams downdrainage from the Tverrefjellet orebody. (Samples taken at depth 10-20cm; data on the -80 mesh fraction).

vicinity of the Porg stream the Grisungbekken banks are characterised by background metal values. These extend as narrow strips into the anomalous zone for a distance of 100 m. down-drainage on both sides of the Grisungbekken.

(iv) Distribution of Ore Elements in Bogs Down-drainage from the Tverrefjellet Orebody

As previously mentioned, the Porg and Rekse bogs occur within the anomalous metal zones surrounding the streams, down-drainage of the Tverrefjellet orebody (Fig.61 and 62). However, there are important differences between the two bogs. For example, in the Rekse bog mineralised and barren waters mix over a fairly narrow front, whilst in the Porg bog there is a gradual transition from the mineralised environment of the Porg stream into the barren western part of the bog. These and other factors have contributed to the development of different metal distributions in the two locations.

(a) Porg bog

The bog was sampled along a traverse at right angles to the drainage direction, and extending from the Porg stream in the east to the western boundary of the bog (Fig.63). The bog in profile consists predominantly of an organic rich surface layer 20 cm. thick, underlain by

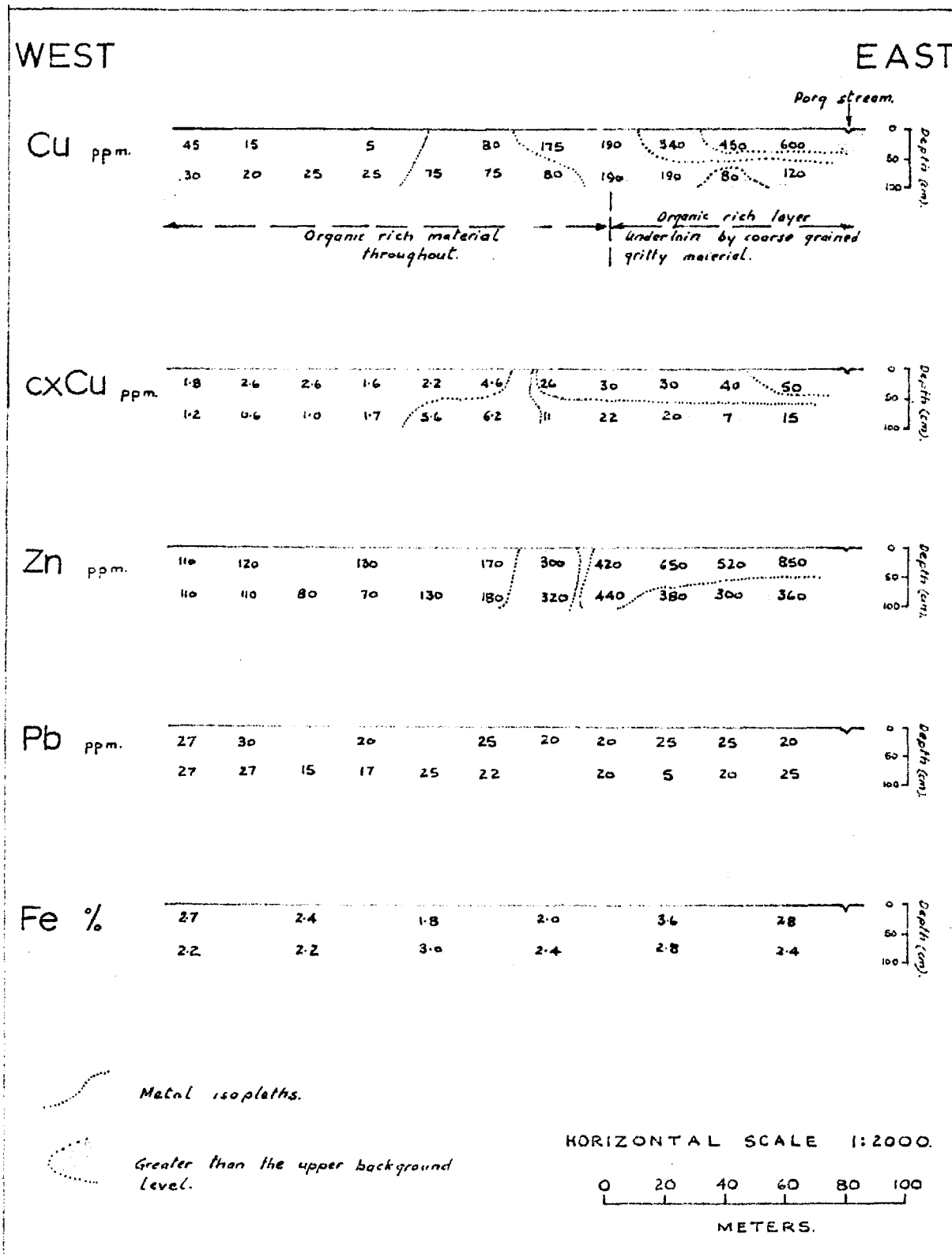


Fig.63. Sections showing the distribution of base metals and Fe in the Porg bog.
(Data on the -80 mesh fraction).

grey semi-organic silt. However, in the vicinity of the Porg stream the organic rich surface layer is underlain by coarse grained sand and silt with a low organic carbon content (Table 38 and Fig.63).

TABLE 38

Properties of Selected Profiles in the Porg Bog

(Data on the -80 mesh fraction)

Sample No.	Depth in profile (cm)	Description of profile and location in meters west of the Porg stream	% Organic Carbon	B.E.C. m.eq/ 100g	Metal Content ppm			
					cx Cu	Cu	Zn	Pb
43/2079	0.20	Red-brown organic silt.. .. ..20m	2.0	11.0	49	590	840	22
43/2080	30-50	Grey coarse-grained sand & silt .. "	0.7	4.7	16	115	220	25
43/2075	0.20	Black-brown organic silt.. .. ..65m	5.7	38.0	31	335	660	27
43/2076	30.50	Grey semi- organic silt.. .. .. "	1.7	9.0	20	190	380	5
43/2065	0.20	Black-brown organic silt.. .. ..160m	7.5	N.D.	1.6	5	130	20
43/2066	50-80	Grey semi-organic silt.. .. .. "	1.1	N.D.	1.7	25	70	17

(N.D. = Not Determined)

The general features of the distribution patterns (Fig.63) are as follows:-

(1) The cx Cu and Cu anomalies are broadly coincident and extend to 140 m. west of the Porg stream, whilst the anomalous Zn values persist for 110 m.

(2) Pb (5 - 30 ppm) is not enriched in the bog compared to other bogs.

(3) The Fe content of the bog is within the background concentration range (1.0 - 3.5%). However, there is a slight tendancy for the surface layer to be enriched in Fe compared to the underlying material.

(4) The cx Cu, Cu and Zn anomalies show a zonation parallel to the course of the Porg stream.

(5) There is a tendancy for the organic layer in the anomalous zone to contain higher metal values than the underlying material. This is particularly evident in the ground near the Porg stream where coarse grained material low in organic carbon underlies the surface layer.

On the east side of the Porg stream, the low lying ground is poorly drained, but is not normally covered by standing water (unlike the Porg bog to the west of the stream). The analytical results of two profiles from the eastern area (Table 39) shows that there is a significant enrichment of the surface layer in Fe and base metals.

TABLE 39.

Distribution of Fe and Base Metals in Profiles from the Low Lying Ground East of the Porg Stream (Data on the -80 mesh fraction)

Sample No.	Depth in Profile cm.	Distance East of Porg Stream (Meters)	METAL CONTENT			
			Fe %	Cu ppm	Zn ppm	Pb ppm
43/2081	0-20	5	15.6	1650	1400	145
43/2082	20-50		4.4	900	700	35
43/2083	0-20	10	8.4	1350	1200	100
43/2084	20-50		4.6	975	900	70

The surface enrichment is probably due, in part at least, to the deposition of fine grained secondary Fe oxides derived from the upper reaches of the Porg stream and carried down-drainage at high water. The ferruginous deposit is not found in the Porg bog to the west of the stream which suggests that the standing water of the bog forms an affective barrier against the stream waters.

(b) Rekse Bog

Broadly the Rekse bog is an elongated depression 450 m. long and oriented north east, south west. It has a maximum width of 180 m. in the north east where it joins the Dloc bog and stream. The Dloc stream has a pH of 6.8 - 7.0, and this barren water enters the Rekse bog to mix

with the mineralised waters that drain into the bog from the west (i.e. the Rekse stream pH 4.1). However, the mineralised waters entering the bog do so largely as groundwater. This is due, in part at least, to the diversion of the Rekse stream into the porous sand and gravels of the esker (by the military). The pH variations in the surface waters of the Rekse bog (Fig.64) do not follow a consistent trend towards less acid conditions near the Dloc stream.

Preliminary sampling of the Rekse bog revealed the presence of complex dispersion patterns. Accordingly the bog was sampled in detail, and the results are shown in Figs. 65, 66, 67, 68, 69 and 70. The data is plotted as areal distributions in the bog at two depths: 0-20 cm. and 50-100 cm. The dispersion patterns of cx Cu, Cu and Zn show significant differences in the two horizons. The principle features are:-

(1) cx Cu at a depth of 0-20 cm. is distributed in zones of varying concentration arranged more or less parallel to the long axis of the bog. In particular the strongly anomalous values occur around the stream channels and also along the north western margin of the bog. In general the values decrease towards the Dloc stream. On traverse X - Y the values decrease from 95 ppm to 0.6 ppm over a distance of 120 m.

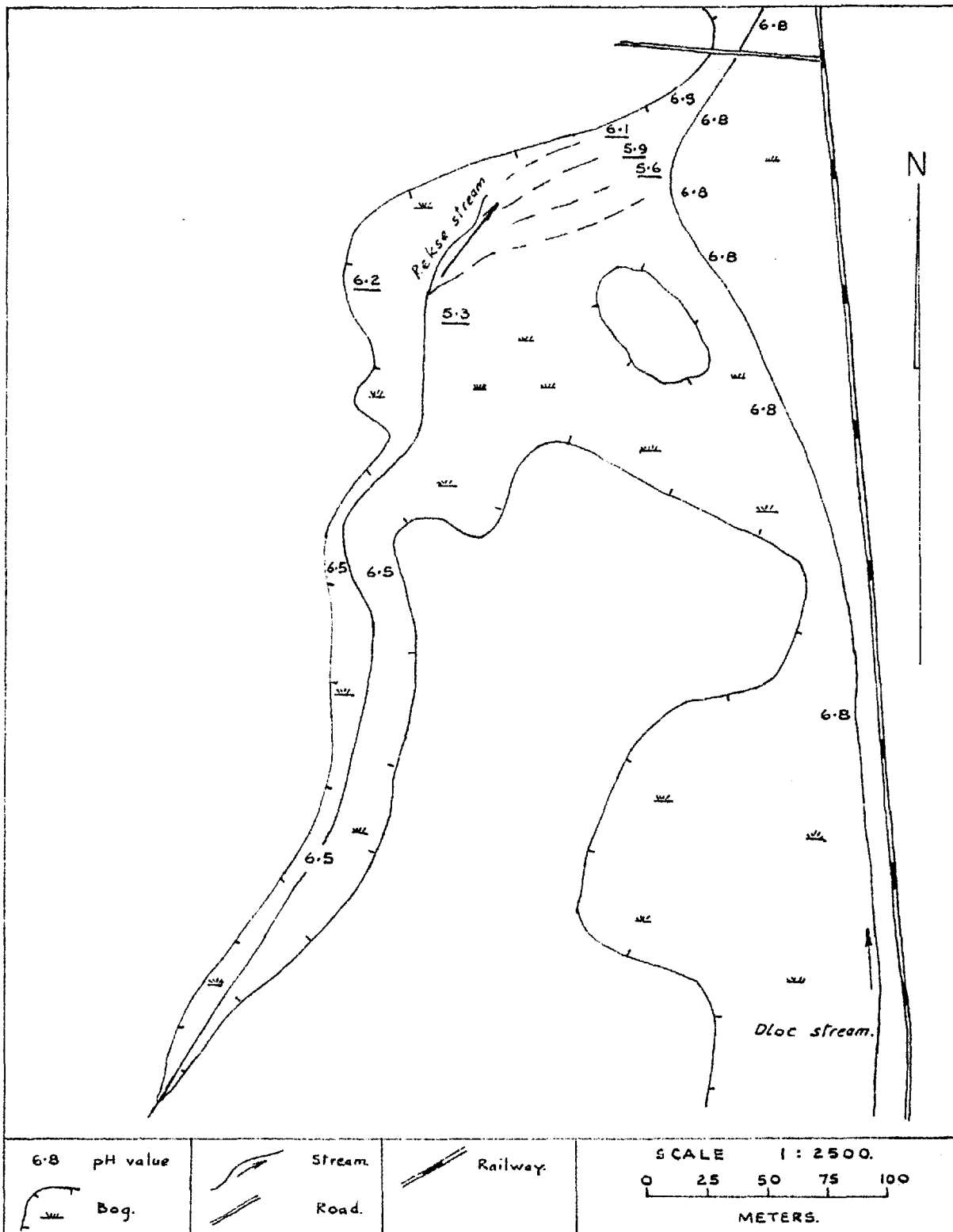


Fig.64. Plan showing the pH values in the surface waters of the Rekse bog.

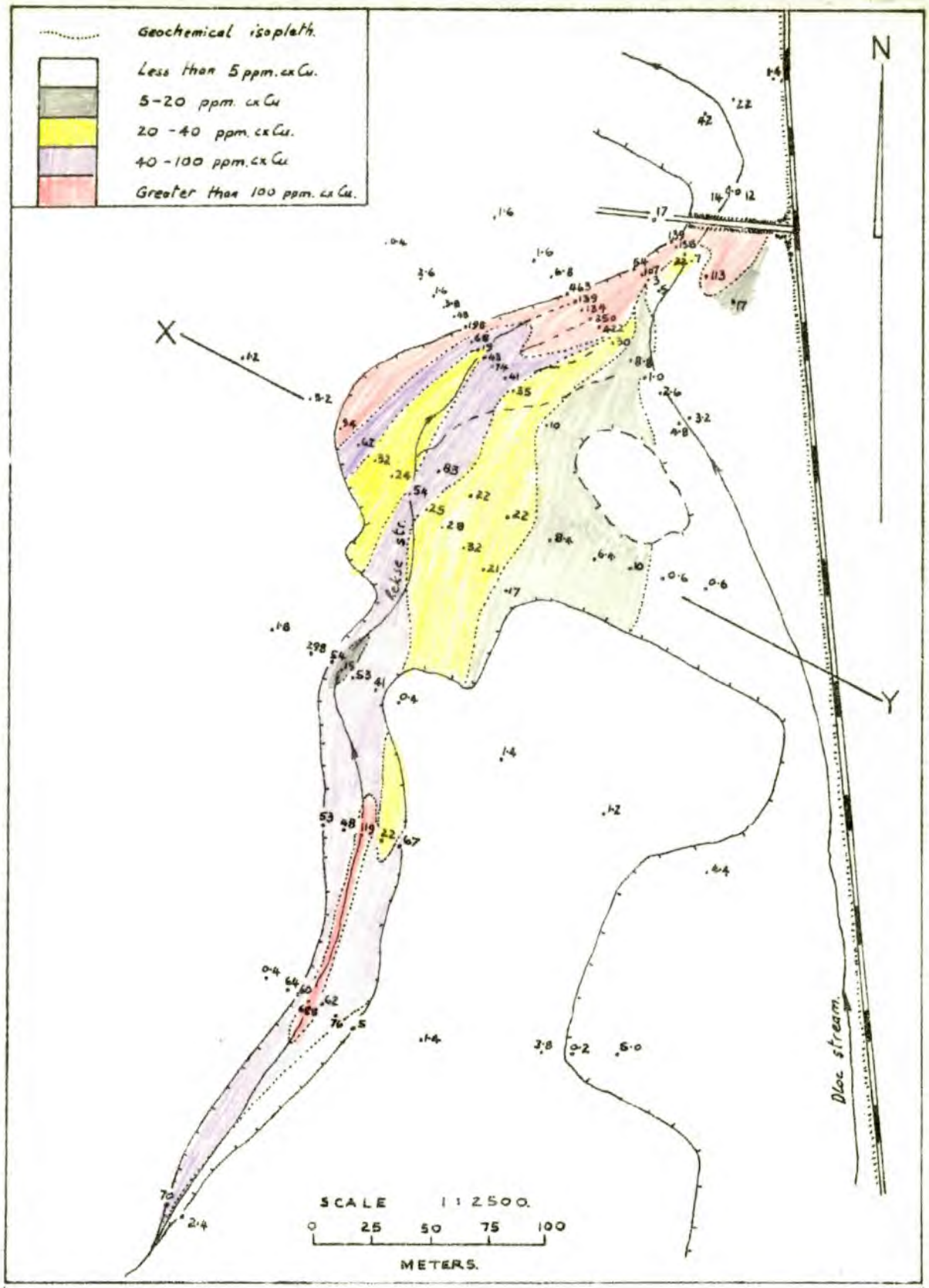


Fig.65. Plan showing the distribution of exCu at a depth of 0-30cm. in the Rekse bog. (Data on the -80 mesh fraction).

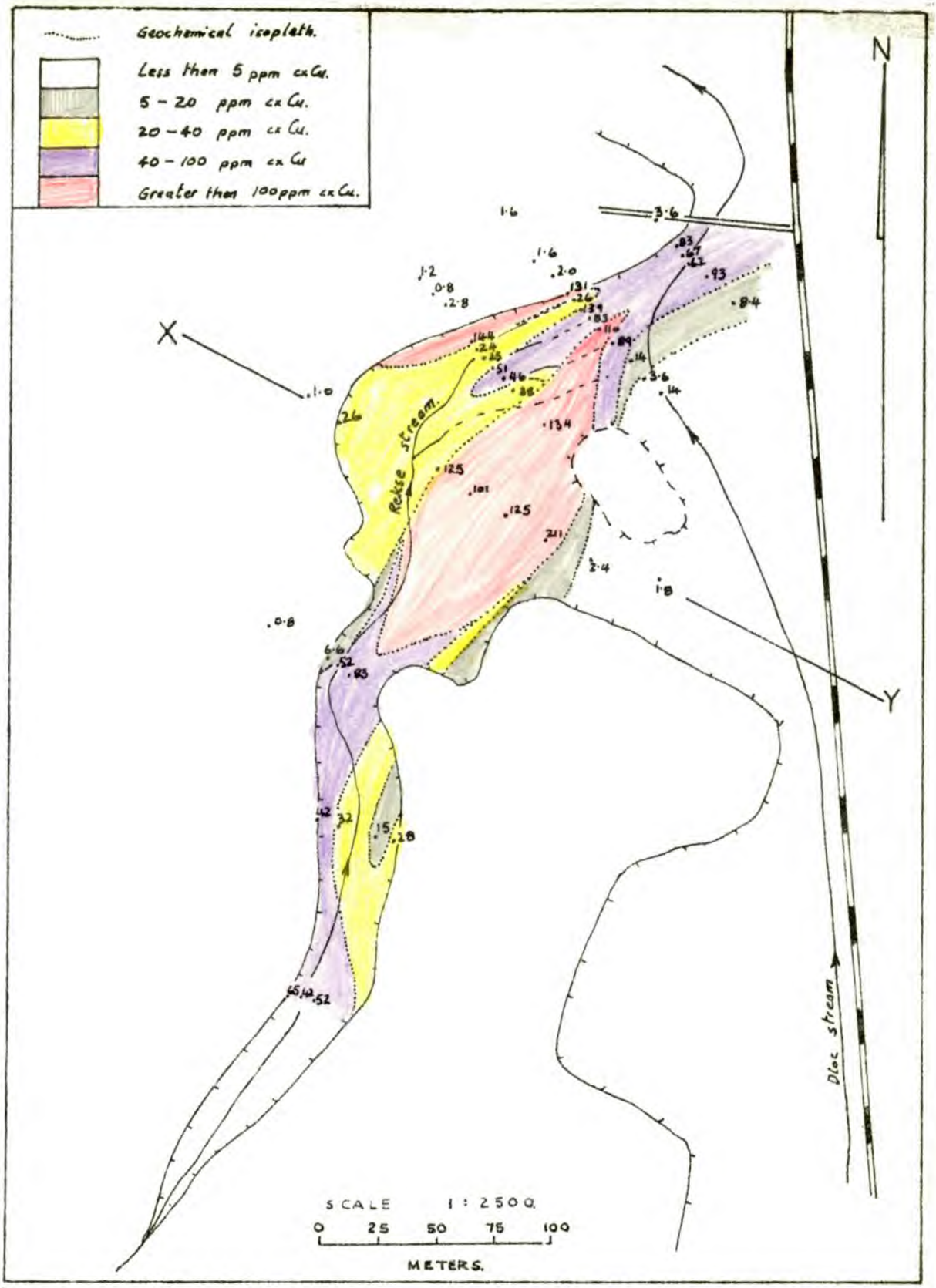


Fig.66. Plan showing the distribution of exCu at a depth of 50-100cm. in the Rekse bog. (Data on the -80 mesh fraction).

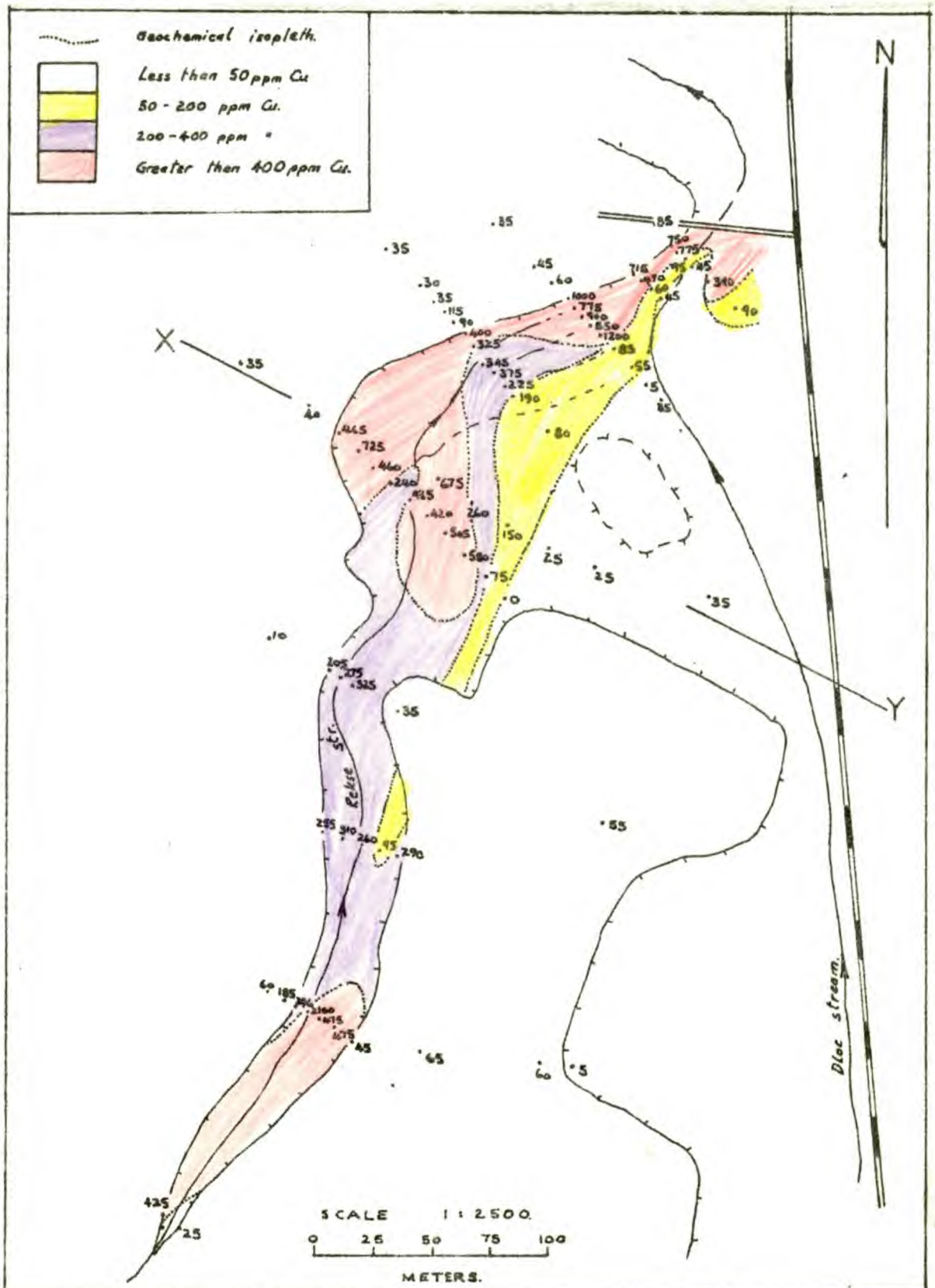


Fig.67. Plan showing the distribution of Cu at a depth of 0-30cm. in the Rekse bog. (Data on the -80 mesh fraction).

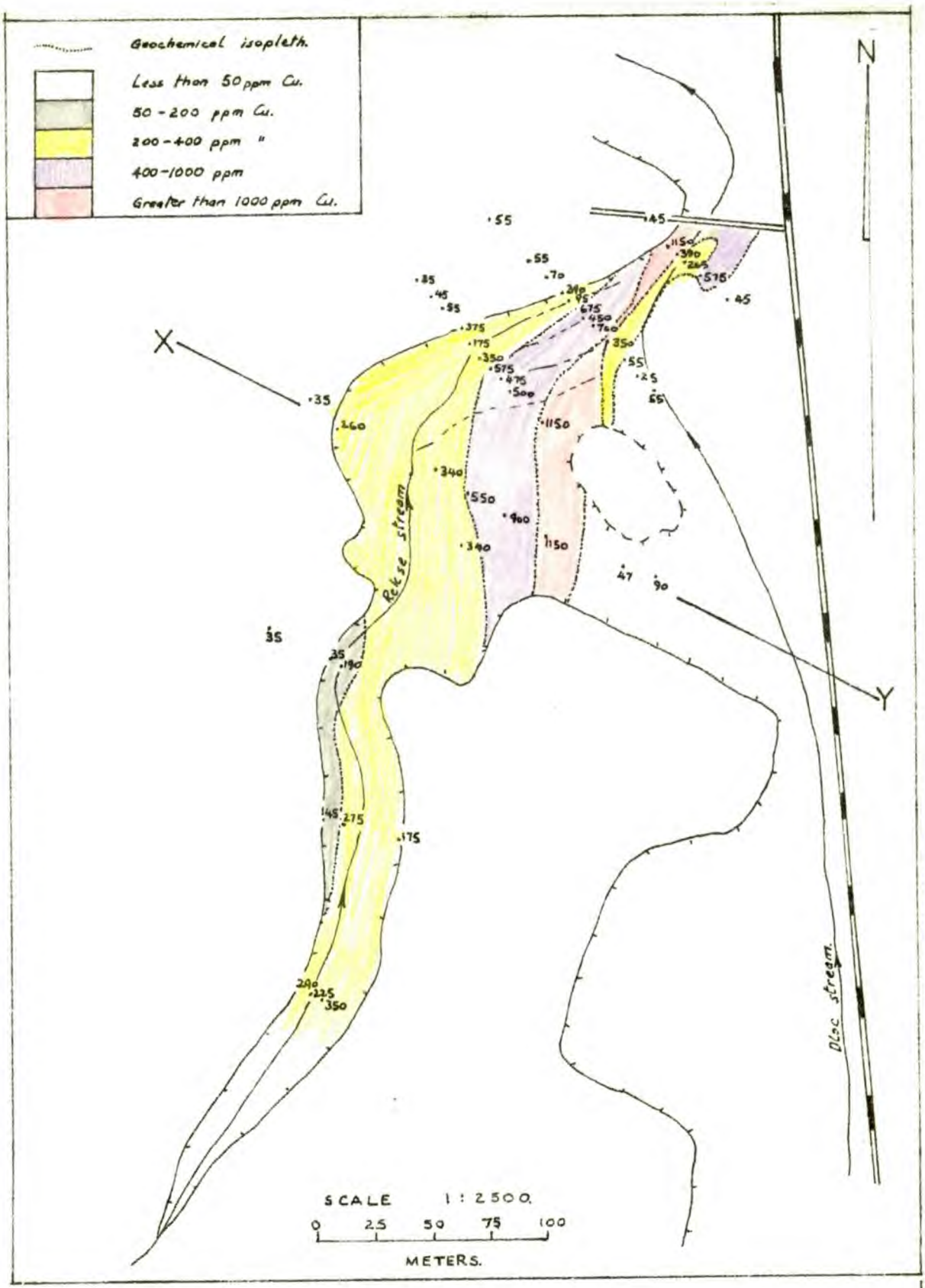


Fig.68. Plan showing the distribution of Cu at a depth of 50-100cm. in the Rekse bog. (Data on the -80 mesh fraction).

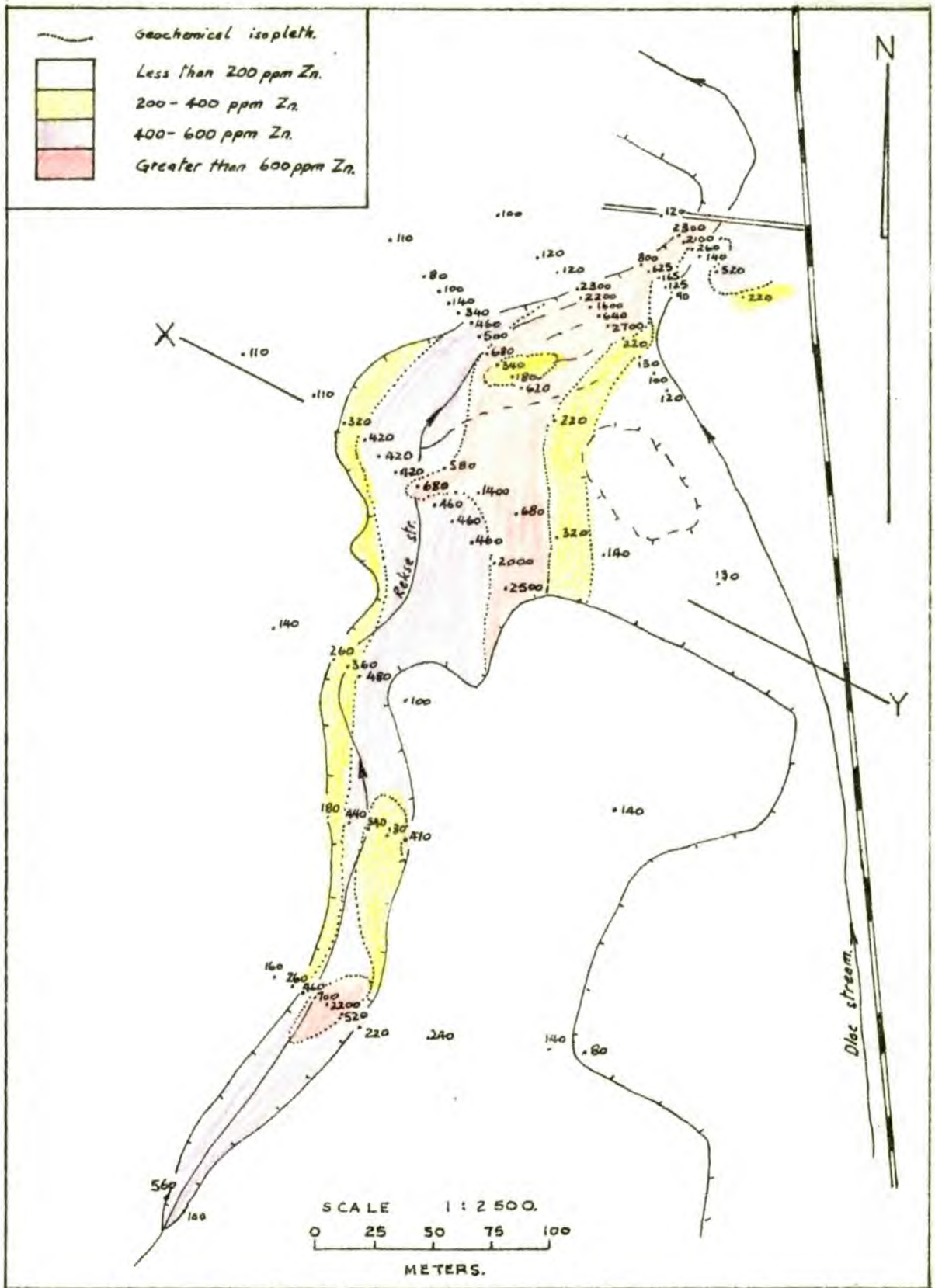


Fig.69. Plan showing the distribution of Zn at a depth of 0-20cm. in the Rekse bog. (Data on the -80 mesh fraction).

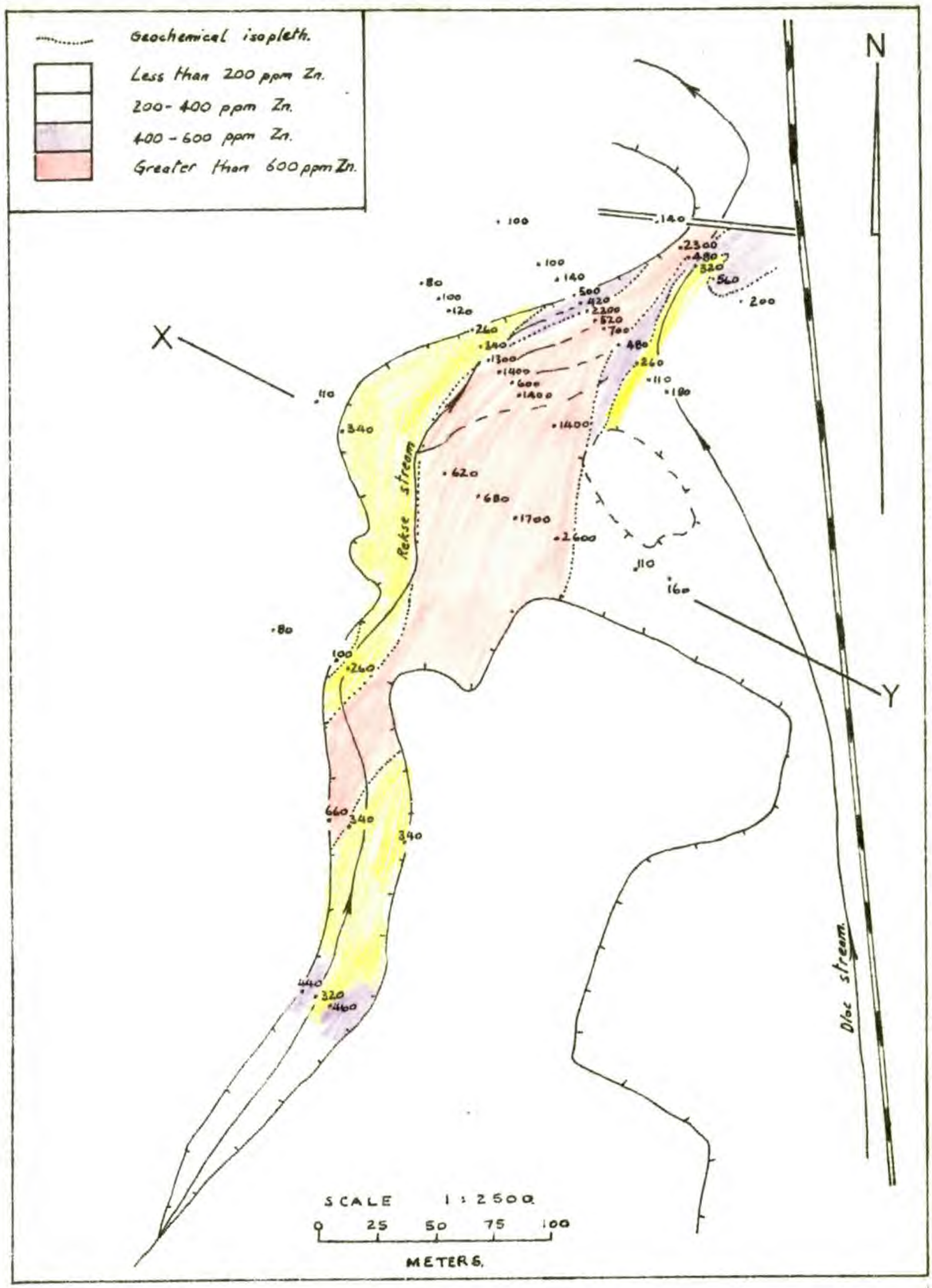


Fig.70. Plan showing the distribution of Zn at a depth of 50-100cm in the Rekse bog. (Data on the -80 mesh fraction).

At a depth of 50-100 cm. cx Cu is enriched in the centre of the bog with values up to 210 ppm. On the north western margin there is a narrow zone of strongly anomalous values up to 140 ppm. There is no spatial relationship of high values with the stream channel. In general the concentration of cx Cu increases towards the Dloc stream to a "cut-off" against barren material at a distance of 95 m. from the western margin on traverse X - Y.

(2) Cu at a depth of 0-20 cm. is concentrated in the south western part of the bog and also along the west and north western margins (Cu content is up to 2000 ppm). The Cu values decrease progressively towards the Dloc stream; background values being recorded 80 m. from the western margin.

By contrast, at 50-100 cm. although the whole of the western side of the bog is anomalous, the maximum Cu zone is 100 m. from the western margin (on traverse X - Y). There is a sharp cut-off to the west of these maxima to background concentration levels.

(3) Zn at 0-20 cm. increases in concentration towards the Dloc stream to a zone in which the values vary between 600 and 2500 ppm. This zone of maximum values

is flanked on the east by a narrow strip in which much lower values are recorded (i.e. just above the upper background level of 200 ppm). Cn traverse X - Y, Zn is at background 90 m. from the western margin.

Zn values at a depth of 50-100 cm. shows an increase in concentration towards the Dloc stream. The maximum values are contained in a broad zone (up to 600 m. in width) in which the Zn concentration varies between 600 and 2600 ppm. This strongly anomalous zone "cuts-out" against barren material along a front which is situated 100 m. from the western margin of the bog on traverse X - Y.

(4) The distribution of Fe and Pb were investigated in one traverse. The metal values are within the background concentration range (i.e. Fe 1.0 - 3.5%, Pb 5-30 ppm). In addition there are no variations that may be correlated with any layer in the bog profile. Accordingly the distribution of Fe and Pb are not shown in the diagrams.

In summary, the distribution patterns in the Rekse bog display the following major features:

(1) The cx Cu, Cu and Zn values occur in well defined zones of varying concentration, which are approximately parallel to the long axis of the Rekse bog.

(2) At a depth of 0-20 cm, the cx Cu and Cu values decrease towards the Dloc stream, whilst Zn increases in

this direction.

(3) At a depth of 50-100 cm. cx Cu, Cu and Zn increase towards the Dloc stream.

(4) In the case of metals increasing in concentration towards the Dloc stream, the "Cut-off" of strongly anomalous against background values occurs along a front situated 90-100 m. from the western margin of the bog (on traverse X - Y).

(5) In the Rekse bog anomalous distributions of Fe and Pb are essentially absent.

The properties of the bog material were investigated (Table 40) to determine the affect of the organic carbon content and other factors on the distribution of the metals.

TABLE 40

Some Properties of the Rekse Bog Material
(Data on the -80 mesh fraction)

pH of Surface Water	Sample No.	Distance from Western Margin of Bog (Meters)	Depth (cm.)	% Organic Carbon	B.E.C. m.eq/ 100g.	pH	METAL CONTENT ppm		
							cxCu	Cu	Zn
6.1	43/2103	25m.	0-20	3	15	5.1	20	225	500
	43/2105	"	50-100	1.9	11	4.9	24	175	340
6.8	43/2117	100m.	0-20	9.6	33	5.0	10	85	220
	43/2118	"	50-80	2.7	21	4.7	90	600	1400

The data (Table 40) shows that the organic carbon content has had little if any controlling influence on the distribution patterns of the metals. In addition there is no correlation between the pH of the sample material and its metal content.

Comparison of the pH of the bog material (measured in the laboratory) with that of surface waters (Table 40) shows that in this respect there is little relationship between the two media. It is significant that bog material in situ was found to have a pH quite different to that of the water in contact with it. For example, at one locality, water squeezed out of moss had a pH of 4.3 whilst the surface water had a pH of 7.0. It is suggested that the humic acids generated by organic material does not necessarily have a significant influence on the waters in contact with it.

CORRELATION OF THE TRACE ELEMENT CONTENT OF GROUND AND SURFACE WATERS IN THE PORG-GRISUNGBEKKEN DRAINAGE SYSTEM

A comparison between the ground and surface water of the Porg drainage (Table 41) shows in general that the surface waters are at a lower pH and contain more metal than the groundwaters. This would imply that at a given point, diluents (barren waters) first enter the groundwater system and only reach surface at a greater distance downd-drainage However, at 850 m. down-drainage from the orebody the $SO_4^=$ content of the surface waters increases from 60 to 90 ppm at the base of the major solifluxion bench. The increase in the $SO_4^=$ content is accom anied by a decrease in the pH from 4.9 to 4.2 but is not reflected by the base metal or Fe content of the surface waters. The data is consistent with an addition of low pH groundwater to the Porg drainage, but from a secondary source down-drainage of the Tverrefjellet orebody. That is to say, these waters possibly originate from nearby weak mineralisation in the bedrock. The lack of similar evidence from points elsewhere on the stream suggests that there are no other important additions of mineralised groundwaters to the Porg drainage channel.

TABLE 41.

Comparison of the Trace Element Content of Ground and Surface Waters in the Porg-Grisungbekken Drainage System

Distance Down-drainage from head of Porg Stream (Meters)	pH	GROUNDWATERS ppb				pH	SURFACE WATERS ppb			
		Cu	Zn	Pb	Fe		Cu	Zn	Pb	Fe
				PORG STREAM						
0	2.5	18400*	23000*	640*	360000*	2.5	18400*	23000*	640*	360000*
700	4.6	460	1520	2	120	3.2	1450*	1600*	55	6400*
1400	5.7	110*	1300*	4*	N.D.	4.2	550*	1260*	14*	130*
				GRISUNGBEKKEN						
1600	N.D.	85*	650*	3*	N.D.	6.8	19	64	6	90
2000	6.4	25	60	8	260	6.8	3	28	6	120

(Results are for total metals except where indicated by asterisk when ionic metal values given.
(N.D. = Not Determined

The changes in the metal content of the Porg stream groundwaters have previously been discussed (see P.145). The main conclusions are:-

(1) In the first 700 m. down-drainage from the ore, base metals and Fe precipitate from the groundwaters as the pH increases from 2.5 to 4.6. In this section of the drainage Fe and Pb are almost totally eliminated from groundwater solution.

(2) Cu continues to precipitate from the groundwaters over the last 700 m. of the Porg drainage, whilst Zn does not.

(3) The renewed precipitation of Zn takes place in the Grisungbekken groundwaters where the pH increases from 5.7 to 6.4.

In the surface waters of the Porg stream the decrease in the Cu and Zn contents have been shown to be in direct proportion to the amount of dilution by barren waters, as indicated by the pH. On theoretical grounds there is evidence to suggest that the waters are unsaturated with respect to Cu (Table 42). The calculations are based on Sillmans theoretical data (Sillman, 1958); unfortunately data for calculating the saturation concentrations of Pb and Zn are not available. However, the very similar decrease in the Cu and Zn contents of the surface water down-drainage indicates that the Zn concentrations are also below the saturation level.

TABLE 42.

Calculated Solubilities of Cu in the Porg Stream Surface Waters (based on the data of Sillman, 1958), Compared with the Observed Cu Concentrations

(a = activity of dissolved species)

pH	Observed $a_{SO_4^{=}}$	Theoretical $a_{Cu^{++}}$	Observed Concentration Cu ppm	Theoretical Solubility Cu ppm
3.0	$10^{-2.86}$	10^{0}	3.4	63,540
3.8	$10^{-3.36}$	$10^{-1.0}$	1.4	6,354
4.2	$10^{-3.30}$	10^{-20}	0.60	635
6.4	$10^{-3.4}$	$10^{-6.0}$	0.05	0.06

($\Sigma CO_2 = 10^{-5}$)

The decrease in the Pb values is rather more than can be explained entirely by dilution. Pb may therefore be precipitating from the surface waters of the Porg stream. There is no doubt, however, that Fe is precipitating from the surface waters since its concentration decreases by a factor of 1000 within the first 800 m. Hem (1960) states that "brown ferric hydroxide precipitates from aerated water solutions containing more than 10 ppb Fe^{3+} at pH values of 4.5 and above". The observations show that the Fe content of the surface water decreases from 360,000 ppb at the head of the Porg stream to 130 ppb at the junction with the Grisungbekken. The change in the Fe content of the water

is accompanies by an increase in the pH from 2.5 to 4.2, (with minor fluctuations up to a pH of 4.9 half way down the Porg stream).

In summary, the Porg groundwaters lose significantly more metal than the surface waters. The reduction in metal content of the groundwater is too great to be explained entirely by dilution. That is to say, the rate of increase of the pH is less than the rate of decrease of the metal concentrations. The surface water of the Porg stream precipitate substantial quantities of Fe over the first 800 m. down-drainage from the ore and it is possible that Pb is also being deposited by the surface waters. By contrast, Cu and Zn remain predominantly in solution in the surface waters, their concentration decreasing proportionately to the amount of dilution by barren waters.

In the Grisungbekken the surface waters contain metal just above the upper background levels, whilst the groundwater up to 20 m. either side of the stream contains strongly anomalous concentrations of Cu and Zn. The disperity between the metal contents of the surface and groundwaters of the Grisungbekken (Table 41) indicates that the boundary between the two media is sharply defined. It is probable,

for example, that the groundwaters move by laminar flow which prevents the turbulent mixing characteristic of the surface environment. A discussion of the mode of dispersion of the anomalous groundwaters is deferred to a later section dealing also with the metal content of the stream sediments and banks.

The metal content of the Grisungbekken surface waters can be related to the input of mineralised low pH waters from the Porg stream (Table 30). The Cu and Zn contents of the surface water are just above the upper background levels (i.e. Cu 12 ppb, Zn 13 ppb) on the south side of the stream down-drainage from the Porg confluence. On the north side the waters contain background metal concentrations. Equal contents of Cu occurs on both sides of the stream after a distance of 400 m. down-drainage from the Porg entry, and Zn after 700 m. At these points Cu is within the background concentration range, whilst the Zn content is 2.5 times the upper background level. The difference in the distribution patterns of Cu and Zn is possibly indicative of their different solubilities under the prevailing pH conditions.

The Fe and Pb contents of the Grisungbekken surface waters are entirely within the background concentration

range. However, the Fe content, which is approximately constant at 100 ppb is above the theoretical limit for dissolved Fe^{3+} in waters of pH 6.5 - 6.9 (Hem, 1960). This implies a super-saturation in trivalent Fe, or the presence of complex ions unaffected by the pH. Alternatively the Fe may be travelling as particulate Fe in the surface waters of the Grisungbekken.

FORM OF OCCURRENCE OF ORE ELEMENTS IN STREAM SEDIMENT

In the study of the form of occurrence of ore elements in stream sediments, the Porg stream was taken as the type example. Three samples (43/4119, 43/2979 and 43/2985) which occur at increasing distances down-stream (Fig.71) were selected for a detailed laboratory examination.

TABLE 43.

Some Properties of the Porg Stream Sediments Selected for Detailed Study

(Data on the -80 mesh fraction, except where indicated)

Sample No.	Distance down Stream from Source (Meters)	% Fines (-197)	pH	% Organic Carbon	B.E.C. m.eq/100g	% Fe	ppm $SO_4^=$
43/4119	300	8	3.1	1.4	4.0	16	6250
43/2979	700	9	3.7	1.6	10.0	11.5	3500
43/2985	1100	32	4.0	2.3	9.2	6.5	1750

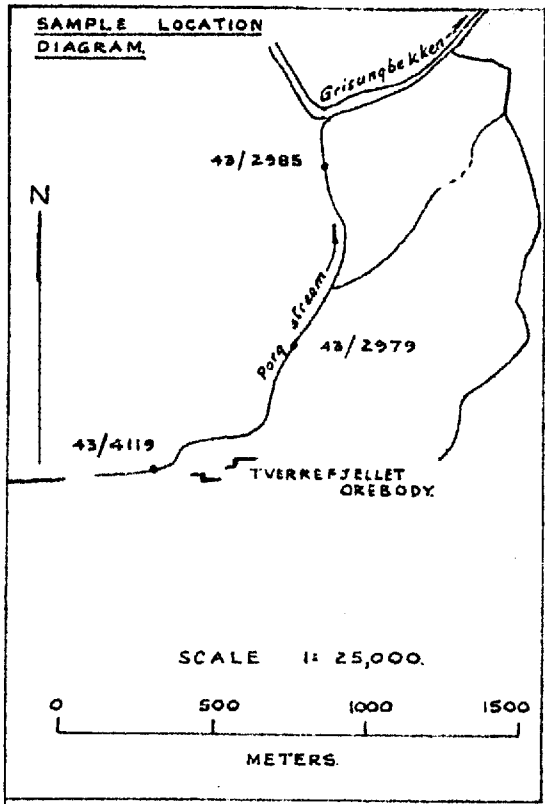
The physical properties of the sample material (Table 43) show that down-drainage the sediments become progressively finer grained and contain more organic carbon, but less Fe and SO_4. The increase down-drainage in the percentage of fine grained material is very marked,

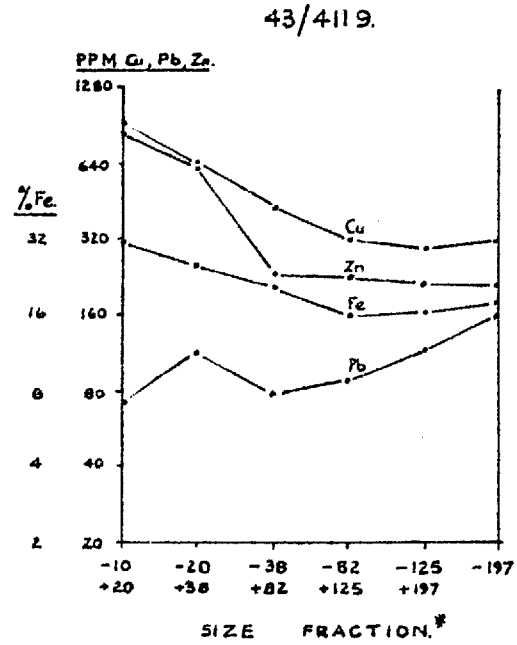
but is not accompanied by a proportionate increase in the base exchange capacity. However, half way down the stream the sediments contain ferruginous ooze which is absent up-drainage where the deposits consist of coarse to medium grained iron oxide, sand and silt. Down-drainage, in the low lying boggy ground the sediments are much less ferruginous and are noticeably more organic and argillaceous. The high base exchange capacity of the sediments which occur half way down the stream may be due to the presence of the ferruginous ooze. Measurements of the base exchange capacity of freshly precipitated ferric hydroxide (precipitated from cold solution by ammonium hydroxide) gave values of 15 m.eq./100g. (Mackenzie, 1952). The base exchange capacity of the organic and argillaceous sediment (9.2 m.eq./100g.) is intermediate in value between the base exchange capacity of moraine (4-6 m.eq/100g.) and that of bog material (11-29 m.eq./100g.).

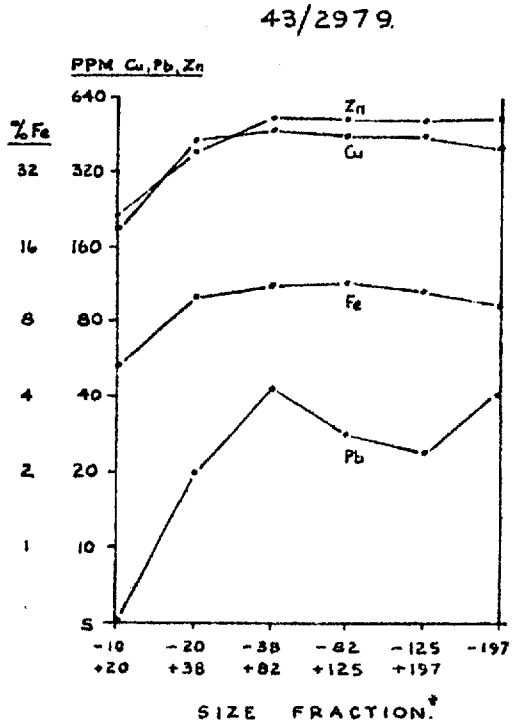
(i) Distribution of Metals between the Size Fractions

(a) $KHSO_4$ Extractable Metal

In sample 43/4119 Cu, Zn and Fe are intimately associated, and the metal values decrease with decreasing grain size (Fig.71). Sample 43/2979 taken half way down







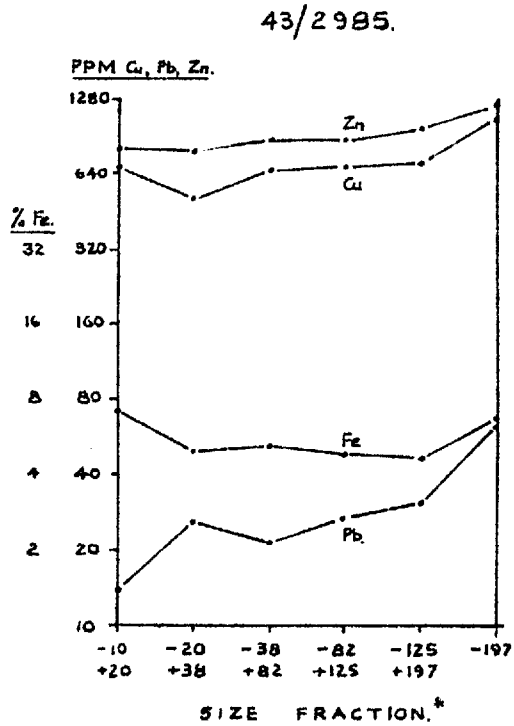


Fig.7I. Distribution of bisulphate extractable Cu, Zn, Pb and Fe in size fractions of selected samples of active sediment from the Porg stream.

(* B.S.S. mesh size).

the stream also shows that Cu, Zn and Fe are closely associated, but the metals are predominantly held in the finer grain sizes of the sediment. Analysis of sample 43/2985 from the lower boggy part of the stream indicates that Cu and Zn occur together and that the values increase with decreasing grain size. Fe shows a reverse trend, indicating that the base metals are not strongly associated with the Fe. In all these samples Pb is consistently enriched in the finer grades of the sediment (Fig.71) and shows little, if any, relationship to the other ore elements.

(b) 0.5 M. Hydrochloric Acid Soluble Cu and Fe

Analysis of the sixe fractions of the three samples (Fig.72) shows that Cu is in an increasingly soluble form downstream. The values increase with decreasing grain size. In the sediments from the upper reaches of the stream Cu appears to occur with Fe. The association of Cu and Fe is not noted in sample 43/2985 from the lower part of the stream.

(c) Exchangeable Metal

The distribution of cx Cu and cx Zn through the size fractions is irregular (Fig.73). However, there is a weakly developed trend towards higher values in the finest

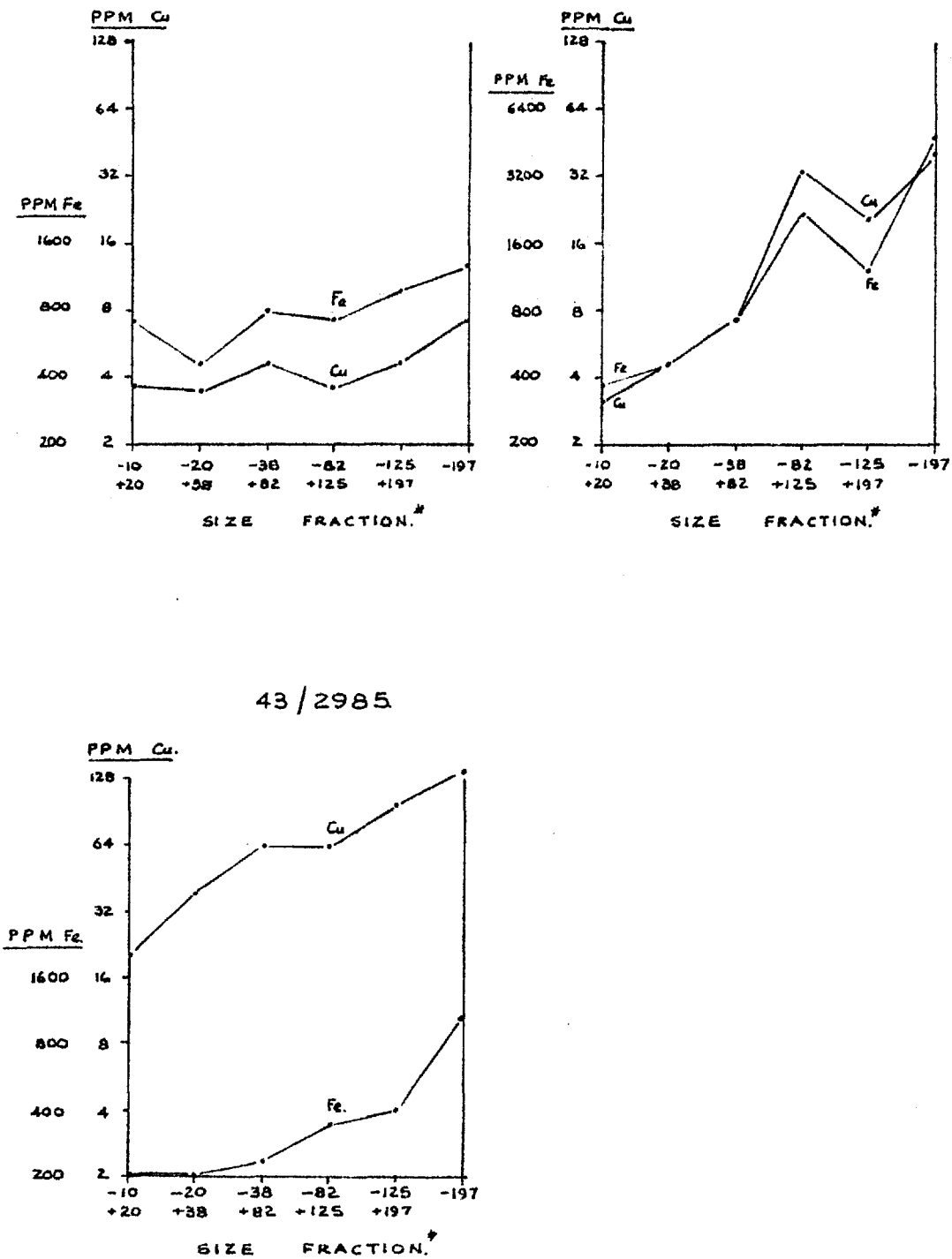


Fig.72. Distribution of 0·5 M. hydrochloric acid soluble Cu and Fe in size fractions of selected samples of active sediment from the Porg stream. (For the location of sample sites see Fig.7I).

(# B.S.S. mesh size).

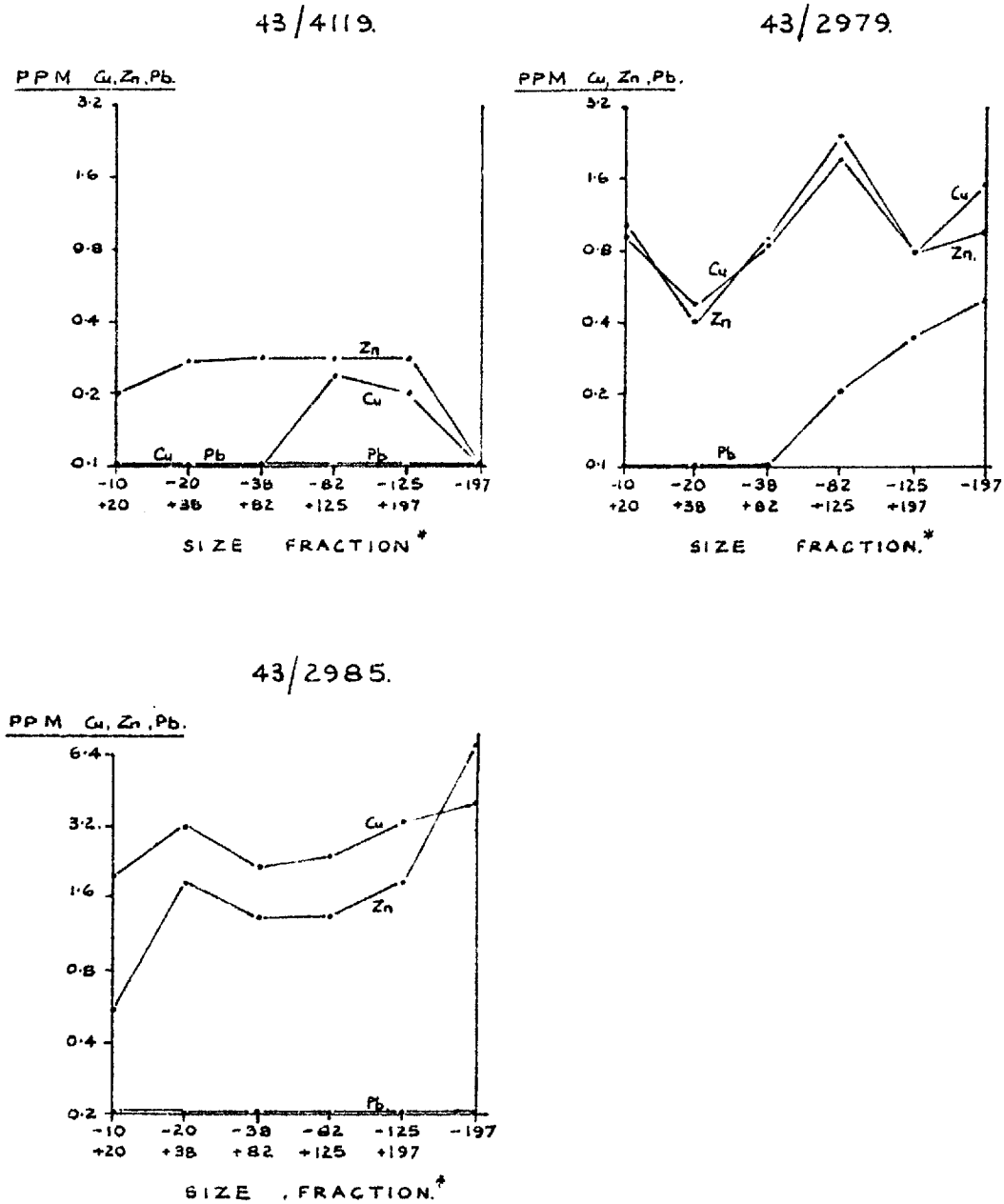


Fig.73. Distribution of exchangeable base metal in size fractions of selected samples of active sediment from the Porg stream.
(For the location of samples sites see Fig.7I).

(* B.S.S. mesh size).

fractions. The amount of cx Cu and cx Zn increase downstream, but the concentrations involved are low. The exchangeable Pb results indicate a virtual absence of Pb in this form in samples 43/4119 and 43/2985. The sample 43/2979 however contains 0.5 ppm cx Pb in the -197 mesh fraction.

The results of size analysis indicate that over the first half of the stream Cu and Zn are predominantly associated with Fe. In particular Cu, Zn and Fe are concentrated in the coarse fractions of the sediment near the source of the stream. Half way down the stream the association of Cu, Zn and Fe is maintained but the metals are concentrated in the fine fractions of the sediment. This may suggest that (a) fine grained ferruginous material is being carried some distance downstream, resulting in mechanical dispersion of Fe, Cu and Zn, or (b) in the section of the drainage the Fe precipitated from solution may remain in a finely divided form.

In the boggy lower reaches of the Porg stream Cu and Zn occur together, but there is no evidence of the associated of these metals with Fe.

In the three samples studied, Pb is consistently enriched in the finest fraction, and shows little, if any,

relationship with the other elements.

(ii) Reaction-Time Experiments

Reaction-time experiments carried out by Kagule-Magambo (1965), has provided additional data on the form of occurrence of Cu, Fe and Mn in the -125 + 197 fraction of samples 43/4119 and 43/2985. The samples from the upper and lower reaches of the stream were selected for this study as the results of size analysis indicated that the ore elements probably occur in different forms in the two samples.

Reaction-time experiments are based on the concept that "the rate at which a trace element comes into solution will be related, in part, to the rate of dissolution of its host mineral", (Tooms, 1965).

In the experiments 5q. of sample was refluxed with 300 ml. of 0.2 N sulphuric acid on a boiling water bath. At selected time intervals the reaction mixture was sampled and analysed for Cu, Fe and Mn. The results are shown in Figs. 74 and 75.

Discussion of the Results of the Reaction-Time Experiments

The interpretation of the data derived from reaction-time experiments has been discussed by Tooms (1965). The following is a quotation: "If there are two forms of the

element being dissolved by the reagent the complete solution of one form will result in a decreased rate of increase in the total concentration of the element in solution. That is to say, there will be a change in the inclination of the graphical plot. In either case, if the form of the trace element which has been taken completely into solution was intimately associated with a major element, complete solution of this form of the trace element must imply complete solution of the major element and there will be, therefore, a break in the inclination of both graphical plots. In other words, if two elements in part or whole are intimately associated, (e.g. in a compound or mineral), in a sample, a change in the relative rate of solution of one will be reflected by a change in the relative rate of solution of the other."

The following comments on the form of the metal in samples 43/4119 and 43/2985 are taken from Kagule-Magambo (1965).

Sample 43/4119

"Three forms of iron, Fe_a, Fe_b, and Fe_c and two forms of copper, Cu_a and Cu_b were taken into solution. The form of iron with intermediate solubility, Fe_b and the easily

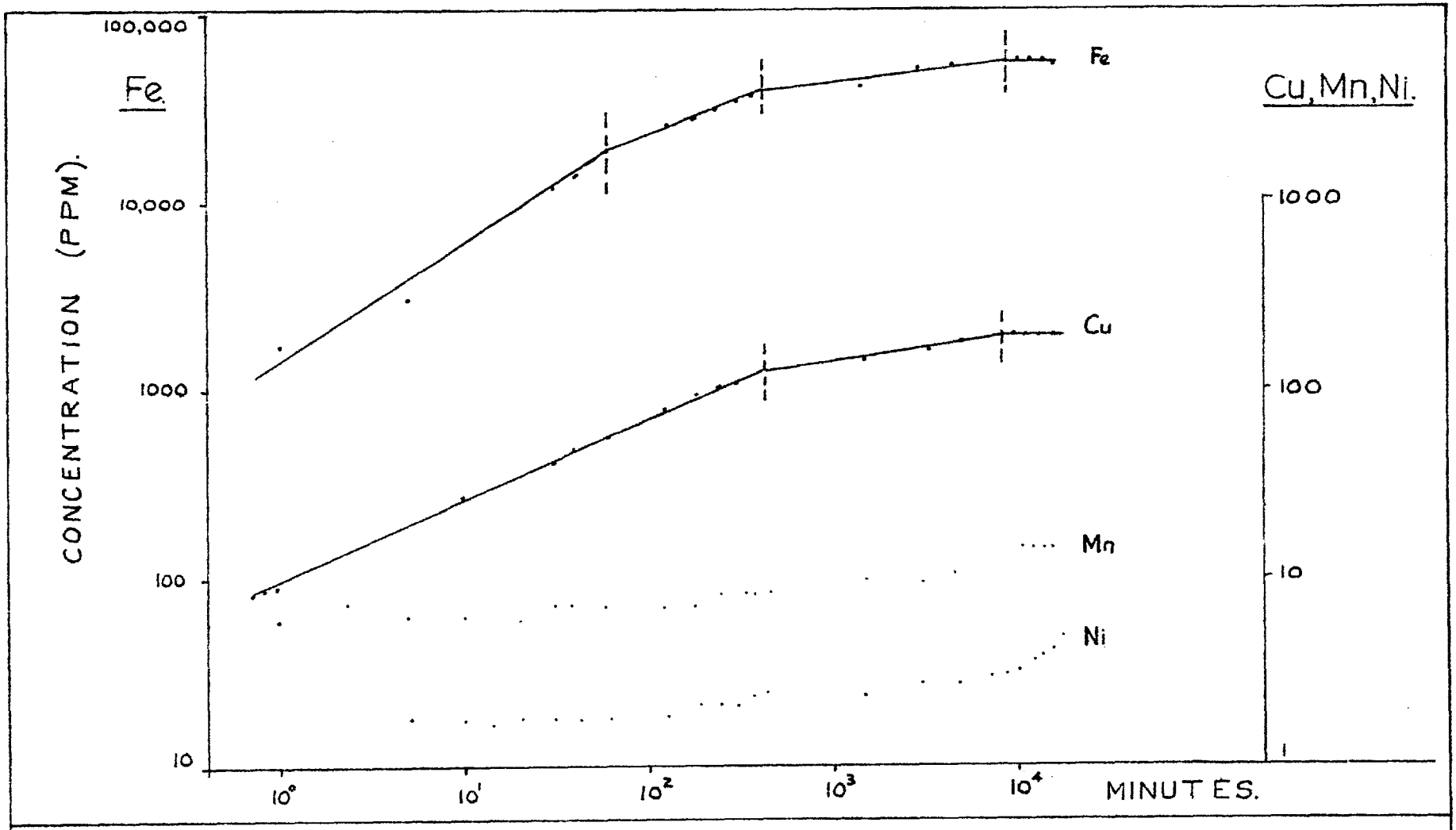


Fig.74. Reaction time experiment (after Kagule-Magambo, 1965). Sample Porg stream sediment 43/4II9: -I25+I97 fraction, 0·I96I N. H_2SO_4, temperature I00°C. (*For location see Fig. 71*).

soluble form of copper, Cu_a, cease to come into solution at the same time. They are probably associated in a single mineral or compound. Similarly, the least soluble forms of iron and copper cease to be taken into solution at the same time. They are also probably associated in a single mineral of compound." At the completion of the experiment, that is to say, when no further metal was dissolved, the solution contained 55,800 ppm Fe and 200 ppm Cu.

Sample 43/2985.

"At least three forms of iron, three forms of copper and manganese were brought into solution.

The easily soluble forms of iron and manganese cease to be taken into solution at the same time. They are thus, probably associated in a single mineral or compound. The forms of manganese and copper with intermediate solubilities cease to be taken into solution at the same time. These, too, are probably associated to form a single mineral or compound.

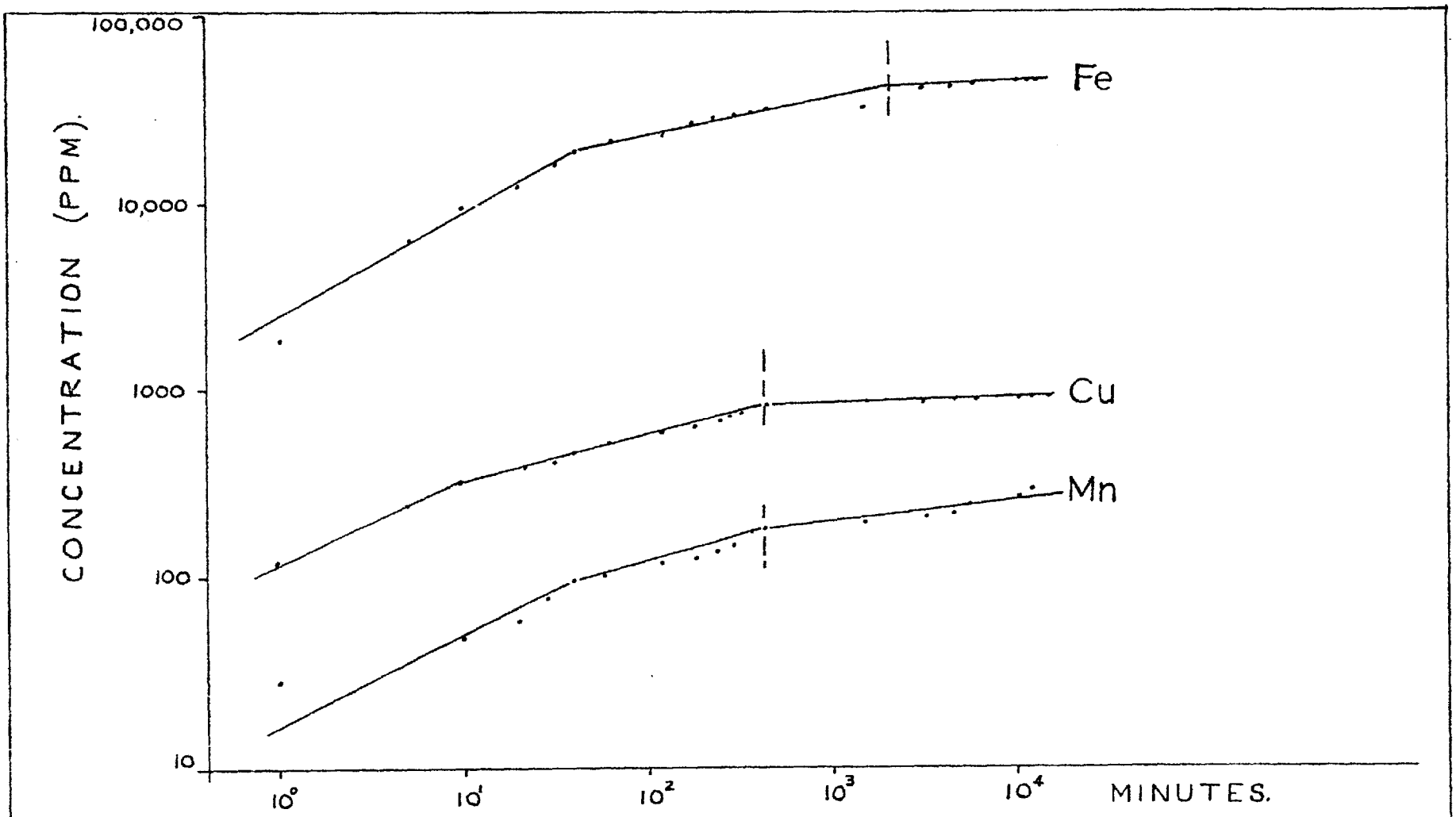


Fig.75. Reaction time experiment (after Kagule-Magambo,1965). Sample Porg stream sediment 43/2985: -I25+I97 fraction, 0·I96I N. H_2SO_4, temperature I00°C. *(For location see Fig. 71).*

Manganese thus forms at least two distinctly different forms of minerals or compounds - one associated with iron and another associated with copper. There is no association between iron and copper revealed by the iron and copper plots." At the completion of the experiment, the solution contained, 43,800 ppm Fe, 900 ppm Cu and 360 ppm Mn.

Comparison of the time required to take completely into solution the different forms of Cu and Fe occurring in the two samples (Table 44) indicate that the most readily available Cu in sample 43/2985 does not occur in sample 43/4119. It is of interest to note that after an interval of one minute from the start of the experiments the solution in contact with sample 43/4119 contained 10 ppm Cu, whilst the 43/2985 reaction mixture contained 120 ppm Cu.

TABLE 44.

Comparison of the Time Required to take Completely into Solution the Different Forms of Cu and Fe Occurring in Samples 43/4119 and 43/2985

(Solvent 0.2 N H_2SO_4, Temperature 100°C)

Time, (Minutes) (Where to = time of commencement of experiment)	43/4119		43/2985	
	Form of Metal	Concentration of element in Solution, ppm	Form of Metal	Concentration of element in Solution, ppm
to + 10			Cu_x	340
to + 50	Fe_a	14,400	Fe_x	17,400
to + 420	Cu_a	130	Cu_y	840
	Fe_b	38,400		
to + 2880			Fe_y	39,000
to + 5760	Cu_b	180		
	Fe_c	52,000		

Assuming that the rate of dissolution in 0.2 N. H_2SO_4 of a given mineral or compound in a sample is constant under controlled conditions, the time required to take the mineral or compound completely into solution would vary according to the amount and grain size of the compound or mineral present in the sample. As previously mentioned, the experiments were carried out on the -125 + 197 fraction employing a solid-liquid ratio of 1:60 and at a temperature

of 100°C. It is unlikely that a given form of an element when occurring in unequal concentrations in different samples would be completely dissolved from both samples in the same time. However, there is a coincidence in the time required to completely dissolve certain forms of Cu and Fe occurring in samples 43/4119 and 43/2985 (Table 44). This may imply (1) that the coincident breaks in the concentration-time plot for Cu and Fe occurring in the two samples are fortuitous, or (2) that the form of the element completely dissolved in the same time from both samples is one and the same. Alternatively, the coincidence may be due to unknown factors. For example, it has not been established that the relative solubilities of the individual minerals or compounds is the only controlling factor. This requires more study before any satisfactory answers can be obtained.

CORRELATION BETWEEN STREAM SEDIMENTS, BANKS AND BOGS WITH SURFACE AND GROUNDWATERS

(1) Stream Sediment

(a) Porg Stream

The ground and surface water data provide positive evidence that Fe is being precipitated in the first 800 m. of the Porg drainage, beyond which only small smounts of Fe (approximately 120 ppb) remain in solution in the ground and surface waters. The field observations are consistent with these data, in as much as, massive accumulations of Fe occur in the moraine at the anomalous seepages near the source of the stream.

The Fe content of the stream sediment decreases from 16% at the head of the stream to 6.5% in the lower reaches. In addition, in the low lying ground immediately to the east of the stream, the surface layer is significantly enriched in Fe compared with the underlying material. The precipitation of Fe from the ground and surface waters in the upper reaches of the Porg stream, followed by mechanical transport of Fe rich sediment down-drainage is consistent with these data.

The correlation of the base metal content of the ground water with that of the surface water has indicated

the probability that the metals are precipitated from the groundwaters, but not from the surface waters (see P.193). Indeed the concentrations of Cu in the surface waters has been shown to be well below the saturation concentration at all points in the stream, except at the junction with the Grisungbekken (Table 42). The surface waters of the Porg stream are therefore more likely to leach Cu from the stream sediment than to deposit it. The higher solubility of Zn compared with Cu (Morris and Lovering, 1952) would imply that the surface waters are also unsaturated in Zn. The data for Pb is less conclusive and there is a possibility that Pb is precipitated from the surface water. However the reduction in the Pb content of the surface water is only slightly greater than the rate of increase of the pH, which suggests that the surface water is not a major source of the Pb content of the stream sediments. The evidence therefore favours the transfer of base metals from the groundwaters to the stream sediments, rather than from the surface waters.

In the first 700 m. down-drainage from the ore, Fe and base metals precipitate from the groundwater. In this section of the drainage the groundwater pH varies between

2.5 and 4.6, which militates against the hydrolysis of the base metals. However, the study of the mode of occurrence of the metals in the sediment from the top of the Porg stream indicates the association of Cu and Zn with Fe, whereas Pb showed an individual trend. This may imply that (a) Cu and Zn are co-precipitated with Fe and (b) Pb may be precipitated as a discrete mineral. It is perhaps significant that in the surface waters, the precipitation of Fe does not result in the co-precipitation of the base metals, their concentration in the water remaining unaffected. The very much slower rate of groundwater movement compared with surface water may be a major factor in the co-precipitation (or sorption) of the base metals with Fe.

The groundwater data indicates that at 700 m. down-drainage from the ore Pb has been essentially eliminated from groundwater solution. In addition, the Pb content of the stream sediment is erratic and decreases down-drainage, which tends to confirm that Pb is precipitated mainly in the upper reaches of the drainage. Thereafter the down-drainage dispersion of Pb probably takes place mainly by mechanical transport.

By contrast, the Cu and Zn contents of the stream

sediment increase down-drainage. In addition one of the most striking features of the dispersion of metals in the sediments of the Porg stream is the fact that base metals are in increasingly readily available forms down-drainage. As previously mentioned, in the sediments from the upper reaches of the Porg stream the association of Cu and Zn with Fe has been established, but there is no evidence of a similar association in the sediment from the lower reaches of the Porg stream (see P. 199).

It has been observed that base metals in association with Fe may be firmly held (Tooms, 1965). The moraine study has shown that only 50% of the total Cu held in ferruginous moraine is extracted by digestion with 1M-hydrochloric acid, and that less than 0.2% of the total Cu is cold extractable (Table 20). In comparison all the Cu is extracted from anomalous non-ferruginous moraine by 1M-hydrochloric acid digestion, and 4% of the Cu is cold extractable. The drainage data would therefore be consistent with the occurrence of increasingly greater proportions of Cu and Zn down-drainage in (a) non-ferruginous compounds, and (b) possibly in loose association with Fe, for example by

sorption on to secondary Fe oxides. In this respect the almost total precipitation of Fe from the ground and surface waters of the Porg stream within the first 800 m. tends to confirm that anomalous quantities of Cu and Zn which remain in solution beyond this point would be transferred to the stream sediments by processes other than co-precipitation with Fe. For example, by sorption on to clays and sesquioxides and by hydrolysis.

The drainage data indicates that Cu is precipitated over the last 700 m. of the Porg drainage from groundwaters with pH values between 4.6 and 5.7. The reduction in the Zn content of the groundwaters would be more readily explained as a dilution affect. However, Zn enters the composition of the sediments in increasing proportions down-drainage. The precipitation of Zn (and possibly Cu) may be due to cyclical changes of a seasonal or longer duration. Alternatively the metals may be transferred to the sediments by sorption processes until a stage is reached where the sediment is in equilibrium with the water. The equilibrium constant may be expected to vary down-drainage in sympathy with the variation in the properties of the ground and surface waters and of

the sediment. On approximation to equilibrium only small quantities of metal would be deposited, unless massive amounts of new sediment is added. If equilibrium is nearly attained, or if the process is slow, the amounts of metal removed from solution may be expected to be very small, and possibly below the limit of detection by the experimental methods employed in this study.

The exchangeable Cu and Zn content of the sediment represents only a small proportion of the total metal, although the values increase down-drainage (see P.199). However "sorbed" metal may be incorporated in the lattice structure of clay minerals and would therefore not be available as exchangeable metal (Hower, 1955).

In summary, the base metals and Fe are thought to be transferred to the stream sediments mainly from the groundwaters. The major exception is the precipitation of Fe from the surface waters of the Porg stream. The deposition of Fe from the groundwater causes the co-precipitation of Cu and Zn, and possibly Pb, although the data is inconclusively in favour of its occurrence as a discrete mineral. The precipitation of Fe and Pb is effectively completed within the first 700 m. down-drainage from the

ore. Beyond 700 m. Fe and Pb are mainly dispersed down-drainage by mechanical processes. At the same time down-drainage dispersion of "Fe-bound" Cu and Zn would occur. Some of the Cu and Zn which remains at anomalous concentration levels in the ground-waters over the last 700 m. of the Porg drainage is transferred to the stream sediments possibly by hydrolysis and by sorption processes. The fact that the base metals occur in increasingly readily available forms down-drainage is correlated with the decreasing proportion of "Fe-bound" Cu and Zn, and the increasing dominance of the occurrence of Cu and Zn in forms not intimately associated with Fe. In addition, the decreasing acidity of the surface water down-drainage implies a reduction in its leaching capacity.

(b) Grisungbekken.

In the Grisungbekken downstream from the Porg confluence, Cu and Zn are enriched in sediments on the south side of the stream. On the north side the sediments contain background concentrations of Cu and Zn. This condition persists for 200 m. down-drainage in the case of Cu, and 350 m. for Zn, after

which the metals are distributed homogeneously across the stream.

A similar pattern is found in the metal content of the surface waters. In this medium however, Cu is at equal concentration on both sides of the stream within 400 m. of the Porg entry, and Zn after 700 m. At these distances the metals are at very low levels of concentration. In practical terms Cu is at near background levels in the stream waters within a few metres downstream of the Porg confluence and Zn after 250 m. The data is consistent with the differential precipitation of Cu and Zn from the stream waters with increasing pH. The striking similarity between the dispersion patterns of the metals in the sediment and the surface waters appears to indicate a genetic relationship.

In contrast, the groundwaters on both sides of the Grisungbekken contain strongly anomalous concentrations of Cu and Zn. These conditions persist for a considerable distance down-drainage from the Porg confluence. Seepage of anomalous groundwaters into the Grisungbekken has clearly not affected any significant dispersion on the north side of the stream where the sediments contain background

metal values. However, the stream at this point passes through a tight bend, causing erosion of the south bank, and a deposition of barren sediments on the north side. These accumulations of barren material may well mask any affects of groundwater seepage on this side of the stream.

Similarly the erosion and transport of anomalous material in the vicinity of the Porg stream, would lead to a dispersion of metal on the south side of the Grisungbekken.

In the Grisungbekken 600 m. downstream of the Porg confluence, where the groundwaters are still anomalous, the stream sediments contain anomalous amounts of cx Cu and background amounts of cx Zn. At this distance down-drainage, Cu is at background levels in the surface waters, whereas Zn is concentrated to 2.0 times the upper background level. The introduction of small amounts of Cu into the stream from the groundwaters would be consistent with the facts, provided that the increments of Zn remained in solution.

The dispersion patterns in the sediments of the Grisungbekken are thought to have been developed by the

transfer of metal from both surface and ground waters coupled with the effects of stream erosion.

(c) Banks.

The anomalous dispersion haloes about the streams down-drainage from the Tverrefjellet orebody occur in ground moraine, glacio-fluvial material and in bogs. The haloes are essentially restricted to Cu and Zn and have developed mainly in ground where the water table is near but not at the surface. The analysis of groundwater has demonstrated that the anomalous haloes in the bank material are associated with the movement of mineralised groundwater from which Pb and Fe have been removed.

Of particular interest is the continuity of the anomalous groundwater of the Porg drainage with the metal bearing groundwater of the Grisungbekken which occurs on both banks (Figs.47 and 48). In the low lying ground 50 to 100 m. north of the Grisungbekken the metal content of the groundwaters and of the bank material are within the background concentration ranges (Figs. 48, 61 and 62). The evidence therefore suggests that the metal source is not located to the north of the Grisungbekken. The anomalous groundwaters of the

Grisungbekken are almost certainly derived from the Tverrefjellet orebody via the Porg drainage. The movement of the metal bearing groundwater below the Grisungbekken and its occurrence in the north bank is probably related to the hydrostatic head which exists between the Tverrefjellet orebody and the Grisungbekken: the fall in height being 150 m. It is thought that the anomalous groundwater of the Porg stream moving under the impetus of the hydrostatic pressure meet, and deflect to the north, the barren groundwaters of the Grisungbekken which are passing through an area having a gradient of only 1° to 2°. The analysis of groundwater from the banks of the Grisungbekken has shown that anomalous groundwater occurs as far as 20 m. to the north of the stream. In the stream the surface waters contain much lower metal values (Table 30) and as previously mentioned the disparity between the metal contents of the ground and surface waters indicates that the boundary between the two media is probably sharply defined. The down-drainage extent of the anomalous groundwaters in the Grisungbekken was not established. However at 600 m. down-drainage

from the Porg confluence the groundwater adjacent to the stream contains Cu and Zn to 2.5 and 2.0 times the upper background levels respectively.

(d) Bogs.

The Porg and Rekse bogs occur in the mineralised drainage system where the water table is at the surface. In these areas metal may be introduced from the ground and surface waters.

(1) Porg bog.

In the Porg bog the surface waters were found to contain anomalous concentrations of the ore elements (Table 29). Base metals and Fe are distributed through the surface waters of the bog in a manner which strongly suggests a lateral migration of the metal rich Porg stream waters. The Pb and Fe values decrease to background levels within 10 m. of the Porg stream, Cu within 30 m., whilst Zn is still anomalous at 60 m. west of the stream. The elevation of pH and decrease in the metal values would be consistent with the differential precipitation of the metals. However, in the bog material the Cu and Zn anomalies are broadly coincident extending to 140 m. west of the Porg stream. The difference between the distribution of anomalous

metal in the surface waters and in the bog material may be due to the fact that at the time of sampling the deeper layers of the bog were frozen. During periods of thaw, the water circulation might be very different, particularly the movement of groundwaters. Metal in the solid may therefore have been deposited when the bog was not frozen.

(2) Rekse bog.

Mineralised low pH water of the Rekse stream (pH 4.1) enters the bog largely as seepage water along its western margin as a result of the recent diversion of the Rekse stream into the esker sand and gravels upslope from the bog. Barren high pH water of the Dloc stream (pH 6.8) has access to the bog from the east. The bog waters at the surface contain intermediate pH values in the range of pH 5.3 to 6.4. The pH and metal content of the groundwaters are not known because the ground in the bog was frozen.

The bog material contains very high cx Cu, Cu and Zn values, but significantly the Fe and Pb values are in the background concentration range. This would imply that, (a) the metal bearing waters enter the bog almost exclusively in groundwater seepages, since Fe

and Pb are removed from ground water solution some 400 m. up-drainage, and (b) even before the Rekse stream was diverted the volume of surface water which entered the bog must have been small.

The very high cx Cu, Cu and Zn values of the bog material occur in well defined zones approximately parallel to the long axis of the bog (Figs. 65 to 70). There is no apparant correlation between the variations in the physical properties of the bog material (i.e. pH, organic carbon and base exchange capacity) and its metal content (Table 40).

The strongly anomalous Cu and Zn values have significantly different distribution patterns in the bog. Briefly, the patterns are as follows: the Cu content of the surface material is strongly anomalous in the western part of the bog, whereas the Zn values of the same material are only weakly anomalous. In the eastern part of the bog adjacent to the Dloc stream very high Zn values characterise the material at all depths down to 1 m. The very high Cu values however, are restricted to the material at a depth of 50 - 100 cm.

The metal distribution patterns are consistent with (a) the precipitation of Cu from the surface waters on

the western side of the Rekse bog in the intermediate pH range of 5.3 - 6.4, whilst Zn is mainly precipitated from the surface waters in the vicinity of the Dloc stream where the surface water pH is at a maximum, and (b) the precipitation of Cu and Zn from the groundwaters where the mineralised and barren waters meet. In other words, it is probable that the surface waters of the bog are composed of fairly freely mixed barren and mineralised water, whilst the groundwaters are divided into a well defined mineralised low pH sector in the west, and a barren high pH zone to the east. As previously mentioned it was unfortunate that frozen ground prevented the sampling of the groundwaters in the bog.

DISTRIBUTION OF BASE METALS IN STREAM SEDIMENTS, BANKS AND BOGS AT GRIMSDAL

As previously mentioned, the Veslgaasaai stream drains the area underlain by the Grimsdal orebody, and flows to the north. The stream is a tributary of the Gaasaai which it joins 2700 m. down-drainage from the orebody. The valley of the Veslgaasaai is broad and open, and contains thick deposits of glacio-fluvial sand and gravel. On either side of the stream there are conspicuous esker ridges which extend for 1800 m. north from the vicinity of the Grimsdal orebody. Two small boggy areas occur in the drainage at 200m. and 900 m. respectively down-drainage from the ore. Between the boggy areas the stream exposes bedrock, but is elsewhere flowing over superficial deposits. In general the Veslgaasaai is 1 to 2 m. wide, 20 - 50 cm. deep and has a "clean" appearance (i.e. iron staining is absent). The pH of the surface waters varies between 6.4 and 6.9. The pH of 6.9 was measured in the stream water immediately down-drainage from the ore, whilst the lowest pH of 6.4 was obtained from measurements 1000 m. further down-drainage.

Ore boulders occur in the stream bed where it crosses

the sub-outcrop of the ore. The boulders are fresh except for a film of rusty weathering, and their angularity would suggest that they have been derived from the nearby mine workings. In this connection it is important to note that the mine shaft is located 100 m. to the west of the stream, and in addition downslope there is an ore dump (Figs. 38 and 78).

(i) Distribution of Ore Elements in the Stream Sediments.

The distribution of cx Cu, Cu, and Zn are shown in Figs. 76 and 77. Pb is not shown in the diagrams since it has no anomalous distribution. The principle features shown by these data are:-

(1) There are two anomalous cx Cu trains in the Veslgaasaai stream sediments, which are separated by cx Cu values in the background concentration range. The first anomalous train starts 100 m. down-drainage from the ore and extends for 500 m. The anomalous values vary between 4 and 11 ppm (i.e. up to 3.7 times threshold), the maximum values being recorded in the bog immediately down-drainage of the ore. The second anomalous train starts 700 m. down-drainage from the Grimsdal orebody and extends for 1700 m. Maximum values

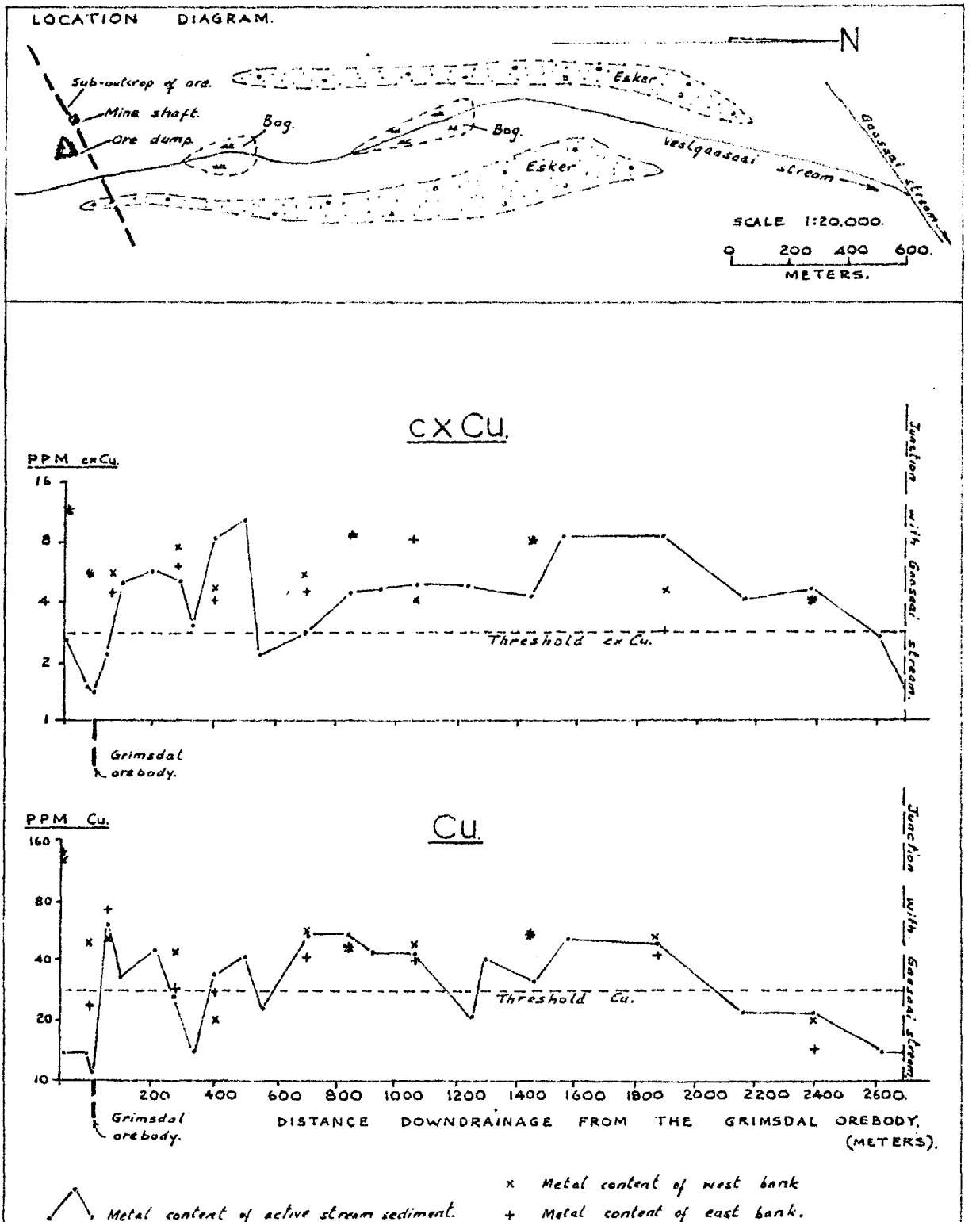


Fig.76. Graphs showing the cxCu and Cu contents of the active sediments and banks of the Veslgaasaai stream downdrainage from the Grimsdal orebody. (Data on the -80 mesh fraction).

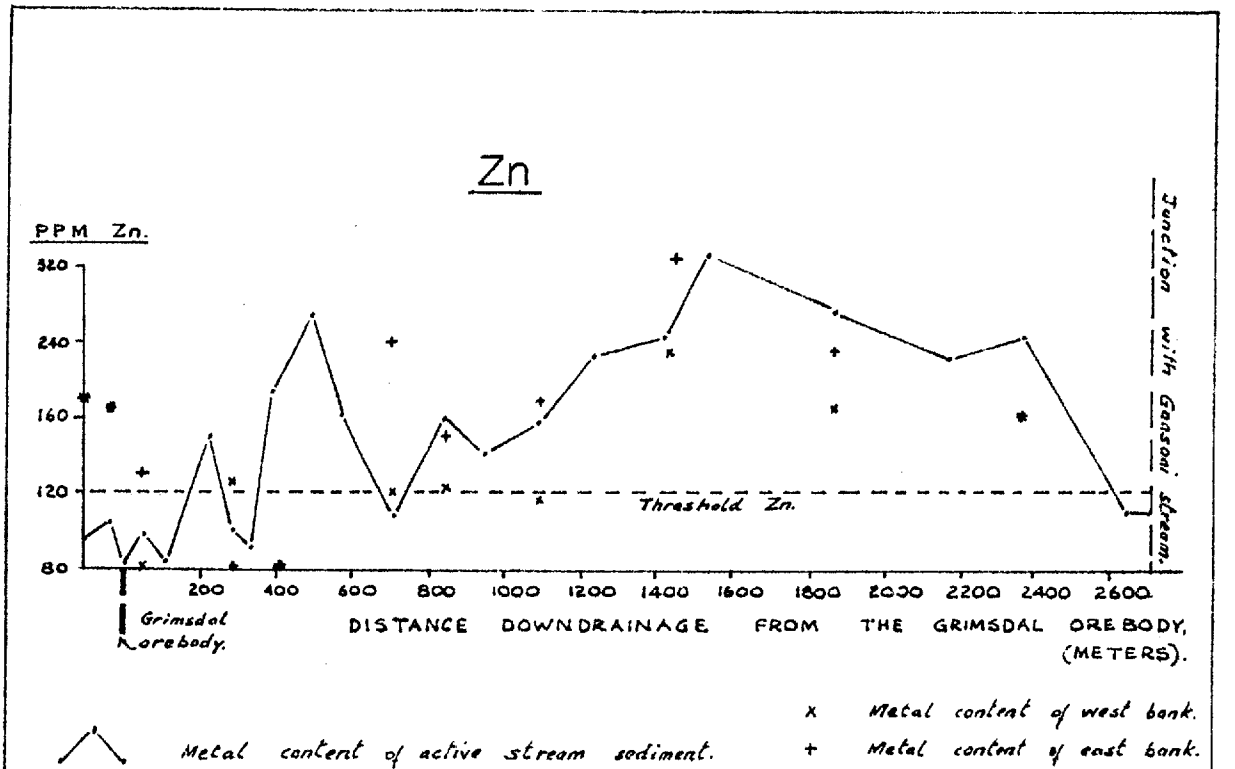


Fig.77. Graph showing the Zn content of the active sediments and banks of the Veslgaasaai stream downdrainage from the Grimsdal orebody. (Data on the -80 mesh fraction). For location see Fig.76.

of 8.6 ppm (2.7 times threshold) occur between 1600 and 1800 m. down-drainage from the Grimsdal orebody. At 200 m. above the junction with the major stream the cx Cu contents of the stream sediments are in the background concentration range (0.5 to 3.0 ppm).

(2) The weakly anomalous Cu values have an erratic distribution and occur between 50 and 1800 m. down-drainage from the Grimsdal orebody. The maximum value of 70 ppm (2.0 times threshold) is located just down-drainage from the sub-outcrop of the Grimsdal orebody where there are blocks of ore in the stream bed. In general the weakly anomalous Cu values are coincident with the anomalous cx Cu values.

(3) There are two weakly anomalous distributions of Zn in the stream sediments. The patterns are very similar to those of cx Cu. Maximum values of 340 ppm (twice threshold) occur between 1600 and 1800 m. down-drainage from the Grimsdal orebody.

(ii) Distribution of Ore Elements in the Banks of the Veslgaasaai.

The results are shown in Figs. 76 and 77.

In general the banks of the Veslgaasaai contain anomalous cx Cu values in the range of 4 to 9 ppm (i.e. 1.3 and 3 times threshold) which are broadly co-extensive

with the stream sediment anomalies. However, strongly anomalous values up to 25 ppm (8 times threshold) occur in the vicinity of the Grimsdal orebody both up and down-drainage of the sub-outcrop.

Cu has an erratic anomalous distribution in the banks of the stream in the vicinity of the ore, where values of up to 150 ppm (5 times threshold) are recorded. Down-drainage weakly anomalous values up to 60 ppm (twice threshold) occur in both banks. The bank anomalies are co-extensive with the stream sediment anomaly in the lower part of the Veslgaasaai.

The distribution of Zn in the stream banks is similar to that of Cu.

(iii) Distribution of Ore Elements in the Grimsdal Bog.

The "Grimsdal bog" is the name given by the writer to a bog located over the eastern extension of the Grimsdal orebody (Fig. 38). Data of the Geophysical Department of the Norwegian Geological Survey indicate that the ore sub-outcrops below the bog. The bog occurs in flat ground east of the Veslgaasaai stream. Drainage through the bog is very sluggish, the surface waters draining out towards the north. The distribution of cx Cu, Cu and Zn in the bog were investigated in a

detailed traverse across the strike of the ore (Figs. 78 and 79). The salient features shown by these data are:-

(1) cx Cu.

Cx Cu values up to 64 ppm (11 times the upper background level) are recorded in the bog. The high values occur in a flat lying zone at a depth of 50 cm. below the surface, the zone being located between the limits of 30 and 70 m. south and up-drainage of the ore (as indicated by the geophysical results). However the zone of maximum cx Cu content is connected in depth with strongly anomalous cx Cu values which may lie directly above the ore. This would imply that the ore is located 30 m. south of the position indicated by the geophysics.

The cx Cu contents of the material above and below the zone of maximum values are anomalous, but, the deepest zone contains less cx Cu than the surface material. South of the anomaly the bog material contains background concentrations of cx Cu.

Down-drainage of the ore, to the north the cx Cu values are in the range of 3 to 23 ppm. The highest values are in general located in the deeper parts of the profile.

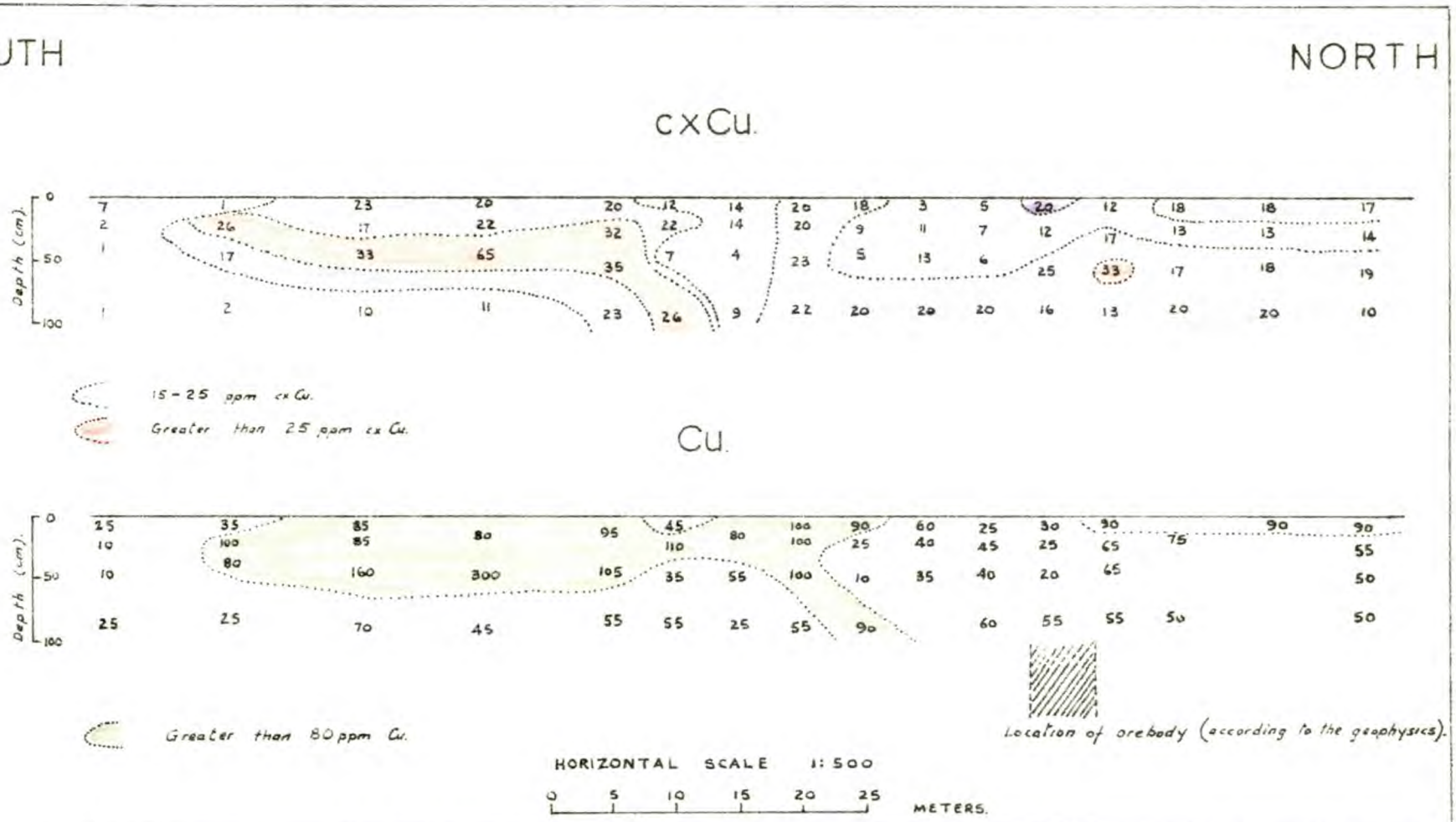


Fig.78. Sections showing the distribution of cxCu and Cu in the Grimsdal bog. (Data on the -80 mesh fraction).
For location of traverse see Fig.38.

(2) Cu.

The distribution of Cu is essentially similar to that of cx Cu. However, north of the ore (i.e. down-drainage) the Cu values are generally at the upper background level of 50 ppm, except for the surface layer where the values increase to 90 ppm.

(3) Zn.

Anomalous Zn values (i.e. greater than 200 ppm) are erratically distributed being mainly confined to small irregularly shaped zones in the near surface material. However the 100 ppm. isopleth outlines areas of Zn concentration which broadly coincide with the zones defined by the anomalous cx Cu and Cu distributions.

The pH of the bog material (Fig. 79) was measured to determine whether there is any significance in the variation of the pH with respect to the ore and to the distribution of anomalous metal. The pH was found to vary between pH 3.1 and 5.9. In bogs overlying barren bedrock and receiving unmineralised drainage, the pH of the bog material (as determined from the Hjerkinn area) is in the range 4.7 to 5.7. In the Grimsdal bog traverse pH values less than 4.0 occur mainly in the sub-surface

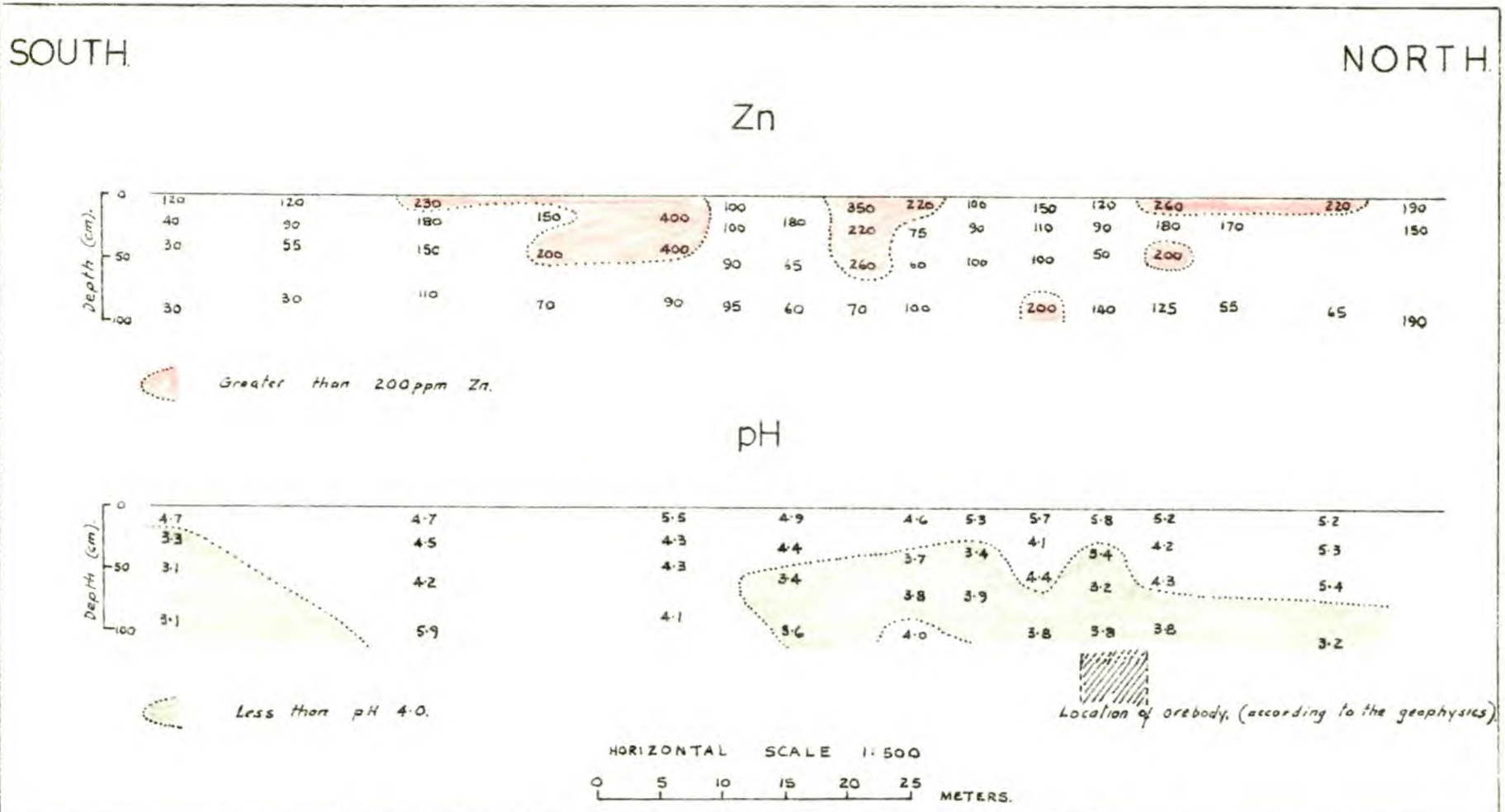


Fig.79. Sections showing the distribution of Zn in the Grimsdal bog, and the pH of the bog material.
(Data on the -80 mesh fraction).
For location of traverse see Fig.38.

material down-drainage from the ore, but a second zone of low pH values is located 50 to 70 m. up-drainage from the ore. The pH values in the range 4.1 to 5.9 are characteristic of the surface layer over the entire traverse, but also occur in the deeper zones of the bog upslope from the ore.

In general the high pH zone is coincident with the zone of high metal values, whereas the low pH zone is mainly developed over and down-drainage from the ore where metal values are considerably lower.

(iv) Discussion.

(a) Dispersion of Ore Elements in the Drainage.

Briefly, the major features of the metal distribution patterns in the drainage at Grimsdal are as follows: the data indicate that there are two weakly anomalous trains in the Veslgaasaai sediments which are separated by 200 m. in which the sediments contain metal values in the background concentration range. In the first drainage anomaly the metal concentrations increase to peak values in a bog 500 m. down-drainage from the Grimsdal orebody. At the next sampling point, 50 m. down-drainage the cx Cu and Cu values are in the background concentration range, whilst

the anomalous Zn values persist for a further 50 m. The second drainage train extends for 1800 m., the last 200 m. of the Veslgaasaai above the junction with the Gaasaai (i.e. the major stream) being characterised by background metal values. In general both banks of the Veslgaasaai contain weakly anomalous cx Cu, Cu and Zn values, which are broadly co-extensive with the anomalous drainage trains in the stream sediment. However, in the vicinity of the ore both banks contain strongly anomalous cx Cu values, and erratic anomalous Cu and Zn values, whereas the stream sediments contain background metal values.

The extent of the anomalous distribution of ore elements in the banks of the banks of the Veslgaasaai strongly suggest that the anomalous metal is entering the drainage via the groundwaters. In addition, the fact that the anomalous drainage trains of cx Cu and Zn end 200 m. above the junction with the major stream would be most readily explained as being due to the massive dilution of anomalous groundwater by the barren underflow of the Gaasaai stream. A major problem however, is the existence of two anomalous dispersion trains in the stream sediments which are separated by

200 m. in which the sediments contain background metal concentrations. The "barren gap" cannot be reconciled with natural processes of dispersion unless the anomaly immediately down-drainage of the orebody is regarded as a contamination feature.

It is possible that contamination has been an important factor since the mine shaft and ore dump are located only 100 m. to the west of the stream, and in addition the ore has been opened on the east side immediately adjacent to the stream. Of particular significance is the fact that the stream banks up-drainage of the sub-outcrop of the ore contain anomalous metal values whilst the stream sediments contain metal in the background concentration range. It is therefore very probable that the drainage anomaly in the immediate vicinity of the Grimsdal orebody is due in part at least to shallow groundwaters deriving anomalous quantities of metal from the ore dumps. However, in the Grimsdal bog located east of the stream and upslope of the contaminated area, anomalous metal values occur above the sub-outcrop of the ore. The bog data would suggest that the anomaly in the stream banks and sediments in the vicinity of the

Grimsdal orebody may not be entirely due to contamination.

The second drainage anomaly starts 700 m. down-drainage of the orebody and because there is no source of contamination in this section of the drainage, the anomaly is considered to be a natural feature. The fact that the Veslgaasaai valley is filled with glacio-fluvial sand and gravel suggests the possibility that mineralised groundwaters may move through the permeable deposits for a considerable distance before appearing at the surface. In particular the esker which crosses the sub-outcrop of the ore and which extends for 1800 m. down-drainage would provide a possible channelway for the movement of mineralised groundwaters. In this connection it is of interest to note that the stream waters in the vicinity of the orebody has a pH of 6.9, whilst 1000 m. down-drainage the pH has decreased to a value of 6.4.

The processes by which ore elements are dispersed at Grimsdal are considered to be similar to those at Tverrefjellet, in as much as, the anomalous drainage trains are thought to be due to the movement of mineralised groundwaters in both cases. However, the occurrence of the swallow hole at Tverrefjellet allowing access of aerated waters to the ore has resulted in the

production of substantial volumes of highly mineralised, very acid groundwaters. The low pH enables both Pb and Fe to move into the drainage in anomalous quantities. At Grimsdal the stream bed is not iron stained and there is no anomalous distribution of Pb in the drainage. In addition the pH of the surface water is very much higher than at Tverrefjellet which may imply a much lower rate of ore oxidation.

(b) Dispersion of Ore Elements in the Grimsdal Bog.

In the bog material there is a trend towards a low pH (i.e. pH less than 4.0) in the sub-surface material lying above and down-drainage of the sub-outcrop of the ore. In contrast, in the surface material over the entire traverse and also in the sub-surface material up-drainage of the ore, the pH values are generally in the range of 4.1 to 5.9. However, a second zone of low pH bog material occurs between 50 and 70 m. up-drainage of the sub-outcrop of the ore. In unmineralised areas the pH of bog material has been found to vary between pH values of 4.7 and 5.7 (Table 37). Since the Grimsdal bog is located to the east and upslope of the contaminated area of the ore dumps, pH values of less than 4.0 in the bog material may be related to an acidic environment in

the vicinity of sub-outcropping ore. The second zone of low pH bog material up-drainage of the known ore is not associated with anomalously high base metal values and may therefore be due to minor sulphide mineralisation in the bedrock.

The zone of high pH contains strongly anomalous cx Cu and Cu values, whereas in the low pH material the metal content is substantially lower. In addition the anomalous Zn values (i.e. greater than 200 ppm) are confined to small erratic zones in the surface material where the pH is in general at maximum values.

Thus there is a close correlation between the ore, the pH of the bog material and its metal content. The data is consistent with the upward migration of ore elements in groundwaters, a large proportion of the anomalous metal in the bog being fixed in zones where the pH of the bog material is greater than 4.0. However, the high cx Cu and Cu values occur in a flat lying zone at a depth of 50 cm. below the surface, up-drainage of the sub-outcrop of the ore. Below the strongly anomalous zone the bog material has a pH of 4.1 to 5.9, but contains much lower metal values. The distribution of the strongly anomalous cx Cu and Cu values would suggest that metal

bearing groundwater from the orebody move upwards (possibly under hydrostatic pressure) before spreading laterally. A feeble artesian flow of mineralised groundwater through a weathered capping of the orebody below the bog is not unlikely in view of the fact that the Grimsdal bog occurs in the valley bottom near to the lowest point of the sub-outcrop of the ore.

Anomalous metal distribution patterns in a bog overlying ore at Malmisuo, Finland are considered (Salmi, 1955) to have developed by the upward migration of mineralised groundwater. The movement being explained as a result of capillarity enhanced by high evaporation from the bog surface.

SUMMARY OF CONCLUSION ON THE DISPERSION OF ORE ELEMENTS IN THE COMPONENTS OF THE DRAINAGE

1. Deep groundwaters draining through fractures in the Tverrefjellet orebody contain very low concentrations of the ore elements which are in general below the upper background levels as determined in near surface groundwaters. In contrast near surface groundwater at the sub-outcrop of the ore contain strongly anomalous metal values. The disparity in metal content between the deep and near surface groundwater within the ore zone at Tverrefjellet, and the lack of evidence of supergene enrichment in the rocks below the water table would indicate that there is no local connection between the near surface and deep groundwater systems at Tverrefjellet. In addition there is considerable evidence to indicate that the near surface mineralised groundwaters move from their points of origin over the sub-outcrop of the ore to enter the surface drainage. It is, therefore, tentatively concluded that the water circulating through fractures in otherwise impermeable rocks is derived from areas where the fractures are exposed at the surface, or where the moraine is permeable.

2. Metal bearing groundwater produced at the sub-outcrop of the ore contain anomalous concentrations of Cu, Zn and Fe, whereas Pb does not enter the composition of the groundwater to the same extent. An exception is the anomalous Pb content of the mineralised groundwater which rises in a series of seepages downslope of the swallow hole in the ore at Tverrefjellet. The dissolution of primary and secondary Pb minerals is perhaps related to the extremely rapid oxidation of the ore in the vicinity of the swallow hole.

3. In the Porg stream (which rises downslope of the swallow hole at Tverrefjellet) the ground and surface waters have an initial pH of 2.5. The increase in the pH indicates that barren high pH water enters the Porg drainage predominantly via the groundwater. The fact that the metal content of the groundwater decreases more rapidly than can be accounted for by dilution, whereas the decrease in the metal content of the surface waters can be entirely accounted for by dilution, implies that metal is transferred to the sediment from the groundwater. An exception is the precipitation of Fe from the surface waters of the Porg Stream.

4. In the first 700 m. of the Porg drainage Fe and Pb are almost totally eliminated from groundwater solution. The reduction in the Cu and Zn contents of the groundwater in the same section of the drainage also indicates that those metals are partially removed from the groundwater in which the pH varies between 2.5 (at the source) and 4.6 (700 m. down-drainage). It is suggested that Cu and Zn are co-precipitated with Fe^{3+} which has a very limited solubility in waters in which the pH values are in excess of 4.0. Studies on the form of occurrence of the metal in the stream sediments from the upper reaches of the Porg drainage support the view that Cu and Zn are intimately associated with Fe.

5. The precipitation of Fe^{3+} from the surface waters of the Porg stream is essentially complete within 800 m., where the pH has increased to 3.5. However, the decrease in the base metal contents of the surface water is proportional to the amount of dilution by barren waters as indicated by the pH. Thus in the surface environment the precipitation of Fe does not cause the co-precipitation of the base metals.

6. In the lower reaches of the Porg drainage, the groundwater pH rises to a value of 5.7 at the junction with the Grisungbekken (the major stream). Cu is precipitated from the groundwater over the lower half of the Porg stream whilst Zn appears to remain in solution, its concentration decreasing in proportion to the amount of dilution by barren waters as indicated by the pH. However the occurrence of increasing amounts of Zn down-drainage in the Porg stream sediments would indicate that Zn is being removed from solution, possibly by sorption processes. It has been suggested that these processes are slow. In addition the metal contents of the waters and the stream sediments may be approaching equilibrium. Under these conditions only small amounts of metal would be deposited, unless massive amounts of new sediments are added. It is possible that the changes in the metal concentration of the ground and surface waters are within the experimental error of the analytical methods used in this study, and have therefore not been detected.

7. In the Porg stream sediments the base metals are in increasingly readily available forms down-drainage. There is no evidence of the association of base metals

with Fe in the sediments from the lower reaches of the stream, which is consistent with the removal of Fe from both ground and surface waters in the upper reaches. The increasing availability of the base metals in the sediments down-drainage is considered to reflect the decreasing proportion of "Fe-bound" Cu and Zn, and the increasing importance of the occurrence of Cu and Zn in forms not intimately associated with Fe. It is thought that the base metals in the lower reaches of the stream are precipitated by hydrolysis and possibly by sorption on to clays and sesquioxides.

8. In the Grisungbekken (the major stream), the weakly anomalous metal content of the surface waters can be related to the input of mineralised water from the Porg stream. Below the junction of the two streams the surface waters of the Grisungbekken contain more Cu and Zn on the south side than on the north side. Cu is distributed at equal concentration across the width of the stream within 400 m. of the Porg stream confluence, and Zn after 700 m. However Cu is essentially at background concentration levels within a few metres of the confluence, whereas Zn is still 2.5 times the upper background level 600 m. down-drainage. The different

distribution patterns of Cu and Zn are thought to reflect their differing solubilities in waters of pH 6.4 to 6.9.

9. The groundwater occurring in both banks of the Grisungbekken below the confluence with the Porg stream contains strongly anomalous Cu and Zn values. The mineralised groundwater extends for at least 600 m. down-drainage from the Porg stream confluence. Evidence of a metal source to the north of the Grisungbekken is lacking which would suggest that the anomalous groundwater is derived from the Porg drainage. There is a difference of 150 m. in elevation between the source of the Porg stream and the valley of the Grisungbekken and in addition the Grisungbekken has a gentle gradient. It is considered that the mineralised groundwater of the Porg drainage moving under the hydrostatic pressure is able to pass below the Grisungbekken and deflect the barren underflow of the major stream to the north.

10. The metal content of the Grisungbekken sediment reflect the distribution of metal in the surface water in as much as, the sediments below the confluence with the Porg stream contain anomalous metal values on the

south side, whilst the sediments on the north side contain metal in the background concentration range. Cu is equally distributed across the width of the stream 200 m. down-drainage from the Porg entry, and Zn after 350 m. However, the anomalous cx Cu train extends for at least 2.5 km. down-drainage from the Tverrefjellet orebody, whilst the anomalous Cn, Zn and cx Zn trains are co-extensive and are last detected 1600-1800 m. down-drainage from the ore. It is therefore probable that increments of Cu and Zn to the surface environment from the anomalous groundwater takes place in the Grisungbekken. The Cu being incorporated in the sediment in a readily available form, whilst the Zn is transferred from ground to surface water solution. The very long saline dispersion train of Zn in the Grisungbekken surface waters would be consistent with the above interpretation.

11. The relatively very high Cu and Zn contents in the banks of anomalous streams and in bogs down-drainage from the Tverrefjellet orebody can be related to the movement of mineralised groundwater from which Pb and Fe have been removed. The occurrence of

significantly different patterns in the distribution of Cu and Zn in the Rekse bog indicates that the metals have been precipitated in response to a variation in the pH of the ground and surface waters.

12. Limited studies in the vicinity of the Grimsdal orebody have indicated that anomalous metal enters the drainage via the groundwater. The existence of two dispersion trains in the stream sediments down-drainage of the orebody, which are separated by only 200 m. of barren sediment is considered to be evidence of contamination in the first 500 m. from ore dumps in the vicinity of the disused mine shaft. The anomaly commencing 700 m. down-drainage of the ore is thought to be a natural feature. The gap between the location of the orebody and the second anomaly down-drainage is possibly due to the passage of anomalous groundwater through the permeable sands and gravels which fill the valley. The metal bearing groundwater may then appear at the surface some considerable distance down-drainage from the ore. The weakly anomalous drainage trains of cx Cu and Zn are equally well developed and extend for 1700 m., the Cu train being less extensive, whereas Pb has no anomalous distribution. At 200 m. above the

junction with the major stream the cx Cu and Zn values are in the background concentration range which is possibly due to the massive dilution of the anomalous groundwater by the barren underflow of the major stream.

13. In the Grimsdal bog which overlies the sub-outcrop of the orebody, the distribution of anomalous metal and the variation in the pH of the bog material indicate (a) that the high pH bog material (i.e. pH greater than 4.0) contains more metal than the low pH (i.e. pH less than 4.0) and (b) the sub-surface bog material overlying and down-drainage of the ore, has pH values in the range 3.1 to 4.0 which is thought to be due to an acid environment surrounding the sub-outcrop of the ore. The low pH of bog material occurring between 30 and 70 m. up-drainage of the ore is not understood, but may be due to minor sulphide mineralisation in the bedrock. It is concluded that ore elements in the bog have migrated upwards from the orebody in groundwaters issuing as springs from the decomposed capping of the ore, the anomalous metal being fixed predominantly in the higher pH zones of the bog.

14. The secondary dispersion patterns in the drainage and in the bog at Grimsdal are less strongly anomalous than those at Tverrefjellet. In particular there is no anomalous distribution of Pb in the drainage and the bed of the Veslgaasaai stream is not iron stained; the pH of the stream waters being in the range 6.4 - 6.9. These features would indicate that the orebody at Grimsdal is undergoing less rigorous oxidation than the Tverrefjellet ore. The occurrence of the swallow hole at Tverrefjellet which allows access of aerated waters to the ore is considered to be the reason for the very much greater extent of ore oxidation at Tverrefjellet as compared to Grimsdal.

Consideration of Minor unexplained Anomalies.

As previously mentioned anomalous concentrations of Pb and Zn were detected in the upper reaches of the Grouback stream. In addition, weakly anomalous erratic results were obtained in the Hjerkinn Hö bog which is located 1 km. north north east of the Hjerkinn Hotel. The possibility that these anomalies are related to economic mineralisation cannot be ignored. However, there are a number of features which indicate that these anomalies are related to a very minor mineralisation in the bedrock:-

Grouback stream: (1) The values are only weakly anomalous and are non-persistent down-drainage.

(2) The drainage anomaly is not associated with Cu, when all known ore in the Hjerkinn-Folldal area contain Cu as well as Pb and Zn.

Hjerkinn Hö bog: (1) The weakly anomalous values are erratically distributed.

(2) The high metal values occur in the moraine and do not appear to be related to the emergence of groundwater.

(3) The bog is located 0.5 km. "down-ice" of the uneconomic mineralised horizon which may indicate that the erratic high values are due to ice transported sulphide material incorporated in the moraine.

PART IV

APPLICATION TO PROSPECTING

In the mineral exploration of glaciated terrain as in other environments, it is important to take into consideration local conditions. The complex variations encountered in glaciated districts indicates that prospecting would be more expensive than in simpler terrain. In addition the integration of geophysics, geology and geochemistry is even more important than elsewhere and it is essential to retain a balance in their application. For example, geochemistry may delineate areas on a broad scale, after which geophysics may be the ideal follow-up technique. In particular, in dealing with strata-bound mineralisation as in central Norway, geology is vital to the overall programme. However, in the following pages only the problems pertaining to geochemical prospecting in glaciated terrain are considered.

(i) Reconnaissance Prospecting

Under the very different conditions of topography, drainage, glacial cover and ore oxidation encountered at Grimsdal and Tverrefjellet, the results obtained by the writer have shown that wide spaced drainage samples would in both cases reveal the presence of metal anomalies.

However, it is important to note that the magnitude of the anomaly is related to the dispersion conditions and not to the size or grade of the orebody. For example, water may freely enter sub-outcropping mineralisation and be returned to surface as strongly mineralised springs and seepages. In other areas only very small quantities of groundwater may have access to concealed ore. This would imply that in the first instance, any anomaly must be considered to be significant. That anomalies can be relatively readily detected by drainage sampling is demonstrated by past work of the Norges Geologiske Undersøkelse.

On the basis of the writer's work satisfactory procedures for drainage reconnaissance in areas such as central Norway may be summarised as follows:-

(1) It is recommended that the drainage be sampled at intervals of not more than 1,000 m. and not less than 500 m. At each sampling site both banks as well as the active stream sediment should be individually sampled, and the pH of the stream waters recorded.

(2) Active stream sediment composed of fine to medium grained sand and silt provides the most suitable material.

(3) In small streams the active sediment should be collected from the centre of the channel, whereas in larger streams (i.e. of width greater than 10 m.) two samples, one from each side of the stream should be obtained, taking care to avoid collection of collapsed bank material. In addition it is recommended that minor streams should not be sampled near to a junction with a major stream. For example, at Grimsdal it was found that the barren underflow of the major stream (the Gaasaai) causes a massive dilution of the anomalous ground and surface waters of the tributary (the Veslgaasaai) which drains the area underlain by the Grimsdal orebody.

(4) Field notes should include the following observations:-

(a) The size, depth, velocity and gradient of the stream and stream waters.

(b) The mechanical and physical composition of the active stream sediment with particular reference to the presence of organic material and/or secondary iron oxides.

(c) The nature of the bank material, and of the overburden at greater distances from the stream with particular reference to the occurrence of glacio-fluvial sand and gravel or other readily permeable surface materials in the vicinity of the drainage.

(5) The analysis of the -80 mesh fraction of the samples for cx Cu, Cu and Zn could be expected to reveal the presence of any significant pyritic mineralisation occurring at sub-outcrop within the catchment area of the sampled drainage.

The above mentioned procedures apply only to central Norway. The far north and south are not considered, although the results of the Norges Geologiske Undersøkelse would indicate that these procedures are applicable to Finmark.

(ii) Follow-up of Drainage Anomalies

The anomalies located in a reconnaissance drainage survey may occur several kilometers away from the source. In fact a reconnaissance anomaly is only an indication of the occurrence of mineralisation in an area which may be 100 or more square kilometers in size. Under certain circumstances, for example at Tverrefjellet, the drainage anomaly is developed immediately downslope of the sub-outcrop of the ore. This may be exceptional. At Grimsdal the drainage anomaly is well displaced, which is in agreement with the unpublished results of the Norges Geologiske Undersøkelse from other areas of Norway.

As the formation of the anomalies in the surface drainage is the result of the entry of mineralised

groundwaters, follow-up procedure must be based on tracing the sourse of the metal bearing groundwaters. In so doing it is important to bear in mind that the movement of ground water will be affected by local hydrostatic heads. Thus the fact that high metal values occur on one side of a bog or stream and not on the other side, cannot be regarded as conclusive evidence that the mineralisation is located upslope of the mineralised margin. Sampling of bogs would provide data on the nature of the groundwater entering the bog and may provide a starting point from which to work. However, by the collection of samples on a broadly spaced grid, of material in contact with groundwater, it may be possible to obtain some indication of the direction in which the mineralised groundwater is moving, and thus the general location of the concealed mineralisation. In freely drained overburden it may be necessary to resort to drilling. Clearly, this kind of prospecting would be both expensive and laborious, but it is felt that under the conditions the approach indicated above would provide the data necessary in following-up drainage anomalies in the glaciated terrain of central Norway. It will be appreciated that it is not possible to itemise

the procedures necessary to locate the general vicinity of mineralisation since the detailed planning must be related to local conditions.

(iii) Detailed Follow-up.

Having located the general vicinity of the sub-outcropping mineralisation, the detailed survey can profitably be undertaken by the following, in combination with geophysical studies.

The characteristics of the moraine, vegetation and drainage are the important factors that will determine the depth of sampling. Where the groundwater is at, or close to surface, sub-outcropping mineralisation can almost certainly be located by sampling the top of the till, as for example, at Nordre Geiteryggen. In areas of coniferous forest, (e.g. Sondre Gjeiteryggen), mineralisation may also be located by shallow sampling. However, where the over-burden is well drained and the vegetation shallow rooted, as at Tverrefjellet, the sampling must be extended to below the water table.

The conclusions on what conditions determine shallow as opposed to deep sampling of the overburden, cannot be stated with any degree of confidence at the

present time. A great deal more work has yet to be done before any well founded conclusions can be formulated. For example, to distinguish ground moraine from ablation moraine is problematical in many areas, and is a subject for further research.

The results obtained in the present study indicate that the -80 mesh fraction of overburden samples should be analysed for cx Cu, Cu and Zn.

Sampling of the sub-arctic vegetation has not been found to provide a suitable medium for prospecting through transported overburden in Norway (Vogt, 1943). The study of the distribution of ore elements in Betula nana twigs during the present work gave erratic results which appear to have no apparant significance in the search for ore.

The sampling of the bedrock has shown that an extensive Fe/Zn aureole surrounds the uneconomic sulphide zone at Tverrefjellet. The aureole decreases in width towards the ore and the Cu content of the uneconomic sulphides increases as distance to the ore decreases. These results may only have a local significance, and further work is required to establish whether bedrock sampling will find any application in the search for ore of Tverrefjellet type.

PART V

SUGGESTIONS FOR FUTURE RESEARCH.

1. The close spatial relationship between pyrite orebodies and thin zones of uneconomic sulphide mineralisation is a striking feature of the metallisation of the Cambro-Silurian rocks of the Trondheim basin. The association is as yet incompletely understood. The results of the present study at Tverrefjellet has indicated that the wall rock aureoles surrounding the uneconomic zone and the orebody are essentially identical in all but size. A study of the structural and metamorphic geology, and of the distribution of ore elements in the country rocks of the mineralised zone would together provide the basis for a clearer understanding of the metallisation.

Comparative studies in other districts would allow an appraisal of the application to prospecting of bedrock dispersion patterns.

2. The movement of mineralised groundwater has been shown to be a major factor in the secondary dispersion of ore elements from sub-outcropping pyrite mineralisation in the Hjerkinn-Folldal area.

In the movement of groundwaters many local variations can be expected. Comparative studies in different districts of Norway would provide valuable basic data of the greatest importance to ore prospecting.

3. In the interpretation of metal anomalies in the overburden, it is essential to recognise the nature of the glacial deposits. Research studies aimed at obtaining criteria for the recognition of different kinds of moraine in central Norway are required, in particular, to distinguish between ground and ablation moraine.

4. The mode of occurrence of the ore elements in stream sediments, in the moraine, and in bogs is as yet imperfectly known. Preliminary data on the occurrence of Cu and Fe in the anomalous stream sediments has indicated a complex variety of different forms in which Cu and Fe occur.

Methods of investigation currently being developed, for example, reaction-time experiments, would seem to provide the fundamental basis for a major advance in this field.

5. The occurrence of anomalous metal in the organic

rich soil horizon and of lower metal values in the underlying material in the vicinity of cupriferous pyrite mineralisation, indicates the importance of biogeochemical dispersion in some areas.

The metal content of Betula nana twigs was not found to show any consistent correlation with the A_o soil anomaly. The investigation of the complete flora would be necessary in order to obtain a thorough understanding of the processes of biogeochemical dispersion.

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