A

THESIS

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DISPERSION OF NICKEL AND MOLYBDENUM FROM MINERALISATION IN GLACIATED TERRAIN; S. NORWAY

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RAYMOND BRIAN BAND

Royal School of Mines,
Imperial College.

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ABSTRACT

A reconnaissance survey conducted over an area of southern Norway containing Ni-Cu and Mo-Cu mineralisation revealed that the metal content of stream sediment samples collected at a density of 1 per 5 sq. miles adequately outlines known areas of mafic bedrock and zones of weak Mo mineralisation.

Studies of bedrock geochemistry indicate the Iveland-Evje amphibolite complex to be a composite body resulting from several phases of basic igneous activity. Subeconomic Ni-Cu mineralisation at Mølland is shown to be genetically associated with the youngest, noritic phase.

The distribution of Ni and Cu in soils and peat bogs at Mølland is described and particular attention paid to the mode of occurrence of anomalous Ni in soils. Soil Ni anomalies are of complex origin and result from both glacial and saline dispersion.

The stream sediment Ni anomaly at Mølland is of restricted length and is due principally to the erosion of anomalous soils. Spurious Ni anomalies, occuring in association with high Mn values and resulting from secondary enhancement, complicate the interpretation of stream sediment data. The effect of climatic fluctuations on the Ni content of stream sediments is studied and is shown to be nonsignificant.

The distribution of Mo and Cu in bedrock, soil, peat bogs and drainage sediments in the vicinity of Mo-Cu mineralisation at Flottorp is described. Mo anomalies in the soil principally reflect syngenetic dispersion patterns in the parent till, but saline dispersion is important in the formation of soil Cu anomalies. Anomalous Mo contents persist in the stream sediment 18,000 ft. downstream from mineralisation. Under favourable circumstances anomalous dispersion trains are unaffected by small lakes in the drainage system.

Procedures are recommended for use in exploration for Ni and Mo mineralisation in glaciated areas similar to southern Norway.

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INTRODUCTION

In the latter half of the 19th century a vigorous Ni mining industry existed in southern Norway, centred on the Flåt mine, for a long period the largest Ni mine in Europe. The discovery of rich Ni-Cu deposits in the Sudbury basin led to the rapid decline of the Norwegian mines which became subordinate in importance to the metallurgical industry established in nearby Kristiansand. Mining activity ceased with the closure of Flåt mine in 1946, and the Ni refinery, operated by Falconbridge Nikkelverk A/S, now processes imported matter exclusively.

In 1965 Sulfidmalm A/S, the exploration subsidiary of Falconbridge Nikkelverk A/S, began a mineral exploration programme over the old mining field and invited the Applied Geochemistry Research Group to investigate the applicability of geochemical prospecting methods in the area. In addition to the Ni mineralisation already mentioned there are widespread molybdenite occurrences in southern Norway and Mo is currently mined at Knaben; the research project, as finally constituted, involved a detailed investigation of the applicability of geochemical methods to mineral exploration for Ni and Mo in the glaciated terrain of southern Norway.

Orientation surveys were conducted over subeconomic mineralisation at the Mølland (Ni) and Flottorp (Mo) prospects (fig. 1) in order to gain a thorough understanding of the factors controlling the dispersion of the ore metals. The orientation investigations are conveniently divided into studies of :

a) the distribution of the ore and associated metals in the bedrock;

b) the distribution and dispersion of the ore metals in soils and peat bogs in the vicinity of mineralisation;

c) the distribution and dispersion of the ore metals in surface waters and stream sediments down-drainage from mineralisation.

At both localities the investigations were extended into unmineralised areas to study the background distribution of the ore metals in the various media.

A rapid reconnaissance survey was also carried out over an area of approximately 2000 sq. mls. (fig. 1) in order to assess, with reference to the orientation localities and other known occurrences, the feasibility of wide interval reconnaissance surveys for mineral exploration purposes in the glaciated terrain of southern Norway.

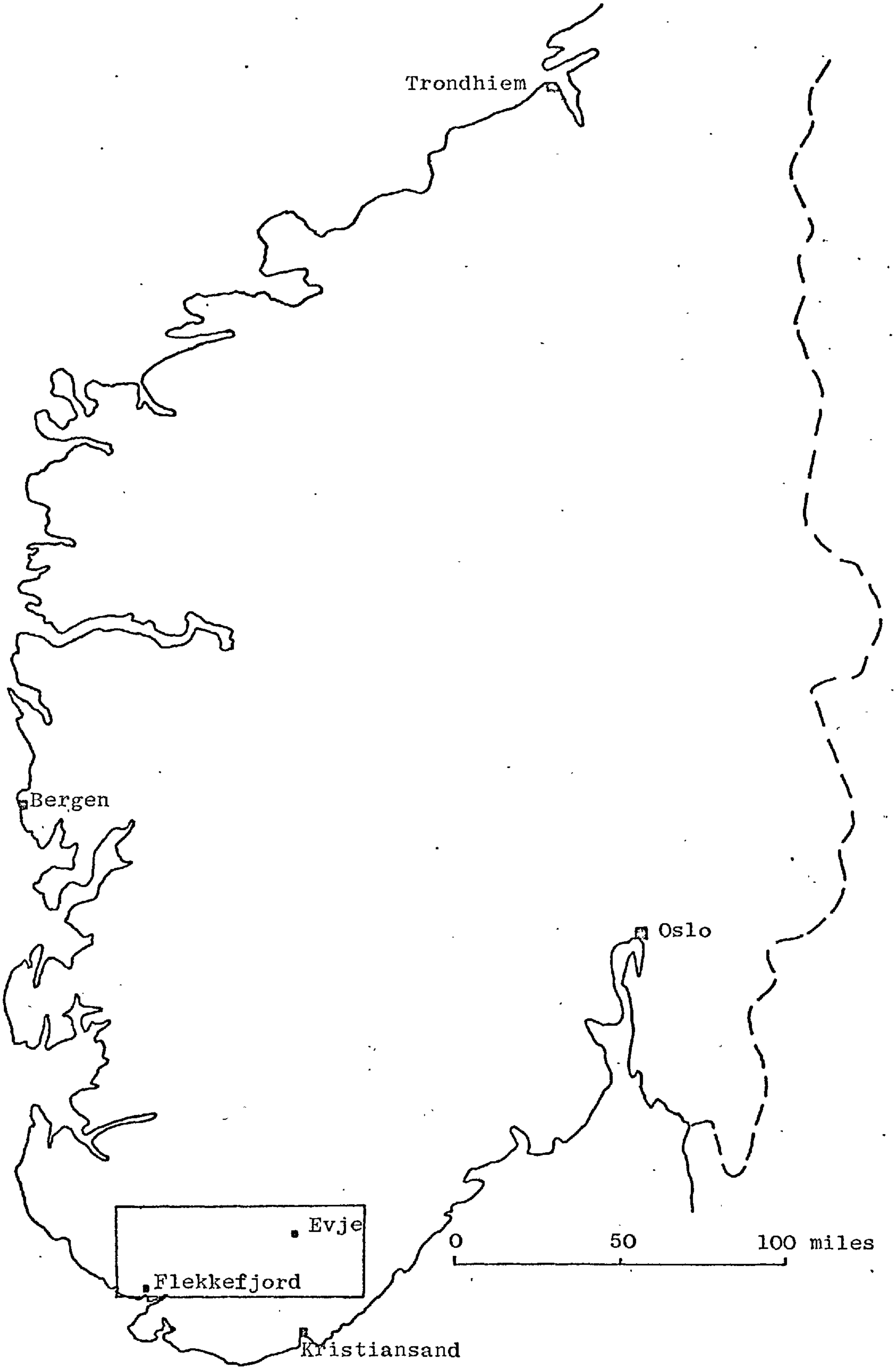

Fig. 1 Location of Field Area

Previous Work

Previous geochemical work in Norway has been concentrated in the central and northern areas, the only published information for south Norway being a study of the distribution of trace metals in peat (Hvatum 1964).

In glaciated regions elsewhere analysis of the -80 mesh fraction of till or mineral soil samples has frequently revealed fan-shaped anomalous dispersion trains extending away from mineralisation in the direction of ice-movement; Kauranne (1958, 1959) describes dispersion trains exceeding 3000 ft. in length related to both Mo and Ni mineralisation in Finland. Depending on the stability of the ore minerals and on the mobility of the metal in question such mechanical dispersion patterns may be modified by hydromorphic dispersion during weathering of the till (Pollock et al 1960, Canney 1965). For the more mobile metals and under favourable conditions dispersion in groundwater from bedrock mineralisation may be the dominant process in the development of superjacent and lateral anomalies in till and soil (Dreimanis 1960, Yardley 1958, Mehrtens 1967). Vinogradov (1957) and Belyakova (1958) have suggested the use of water analyses in the search for Mo mineralisation.

Biogeochemistry has been applied to mineral exploration for both Ni and Mo. Rankama (1940) found that the Ni content of birch leaves reflected the presence of Ni mineralisation concealed by up to 4 metres of drift; Malyuga et al (1956) and Aleskovskii et al (1959) report similar findings and show this to be true also of the humus layer. Miller (1953), on the other hand, found high Ni contents in plants growing on nickeliferous laterite but only background values over pyrrhotite-pentlandite mineralisation. Aleskovskii et al found that the Ni content of leaves increased markedly at the end of the summer and suggested that the humus layer or the B horizon of the soil would provide a better sampling medium. Biogeochemistry has been more widely used in exploration for Mo (Warren et al 1953, 1965, Marmo 1953, Baranova 1957, Malyuga 1958) although Baranova (1957) found the Mo content of humus to be approximately 10 times as great as that of plants. Humus sampling is currently employed as both a detailed and regional prospecting method by the Norwegian and Finnish geological surveys (Kauranne et al 1961, Bolviken 1967).

Salmi (1950, 1955, 1956, 1967) found enhanced contents of Ni and Mo in peat bogs in the vicinity of known mineral occurrences compared with background areas. Hvatum (1964) describes high contents of Mo and Cu in peat bogs in the vicinity of Cu-Mo mineralisation in south Norway and Atkinson (1967) found high Mo contents in peat bogs overlying Mo-rich black shales in Ireland.

Detailed stream sediment surveys have revealed anomalous dispersion patterns related to known mineral occurrences in central and northern Norway (Mehrtens 1966, Bolviken 1967) and close interval drainage sediment surveys are used in both northern Norway and Finland in regional exploration programmes for Cu, Zn, Pb, Ni and Mo mineralisation (Brotzen et al 1967, Wennervita 1968).

Multi-element regional geochemical reconnaissance by means of widely spaced stream sediment samples has become well established as a method of locating potential mineralised areas and of providing fundamental geochemical data to complement geologic mapping (Webb et al 1966, 1968). In glaciated areas in Eire (Atkinson 1967) and Britain (Fletcher 1968) rapid reconnaissance surveys have been used for agricultural purposes in order to delineate broad areas with toxic Mo contents in the soil. Boyle et al (1966) describe a reconnaissance survey for mineral exploration purposes in New Brunswick, which revealed anomalous Mo contents in stream sediment derived from granitic stocks, some of which were known to have associated minor Mo mineralisation.

ACKNOWLEDGEMENTS

The present work forms part of the general programme of the Applied Geochemistry Research Group at Imperial College, London, under the direction of Professor J.S. Webb. The writer wishes to record his gratitude to the staff of the group and in particular to Dr. P.M.D. Bradshaw for his invaluable advice and assistance throughout the study.

Sincere appreciation is expressed to Falconbridge Nickel Mines Limited, who financed the project and provided financial assistance to the writer in the form of a research bursary.

In Norway, field work was financed by Falconbridge Nikkelverk A/S and the advice and assistance received from the company's staff is gratefully acknowledged. Thanks are also due to the staff of A/S Sulfidmalm who provided logistical support during the sampling programme and in particular to Dr. E.G. Haldemann, chief geologist, and Messrs. E. Overwein, V. Wiik and F. Nixon for the loan of maps and reports and for many helpful discussions.

Field work at Flottorp was carried out in an area where the mineral rights are owned by Mr. T.O. Flottorp; his co-operation in making assay plans available is gratefully acknowledged.

CHAPTER I. SAMPLING AND ANALYTICAL TECHNIQUES

1. Sampling

Samples were collected in numbered Kraft paper envelopes; for routine samples these measured 3x5 inches, but for bulk and rock samples larger envelopes measuring 5x9 inches were used.

(a) Stream Sediments were taken from the active sediment in the middle of streams. Sample sites were recorded on 1:50,000 topographic sheets and during the regional survey the following parameters were noted:

- (i) Width, depth and rate of flow of the stream
- (ii) Grain size, colour and degree of sorting of the sediment
- (iii) Mineralogy of the sample
- (iv) Organic content of sample
- (v) Nature of banks
- (vi) Proportions of major rock types in stream float
- (vii) Outcropping rock-type
- (viii) Possible sources of contamination.

In subsequent detailed sampling streamwater pH was also noted.

(b) Soil samples were collected using a hand auger. For the nickel and molybdenum orientation studies individual samples were taken of each horizon of the soil profile and sampling was then continued at depth invervals of one foot to the bedrock surface if possible. Texture and colour of the samples were recorded and note was taken of the topography at each sample site. In subsequent follow-up surveys samples were taken only of the B horizon, at a depth of 12-18 inches. A limited number of bulk samples were collected using a small spade.

(c) Bog samples were collected with a Hiller peat auger. Samples were taken at depth intervals of 12 inches to the bottom of the bog and it was generally also possible to sample underlying moraine, where present.

(d) Rock. Care was taken that the rock samples collected were as fresh as possible. When sampling along traverses at the orientation localities large joint-bounded blocks were broken open and any obviously weathered fragments rejected; an exception was made to this at the Flottorp Mo orientation locality where it was possible to sample freshly blasted rock over the ore zones. A representative suite of the mafic rocks of the Iveland-Evje area was collected from recent road cuts, as were a limited number of background samples at Flottorp. A sample weight of approximately 1 kg. was aimed at.

(e) Lake Sediments were collected at Flottorp from a maximum depth of 15 ft. using a rowing boat and a stainless steel scoop. The lake bottom to a depth of 40 ft. was examined by SCUBA diving but the loose organic debris covering the bottom at this depth proved unsampleable.

(f) Water. Two-litre samples of spring and stream waters were collected in acid-scrubbed, screw-top polythene bottles. The bottles were thoroughly rinsed at the sample site before taking the sample. pH and Eh of the water was measured and the relative rate of flow, width and depth were recorded for each site.

2. Sample Preparation

(a) Stream sediments, soils and bogs

Samples were oven-dried at a temperature of 80°C. Bog samples were found to have hardened to compact briquettes during drying; these were coarsely crushed and the fragments ground in a mechanical agate mortar prior to sieving to -80 mesh through nylon bolting cloth. Stream sediment and soil samples required only light grinding in a pestle and mortar before sieving. After each operation the sieve, mortar and pestle were brushed clean to avoid contamination between samples. The -80 mesh fraction was selected for routine analysis in accordance with standard departmental practice.

(b) Rocks

A small reference hand specimen was taken from each sample and the remainder was reduced to less than 2 mm using two jaw crushers in tandem. The sample was then quartered to provide a charge of about 20 g. which was ground for one minute in a tungsten carbide mill; the jaw crushers and mill were carefully brushed clean between samples.

(c) Mineral Separation

Monomineralic fractions were prepared from 36 selected rock samples from the Iveland-Evje basic belt. From Barth's (1947) account of the area the minerals expected were plagioclase, hornblende, quartz, magnetite and occasionally pyrrhotite in the amphibolite, ore-diorite and metagabbro samples and plagioclase, hypersthene and hornblende plus pyrrhotite and magnetite in the norite.

Crushed rock samples were wet-sieved to give material in the -100 mesh +140 mesh size range. After drying overnight at 60°C, the strongly magnetic fraction (magnetite and pyrrhotite) was removed with a hand magnet and plagioclase fractions were then prepared, using a Cook magnetic separator at maximum current (2 amps) and a side tilt of 20°. The plagioclase fractions were examined with a binocular microscope and recycled through the separator until free of mafic minerals; the possibility of quartz occurring in this fraction was accepted.

The mafic fractions of norite samples were further separated magnetically into the hypersthene and hornblende concentrates, operating conditions being adjusted to give optimum separation on the basis of colour. The mafic fractions of all samples were then freed from plagioclase and quartz by heavy liquid separation with tetrabromoethane. A final separation with methylene iodide was used to prepare hypersthene and hornblende fractions, the purity of the final mineral separates being verified under the binocular microscope.

(d) Size Analysis

Selected bulk samples were quartered and sieved to -2 mm. 100 g. and 200 g. of soil and stream sediment respectively were dispersed in 1% Calgon solution in an ultra-sonic vibrator and the resultant slurry washed through an 80 mesh nylon screen into 1 litre sedimentation cylinders. The weight of clay and silt present was determined using a Bouyoucos hydrometer; the American Department of Agriculture definitions of clay and silt were followed and hydrometer readings were accordingly taken after sedimentation for 40 secs. and for 5 hours at a temperature of 19°C. The +80 mesh and remaining -80 mesh material was then wet-sieved into constituent size fractions, dried and weighed. Fractions coarser than 80 mesh were quartered and a representative portion ground to -80 mesh for chemical analysis; samples of silt and clay for chemical analysis were separated by sedimentation. Mesh sizes used and equivalent particle diameters are given in table 1.

Table 1. Equivalent particle diameter (mm) for mesh sizes used in mechanical analysis.

Mesh Size (B.S.S.)	2	20	38	80	125	200	Silt	Clay
Diameter (mm)	2.0	1.04	0.49	0.21	.107	.053	.05-.002	< .002

3. Measurement of pH and Eh

Field measurements of pH and Eh were made in the course of the orientation studies using a battery operated pH meter manufactured by Analytical Instruments Limited. This has a scale graduated in both pH units and volts and is supplied with interchangeable pH and Eh electrodes. Since the meter is calibrated using a buffer solution of known pH (in the present case 4.0) the voltmeter readings are relative only, the scale being graduated from +.3 to -.3 volt at intervals of 0.01 volt. The voltmeter readings must therefore be converted to an absolute scale and this is done with the aid of a reference solution* with an oxidation potential at 25°C. equal to 0.430 volt with respect to the standard hydrogen electrode. After calibration of the pH scale with buffer solution of pH 4.0, the voltmeter reading given by the reference solution (Vr)

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* 1.408 g potassium ferrocyanide tri-hydrate, 1.098 g potassium ferricyanide, 7.455 g potassium chloride dissolved in 1 litre deionised water.

using the platinum Eh electrode was noted; subsequent field readings (Vf) in volts were then easily converted to Eh values by the addition of the calibration factor (0.430 - Vr) i.e. Eh (volt) = Vf + (0.430 - Vr).

The method of determining pH and Eh in the field varied for different media as did the reliability of the values obtained. These are described below in order of decreasing reliability:

(a) Surface Waters

Measurements were made by placing the electrodes several inches below the surface of the water. pH was measured to 0.2 pH unit and Eh to 0.02 volt, although the voltmeter readings were commonly full scale positive deflection (i.e. Eh greater than 0.5 volt).

(b) Groundwaters

Measurements were made by lowering the electrodes several inches below the surface of groundwater filling freshly drilled auger holes. pH readings by this method are thought to be as reliable as those for surface waters, but since it was not possible to exclude air from the auger holes Eh values for groundwaters are probably high.

(c) Soil and Bog

Measurements were made on these materials by inserting the electrodes into naturally wet, freshly augered samples; this method is considered more reliable than laboratory determinations on soil slurries (Baas Becking et al 1960, Garrels and Christ 1965). The two

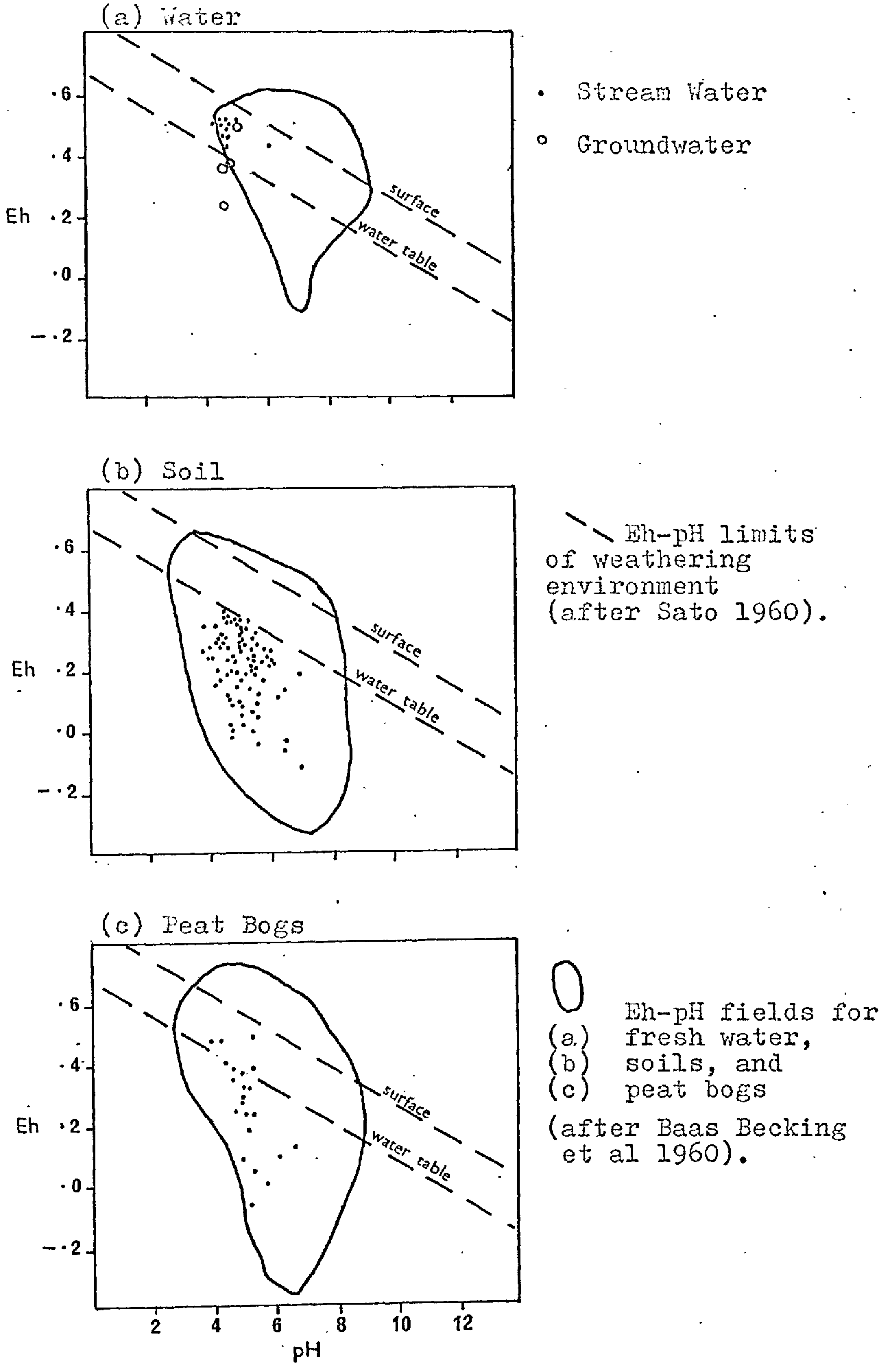


Fig. 2 Eh-pH data for water, soils and peat bogs from Mølland and Flottorp orientation localities.

main sources of error in this method are the introduction of air into the sample along with the electrodes, and the change in Eh of the sample as it reaches equilibrium with the atmospheric environment. In order to reduce the latter effect measurements were made immediately the samples were taken, and the sample was squeezed around the electrode in order to expel as far as possible introduced air. Eh readings taken in this matter showed an initial drift before becoming stable after about 1 minute. In general, Eh readings repeated within 0.05 volt, although occasionally the meter fluctuated wildly, interpreted as being due to air bubbles trapped around the electrode. pH readings for soils and bogs repeated within ±0.2 units.

Eh and pH data for surface water, groundwater, soils and bogs are plotted in fig. 2. Eh-pH fields for the various media given by Baas Becking et al (1960) are also plotted and it is evident that the two sets of data are compatable.

4. Spectrographic analysis

Regional stream sediment samples were analysed for Co, Cr, Cu, Fe (expressed as Fe_2O_3), Mn, Mo, Ni and Zn by a rapid emission spectrographic technique developed at the Applied Geochemistry Research Centre. The method is described fully by Nichol and Henderson-Hamilton (1965).

Analytical precision was determined from a series of control samples of known Ni content, inserted at a frequency of one per spectrographic plate of 13 samples (Stanton 1966). Precision for Ni, Cr, Co, Cu, Mn, Zn and Fe at the levels encountered during the regional survey are given in table 2. Precisions quoted are at the 95% confidence level (i.e. ± 2 standard deviations) and were calculated from repeat analyses of control samples using the formula:

$$\text{precision at } 95\% = \pm \frac{2\text{x}100}{\bar{X}} \sqrt{\frac{(X-\bar{X})^2}{n-1}}$$

No precision data are available for Mo since the Mo content of the control samples was below the detection limit.

Comparison of Ni contents obtained for the control samples with the accepted values (based on previous departmental analyses) indicates a positive bias at intermediate levels (100 - 400 ppm), while at high and low levels the data show a wide scatter but do not appear to be significantly biased (fig. 3).

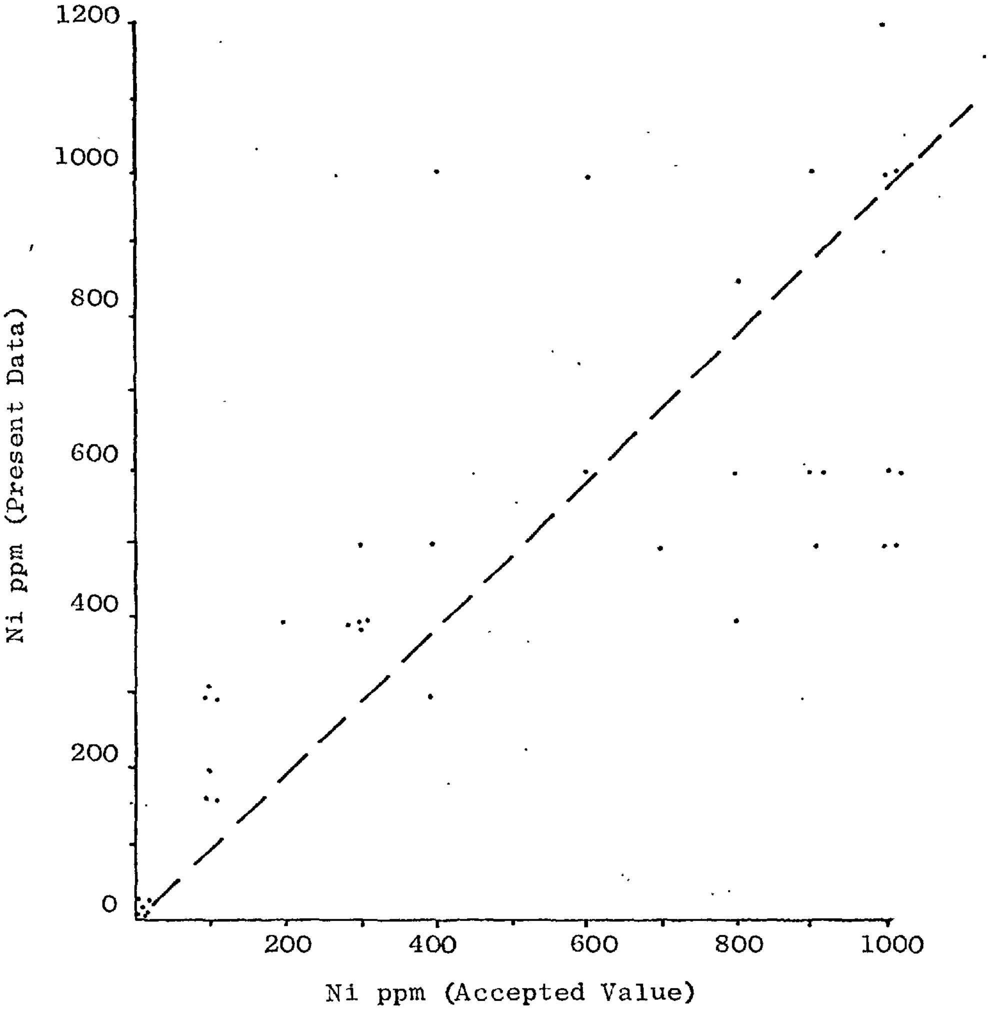


Fig. 3 Analytical bias of spectrographic data illustrated by comparing determined Ni content of the control samples (7809-7820) with accepted values.

Table 2.

Precision data for spectrographic determination of Ni, Cr, Co, Cu, Mn, Zn and Fe_2O_3 based on 6 replicate analyses of control samples 7818, 7819 and 7820.

	Ni	Cr	Co	Cu	Mn	Zn	Fe_2O_3
			(ppm)				(per cent)
7818							
Mean level	236	85	19	70	366	<50	1.12%
Precision	60%	117%	17%	88%	45%	*	63%
7819							
Mean level	400	316	38	191	227	120	2.04%
Precision	32%	93%	61%	119%	115%	116%	47%
7820							
Mean level	15	8	7	4	127	<50	0.6 %
Precision	128%	166%	77%	84%	166%	*	114%

* Precision not determined since Zn below detection limit.

5. Atomic absorption analysis

(a) Sample attack: two attacks were used to prepare samples for analysis by atomic absorption:

(i) Hydrofluoric-perchloric acid

This attack was used for the analysis of rock samples and mineral separates from the nickel orientation area. 0.25g of sample (accurately weighed for mineral separates) was digested with 10 ml hydrofluoric acid, 2 ml perchloric acid and 2 ml nitric acid in a platinum dish; after the acids had been completely driven off the residue was dissolved in about 5 ml of 1 M hydrochloric acid. For rock samples the leach solution was transferred to test-tubes calibrated at 10 ml and the volume made up with 1 M hydrochloric acid washings from the platinum dish; since greater precision was required, the procedure was modified for mineral analyses, the leach solution being transferred quantitatively to 25 ml volumetric flasks by repeated washing with 1 M hydrochloric acid.

(ii) Nitric-perchloric acid

This was the routine method of preparing samples for atomic absorption analysis. 5 ml of a 1:4 mixture of perchloric acid (60%) and concentrated nitric acid were added to 0.25 g of sample in a rimmed pyrex test-tube. The tubes were suspended in an oven and evaporated to dryness at a temperature of about 200°C. After cooling the residue was leached with 10 ml of 1 M hydrochloric acid delivered from a Zipette automatic dispenser.

As the nitric-perchloric acid mixture is strongly oxidising the sample attack is considered to be complete for organic material (i.e. humus and peat samples). Comparison of Ni contents determined for the control samples (tropical soils) after nitric-perchloric acid and hydrofluoric acid digestion (fig. 4) reveals that the routine sample attack may also be considered complete for highly weathered material.

Tables 3 and 4 compare the Ni, Co, Cu, Fe and Mg contents of unweathered hypersthene and hornblende samples determined after nitric-perchloric acid and hydrofluoric acid digestion. The limited extraction of the major metals (Mg and Fe) indicates that the nitric-perchloric attack has little effect on the silicate lattice; it is noticeable that the proportion of the total Mg and Fe content liberated is greater for hornblende, and that for both minerals this shows a slight increase with decreasing grain-size.

Digestion with nitric-perchloric acid liberates a significantly greater proportion of the total content of the trace metals, the proportion liberated increasing in the order Co, Ni, Cu (table 4). Except in the case of Cu, the proportion of the total metal liberated increases with decreasing grain-size; the causes of this were not investigated. However, Smirnova et al (1968) have recently demonstrated, by means of phase analysis, that Ni and Co occur in mafic silicates partly by isomorphous substitution for Mg and partly as extremely fine sulphide inclusions, and it is thought that the trace metals liberated by nitric-perchloric acid digestion are present as minute sulphide inclusions.

Table 3. Ni, Cu, Co, Fe and Mg determined after nitric-perchloric attack on sized hypersthene and hornblende samples.

(a) Hypersthene

Grain-size	- 80 + 125	- 125 + 140	- 200	Total (HF)
Ni ppm.	185	260	295	560
Cu ppm.	43	46	41	50
Co ppm.	14	15	22	115
Fe%	0.35	0.42	0.70	15.0
Mg%	0.19	0.24	0.44	13.9

(b) Hornblende

Grain-size	- 80 + 125	- 125 + 140	- 200	Total (HF)
Ni ppm.	185	180	240	410
Cu ppm.	90	70	95	60*
Co ppm.	22	22	30	130
Fe%	1.04	1.08	1.95	6.3
Mg%	0.82	0.99	1.54	12.0

* This discrepancy is within the analytical precision for Cu, see table 7.

Table 4. Proportion of total metal (HF attack) liberated from sized hypersthene and hornblende samples by nitric-perchloric acid digestion.

Metal		-80 +125	-125 +140	-200
Ni	Hypersthene	35	45	55
	Hornblende	45	45	60
Cu	Hypersthene	85	90	80
	Hornblende	100	100	100
Co	Hypersthene	10	15	20
	Hornblende	15	15	25
Fe	Hypersthene	2	3	5
	Hornblende	15	15	30
Mg	Hypersthene	1	2	3
	Hornblende	7	8	13

(b) Determination of Ni, Cu, Co, Fe, Mn, Mg, Zn

(i) Procedure

The above elements were determined using the standard procedure adopted at the Applied Geochemistry Research Centre. The instrument used is a Perkin Elmer Model 303 atomic absorption spectrophotometer linked to a DCR-1 readout unit. An acetylene-air mixture is used for all determinations. To minimise instrumental errors a noise suppression of 2 and a x8 integration setting on the DCR-1 were used throughout.

Standard solutions covering the range expected in the samples are prepared for each element and aspirated after every 10 sample solutions. Calibration curves are then

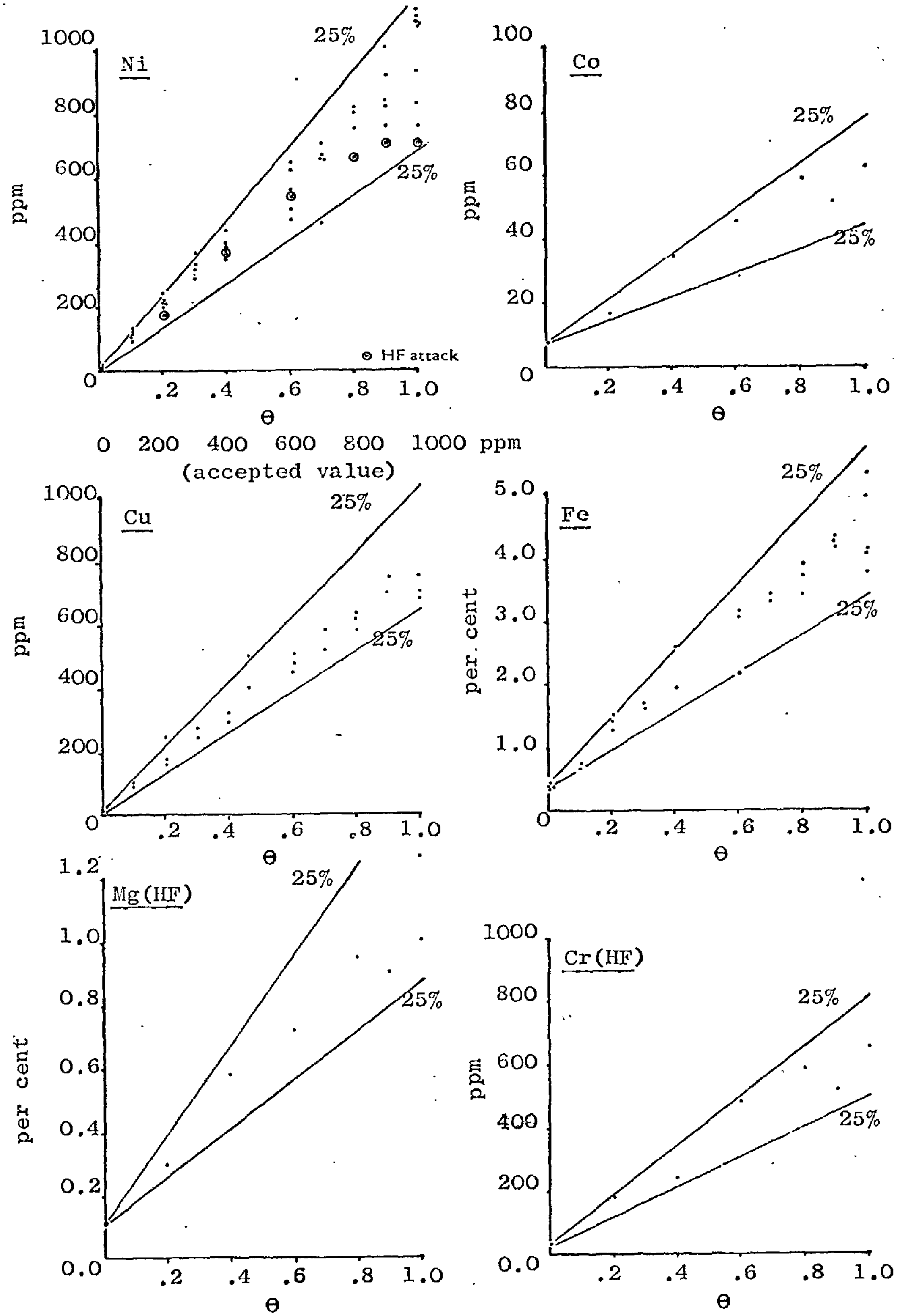


Fig. 4 Graphical presentation of precision obtained during routine analysis for Ni, Co, Fe, Mg and Cr by atomic absorption (control series 7809-7820).

prepared plotting absorbance counts against metal content and these are used to read off the metal content of the samples. A new curve is drawn up if the absorbance for the standard solutions drifts beyond 2% of the mean value used in drawing up the original calibration curve.

The presence of Al interferes with the determination of Mg and to overcome this La_2O_3 is added to both samples and standards to give a final concentration of 1% La_2O_3 in solution. The presence of Na, Ca, Mg, Fe, Mn and Al does not interfere with the determination of other elements. Operating conditions for the various elements are summarised in table 5.

(ii) <u>Precision and accuracy</u>

Analytical precision was controlled during routine analysis by inserting a statistical control series (Stanton 1966). Data for Ni, Co, Cu, Fe and Mg are plotted in fig. 4 from which it can be seen that overall precision for each element is of the order of 25%. The accepted Ni content of the control series (based on previous departmental analyses) is also given in fig. 4 as an indication of accuracy.

Analytical precision was determined more rigorously during an investigation into variations in stream sediment Ni content for which it was critical to determine precision near the detection limit of the method. Precision data based on 5 analyses of samples selected from background and anomalous localities are given in table 6. Precisions at higher mean Ni contents, based on 5 replicate analyses of the control samples are also given and it is evident that the magnitude of precision increases markedly near the detection limit.

Table 5. Routine operating conditions used in atomic absorption analysis for Ni, Cu, Co, Fe, Mn, Mg and Zn.

	Wave Length (Å)	Slit	Gain	Air/Fuel	Standards (ug/ml)
Ni	2320 (uv)	3	6	8.0:8.5	0.25 - 20
Cu	3250 (uv)	4	3	8.0:8.5	0.1 - 5.0
Co	2407 (uv)	3	5.5	8.0:8.5	0.5 - 20
Fe	3720 (uv)	3	5	8.0:8.5	10 - 300
Fe	3868 (uv)	3	5	8.0:8.5	50 - 500
Mn	4030 (vis)	4	3	8.0:8.5	25 - 200
Mg	2852 (uv)	5	4-5	4.0:4.5	1 - 40 (+ 1% La_2O_3)
Zn	2138 (uv)	5	6	8.0:8.5	0.5 - 5.0

N.B. (1) To avoid excessive dilutions two lines of differing sensitivity were used in determining Fe.

(2) Mg was determined only after HF attack.

(3) A Boling burner was used for all elements except Mg, for which an obliquely mounted single slot burner was used.

Table 6. Calculated precisions at different Ni contents based on 5 replicate analyses.

Mean Ni Content (ppm)	20	30	50	112	204	327	386	560	637	780	833	904	959
Precision at 95% confidence.	60	40	25	25	22	16	15	22	29	31	25	38	30

Precisions for the analysis of Ni, Cu, Co, Fe, Mn, Mg, Zn in mineral separates, based on 5 analyses of a hypersthene sample, are given in table 7; for convenience precisions for Cr, Ca and Sr determined on mineral separates are included.

Table 7. Precision data for mineral samples, based on 5 replicate analyses.

Element	Ni	Cu	Co	Fe	Mn	Mg	Zn	Cr	Sr*	Ca*
Mean level (ppm)	560	47	106	14%	2780	13.5%	242	1314	950	6.5%
Precision (per cent)	6	41	27	22	3	5	10	2.5	0	0.3

* Plagioclase

(c) Determination of Cr

As no previous development work had been done in the department on the determination of Cr by atomic absorption, some time was spent on investigating possible interference effects and establishing optimum operating conditions. The conditions finally adopted are shown in table 9.

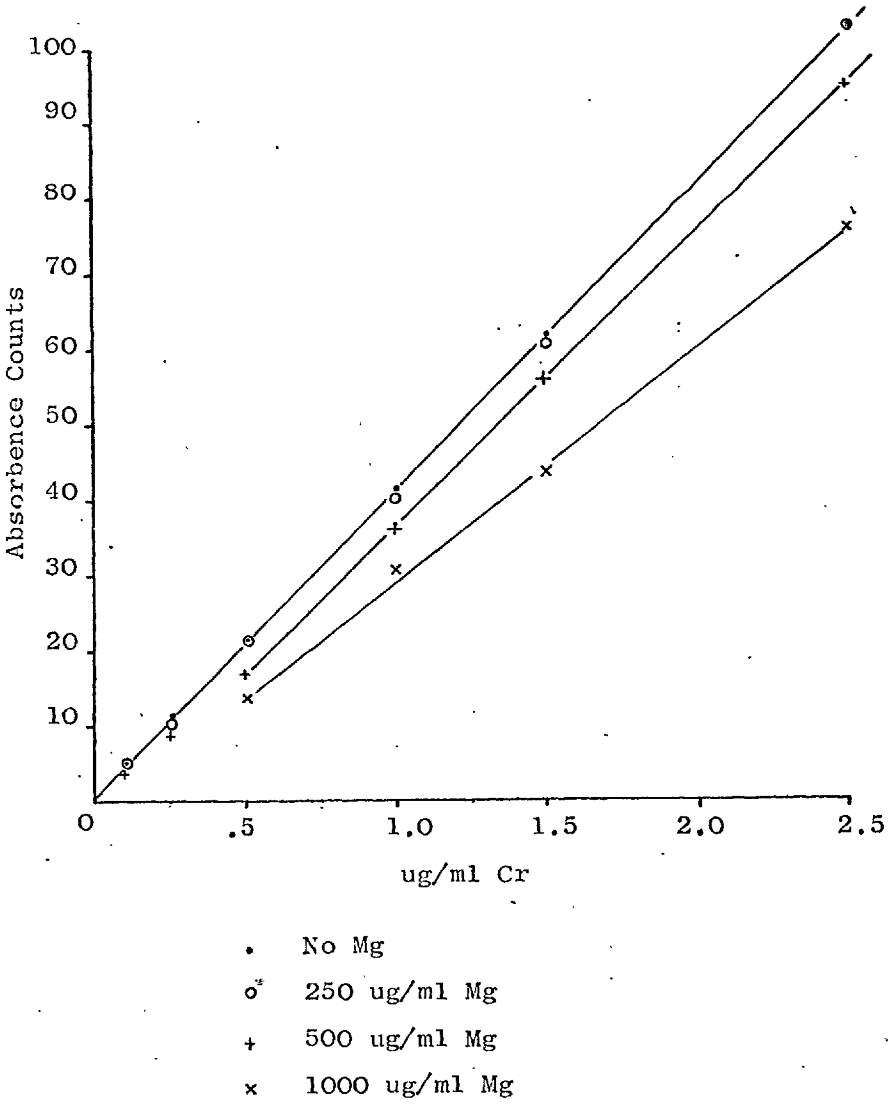


Fig. 5 The effect of Mg concentration on the calibration curve for the determination of Cr by atomic absorption.

Giammarise (1966) investigated the suppressive effect of Fe on the determination of Cr and reported that in a fuel-rich flame Fe interference could be eliminated by the addition of 2% NH_4Cl. This was confirmed experimentally and a similar effect found when a lean flame was used, although the lean flame gave the advantage of a more stable calibration. The interference effects of other major elements likely to be present in sample solutions from basic rocks and minerals were checked using both lean and rich flames. The effect of 1000 ug/ml Mn, Mg, Ca and Al on the absorbance count of a 5 ug/ml Cr standard (with 2% NH_4Cl) are shown in table 8; in a lean flame only magnesium was found to interfere. The effect of varying concentrations of Mg on the calibration curve for Cr was then investigated. The results are shown in fig. 5 from which it may be seen that no interference is caused by a Mg concentration of 250 ug/ml. Since it was intended to determine the Mg content of the samples selected for Cr analysis the interference effect was overcome by a suitable dilution (in practice found to be x500) to bring Mg content below a maximum of 300 ug/ml.

Initial trials on rock samples showed that only 10% of total Cr (HF-attack) was liberated by the routine nitric-perchloric attack, and accordingly hydrofluoric acid digestion was used for all Cr determinations. Analytical precision for rock analyses was controlled by a partial statistical control series (fig. 4) which indicated an overall precision of better than ± 25%. Precision for the mineral separate analyses, based on 5 replicate analyses of a sample with a mean Cr content of 1300 ppm, was ± 2.5%. The detection limit (employing a x500 dilution to overcome Mg interference) is 50 ppm in the sample.

Table 8. Absorbance counts obtained for 5 ug/ml Cr and 2% NH_4Cl in presence of additives.

Additive	Absorbance Counts Lean flame (Air/fuel 8.0:9.0)	Rich flame (Air/fuel 7.5:9.5)
1000 ug/ml Mn	210	294
" " Mg	182	261
" " Al	206	293
" " Ca	208	302
NIL	207	305

Table 9. Operating conditions for Cr analysis by atomic absorption.

Wave length	3579 (Å)
Slit	3 (Å)
Gain	6
Burner type	Boling
Burner height setting	0
Air/Acetylene mixture	8.0:9.0
Dilution	x500 + 2% NH_4Cl
Standards	0.1 - 5.0 ug/ml + 2% NH_4Cl
Sample attack	HF

(d) Determination of Ca and Sr

Ca and Sr were determined on mineral separates following HF digestion. The analyses were carried out in the Sedimentology Section of the Geology Department, using a Unicam S.P.90 spectrophotometer. Operating conditions are summarised in table 10.

Table 10. Operating conditions for determination of Ca and Sr.

	Ca	Sr
Wavelength	4227 Å	4700 Å
Slit	0.08 mm	0.85 mm
Current	12 ma	12 ma
Fuel	Acetylene/air	Acetylene/air
Standards	2-20 ug/ml (+ 1% La_2O_3)	1-20 ug/ml (+ 1% La_2O_3)
Dilution (plagioclase)	x 4000 or x 8000	x 200
(mafics)	x 5000	-
Remarks	1% La_2O_3 added to solutions and standards to prevent Al interference.	

Precision was determined by 5 replicate analyses of a plagioclase sample. For a Ca content of 6.5% precision was found to be 0.3% at the 95% confidence level, while for Sr precision was found to be 0% at a content of 950 ppm Sr.

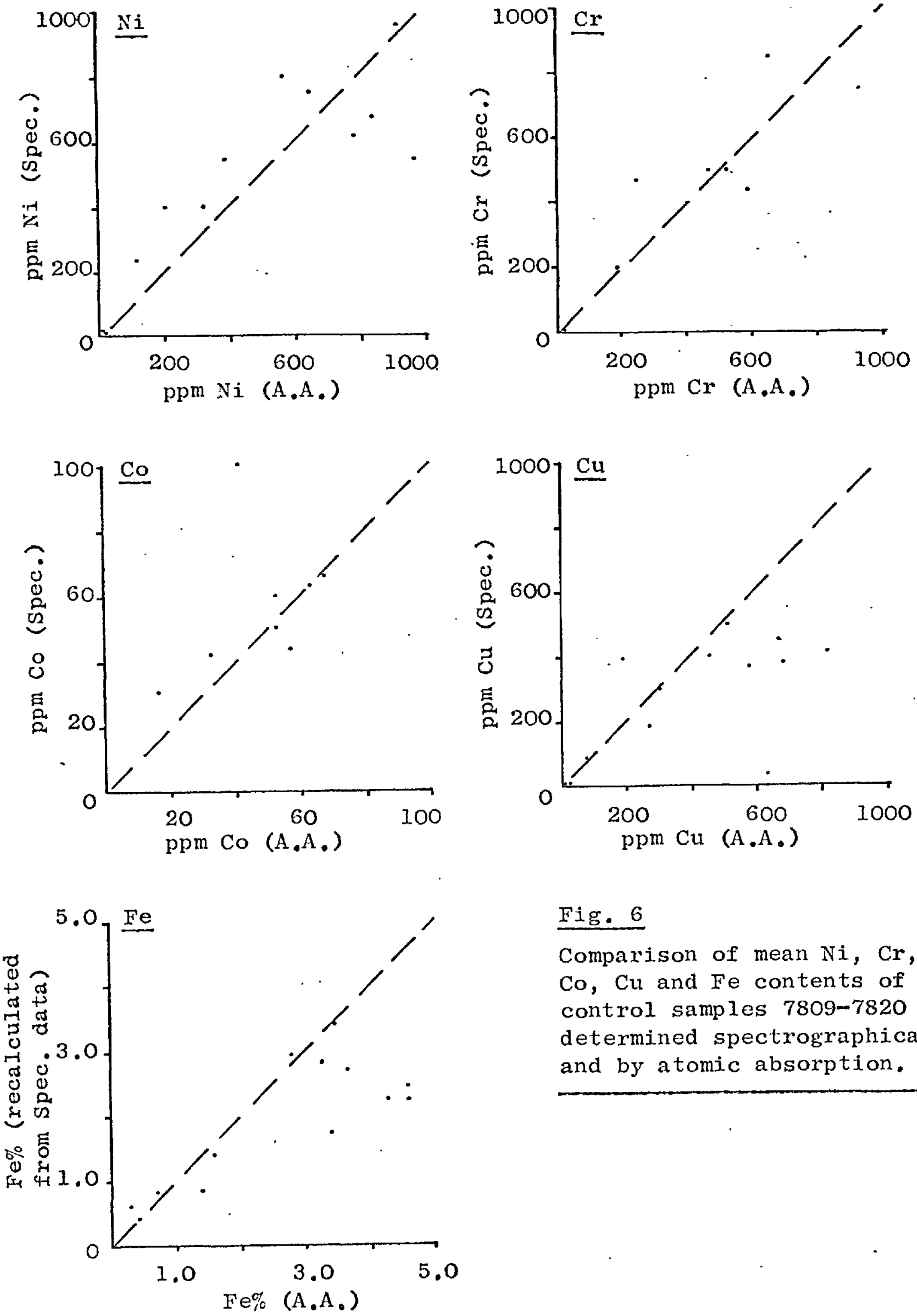


Fig. 6

Comparison of mean Ni, Cr, Co, Cu and Fe contents of control samples 7809-7820 determined spectrographically and by atomic absorption.

(e) Comparison of spectrographic & atomic absorption data

In the interpretation of data from two sources it is essential to know the relative analytical bias of the methods used. Since the same control series (7809-7812) was used in both spectrographic and atomic absorption analysis it is possible to establish the relative bias of the two methods by comparing mean values obtained from repeat analyses of the control samples. This is done graphically in fig. 6 from which it is apparent that with respect to the atomic absorption data the spectrographic values have a tendency to be high for Ni, low for Cu and Fe and of the same order for Cr and Co. The difference in Ni contents determined by spectrographic and atomic absorption analysis is referred to in the section on stream sediment investigations in the Mølland area (p.160).

6. Colorimetric determination of Mo

Mo was determined colorimetrically using the zinc dithiol method (Stanton and Hardwick, 1967); rock, soil and stream sediment samples were decomposed by fusion with potassium bisulphate,and organic rich samples (i.e. humus and peat) by digestion with a nitric-perchloric acid mixture, as described on p. 17).

For the analysis of routine samples the procedure described by Stanton and Hardwick was followed; analytical precision was controlled by replicate analyses of rock

Table 11. Analytical precisions for colorimetric determination of Mo, based on replicate analyses.

(a) Routine samples

Sample No.	Mean Mo Level	Precision	No. of Analyses.
1915	116 ppm	30%	9
1904	111 ppm	22%	8
1919	109 ppm	37%	9
1900	48 ppm	48%	9
1637	44 ppm	67%	11
1591	23 ppm	45%	8
1588	2 ppm	106%	11
1597	2 ppm	80%	12

(b) Detailed investigations

Sample No.	Mean Mo Level	Precision	No. of Analyses.
		Soil	
2227	175 ppm	12%	5
2230	35 ppm	10%	5
2190	32 ppm	17%	6
2220	12 ppm	33%	5
2210	6 ppm	35%	5
2200	5 ppm	28%	5
		Humus	
1804	77 ppm	11%	5
1124	23 ppm	18%	6
1780	16 ppm	60%	5
1520	7 ppm	65%	5
1246	2 ppm	6%	6

samples covering the range of Mo contents encountered in the field and calculated precisions at 95% confidence level are given in table 11a. For subsequent detailed investigations the method was modified slightly, the solvent phase being delivered more precisely from a graduated pipette, rather than the rapid automatic dispenser used in routine analyses. Analytical precisions caluclated from replicate analyses of soils and humus during the detailed investigations are given in table 11b.

7. Mo in Water

The Mo content of freshly collected water samples was determined in the Quality Control laboratory of Falconbridge Nikkelverk A/S, Norway. Mo was concentrated from 500 ml of buffered water sample by solvent extraction with 8-hydroxyquinolene in chloroform (A.G.R.G., 1966). The extract was evaporated to dryness, digested with concentrated nitric acid and perchloric acids and, after evaporating to dryness a second time, was taken up in 10 ml of 10% nitric acid. The Mo content was then determined using a Harwell pulse polarograph linked to a chart recorder. Standard solutions were treated in the same manner to provide data for a calibration curve. Due to instrumental noise at low levels the detection limit, 3 ppb in the sample, was too high for a study of the distribution of Mo in background waters, but was adequate for the recognition of anomalous patterns related to contamination.

8. Mercury Analysis

The mercury content of ground rock samples was determined using a double beam mercury vapour meter as described by James and Webb (1964). Analytical precision, calculated from replicate analyses, was 30% at the 95% confidence level.

9. X-ray Diffraction Analysis

Selected samples were analysed mineralogically using a Phillips Proportional Counter X-ray diffractometer with a wide angle goniometer. Cavity mounts were used for all samples. Initially Co-Kα radiation was used but the majority of the samples were run using Cu-Kα radiation. Operating conditions are summarised in table 12.

Table 12. Operating conditions for X-ray diffraction analysis.

Scan speed	1° (2θ) per min.
Time constant	1 or 2
Scale factor	16 x 1
Divergence (α)	1°
Receiving slit width	0.1
Counter-type	Scintillation
Range	4° - 60° (2θ)

CHAPTER II. THE REGIONAL SURVEY

1. Introduction

The regional survey was conducted over an area of 2000 sq. mls. in the extreme south of Norway, including the Ni and Mo orientation localities (fig. 1). Multi-element regional stream sediment surveys have been used as a means of locating potentially mineralised areas (Webb et al 1964) and of providing fundamental geochemical data both as a complement to geological mapping (Nichol et al 1966, Garret et al 1967, Horsnail 1968) and for agricultural purposes (Atkinson 1967, Fletcher 1968). The principal objective of the present survey was to demonstrate, with reference to the orientation localities and other known occurrences, the applicability of rapid reconnaissance surveys to the search for Ni and Mo mineralisation in glacial terrain. The relation of geochemical patterns to bedrock geology and to changes in the secondary environment was also examined.

As only limited time was available the boundaries of the survey area (fig. 7) were largely governed by road access. Samples were collected from streams with catchments of 1-5 sq. mls. (Horsnail 1968), at road/stream intersections and in six weeks a uniform coverage was obtained at a mean density of 1 sample per 5 sq. mls.

The geology, mineralisation and glacial deposits are first briefly described, together with the main physical features of the survey area. The results of the survey are then presented and the significance of the geochemical patterns discussed.

2. Description of Area

(a) Geology

Barth (1945, 1947, 1960) describes the geology of the area and the following account is largely based on his work; the distribution of the major rock units, all of Precambrian age, is shown in fig. 7 (after Barth 1960).

The most important unit in terms of outcrop area is the gneiss group which, in addition to granite gneiss proper, includes zones of augen gneiss, anatexic granite and migmatite. The gneisses have a regional N-S strike and a generally steep dip; they were considered by Barth (1960) to represent a granitised sequence of quartzites, greywackes, limestones and basic volcanics.

The Iveland-Evje amphibolite, the largest basic mass in the area, is an elongate body 1 to 6 miles wide and about 20 miles in length, entirely surrounded by gneissose granite and augen gneiss; it consists predominantly of schistose amphibolite although massive rocks occur at a number of localities. The principal Ni occurrences are associated with this amphibolite body and, by analogy with

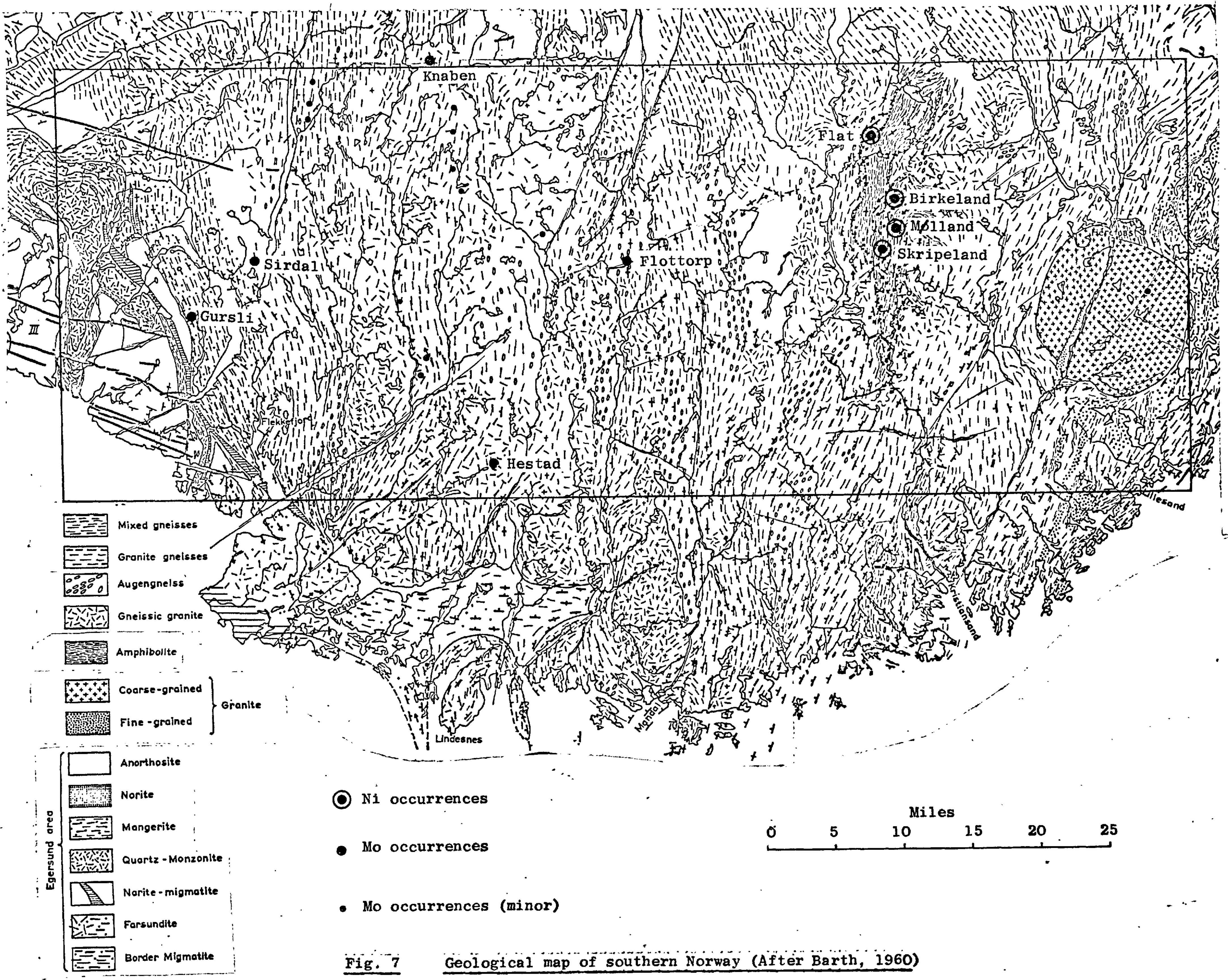


Fig. 7 Geological map of southern Norway (After Barth, 1960)

Sudbury, both Vogt (quoted in Barth (1947)) and Barth (1947) considered the amphibolite mass to represent a granitised noritic intrusion.

The Egersund anorthosite complex, in the extreme west of the area, is a distinctive suite of rocks comprising coarse-grained anorthosites with minor norite. The margin of the anorthosite complex is marked by a narro band of norite-migmatite, and the enclosing granite gneisses are heavily migmatised up to 5 miles from the anorthosite contact. According to Barth (1960) the anorthosites are the result of deep level anatexis leading to the complete elimination of ferromagnesian constituents; these were considered to have formed a basic front which, on permeating the enclosing granite gneisses, gave rise to a border facies enriched in mafic material. Ilmenite deposits associated with the anorthosites are worked at Titania and Blafjell mines.

A coarse-grained, post-orogenic granite body occurs at Herefoss in the east of the survey area. It has a circular outcrop 12 miles in diameter and sharp contacts with the enclosing gneisses, the schistosity of which tends to parallel the granite contact.

(b) Mineralisation

The locations of the most important Ni and Mo occurrences are shown in fig. 7.

Ni mineralisation

Nickeliferous pyrrhotite occurs at a number of localities within the Iveland-Evje amphibolite belt, but the only deposit of economic size was mined at Flåt, where 3,000,000 tons of ore were produced during the period 1870 to 1946. Bjørlykke (1947) gives the overall average grade as 0.72% Ni and 0.48% Cu and the Ni:Co ratio for the ore as 9:1. For the Mølland occurrence Bjørlykke indicates a grade of 0.8% Ni and 0.25% Cu and records that an intensive diamond drilling and underground exploration programme carried out in 1937 failed to locate a deposit of economic size. At the Skripeland and Birkeland prospects exploration pits were sunk on minor sulphide mineralisation and subsequently abandoned; there are no records of the grade encountered.

Mo mineralisation

A Mo metallogenic sub-province has been described stretching S.W. - N.E. across southern Norway (Hoftedahl 1960, Bugge 1963). A large number of small deposits are recorded but Mo has only been worked profitably at Knaben mine, on the northern boundary of the survey area. The principal molybdenite occurrences are shown in fig. 7 and it may be seen that these appear concentrated in the western granite-gneiss area.

Bugge (1963) states that molybdenite has two principal modes of occurrence: (i) as low-grade impregnations in elongate weakly mineralised zones (fahlbands) generally conformable with the granite gneisses; (ii) as impregnations, occasionally of ore-grade and economic size, in minor intrusions of granite, pegmatite, aplite or vein quartz. At Knaben a weakly mineralised fahlband zone has been traced for a total north-south distance of 20 miles, although workable deposits are confined to minor intrusions intersecting the fahlband. Three parallel fahlbands at Flottorp, 12 miles east of the Knaben zone, have strike lengths of at least 6 miles (Bugge 1963).

Mining operations commenced at Knaben on a limited scale in 1885. The demand for Mo by the armament industry during 1914-18 led to a prospecting boom in the area and it was at this time that most of the small deposits were found and attempts, generally unsuccessful, made to bring them into production; a number of prospects were re-examined during 1939-45. Production from Knaben up to 1962 totalled 7,700 tons Mo and current production is about 250 tons Mo annually from an average ore grade of 0.14% Mo; 22 tons Mo were extracted from Flottorp during 1914-1919.

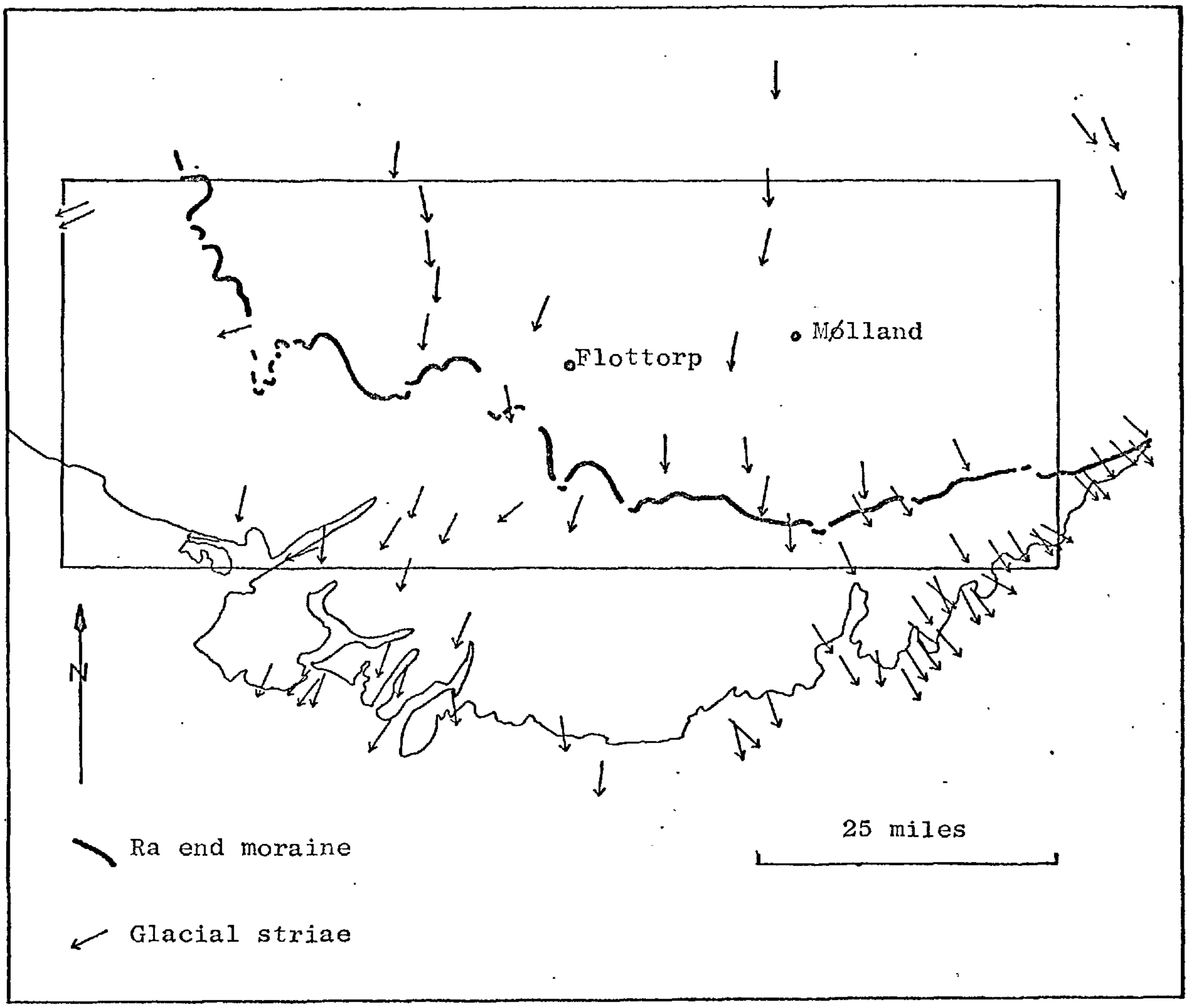


Fig. 8 Direction of ice-movement and the position of the Ra end moraine (after Hoftedahl and Andersen (1953) and Andersen 1960).

(c) Pleistocene Geology

The Pleistocene deposits of the area are described by Andersen (1960) and the following account is based largely on his work.

The direction of ice-movement, as indicated by glacial striae is essentially from north to south over the whole area; there is however a tendency for striae to be aligned slightly east and west of south respectively in the east and west of the area (fig. 8). Southern Norway lay close to the margin of the Scandinavian ice-sheet during the Würm glaciation and Andersen recognises end-moraines of four distinct sub-stages, marking pauses in the retreat of the ice-sheet. Only the youngest, or Ra end moraine, of Younger Dryas age (i.e. 10,800 - 10,000 years B.P.) occurs in the survey area and forms an almost unbroken belt from near Grimstad to N.W. of Sirdalsvatn, a total distance of 90 miles (fig. 8). The end moraine consists of very bouldery till and is normally between 300 - 1500 ft. wide, with a maximum height of 60 ft. Extensive glaciofluvial outwash deposits occur in the main river valleys to the south of the moraine ridge and are the thickest Quaternary deposits in the area. Ice-dammed lake terraces are observed in some valleys to the north of the Ra moraine.

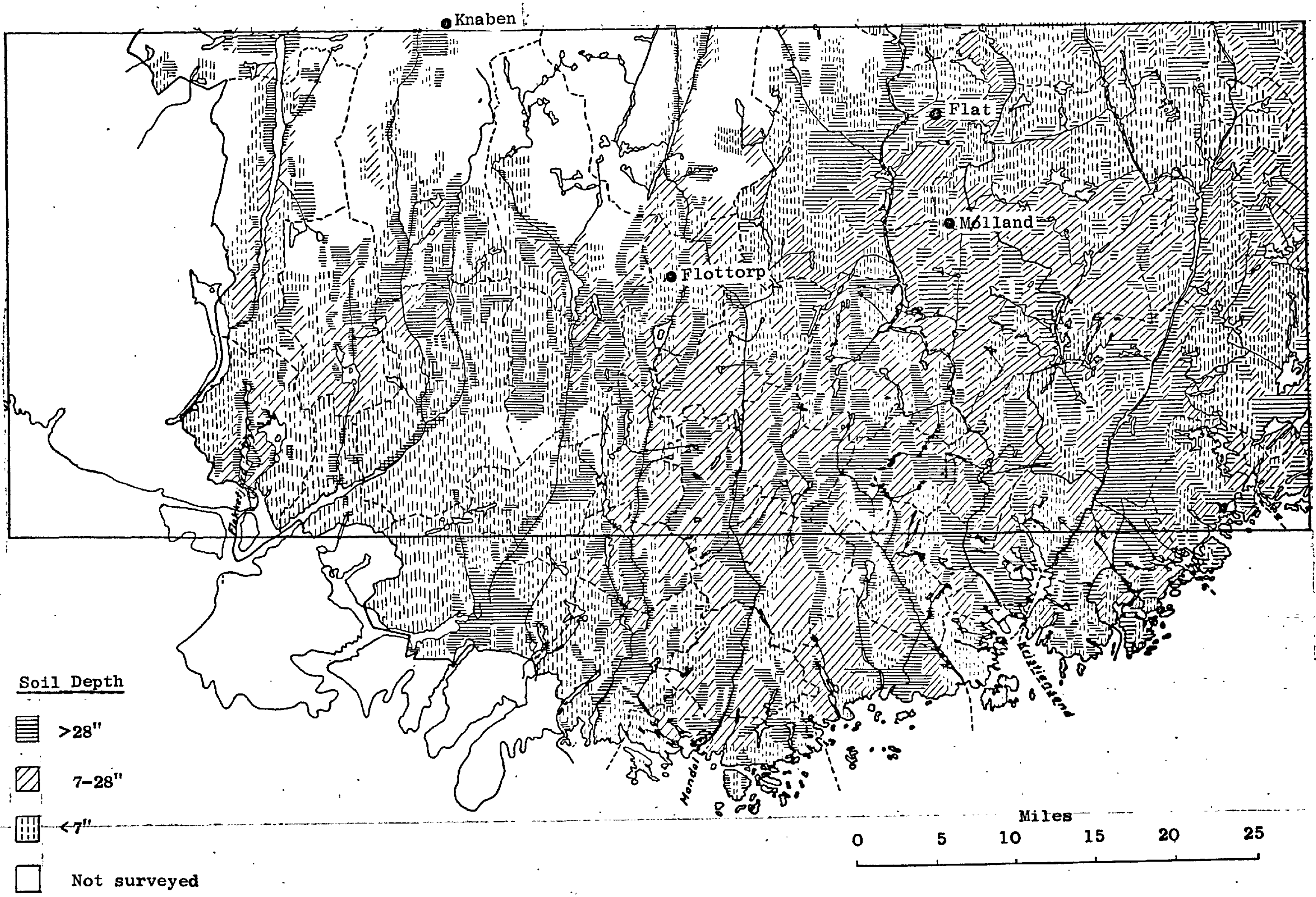


Fig. 9 Soil depths in Southern Norway (After Låg, 1957)

In general, the cover of Quaternary deposits is thin, particularly on the hill slopes between major rivers where bare rock surfaces are common. Låg (1957) gives a schematic map of soil depths in south Norway (fig. 9); organic swamp soils are included but, as these cover barely 5% of the area, soil depths closely reflect the thickness of moraine or glaciofluvial deposits. It is evident that depths in excess of 28 ins. are largely confined to the main river valleys and that over extensive areas in the west and north the depth of cover is less than 8 inches.

(d) Topography

Topographically the area consists of an undulating plateau rising from 600 ft. in the east to over 1800 ft. in the extreme north-west, the plateau surface sloping generally southwards. The drainage system is well developed and the main rivers flow in deep, predominantly north-south, glacial valleys joined by abundant tributaries.

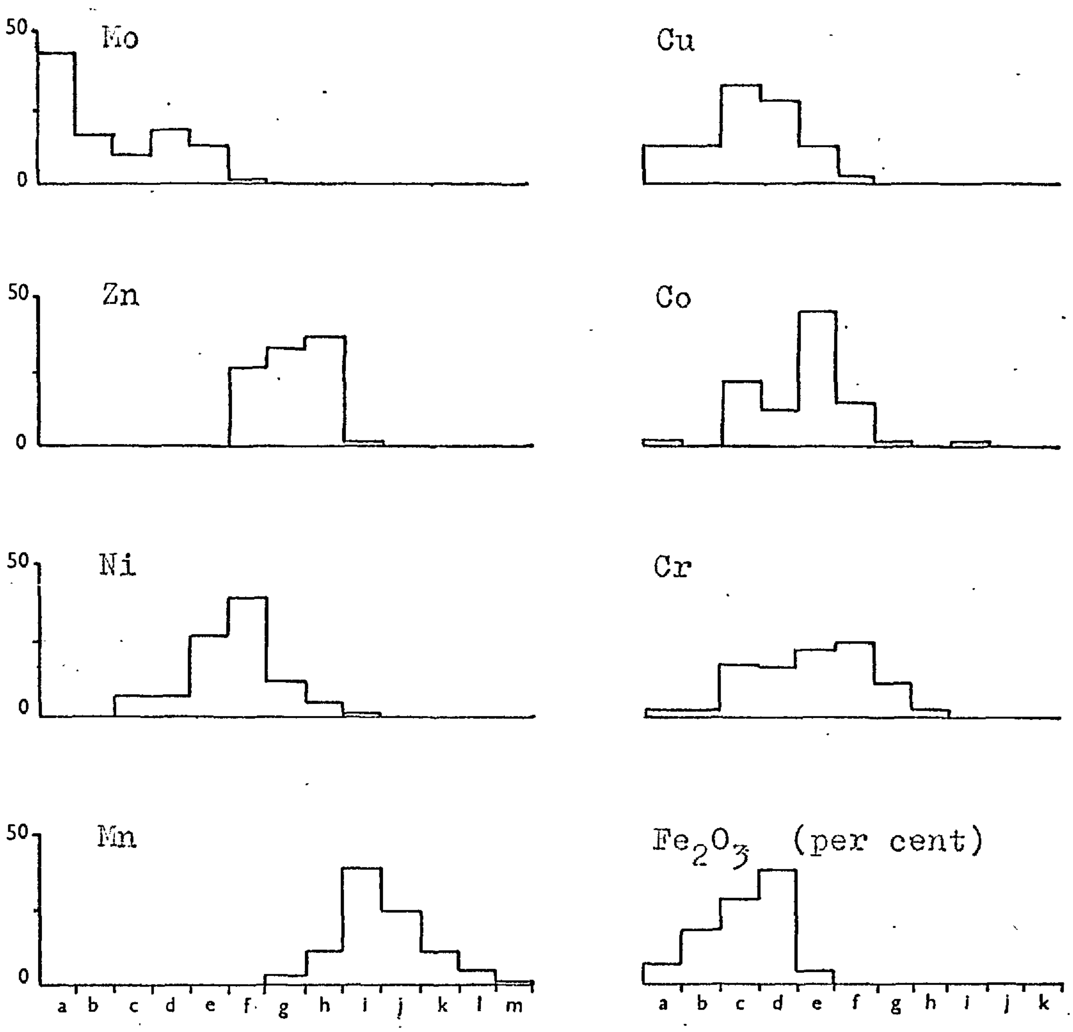
Lakes are common features in the drainage system; they are of all sizes and occur in both ice-scoured rock basins and in major valleys dammed by the end moraine ridge. Lakes form local base levels of erosion and act as effective barriers to the mechanical transport of sediment. Bogs are also extremely common, occurring as selvedges around the majority of lakes and in small rock-basins and the flatter portions of valley floors; the abundance of bogs forms a second effective barrier to the mechanical transport of stream sediment. The drainage system is in a youthful stage and the possible effects of stream capture need to be considered when interpreting detailed stream sediment data.

(e) Climate, Soils and Vegetation

Mean summer and winter temperatures are respectively 14^{o}-16^{o}C. and about 0^{o}C. Mean annual precipitation is 40-60 inches; this is evenly distributed throughout the year but, since the winter precipitation accumulates as snow, the spring thaw is accompanied by widespread flooding. Much of the summer precipitation occurs as heavy storms during which the rate of surface run-off is high and floods common.

The soils and vegetation of the area are described by Låg (1957). Podzols are by far the most common soil type and in general show a well developed soil profile; brown earths are much less widespread and are restricted in the main to a small area in the S.E. In areas of exceptionally shallow soil this typically takes the form of an accumulation of black humus separated from the bed-rock surface by a thin veneer of coarse, light-grey sand.

About 45% of the area is covered by productive, predominantly coniferous forest, according to figures given



Key: (value in ppm except Fe_2O_3)

a	<1.5	f	35-70	k	1500-3000
b	1.5-3	g	70-150	l	3000-7000
c	3-7	h	150-300	m	7000-15000
d	7-15	i	300-700		
e	15-35	j	700-1500		

Fig. 10. Per cent histograms for regional survey data

by Låg (1957). Farm land, swamps and lakes each account for a further 5% of the total area while the remainder, classified as barren, consists of outcrop more or less covered with lichen and moss.

3. Regional Survey Results

(a) Presentation of data

Analytical data for the regional samples, together with sample site co-ordinates, are tabulated in Appendix I. Percentage histograms of the data are presented in fig. 10; the frequency class boundaries are mid-points between the standards used in spectrographic analysis and the class intervals are logarithmic. From fig. 10 it can be seen that the majority of elements have distributions which approach log-normality, but with a tendency to be skewed negatively, exceptions being Mo (markedly bi-modal) and Co (bi-modal). Table 13 gives mean values for the elements with approximately log-normal distributions.

Table 13. Mean values for Cr, Cu, Mn, Ni, Zn and Fe (as Fe_2O_3).

Cr	Cu	Mn	Ni	Fe	Zn
20	6	698	35	5.4	115

N.B. Values in ppm except Fe_2O_3 (per cent).

Previous work (Garrett 1966, Nichol et al 1966) has shown that the interpretation of regional reconnaissance data is facilitated by the use of rolling mean analysis, a smoothing process which allows data showing high relief to be more readily contoured. In the computer programme used a search area is moved step-wise across a "map" of the data and the rolling mean is calculated as the mean of all values lying within the search area, its co-ordinates being the mean of the sample site co-ordinates. The extent to which the data are smoothed is governed by the size of the search area relative to sample density and by the overlap between search areas; for investigations into the fundamental trends underlying regional data a high degree of smoothing is necessary (Nichol et al 1966), with the result that minor features related to mineralisation may be suppressed. As the primary objective of the present survey was mineral exploration it was important that such small-scale features be preserved; data smoothing was therefore kept to a minimum and in practise a 5 km. square search area was used with a 50% overlap between squares. As the majority of the elements showed distributions more nearly log-normal than normal the data were logarithmically transormed prior to rolling mean analysis.

Computer output was plotted automatically at a scale of 1:250,000 using a Calcomp X-Y plotter and the resultant maps contoured by hand. In view of the generally poor precision of the spectrographic data (p. 16) it was decided to contour the rolling mean map at values coinciding with the mid-points between the spectrographic standards, on the assumption that grouping in this way would reduce the effects of analytical imprecision. The contour intervals are therefore logarithmic and coincide with the histogram class boundaries (fig. 10). For metals with distributions approximating log-normal (i.e. Cr, Cu, Mn, Ni, Zn and Fe_2O_3), contours were drawn at the standard mid-point value immediately above the geometric mean (table 13), and at succeeding mid-point values. Metals showing a bi-modal distribution were contoured at the standard mid-point nearest to the value giving optimum separation of the two populations (i.e. 3 ppm Mo and 15 ppm Co, fig. 10) and then at succeeding mid-point values. A standard mid-point was not used if it produced uncontourable, isolated highs and it was this consideration which governed the choice of the top contour in each case.

(b) Results

Contoured rolling mean maps for Mo, Ni, Cr, Co, Cu, Mn, Zn and Fe are presented in figs. 11-18; the main features of the bedrock geology are also shown (Egersund complex and Herefoss granite after Barth 1960, Iveland-Evje amphibolite outcrop as mapped by A/S Sulfidmalm 1968).

The principal features of the distribution of individual elements are described below and interpretations are given for those patterns which may be readily related to known bedrock geology or mineralisation. For each element, however, there are features which cannot be accounted for in this way; these are best considered in terms of multi-element distribution patterns, and their interpretation is reserved for the discussion (section 4).

Mo (fig. 11)

The histogram for Mo (fig. 10) indicates the data consist of two populations best separated at 3 ppm; as all major rock types have average Mo contents well below 3 ppm (Kuroda and Sandell 1954), the upper population is anomalous and may be related to molybdenite mineralisation.

The most extensive anomaly occurs at Flottorp where three parallel fahlbands form a zone ½-mile in width carrying more or less continuous low-grade mineralisation over a proven strike-length of 6 miles (Bugge, 1963); the best known mineralisation occurs more or less centrally in this zone, over a strike length of 1.7 miles (fig. 44). The area outlined by the 15 ppm Mo contour coincides with the best known mineralisation; the anomaly is marginally foreshortened in a north-south direction (1.3 miles) but is considerably wider (2.5 miles) than the mineralised

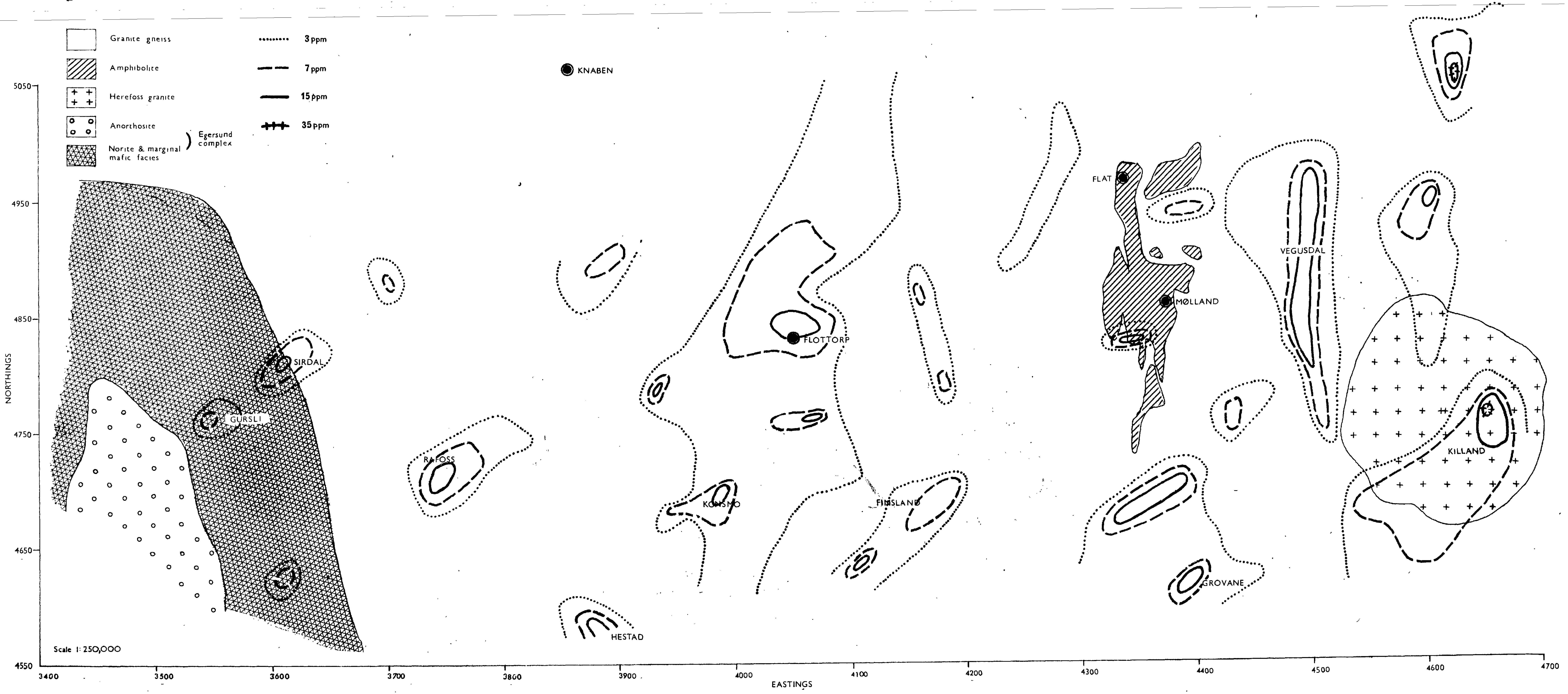


Fig. 11 ROLLING MEAN OF Mo CONTENT, REGIONAL SURVEY DATA

zone, due to drainage dispersion. The 7 ppm Mo contour includes the area known to be underlain by the weakly mineralised fahlband system; it has a greater north-south length (7 miles) than the proven strike length of the fahlbands and is much wider (maximum 6 miles). The extension to the east and west is thought to be largely due to dispersion in the drainage system (see fig. 51) while the greater north-south length may reflect glacial dispersion, or a hitherto unknown strike extension of the fahlbands. The 3 ppm contour outlines a continuous zone which strikes N.N.E. for 26 miles and includes Flottorp and two small highs lying to the south, approximately on strike. This zone may reflect a more or less continuous fahlband, or fahlband zone which locally, as at Flottorp, has enhanced Mo content.

The second most extensive anomaly is the zone of high values occurring in the east of the area (the Vegusdal anomaly). Although narrower, this is similar in other respects to the Flottorp anomaly and, while there are no records of mineralisation or fahlbands from the area, this zone is thought to be of possible economic potential. Subsequent follow-up work (p. 244) confirmed the presence of an anomalous zone with a strike length of at least 9 miles.

In the south-east a broad area of high Mo values (the Killand anomaly) coincides with the outcrop of the post-orogenic Herefoss granite. Minor molybdenite has been found occurring as impregnations in late pegmatite and quartz veins within this granite (Bugge 1963), and it is considered that the anomaly is related to low-grade molybdenite impregnations occurring throughout the granite intrusion. Bugge stresses that in southern Norway molybdenite deposits of economic grade and tonnage occur only as impregnations in the younger intrusions; the dimensions of the Herefoss granite intrusion (an outcrop area of about 100 sq. mls.) and the fact that it demonstrably has a high Mo content indicate this to be an area of considerable economic potential. The results of preliminary follow-up sampling at the Killand anomaly (p. 247) support this view.

Three molybdenite occurrences in the west of the area, Sirdal, Gursli and Hestad, are distinguished by small, roughly circular anomalies with central values greater than 15 ppm. Bugge (1963) describes molybdenite at Gursli as being associated with quartz veins and a dyke of anorthosite, an offshoot presumably of the nearby Egersund complex. The Sirdal occurrence is described as being a series of molybdenite-bearing quartz veins, while at Hestad molybdenite occurs in a group of narrow pegmatite dykes. The regional geochemical results suggest that these are

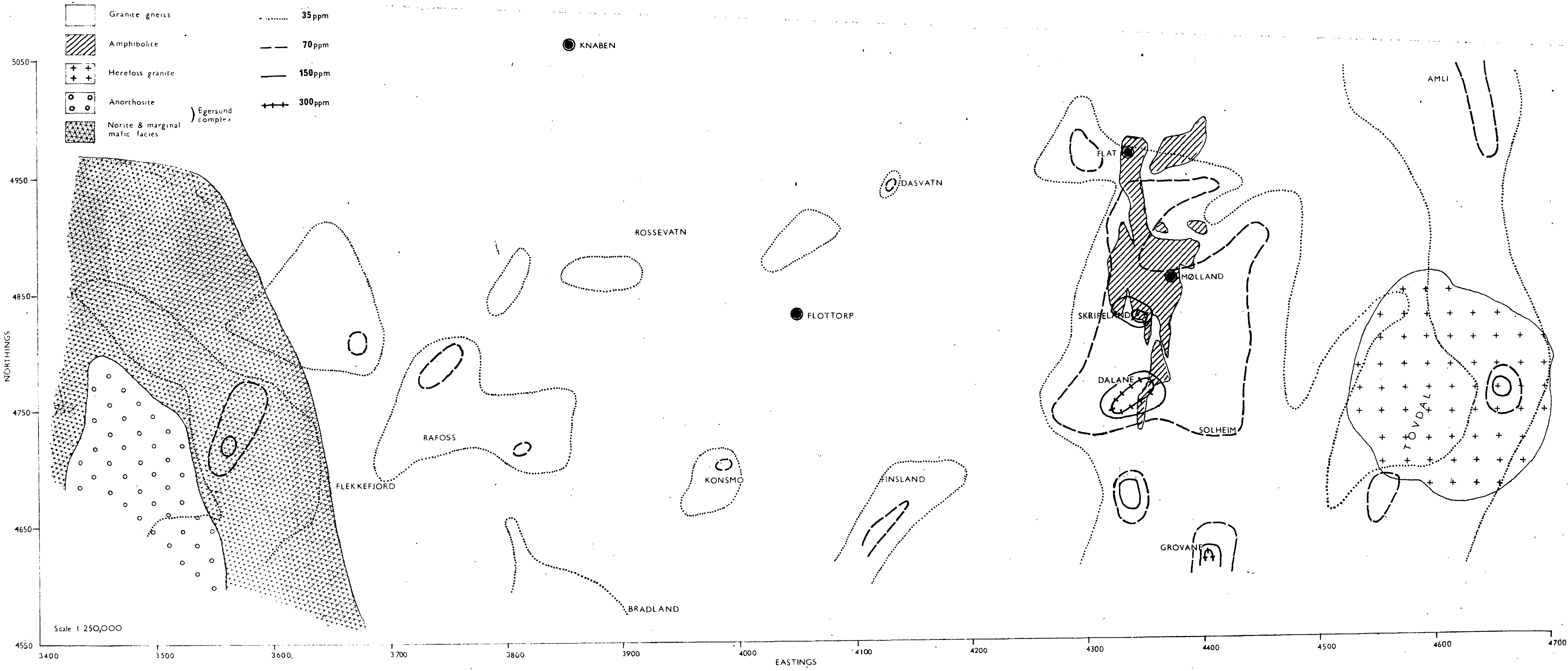


Fig. 12 ROLLING MEAN OF Ni CONTENT, REGIONAL SURVEY DATA

isolated deposits which do not form part of a more extensive fahlband system.

There are in addition, a number of small equidimensional anomalies for which the Mo source is not known; interpretation of these is reserved until a later section.

Ni (fig. 12)

In the Iveland-Evje area the 35 ppm contour outlines a broad zone centred on the amphibolite belt, but extending beyond the amphibolite outcrop to the south and east; the 70 ppm contour is more closely related to the outcrop of the mafic rocks but again shows a marked overlap to the south and east. Within this zone there are two areas with Ni contents in excess of 300 ppm, one apparently centred on the Skripeland prospect and the other (Dalane) occurring in a position marginal to the southernmost offshoot of the amphibolite outcrop; the absence of a similar zone of high Ni contents centred on the Mølland prospect is worthy of particular note.

The mafic marginal facies of the Egersund anorthosite is marked by a semi-circular zone of Ni contents >35 ppm, with values locally >150 ppm Ni. Low Ni contents occur over the outcrop of the anorthosite proper.

In the extreme east of the survey area an elongate zone of Ni contents >35 ppm and locally exceeding 150 ppm is not related to mafic rocks, and in fact occurs partly

Fig. 13 ROLLING MEAN OF Cr CONTENT, REGIONAL SURVEY DATA

over the Herefoss granite. The south and centre of the survey area contains a number of smaller irregular zones of comparable Ni content, which are also unrelated to mafic bedrock. The significance of these is discussed on page 55.

Cr (fig. 13)

The most striking feature of fig. 13 is the marked concentration of high Cr values in the east and extreme west of the survey area compared with the uniformly low values occurring throughout the central area.

In the east, the 35 ppm contour outlines a broad N-S trending zone centred on the Iveland-Evje amphibolite, but continuing south beyond the limit of the mafic belt and extending eastwards to join a second elongate N-S zone. The 70 ppm contour outlines a zone of high values which is coincident with the outcrop of the amphibolite belt but extends S.E to Solheim.

The mafic marginal facies of the Egersund anorthosite is marked in part by an area of moderate Cr contents (i.e. >35 ppm). Low Cr contents occur over the anorthosite proper.

The high Cr values in the extreme east of the survey area (i.e. southwards from Amli) and at Dasvatn are not related to areas of known mafic bedrock; their interpretation is reserved for a later section.

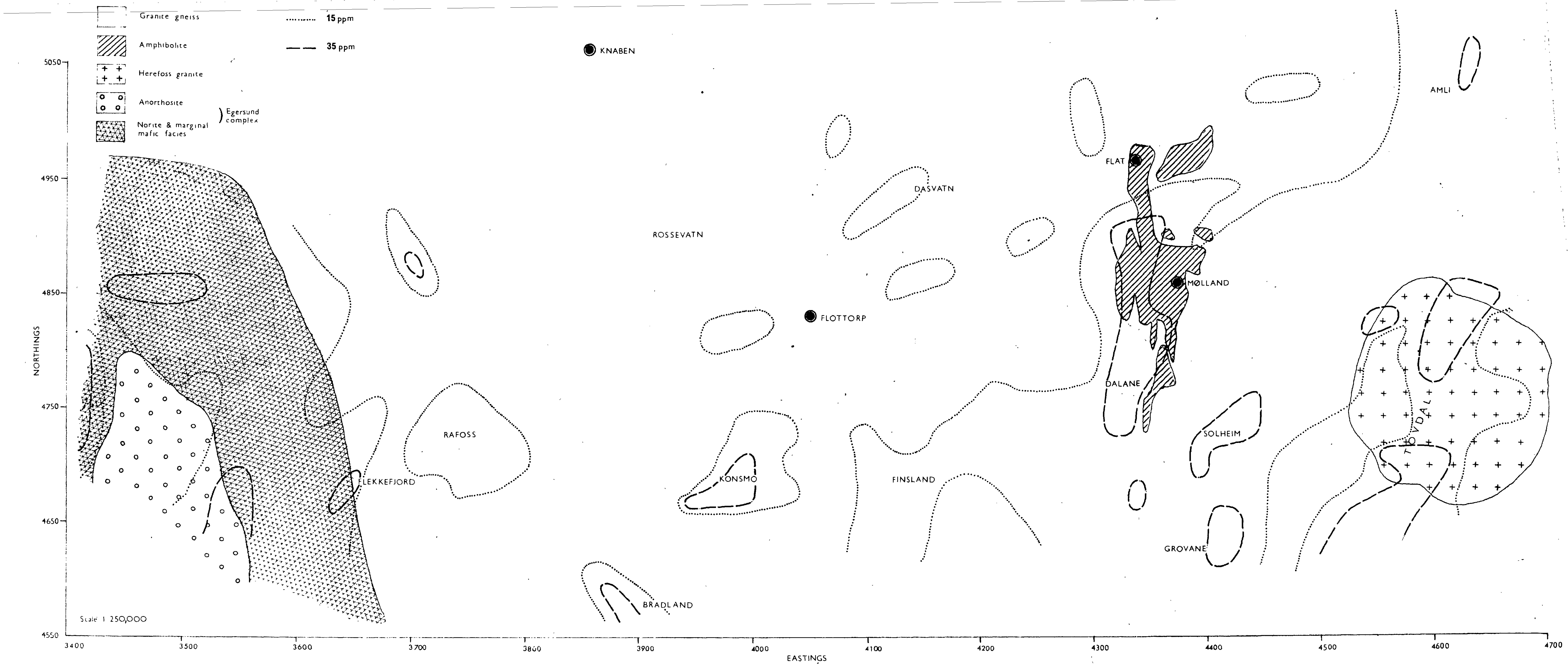


Fig. 14 ROLLING MEAN OF Co CONTENT, REGIONAL SURVEY DATA

Co (fig. 14)

Almost the entire south-east of the survey area has Co contents >15 ppm. Within this broad area the outcrop of the Iveland-Evje complex is marked by values >35 ppm Co, although the high zone extends beyond the mafic outcrop south-westwards to Dalane. Other distinct zones with Co contents >35 ppm occur at Tovdal, Solheim and Grovane and are not related to mafic bedrock.

The mafic marginal rocks of the Egersund complex are distinguished by a broad zone with Co >15 ppm and locally >35 ppm. Low Co values occur over the outcrop of the anorthosite proper.

There are in addition a number of zones in the south and centre of the survey area with Co contents >15 ppm, and locally >35 ppm which are unrelated to bedrock geology.

Cu (fig. 15)

Apart from two small areas with >7 ppm Cu, low Cu contents occur over the Iveland-Evje amphibolite complex. The mafic marginal facies of the Egersund complex is likewise marked only by restricted areas with Cu >7 ppm; these do not form a clear-cut zone. Low Cu values occur over the anorthosite proper.

Minor Cu occurs in association with molybdenite mineralisation at Flottorp; a very restricted zone with 7-15 ppm Cu overlies the best known mineralisation at the

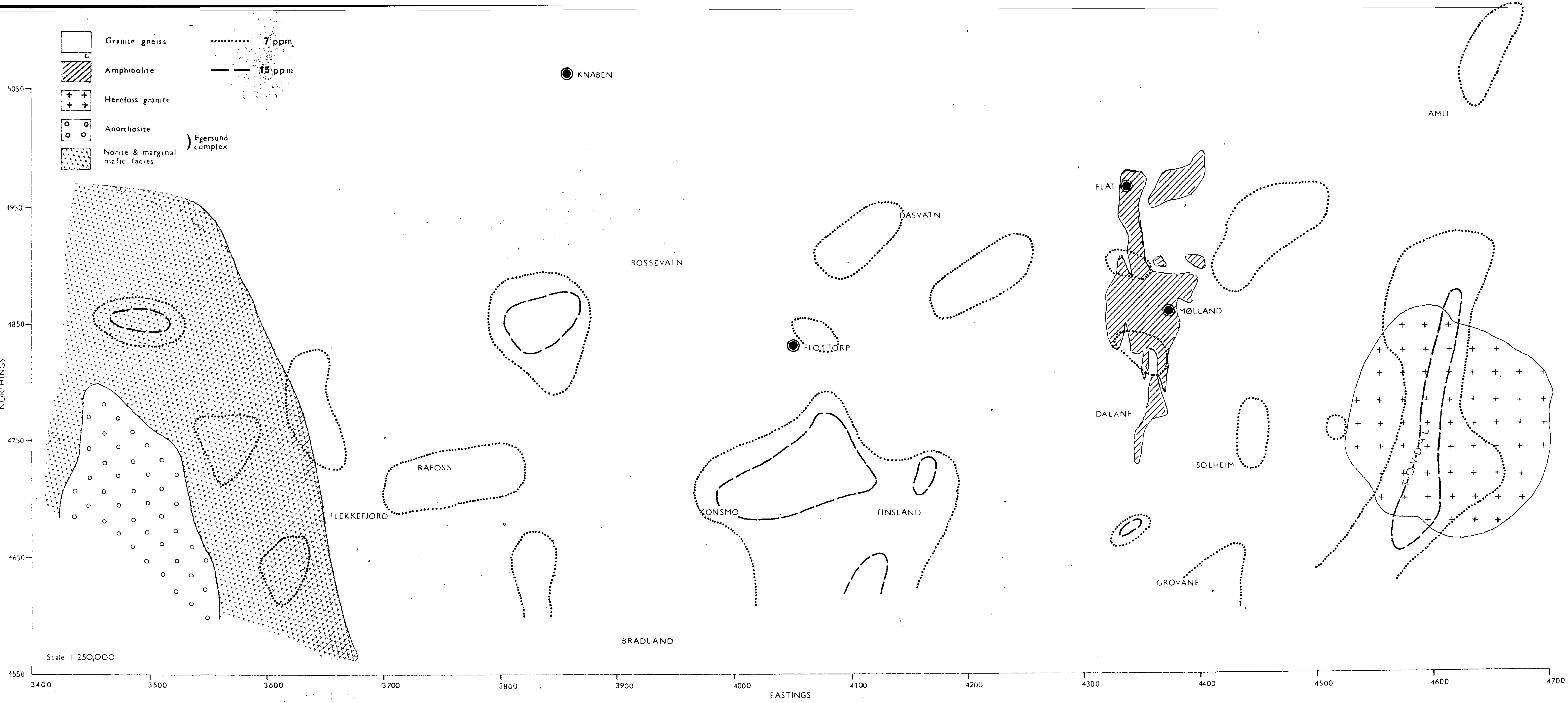


Fig. 15 ROLLING MEAN OF Cu CONTENT, REGIONAL SURVEY DATA

prospect and coincides with the zone of highest Mo values (fig. 11).

Interpretation of the extensive areas of moderate to high Cu content occurring over granite gneiss areas in the south and east is reserved for a later section, (p. 55).

Mn (fig. 16)

The mafic rocks of the Iveland-Evje amphibolite complex are characterised by a broad area with Mn values >700 ppm; the central zone, with values >1500 ppm Mn is however displaced to the south and east of the mafic rock outcrop, which it barely overlaps. Local very high areas (>3000 ppm Mn) at Grovane and Solheim are not related to mafic bedrock.

In the extreme west the mafic marginal facies of the Egersund anorthosite complex is also characterised by moderate (>700 ppm) and locally high (>1500 ppm) Mn contents. High Mn values also occur over the southern portion of the anorthosite outcrop but further north this is marked by generally low Mn contents.

In the east and centre of the survey area there are distinct zones of moderate (>700 ppm) to very high (>3000 ppm) Mn contents which are not related to changes in bedrock type (i.e. Tovdal, Finsland, Konsmo, Bradland, Dasvatn, Rafoss and Rossevatn). The significance of these zones will be discussed in a later section, (p. 55).

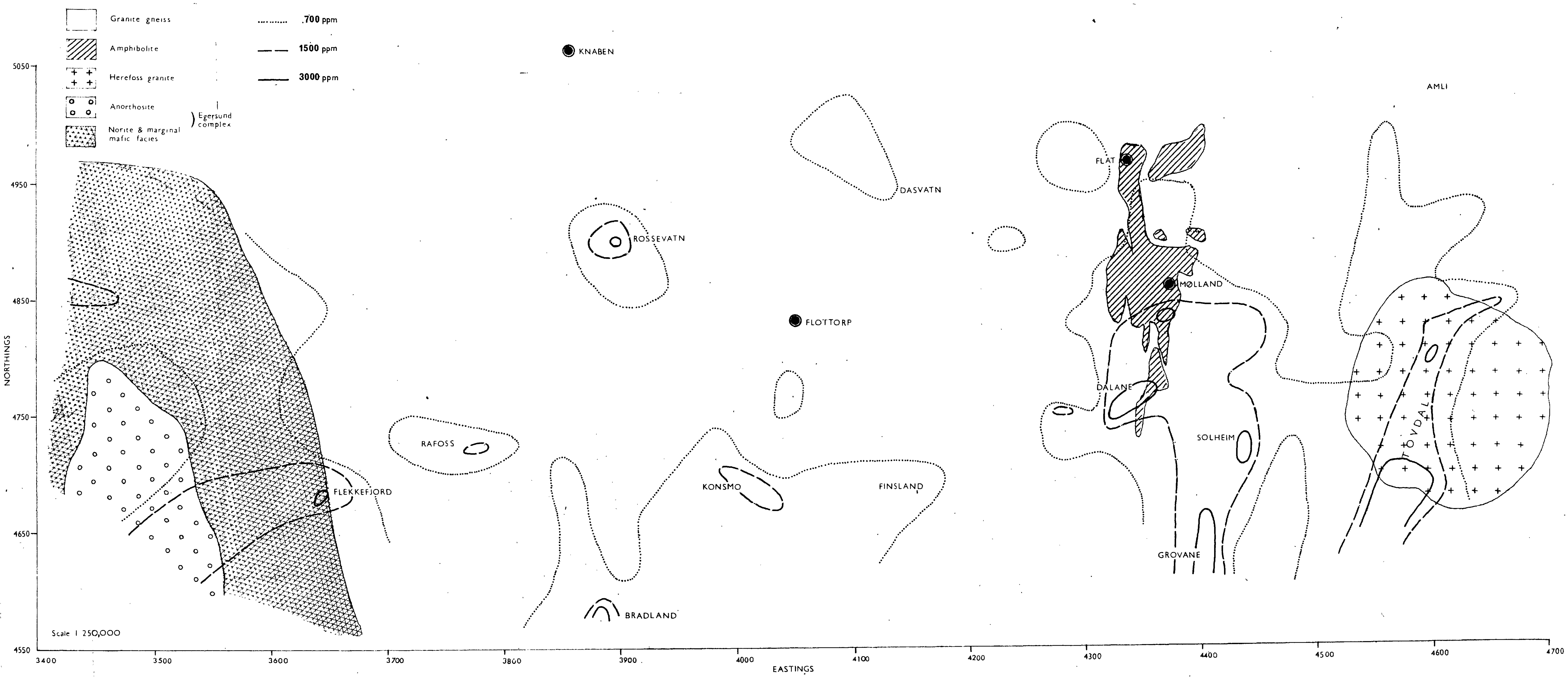


Fig. 16 ROLLING MEAN OF Mn CONTENT, REGIONAL SURVEY DATA

in conjunction with data for other elements.

Zn (fig. 17)

Moderate Zn values (150-300 ppm) occur over only part of the Iveland-Evje amphibolite outcrop. The marginal mafic facies of the Egersund complex is likewise marked in part by high Zn values; similar values (150->300 ppm Zn) occur over the southern part of the anorthosite outcrop, but further north the Zn content of the anorthosite is low.

The most extensive zones of high Zn occur in the south and south-east, over granite and granite gneiss areas; an interpretation of these is given in section 4 (d).

Fe (fig. 18)

The Iveland-Evje amphibolite complex is characterised by moderate Fe contents, the 7% Fe_2O_3 contour coinciding with the main outcrop of mafic rocks. Disconnected areas with >7% Fe_2O_3 and locally >15% Fe_2O_3, occur over the marginal mafic facies of the Egersund anorthosite complex, while low Fe contents occur over the outcrop of the anorthosite proper.

In the east and centre of the survey area there are a number of zones of moderate (>7% Fe_2O_3) and locally high (>15% Fe_2O_3) Fe content which are not related to changes in bedrock type. The significance of these is discussed in section 4 (d).

Fig. 17 ROLLING MEAN OF Zn CONTENT, REGIONAL SURVEY DATA

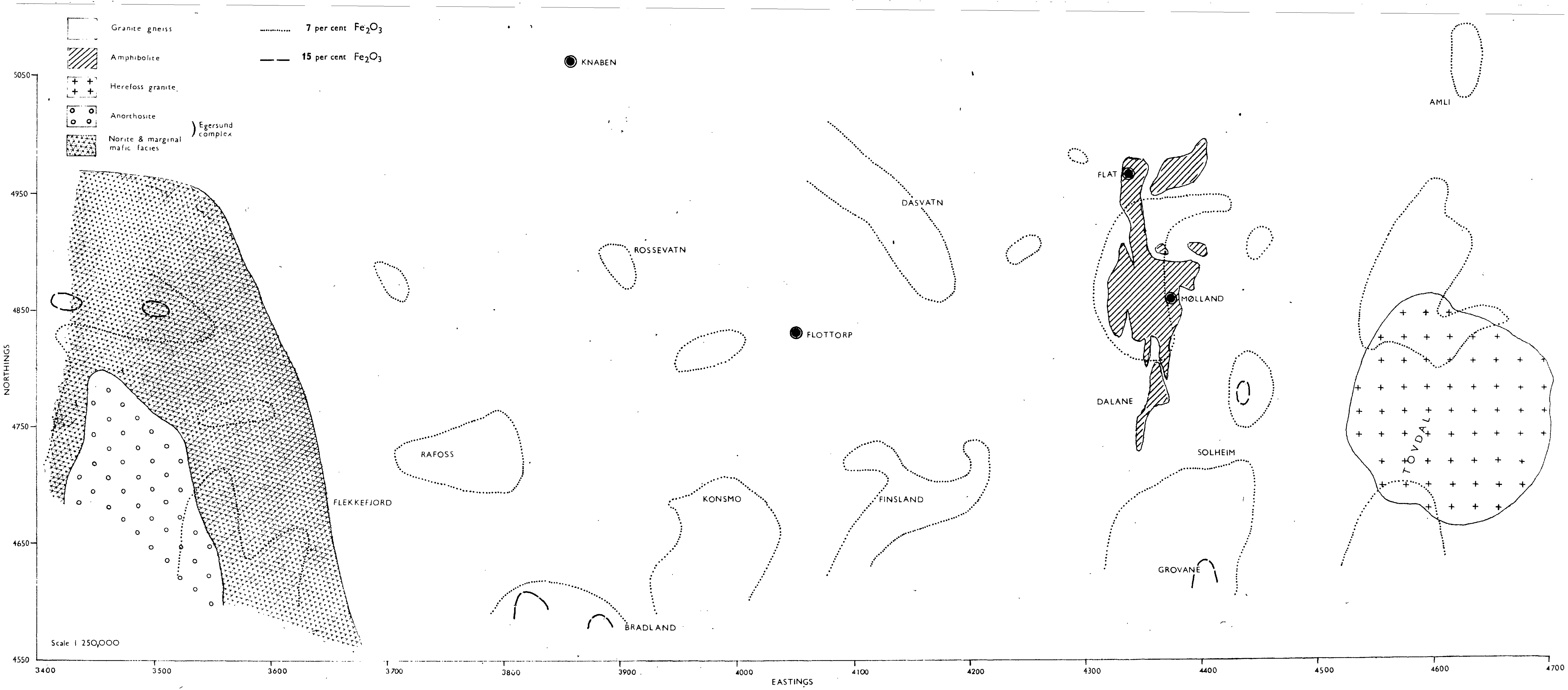


Fig. 18 ROLLING MEAN OF **Fe** CONTENT, REGIONAL SURVEY DATA

4. Discussion.

It is considered that there are four principal factors responsible for the distribution patterns of the various elements and that, although these factors are likely locally to interact, the distribution patterns may be conveniently classified as:

a) Geochemical patterns related to bedrock geology
b) Geochemical patterns related to mineral occurrences
c) Geochemical patterns related to glacial dispersion
d) Geochemical patterns related to secondary environmental factors.

The relative importance of these factors in terms of multi-element distribution patterns is discussed below.

(a) Geochemical patterns related to bedrock geology

For present purposes the major rock units of the area may be considered as either mafic (i.e. the Iveland-Evje amphibolite, and the marginal facies of the Egersund complex), or acidic in composition. Average contents of Co, Cr, Cu, Mn, Mo, Ni, Zn and Fe in acid and basic igneous rocks (Hawkes and Webb 1962) are compared in table 14, from which it is evident that, with the exception of Mo, the content of all elements is considerably higher in basic rocks.

Table 14.

Average contents of Co, Cr, Cu, Mn, Mo, Ni, Zn and Fe (as Fe_2O_3) in acid and basic igneous rocks (data from Hawkes and Webb 1962).

	Acid	Basic
Co	5 ppm	45 ppm
Cr	25 ppm	300 ppm
Cu	30 ppm	140 ppm
Mn	600 ppm	2200 ppm
Mo	<2 ppm	<2 ppm
Ni	8 ppm	160 ppm
Zn	60 ppm	130 ppm
Fe	3.5%	11%

Figs. 11-18 show the Iveland-Evje amphibolite to be distinguished by moderate to high contents of Ni, Cr, Co, Mn, Fe, and to a lesser extent Zn, but that Cu values are generally low.

The marginal facies of the Egersund complex is marked by generally less well-defined zones of moderate to high Ni, Cr, Co, Mn and Fe, and by restricted areas of moderate Cu and Zn contents.

A similar pattern, with moderate to high Ni, Cr, Co and Fe occurs in the N.E. (Amli), in an area mapped by Barth (1960) as mixed gneisses. For each element a north-south trend is apparent, parallel to the regional strike; it is suggested that this geochemical pattern represents a palingenetic bedrock feature and that prior to granitisation the supracrustal sequence in the east of the area consisted predominantly of mafic rocks, possibly a basic volcanic formation. A smaller zone of moderate Cr, Co, Mn, Fe and possibly Ni at Dasvatn may be of similar origin.

Over the granite gneiss, granite and anorthosite outcrops, the content of all metals except Cr varies widely. There are areas with low contents of all metals, but there are also extensive areas of high Mn, Fe, Ni, Co, Cu and Zn which bear no relation to bedrock geology.

(b) Geochemical patterns related to mineral occurrences

(i) Mo:

A well-defined Mo anomaly (>7 ppm Mo) overlies the general position of the mineralised zones at Flottorp; this anomaly has a greater N-S length (7 miles) than the proven strike length of the mineralised zones (6 miles), and is much wider (maximum 6 miles) than the combined width of the mineralised zones ($\frac{1}{2}$ mile), the latter feature due to dispersion in the drainage system. Smaller anomalies were found associated with other Mo prospects in the west of the area (Sirdal, Gursli and Hestad) and an extensive area of high Mo values occurs over the Herefoss granite, which is known to have local molybdenite impregnations.

A striking feature of the distribution of Mo is that the anomalous areas outlined are of two distinct forms, being either markedly elongate (e.g. Flottorp and Vegusdal) or more or less equidimensional (e.g. Sirdal, Gursli, Hestad and Killand). As already mentioned (p. 35), molybdenite in southern Norway is found either in fahlbands of considerable length and conformable with the regional strike, or as impregnations in younger intrusions, principally of granite, pegmatite, aplite or vein quartz, and the two anomaly forms may therefore be related respectively to mineralisation of the fahlband and impregnation types. Anomalies for which the source of the Mo is known support this interpretation.

The extensive weakly mineralised fahlbands provide excellent primary targets for reconnaissance surveys and as the present results show, reconnaissance surveys may also detect distinct Mo anomalies associated with individual molybdenite occurrences.

(ii) <u>Ni</u>:

Samples were not collected down-drainage from Flåt mine, in order to avoid spurious results arising from contamination. It is noteworthy that of the other Ni occurrences in the amphibolite belt, Mølland is not marked by higher than normal contents of Ni in the stream sediment, but values >300 ppm occur near the smaller

Skripeland prospect. It should be stressed however that the regional survey has revealed similar Ni contents in areas where there is no known mineralisation (Dalane) and over granite gneiss bedrock (Grovane).

(iii) Cu:

Cu frequently accompanies Mo mineralisation and minor chalcopyrite and malachite were observed at Flottorp. A small zone of moderate Cu values (7-15 ppm Cu) occurs over the best known mineralisation at the prospect but is insignificant in comparison to the extensive zones of higher Cu content elsewhere in the survey area. Chalcopyrite also accompanies nickeliferous pyrrhotite at Mølland but, as was the case for Ni, there is no Cu anomaly related to this prospect.

It is clear, therefore, that in the present regional survey only Mo has given rise to distinct geochemical patterns related to known mineralisation. It should be stressed, however, that apart from Flåt mine, the Ni occurrences in the Iveland-Evje area are small and that Cu is only a minor component of the Flottorp mineralisation; the lack of distinct Ni and Cu dispersion patterns may therefore reflect the low grade and restricted size of the mineralisation.

(c) Geochemical patterns related to glacial dispersion

Available data indicate that the direction of ice-movement varied from dominantly S.S.E. in the east of the area to S.S.W. in the west (fig. 8). As the direction of ice-movement diverges at only a shallow angle from the regional north-south strike it is difficult to obtain unambiguous evidence of glacial dispersion; the present data suggest that glacial dispersion may have given rise to geochemical patterns at three localities, although an equally acceptable alternative origin may be proposed in each case. Brief descriptions of the geochemical patterns which it is thought may reflect glacial dispersion are given below:

(i) The zones of moderate to high Ni, Cr, Co, Mn and Fe associated with the Iveland-Evje amphibolite complex show a general south-easterly displacement, terminating in the case of Ni, Cr, Co and Mn in zones of moderate values at Solheim, in the granite gneiss area. Interpreted in terms of glacial dispersion this indicates a displacement of the order of 6 miles from the amphibolite outcrop. It should be stressed however that the geology of the Solheim area is incompletely known and it is possible that a bedrock feature similar to that proposed for Amli may provide a local source of Ni, Cr, Co and Mn.

(ii) The Killand Mo anomaly (fig. 11), associated with the Herefoss granite, overlies only the south-eastern half of the granite outcrop. This possibly reflects glacial dispersion to the south-east, but may equally well be due to a primary feature of the distribution of Mo within the granite intrusion.

(iii) The zone of moderate Mo values extending southwards from Flottorp is thought to be due primarily to a continuation of the north-south trending Flottorp fahlband zone; it is possible, however, that glacial dispersion from the molybdenite mineralisation at Flottorp is a contributory factor.

It is concluded that in the present regional survey there is no unambiguous evidence for the occurrence of glacial dispersion patterns on a scale sufficently coarse to be detected by wide-interval stream sediment sampling. It should be emphasised, however, that in this area the dominant direction of ice-movement diverges at only a shallow angle from the regional strike; in interpreting regional survey data from other areas, where there may be a greater divergence between ice-movement and regional strike, the possibility of geochemical patterns arising from glacial dispersion should be borne in mind.

(d) Geochemical patterns related to secondary environment

In the course of regional stream sediment surveys in Britain, Horsnail (1968) found extensive areas with high contents of Mn, Co, Fe, Ni and Zn which were not related to bedrock geology, but occurred in poorly drained areas over a range of bedrock types; similar features have been reported from Canada (Boyle 1966, Canney 1966). In a detailed investigation into the cause of such patterns, carried out in N. Wales, Horsnail (1968) obeserved that, compared to bedrock, waterlogged soils had low contents of Mn, Co, Fe, Ni and Zn, but that the content of these metals in the stream sediment was greatly enhanced. The area studied by Horsnail has a cover of glacial drift and he concluded that under the low Eh-pH conditions of waterlogged soils Mn, Co, Fe, Ni and Zn are leached from fine-grained rock fragments and removed in groundwater solution. The enhanced metal contents in the stream sediment were regarded as due to precipitation of hydrous oxides of Fe and Mn where metal-enriched groundwaters came into contact with aerated surface water. Horsnail considered it unlikely that the concentration of Co, Ni and Zn in groundwater solution would be sufficient for the direct precipitation of oxides or hydroxides of these metals which were thought to be concentrated largely through adsorption by freshly precipitated hydrous oxides of Mn and Fe.

Horsnail found that greatly enhanced contents of Mn in the stream sediment were frequently accompanied by only moderate Fe contents. He regarded this separation of Fe and Mn as due to the lower solubility of the former under conditions of increasing Eh, which he thought commonly leads to the precipitation of hydrous Fe oxides in bank soils adjacent to the stream bed, where metal-rich groundwater and aerated surface waters intermix. Precipitation of the relatively more soluble Mn was thought to be confined to the high Eh environment of the stream bed. Bacterial precipitation of hydrous Fe oxides may locally give rise to greatly enhanced stream sediment Fe contents and a considerable range in the relative concentration of Fe and Mn is therefore to be expected in stream sediments affected by secondary environmental factors. As certain of the trace metals are preferentially adsorbed by hydrous Fe oxides (i.e. Mo) and others by hydrous Mn oxides (i.e. Co, Zn, Ni) this may lead to differences in multi-element geochemical patterns related to essentially similar features of the secondary environment.

The rolling mean maps for Mn and Fe (figs. 16 & 18) show zones of high values over granite gneiss and granite bedrock in the south of the survey area (i.e. Tovdal, Grovane, Finsland, Konsmo, Bradland and Rafoss) which, in view of Horsnail's work, are interpreted as due to secondary enhancement. The distribution of high values is similar for Mn and Fe, although more restricted for the latter.

Zn, Co, Cu and Ni show high zones broadly coincident with the Mn and Fe highs at each locality, and these are likewise interpreted as due to secondary enhancement. The Mo rolling mean map (fig. 11) reveals Mo anomalies coinciding with Fe highs at Rafoss, Bradland, Konsmo, Finsland, Grovane and also north of Grovane and north of Tovdal. These Mo anomalies may be related to mineralisation (as in the case of the Hestad molybdenite showing which occurs within the area of high Fe contents at Bradland) but the association with high Fe values suggests that secondary enhancement is an important factor.

Comparison of the degree of enrichment shown by the various metals (table 15) indicates that this is of the same order for Fe, Mn, Co, Zn and Mo but is considerably higher for Ni and lower for Cu. The mean Cu content of stream sediments collected during the regional survey (6 ppm, table 13) is much lower than the average value for acid igneous rocks however, and the measure of enhancement given by comparing the maximum rolling mean contour for Cu with the mean value (i.e. enhancement = x6) is similar to that for other metals.

Table 15.

Enrichment of Fe, Mn, Co, Zn, Ni, Cu and Mo in areas of secondary enhancement, estimated by comparing the maximum rolling mean contour with the average content of acid igneous rocks.

	Maximum contour	Acid igneous rocks	Enhancement
Fe	15%	3.5%	x 4
Mn	3000	600	x 5
Co	35	5	x 7
Zn	300	60	x 5
Ni	300	8	x 38
Cu	35	30	x 1.2
Mo	15	<2	x 8

As already mentioned, Horsnail has related secondary enhancement of Mn, Fe, Co, Zn and Ni in the stream sediment to areas of waterlogged soils. Soil cover over most of the survey area is thin, depths in excess of 28 inches being largely confined to the main glacial valleys (p. 37) where the thickest overburden generally consists of outwash deposits from the Ra end moraine. Extensive areas of waterlogged soils are likely, therefore, to be restricted to the main glacial valleys particularly to the south of the Ra moraine, and it is only in these that favourable conditions for secondary enhancement are likely to occur. This relationship is well domonstrated in the extreme east of the area, where a linear zone with high Mn, Co, Zn and Cu contents coincides with a major glacial valley (Tovdal).

5. Conclusions - Applications to mineral exploration

From a mineral exploration viewpoint the purpose of a regional survey is to provide rapid reconnaissance cover over large blocks of country so that areas of low economic potential may be eliminated and favourable targets selected for subsequent more detailed exploration. The nature of the target areas will depend on the type of mineralisation sought; thus, in the present survey, zones of weak mineralisation act as primary targets in the search for molybdenite deposits and areas of basic and ultrabasic rock are favourable initial targets for nickel sulphide mineralisation.

The results of the regional survey indicate that in southern Norway reconnaissance by means of stream sediment samples collected at a mean density of 1 sample per 5 sq. mls., from streams with catchment areas of 1-5 sq. mls., adequately outlines the known areas of mafic bedrock and the zone of weak Mo mineralisation in the Flottorp area. It is also evident that distinct Mo anomalies are revealed related to individual molybdenite deposits. The lack of similar anomalies in the case of Ni or Cu may be due to the low-grade and restricted size of the mineralisation, as samples were deliberately not collected down-drainage from Flåt mine, the only Ni-Cu deposit of economic grade and size in the area.

Secondary processes may, in areas with extensive waterlogged soils, lead to enhanced contents of Mn, Fe, Co, Ni, Zn, Cu and Mo in the stream sediments. These may be distinguished from the broadly similar patterns related to mafic bedrock features (i.e. moderate to high Ni, Cr, Co, Mn and Fe) by the association of moderate to high Cr values with the latter. Unfortunately, no such criterion is available for distinguishing between Mo anomalies related to secondary enhancement and molybdenite mineralisation; it is suggested that in follow-up investigations priority be given to Mo anomalies unaccompanied by high Fe contents, but that follow-up sampling is justified on all Mo anomalies.

No unambiguous evidence of the effects of glacial dispersion was found during the present survey. Where glacial dispersion trains do occur however, it is thought that these will increase the likelihood of major bedrock features being detected by wide interval reconnaissance surveys, although minor features may be obscured.

It is concluded that rapid reconnaissance, by means of widely spaced stream sediment samples, is a valuable technique in the initial stages of mineral exploration programmes for Mo in glaciated terrain. In exploration for Ni, however, areas of mafic and ultrabasic bedrock are perhaps more easily recognised from aeromagnetic maps; as these are generally readily available it is thought that reconnaissance stream sediment surveys will in practice have little application to mineral exploration for Ni.

THE NICKEL ORIENTATION SURVEY

The purpose of the orientation survey was to gain a thorough understanding of the factors controlling the dispersion of Ni and associated metals in the primary and secondary environments and to establish optimum techniques for use in exploration for Ni mineralisation in southern Norway. The survey was conducted principally at the Mølland Ni prospect but was extended where necessary to other areas in the Iveland-Evje amphibolite complex.

The orientation survey may be conveniently divided into studies of the distribution of Ni and associated ore metals in three distinct media, bedrock, overburden and stream sediments; the results of these investigations are presented and discussed in Chapters 3, 4 and 5 respectively.

CHAPTER III. BEDROCK INVESTIGATIONS

1. Introduction

The objectives of the bedrock investigation were:

a) to determine the distribution of the ore and associated metals in the bedrock of the Mølland orientation locality in order to facilitate the interpretation of the secondary dispersion data;

b) to determine the applicability of regional bedrock sampling to the search for Ni mineralisation in this area;

c) to determine, if possible, the factors controlling the localisation of the Mølland mineralisation in order to establish guides for subsequent exploration in the Iveland-Evje area;

d) to throw some light on the question of the origin of the amphibolite complex.

A brief account of the geology and mineralisation of the Iveland-Evje area is given in an opening section, and is followed by a more detailed description of the Mølland orientation locality. The analytical data are then briefly presented and used to establish the distribution of Ni, Cu and Hg in the bedrock of the Mølland prospect. This is followed by the principal section of the bedrock investigation, in which data from whole rock and mineral analyses are used to establish the relationship between the principal rock types at Mølland and to support the suggestion that the sulphide mineralisation is syngenetic and related to a distinct younger intrusion. In succeeding sections the economic potential of the Iveland-Evje area is reviewed in the light of this conclusion and the rock data are then used to assess the feasability of bedrock sampling as a reconnaissance mineral exploration technique in this area.

2. Geology and Mineralisation of the Iveland-Evje area

(a) Geology

The Iveland-Evje amphibolite complex is an elongate body of mafic rocks approximately 20 miles in length and 1 - 6 miles wide, completely surrounded by gneissose granites. The complex is of Precambrian age and has been subjected to high-grade regional metamorphism so that boundaries between rock units are gradational and ill-defined. The area has been mapped by Barth (1947) and more recently by the geologists of A/S Sulfidmalm (Wiik 1968, Nixon 1968, and Haldemann *pers. comm.*); the following description is based on their work.

Three principal rock types have been recognised within the amphibolite complex:

(i) *Amphibolite* is the dominant rock type; it is typically schistose or gneissic in appearance although massive amphibolites are occasionally encountered.

Plagioclase and hornblende are invariably present, and frequently biotite and quartz. Barth (1947) gives a table showing the mafic content of the amphibolites to range from 25% to 60%, with up to 20% occurring as biotite. Towards the margins of the complex the amphibolites show signs of granitisation and mafic minerals may be locally subordinate to plagioclase and quartz; the contact with the enclosing granite gneisses is gradational and generally marked by a broad zone of augen gneiss.

(ii) Massive gabbroic rocks are found as small rounded bodies which appear to be particularly concentrated in a zone at the geographic centre of the amphibolite belt. Unaltered samples reveal these rocks to be norite or 2-pyroxene gabbro. The relation between the gabbroic bodies and the enclosing amphibolites is the centre of a controversy over the origin of the amphibolite belt; this is variously regarded as a single basic intrusion which has been almost completely recrystallised with only minor massive relics (Barth 1947), or the result of several periods of basic igneous activity (Wiik 1968). Contact relations are obscure but fresh gabbroic rock can be seen to pass gradationally, both marginally and within the gabbroic body, into a hornblende-rich rock indistinguishable in isolated outcrops from amphibolite. Small bodies of ultrabasic rock are also found in this central area; pyroxenite and peridotite have been reported (Barth 1947, Buchan 1968).

(iii) Diorite is concentrated in the marginal area to the north-east of the amphibolite belt and is a massive rock consisting of plagioclase (commonly as phenocrysts) and hornblende, with some quartz. The Ni ore at Flåt occurs within a diorite body of this type, referred to specifically as ore diorite.

In addition to the major rock units, small pegmatite bodies are found throughout the amphibolite belt.

(b) Ni Mineralisation

Nickeliferous sulphides have been found in all three major rock types of the amphibolite belt. The occurrences of principal economic interest (i.e. Flåt mine and the prospects at Mølland and Skripeland, fig. 19) are, however, associated with the more massive gabbroic and dioritic rocks, sulphide occurrences in the amphibolites being of very minor importance. Bjørlykke (1947) describes the geology of the Flåt mine, and Barth (1947) gives additional information and also brief descriptions of the other prospects; the following is largely based on their work:

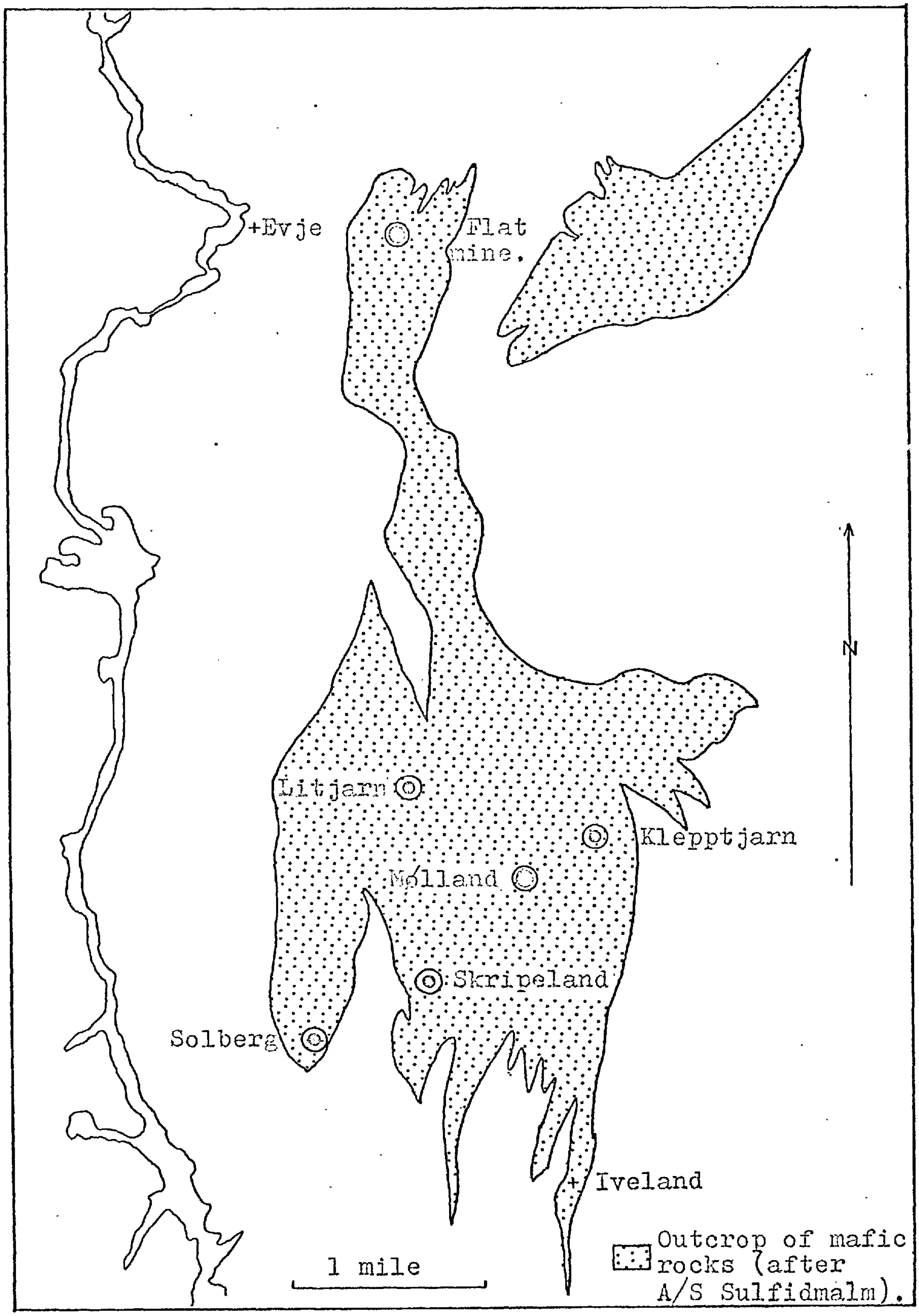


Fig. 19 Map of the Iveland-Evje area showing location of bedrock sampling sites.

(i) Flåt mine. The Ni orebody at Flåt was discovered in 1870 and worked almost continuously from 1872 to 1945, producing a total of 3,000,000 tons of raw ore with an average grade of 0.72% Ni and 0.48% Cu. According to Bjørlykke mining ceased in 1945 because operations were no longer economic and an extensive diamond drilling programme carried out during the previous 15 years had failed to disclose further economic mineralisation. Production statistics reveal a steady decrease in the annual average grade of the ore, reaching a final low of 0.55% Ni and 0.37% Cu.

Mineralisation is confined to a massive quartz diorite (the "ore diorite"); within the orebody there are irregular variations from practically massive sulphides to weakly impregnated diorite, although the average ore mined consisted of 12 - 13% sulphides, 8% magnetite and 4% apatite. According to Bjørlykke (1947) the sulphides and their approximate proportions are pyrrhotite (71%), pentlandite (14%), chalcopyrite (12%) and pyrite (3%), with millerite and violarite locally present as alteration products of pentlandite.

Bjørlykke concluded that the Flåt ore was of magmatic origin and had formed by segregation from a sulphide-enriched diorite magma intruded into the barren amphibolite. Later work (Haldemann pers. comm.)

has raised the possibility that the deposit is of epigenetic origin and that the petrographic features of the ore diorite may be due to hydrothermal alteration.

(ii) Mølland Prospect. Minor nickeliferous sulphides occur at Mølland as disseminations in massive norite. Bjørlykke (1947) describes an exploration programme carried out in 1937 when a 60 ft. exploration shaft with a cross-cut 150 ft. in length and two shallower pits were sunk on what appears to be a continuous zone of sulphide impregnations striking N 20° E; a considerable amount of drilling and surface sampling was also carried out before the prospect was abandoned. The assay results are classified as 'rich ore' containing 1-2% Ni, 'usual ore' averaging 0.78% Ni and 0.24% Cu and 'poor ore' averaging 0.30% Ni and 0.07% Cu; there are no indications of tonnages.

The Mølland prospect is the most favourable of the mineral occurrences for an orientation survey since the early prospecting work serves to outline the extent of the mineralisation, but contamination of the secondary environment by exploration activity is thought to be minimal.

(iii) Other prospects. A small shaft at Birkeland prospect shows pyrrhotite with minor pyrite and chalcopyrite occurring in a schistose hornblendite which, according to Barth, contains 2% Ni. Minor nickeliferous sulphides are also found at Skripeland, occurring in a massive meta-gabbro, but no assay data are available. There are, in addition, a number of minor sulphide occurrences in the amphibolite belt where only limited surface sampling has been carried out.

(c) Geology of the Mølland Prospect

The following account is compiled from notes made during the rock sampling programme and from a 1:5000 geological map made available by A/S Sulfidmalm. Field descriptions were supplemented by a brief thin-section examination of selected rock samples. Three principal rock types are recognised (fig. 20), norite, amphibolite and metagabbro, and are described in turn below:

(i) Norite This is a dark-grey, medium to coarse-grained rock, which in thin section proved to consist of strongly pleochroic hypersthene, plagioclase, dark green hornblende and pale green augite. A number of the sections examined were strictly hypersthenite and Vogt (1923) described the rock unit as hypersthenite-norite; for convenience it will be referred to simply as norite. In general the hypersthene is fresh and shows only limited replacement by pale green hornblende along grain boundaries and cleavage cracks. Dark green hornblende, an important constituent of the majority of

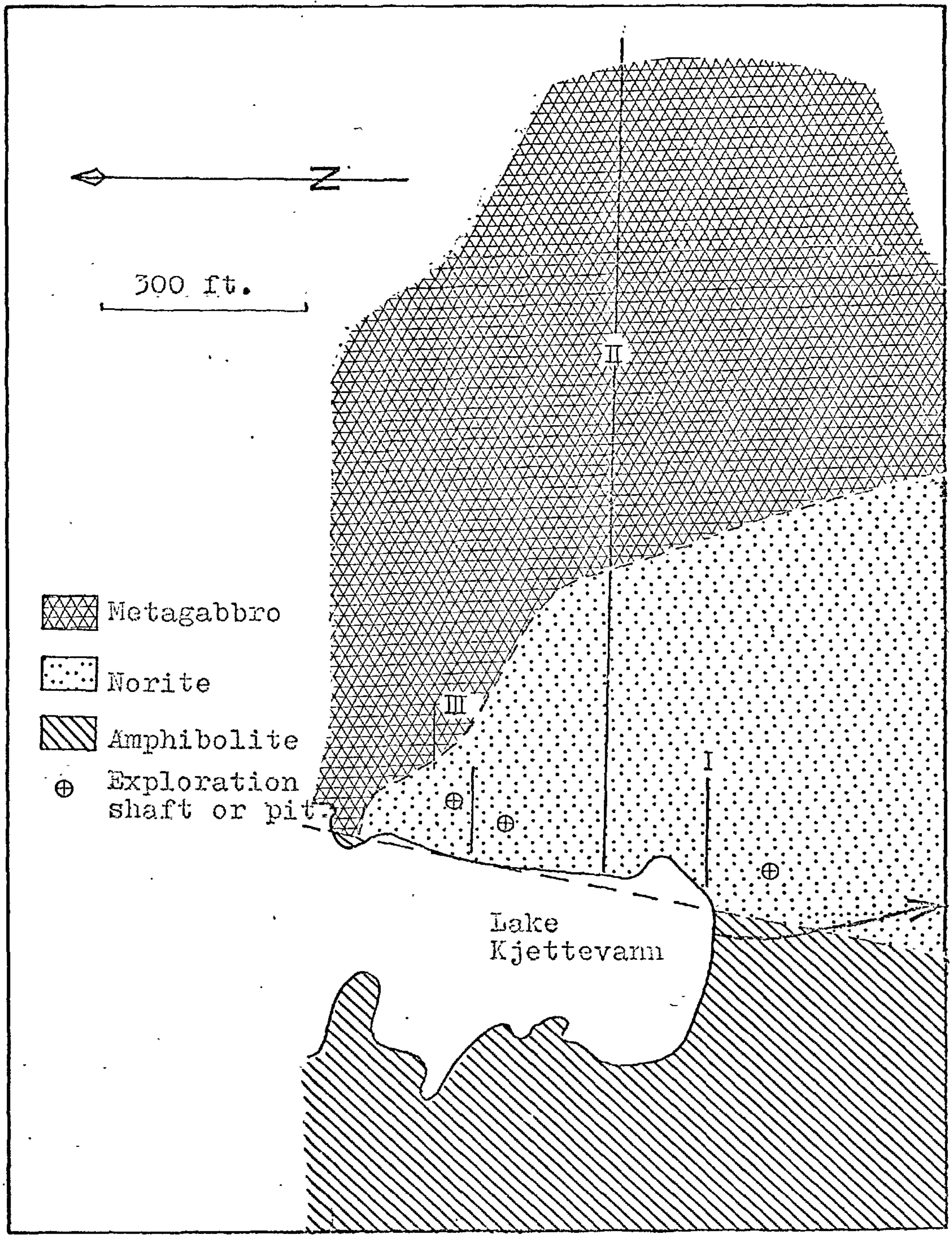


Fig. 20 Geological map of Mølland prospect, showing location of bedrock traverses.

the norite sections, occurs predominantly as anhedral grains which occasionally contain relics of pale green augite. Plagioclase is clear and unaltered.

(ii) Amphibolite The country rocks to the west of the norite body are typical schistose amphibolites which strike N-S and dip steeply to the east. Thin sections reveal euhedral dark-green hornblende crystals together with optically discontinuous poikiloblastic aggregates of green hornblende and plagioclase, crowded with inclusions. The contact between the norite and amphibolite was seen in a single exposure, where it was sharp and parallel to the schistosity of the amphibolite.

(iii) Metagabbro The rock-unit described as metagabbro occurs to the east of the norite body; it generally shows a weakly gneissic appearance although relics of igneous texture may locally be discerned. In hand specimen the metagabbros are distinctive and consist of pale pink plagioclase and aggregates of dark green acicular hornblende in varying proportions. Thin sections show that hornblende occurs either as irregular platy-aggregates of small crystals showing no preferred orientation, or as optically continuous anhedral grains crowded with rounded inclusions of plagioclase. The contact between norite and metagabbro was not seen and such field evidence as there is for their relationship is ambiguous. Local schistose patches similar in appearance to the metagabbro occur within the norite outcrop and may represent zenoliths, while massive, hypersthene-bearing rocks found in the metagabbro area may be dyke-like offshoots of the norite body. It may equally well be argued, however, that the 'metagabbro' is in fact metamorphosed norite and that these features are caused by localised variations in the intensity of alteration.

Nickeliferous sulphides are confined to the norite body, although minor barren pyrrhotite and pyrite are found in both metagabbro and amphibolite. The sulphides form more or less rounded blebs impregnating both norite proper and hypersthenite and occur principally in a roughly N - S trending zone near the western margin of the norite body. Bjørlykke lists the sulphide minerals as pyrrhotite, pentlandite, chalcopyrite and pyrite with much of the pentlandite altered to violarite. Thin sections reveal irregular sulphide blebs interstitial to the silicate minerals and also narrow sulphide stringers traversing the silicates and, particularly in the case of hypersthene, following cleavage cracks.

3. Results

Whole rock samples were analysed for Fe, Mg, Ni, Cu, Cr and Hg. The results, grouped according to the three major rock units, are tabulated in Appendix II, tables 1, 2 and 3.

Monomineralic fractions of plagioclase, hornblende and, where applicable, hypersthene, were prepared from selected rock samples; mafic minerals were analysed for Fe, Mg, Ca, Mn, Cr, Ni, Co, Cu and Zn, and plagioclase analysed for Ca and Sr. The plagioclase fraction was also analysed for the ore metals but spurious results were obtained due to contamination with non-magnetic sulphides (pentlandite, millerite or violarite). The strongly magnetic fraction of the rock samples (i.e. magnetite, pyrrhotite plus a variable amount of silicates) was analysed for Ni only. Mineral separate data are given in Appendix II, tables 4 and 5; sample locations are shown in tables 1, 2 and 3 and fig. 19.

4. The distribution of the ore and associated metals at Mølland.

The sulphides at Mølland appeared in the field to be confined to a N-S trending zone near the western margin of the norite outcrop. Whole rock data for Ni, Cu and Hg for primary Traverses I, II and III are given in fig. 21; rock type and the estimated sulphide content

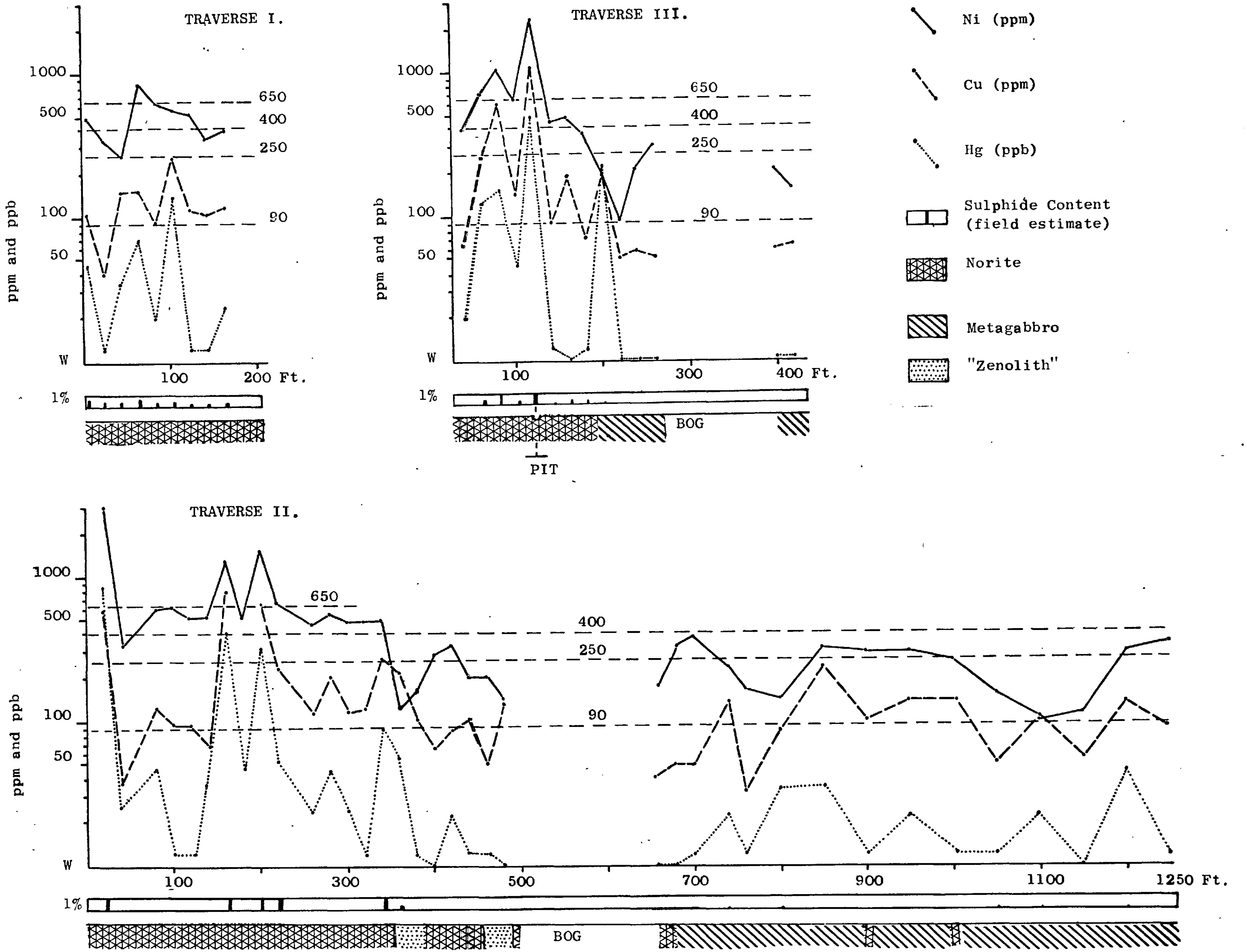


Fig. 21 Distribution of Ni, Cu and Hg in bedrock traverses, Mølland.

are also shown.

The mean Ni content of the norite (455 ppm excluding mineralised samples) is twice that of the metagabbro (221 ppm) and four times that of the amphibolite (111 ppm, table 16a); the Kolmogorov-Smirnov test shows a highly significant difference in distribution in both cases (table 16b). If threshold is taken as the upper limit of variation in unmineralised samples (650 ppm) a narrow anomalous zone results, coinciding as is to be expected, with the mineralised zone as mapped on sulphide content. When, on the other hand, threshold is taken as the upper limit of variation in metagabbro and amphibolite samples only (400 ppm), almost all the norite samples are anomalous, and the result is a broad anomaly more or less symmetrically distributed about the mineralised zones. Anomaly widths and peak to threshold contrasts for Traverses I, II and III are summarised in table 17 for threshold levels of 400 ppm and 650 ppm.

The mean Cu content of the norite (117 ppm, including mineralised samples) shows an almost two-fold increase on that of metagabbro and amphibolite (74 ppm and 63 ppm, table 16a). The upper limit of variation in metagabbro and amphibolite samples is 230 ppm and that of unmineralised norite samples 270 ppm. Threshold was accordingly taken as 270 ppm and the

Table 16 (a) Geometric mean values for whole rock analyses (ppm unless otherwise stated).

	Fe%	Mg%	Cr	Ni *	Cu	$\frac{Ni}{Mg}$ *	$\frac{Sr}{Ca}$ +
Norite	6.1	9.1	1130	455	117	45.8	14.0
Amphibolite	6.6	4.2	126	111	63	28.6	11.7
Metagabbro	4.5	6.1	445	221	74	36.7	25.3

Table 16 (b) Values of the Kolmogorov-Smirnov statistic for testing the significances of differences in element distributions between rock types.

	Fe	Mg	Cr	Ni	Cu	$\frac{Ni}{Mg}$	$\frac{Sr}{Ca}$
(i) Norite : Amphibolite							
K-S Statistic	.237	.835	.867	1.00	.496	.847	.444
Significance	N	HS	HS	HS	HS	HS	N
(ii) Norite : Metagabbro							
K-S Statistic	.466	.541	.643	.692	.489	.485	-
Significance	HS	HS	HS	HS	HS	HS	-
(iii) Metagabbro : Amphibolite							
K-S Statistic	.642	.680	.686	.642	.295	.436	-
Significance	HS	HS	HS	HS	N	S	-

* Excluding mineralised samples (Ni 800 ppm)
+ Sr/Ca on plagioclase

HS = highly significant (99%)
S = significant (95%)
N = not significant.

anomalies thus outlined were found to be coincident with the mineralised zone.

The mean Hg content of unmineralised samples is the same for all rock types (30 ppb, table 16a); threshold is taken as 90 ppb, the upper limit of variation in non-mineralised samples. The Hg anomalies so defined are again closely related to the mineralised zone, but Hg appears to be associated with sulphides rather than Ni, as is well shown by an amphibolite sample from N.W. of Kjettevann which carried large grains of pyrrhotite and contained 1040 ppb Hg but only background Ni and Cu (140 ppm and 216 ppm respectively).

The rock samples were ground in a tungsten carbide mill and, due to contamination, were not analysed for Co. A single picked sulphide sample was analysed and contained 800 ppm Co and 1.8% Ni, indicating an association of Co and Ni in the Mølland sulphides. Bjørlykke (1947) gives an average value of 8.0 for the Ni:Co ratio of the Flåt ore.

Bedrock sampling therefore confirms the field observation that mineralisation at Mølland is confined to a relatively narrow N-S zone near the western margin of the norite outcrop. The sulphide zone is characterised by high contents of Ni, Cu, Hg and probably Co; equally high Hg contents occur however in barren sulphides elsewhere.

Table 17. Main features of the bedrock anomalies at Mølland on Traverses I, II and III.

	Threshold	Trav. I W(ft.)	C	Traverse II W (ft.)	C	Traverse III W (ft.)	C
Ni	(400 ppm)	80	2.1	20, 290	7.5	120	5.8
Ni	(650 ppm)	20	1.3	20, 30, 35	4.6	80	3.5
Cu	(270 ppm)	-	-	10, 60	3.0	30, 30	4.0
Hg	(90 ppb)	10	1.6	10, 30, 30	9.6	30, 20, 10	5.3

W = width of anomaly (ft.)
C = anomaly peak/threshold.

5. Relationship between rock units at Mølland

The Mølland sulphide zone is spatially related to the western margin of a massive norite body. This norite has a high Ni content when compared with the surrounding schistose amphibolites and metagabbros and two possibilities suggest themselves:

a) The sulphides are syngenetic and formed as immiscible blebs during the crystallisation of a high Ni norite magma, intrusive into the amphibolites and possibly the metagabbro. Examples of this are well known (e.g. Vogt 1923, Hawley 1962, Häkli 1963).

b) The mineralisation is epigenetic, the high Ni content of the norite representing a primary dispersion aureole; the spatial relationship of the sulphide zone with the massive norite would in this case be fortuitous, determined by the structural factors controlling mineralisation.

As a first approach the major and minor element chemistry of the principal rocks of the Mølland area and their constituent minerals was investigated in an attempt to determine whether the norite was in fact a distinct rock unit, since it was felt that this would most convincingly demonstrate the magmatic origin of the sulphides. As has already been mentioned the field evidence for the relationship between the various units of the amphibolite belt as a whole is ambiguous, and a number of theories may be advanced to explain their origin. These may be summarised as:

a) The amphibolite belt represents a single large mafic intrusion which has been subjected to progressive regional metamorphism to produce hornblende gneiss and amphibolites, the relatively minor massive phases being either unmetamorphosed relics of the parent rock or the products of recrystallisation under locally static conditions (Barth, 1947).

b) A composite basic mass, the rock units distinguished by decreasing grade of metamorphism representing successively younger phases of intrusion. According to this view the massive Mølland norite is a younger intrusion cutting metagabbro and amphibolite, the latter being the oldest rock in the Mølland area (Wiik 1968). The amphibolites may be either para- or ortho-amphibolites or a combination of both.

c) A single or composite mafic mass which, after regional metamorphism to the hypersthene granulite facies, underwent retrograde metamorphism to produce widespread amphibolites (cf. Edwards, 1958). This is thought to be unlikely in view of the massive nature of the norite.

If the major rock types in the Mølland area are of different origins it is to be expected that they will show differences in major and trace element chemistry. Edwards (1958), in a study of the amphibolites of Broken Hill, N.S.W., concluded that the conversion of hypersthene granulite to amphibolite during retrograde metamorphism, took place by the formation of green hornblende as a product of reaction between unstable hypersthene and calcic plagioclase, and demonstrated that this occurred without significant change in the overall composition of the rock. Differences in both major and trace element composition have been used to distinguish para- and ortho-amphibolites formed by regional metamorphism without accompanying metasomatism (Walker et al, (1960), Engel (1956)); the recognition of differentiation trends characteristic of the crystallisation of igneous rocks has been proposed as a more reliable method of distinguishing ortho- and para-amphibolites than a comparison of absolute metal contents (Leake 1964).

In areas affected by intense metasomatic-metamorphism however, amphibolites of markedly different origin (i.e. basic igneous rocks and lime-magnesia sediments) show a convergence in major, and to a lesser extent minor, element composition, resulting in chemically indistinguishable end-products (Walker et al, 1960). Higazy (1952) demonstrated that during metasomatic-metamorphism trace metals tend to follow the major elements with which they are normally associated in silicates and that only negligible changes in the ratio between associated trace and major elements (in particular Ni and Mg) occur. Suslova and Polferov (1965), working on a large differentiated basic body, found that during hypothermal metasomatism related to granite intrusion there was a redistribution of metals resulting in the homogenisation of an initially heterogenous massif. Thus, while it cannot be effectively shown with the available data whether the rocks of the Iveland area have been subjected to widespread metasomatism, this process, if it occurred, would tend to suppress rather than enhance initial differences in composition.

(a) Whole Rock Data

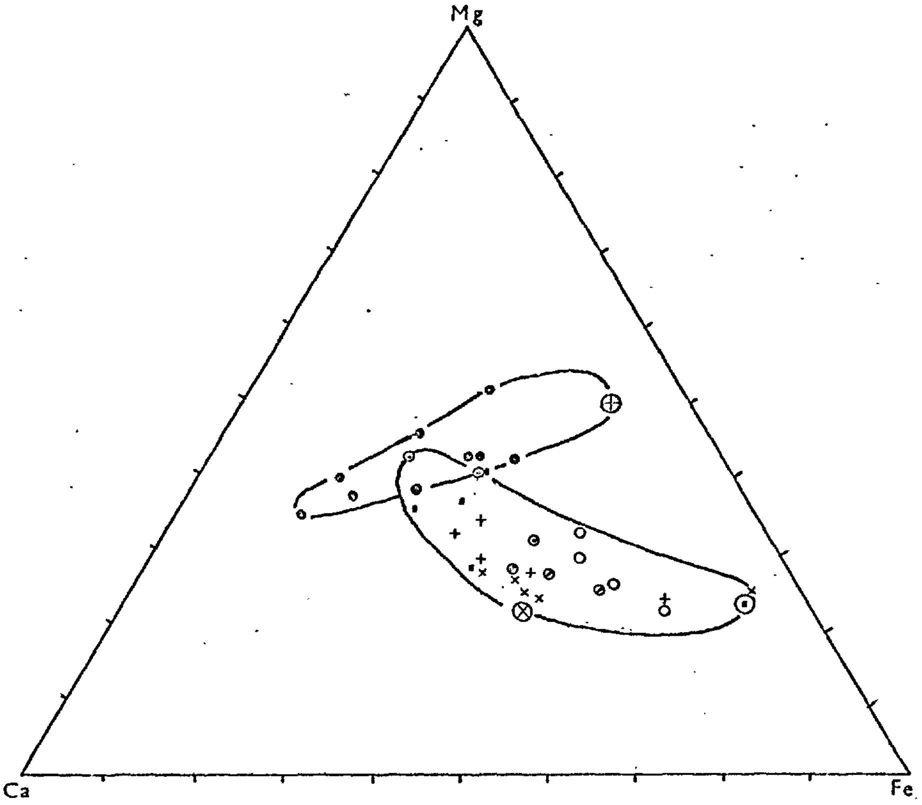
From table 16 it is evident that there is a considerable difference in major element chemistry between the three principal rock units at Mølland. The mean Mg content is highest in norite samples and lowest in amphibolite, the differences in distribution being highly significant in all cases. The mean Fe content, on the other hand, is highest in amphibolite and lowest in metagabbro, there being significant differences in distribution only between amphibolite/norite and amphibolite/metagabbro.

There are highly significant differences in the Cr distribution for all three rock types, the mean level in the norite samples (1130 ppm) being double that of the metagabbro (445 ppm), and nine times that of the amphibolite (126 ppm). No comparison is made at this stage between the ore metal contents of the norite and the other two rock types since it may be argued that the higher mean values of Ni and Cu in the norite samples are a reflection of epigenetic mineralisation and not a primary feature of the norite itself. Metagabbro and amphibolite samples show a highly significant difference in the distribution of Ni, and have mean levels of 221 ppm and 111 ppm respectively. The distributions of the Ni/Mg ratio also differ significantly (95% probability) in the amphibolite and metagabbro samples, and it will be recalled that this particular ratio has been shown to remain constant during metasomatic-metamorphism (Higazy 1952). Cu does not show a significant difference in distribution between metagabbro and amphibolite.

(b) Mineral Separate Data

It is possible that the differences noted above may in part be due to variations in the relative proportion of mafic to felsic minerals in the various rock types and, in order to overcome this, monomineralic fractions were prepared from selected samples. The norite samples contained hypersthene, hornblende and labradorite while both metagabbro and amphibolite contained green hornblende and plagioclase with minor quartz and biotite.

The major element composition of hornblendes from norite, amphibolite, metagabbro, Flåt ore diorite and "zenoliths" from the Mølland norite are compared on a triangular Ca, Fe, Mg diagram in fig. 22. The norite hornblendes fall into a distinct high Mg (35-50%) field and show a linear trend from high Ca (50%) to moderate Ca (20%); when the mean composition of nine norite hypersthenes is plotted it lies directly on this linear trend. Hornblendes from amphibolites collected at Mølland, Solberg and Flat form a second distinct field, characterised by lower Mg (20-35%) and showing a trend from moderate to high Fe (30-70%). Metagabbro and



● hornblende, from norite, (Mølland)
\+ " " amphibolite, (Mølland)
▪ " " 'zenoliths', (Mølland)
⊖ " " metagabbro, (Mølland)
× " " amphibolite, (Solberg)
○ " " ore diorite, (Flat)
-⊘ " " from other massive rocks
⊕ hypersthene from norite, (Mølland)
(mean of 10 samples)
⊗ hornblende, from ortho-amphibolite, N.S.W. (Edwards 1958)
⊙ hypersthene from granulite, N.S.W. (Edwards 1958)

Fig. 22 Mg-Fe-Ca plots of hornblendes separated from mafic rocks of the Iveland complex.

"zenolith" hornblendes appear to be transitional and occur in both fields, although this may be due to the small number of samples involved. Analyses of metamorphic hypersthene and of green hornblende from an amphibolite of definite igneous origin (Edwards 1958) are also plotted and it will be noted that both fall within the "amphibolite field". Hornblendes from four Flåt ore diorite samples are also plotted and although these fall within the amphibolite field they show a very limited compositional range (22-33% Mg, 47-63% Fe, 17-23% Ca) compared with that shown by the Mølland and Solberg amphibolites. Wiik (1968) has suggested that the Flat ore diorite is a late intrusion and this perhaps accounts for the uniform composition of the hornblendes.

Hypersthene and hornblende separated from norite samples show marked differences in major element composition, but differences shown by the minor elements Mn, Cr, Ni and Cu are not significant (table 18). Minor element data for the amphibolite hornblendes reveal marked differences when compared to data for hornblendes and hypersthenes from the norite. The mean Cr and Ni contents are much higher in both norite minerals and the Kolmogorov-Smirnov test shows the differences to be highly significant (table 18); the Ni/Mg ratio is also higher for the norite minerals, differences in distribution being highly significant (99%) between hornblendes

Table 18. (a) Geometric mean values for mineral separate data.

	Fe%	Mg%	Ca%	Mn	Cr	Ni	Co	Cu	Zn	$\frac{\text{Ni}}{\text{Mg}}$
Norite (hypersthene) (10)	11.1	13.7	2.3	1730	1060	442	113	64	160	30.9
Norite (hornblende) (9)	5.5	9.7	7.7	1290	1270	400	78	40	77	41.2
Amphibolite (hornblende) (9)	10.3	6.3	6.8	2090	148	107	64	47	170	14.9
Metagabbro (hornblende) (3)	7.6	9.2	7.4	1525	914	413	80	41	82	44.9
"Zenolith" (hornblende) (4)	7.0	7.7	7.4	1810	245	212	52	51	143	27.5
"Zenolith" (hypersthene) (4)	14.2	11.9	3.0	2090	189	187	118	96	250	15.7
Ore diorite (hornblende) *(4)	12.9	6.5	4.9	2130	406	284	65	137	296	41.0

* Excluding sample with 6000 ppm Ni.

Table 18. (b) Values of Kolmogorov-Smirnov statistic for the distribution of metals between minerals.

	Fe%	Mg%	Ca%	Mn	Cr	Ni	Co	Cu	Zn	$\frac{Ni}{Mg}$
(i) Norite hornblende : norite hypersthene										
K-S statistic	1.00	.889	1.00	.556	.340	.178	.667	.333	.689	.600
Significance	HS	HS	HS	N	N	N	HS	N	HS	S
(ii) Amphibolite hornblende : norite hornblende										
K-S statistic	.700	1.00	.444	.778	.890	1.00	.333	.286	.700	.900
Significance	HS	HS	N	HS	HS	HS	N	N	HS	HS
(iii) Amphibolite hornblende : norite hypersthene										
K-S statistic	.300	1.00	.899	.333	1.00	1.00	1.00	.349	.400	.600
Significance	N	HS	HS	N	HS	HS	HS	N	N	S

N = not significant S = significant (95%) HS = highly significant (>99%)

and significant (95%) between norite hypersthene and amphibolite hornblende. Highly significant differences (99%) in distribution between norite hornblende and amphibolite hornblende are also shown by Zn and Mn and between amphibolite hornblende and norite hypersthene in the case of Co.

The number of samples involved is too small to allow statistical comparison of the mineral separate data for metagabbros and "zenoliths", but a simple inspection of mean levels is instructive. Table 18 shows that for all elements the mean level of the metagabbro hornblendes is much closer to the mean level of the norite hornblendes than that of the amphibolites, indeed the means are virtually identical in the case of Ni, Co, Cu and Zn. The Ni/Mg ratio is high in the metagabbro hornblendes and is again of the same order as that of the norite hornblendes.

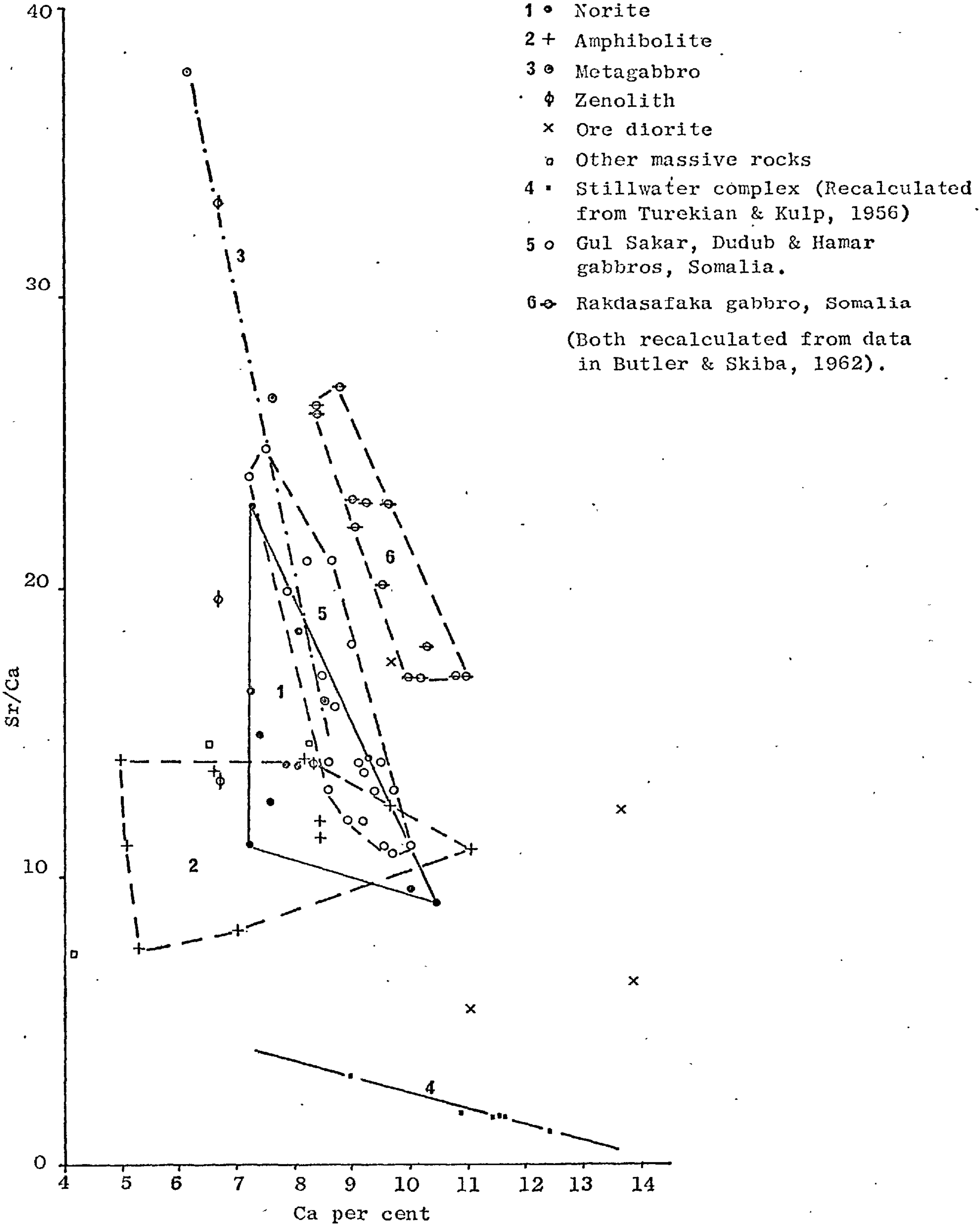
The "zenolith" hornblendes, on the other hand, show a much greater resemblance to the amphibolites than to the norite, particularly in having low contents of Cr and Ni. The "zenoliths" also carry hypersthene and comparison with the norite hypersthenes reveals much lower mean levels of Cr, Ni and Ni/Mg. The similarity of the minor element data for both hypersthene and hornblende from the "zenolith" samples to that of the amphibolite hornblendes suggests that the "zenoliths" are inclusions of amphibolite partially recrystallised to hypersthene-hornblende-plagioclase rock.

(c) Sr/Ca in Plagioclase

Butler and Skiba (1962) in a study of four layered basic bodies in Somalia used the Sr content of plagioclases to demonstrate that these were not part of a single layered sequence. In a later study (Skiba and Butler, 1963) the use of the Sr content of plagioclase was extended to the distinction of metagabbros and para-amphibolites.

The technique was applied to the problem of the relation of the Mølland norite to the amphibolites and metagabbro, although the presence of a variable proportion of quartz in the plagioclase separated from the amphibolites precluded a straight comparison of Sr contents. It has been shown however, (Butler and Skiba 1962, Turekian and Kulp 1956), that in a single mafic intrusion there is an inverse linear relationship between the Sr and Ca (An) contents of calcic plagioclases, the published data indicating that the tenor of Sr may vary widely in different intrusions. This suggested that the Sr/Ca ratio might be diagnostic. The mean values for norite (14.0) and amphibolite (11.7) are similar and are approximately half that of metagabbro (25.3) (table 18), although it should be stressed that the number of metagabbro samples is small (3). The Kolmogorov-Smirnov test showed the difference in distribution of the Sr/Ca ratio between norite and amphibolite plagioclases to be non-significant.

In fig. 23 the Sr/Ca ratio is plotted against Ca content for plagioclases from the various rock types of the Mølland area; data from the Stillwater complex (Turekian and Kulp 1956) and from Somali gabbros (Butler and Skiba 1962) are plotted for comparison. The differences shown to exist by Butler and Skiba between the Gul Sakar, Dudub and Hamar gabbros and the Rakdasafaka gabbro are also apparent in fig. 23, where the Somali data plot into two distinct fields (5 and 6). Data for the Mølland norite plagioclases plot into a distinct field (1) which shows a general parallelism with the Somali gabbro fields and overlaps on to field 5. The metagabbro data also show a marked linear trend (3) which parallels the gabbro trends and appears to be a continuation of the norite field. It is not clear to what extent this indicates a connection between the norite and metagabbro bodies, but the feature could be interpreted as an indication that the two rock units are derived from a single differentiation sequence. The high Sr/Ca ratio shown by the metagabbro plagioclases may however largely be due to decalcification of the original plagioclase as a result of reaction with mafic



<u>Fig. 23</u> Sr/Ca vs Ca for plagioclase feldspar separated from mafic rocks of the Iveland complex.

silicates to produce green hornblende; Butler and Skiba (1962) demonstrated that Sr remained in the feldspar lattice during decalcification, the resultant plagioclase being enriched in Sr with respect to the final Ca content.

The amphibolite data plot into a field (2) which is characterised by a relatively narrow Sr/Ca range coupled with a wide variation in Ca content. As already mentioned quartz is present in variable proportions in the amphibolites, recalculation of modal analyses given by Barth (1947) indicating that quartz may constitute 0-30% of the feldspathic fraction. It is possible, therefore, that the form of field 2 is largely determined by dilution of the plagioclase fraction with quartz.

The "zenolith" data shows a wide scatter: two samples fall within the amphibolite field, one lies on the metagabbro trend with a high Sr/Ca ratio and one, while not falling in any distinct field, shows some affinity to the norite. Data for four 'ore diorite' plagioclases are plotted but show a broad scatter unrelated to the established fields. Data from three localities in the Iveland belt, where massive rocks had been tentatively mapped as metagabbro (Nixon 1968) lie close to the amphibolite field.

It is noticeable that the Sr/Ca ratios for all plagioclases from the Iveland area are, in common with the Somali data, significantly higher than the corresponding levels from the Stillwater complex (field 4).

(d) Evidence for differentiation

The wholerock data strongly suggest that the amphibolite, metagabbro and norite are distinct rock types. The mineral separate data confirm this in the case of amphibolite and norite, but suggest similarities between the norite and metagabbro, although it should be stressed that the number of mineral separate samples from the metagabbro is small (3), and that for this reason the results are by no means conclusive.

In order to test the hypothesis that these observed differences could have arisen from the differentiation of a single basic magma, the ratio $\frac{Fe}{Fe+Mg}$ was calculated from the whole rock data for amphibolite, metagabbro and norite (sulphide-free) samples, advancing magmatic differentiation being indicated by an increase in this ratio (Walker 1953). The Kolmogorov-Smirnov test showed highly significant differences (>99% probability) in the distribution of the $\frac{Fe}{Fe+Mg}$ ratio between the amphibolite and both metagabbro and norite samples, and a difference significant at the 95% probability level

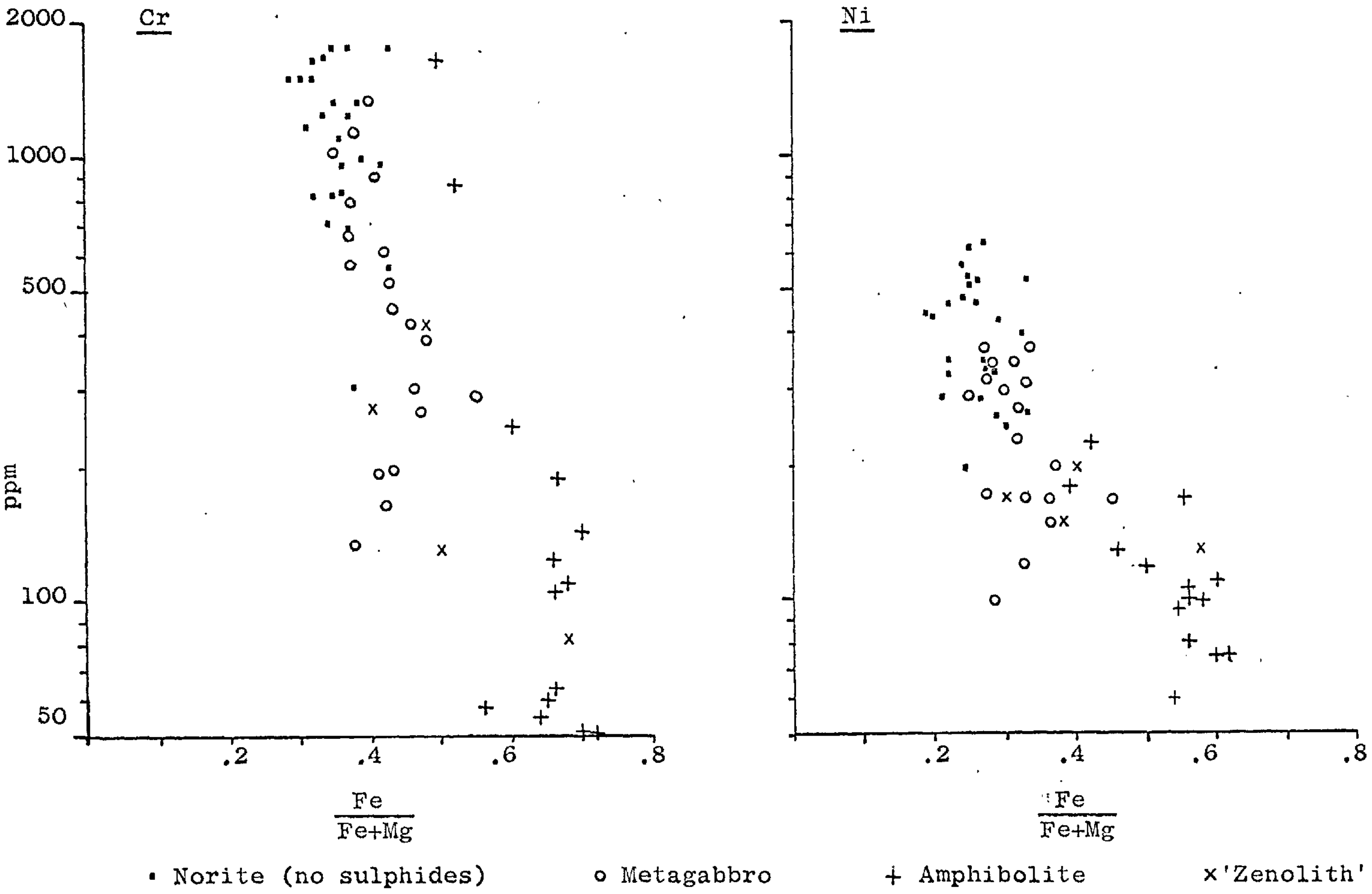


Fig. 24 Plot of Cr and Ni vs $\frac{Fe}{Fe+Mg}$ for the principal rock types of the Mølland area (whole rock data).

between norite and metagabbro.

Whole rock Ni and Cr contents are plotted against $\frac{Fe}{Fe+Mg}$ in fig. 24; the strong negative correlation with advancing fractionation stage indicates all three rock units to be of igneous origin, (Leake 1964), and in particular that the amphibolites are ortho-amphibolites. In order of advancing differentiation stage (i.e. increasing mean value of $\frac{Fe}{Fe+Mg}$) the rock units are norite, metagabbro and amphibolite, and thus if the rocks of the Mølland area do represent a single differentiation sequence, the oldest unit would be the massive norite and the youngest the amphibolite.

It is difficult to envisage a process by which the youngest phase of a differentiating sequence could be completely recrystallised while the norite remained in an almost pristine condition and it will be recalled that the samples collected as "zenoliths" within the norite body were shown to have a chemical affinity with the amphibolite rather than the norite. It is suggested therefore that the chemical evidence cited indicates the norite to be a distinct rock unit intrusive into the amphibolites.

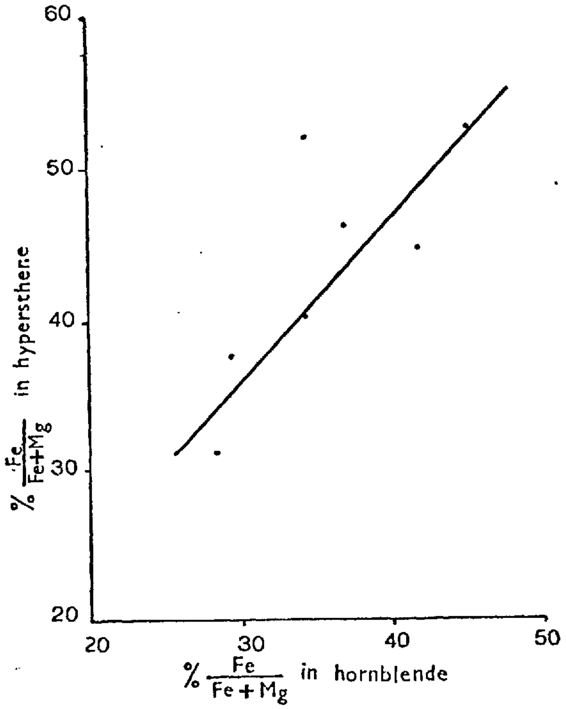
The relation between the norite and metagabbro is not so well defined since the similarity in minor element content and Ni/Mg shown by the metagabbro and norite hornblendes and the evidence of Sr/Ca in plagioclase suggests that they may form a differentiation sequence.

In order to provide an indication of the degree of fractionation within the norite body $\frac{Fe}{Fe+Mg}$ ratios for co-existing hornblende and hypersthene from norite samples are plotted in fig. 25; a linear plot results, with a Spearman rank correlation coefficient of +.84 (significant at 99% probability) indicating a distinct fractionation trend in the mafic silicates. Relics of clinopyroxene were noted in the hornblende, which is considered to be of secondary origin, and it appears that the alteration of clinopyroxene to hornblende occurred with little change in major element composition. This is in agreement with the conclusions reached by Leake (1968) that the composition of secondary amphiboles is governed by the chemistry of the primary minerals they replace and bears the same relation to the composition of the remaining primary minerals as if they had crystallised simultaneously.

Fig. 26 shows the areal distribution of the $\frac{Fe}{Fe+Mg}$ ratio for both hypersthene and hornblende over the norite outcrop. It is evident that there is a steady increase in the ratio from east to west (31% Fe - 53% Fe in the case of hypersthene and 28% Fe - 45% Fe for hornblende).

Fig. 25

Correlation of $\frac{Fe}{Fe+Mg}$ % in hornblende & hypersthene from Mølland norite.



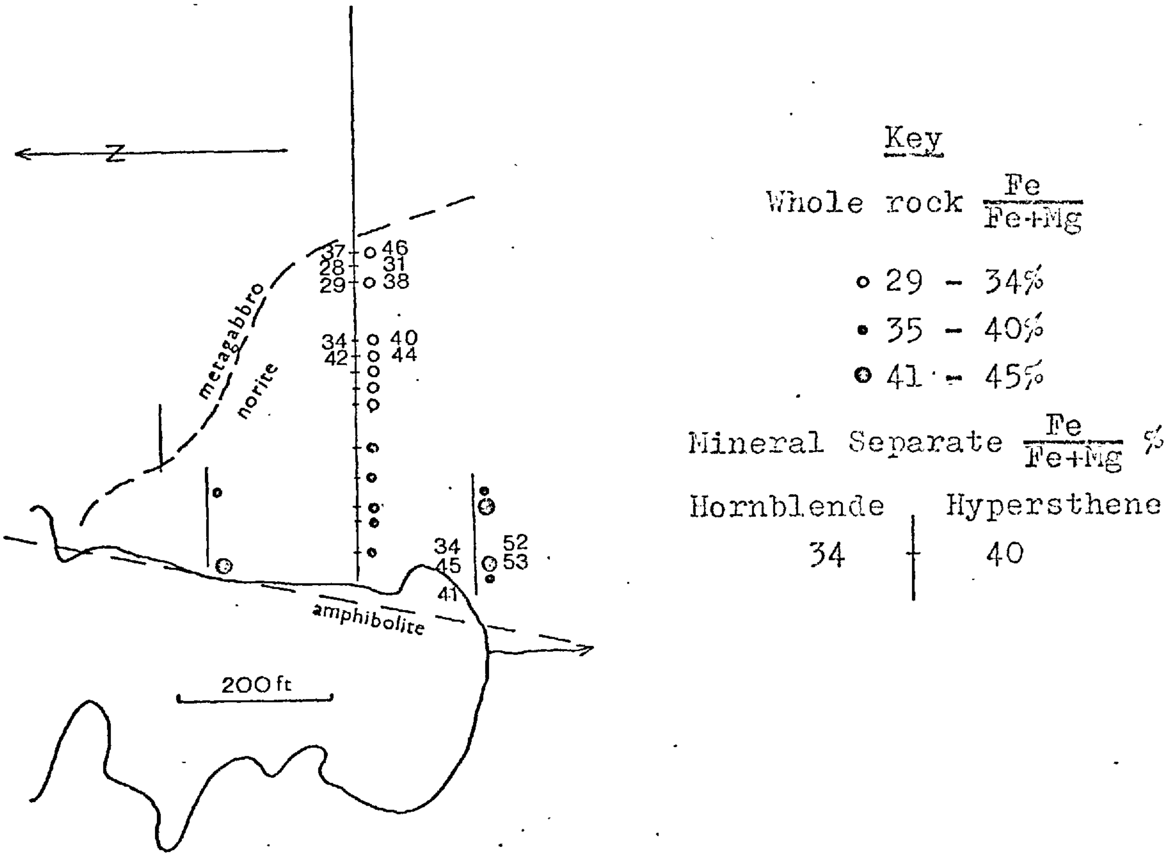


Fig. 26 Areal distribution of $\frac{Fe}{Fe+Mg}$% in whole rock and mineral separates for Mølland norite.

The $\frac{Fe}{Fe+Mg}$ ratio for whole rock data from sulphide-free norite samples shows a similar, although less well-defined trend, samples from the eastern half of the norite outcrop having 29-35% Fe compared with 35-43% Fe in the western half (fig. 26). On this evidence the base of the norite body is the contact with the metagabbro, the sharp boundary with the amphibolites being the upper contact (cf. Leake, 1964, p. 252). It is considered most unlikely, therefore, that the metagabbro is a differentiation product of the norite magma and it is concluded that there are in fact three distinct rock units at Mølland, the metagabbro being intrusive into the amphibolites and the younger norite body being implaced along a line of weakness at the metagabbro-amphibolite contact.

The variation of the minor element content of hypersthene and hornblende across the norite body are shown in fig. 27; the variation in $\frac{Fe}{Fe+Mg}$ is also shown together with the distance of the sample site from the approximate eastern contact of the norite body. The width of the norite outcrop is of the order of 500 ft. and marked fractionation of the minor elements is perhaps not to be expected. Mn and Zn, however, show a tendency to increase in both hypersthene and hornblende with increasing fractionation; Ni also shows a slight tendency to increase with advancing fractionation

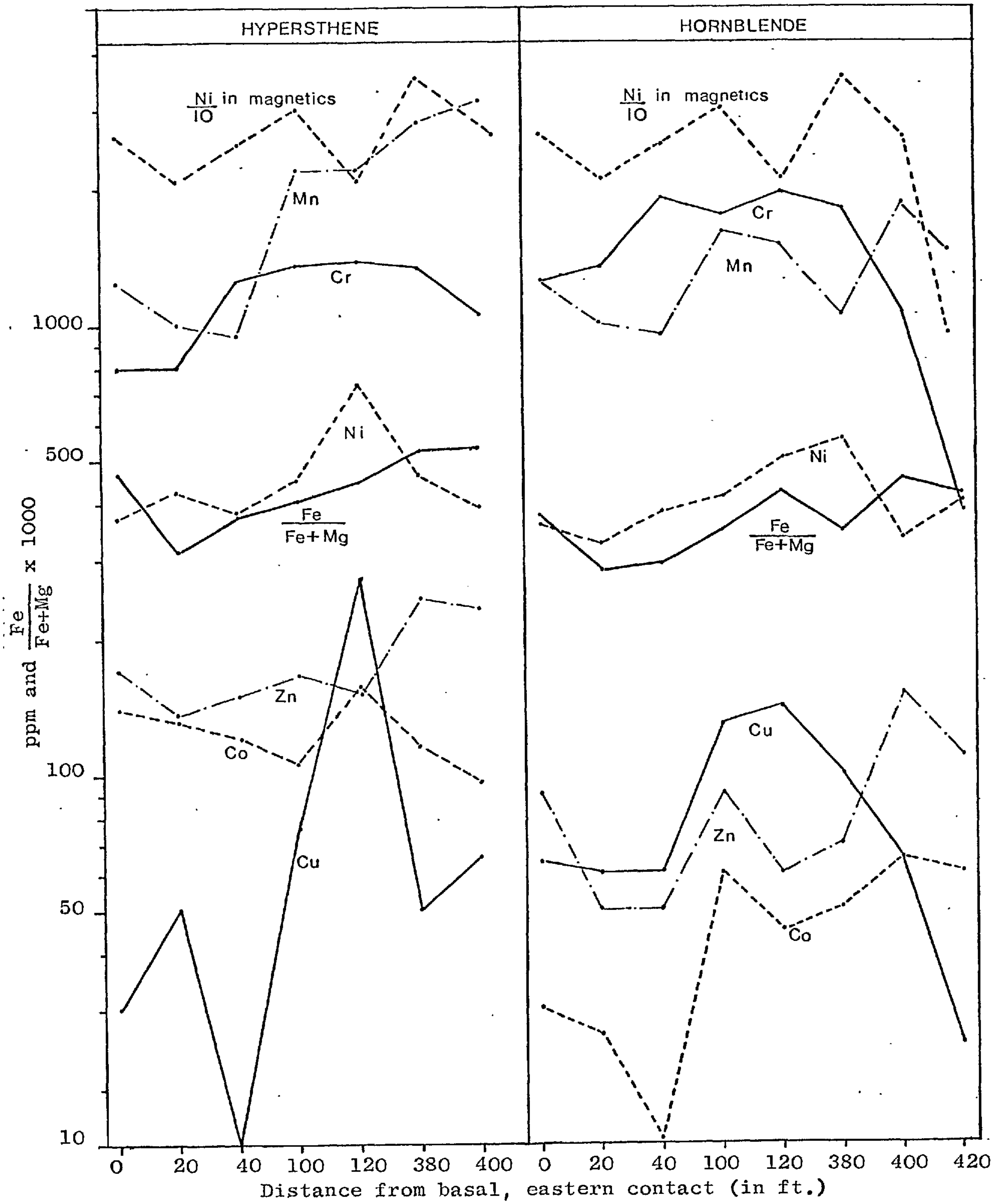


Fig. 27 Variation in $\frac{Fe}{Fe+Mg}$ x 1000, and minor element content in hypersthene and hornblende from Mølland norite.

particularly in hornblende, but the Ni content in both minerals decreases at distances greater than 380 ft. east of the basal contact. Cr in both hornblende and hypersthene also increases slightly with advancing fractionation up to 380 ft. west of the basal contact, and then shows a marked decrease; the behaviour of Cr is thus similar to that noted by Turekian and Carr (1960) in the differentiation of the Stillwater complex.

6. Further evidence for the magmatic origin of the sulphides.

The foregoing has demonstrated that the norite body within which the sulphides are confined is a younger intrusion cutting both amphibolite and metagabbro; furthermore the sulphides have been shown to be concentrated in a distinct zone near the western or upper contact of the norite body.

The common association of magmatic nickel-bearing sulphides with noritic intrusions was noted by Vogt (1923) and confirmed by Wilson (1953). The mode of formation of these sulphides has been widely discussed in the literature (e.g. Vogt 1923, Wilson 1953, Wager et al 1957, Hawley 1962) and there is general agreement that they are the result of the separation of an immiscible sulphide liquid during the fractional crystallisation of basic magmas. The initial sulphur content of the magma is important (Edel'shtein, 1960), since an immiscible phase cannot develop until the solubility of sulphur in the silicate melt is exceeded. Wilson (1953) also considered the bulk composition of the magma to be an important factor governing the separation of an immiscible sulphide phase and related the common association of magmatic sulphides with norites rather than peridotites to the greater solubility of S in the latter. In noritic or gabbroic magmas relatively rich in sulphur, an immiscible sulphide phase separates early and a chemical equilibrium is set up governing the partition of Fe, Ni, Cu and Co between the sulphide and silicate phases (both solid and liquid). Wager et al (1957) demonstrated that in a sulphur-poor magma the sulphide phase separates at a late stage and, if strong fractionation has been operative, may have a very low Ni content.

(a) Ni in magnetics

The Ni content (ppm ÷ 10 for convenience in plotting) of the magnetic fraction is shown in fig. 27; as already mentioned (p. 74) this consisted of sulphides plus adhering silicates separated from the crushed rock samples with a hand magnet. Although the data are limited, the following observations may be made:

(i) Nickeliferous sulphides are present throughout the norite body, although concentrated to form a mineralised zone in the upper portion.

(ii) The nickel content of the magnetic fraction is fairly constant throughout most of the norite, bearing in mind the variable porportion of silicates present, and ranges from 2-3.5% Ni over the first 380 ft., with a mean of 2.6% Ni. In the uppermost sample (490) however, collected west (or above) the mineralised zone, the Ni content drops to 1%.

Both Ni and Cr in hornblende (fig. 27) show a gradual increase from east to west over the first 380 ft. of the norite and then a sharp decrease in the uppermost section, coinciding with the decrease shown by the magnetic fraction. This parallel with the behaviour of Ni and non-chalcophile Cr in the silicates is taken as strong evidence that the Ni content of the sulphides was affected by the fractionation of the norite magma, and hence of a magmatic origin for the sulphides.

Vogt (1923) considered that once separated the heavy sulphide liquid tended to sink through the silicates to accumulate at the base of the intrusion, and the concentration of sulphides near the upper contact of the Møllland norite would thus appear to be anomalous. It is possible, however, that the initial concentration of sulphur in the norite was such that the magma was just saturated with sulphur during the period when the bulk of the norite crystallised, so that only minor sulphides formed, the sulphide zone representing the development of an immiscible sulphide liquid at a relatively late stage. Veinlets of sulphide were noted following cleavage cracks in hypersthene (p. 73) and indicate that at least some of the sulphide was mobile after crystallisation of the silicate minerals.

(b) Distribution coefficient for Ni

Häkli (1963), in a study of Ni mineralisation in Finland, investigated the coefficient of distribution of Ni between silicate minerals and sulphides. He found that the coefficient of distribution of Ni between orthopyroxene and sulphides for a variety of mineralised intrusions ranged from 0.006 to 0.014, the average being 0.0076; he considered this narrow range to be indicative of an equilibrium governing the distribution of Ni between the silicate and sulphide phases, and hence most probably of a common magmatic origin.

The distribution coefficient between hypersthene and sulphides was calculated for the Mølland mineralisation using the mean Ni content of 8 hypersthenes and Bjørlykke's calculated average value of 5.5% Ni for the sulphides. It was found that

$K = \frac{XNi \text{ hypersthene}}{XNi \text{ sulphide}} = .008$, approximated closely Häkli's average value and this is taken as further support for the magmatic origin of the sulphides.

Häkli found that for amphiboles the value of K varied considerable (from 0.006 to 0.015) and suggested that it was dependent on the primary or secondary nature of the amphibole, primary amphiboles having an average K = 0.014, while for secondary amphiboles the value of K approximates that of the primary pyroxene. For Mølland $K = \frac{XNI \text{ hornblende}}{XNi \text{ sulphide}} = .007$ was found to be similar to that for hypersthene.

The distribution coefficient for hornblende and sulphide for the Flåt ore diorite was also calculated, using the mean Ni content of 3 hornblendes. Bjørlykke's average value of 4.5% Ni was used for the sulphide and it was found that $K = \frac{XNi \text{ hornblende}}{XNi \text{ sulphide}} = .006$ was similar to that obtained for Mølland hornblendes. It is emphasised that only limited samples were available from Flåt, but the similarity in the value of the distribution coefficient for Mølland and Flåt may indicate a common magmatic origin.

7. Reconnaissance bedrock sampling as a mineral exploration method.

Systematic wide interval bedrock sampling is used as a reconnaissance mineral exploration method both in North America (Holman 1962, Smith 1966) and the U.S.S.R. (Nyuppen 1966, Beus and Sitnin 1968). It has application only in exploration for syngenetic mineralisation, when the host rock frequently, but not invariably, has a greater than average content of the ore metals.

In its simplest form the method relies on a comparison of the ore metal content of a given rock unit either with similar rock units in the exploration area or with an established average value (i.e. as given by Green 1959, or Vinogradov 1962). Thus in order to recognise potentially nickeliferous mafic or ultramafic rock units a value KNi may be calculated using average Ni contents for these rock types (Vinogradov 1962) such that:

$$\text{KNi} = \frac{\text{mean ppm Ni in mafic rock unit}}{160}$$

or

$$\text{KNi} = \frac{\text{mean ppm Ni in ultramafic unit}}{2000}$$

Rock units for which the calculated KNi value is greater than unity are then considered potentially nickeliferous.

Nyuppen (1966) has criticised this method on the grounds that the classification of rock units as mafic or ultramafic on petrographic evidence is frequently an arbitrary decision, and that Vinogradov's average values allow no account to be taken of rock types intermediate between the mafic and ultramafic extremes. Vogt (1923) recognised a close relationship between the Ni and Mg content of the mafic rocks and it is thought that a comparison of mean Ni/Mg ratios may provide a more rigorous method of recognising potentially nickeliferous rock units. Ni/Mg ratios may of course be compared using a 'K' value calculated from Vinogradov's (1962) averages for the Ni amd Mg contents of mafic and ultramafic rocks.

Mean Ni contents, KNi values, Mg contents, Ni/Mg ratios and K(Ni/Mg) values are compared in table 19 for norite (sulphide-free), metagabbro, Mølland amphibolite, Flåt amphibolite and the world average for mafic rocks (Vinogradov 1962).

Comparison of mean Ni contents and of KNi values reveals the Mølland norite as potentially nickeliferous, while the Mølland metagabbro appears of possible interest. Using the proposed K(Ni/Mg) parameter only the Mølland norite is potentially nickeliferous, with K(Ni/Mg)=1.28. The Flåt amphibolite samples, however, collected in the immediate vicinity of the mine, have KNi = 0.9 and it is evident that on the basis of systematic bedrock sampling the Flåt area would not have been recognised as potentially nickeliferous.

Table 19. Mean Ni contents, KNi values, Mg contents, Ni/Mg ratios and K(Ni/Mg) values for rock types from the Iveland-Evje complex.

	Norite	Meta-gabbro	Mølland Amphibolite	Flat Amphibolite	Vinog-radov's Average
Ni (ppm)	445	221	111	142	160
KNi	2.85	1.38	0.7	0.9	1.0
Mg%	9.1	6.1	4.2	-	4.5
Ni/Mg	45.8	36.7	28.6	-	35.6
K(Ni/Mg)	1.28	1.03	0.8	-	1.0

It is concluded that bedrock sampling should not be used as the sole reconnaissance method in mineral exploration for Ni, although it may have an application in deciding exploration priorities between areas of basic or ultrabasic rock which on other grounds are considered equally favourable.

8. Economic potential of the Iveland-Evje mineralisation

The foregoing has established that the Mølland mineralisation is syngenetic and is associated with a distinct norite body intrusive into both metagabbro and ortho-amphibolite. Two theories have been put forward to account for the Flåt mineralisation (i.e. syngenetic and associated with an intrusion of 'ore diorite' (Bjørlykke 1947), or epigenetic and controlled by a prominent N-S shear zone (Haldemann, *pers. comm.*)), both implying that mineralisation is related to post-amphibolite igneous activity. The limited sampling at Flåt has established that the amphibolites in the mine vicinity have a low Ni content, supporting the view that mineralisation post-dates the amphibolites; the similarity in the distribution coefficient for Ni between hornblende and sulphides calculated for Flåt and Mølland lends some support to Bjørlykke's view of a magmatic origin, but the Flåt value is based on too few samples for any firm conclusion to be drawn.

Thus the two principal Ni occurrences in the Iveland-Evje area are considered to be associated with a phase of igneous activity post-dating the formation of the main body of ortho-amphibolites. Other younger dioritic, basic or ultrabasic intrusions within the complex should therefore be regarded as favourable areas, warranting detailed exploration. However, according to Barth (1947), amphibolites comprise approximately 90% of the total outcrop area of the Iveland-Evje complex, so that if, as the present results suggest, significant mineralisation is exclusively associated with post-amphibolite intrusions, the economic potential of the area as a whole must be regarded as low.

Vogt (1923) considered that in general the size of magmatic Ni-pyrrhotite deposits is dependent on the size of the parent intrusion and that large deposits occur only in association with large intrusive masses. On the evidence of the surface outcrop, the Mølland norite and other younger intrusions are of only limited size and, therefore, following Vogt, of only limited economic potential. It must be borne in mind, however, that only surface data is available and that in sub-outcrop these intrusions may be more extensive; although beyond the scope of the present investigation the use of geophysical methods to determine the form of the norite body in depth would clearly allow a more valid assessment of the economic potential of the Mølland area.

9. Conclusions

(1) On geochemical evidence, principally from the Mølland area, the Iveland-Evje amphibolite complex is considered to be a composite body resulting from at least three distinct phases of basic igneous activity: (a) the wide-spread ortho-amphibolites are regarded as the oldest rocks within the complex; (b) the meta-gabbro cropping out in the Mølland area has been shown to be chemically distinct from the ortho-amphibolites and is, therefore, considered to have been emplaced during a second phase of igneous activity; (c) it has been demonstrated that the Mølland norite is a distinct rock unit intruding both amphibolite and metagabbro.

(2) Mineralisation at Mølland has been shown to be genetically related to the norite intrusion. Nickeliferous sulphides, while occurring throughout the norite body, are concentrated in a distinct zone near the western, or upper, contact.

(3) Available evidence indicates that the Flat mineralisation is likewise associated with igneous activity post-dating the formation of the main body of ortho-amphibolites. Other younger dioritic, basic and ultrabasic intrusions within the Iveland-Evje complex are therefore considered to be potentially favourable areas warranting detailed examination.

(4) On surface indications ortho-amphibolites comprise approximately 90% of the Iveland-Evje complex and, since the individual younger intrusions appear of limited size, the economic potential of the area as a whole is regarded as relatively low.

(5) The mean Ni content of the unmineralised norite samples is approximately four times that of the ortho-amphibolites, and on this basis almost all the norite samples are anomalous; with respect to the local threshold value for the norite intrusion, anomalous Ni contents are confined to the main sulphide zone. Anomalous Cu and Hg values are likewise confined to the main sulphide zone at Mølland. Rock samples were not

analysed for Co, due to contamination during sampling preparation, but a single analysed sulphide sample showed that Co accompanies Ni and Cu in the Mølland ore.

(6) Wide interval bedrock sampling is not considered to be a reliable reconnaissance method in exploration for Ni in this area. Comparison of mean Ni/Mg ratios may, however, provide a useful method of establishing the order of priority for detailed exploration between basic areas considered on other evidence to be equally favourable.

CHAPTER IV. OVERBURDEN INVESTIGATIONS

1. Introduction

The distribution of the ore and associated metals in soil and peat bogs was studied in the vicinity of mineralisation and in background areas of the Mølland orientation locality in order:

a) to establish optimum exploration techniques for use in the search for Ni mineralisation in this area;

b) to gain a thorough understanding of the factors controlling the dispersion of Ni and the associated metals in soil and peat, to facilitate the interpretation of data from subsequent exploration programmes.

The bedrock surface at Mølland slopes fairly steeply (about 20°) towards the eastern shore of Lake Kjettevann. Till cover at the prospect is shallow (generally $<$ 24") and patchily distributed, being largely confined to depressions in the bedrock surface; glaciofluvial sands occur north of the prospect and also along the western lake shore. Podzolic soil profiles are developed on both materials; descriptions of individual soil profiles are given in tables 21 and 22. pH and Eh data for soils are given in fig. 2; pH varies from 4.0 to 7.0 and Eh conditions range from strongly reducing to oxidising.

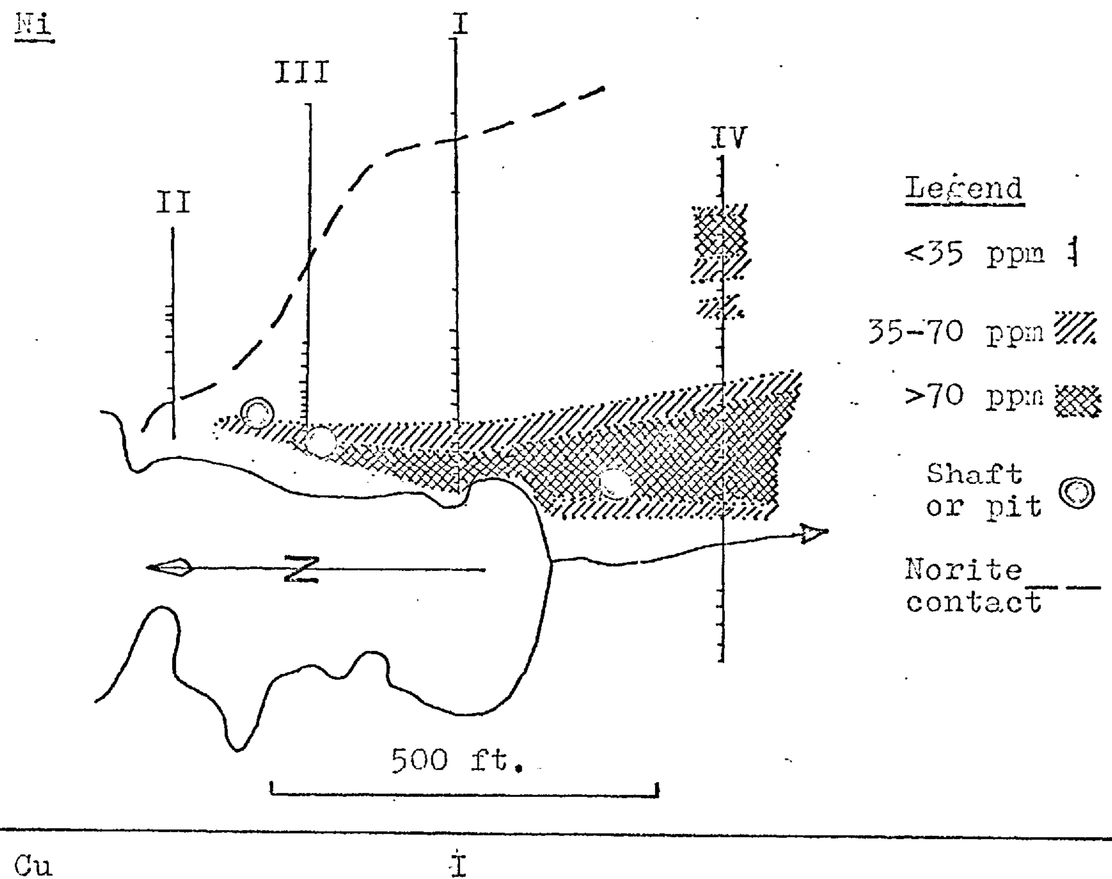
Peat bogs are common features at Mølland and are present wherever drainage is locally impeded. They range from small accumulations in bedrock hollows to bogs hundreds of feet across; the average depth of the bogs sampled was 5 ft., but depths of up to 15 ft. were encountered. Detailed pH and Eh data for bogs are given in table 27.

Analytical and mineralogical data for Mølland soils are given first, the significance of the data presented being discussed in each section. Data for peat bogs are then presented and suggestions made as to the manner in which various peat anomalies originate. The results of two reconnaissance soil traverses at Flåt mine are conveniently presented next. The relative importance of glacial and saline dispersion in the formation of secondary dispersion patterns is then assessed using the available information, and in a final section the conclusions of the overburden investigations are summarised.

2. Soil Results

(a) Ni and Cu in B horizon

Soil samples were collected systematically along four traverses perpendicular to the strike of the mineralised zone (fig. 28). In order to outline the position of the soil anomaly, B horizon samples were analysed for



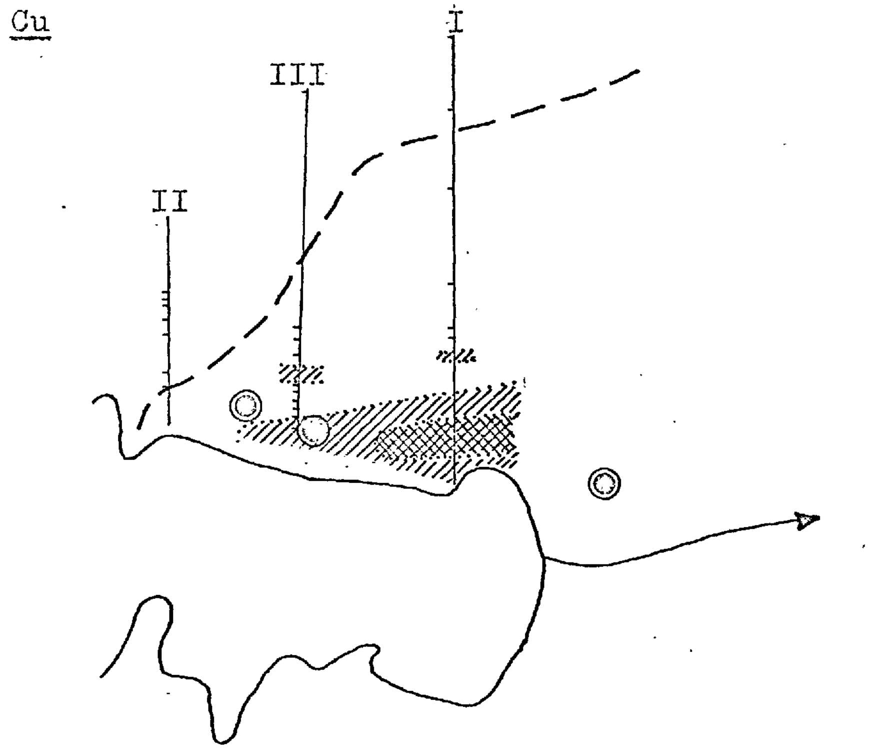


Fig. 28 Distribution of Ni and Cu in B horizon, Mølland.

Ni and Cu; data for the four traverses are shown in figs. 29 and 30. Background samples show a range of 10-35 ppm for Ni and Cu and threshold for both metals was taken as the upper limit of background variation (i.e. 35 ppm).

Ni and Cu show well-defined, more or less coincident anomalies trending N-S, parallel to the strike of the mineralised zone (fig. 28). The Ni anomaly has a proven length of 600 ft. and although closed to the north, its form suggests that it may well extend beyond the southernmost traverse (IV); the samples from Traverse IV were unfortunately not analysed for Cu. It is evident from fig. 28 that the Ni anomaly is broadly coincident with the position of the mineralised zone, as evidenced by the shaft and prospect pits, but extends south of the main prospect shaft into an area where mineralisation has not been reported. It is interesting to note that a recent EM survey revealed a conducting zone coincident with this southern part of the soil anomaly (Haldemann, pers. comm.).

The detailed relationship between the Ni and Cu content of the B horizon and bedrock may be seen in figs. 29 and 30; the width and location of the mineralised zone is in each case projected from the adjacent bedrock traverse (fig. 21). The anomalous samples on soil

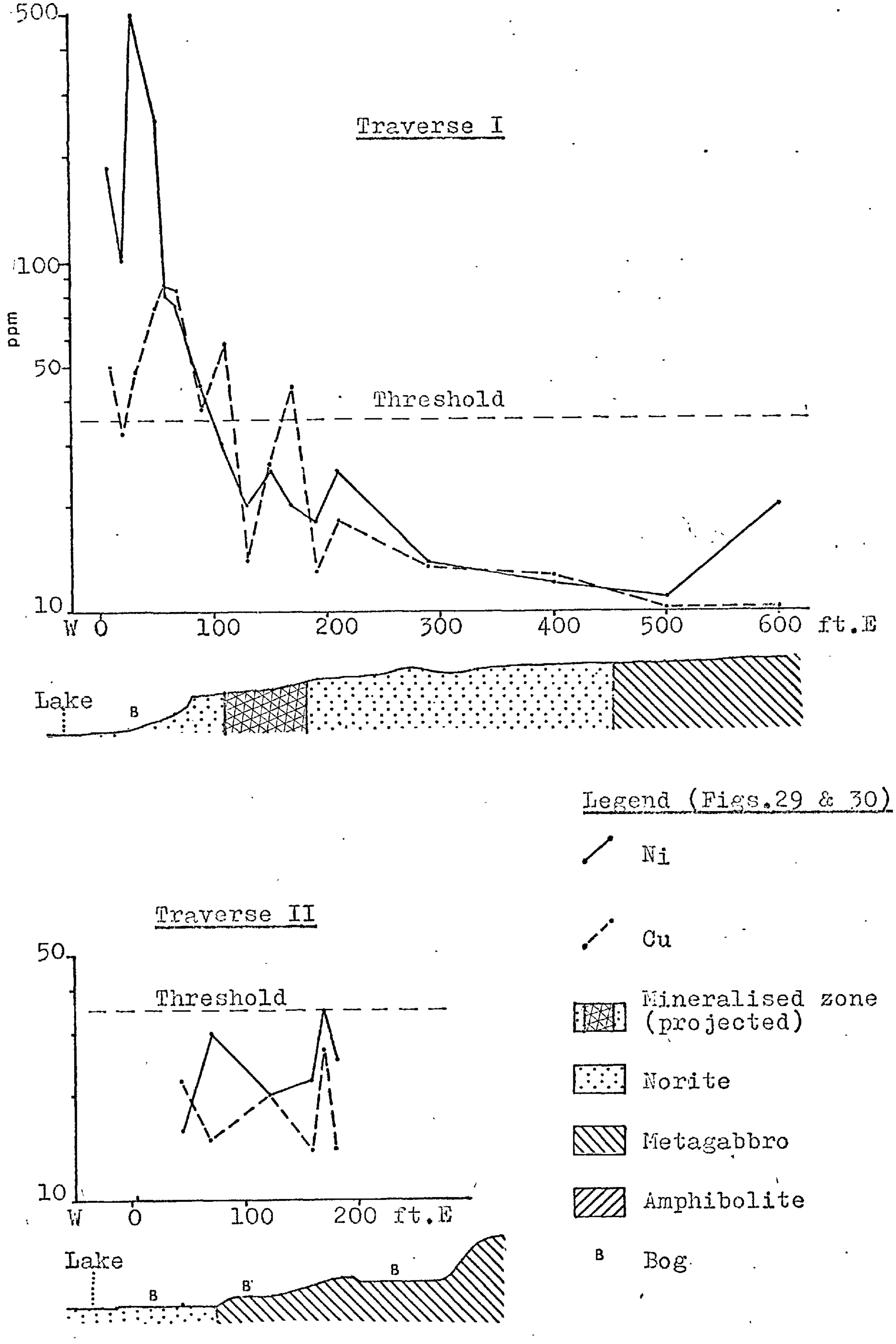


Fig.29. Ni & Cu in B horizon soil, traverses I & II, Mølland.

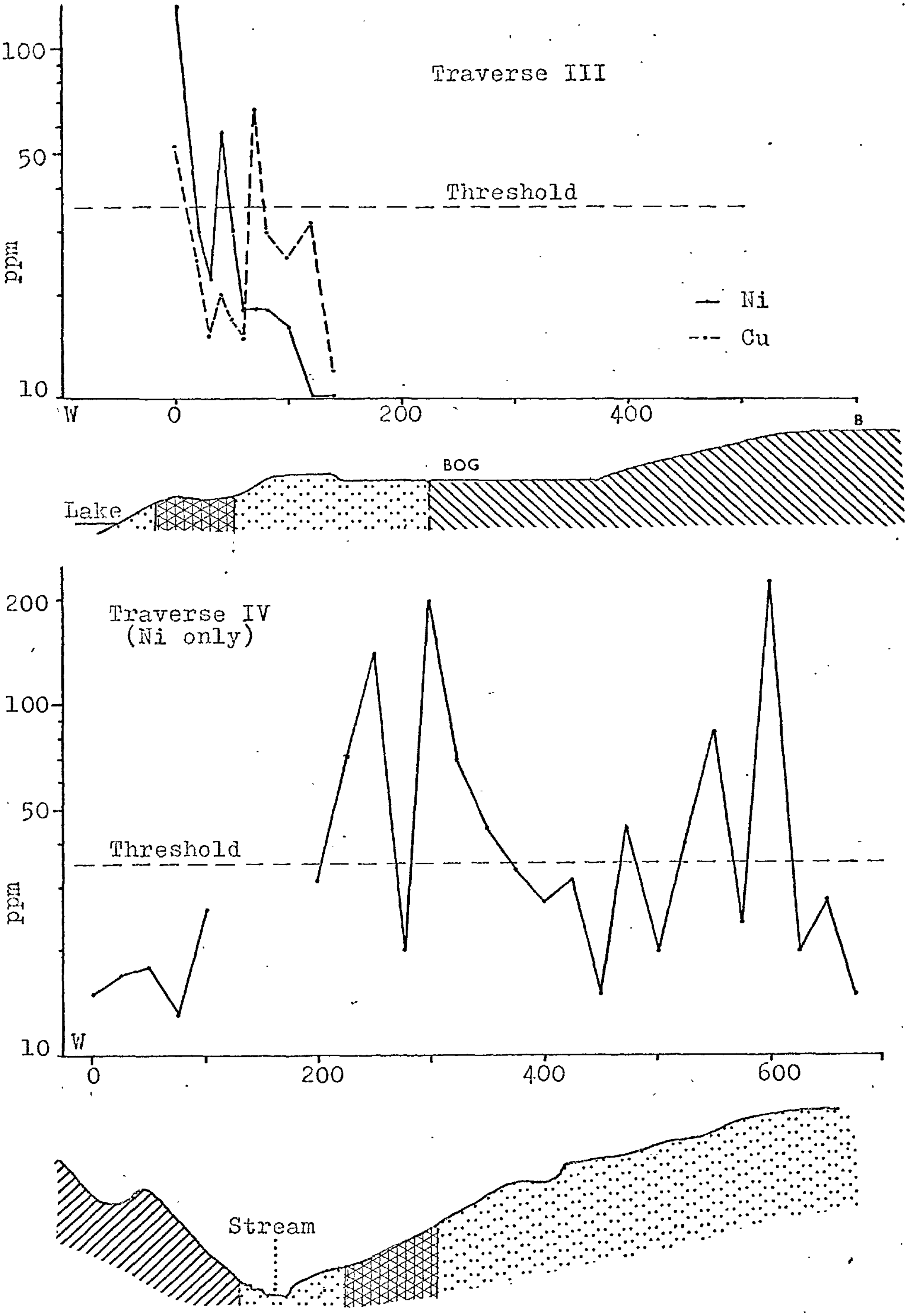


Fig. 30 Ni and Cu in B horizon soil
Traverses III and IV, Mølland.

Traverse III (fig. 30) were collected from shallow depressions on an otherwise bare rock surface, sloping westwards to the lake shore; it is clear that in this instance high Ni and Cu occurring as sulphide mineralisation in bedrock is reflected by anomalous Ni and Cu in the immediately overlying soil.

The anomalous section of soil Traverse I runs along a narrow, partially till-filled gulley, the floor of which slopes steeply down to the lake shore; an intermittent stream follows the gulley, and a spring emerges near the shoreline of the lake. Fig. 29 shows a marked displacement of the soil anomaly downslope from the projected position of the mineralised zone; this may reflect mechanical movement of anomalous material although the difference in displacement shown by the Ni and Cu peaks is suggestive of hydromorphic dispersion.

Anomaly width and contrast for Traverses I, III and IV are summarised in table 20. Comparison with similar data for the bedrock traverses (table 17) reveals that while contrast for Ni is higher in soil than in bedrock, the reverse is true for Cu. This is thought to reflect a difference in the supergene mobility of the two metals and to indicate that Cu is relatively more mobile than Ni under moderately acid weathering conditions.

Table 20. Main features of the B horizon anomalies on Traverses I, III and IV. Mølland.

	Traverse I		Traverse III		Traverse IV	
	W (ft.)	C	W (ft.)	C	W (ft.)	C
Ni	100	14	40	4.0	175, 100	6.0
Cu	110	2.5	10, 10	2.0	Not Analysed	
Nearest Rock Traverse:	II (50' N.)		III (50' North)		I (250' North)	

W = anomaly width (ft.)
C = anomaly peak/threshold.

(b) Distribution of Ni and Cu in soil profiles

The variation in Ni and Cu content within the soil profile at background and anomalous localities is shown in tables 21 and 22. As already mentioned, till cover at Mølland is generally less than 24 inches deep and it was difficult to obtain complete soil profiles; for this reason data for 2 profiles from Flåt are included.

For background localities (table 21) Ni and Cu are uniformly distributed through the deeper levels of the mineral soil (B and C horizons); the content of both metals appears to be much lower in the leached A_2 horizon and Ni alone is enriched significantly (x2) in the A_1 horizon.

The anomalous profiles (table 22) suggest a general decrease in both Ni and Cu content with depth. The single humus sample (Flåt II) is significantly enriched in both Ni and Cu compared to the underlying mineral soil; in the remaining anomalous profiles both Ni and Cu are enhanced in the B horizon relative to the deeper soils. The degree of enhancement is greater for Cu, which in general shows a two-fold increase in the B horizon compared to the deeper soils, where Cu values are at or near threshold level.

Table 21. Variation in Ni and Cu content with depth in background soil profiles.

Sample No.	Depth (ins.)	Description	Horizon	Ni (ppm)	Cu (ppm)
Mølland, Traverse I, 150' E					
784	6-12	Humus.	A_1	44	19
785	12-18	Light pink-brown sandy clay.	A_2	6	8
786	18-24	Dark-brown clay.	B	14	19
Flat, I					
664	3-6	Light grey loose sand.	A_2	8	3
665	6-12	Orange-brown sandy clay.	B	16	28
666	18-24	Light grey sandy clay.	C	16	24
667	30-33	Light grey-green sandy clay.	C	26	25

Table 22. Variation in Ni and Cu with depth in anomalous soil profiles.

Sample No.	Depth (ins.)	Description	Horizon	Ni (ppm)	Cu (ppm)
Mølland, Traverse I, 50' E					
770	6-12	Orange-red sandy clay.	B	250	78
771	18-24	Light brown sand.	C	175	39
Mølland, Traverse I, 60' E					
772	6-12	Dark red-brown clay.	B	80	85
773	18-24	Light brown sand.	B-C	75	40
Mølland, Traverse III, 0' E					
807	9-12	Dark red-brown clay.	B	130	53
808	12-18	Medium grey-brown sandy clay.	B-C	76	36
Flat, II					
893	0-6	Humus.	A_1	140	206
894	6-12	Medium brown sandy clay.	B	84	37

Enrichment of trace metals in the A_1 and B horizons is a commonly observed feature in podzols. The factors producing this pattern are thought (Hawkes and Webb 1962) to be:

(i) uptake of trace metals from the deeper levels of the soil by plants, and subsequent accumulation in the humus layer;

(ii) leaching of metals from the A_2 horizon by downward percolating rain-water enriched in humic acids released from decomposing organic debris in the humus layer.

(iii) Accumulation in the B horizon of metals leached from the A_2 horizon, and also released during the decomposition of organic debris in the humus layer.

(c) Mechanical analysis and the distribution of metals between size fractions

All the samples investigated were from the B horizon of the soil profile; for 3 samples (2400, 2401 and 2402) the parent material was shallow glacial till, while for the fourth (2405) it was glaciofluvial sand. Samples 2400 and 2402 were collected from the anomalous section of soil Traverse I, approximately at stations 30' E and 40' E (figs. 28 and 29); the sample sites are in a narrow gulley and are freely drained, although there is an abundant groundwater flow from poorly-drained areas up-slope, as evidenced by a spring emerging at the mouth of the gulley. Sample 2401 was collected at station 600' E, Traverse I (figs. 28 and 29), a well-drained background site. Sample 2405 was taken from a roadcut ½-mile south of the prospect, also a well-drained background location. The mechanical composition and the distribution of Ni, Cu, Fe, Mn and Co for the -2mm fraction of the samples is shown in fig. 31. The samples derived from till have virtually identical mechanical compositions, being poorly sorted with a bi-modal size distribution and an abundant silt fraction; sample 2405

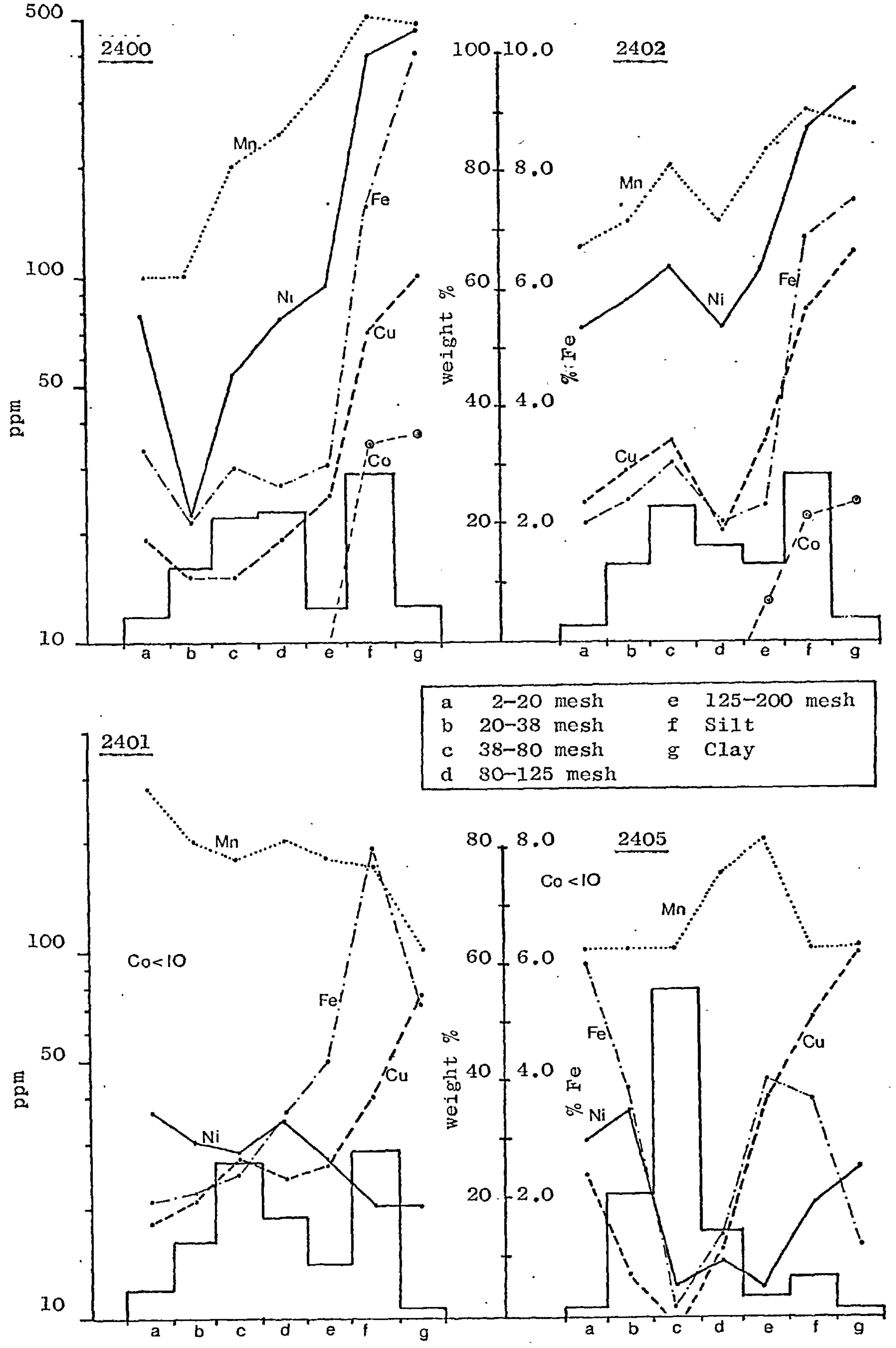


Fig. 31 Mechanical composition and the distribution of Ni, Cu, Fe, Mn and Co between size fractions for B horizon soils, Mólland.

is well sorted, the particle-size distribution being similar to that of modern stream sediments (cf. fig. 43).

The two anomalous samples show a distinct increase in the content of all metals with decreasing grain-size, but it is evident that there is an increase of similar magnitude in the background samples in the case of Fe and Cu. Differences in metal distribution for anomalous (mean of 2400 and 2402) and background (2401) samples are compared more rigorously in table 23, where the contrast between the background and anomalous value (i.e. metal content of anomalous sample ÷ metal content of background sample) is given for each size fraction. The most significant features are :

(i) in size fractions coarser than 125 mesh Ni shows a consistent two-fold contrast. Contrast increases slightly in the (-125 +200) fraction but is an order of magnitude higher in the silt and clay fractions.

A mineralogical investigation (p.118) was carried out to determine if the variation in Ni content between size fractions was related to changes in mineralogy, and a series of experiments (p.126) conducted to investigate the mechanism by which Ni is concentrated in the silt and clay fractions of anomalous soils.

(ii) Cu shows negligible differences in fractions coarser than 200 mesh and contrast is low (1.8 and 1.5) in the silt and clay fractions.

Table 23. Distribution of Ni, Cu, Co, Fe and Mn in the constituent size fractions of anomalous and background soils.

Size fraction	Ni			Cu			Co			Fe%			Mn		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
2mm-20mesh	74	36	2.0	24	18	1.3	5	12	0.4	2.7	2.0	0.7	100	280	0.4
20 - 38	54	30	1.8	22	22	1.0	6	8	0.8	2.3	2.1	1.1	120	200	0.6
38 - 80	82	28	2.9	25	27	0.9	8	8	1.0	3.0	2.5	1.2	200	180	1.1
80 - 125	74	34	2.2	20	24	0.8	8	10	0.8	2.4	3.4	0.7	190	200	1.0
125 - 200	99	27	3.6	30	27	1.1	10	10	1.0	2.7	4.4	0.6	280	165	1.7
Silt	320	20	16.0	74	40	1.8	28	8	3.5	7.2	8.0	0.9	395	100	4.0
Clay	390	20	19.5	107	70	1.5	30	6	5.0	8.8	5.3	1.7	360	100	3.6

A = mean of two anomalous samples (2400 and 2402)

B = background sample (2401)

C = A/B

(iii) Contrast for Fe is negligible or low in all fractions. Fe content increases markedly in the silt and clay fractions of both anomalous and background soils compared with size fractions coarser than 200 mesh.

(iv) Mn shows a moderate contrast in the silt (4.0) and clay (3.6) fractions, and since Mn is not associated with the sulphide mineralisation, this is at first sight surprising. Horsnail (1968) demonstrated that Mn is leached from waterlogged soils, and after travelling in groundwater solution may be reprecipitated in better drained areas adjacent to drainage channels. The explanation for the higher Mn content of the anomalous samples is therefore thought to lie in the different hydrological conditions at the anomalous and background sample locations; the background sample was collected from a freely-drained, open slope, whereas the anomalous localities lie in a narrow drainage gulley containing an intermittent stream and receiving an abundant groundwater flow from waterlogged areas up-slope.

(v) Co shows a moderate contrast in the silt (3.5) and clay (5.0) fractions and, since Co occurs with Ni and Cu in the sulphides, this may simply reflect the low Co tenor of the ore. A second possibility which must be considered, however, is the scavenging effect of secondary Mn oxides on Co (Horsnail 1968), particularly in view of the similar contrast shown by the two metals in the silt and clay fractions.

(d) Mineralogical analysis

The mineralogy of the constituent size fractions of bulk sample 2401 was investigated to determine if the distribution of metals between size fractions was related to changes in mineralogical composition. Selected soil and rock samples were also investigated to determine to what extent the mineralogy of the -80 fraction of the solonised till reflects that of the underlying bedrock. As pure mineral fractions had already been prepared from a number of rocks from the Mølland area, it was convenient to use these as standards in the interpretation of the X-ray diffraction data for soil and rock samples. Values of 2θ (Cu kα radiation, λ = 1.54050 Å), d-spacings and relative intensity of the principal Bragg reflections of hornblende, hypersthene, plagioclase and quartz (A.S.T.M. index) are given in table 24.

(i) Size fractions

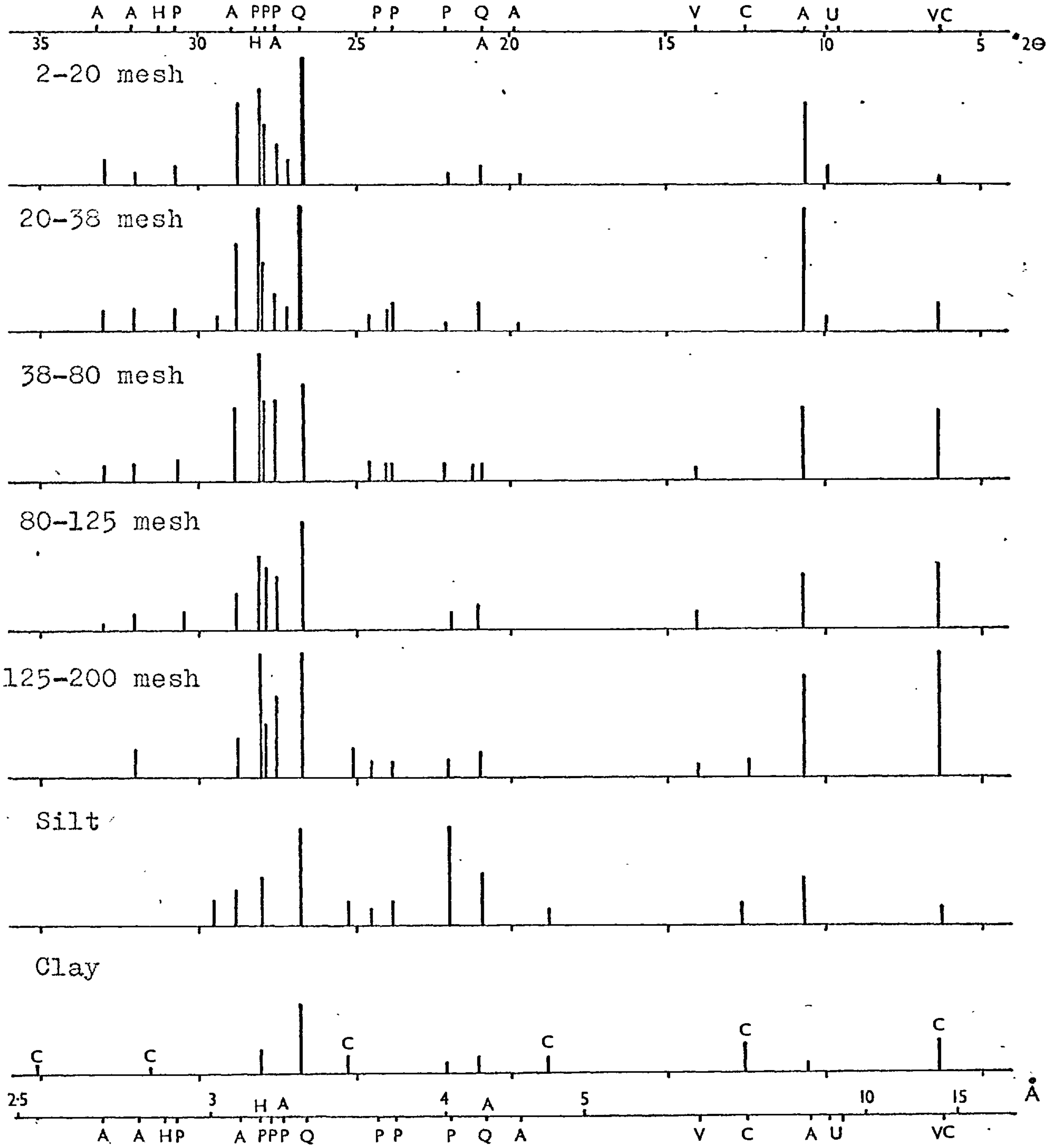
The principal Bragg reflections given by the various size fractions are given in fig. 32. The samples were initially run under standard operating conditions (p. 30); for the silt and clay fractions

Table 24. X-ray diffraction data for minerals separated from rock samples from the Mølland area.

$2\theta^{o}$ (Cu K_{α})	D-spacing (Å)	Relative intensity.
Hornblende (2455)		
10.55	8.38	100
28.7	3.11	100
32.0	2.79	80
27.3	3.26	20
21.2	4.19	20
33.1	2.70	10
Hypersthene (493)		
28.1	3.17	100
31.1	2.87	90
45.5	1.99	20
36.3	2.47	10
35.7	2.54	10
9.5	9.30	10
19.5	4.55	10
Plagioclase (519)		
28.1	3.17	100
27.9	3.19	100
23.8	3.74	20
22.1	4.03	20
24.4	3.64	20
28.5	3.14	20
Quartz (A.S.T.M. Index)		
26.6	3.35	100
20.9	4.25	15
36.5	2.46	10

this resulted in a very high background due to a combination of scatter by amorphous material and secondary fluorescence from the high iron content. In order to suppress background interference the silt sample was re-run with an assymetrically mounted aperture, and to enhance clay mineral peaks an oriented sample of the clay fraction was prepared and run under standard operating conditions. The Bragg reflections for the silt and clay fractions obtained by these methods are given in fig. 32.

It is evident that the mineralogy of the various size fractions is essentially uniform although the proportions of the dominant minerals, quartz, plagioclase and hornblende, vary somewhat between fractions. A moderate to strong reflection at about 14 Å (6.3° 2θ) occurs in all fractions and since the mineral was not readily identifiable the determinative scheme given by Dumbleton and West (1966) was followed. Results for the(-125 +200) fraction, in which the 14 Å peak was strongest, and the silt and clay fractions are summarised in table 25, from which it can be seen that vermiculite is dominant in the (-125 +200) fraction, and chlorite in the silt and clay fractions. Identification of vermiculite was confirmed by preparing a concentrate of the mica-like mineral present in the (-125 +200) fraction and verifying that this exfoliated



Key for Figs. 32, 33 & 34

A-hornblende
P-plagioclase
U-unidentified peak
C-chlorite
Q-quartz
H-hypersthene
V-vermiculite

Fig. 32 Principal Bragg reflections given by the constituent size fractions of soil sample 2401.

on heating. Both vermiculite and chlorite are alteration products of mafic minerals and have previously been reported from glacial soils derived from mafic or ultramafic rocks (Gjems 1967); their partition between the various size fractions of the till is thought to reflect the grain-size distribution of the secondary minerals in the parent rock. No pedogenic clay minerals were detected during this investigation and the silt and clay fractions of the soil are regarded as essentially weathered rock flour.

Table 25. Identification of Vermiculite and Chlorite in size fraction samples (following the method of Dumbleton and West, 1966).

Treatment	(-125 +200)	Silt	Clay
Untreated sample.	Peaks at 14.0 Å and 6.37 Å.	Peaks at 13.8 Å, 7.01 Å and 4.72 Å.	Peaks at 14.2 Å, 7.08 Å and 4.72 Å.
Heated at 550°C. for 1 hour.	14 Å peak destroyed.	Peak at 13.8 Å enhanced.	Peak at 14.2 Å enhanced.
Glycerol added.	Unaffected	Unaffected	Unaffected
Boiled in 50% HCl for 15 mins.	Not tested	13.8 Å and 7 Å peaks destroyed.	14.2 Å and 7 Å peaks destroyed.
Conclusion	Vermiculite	Non-swelling chlorite.	Non-swelling chlorite.

The presence of vermiculite in the coarser fractions of the soil is thought to be largely responsible for the anomalous Ni content in these fractions. Ross et al (1928) have shown that in the weathering environment vermiculite is able to fix Ni^{+2} moving in a dilute groundwater solution by base exchange replacement of Mg, and vermiculites containing up to 8.6% Ni were reported from soils overlying weathered dunite. Vermiculite separated from an anomalous sample (2400, -80 +125) was found to contain 230 ppm Ni compared with 95 ppm Ni in a background sample (2401, -80 +125) equivalent to a contrast of 2.4. Supporting evidence for the role of vermiculite is provided by the increased contrast shown by the (-125 +200) fraction (table 23), the size fraction in which the proportion of vermiculite is highest.

(ii) Soil and Bedrock

The mean Ni and Cu contents of background soils and underlying bedrock are compared for four localities in table 26, from which it is evident that at each locality the mean Ni and Cu contents of the soil are markedly lower than those of the bedrock. It is also noticeable that the change from norite to amphibolite or granite gneiss bedrock is marked by a decrease in mean Ni content of the soil, shown by the Kolmogorov-Smirnov test to be highly significant (99% probability) in each case; the difference in mean Cu content of the soils is, on the other hand, statistically not significant.

The mineralogy of selected soils (-80 mesh) and rocks from Mølland was compared to determine to what extent soil mineralogy reflects that of the underlying bedrock, and if leaching during soil formation or a pronounced difference in mineralogical composition is responsible for the markedly lower mean Ni and Cu contents of the soil.

The principal Bragg reflections of soil samples from Traverse I are shown in fig. 33, while fig. 34 gives the principal reflections of 5 norite samples. If the two are compared the following observations may be made:-

a) The soil samples have a high quartz content while the norite is quartz-free.

b) The plagioclase content of the soil samples increases eastwards, soils from the western part of the traverse having a similar plagioclase content to that of the norite samples.

c) Comparison of the hypersthene content of soils and bedrock is complicated by the fact that the most intense reflections of hypersthene and plagioclase

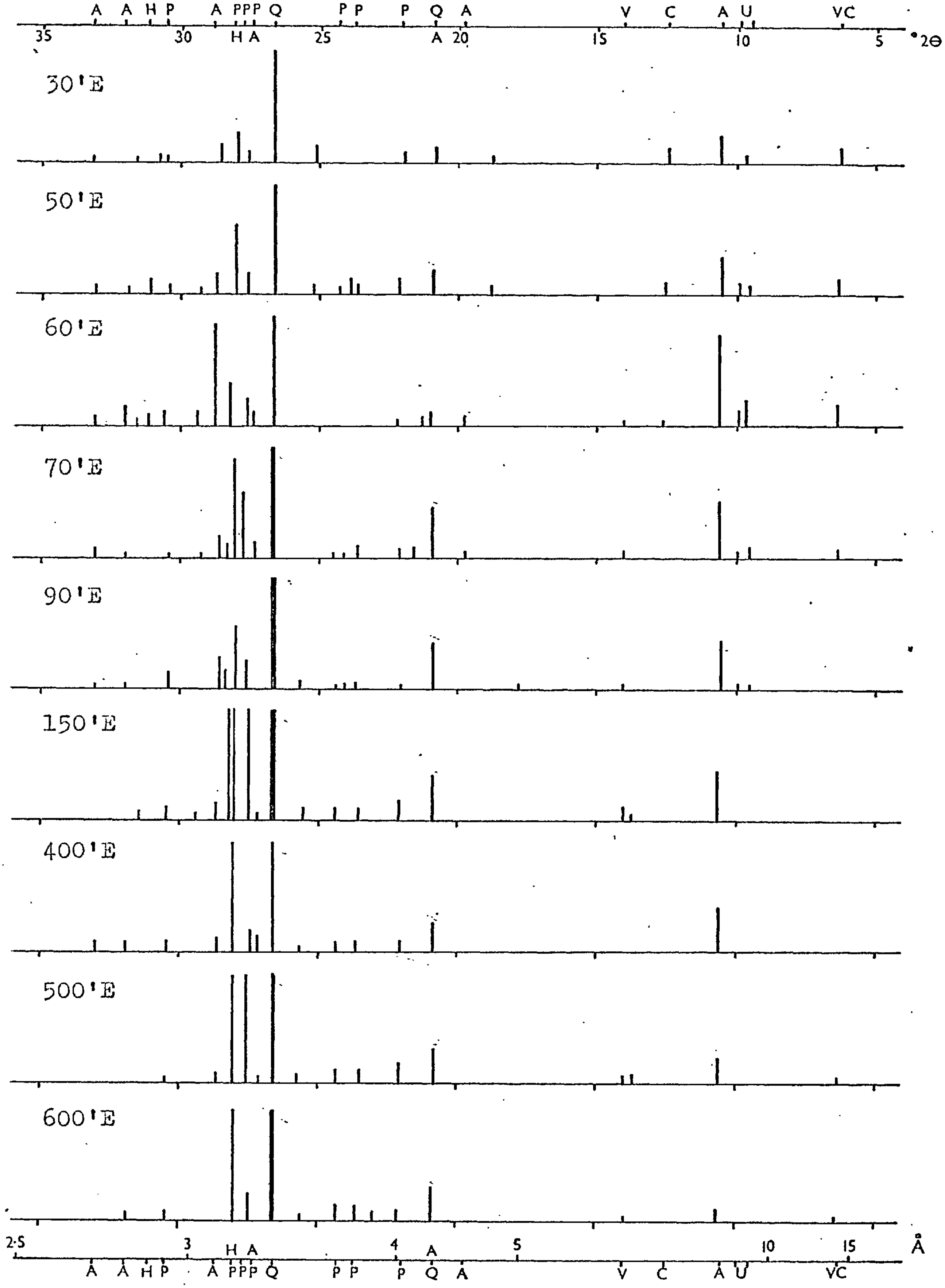


Fig. 33 Principal Bragg reflections given by B horizon soils from Traverse I, Mølland.

coincide (table 24). Hypersthene has a secondary reflection at $2\theta = 31.1^\circ$ ($d = 2.87$ Å), however, and this may be recognised in soil samples from stations 50' E and 60' E, indicating the presence of hypersthene in soils from the eastern part of the traverse.

d) The soil samples have a hornblende content similar to that of the norite.

It is concluded, therefore, that the -80 fraction of the solonised till reflects to some extent the mineralogy of the underlying bedrock (as evidenced by the hypersthene at 50' E and 60' E), but it is clear that a large proportion of the material, in particular the quartz content, is derived from beyond the immediate vicinity of the sample site.

Quartz occurs in the rocks of the Iveland complex, as a major constituent of widespread but small pegmatite bodies and as a minor mineral in the amphibolite, but it is considered most likely that the quartz content of the till is derived largely from the surrounding granite gneisses. The dominant direction of ice-movement in the Mølland area was from north to south (fig. 8); granite gneiss outcrops occur 2½ miles north of the Mølland prospect and this indicates the minimum distance over which the granite gneiss portion of the till has been transported.

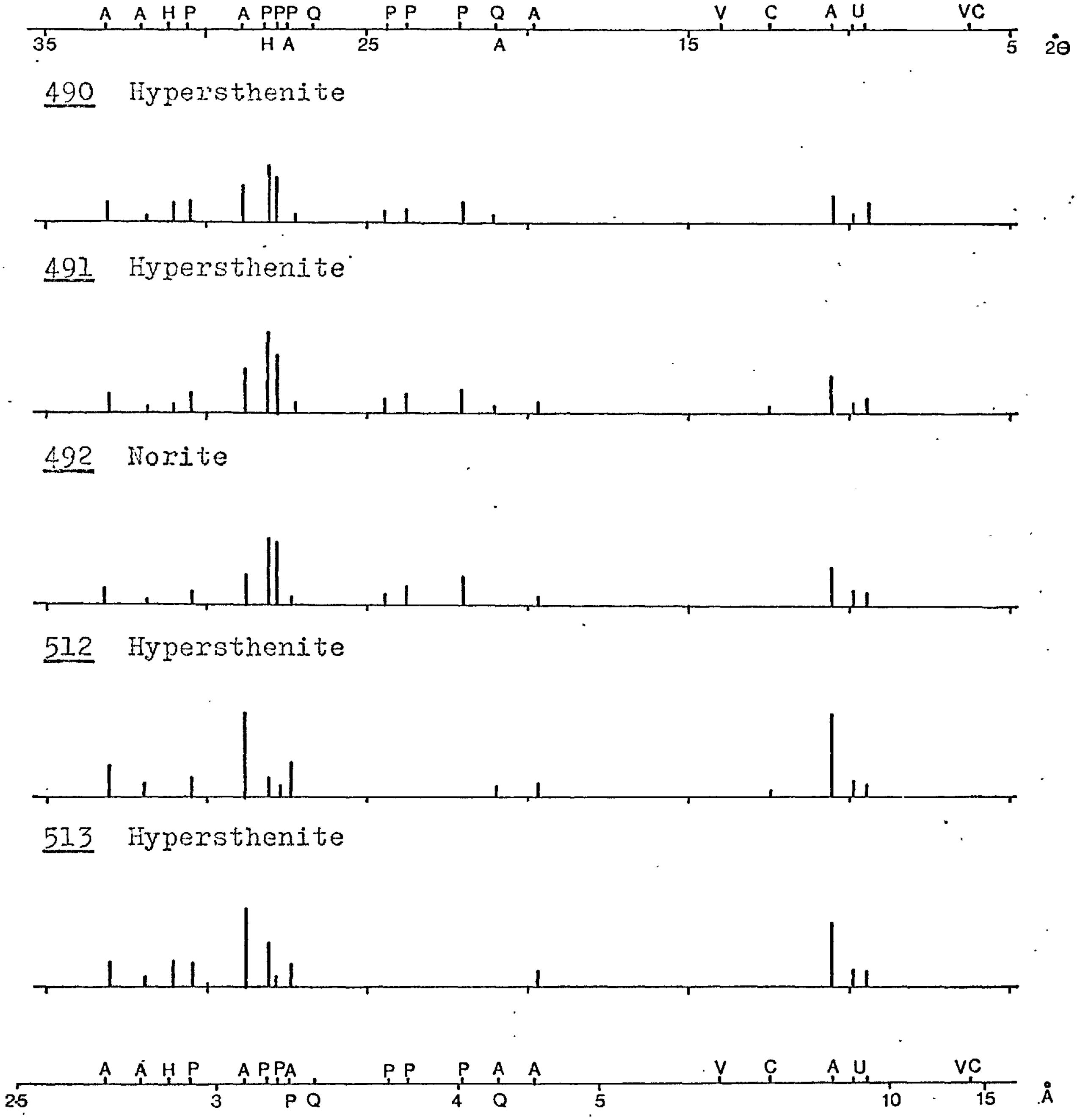


Fig. 34 Intensities of principal Bragg reflections for samples of the Mølland norite.

Table 26. Comparison of mean Ni and Cu contents in background B horizon soils and bedrock (rock data from tables 16 & 41).

Locality		Mean Content		Remarks
		Soil	Rock	
Mølland	Ni	19 ppm (66 samples)	445 ppm	Soil traverses underlain by norite.
	Cu	18 ppm (37 samples)	117 ppm	
Flåt*	Ni	13 ppm (91 samples)	111 ppm	Amphibolite dominant rock type.
	Cu	17 ppm (21 samples)	63 ppm	
Solberg*	Ni	<10 ppm (38 samples)	111 ppm	On amphibolite/granite gneiss contact, see fig. 40.
	Cu	N.A.	N.A.	
Flottorp	Ni	<10 ppm (10 samples)	21 ppm	Granite gneiss area.
*	Cu	23 ppm (37 samples)	42 ppm	

* Data presented on pages 144, 250 and 205 respectively

Table 26 reveals, however, that for each locality the mean contents of Ni and Cu in the soil are lower than those of the granite gneiss, and dilution by the granite gneiss derived component of the till is clearly not the only process involved in the observed discrepancy between Ni and Cu in soil and bedrock at Mølland, Flåt and Solberg.

Incomplete digestion of silicate minerals by the nitric-perchloric acid attack used in soil analyses may be a contributing factor in the case of Ni; this attack has been shown to be virtually complete for Cu however (tables 3 and 4), and it is concluded that both Ni and Cu are leached from the till during soil formation.

(e) Adsorption Experiments

Size fraction analysis (fig. 31) showed Ni to be markedly concentrated in the silt and clay fractions of anomalous soil samples, strongly suggesting a hydromorphic dispersion process. The Ni-bearing sulphide minerals at Mølland (violarite, pendtlandite and pyrrhotite, p. 73) are extremely unstable in the weathering environment and Ni is rapidly leached from the oxidising ore (cf. Michener et al 1944). Available data (Morris and Lovering 1952, Garrels 1960, p.177-179) indicate that under the Eh-pH conditions of the Mølland soils the soluble cation, Ni^{+2}, is the stable form of Ni and it is thought Ni derived from weathering sulphides will migrate principally in ionic solution.

The high Fe content of the silt and clay fraction suggested that adsorption by hydrous Fe oxides might be an important process in the fixation of Ni in anomalous soils; the adsorption of Ni by silt, clay and freshly prepared hydrous Fe oxide was therefore compared in a series of experiments modelled on the work of Jones (1957). The silt and clay used were obtained from the mechanical analysis of background sample 2401 and the hydrous Fe oxide was prepared by the method described by Jones: a solution of 405g Fe $(NO_3)_3.9H_2O$ in 1 litre of water is run slowly into 1 litre of 3.5 M NH_3, stirring continuously, then after settling, the precipitate is washed with deionised water, filtered, dried at 60°C. for two days and finally ground to -200 mesh.

Weighed amounts of silt (0.25g), clay (0.25g) or hydrous Fe oxide (0.5g) were placed in a series of numbered centrifuge tubes, followed by 20 ml of 0.1 M HCl containing 10 ug/ml Ni. The pH of the individual solutions was adjusted with 1 M NaOH to cover the range 4.0 to 8.0 at intervals of approximately 0.5 unit, and the volume then made up to 40 ml. with deionised water. Sample weight and Ni content of the solution were selected to give a final Ni content of the solid phase approaching that of naturally anomalous samples (2400 and 2402, fig. 31), given complete sorption of the available Ni. The suspensions were then shaken for 20 hours, centrifuged, the pH of the supernatant liquid checked and an aliquot taken for colorimetric determination of Ni by the method of Stanton (1966). This was repeated after shaking for

40 and 60 hours. It was found that the concentration of Ni remaining in solution did not differ significantly with time beyond the intial 20 hour period, indicating equilibrium had been reached, and the 3 colorimetric Ni and pH determinations were therefore meaned for subsequent plotting (fig. 35).

It is evident from fig. 35 that data for silt and hydrous Fe oxide plot, within the limits of experimental error, on a common curve; adsorption of Ni by both materials is clearly pH dependent, being negligible below pH 4.5 and complete at pH 6.5. Adsorption of Ni by the clay fraction on the other hand appears to be only marginally pH dependent, 60% of the available Ni being adsorbed from solutions as acid as pH 4.3.

The pronounced difference in the effect of pH on the sorption of Ni by (a) the silt fraction and synthetic hydrous Fe oxide, and (b) the clay fraction, suggests that two distinct mechanisms may be operative. Morris and Lovering (1952) cite an experimentally determined value of 6.7 for the pH at which precipitation of insoluble $Ni(OH)_2$ begins, and removal of Ni from solution by hydroxide precipitation may therefore be discounted in considering the adsorption experiment results at $pH < 7.0$.

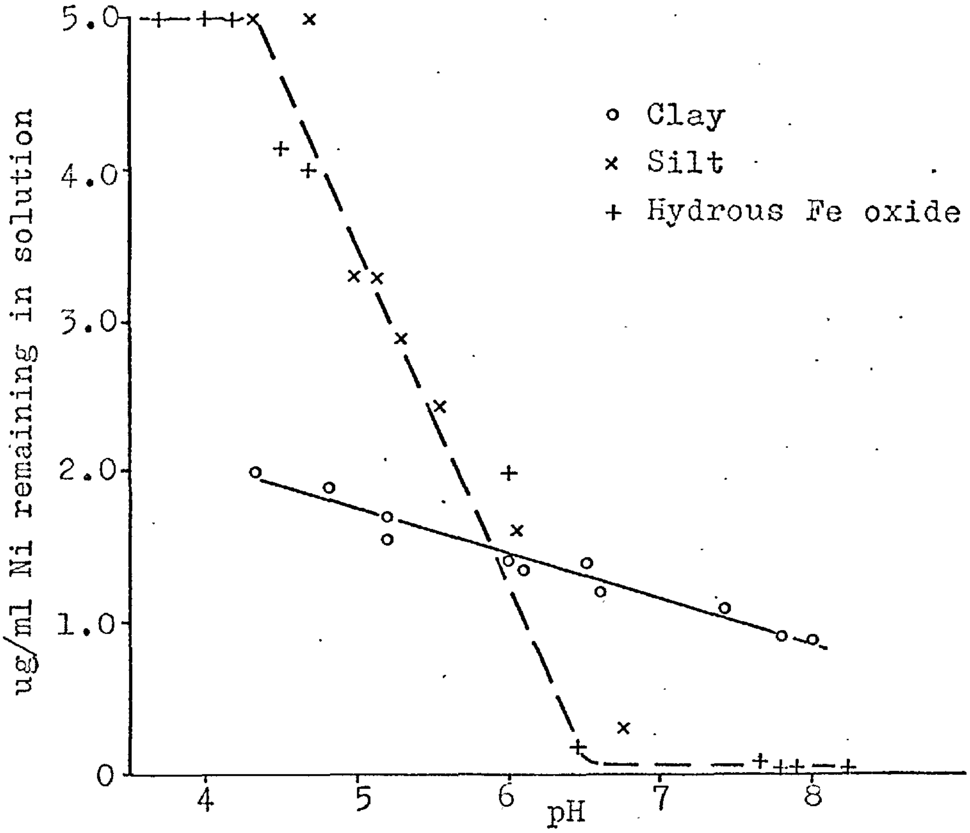


Fig. 35 Effect of pH on adsorption of Ni by clay, silt and hydrous Fe oxide (initial concentration 5 ug/ml Ni).

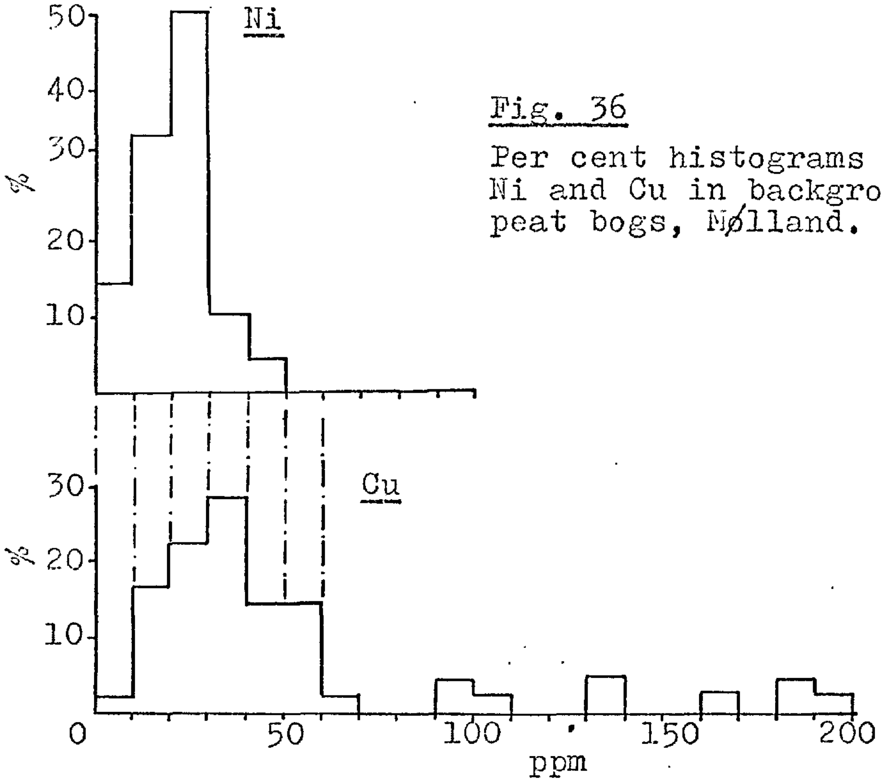


Fig. 36

Per cent histograms for Ni and Cu in background peat bogs, Mølland.

Skougstad and Hem (1960) found that adsorption of Cu by precipitates of $Fe(OH)_3$ is dependent on pH, and occurs only from solutions with a pH greater than 5.5. They considered that under acid conditions the positive zeta potential of $Fe(OH)_3$ colloids prevents adsorption of cations, but that this potential decreases with increasing pH, the colloids becoming negatively charged at high pH and therefore readily able to adsorb cations. Experimentally, Skougstad and Hem (1960) found that neutralisation of $Fe(OH)_3$ particles occurred between pH 5.0 and 6.0, while Krausse (1928) states that $Fe(OH)_3$ has an isoelectric point at pH 5.2; the present data for the effect of pH variations on Ni adsorption by hydrous Fe oxide (fig. 35) are in accord with these findings.

Jenne (1968), in a review article, considers that adsorption by hydrous oxides of Mn and Fe provides the principle methods of fixation of Co, Ni, Cu and Zn in soils and fresh water sediments. The virtually identical effect of pH on the adsorption of Ni by synthetic hydrous Fe oxide and by natural silt provides strong evidence that this is the dominant mechanism in the fixation of Ni in the silt fraction of anomalous soils.

The effect of hydrous Fe oxides is not so apparent in the case of the clay fraction which adsorbs approximately 60% of the total available Ni from solutions as acid as pH 4.3. Jenne lays great emphasis, however, on the importance of the surface area available for adsorption and considers that because of their great surface area hydrous Fe oxides occurring as partial coatings on clay minerals may exert a chemical activity far out of proportion to their concentration. It may be argued, therefore, that the observed differences between the silt and clay fraction are a reflection of the greater surface area of the latter, and that the dominant process in both cases is adsorption by hydrous Fe oxides.

Aleksandrova (1960) and Schnitzer (1968), however, have related the high Fe content of the B horizon of podzols to the accumulation of Fe-rich organo-mineralic complexes. Schnitzer showed experimentally that the solubility of metal-fulvic acid complexes decreased as the proportion of metal in the complex increased. He considered that fulvic acid, produced in the A_0 horizon, percolates downwards through the soil forming at first water soluble metal-organic complexes, principally with Fe and Al, but that by reaction with additional metals these complexes become increasingly insoluble and are finally precipitated as organo-mineralic colloids in the B horizon. Gradual mineralisation of such complexes leads to the accumulation of secondary hydrous oxides of Fe and Al (Aleksandrova 1960).

The Fe- and Al-humic colloids of the B horizon are described by Aleksandova as negatively charged over the normal range of soil pH and as such are readily able to adsorb cations. It is suggested, therefore, that in the clay fraction adsorption by high-Fe organo-mineralic colloids is the dominant process in the fixation of Ni, and that adsorption by hydrous Fe oxides is a minor factor, contributing perhaps to the slight increase in Ni adsorption with increasing pH.

At the end of the sorption experiments the aquaeous phase above the silt and hydrous Fe oxide samples was virtually colourless, whereas that above the clay samples was invariably deep brown, indicating that part of the organic matter in the clay fraction is present in a form soluble over the pH range 4 to 8. A number of workers have demonstrated that humic acids form chelate complexes with Ni (Broadbent and Ott, 1957, Pratt et al 1964, Schnitzer and Skinner 1967), and it is thought that the incomplete fixation of Ni by the clay fraction over the pH range 4 - 8 is due to the formation of soluble Ni-chelates which are not adsorbed by the high Fe- and Al-organo-mineralic colloids of the B horizon.

In an earlier section it was shown with reference to data for background B horizon soils that Ni was leached from the till during soil formation (p.126) although Ni derived from weathering sulphides was found to accumulate in the B horizon (p.112).

Bugelskii et al (1966) considered that humic substances in natural waters play an important part in solubilising Ni during the weathering of basic and ultrabasic rocks; in contrast to that derived from oxidising sulphides, therefore, Ni liberated from weathering till or bedrock is likely to migrate in groundwater solution principally in the form of organic complexes. The adsorption experiments with the clay fraction indicate that such Ni-chelates are not adsorbed by organo-mineral colloids in the B horizon. Size fraction analysis of background B horizon soils (fig. 31) supports this observation, in particular the data for the untreated silt and clay fractions of sample 2401 (used in the adsorption experiments) show no increase in Ni content compared to the coarser size fractions. It is concluded, therefore, that the dispersion or accumulation of Ni in the soil is dependent on the form in which it migrates in the groundwater, ionic Ni^{+2} being readily adsorbed by the silt and clay fraction of the soil, while Ni-chelates tend to be dispersed in the drainage system.

The effect of variations in Eh on the adsorption of Ni was not investigated but some theoretical inferences may be made. Jenne (1968) considers that Eh affects the fixation of heavy metals only in so far as it governs the precipitation or dissolution of the hydrous oxides of Fe and Mn in the soil or stream sediment. Fixation of Ni in the silt fraction of the soil is, therefore, likely to be limited by the dissolution of hydrous Fe oxides under conditions of low Eh. High Eh conditions may lead to the oxidation of organo-mineralic colloids in the soil, but as this results in the accumulation of secondary hydrous Fe oxides (Aleksandrova 1960) the fixation of ionic Ni from groundwater solution is unlikely to be materially affected.

The experimental data indicate that over the range of most frequently occurring soil pH (i.e. pH 4.5 - 5.5, fig. 2) ionic Ni is most effectively fixed from aqueous solution by the organo-mineralic colloids of the clay fraction, but that adsorption by hydrous Fe oxides in the silt fraction is also important. The size fraction data (table 23) reveal that for anomalous samples contrast is greater for the clay than the silt fraction, and this agreement between experimental and field data is taken as confirmation that adsorption is the dominant mechanism responsible for the fixation of ionic Ni in anomalous soils.

3. Ni and Cu in Peat

Background peat profiles were collected along the line of soil Traverses II and III; anomalous profiles were collected from a very restricted gulley-bottom bog on soil Traverse I and additional, possibly anomalous, profiles were collected over the strike extension of the mineralised zone on Traverse II. Sample locations are given in tables 27, 28 and 29, and positions of the bogs are shown on figs. 29 and 30.

pH and Eh data for background profiles are given in table 27. It is evident that while pH shows no systematic change with depth, being in fact remarkably constant for a given profile, there are marked variations between profiles; in this respect the present data are similar to the findings of Armands (1967) who related variations in pH to upwelling groundwater. Eh values range from mildly oxidising to strongly reducing, and as is to be expected, show a marked tendency to decrease with depth.

Ni and Cu data for anomalous and background peat profiles are given in tables 28 and 29; where available data for the underlying till are included and in table 28(a) the Ni and Cu content of soils immediately

Table 27. pH and Eh data for background peat profiles, Traverse III.

Depth (ins.)	160'E		180'E		200'E		250'E	
	pH	Eh	pH	Eh	pH	Eh	pH	Eh
18 - 24	5.0	.31	6.0	.27	5.0	.34	5.0	.33
30 - 36	5.4	.27	5.6	.21	5.4	.23	4.8	.37
42 - 48	5.4*	.31	5.4	.25	6.0	.23	4.0	.28
54 - 60			5.8	.27	5.5	.21	4.6	.27
66 - 72			5.4	.24	5.8	.17	4.6	.24
78 - 84			5.5	.29*	5.8	.24	4.8	.25
90 - 96					-	-	4.8	.20
102 - 108					5.5	.19	-	-
114 - 120							5.0	.17
138 - 144							5.2	.24

* Underlying till.

Table 28. Variation in Ni and Cu for anomalous peat profiles.

(a) Traverse I (over soil anomaly)

Depth (ins.)	(Soil) + 10'E		Sample 20'E		Location 30'E		40'E		(Soil)+ 50'E	
	Ni	Cu	Ni	Cu	Ni	Cu	Ni	Cu	Ni	Cu
6 - 12	185	50	95	55	140	49	120	42	250	76
18 - 24			120	53	400	86	120	93	175	39
30 - 36			270	64	500*	48*				
42 - 48			100*	32*						

\+ Soil samples, no peat cover

* Underlying till.

(b) Traverse II (possibly anomalous)

Depth (ins.)	Sample 20'E		Location 30'E		40'E	
	Ni	Cu	Ni	Cu	Ni	Cu
6 - 12	30	32	22	38	16	35
18 - 24	36	72	44	215		
30 - 36	48	207	52	282		
42 - 48	32	79	28	108		
54 - 60	20*	24*	30*	100*		

* Underlying till.

Table 29. Variation in Ni and Cu for background peat profiles.

(a) Traverse III

Depth (ins.)	160'E		180'E		200'E		250'E		350'E		600'E	
	Ni	Cu	Ni	Cu	Ni	Cu	Ni	Cu	Ni	Cu	Ni	Cu
18 - 24	15	32	28	28	22	26	36	47	22	21	20	39
30 - 36	15	10	20	23	25	37	20	33	15	15	20	22
42 - 48	10*	10*	16	35	25	37	24	62	20	15	36	22
54 - 60			24	57	22	34	48	54	22	21	25	21
66 - 72			25	54	22	44	30	60	25	187	25	36
78 - 84			15*	24*	32	56	-	-	20	184	25	49
90 - 96					28	50	-	-			28	95
102 - 108					28	53	36	56			22	197
114 - 120					40	83	20	42				
126 - 132							-	-				
138 - 144							25	45				

(b) Traverse II

Depth (ins.)	90'E		100'E		110'E		200'E		220'E		240'E		270'E	
	Ni	Cu	Ni	Cu	Ni	Cu	Ni	Cu	Ni	Cu	Ni	Cu	Ni	Cu
6 - 12	-	-	12	39	5	36	-	-	-	-	-	-	20	25
18 - 24	-	-	10	45	10	32	10	20	12	17	8	18	12	22
30 - 36	25	39	24	139	20	31	5	13	4	7	16	167	16	25
42 - 48	50	136					12	35	25*	9*			20	39
54 - 60													30	86

* Underlying till.

east and west of the anomalous bog are given. Background data for Ni has an approximately normal distribution (fig. 36) and threshold is taken as the upper limit of background variation (i.e. 50 ppm Ni). Background data for Cu, on the other hand, appear to consist of two populations, a lower, closely grouped distribution with a mean value of 33 ppm Cu, and a higher population represented by values ranging up to 200 ppm Cu (fig. 36). Reference to table 28(a) reveals that the Cu content of the Traverse I anomalous bog does not exceed 100 ppm; the lower distribution is therefore regarded as the background population and threshold for Cu taken as 60 ppm (the mean + two standard deviations of this distribution).

Both Ni and Cu increase with depth in the peat bog adjacent to mineralisation (table 28(a)); all samples from this bog are strongly anomalous for Ni but the basal peat layer alone is anomalous (weakly) for Cu. Contrast for Ni and Cu in the basal peat layer is compared with that of the underlying till and nearby soils in table 30, from which a close relationship between the Ni and Cu content of the basal peat and till is apparent.

Table 30. Contrast for Ni and Cu in basal peat layer, underlying till and nearby soil, anomalous bog, Traverse I.

	Basal Peat			Underlying Till		Nearby Soil	
	20'E	30'E	40'E	20'E	30'E	10'E	40'E
Ni	5.5	8.0	2.4	3.0	15	5.0	7.0, 5.0
Cu	1.0	1.5	1.5	1.0	1.4	1.4	2.0, 1.1

The peat profiles from Traverse II, 20'E to 40'E (table 28(b)) include strongly anomalous Cu contents and Ni values at or near threshold level. Recent EM surveys failed to reveal a continuation of the mineralised zone north of the northernmost exploration pit (Haldemann pers. comm.), and in view of the background Ni contents found in the underlying till at 20'E and 30'E (table 28(b)) it is considered unlikely that mineralisation extends as far north as Traverse II. Relatively rich sulphides are exposed in an exploratory pit 100 ft. south of the traverse however, and since the bedrock surface slopes down to the bog the high Ni and Cu values in the peat are thought to represent a lateral hydromorphic anomaly. It is noteworthy that, in contrast to Traverse I, the highest Ni and Cu contents occur at an intermediate depth, rather than in the basal peat layer and that the relative abundance of Ni and Cu is reversed.

The Ni content of background bogs appears not to vary significantly with depth. The Cu content, on the other hand, shows a marked tendency to increase with depth and occasional strongly anomalous Cu contents occur in the basal peat layer at background localities (e.g. Traverse II 100'E, 240'E and Traverse III 350'E and 600'E). The peat bogs in question are situated at a higher level than the outcrop of the mineralised zone (figs. 29 and 30) and lateral hydromorphic dispersion from known mineralisation may be discounted. It is unfortunate that samples of the underlying till were not available from these localities, although the consistently low Ni values suggest that the anomalous Cu is not related to mineralisation.

The distribution of trace metals in peat bogs has been studied by a number of workers (e.g. Mitchell 1954, Salmi 1955, 1956, 1967, Manskaya et al 1960, Hvatum 1964, Gleeson et al 1966, Kochenov et al 1967) and there is general agreement that the content of both Ni and Cu tends to increase with depth as indicated by the present data. Kochenov et al considered the dominant processes governing the accumulation of trace metals in the peat bog environment to be (a) biogenic accumulation, and (b) sorption from groundwater, the former being important only where the trace metal content of the peat is low.

Groundwater enters peat bogs either by diffusion from the underlying till in response to the high rate of evaporation from the bog surface (Salmi 1967), or locally as springs and seepages; Kochenov et al (1967) reported areas of metal enrichment in background bogs related to localised groundwater flows of this type.

Unfortunately, there are no data for the Ni and Cu content of groundwaters at Mølland, although a single sample of surface water draining an oxidising ore dump at Birkeland contained 270 ppb Ni and 2100 ppb Cu. Inferences regarding the relative concentrations of Ni and Cu in Mølland groundwaters may however, be drawn from the available soil and bedrock data, and are used below to account for the three distinct anomalous patterns revealed by the peat data (i.e. (a) strongly anomalous Ni associated with weakly anomalous Cu, (b) threshold Ni associated with strongly anomalous Cu, and (c) strongly anomalous Cu with low Ni).

The Ni:Cu ratio of the average Mølland ore is 3:1 (Bjørlykke 1947); the greater mobility of Cu, indicated by data for soils overlying mineralisation (p.110), suggests however that the relative concentrations of Ni and Cu in waters draining oxidising mineralisation may be reversed, as was noted at Birkeland. Since Cu is rapidly fixed from groundwaters by peat humic acids (Manskaya et al 1960, Ling Ong et al 1966), peat bogs into which these groundwaters drain may be expected to show a further enhancement of Cu relative to Ni. This pattern is readily apparent in the data for the anomalous section of Traverse II (table 28(b)), and it will be recalled that lateral hydromorphic dispersion from mineralisation in the higher ground to the south was suggested to account for this anomaly.

The anomalous peat bog on Traverse I, although downslope from mineralisation, appears on the above criterion, not to receive a direct groundwater flow from the weathering sulphides. Comparison of anomaly to threshold contrasts for the basal peat layer, the underlying till and nearby soil (table 30) indicates a close relationship between the Ni and Cu contents of the peat and mineral soil. In this instance the anomalous metal content of the peat appears to be due to upward diffusion of groundwater from the anomalous underlying till, the data suggesting an equilibrium between the metal content of the soil and groundwater.

The peat bog in question terminates 10 ft. from the lake shore in a steep face 2-3 ft. in height, the base being slightly above lake level. This is clearly a transient feature and suggests the peat accumulated at a time when the lake level stood somewhat higher than at present. A man-made dam partially blocks the exit of the lake but is currently disused; human activity may therefore have been responsible for a temporary rise in lake level, or the lake may have been dammed by beaver at an earlier stage. In either case the bog appears of fairly recent origin, and it may be assumed that, prior to the rise in lake level, a normal soil profile was developed on the underlying till.

It has been shown that hydrous oxides of Fe and Mn are largely responsible for the fixation of Ni and Cu in the silt fraction of freely-drained soils (section 2(e) above, and Jenne 1968), while in the clay fraction Ni is fixed principally through adsorption by organo-mineralic colloids (section 2(e)). Reducing conditions below the peat bog will lead to the dissolution of hydrous Fe and Mn oxides in the silt fraction, but will not affect the organo-mineral colloids of the clay fraction, and the soil environment below peat bogs is therefore thought to particularly favour the development of an equilibrium between anomalous metal contents in the soil and groundwater. It was earlier remarked (p.110) that the distribution of Ni and Cu within the Traverse I soil anomaly was suggestive of hydromorphic dispersion from mineralisation upslope; if correct, this indicates that metal-rich groundwater from the weathering sulphides is channelled at too low a level to enter the bog directly.

As already mentioned, the background bogs which carry strongly anomalous Cu in the basal peat layer (e.g. Traverse II 100'E, 240'E and Traverse III 350'E and 600'E) are located well upslope from the mineralised zone which is therefore discounted as the source of the anomalous metal; the consistently low Ni contents further suggest that the anomalous Cu values are not related to mineralisation. The high Cu values are thought in fact to reflect localised inflows of groundwater rich in Cu, leached during the weathering of till or bedrock, as described by Kochenov et al (1967). Spurious anomalies of this type complicate the interpretation of Cu data from peat surveys.

4. Reconnaissance soil traverses at Flåt mine

Two reconnaissance soil traverses were collected over the mined-out Flåt ore-body in an attempt to determine if leakage haloes related to suboutcropping give rise to anomalous Ni contents in the soil. To avoid contamination from the mine workings it was necessary to site the traverses on a steep, thickly wooded slope to the south of the main shaft. Traverse locations and the form of the ore-body (after Bjørlykke 1947) are shown in fig. 37, from which it can be seen that the ore-body is blind at 900 ft. and 1300 ft. for Traverses I and II respectively.

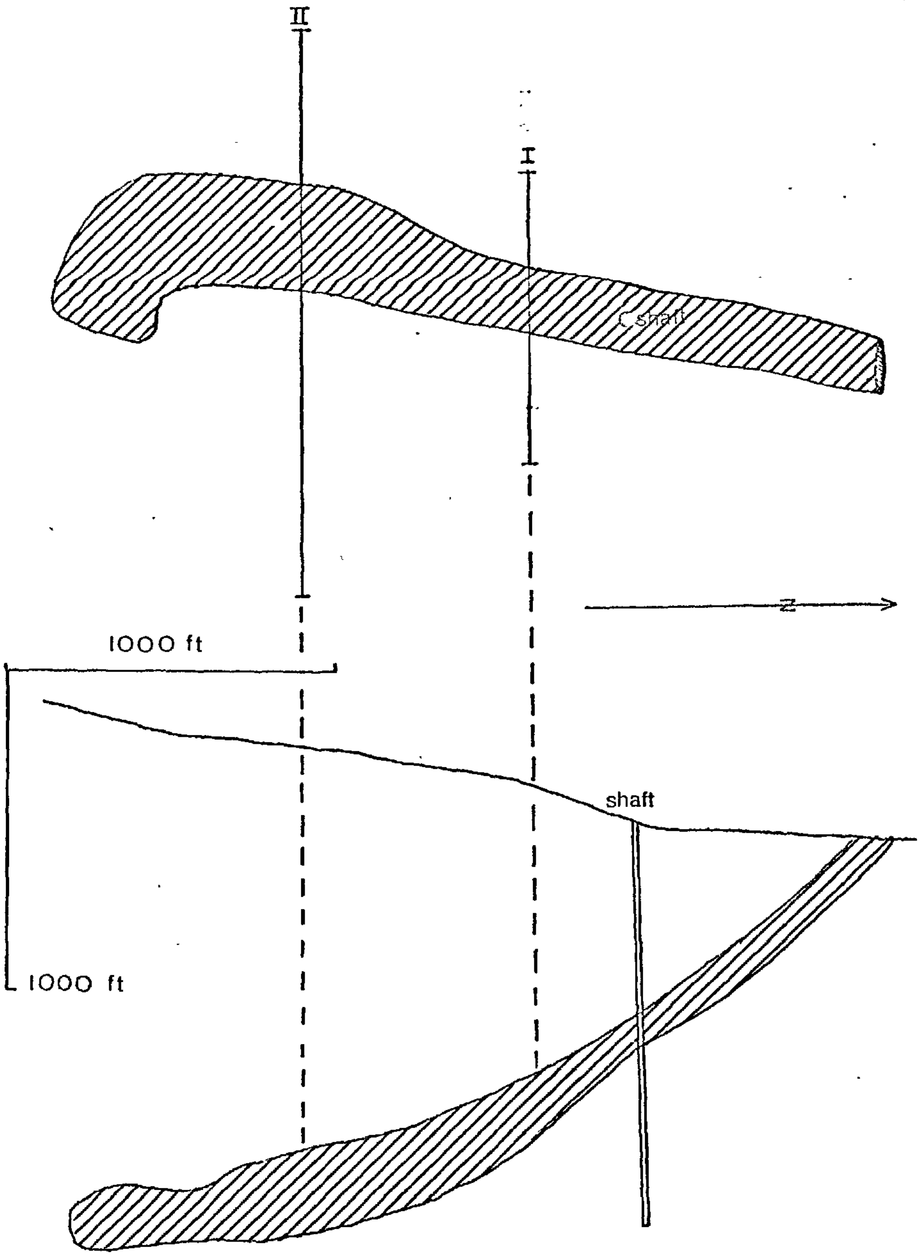


Fig. 37 Locations of reconnaissance soil traverses at Flat mine with relation to a suboutcropping ore body (ore body data after Bjørlykke, 1946).

Data for the soil traverses are given in figs. 38 and 39; samples from Traverse I were analysed for Ni and Cu, those from Traverse II for Ni only.

Ni and Cu show very similar distributions on Traverse I, anomalous values (up to 85 ppm Ni and 100 ppm Cu) occurring in soils over the inferred position of the ore-body and also at the foot of the slope. The latter is interpreted as a lateral hydromorphic anomaly due to a seepage of metal-enriched groundwater emerging in the poorly drained ground at the foot of the slope. On Traverse II a single sample is weakly anomalous but there is a tendency for high background Ni contents to occur over the inferred position of the ore-body while values elsewhere are much lower.

The Ni and Cu contents of the soil on Traverse I clearly indicate the presence of mineralisation blind at 900 ft., while on Traverse II mineralisation at 1300 ft. is reflected by a zone of high background Ni contents. It should be emphasised that the ore-body is defined by assay-wall boundaries and undoubtedly continues to higher levels as sub-ore grade mineralisation. Bjørlykke (1947) shows that a fault zone forms the eastern boundary of the ore-body and it is thought that this could well have provided a channel for the development of leakage anomalies at higher levels.

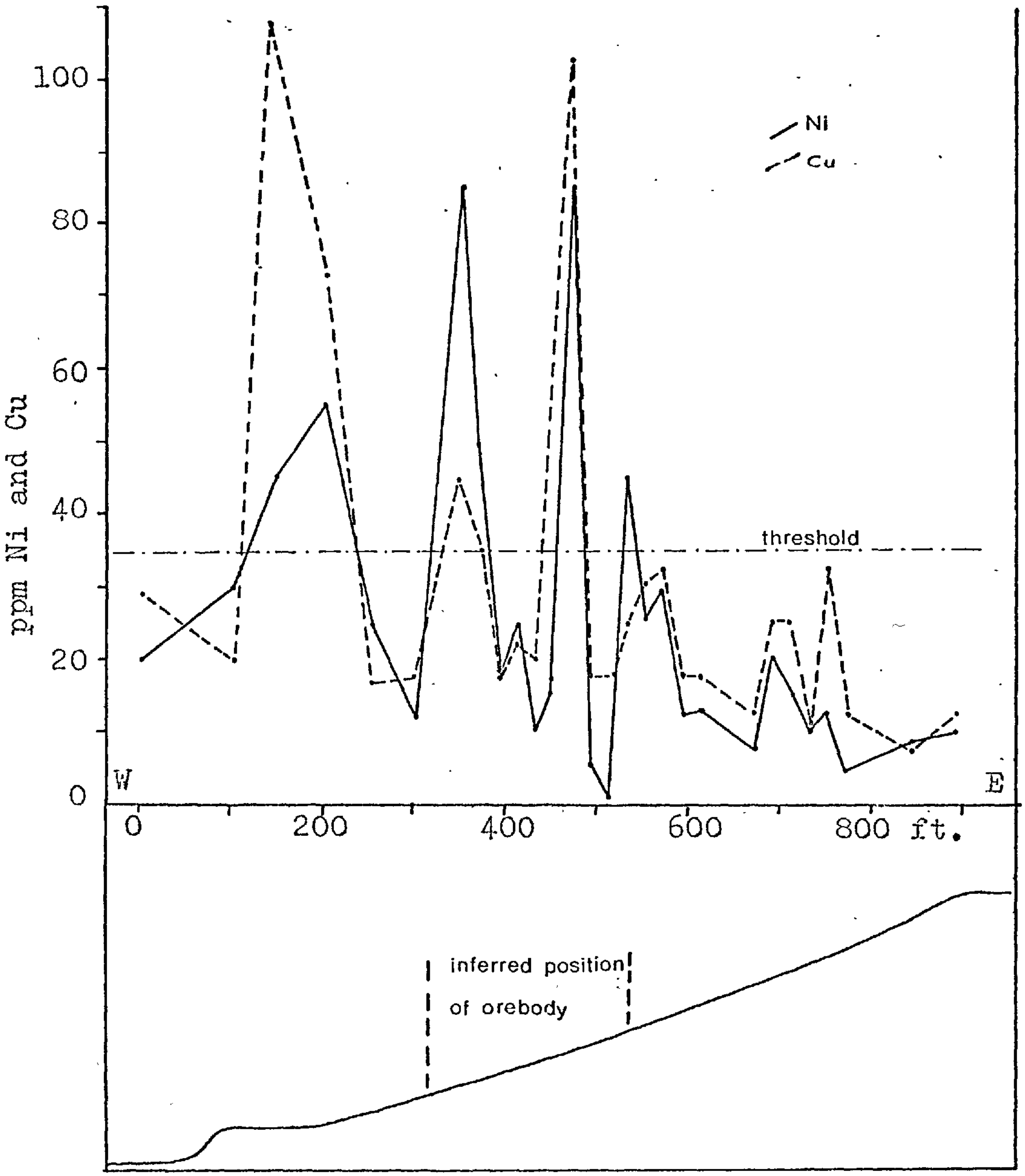
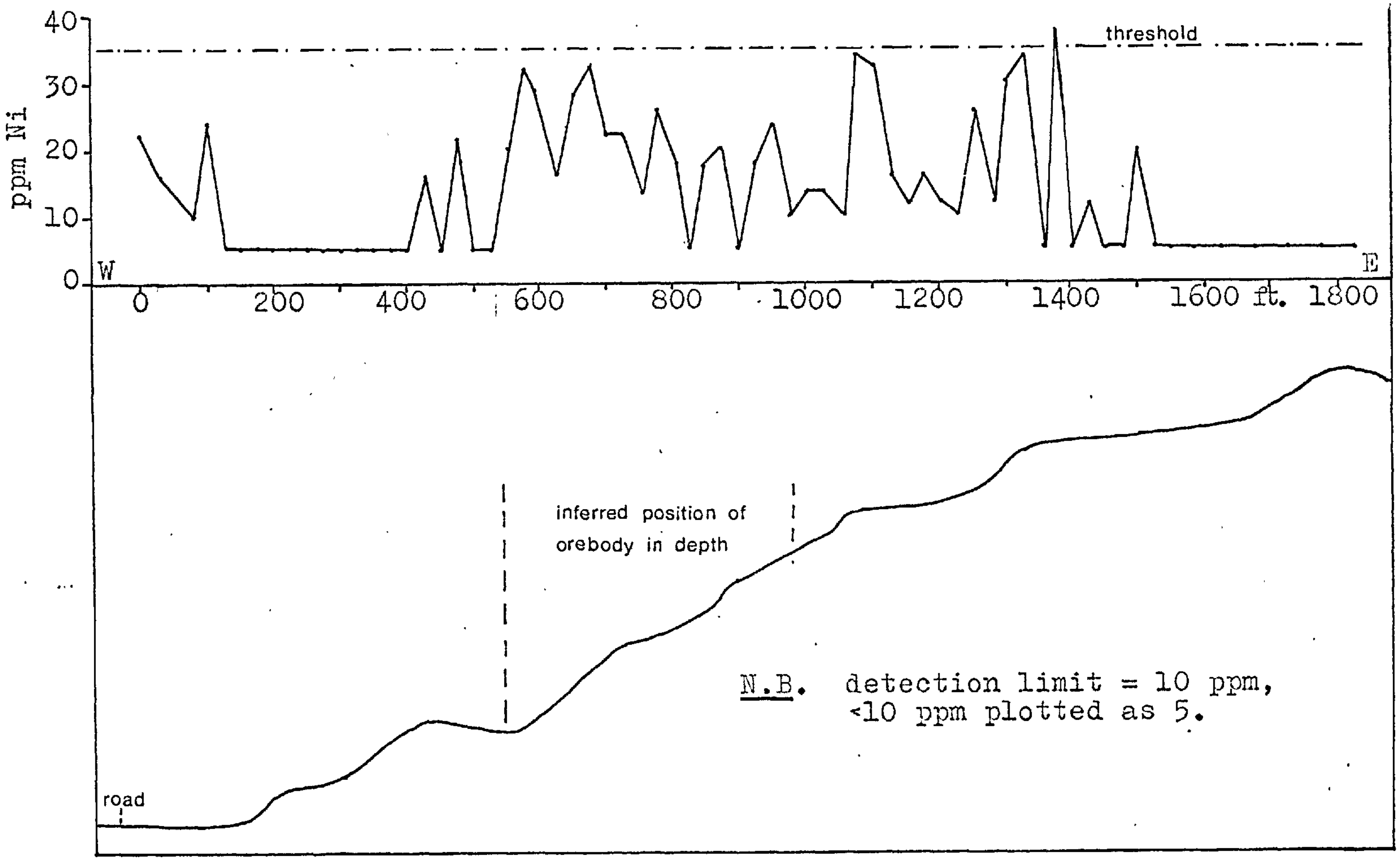


Fig. 38 Ni and Cu in B horizon soils, Reconnaissance Traverse I, Flat.



N.B. detection limit = 10 ppm,
<10 ppm plotted as 5.

Fig. 39 Ni in B horizon soils, Reconnaissance Traverse II, Flat.

Such features are by no means unique to the Flat deposit however, and it is concluded that under favourable circumstances soil sampling may serve as an effective method of detecting blind ore-bodies.

5. The relative importance of glacial and saline dispersion.

A knowledge of the processes by which secondary dispersion patterns are formed is clearly necessary for the successful interpretation of soil survey data. In glaciated areas mechanical dispersion is potentially an important factor and may lead to the development of distinct syngenetic dispersion trains. Fan-shaped trains of mineralised boulders have been traced as far as 25 miles down-ice from the source of the deposit (Grip 1953), although boulder fans 1-2 miles in length appear more common (Dreimanis 1958, Kauranne 1959); mineralised "micro-boulders" occurring in the till also give rise to fan-shaped anomalous dispersion trains which are generally shorter than the co-existing boulder fan (Kauranne 1959, Dreimanis 1958, 1960).

The strike of the mineralised zone at Mølland roughly parallels the general southerly direction of ice movement in the area (fig. 8) rendering it difficult to distinguish a glacial train with certainty. It is evident from fig. 28 however, that the soil anomaly is distinctly fan-shaped, being much wider on the southernmost or down-ice traverse (IV); the easterly extension of the anomaly on this traverse, if not related to new mineralisation, involves considerable upslope displacement (fig. 30) which can have occurred only as a result of glacial dispersion. Some degree of glacial dispersion is also indicated by the presence, in two of the soil samples selected for mineralogical analysis, of hypersthene, clearly derived from the underlying norite (p.124).

The principal sulphide mineral, pyrrhotite, is extremely unstable in the weathering environment and the features of glacial dispersion may be largely modified during weathering of the till (Pollock et al 1960, Canney 1965). Thus the distribution of Ni in the anomalous soil profiles, its concentration in the silt and clay fraction of the soil and the mode of occurrence of the anomalous Ni (i.e. adsorbed by organo-mineralic colloids in the clay fraction, by hydrous Fe oxides in the silt and by vermiculite in the coarser fractions), are all indicative of saline dispersion, but it is difficult to determine whether the Ni originates from oxidising sulphide "micro-boulders" within the till, or from in situ mineralisation.

Convincing evidence for a degree of saline dispersion from bedrock mineralisation is provided by the peat investigations, where a peat anomaly (Traverse II) was attributed to hydromorphic dispersion from mineralisation approximately 100 ft. from the sample point (p.139). For a second anomalous bog, (Traverse I) lying downslope from mineralisation, no evidence was found for a metal-rich groundwater flow from weathering in situ sulphides and the peat anomaly was attributed to upward diffusion of groundwater from underlying anomalous soil. The distribution of peak values for Ni and Cu in the soil anomaly on this traverse is, however, suggestive of hydromorphic dispersion and it is possible that metal-rich groundwater from the weathering sulphides is channelled at too deep a level to enter the peat bog directly (p.143). Hydromorphic dispersion is also thought to be responsible for the Ni and Cu anomalies in poorly drained ground at the foot of a steep slope on Traverse I at Flåt.

It is concluded that glacial transport has played a major role in the development of anomalous dispersion patterns at Mølland, but that these patterns have been modified by soil forming processes so that it is difficult in many cases to distinguish glacial and hydromorphic dispersion patterns. Locally, as in the

Traverse II peat anomaly, pure hydromorphic dispersion patterns may be recognised and it is thought that saline dispersion from weathering bedrock sulphides is also an important factor in the development of soil anomalies. It appears probable that the majority of soil anomalies overlying or adjacent to mineralisation are of complex origin, developed by a combination of both glacial and saline dispersion.

6. Conclusions

(1) Detailed soil sampling at the Mølland prospect has shown that anomalous Ni and Cu contents occur in the B horizon in the vicinity of known mineralisation. The Ni and Cu soil anomalies are broadly coincident with the mineralised zone, although the Ni anomaly at least extends beyond the most southerly known mineralisation; anomalies in the soil are wider than the underlying mineralised zone. For Ni the contrast between anomaly peak and threshold is greater in soil samples than in the bedrock mineralisation; for Cu the reverse is true, contrast being greater in the bedrock samples.

(2) Reconnaissance soil sampling at Flåt revealed anomalous Ni and Cu contents in the B horizon in an area where the ore-body is blind at 900 ft. The anomalous metal contents in the soil are considered to be related to leakage anomalies present in the bedrock above the Flåt ore-body.

(3) Anomalous soil profiles show a general decrease in Ni and Cu content with depth, both metals accumulating significantly in the B horizon. In background soil profiles Ni and Cu are uniformly distributed through the deeper levels of the soil, there being no significant accumulation of either metal in the B horizon. The content of both Ni and Cu is low in the eluvial A_2 horizon of background profiles and Ni shows a significantly enhanced content in the humus layer.

(4) It is concluded that close interval (approximately 25 ft.) sampling of the B horizon is an effective method of locating Ni-Cu mineralisation occurring beneath a thin cover of glacial overburden. Under favourable circumstances blind mineralisation may be detected by close interval sampling of the B horizon.

(5) The constituent size fractions of anomalous B horizon soils show a distinct increase in Ni, Cu, Co, Fe and Mn content with decreasing grain-size; a similar feature is shown by Fe and Cu in background samples. For size fractions coarser than 125 mesh the Ni content of anomalous samples is approximately twice that of background samples; this contrast increases slightly in the (-125 +200) fraction, but is an order of magnitude greater in the silt and clay fraction.

Cu on the other hand shows low contrast in the clay and silt fractions only.

(6) All size fractions of the soil contain quartz, plagioclase and hornblende, the principal mineralogical difference being the presence of vermiculite in size fractions coarser than 200 mesh, while chlorite is present in the silt and clay fractions. No pedogenic clay minerals were identified in the clay fraction which is regarded as essentially weathered rock flour.

(7) In the coarser size fractions of anomalous soils, Ni is present largely through adsorption by vermiculite. On experimental evidence it was concluded that anomalous Ni occurs in the silt fraction as a result of adsorption by secondary hydrous Fe oxides; adsorption by high-Fe organo-mineralic colloids is the dominant process by which anomalous Ni is fixed in the clay fraction.

(8) The mean Ni and Cu content of background B horizon soils is markedly lower than that of the underlying bedrock. Comparative mineralogical studies of bedrock and soils from Mølland showed that a large proportion of the -80 mesh fraction of the soil is derived from granite gneiss bedrock transported a minimum distance of 2½ miles. It was concluded, however, that the discrepancy between soil and bedrock metal contents is due not only to

dilution by glacial smearing but to leaching of Ni and Cu from the till during soil formation.

(9) The dispersion or accumulation of Ni in the soil is considered to be primarily a function of the form in which Ni migrates in the groundwater. Experimentally ionic Ni was shown to be readily adsorbed from solution by the silt and clay fractions of B horizon soils; Ni also forms soluble complexes with a constituent of the clay fraction organic matter and it was found that these Ni-chelates remained in solution under the conditions of the experiment. It is concluded that Ni derived from oxidising sulphides migrates in groundwater principally in ionic form and is therefore accumulated in the B horizon of the soil; weathering of till or bedrock, on the other hand, liberates Ni principally in the form of soluble Ni-organic complexes, which are not fixed in the B horizon but tend to be dispersed in the drainage system.

(10) Anomalous Ni and Cu contents occur in peat bogs at Mølland in the vicinity of known mineralisation. The content of both metals tends to increase with depth in anomalous peat profiles. Ni shows no significant variation with depth in background profiles, but the content of Cu increases markedly and may locally be very high at the base of background bogs.

(11) The relative concentration of Ni and Cu and their distribution in the peat profile offers a method of distinguishing superjacent and lateral peat anomalies. In superjacent anomalies the contents of both metals increase with depth, Ni being strongly anomalous throughout the profile while Cu may be anomalous only in the basal peat layer. In lateral anomalies the relative concentration of Ni and Cu is reversed and peak anomalous values may occur at intermediate depths in the peat profile, dependent on the levels at which the anomalous groundwater flow is channelled.

(12) It is concluded that close interval (approximately 25 ft.) sampling of peat profiles is an effective method of locating Ni-Cu mineralisation in bog covered areas. Peat profiles should be sampled at depth intervals of 1-2 ft., and if possible the underlying glacial deposits should also be sampled.

(13) Glacial dispersion is considered to have been an important factor in the development of the Mølland soil anomaly, but due to the instability of the ore minerals under weathering conditions the initial syngenetic dispersion patterns have been largely modified by soil forming processes. Saline dispersion from weathering bedrock sulphides is also an important factor and it is

concluded that the majority of soil anomalies overlying or adjacent to mineralisation are of complex origin, developed by a combination of both glacial and saline dispersion.

CHAPTER V. DRAINAGE SEDIMENT INVESTIGATIONS

A detailed drainage survey, sampling along all streams at 500 yard intervals, was conducted over the southern portion of the Iveland-Evje amphibolite and the enclosing granite gneisses, a total area of 40 sq. mls. The area covered by the detailed survey was selected in consultation with the Sulfidmalm A/S exploration team and includes the zone considered on geological evidence to be the most favourable for Ni mineralisation (Haldemann, *pers. comm*). The objectives of the survey were:-

a) to check the validity of the regional survey conclusions for this area;

b) to obtain orientation data at the Mølland prospect;

c) to identify targets for subsequent follow-up work.

Comparison of the detailed survey data with earlier results revealed variations in the Ni content of stream sediments collected from the same sample site at different periods; to investigate the causes of this variation a repeat sampling programme was undertaken at selected background and anomalous localities. The distribution of trace metals in the constituent size fractions of bulk samples collected from these localities was studied to ascertain the mechanism controlling dispersion of Ni in the drainage sediment.

The results of the detailed drainage survey are first discussed and compared with the findings of the regional survey. Orientation data for the Mølland prospect are then presented and used to assess the potential of other anomalous localities in the survey area. Details of the distribution of trace metals in the constituent size fractions of bulk stream sediments are then given; comparisons are made with similar data for soils and conclusions drawn regarding the dispersion of anomalous Ni in drainage sediments. Data from the repeat sampling programme are presented next and used to evaluate the relative importance of analytical error, sampling error and climatic fluctuations. Sampling error is shown to be a major cause of non-reproducibility at anomalous localities and methods of reducing this are suggested in a final section.

1. The Detailed Drainage Survey

Data from the detailed drainage survey (excluding the anomalous Mølland drainage system) are presented in fig. 40; the distribution of mafic rocks (as mapped by A/S Sulfidmalm geologists) is also shown. The data may be subdivided according to whether the stream catchment is underlain by:-

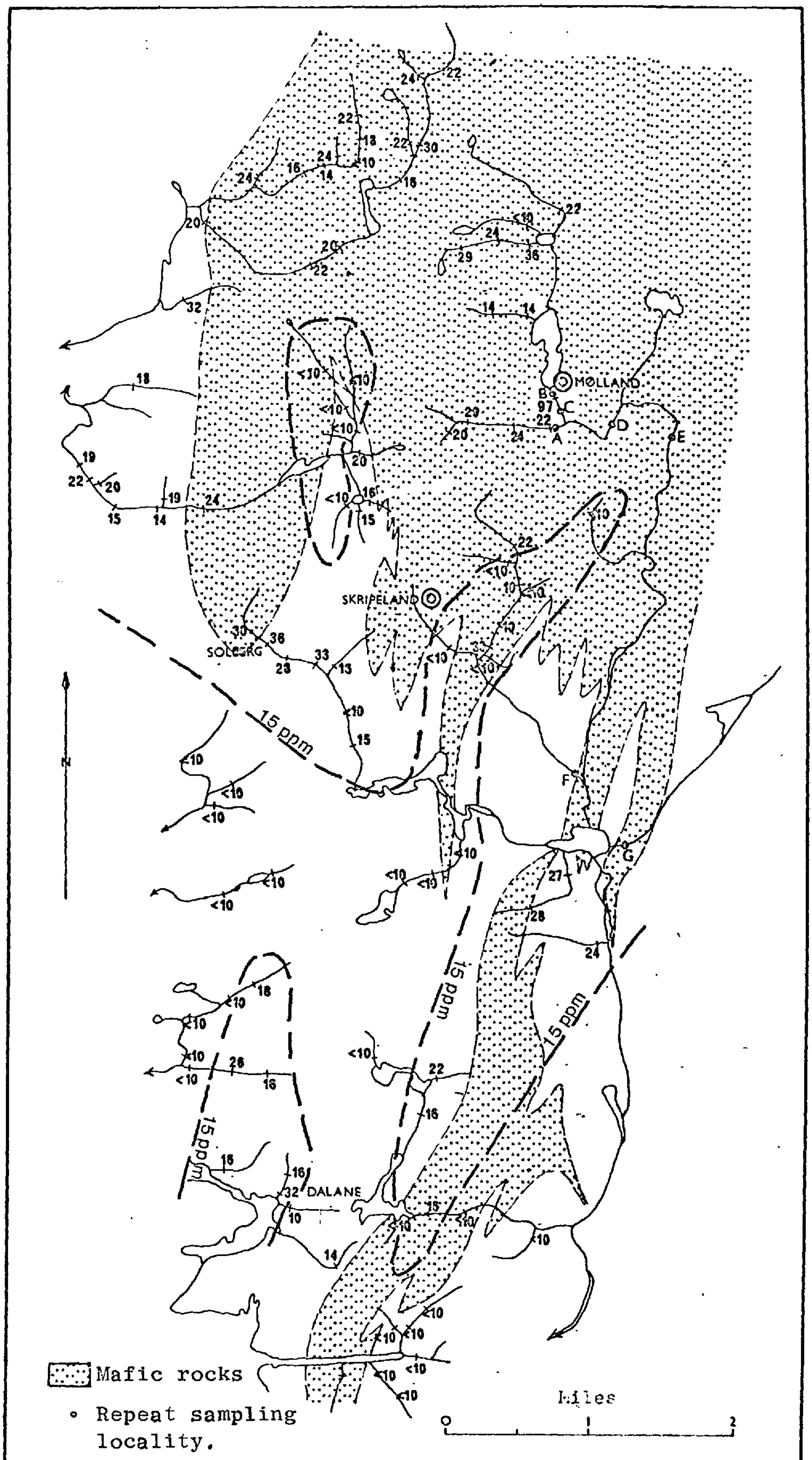


Fig.40 Ni (ppm) in stream sediments, Iveland detailed survey.

(i) mafic rocks exclusively;
(ii) both mafic rocks and granite gneisses;
(iii) granite gneiss exclusively.

Cumulative frequency plots for the three subsets are given in fig. 41(a). The Kolmogorov-Smirnov test indicates that subsets (i) and (ii) differ only at the 90% probability level whereas the granite gneiss subset differs significantly from both subsets (i) and (ii) at probability levels of 99% and 95% respectively. The data for all streams draining mafic rock areas (i.e. subsets (i) and (ii))may therefore be regarded as a single distribution; this differs significantly (99%) from the exclusively granite gneiss subset which is therefore considered as a second distinct distribution. Comparison of mean values for the two distributions (table 31) reveals that the change from mafic bedrock to granite gneiss is marked by a decrease in mean Ni content of the stream sediment similar to that already demonstrated for soils (table 26).

Table 31. Comparison of mean Ni content in stream sediment and soils in areas of granite gneiss and mafic bedrock.

Rock Type	Sediment	Soil
Amphibolite	17 ppm	13* ppm
Norite	-	19+ ppm
Granite gneiss	<10 ppm	<10 ppm

* Flat + Mølland

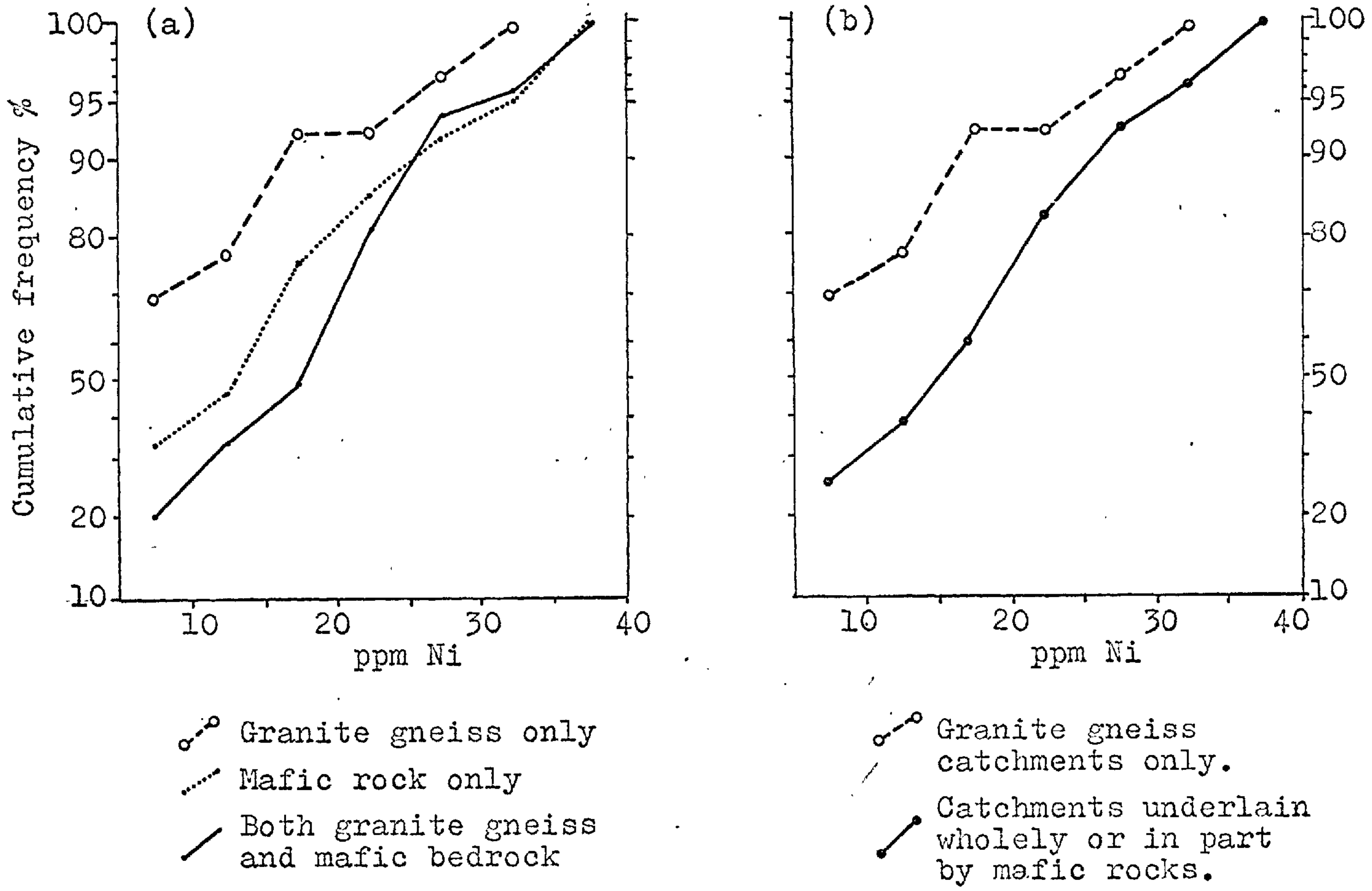


Fig. 41 Cumulative frequency plots for Iveland detailed stream sediment survey Ni data (excluding Mølland samples), classified according to bedrock cropping out in stream catchment.

Maximum separation of the mafic and granite gneiss catchment data occurs at a level of 10 ppm (fig. 41(b)) and the contour at 10 ppm effectively outlines the mafic rock outcrop (fig. 40). The cumulative frequency plot for the mafic catchment data shows no pronounced inflection, indicating an approximately normal distribution, and threshold for mafic areas is estimated as 35 ppm Ni, the value exceeded by 2.5% of the data (Hawkes and Webb 1962, p.31). This reveals, in addition to Mølland, two weakly anomalous localities, represented by an isolated sample north of Mølland and a group of high background to weakly anomalous values at Solberg. A narrow rust zone overlying minor Ni-bearing sulphides was found in a road cut at Solberg and the stream sediment anomaly was followed-up with a reconnaissance soil traverse (p. 250). The low Ni content (<10 ppm) immediately downstream from the Skripeland prospect is worthy of note.

The granite gneiss frequency plot (fig. 41(b)) shows a pronounced inflection, indicating the data consist of two populations (Tenant and White, 1959). The upper population is regarded as anomalous and threshold for granite gneiss areas is taken as 15 ppm (i.e. the Ni content at which the two populations are best separated); the association of Ni-bearing sulphides with mafic rocks suggests, however, that anomalous values in granite gneiss areas are unlikely to be related to mineralisation. Anomalous values within the granite gneiss outcrop are in fact confined to the Dalane area where the regional survey indicated an area of high Ni (fig. 12) and Mn (fig. 16). The coincidence of the Ni and Mn highs suggests that precipitation of Mn oxides in drainage channels may have led to enhancement of the Ni content of the Dalane stream sediment (Canney 1966, Horsnail 1968); further examples of the association of enhanced Ni and Co contents with Mn oxide precipitation are given on pages 169 and 177. Additional field work in the Dalane area, including soil sampling, is required to confirm this interpretation.

As in the case of the regional survey (p. 56), the present data provide no clear evidence for displacement of material from the mafic rock outcrop on to areas of granite gneiss bedrock as a result of glacial dispersion. It should be stressed, however, that the dominant direction of ice-movement was towards the south-south-east (fig. 8) and that samples were not collected in the area to the south-east of the mafic outcrop, where glacial dispersion patterns are most likely to occur.

The detailed drainage survey therefore confirms the principal conclusion of the regional study, that the Ni content of stream sediments may be used to delineate areas of mafic rock. Comparison of fig. 40 and the regional survey Ni rolling mean map (fig. 12) reveals a general similarity in Ni distribution, in particular both surveys show high Ni areas at Dalane and near Solberg, but there are important exceptions, the most significant being the complete failure of the regional survey to detect the anomalous Mølland dispersion. It is also apparent that the level of Ni contents in mafic rock areas is considerably lower for the detailed survey data, with the result that the differential between granite gneiss and mafic areas is reduced compared to the regional survey. It should be stressed, however, that two factors render a comparison of absolute levels between the two sets of data invalid:

(a) the positive analytical bias of the spectrographic method at low to intermediate Ni contents (p.15).;

(b) negative bias of the detailed survey data due to incomplete digestion of partially weathered silicates during the nitric-perchloric acid attack used to prepare samples for atomic absorption analysis (p. 18).

2. Dispersion of Ni in the Mølland drainage system

The Ni content of the -80 mesh fraction of stream sediments from the Mølland drainage system is shown in fig. 42; where more than one sample was collected at a sample location (e.g. the repeat sampling localities)

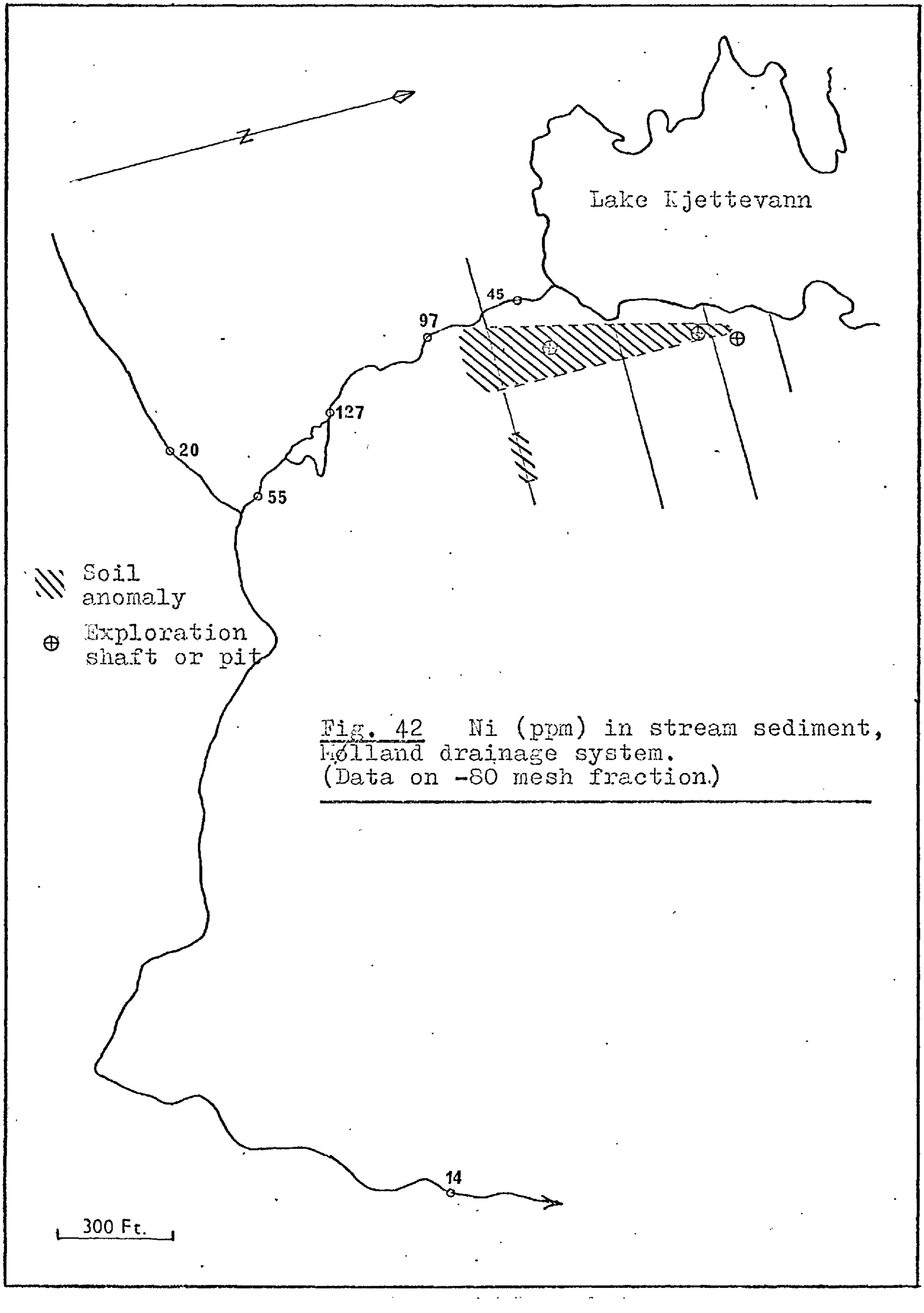


Fig. 42 Ni (ppm) in stream sediment, Mølland drainage system. (Data on -80 mesh fraction)

the mean Ni content is given. Soil traverses and the position of the soil anomaly are also shown, while the extent of the known mineralisation may be inferred from the exploration shaft and pits.

It is evident that the minor tributary draining the Mølland prospect is anomalous over its whole length (1000 ft.). The distribution of Ni values with respect to the projected intersection of the stream with the soil anomaly strongly suggests that direct erosion of anomalous soils is largely responsible for the peak Ni contents (127 and 97 ppm), although the size fraction data (p. 166) indicate that seepages of metal-rich groundwater draining from weathering mineralisation are a contributing factor. The lower values in the Mølland stream (45 and 55 ppm Ni) may be more typical of those to be expected under less favourable circumstances, where mineralisation and the associated soil anomaly lie some distance from the drainage channel. Fig. 42 shows rapid downstream decay of the drainage anomaly, background Ni contents occurring in the main stream 2800 ft. below the Mølland confluence, indicating the anomalous dispersion train to be of restricted length.

No firm conclusions concerning the effect of lakes on drainage sediment anomalies can be drawn from the Mølland data, since material eroded from the soil anomaly undoubtedly masks any anomalous dispersion pattern which may have persisted through the lake. Data from the Flottorp orientation locality (Chapter VIII) indicate that anomalous Mo dispersion patterns persist through small lakes in the drainage system and it is possible that a similar process may operate in the case of Ni. It is considered advisable, however, that stream sediment samples be collected upstream from lakes wherever possible.

Comparison with the Mølland orientation data suggests that neither of the weakly anomalous localities revealed by the detailed survey is likely to prove significant. Follow-up sampling was confined to the Solberg locality (p. 250), as the grouping of weakly anomalous and high background values indicated this to be the more favourable area.

3. Mechanical analysis and the distribution of metals between size fractions.

Bulk samples were collected for mechanical analysis from repeat sampling localities A, B, D, F and G (fig.40). The mechanical composition and the distribution of Ni, Cu, Fe, Mn and Co for -2mm material is shown in fig. 43. Comparison with particle-size distribution data for soils (fig. 31) reveals that stream sediments contain a much lower proportion of finer size material, the

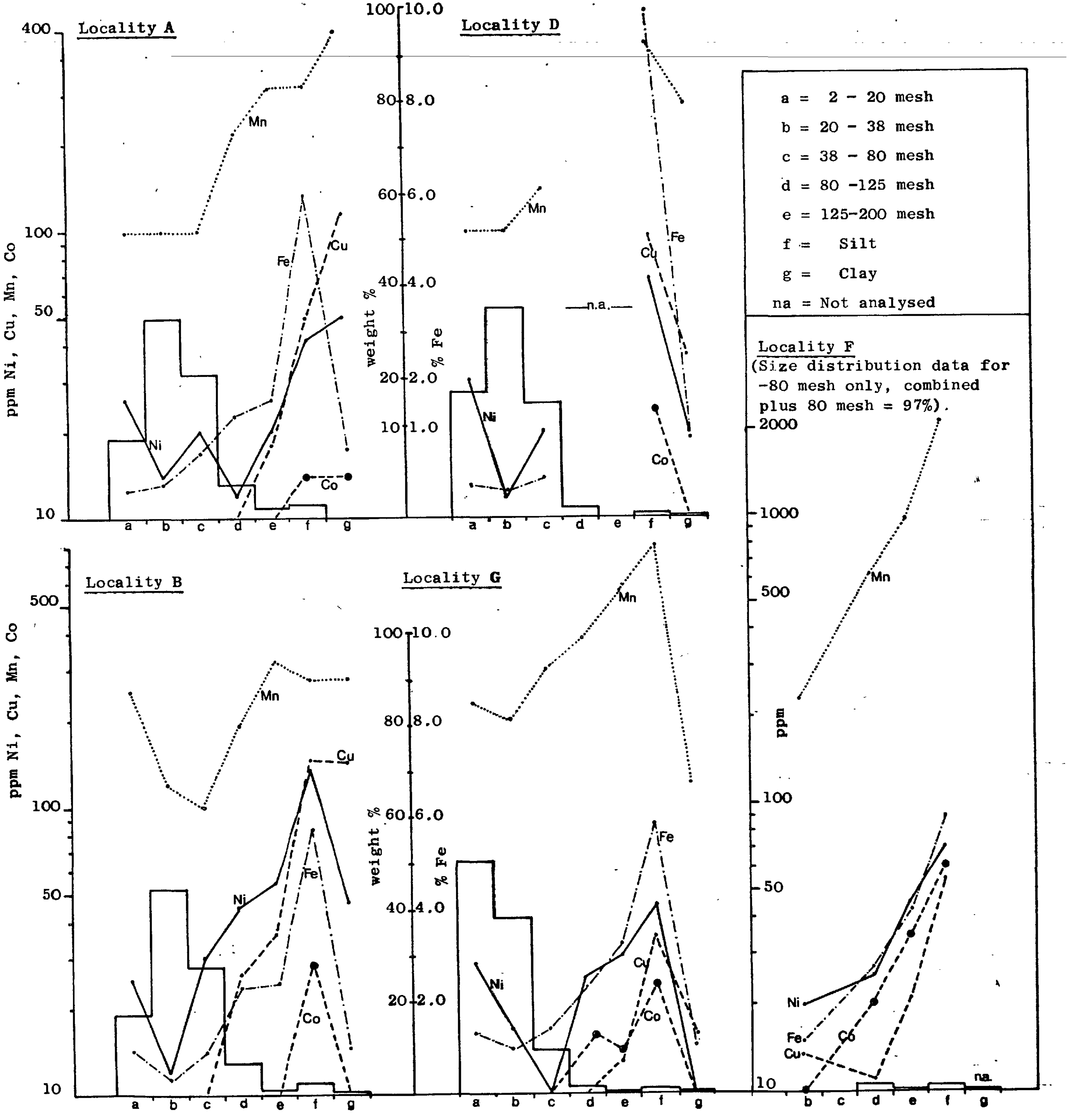


Fig. 43. Mechanical composition and the distribution of Ni, Cu, Fe, Mn and Co between size fractions for stream sediments, Iveland area.

difference being most marked in the silt fraction; this is evidently due to the ease with which the finer fractions are transported by moving water, particularly during periods of increased discharge.

The distribution of metals between the size fractions of stream sediments is broadly similar to that found in soils (i.e. metal contents show a general increase with decreasing grain-size); an important difference, however, is that all metals except Cu show a marked decrease in the clay fraction of both anomalous and background stream sediments. The significance of the latter feature is discussed on p. 167.

Metal contents of the constituent size fractions of anomalous (locality B) and background (mean of localities A and G) stream sediments are compared in table 32; contrast (i.e. anomalous value ÷ background value) is also given for each size fraction. The most significant features are:

(a) Ni shows no contrast in fractions coarser than 38 mesh; for size fractions from 38-200 mesh contrast ranges from 2 - 2.5; maximum Ni contrast (x3) occurs in the silt fraction. Contrast is low (1.5) in the clay fraction, the Ni content of the clay fraction from anomalous locality B being approximately $\frac{1}{3}$ that of the silt fraction.

(b) Cu shows an approximately 3-fold contrast in all size fractions less than 80 mesh; the content of Cu in the clay fraction approximately equals that of the silt fraction for both anomalous and background samples.

(c) The Fe content of the clay fraction is considerably less than that of the silt fraction in both background and anomalous samples. A similar but less marked feature is shown by Co and Mn.

Comparison of table 32 with size fraction data for soils (table 23) reveals that:

(a) Ni contrast is considerably lower in the stream sediment, particularly in the silt and clay fractions.

(b) Cu contrast is greater in the stream sediment, the anomalous stream sediment silt and clay fractions having a higher Cu content than the corresponding fractions in the soil.

(c) The Fe content of the steam sediment clay fraction is markedly lower than that of the soil (on an average by a factor of 7); in other size fractions Fe is only slightly lower in the stream sediment.

Table 32. Comparison of distribution of Ni, Cu, Co, Fe and Mn in constituent size fractions of anomalous and background samples.

Size fraction	Ni			Cu			Co			Fe%			Mn		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
2- 20	25	26	1.0	11	7	1.6	2	4	0.5	0.9	1.0	0.9	120	160	0.8
20- 38	12	16	0.8	4	6	0.8	1	4	0.3	0.4	0.8	0.5	100	150	0.7
38- 80	30	15	2.0	7	7	1.0	4	2	2.0	0.9	1.4	0.6	180	260	0.7
80-125	45	18	2.5	26	8	3.3	10	10	1.0	2.3	2.2	1.0	260	310	0.8
125-200	54	25	2.2	36	16	2.2	10	12	0.8	2.4	2.9	0.8	280	450	0.6
Silt	132	43	3.0	136	42	3.2	28	19	1.5	5.2	6.4	0.8	280	650	0.4
Clay	46	31	1.5	132	65	2.0	8	10	0.8	1.0	1.3	0.8	100	180	0.6

A = weak anomalous locality B

B = background (mean of locality A and G)

C = B/A

It was remarked above (p. 161) that erosion of anomalous soils was the most likely source of the Mølland stream sediment Ni anomaly. The increased Cu contents of the silt and clay fractions compared with those of anomalous soils indicate the addition of Cu to the stream bed environment, most probably by way of a groundwater seepage from weathering mineralisation known to occur east of the stream. It was inferred in an earlier section (p. 141) that such waters are enriched in Cu relative to Ni, and the low Ni content of the stream sediment silt and clay fractions compared to those of anomalous soils is taken as evidence that, in the case of Ni, the hydromorphic component of the stream sediment anomaly is of minor importance.

In general the lower Ni contrast shown by the stream sediment data is thought to be due to dilution by barren material eroded from background soils. The soil samples were collected exclusively from the B horizon and the slightly lower Fe content of the silt and coarser size fractions of the stream sediment is also regarded as due to dilution, in this case by material from soil horizons other than the Fe-rich B horizon. It is extremely unlikely, however, that dilution alone can account for the markedly low Fe content of the stream sediment clays (approximately 1/5 that of the silt fraction and 1/7 that of soil clays), nor for the low Ni contrast in this fraction; if correct this implies a fundamental difference in the effect of the stream environment on (a) the clay, and (b) the coarser fractions of eroded soils.

The mineralogy of the stream sediment clay fraction was not investigated, as barely sufficient material was obtained for chemical analysis. However, Griffin (1962) found the clay mineralogy of stream sediments to be directly related to that of the soil from which they were derived and thus, apart from the marked reduction in Fe content, the stream sediment clay fraction should be identical to that of the soil. Kennedy (1967) studied the cation-exchange capacity of stream sediments and concluded that the clay fraction tends to stabilise the composition of stream waters by alternately releasing and adsorbing cations. The extremely low solubility of Fe in aerated waters of pH >5.0 (Hem and Skougstad 1960) suggests that this process cannot account for the low Fe content of the stream sediment clays in the Mølland area, although it may have affected the Ni content of the anomalous clay sample.

In an earlier section (p. 131) it was concluded that Ni differs in its mode of occurrence in the silt and clay fractions of anomalous soils, being fixed through adsorption by hydrous Fe oxides in the silt fraction and by high-Fe organo-mineralic colloids in the clay fraction. Under oxidising conditions the clay fraction organo-mineralic colloids break down with the formation of secondary hydrous Fe oxides; adsorbed cations released by the breakdown of these colloids are likely to be readsorbed by the newly formed hydrous Fe oxides and, in the soil, gradually accumulate (Aleksandrova 1960). The low Fe content of the stream sediment clay fractions (approximately 1/7 that of soil clays) suggests that under the high Eh conditions of the stream environment organo-mineralic colloids are rapidly oxidised and the resultant hydrous Fe oxides dispersed as suspensions in the stream water. Adsorbed cations, particularly Ni^{+2} in the case of anomalous soil clays, are likely to be dispersed along with the hydrous Fe oxide suspensions, and it is this process which is thought to be principally responsible for the general low metal content of the stream sediment clay fraction.

Thus, while the difference in the mechanism controlling the fixation of Ni in the silt and clay fraction of anomalous soils has little effect on the distribution of Ni between these size fractions (table 23), it is of critical importance when, on erosion, anomalous soils are removed to the oxidising stream environment. Ni fixed in the silt fraction of anomalous soils, through adsorption by hydrous Fe oxides, will remain in the silt fraction of the stream sediment and the Ni content of this fraction will be affected only by dilution with barren material eroded from background soils. Ni fixed in the clay fraction of anomalous soils, through adsorption by high-Fe organo-mineralic colloids, will on the other hand be readily dispersed upon the oxidation of these colloids.

It is not clear from the present data whether the 1% Fe present in the stream sediment clay fraction occurs in silicates or as a minor hydrous Fe oxide phase. The source of the weakly anomalous Ni content (46 ppm) is likewise uncertain; it may be due to Ni fixed in the soil by a minor hydrous Fe oxide phase of the soil clay or, alternatively, may have been adsorbed from the groundwater seepage referred to earlier (p.166).

A final point worthy of comment is the high Mn content (2000 ppm) shown by the silt fraction at locality F. This fraction also has high contents of Ni (70 ppm) and Co (60 ppm) and serves to illustrate the scavenging effect of Mn oxides mentioned on page 159.

4. Repeat Sampling Investigation

Comparison of the detailed drainage survey results with data from an earlier sampling programme revealed variations in the Ni content of stream sediments collected from the same sample site at different periods.

It was considered that this variation could be attributed to three principal factors, i.e. (a) analytical error, (b) sampling error, and (c) climatic fluctuation (De Grys 1962, Donovan 1965), and a sampling programme was devised to test their relative importance.

Samples were collected from a total of seven background and anomalous localities during October 1966, June, July and August 1967 (marked by heavy rainfall and frequent flooding) and at weekly intervals from 26 June to 8 August 1968 (a dry summer with very low water levels), thus providing material collected under a range of climatic conditions. Sample locations are shown in fig. 40, and briefly described in table 33. To provide control for the investigation replicate samples were collected from localities A, B, D, E, F and G on the first day of the weekly sampling programme, thus excluding any climatic effect; control replicate samples were not collected at locality C, where only very limited sediment was available for sampling. Data for the repeat samples (1-11) and for the replicate control samples (12-17) are given in table 34. In order to eliminate spurious effects due to variable analytical bias, all the data were obtained from a single analytical sequence.

Table 33. Details of repeat sampling locations

Locality	Description
A	Background; abundant, poorly sorted sediment.
B	Anomalous; 20 yards downstream from dam below Mølland prospect. Mainly coarse sediment, difficult to sample.
C	Anomalous; 200 yards downstream from dam. Mainly coarse sediment, difficult to sample.
D	Background; abundant well sorted sand, broad open valley, 1200 yds. below Mølland.
E	Background; major stream with abundant, sandy sediment.
F	High background or low anomalous; narrow valley with abundant poorly sorted sediment. 3000 yds. downstream from Skripeland prospect.
G	Background; abundant, poorly sorted sediment.

In assessing the importance of analytical, sampling and climatically induced errors, a variation of the model proposed by Miesch (1967) is used, viz:-

$$X_{ij} = u_j + e_{ij} \qquad (1)$$

$$e_{ij} = (a + w + c)_{ij} \qquad (2)$$

$$s^2(e_j) = s^2(a_j) + s^2(w_j) + s^2(c_j) \qquad (3)$$

where: X_{ij} = Ni content of i-th sample from locality j.

u_j = mean Ni content of locality j.

e_{ij} = total experiment error for i-th sample from locality j.

a = analytical error

w = sampling error

c = error induced by climatic fluctuations

$s^2(e_j)$ etc. = variance of total experimental error for locality j (etc.)

It will be seen (equation 3) that the variance of total experimental error for a given locality (i.e. the variance of the Ni contents of the repeat samples) equals the sum of the variances of the analytical, sampling and climatic errors for that locality.

The variance of analytical error is readily determined from replicate analyses (table 35) and was found to be uniform over the range of Ni contents encountered in the repeat sampling investigations. This parameter is therefore regarded as a constant, equal to the mean of the values in table 35 (i.e. 35) and equation (3) above becomes:

$$s^2(e_j) = 35 + s^2(w_j) + s^2(e_j) \qquad (4).$$

Table 34. Ni content (ppm) of repeat samples from Mølland area (for details of locations see fig. 40. and table 33).

Locality	REPEAT SAMPLES																	MEANS		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	1–11	12–17	1–17
A	17	25	22	19	19	19	19	21	16	17	19	20	17	18	22	30	19	19	21	20
B	36	29	57	47	47	32	52	38	37	35	40	53	50	42	76	47	–	41	54	45
C	114	–	–	–	147	140	125	118	127	114	134	–	–	–	–	–	–	127	–	127
D	–	14	12	19	14	17	14	19	16	16	16	20	12	11	12	11	14	16	13	14
E	–	16	16	11	16	20	12	16	12	19	18	21	17	16	22	32	16	16	21	18
F	43	44	–	–	25	25	–	17	29	34	29	27	27	29	34	34	25	31	29	30
G	19	16	–	19	17	16	14	16	11	12	10	14	14	25	21	19	17	15	18	16

1 = October 1966

2 = June 1967

3 = July 1967

4 = August 1967

5 – 11 = Weekly samples June – August 1968

12 – 17 = Control replicate samples

Table 35. Calculated values of the variance of analytical error at various mean Ni contents.

Source	Ni ppm	Variance (s^2a)
5 replicates	51	35
"	30	36
"	20	36
23 replicates	10-120	32

The relative importance of sampling error may be inferred from the control replicate samples (i.e. samples 12-17, table 34) since, as these were collected during a single afternoon, the climatic factor (c_j) is absent; the variance of sampling error is therefore given by:

$$s^2(w_j) = s^2(e_j) - 35 \quad \text{(from equation 4).}$$

Substituting the calculated variance of the Ni content for the control samples (table 36, column 2) reveals a negligible sampling error for background localities A, D, E, F and G and it is evident that sampling error is a significant factor only at anomalous locality B.

Table 36.

Comparison of variance of the Ni content of control replicates (12-17) and repeat samples (1-11) by Snecedor's F-test, to determine importance of climatic factors.

Local-ity.	Control (12-17)		Repeat (1-11)		F	Signif-icance.
	Variance	d.f.	Variance	d.f.		
A	22	5	6.5	10	3.4	5%
B	173	4	76	10	2.3	NS
C	-	-	149	7	-	-
D	12	5	8.5	9	1.4	NS
E	37	5	9.4	9	3.9	5%
F	15	5	93	7	6.2	>5%
G	18	5	10	9	1.8	NS

The effect of climatic fluctuations is assessed by comparing the variance of the Ni contents of control (12-17) and repeat (1-11) samples for each locality using Snecedor's F test and the null hypothesis that climatic fluctuations have no effect on the Ni content of the stream sediments (table 36). The repeat sampling variance exceeds that of the control samples only at locality F and is in fact significantly lower (in statistical terms) for localities A and E.

It may therefore be concluded that the considerable climatic fluctuations over the three year period of the repeat sampling programme have affected the Ni content of the stream sediment only at locality F and that for all other localities the variation in Ni content over the three year period is no greater than that which would be expected from a combination of sampling and analytical errors.

A detailed examination of the locality F data (table 34) reveals two samples with anomalous Ni contents (1 and 2) the remainder being at or below threshold level (35 ppm, p. 158). If these two samples are omitted the variance of the repeat samples is reduced to 33; the F-test shows that this does not differ significantly from the variance of the control samples, confirming that these two anomalous values are responsible for the high variance of locality F.

Samples 1 and 2 were collected during periods of heavy rain and a process must be sought by which the Ni content of stream sediments may be enhanced during flood conditions. Unfortunately this was not recognised in time for a specific field investigation to be undertaken, but some deductions may be made from the available information. There are marked similarities between localities D and F in that both occur at approximately the same distance downstream from known mineralisation (i.e. Mølland and Skripeland, see fig. 40) and below confluences with background streams, although differences exist in sediment type and valley form (table 33).

Climate fluctuations have no effect on the Ni content of locality D and it is therefore concluded that the process operative at locality F is not of universal application but depends on a specific feature of either locality F or the Skripeland prospect.

The high Mn content (2000 ppm) in the silt fraction from locality F has already been mentioned (p. 169). Comparison of the mean Mn contents of the control samples (table 37) is also indicative of Mn oxide precipitation in the drainage channel at locality F. Horsnail (1968) related this to locally waterlogged soils and Mn oxide precipitation may therefore be regarded as reflecting a specific feature of locality F. Scavenging of trace metals, in particular Co, Zn and Ni, by Mn oxide precipitates has already been referred to (p. 57) and the high mean Co content at locality F (double that of other localities) is taken as evidence that Mn oxide scavenging is responsible for the near threshold Ni contents at this locality. It is difficult, however, to envisage that this process alone is the cause of the anomalous Ni contents after heavy rain.

Contamination of the drainage system with material derived from waste dumps at the Skripeland prospect may well be confined to periods of prolonged rain, particularly if the dumps are sited some distance from a drainage channel so that soluble weathering products and discrete, partially oxidised ore-particles are flushed into the drainage system only after exceptionally heavy rain. A similar mechanism was proposed by Donovan (1965) to account for fluctuations in the Zn content of weakly anomalous samples downstream from Pb-Zn mineralisation in Eire, and would, in this instance, lead to a sharp rise in the total Ni content of the stream water during floods, although due to the increased discharge the actual Ni content of the stream water probably decreases. Scavenging by Mn oxide precipitates would lead to anomalous Ni contents in the stream sediment in favourable locations (e.g. F) while, owing to rapid oxidation of the pyrrhotite fragments, the Ni content of the sediment in the upper reaches of the stream would return to normal once contamination ceased.

It is therefore concluded that locality F is atypical, the response to climatic fluctuations being largely governed by contamination from the Skripeland prospect, and that under normal circumstances climatic fluctuations do not give rise to significant variations in the Ni content of the stream sediment.

Table 37. Comparison of mean Mn, Ni and Co contents of control samples 12 - 17 for localities A, B, D, E, F and G.

	A	B	D	E	F	G
Mn (ppm)	288	246	300	294	785	385
Ni (ppm)	21	54	13	21	29	18
Co (ppm)	12	17	12	16	32	14

5. Sampling error at anomalous locations

In the absence of climatically induced variations the repeat and control sampling data for localities A, B, C, D, E and G may be pooled to arrive at a best estimate of sampling error; sampling error may also be assessed for locality F if the climatically influenced samples (i.e. 1 and 2) are omitted. Reference to table 38 confirms the earlier conclusion that sampling error is significant only at anomalous localities and that for background locations it is negligible with respect to analytical error. A higher sampling error is to be expected at anomalous localities since, while background stream sediment may be regarded as essentially homogeneous, that at anomalous localities will in the general case consist of three components, i.e. (a) sediment derived from the erosion of background soils, (b) sediment derived from the erosion of anomalous soils, (c) material fixed from metal-rich stream waters or groundwater seepages.

Table 38. Variance of total experimental error (s^2e_i), mean Ni content, and variance of sampling error ($s^2e_i - s^2a$) for repeat sampling localities, pooling all available data.

Locality	Mean Ni content	$s^2(e_i)$	Sampling error variance ($s^2e_i - s^2a$)
A	20	12	N
B	45	134	99
C	127	149	114
D	14	10	N
E	18	25	N
F*	28	24	N
G	16	15	N

N = Negligible   * = Replicates 5-17 only

It is unfortunate that conditions at anomalous localities B and C (in particular the fact that the stream sediment consisted of large blocks with little fine-grained material) made sampling difficult, and that there is no data regarding the magnitude of sampling error for background localities under precisely similar conditions, or for anomalous localities with abundant sediment free from possible contamination. However, the values given in table 38 may be considered representative of the magnitude of sampling error under adverse conditions, and as such have important implications for mineral exploration.

At weakly anomalous localities sampling error is a critical factor, as may be demonstrated with the aid of data from locality B. Threshold has been estimated as 35 ppm (p. 158) and the difference in Ni content between low anomalous locations (B) and threshold (T) may therefore be taken as 10 ppm; if the variance of sampling error is taken as 107 (mean for localities B and C, table 38), the standard deviation of sampling error is 10.3 and it is evident that:

$$
\begin{aligned}
B-T &= 10 \\
&= 1 \text{ standard deviation of sampling error.}
\end{aligned}
$$

Thus for weakly anomalous localities, such as B, 1 sample in 6 may be expected to have a Ni content below threshold level as a result of sampling error alone. If total experimental error is considered (i.e. incorporating analytical error) the variance becomes 142 (mean of B and C), and:

$$
\begin{aligned}
B-T &= 10 \\
&= .83 \text{ standard deviation of total error,}
\end{aligned}
$$

so that 1 in 5 samples may be expected to register as non-anomalous.

The successful application of the drainage survey technique is dependent on its ability to detect anomalous dispersion patterns related to mineralisation. When, as in the case of Ni, these patterns are expected to be weak and of restricted length it is imperative that the method be improved either by reducing the magnitude of sampling error or by increasing the contrast between low anomalous localities and threshold. The relative merits of three potential methods of achieving this are discussed below.

(a) <u>Improved analytical technique</u>

Analytical error has been shown to be a minor factor in the total experimental error of anomalous localities and a reduction in the magnitude of analytical error would therefore lead to only a minor reduction in the total error.

For background samples on the other hand, analytical error is the dominant factor in total experimental error. The observed range of background values for the Iveland area (fig. 40) may be considered as comprising:

(i) the range of true background values

(ii) a component due to analytical error.

A reduction in analytical error should therefore lead to a slight reduction in the range of background values and, since it is defined as the upper limit of background variation, to a similar decrease in threshold.

The present analytical technique has been developed to allow the processing of a large number of samples, and a significant improvement in precision can be achieved only by sacrificing the high productivity essential to mineral exploration programmes. In view of this, and the marginal improvements in anomaly recognition likely to result from a reduction in analytical error, the analytical technique is considered adequate.

(b) Replicate sampling

The collection of replicate samples at each sample locality will lead to a reduction in effective experimental error according to the relationship:

$$\text{S.D. (Mean)} = \frac{\text{S.D. (Experimental error)}}{\sqrt{n}}$$

where: S.D. (Mean) = standard deviation of the mean of replicate samples, and hence of the effective experimental error,

n = number of replicates collected.

The probability that for a low anomalous locality the mean Ni content of a given number of replicate samples will be below threshold may be readily calculated. Examples are given in table 39, using the mean Ni content of locality B (45 ppm), a threshold of 35 ppm and the calculated standard deviation of total experimental error (12).

Table 39. Probability of Ni content of low anomalous locality being less than threshold for a given number of replicate samples.

Replicates	S.D. of Mean	Probability
1	12	20.3%
2	8.5	12.1%
3	6.9	7.3%
4	6	4.7%
5	5.4	3.2%
6	4.9	2.1%

It is evident from table 39 that a 95% success rate in the recognition of weak anomalous localities may be achieved by collecting 4 replicate samples at each locality. The variance of the mean of 4 replicates (i.e. the variance of total experimental error) is 36 and since this is equivalent to the variance of analytical error there will be little advantage in collecting additional samples. The economics of sample collection may dictate a smaller number of replicates but it is recommended that a minimum of two samples be collected at each sample site.

(c) Analysing a finer size fraction

The size fraction data (p. 162) suggest that contrast for low anomalous samples may be improved by analysing a finer size fraction. The mechanical composition of the -80 mesh and -125 mesh fractions (calculated from the data in fig. 43), the Ni contents of the constituent size fractions and the computed Ni content of the -80 and -125 fractions are given in table 40 for localities A, B, D and G. It is evident that the increase in computed Ni content due to analysing the finer size fraction is much greater for anomalous locality B (30 ppm) than the corresponding increase for background (9 ppm, mean of localities A and G). For present purposes the -125 fraction threshold may be estimated as 44 ppm (i.e. -80 threshold + mean increase for samples A and G, table 40); analysis of the finer fraction will therefore result in an increase of approximately 20 ppm in the difference between threshold and the Ni content of weakly anomalous localities. In terms of the established experimental error this is equivalent to an increase of 1.25 standard deviation (cf. p. 181) and the probability that such a locality will be missed due to sampling error is accordingly greatly reduced.

Table 40. Computed effect of taking -125 rather than -80 fraction for analysis.

(a) -80 Mesh fraction

Size fraction	A		B		D		G	
	1	2	1	2	1	2	1	2
- 80 +125	62%	12	61%	45	70%	25?	47%	25
-125 +200	14%	20	12%	54	5%	30?	7%	30
Silt	23%	42	22%	132	17%	68	30%	45
Clay	1%	52	6%	46	8%	20	15%	10
Y	20 ppm		66 ppm		32 ppm		29 ppm	

Mean of A & G = 25 ppm

(b) -125 Mesh fraction

Size fraction	A		B		D		G	
	1	2	1	2	1	2	1	2
-125 +200	37%	20	29%	54	17%	30?	14%	30
Silt	61%	42	55%	132	55%	68	57%	45
Clay	2%	52	15%	46	28%	20	29%	10
Z	34 ppm		95 ppm		48 ppm		33 ppm	

Mean of A & G = 34 ppm

1 = % by weight
2 = Ni ppm
Y = Calculated ppm Ni in -80 fraction
Z = Calculated ppm Ni in -125 fraction.

A further advantage arising from this modification to the procedure is that the improvement in anomaly to threshold contrast should result in anomalous dispersion trains being detectable at greater distances from the source than is the case with -80 mesh data. An example of this is provided by locality D, which was established as a background location using -80 mesh data. Comparison of the Ni contents of the silt fractions in table 32 indicates that in this size fraction the anomalous Mølland dispersion train may persist as far as locality D; the calculated Ni content of the -125 mesh fraction (48 ppm, table 40(b)) reflects the higher Ni content of the silt fraction and the locality is revealed as weakly anomalous with reference to the estimated threshold value for -125 mesh data (44 ppm, p.185). An additional, but minor, advantage is the reduction in analytical error which should attend the analysis of material in a finer size range (Kleeman 1967).

A major difficulty of taking a finer size fraction for analysis is of course the difficulty of obtaining sufficient material for analysis, a factor which prevented experimental confirmation of the above deductions. Sufficient material could of course be obtained by collecting larger samples or by a preliminary screening at the sample site, aimed at excluding material coarser than (say) 2 mm from the sample.

6. Conclusions

(1) Stream sediment dispersion patterns related to Ni mineralisation are of restricted length and low contrast in the -80 mesh fraction; anomalous dispersion patterns may however be detected by detailed stream sediment surveys. The recommended technique for such surveys, based on the orientation results, is:-

(a) samples of the active sediment should be collected in duplicate from all streams draining the area of interest, at a maximum sampling interval of 1500 ft.;

(b) samples should be collected upstream from any lakes occurring in the drainage system;

(c) Ni analyses should be based on the -125 mesh fraction to improve anomaly contrast;

(d) anomalous samples should be analysed for Mn to outline possible areas of high Ni content resulting from scavenging by Mn oxide precipitates.

In selecting areas for follow-up sampling, priority should be given to anomalous localities with low Mn contents, but areas of anomalous Ni and high Mn should also be followed-up.

(2) Stream sediment Ni anomalies related to mineralisation result principally from the erosion of anomalous soils. Hydromorphic dispersion from weathering mineralisation, while important in the formation of Cu anomalies at Mølland, is a minor factor in the development of stream sediment Ni anomalies.

(3) Under normal circumstances marked climatic fluctuations do not give rise to significant variations in the Ni content of the -80 mesh fraction of anomalous or background stream sediments. Observed variations in the Ni content of the -80 mesh fraction of stream sediments from anomalous localities are attributed principally to sampling error; the more limited variation noted for background localities is attributed principally to analytical error.

(4) A detailed drainage survey over the southern part of the Iveland-Evje amphibolite complex confirmed the findings of the regional survey regarding the distribution of Ni in this area. The change from mafic to granite gneiss bedrock was marked by a decrease in the Ni content of the -80 fraction of the stream sediment similar to that noted earlier for soils.

(5) In addition to Mølland the detailed survey revealed two weakly anomalous localities within the mafic rock outcrop, at one of which (Solberg) minor Ni-bearing sulphides were found in bedrock exposures adjacent to the stream. Anomalous Ni values also occur at Dalane, in the granite gneiss area, in association with high Mn contents; these are interpreted as due to secondary enhancement.

CHAPTER VI.

THE FLOTTORP MOLYBDENUM ORIENTATION SURVEY

The Flottorp orientation survey was undertaken to gain an understanding of the factors controlling the dispersion of Mo in the primary and secondary environments, and to determine the applicability of geochemical techniques to the search for molybdenite mineralisation in southern Norway.

During the course of the orientation survey investigations were carried out into the distribution of Mo, and to a lesser extent Cu, in the bedrock, overburden and drainage sediments of the Flottorp area. After a brief description of the Flottorp molybdenite deposit, the results of the bedrock distribution study are presented and a suggestion made as to the origin of the mineralisation. Data for the distribution of Mo and Cu in the overburden are then given and are used to establish the dominant process by which soil and peat anomalies are formed. The results of a detailed drainage survey covering the Flottorp area are presented next and the effect of lakes on anomalous dispersion trains is discussed. In a final section the conclusions of the orientation survey are reviewed and a procedure recommended for geochemical exploration for Mo mineralisation in similar areas.

1. Bedrock Investigation

(a) Introduction

The aims of the bedrock investigation were:

(i) to provide information concerning the distribution of Mo and Cu in the bedrock as an aid in the interpretation of the secondary dispersion data;

(ii) to test the applicability of bedrock sampling as an exploration technique for Mo;

(iii) to throw additional light on the origin of the Flottorp mineralisation.

The sub-economic molybdenite mineralisation at Flottorp is described by Bugge (1963) and the following account is largely based on his work. Mineralisation in the Flottorp area is confined to three relatively narrow zones which trend north-south, parallel to the regional strike, and have a proven strike length of six miles (fig. 44). In addition to the dominant granite gneisses, localised augen gneiss, and minor intrusions of grey granite, aplite and pegmatite crop out in the Flottorp area. According to Bugge (1963) the mineralised zones are characterised by the presence of narrow biotite-schist bands which form part of the granite gneiss sequence and which, although seldom exceeding 3 ft. in thickness, are contorted into a series of tight sub-horizontal folds to give zones with an effective width of up to 700 ft. Within these zones molybdenite, accompanied by minor pyrite and chalcopyrite, occurs either intimately associated with the biotite-schist bands or as segregations in dykes of pegmatite, aplite or vein-quartz which intersect them; molybdenite is also occasionally found in joint planes in the granite gneiss adjacent to such dykes.

Molybdenite mineralisation was known at Flottorp prior to 1910, but the area was most thoroughly explored during the molybdenum boom induced by the 1914-18 war. Intensive exploration and development was largely concentrated at the two richest localities, Lower and Upper Flottorp; the Upper Flottorp deposit was worked by A/S Ündalen Molybdengruber during 1914-1919 when a total of 22 tons Mo were extracted. In 1941-1942 Raffineringsverk A/S carried out considerable exploration at both prospects, including extensive diamond drilling, but did not re-open the mine workings. Further exploratory work was carried out in 1964 by Placer Management Ltd., and in 1967-1968 by Kristiania Spikeverk A/S; in both instances this took the form of systematic surface sampling at both the Upper and Lower Flottorp localities and led, apparently, to the conclusion that neither was currently economic. Assay data from the Placer Management Ltd. sampling programme (Lonergan 1964) were made available by the owner of the

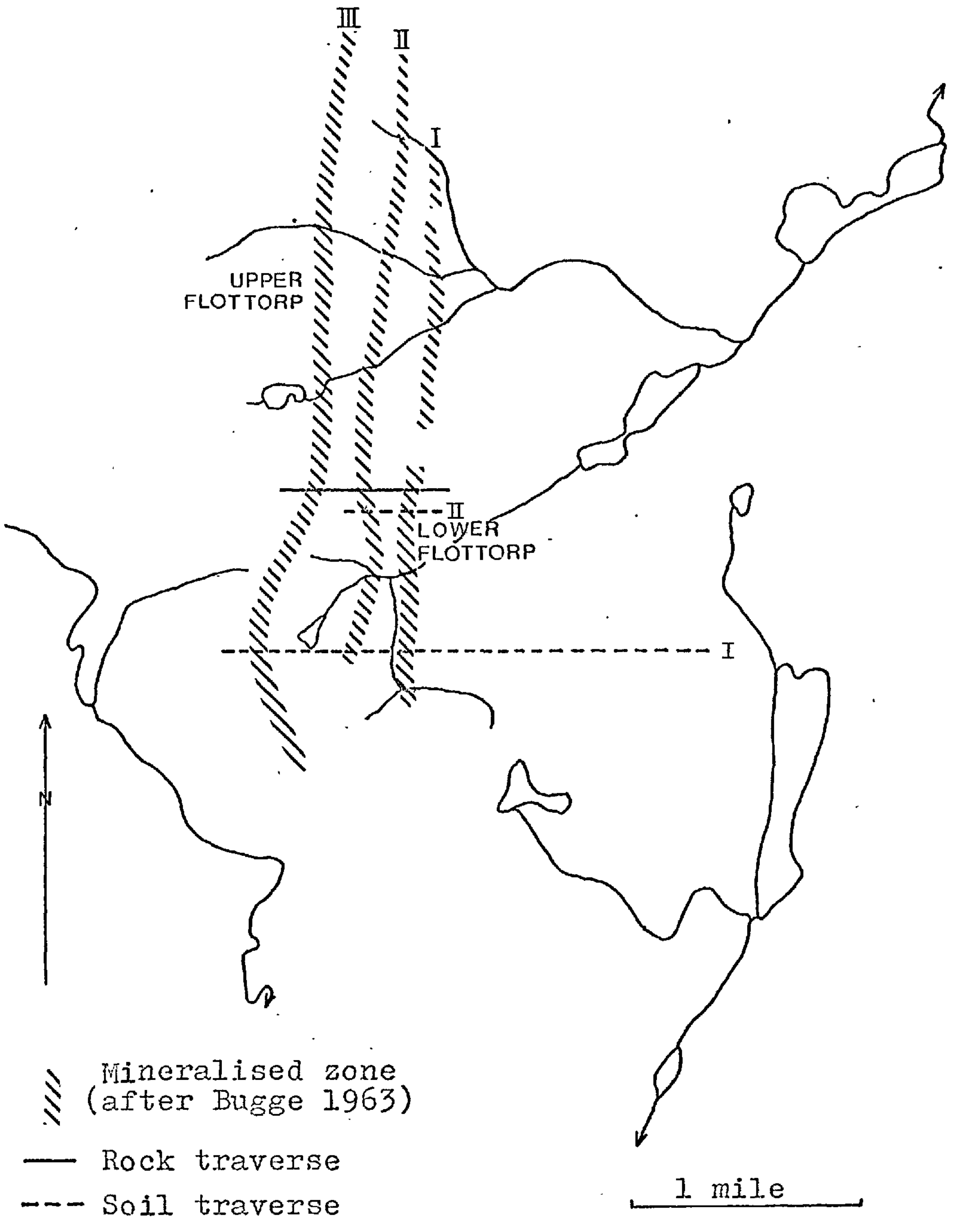


Fig. 44 Location of rock and soil traverses at Flottorp in relation to the mineralised zones.

prospect and are incorporated where applicable. The present orientation study was conducted at Lower Flottorp since stock-piled ore at Upper Flottorp has almost certainly resulted in contamination of the secondary environment. The principal mineralised zones at Lower Flottorp are zones I and III, zone II being narrow (10 ft.) and only weakly mineralised.

Rock samples were collected systematically along an east-west traverse, crossing all three mineralised zones (fig. 44). Recent trenching and grid sampling enabled the boundaries of the mineralised zones to be located within narrow limits, and samples were collected at intervals of 25 ft. over these zones, and for approximately 200 ft. either side; over barren ground a wider sampling interval (100 ft.) was employed. This traverse provided representative samples of all rock types except grey granite and augen gneiss. Grey granite is principally found cutting zone III at Upper Flottorp and samples were collected from this locality; augen gneiss samples were collected from background road exposures 2000-6000 ft. east of zone I. Since the aim was to obtain representative samples of the various rock types care was taken when sampling within the mineralised zones to avoid, as far as possible, the collection of material containing visible molybdenite segregations. In addition to fresh rock samples a number of samples of highly weathered material were collected to determine the effect of weathering on the Mo and Cu content of mineralised samples.

(b) Results

(i) Background data

Background ranges for Mo and Cu for the major rock types are given in table 41, together with average values for granites, taken from Kuroda and Sandell (1954) and Vinogradov (1962). It is evident that the background Mo values lie within the range previously obtained for granites while the mean background Cu value is close to Vinogradov's average for acid igneous rocks. Threshold is taken as the upper limit of background variation (i.e. 6 ppm Mo and 90 ppm Cu).

Table 41. Background values for Mo and Cu for the major rock types at Flottorp.

Rock type	No. of samples	Mo (1)		Cu	
		Range	Mean	Range	Mean
Pink granite gneiss	36	<2-5	-	20-90	42
Augen gneiss	8	<2-3	-	-	-
Aplite	1	5	-	-	-
Biotite Schist	1	6	-	-	-
Grey granite*	6	<2-6	-	40-45	44
Average Values:		Kuroda & Sandell		Vinogradov	
Granite		0-7	1.0	-	30

(1) Effective detection limit of analytical method was 2 ppm.

* Barren samples from ore zone III, Upper Flottorp.

(ii) Data for mineralised zones

The distribution of Mo and Cu across zones I, II and III is shown in figs. 45 and 46, together with the variation in rock type. The mineralised zones are marked by anomalous Mo and Cu values but, with the exception of the eastern margin of zone III, there is no evidence of a transitional border of intermediate Mo and Cu content, the bedrock anomalies being sharply defined and not extending beyond the visually observed limits of the ore zones. Assay data for part of zone I (Lonergan 1964) are also shown in fig. 45 and are notably higher (up to 8000 ppm Mo) than the present grab samples. It is well known that a rigid procedure is essential when sampling for assay, particularly in the case of low-grade, high value mineralisation such as Mo; figs. 45 and 46 demonstrate however that for exploration purposes mineralised zones are satisfactorily defined by a rapid, grab sampling technique.

A correlation between Mo and Cu is strongly suggested in figs. 45 and 46. The significance of the correlation for (a) samples from within the ore zones, and (b) background samples, was tested using the Spearman rank correlation coefficient and in both cases was found to be highly significant (table 42).

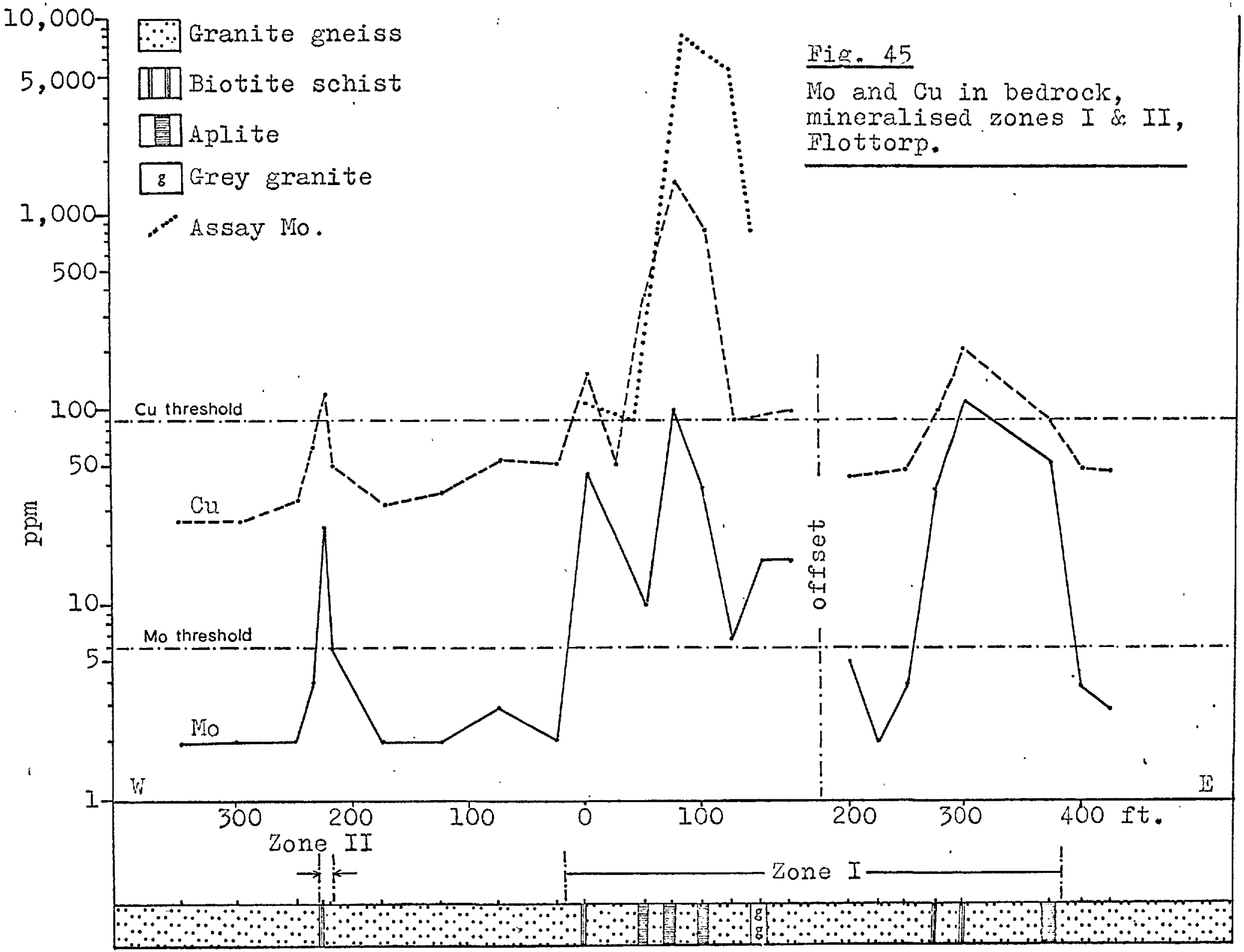


Fig. 45

Mo and Cu in bedrock, mineralised zones I & II, Flottorp.

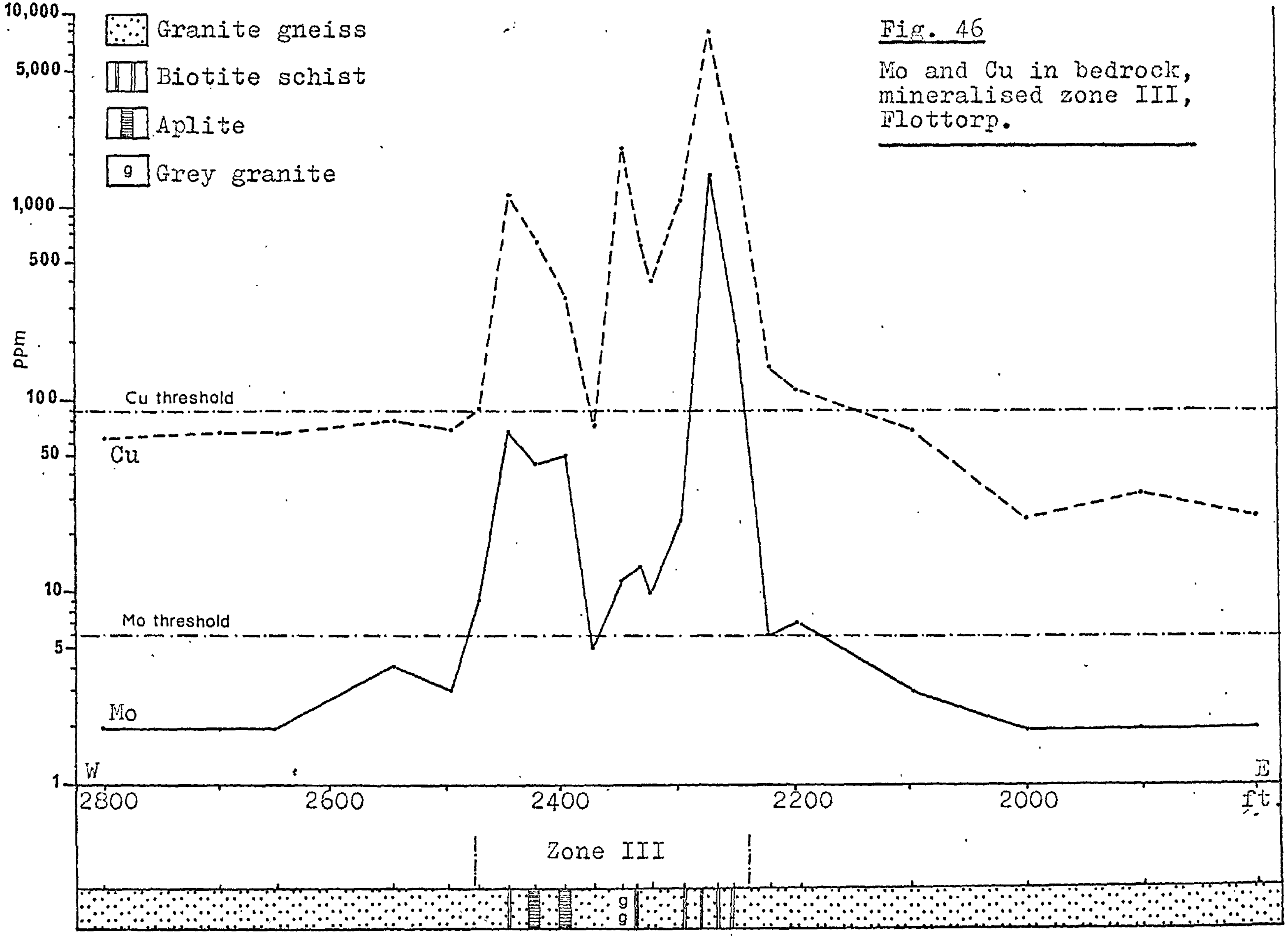


Fig. 46

Mo and Cu in bedrock, mineralised zone III, Flottorp.

Table 42. Spearman rank correlation coefficient test for Mo and Cu in bedrock.

	Correlation coefficient	't' test	Degrees of freedom.	Significance.
Background	+ 0.578	4.309	37	>99.5%
Ore zone	+ 0.731	5.356	26	>99.5%

(iii) Effect of weathering on Mo and Cu content of bedrock

To determine the effect of weathering on the Mo and Cu content of the bedrock, four weathered samples were collected within the mineralised zones. In order that the data be strictly comparable, the limonite-rich outer skin was chipped from large blocks to provide weathered samples and then fresh material taken from the centre of these blocks.

Mo and Cu contents of fresh and weathered samples are given in table 43. Mo is markedly higher in the weathered material for two locations (100'E and 175'E), the difference for the other locations being not significant with respect to analytical error. Cu, on the other hand, is markedly lower in the weathered material at two localities (100'E and 2275'W), the difference for the other locations being not significant with respect to analytical error.

Table 43. Comparison of Mo and Cu contents (ppm) in fresh rock and the highly weathered outer skin.

	100'E		125'E		175'E		2275'W	
	Mo	Cu	Mo	Cu	Mo	Cu	Mo	Cu
Fresh rock	40	827	7	87	18	97	1600	7800
Weathered	120	290	8	77	90	75	1200	2300

It is concluded that for Mo exploration purposes there is no objection to the inclusion of weathered material in the rock sample, indeed the enhanced Mo content of the weathered material will favour the recognition of areas of weak mineralisation which may be related to ore-grade material nearby or in depth. In addition, by obviating the need to trim away weathered material, sample collection will be greatly speeded up.

(c) Discussion - origin of the Flottorp mineralisation

Mafic-rich bands which carry minor sulphides and form a concordant part of a metamorphic sequence have long been referred to as fahlbands (Beyschlag, Vogt and Krusch (1916)), and the north-south trending mineralised zones at both Flottorp and Knaben have been placed in this category (Bugge, 1963). Economic concentrations of molybdenite are not found in the fahlbands themselves, but workable deposits occur at Knaben as impregnations in dykes of aplite, pegmatite or quartz intersecting molybdenite-bearing fahlbands.

The Mo content of background igneous rocks is considered to be concentrated principally in biotite (Studdenikova et al 1957, Kostetskaya and Petrova 1966) by substitution for Fe^{+3} and Ti^{+4} (Kuroda and Sandell 1954). In a study of the distribution of Mo in granitoid intrusions however, Kozlov and Roshchupkina (1965) showed that there was no significant difference in the Mo content of rock forming minerals separated from intrusions with low (<2 ppm) or high (5-39 ppm) Mo contents, and demonstrated that in the latter case the anomalous Mo was present in the form of molybdenite, either in discrete flakes or as intergrowths with biotite or feldspar.

From figs. 45 and 46 it appears that within the mineralised zones the tenor of Mo and Cu varies with rock type. The data are summarised in table 44 and suggest that mineralisation (in the form of molybdenite and chalcopyrite) is preferentially associated with the biotite schist samples, as noted by Bugge (1963). To test the significance of this association the Spearman rank correlation coefficient (Rs) between Mo content and rock type was calculated, rock types being ranked 1 to 4 in the order pink granite gneiss, grey granite, aplite and biotite schist. A highly significant correlation (Rs = +0.812) was found between Mo content and rock type, confirming Bugge's field observation that molybdenite is intimately associated with the biotite schists and indicating that, except where rich molybdenite segregations occur, the minor intrustions generally have a lower molybdenite content than the biotite-rich fahlbands.

Gammon (1966), working on the Ag and Co deposits at Kongsberg and Modum concluded that fahlbands at these localities represented the high-grade metamorphic equivalents of sapropelic sulphide muds and listed a number of mineral occurrences in Scandinavia and elsewhere considered to be of analogous origin. Dunham, (1961) discussing the relation between sulphide bodies and black shales, gives further examples of concordant Precambrian sulphide bodies considered to be of syngenetic origin.

Black shale horizons with a high Mo content ($>$100 ppm) have been described from a number of localities (Goldschmidt (1954), Kuroda and Sandell (1954), La Riche (1959), Atkinson (1967)), and it is suggested that the molybdeniferous fahlbands at Knaben and Flottorp represent the high-grade metamorphic products of shales of this type. Krauskopf (1955) reports the ranges of trace metals in black shales as 10-1000 ppm Mo and 20-1000 ppm Cu and the Mo and Cu contents of the biotite schist samples (table 44) are consistent with these values.

There is a difference of opinion concerning both the mode of occurrence of Mo in black shales and the method by which it is concentrated, although there is general agreement that Mo, together with the commonly associated metals V, Ni, Cu and Co, is derived initially from sea-water. A widely held view, (Goldschmidt (1954), Kuroda and Sandell (1954) and Korolev (1958)), is that in reducing black mud environments Mo accumulates along with black pyrite as finely dispersed, amorphous MoS_2. Korolev (1958) demonstrated experimentally that Mo co-precipitates with FeS_2 from solutions approaching the composition of natural waters if these are saturated with H_2S, and on this evidence concluded that the organic matter present in black shales has only an indirect influence on Mo accumulation in so far as, under certain conditions, it contributes to the formation of H_2S. La Riche (1959), on the other hand, considered adsorption by organic matter to be the dominant process in the concentration of Mo, pointing out that in the shale samples he investigated the Mo content of the light fraction was higher than that of the pyrite. This view-point is countered however by Korolev's observations on the ageing of freshly precipitated Fe sulphides which led him to conclude that sorbed MoS_2 was abstracted from the coarsely crystalline diagenetic pyrite and concentrated in a finely dispersed sulphide phase. This dispersed sulphide phase, Korolev claims, is inseparable mechanically from the organic and silicate constituents of shales and is the primary cause of the reported high Mo contents of the light fraction of some shale samples.

Table 44. Range and mean value of Mo and Cu contents for samples of the major rock types from within the mineralised zones at Flottorp.

Rock type	Mo Range	Mo Mean	Cu Range	Cu Mean	No. of samples.
Pink granite gneiss	2-18	6	45-410	100	12
Aplite	10-110	52	90-1620	651	6
Grey granite	12-18	15	2200	-	2
Biotite schist	14-1600	237	90-7800	1490	9

Graphite has not been recorded from the fahlbands at Flottorp or Knaben, nor from one of the localities studied by Gammon (1966), although he does record the occurrence of a number of graphite-bearing fahlbands elsewhere. However, since Korolev's work indicates that the accumulation of Mo in black shales is not dependent on a high organic carbon content, the absence of graphite at Flottorp is not considered an objection to a black shale origin for the weakly mineralised fahlbands.

Minor intrusions (i.e. aplite and grey granite) intersecting the fahlband zones also carry molybdenite, whereas similar intrusions elsewhere have only background Mo contents (table 41). Anomalous Mo present in the minor intrusions, therefore, is considered to be derived from the fahlbands, either through incorporation of molybdenite-bearing inclusions or the migration of molybdenite towards areas of locally higher temperature; a degree of remobilisation is indicated by the molybdenite occasionally found on joint-planes in the granite gneiss adjacent to minor intrusions. The Mo content of the minor intrusions sampled during the present study was generally lower than that of the biotite schists (p.200), although at Knaben economic concentrations of molybdenite occur exclusively in such intrusions. Khitarov et al (1967) showed experimentally that the fugacity of Mo in granitic melts increased with temperature and with the presence of other materials (e.g. NaCl) in the gaseous phase; concentration of Mo to form ore-grade deposits (as at Knaben) may therefore depend on a specific feature of the minor intrusion (e.g. temperature or composition of the gaseous phase), rather than on an abnormally high initial Mo content.

2. Overburden Investigations

(a) Introduction

Bedrock at the orientation area is covered by a thin veneer of ground moraine, seldom exceeding a depth of 36 ins.; podzols are universally developed except in areas of peat cover. Soil samples were collected at 25 ft. intervals along two traverses perpendicular to the strike of the mineralised zones (fig. 44); where possible samples were taken of the humus, A_2 and B horizons and subsequently at intervals of 12 ins. to the bedrock surface. The longer traverse (I) crosses all three zones and extends 400 ft. west and 1000 ft. east of known mineralisation; further background samples were collected on the line of this traverse at distances of 1500, 2000, 3000, 4000, 7000, 13,000 and 16,000 ft. east of zone I, three soil profiles spaced 25 ft. apart, being taken at each background station. Traverse II crosses zones I and II, extending respectively 500 ft. west and 400 ft. east of these zones, and was sited as close to the line of the bedrock traverse as circumstances allowed.

In a preliminary investigation Mo and Cu were determined for humus and B horizon samples for both traverses; in a more detailed study the variation of Mo with depth for selected anomalous and background soil profiles was investigated.

Peat bog profiles were collected over mineralisation on soil traverse I (zone I) and south of traverse II (zones I and II). Individual bogs are of restricted extent, developed in local areas of impeded drainage, and the sampling pattern was necessarily discontinuous. Background data was obtained from six profiles collected near Sveindal, 3 miles east of Flottorp and a series of widely spaced reconnaissance profiles were also collected along the central axis of a series of bogs paralleling Traverse I at approximately 900'W - 1500'W.

(b) Results

(i) Soil traverse data

Mo and Cu data for humus and B horizon samples from background localities are summarised in table 45.

Table 45 Background values for Mo and Cu in humus and B horizon soil samples.

Media	Mo (ppm) Range	Mo (ppm) No.	* Cu (ppm) Range	* Cu (ppm) Mean	* Cu (ppm) No.
Humus	<2-5	40	20-50	35	22
B horizon	< 2-5	61	20-30	23	37

(* Detection limit = 20 ppm Cu)

Threshold for each medium is taken as the upper limit of background variation, although it should be stressed that for Mo the variation is of the same order as the analytical error (table 11a, p.28).

Data for the sections of Traverses I and II which cross the mineralised zones are given in figs. 47 and 48; the position of the mineralised zones is also shown.

Data for Traverse II (fig. 47) will be discussed first since the proximity to the bedrock traverse allows a more rigorous interpretation of the results; this traverse was run across the south-facing slope of a major E-W valley and was kept, as far as possible, at a constant elevation to eliminate the effects of topographic variation from the interpretation. Bedrock Mo and Cu values together with available assay data (Lonergan 1964) are also plotted in fig. 47; the assay data are more representative of the Mo content of the mineralised zone than the bedrock sampling data (p. 196) and are included for this reason.

In the B horizon Mo shows a broad anomaly, with a total width of 950ft., extending over mineralised zones I and II. Comparison with bedrock data reveals that there are anomaly peaks in the soil directly overlying the mineralised zones and that the soil anomalies are more or less symmetrically distributed about these zones. The anomalous dispersion pattern persists for 250 ft. west and 150 ft. east of known mineralisation and it appears that there is no significant displacement of the soil anomaly down the steep slope at the eastern end of the traverse.

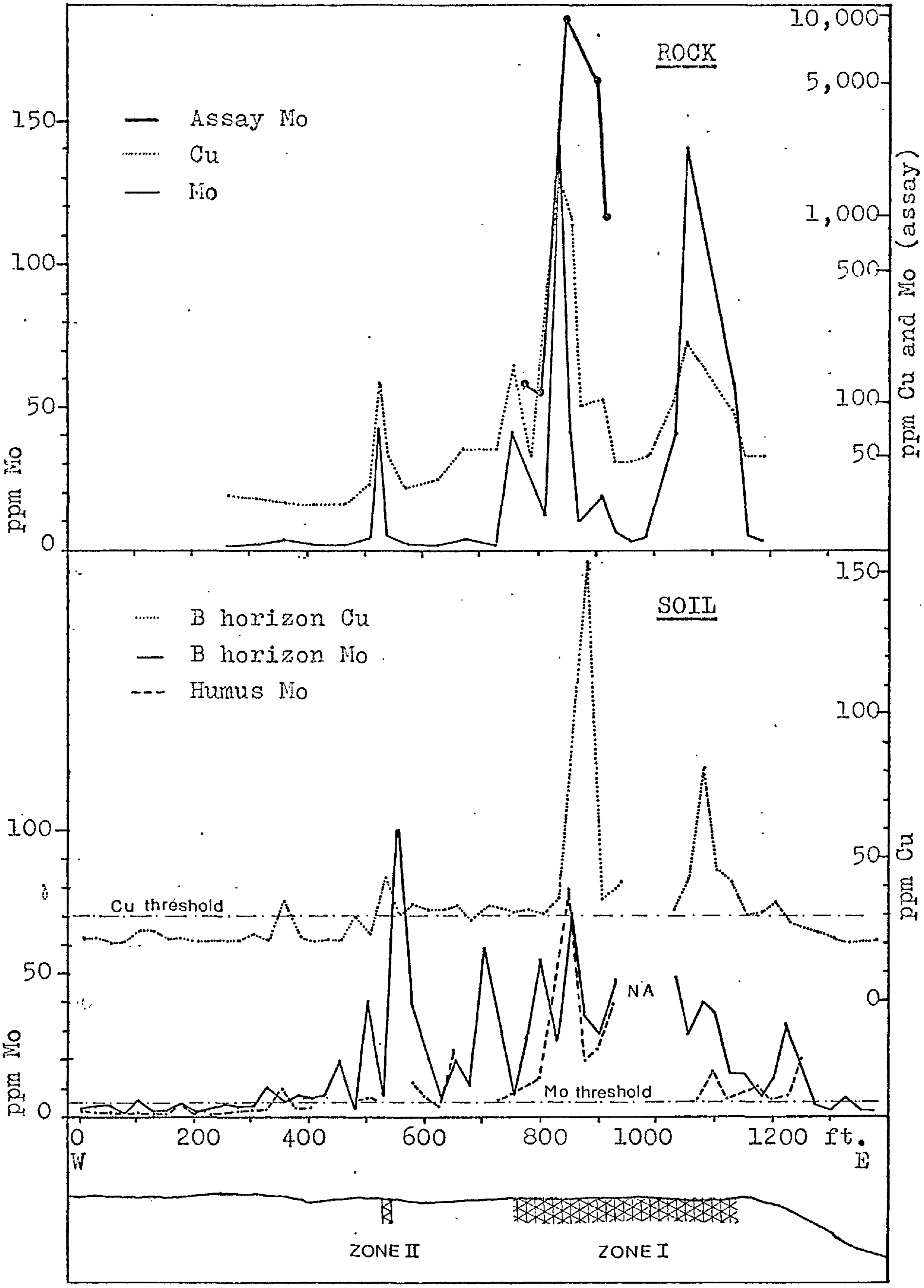


Fig. 47 Mo and Cu in B horizon and Mo in humus, soil Traverse II, Flottorp (Mo and Cu data for the nearby bedrock traverse, from fig.45, are plotted for comparative purposes).

Humus samples were not collected at every sampling locality and the data are not as complete as those for the B horizon. Humus samples from Traverse II were analysed for Mo only. The width of the anomalous zone is of the same order as that in the B horizon although it is noticeable that the level of Mo in the humus is generally lower than that of the underlying mineral soil; the single very high Mo content (80 ppm) occurs over the highest grade mineralisation as indicated by the assay data.

Cu in the B horizon shows weakly anomalous values over a total width of 700 ft.; although narrower and much weaker the Cu anomaly is broadly coincident with that already described for Mo. Within the broad Cu anomaly two distinct peaks (150 ppm and 80 ppm) occur over parts of mineralised zone I; comparison with bedrock data reveals that the peak soil Cu contents are in both cases directly related to high Cu and Mo in the bedrock.

For Traverse I (fig. 48) the position of mineralised zone I is known from a series of exploration trenches and the general position of zones II and III is inferred from fig. 44. Molybdenite showings at 2200'W and 2850'W serve to confirm the location of zone III, although it is not certain that there is continuous mineralisation between the two showings; there is no field indication

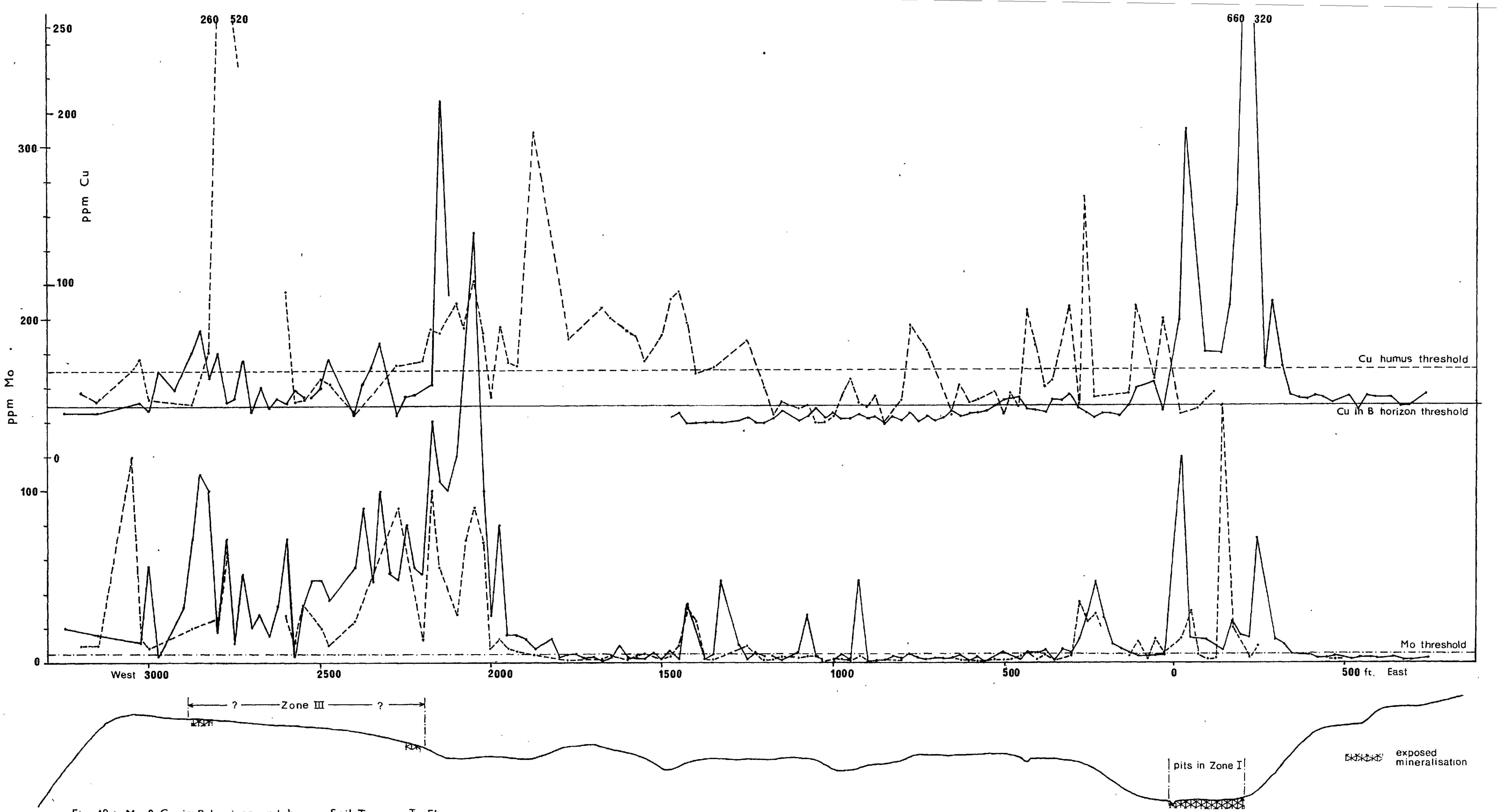


Fig 48 : Mo & Cu in B horizon and humus Soil Traverse I Flottorp of the position of zone II, which appears from fig. 44 to be of minor significance as far south as this traverse.

Over zone I broad anomalies (800 ft. in width) are shown by Mo in both B horizon and humus. Peak Mo contents occur in the valley bottom over known mineralisation and anomalous values persist up the valley sides, high Mo contents occurring in both media on the hill-top at 200'-300'W. Cu in the B horizon is strongly anomalous over known mineralisation in the valley bottom, and weakly anomalous values persist up the eastern valley slope to give a total anomaly width of 800 ft. In contrast to Mo, background Cu contents occur on the western valley side and there are weakly anomalous values only at 300'-350'W. Humus Cu values are below threshold over known mineralisation in the valley bottom but there is a distinct anomaly on the hill-top at 200'-400'W, coinciding in part with the Mo anomaly already mentioned.

The Mo content of both humus and B horizon is strongly anomalous over mineralised zone III. The anomalies are coincident and extend to the western limit of the traverse in both media; anomaly widths are 1350+ ft. and 1450+ ft. respectively in the humus and B horizons. B horizon Cu values are also anomalous, but the anomaly is narrower (900+ ft.), and in particular background values occur beyond 3000'W. The molybdenite showing at 2850'W is marked by peak Mo and Cu values in the B horizon; strongly anomalous Cu values occur in humus samples downslope from this showing.

Molybdenite was also found at 2200'W and the strongly anomalous Mo and B horizon Cu values at 2000'-2200'W are likewise thought to be related to bedrock mineralisation. In the humus layer a broad Cu anomaly extends eastwards (i.e. downslope) from 2200'W for a total distance of 1000 ft; this is thought to principally reflect groundwater dispersion of Cu from mineralisation occurring at 2000'-2200'W. Isolated Mo highs occur in both humus and B horizon at 900'-1500'W and possibly overlie a weakly mineralised extension of zone II.

A highly significant correlation was found between Mo and Cu in both mineralised and barren bedrock (p. 196). Figs. 47 and 48 suggest that a similar correlation might exist in the soil and this was investigated by calculating Spearman rank correlation coefficients for the various sets of soil data. The results are summarised in table 46 and confirm that highly significant correlations exist between Mo and Cu in the B horizon, and between humus Mo and B horizon Mo and Cu; there is no correlation however between the Mo and Cu contents of humus samples.

Table 46. Spearman Rank Correlation Coefficients (Rs) for Flottorp Soil Data.

Correlation	Rs	No.	Significance
Humus Mo/'B' Mo *	+ 0.791	30	>> 99%
'B' Mo/'B' Cu *	+ 0.655	30	>> 99%
Humus Mo/'B' Cu *	+ 0.767	30	>> 99%
Humus Mo/Humus Cu +	+ 0.224	45	NOT

* = Data from soil traverse II
\+ = Data from soil traverse I

The main features of the anomalies on soil Traverses I and II are summarised in table 47; the estimated width of the mineralised zone is also given for comparative purposes. Contrasts for Mo and Cu in the mineralised zones, based on the highest values obtained from bedrock analyses, are respectively x270 and x870; if the maximum assay value is used (i.e. 8000 ppm Mo) contrast for Mo in the mineralised zones is x1600.

Table 47. Main features of the principal anomalies on soil Traverses I and II, Flottorp.

	Mo		Cu		Ore zone width.
	B horizon	Humus	B horizon	Humus	
Traverse I, zone I					
Width (ft.)	800	800	800	200[a]	200
Contrast	24	30	22	3	
Traverse I, zone III					
Width (ft.)	1450+	1300+	900+	200[b]	700
Contrast	50	24	7	10	
Traverse II, zones I & II					
Width (ft.)	950	950	700	NA	650
Contrast	20	16	5	NA	

Contrast = anomaly peak/threshold
a = background values over known mineralisation
b = also 1000 ft. wide lateral hydromorphic anomaly (contrast = x4).

The topographic situations of the three principal anomalies are markedly different: on Traverse I mineralised zone I underlies a broad, poorly drained valley and zone III crops out on a freely drained slope, with a component parallel to the traverse line, while for Traverse II the anomalous section is essentially horizontal and crosses a freely drained slope. The differences in anomaly width and contrast for Mo almost certainly reflect primary features of the mineral zones at each locality. This may also be true of the B horizon Cu data but it is noticeable that contrast for the two freely drained anomalies is similar, while for the poorly drained locality contrast is greatly increased. The effect of topography is most clearly shown by the Cu content of the humus, which is below threshold in the poorly drained valley overlying zone I but is locally high on freely drained slopes near exposed mineralisation (zone III); the broad anomaly at 1200'W to 2200'W also provides clear evidence of the importance of groundwater dispersion in the formation of humus Cu anomalies.

(ii) Soil profile data

The variation in Mo content with depth in the most complete soil profiles available for anomalous and background localities is given in tables 48 and 49. The following observations may be made:

(a) The variation in Mo content shown by background profiles is not significant with respect to analytical error.

(b) The Mo content of the humus layer of anomalous profiles is lower than that of the underlying mineral soil by a factor of 1/3 to 1/10. A similar feature is apparent from the soil traverse data (figs. 47 and 48).

Table 48. Variation in Mo content of soil with depth at background localities.

Sample No.	Depth (ins.)	Description	Horizon	Mo (ppm)
Traverse I, 13,000'W				
1682	0-6	Humus	A_1	2
1683	6-12	Orange-brown clay	B	<2
1684	18-24	Light brown sand	B-C	3
1685	24-30	Light grey sand	C	3
Traverse I, 13,025'W				
1686	0-6	Humus	A_1	4
1687	6-12	Red-brown sandy clay	B	4
1688	18-24	Orange-brown fine sand	B-C	3
1689	30-36	Pale yellow fine sand	C	2
1690	42-48	Pale yellow fine sand	C	2
1691	54-60	Pale yellow fine sand	C	3
Traverse I, 16,000'W				
1695	0-6	Humus	A_1	2
1696	6-12	Medium brown sand	A_2+B	2
1697	18-24	Dark brown clay	B	2
1698	24-30	Dark brown clay	B	2

Table 49. Variation in Mo content of soil with depth at anomalous localities.

Sample No.	Depth (ins.)	Description	Horizon	Mo (ppm)
Traverse I, 1975'E				
1328	0-6	Humus	A_1	12
1329	6-12	Dark brown, clay-rich till	B	120
1330	12-18	Dark brown, clay-rich till	B	90
1331	30-36	Light-medium brown till	B-C	80
Traverse I, 2025'E				
1336	0-6	Humus	A_1	70
1337	6-12	Medium grey sand	A_2	200
1338	18-24	Dark brown, clay-rich	B	140
1339	30-36	Light-medium brown clay	B-C	110
Traverse I, 2100'E				
1346	0-6	Humus	A_1	28
1347	6-12	Light grey loose sand	A_2	160
1348	12-18	Red-brown clay	B	140
Traverse I, 2375'E (Minor molybdenite in nearby outcrop)				
1380	0-6	Humus	A_1	20
1381	6-12	Light grey sand	A_2	120
1383	18-24	Medium brown clay	B-C	160
Traverse I, 2625'E				
1404	3-6	Light grey sand	A_2	60
1405	6-12	Dark-red clay	B	55
1406	18-24	Orange-red clay	B-C	50
1407	28-34	Orange-red clay	B-C	90

(c) At anomalous localities mineral soils from all depths have high Mo contents. Mo content decreases significantly with depth at station 2025'E, where maximum Mo occurs in the eluvial A_2 horizon, and at station 1975'E where the A_2 horizon was absent and maximum Mo occurs in the B horizon, at a depth of 6-12 ins. At station 2625'E, on the other hand, Mo is significantly higher in the basal till, at a depth of 28-34 ins., than in either the A_2 or B horizons. At stations 2100'E and 2375'E the observed variation in Mo content is not significant with respect to analytical error.

It is concluded that there is no systematic variation in Mo content with depth in the mineral soil and that the depth at which mineral soil samples are collected is not critical for exploration purposes.

(iii) Mo in peat

Data for the distribution of Mo in peat profiles are presented in table 50; for ease of reference distances are given with respect to the origins of figs. 47 and 48. Data for the background profiles are not included in table 50 since Mo contents in these profiles were consistently less than 2 ppm, which is taken as threshold level.

Considering first the data from south of Traverse II it is evident that, with the exception of 3 samples, all values are anomalous and that the positions of mineralised zones I and II are clearly indicated by peaks in the peat anomaly.

Data for Traverse I reveals anomalous values in peat over zone I and also for the reconnaissance profiles at 1150'W (weak) and 1250'W. Reference to fig, 48 reveals a poorly defined Mo anomaly in both B horizon and humus at approximately this position (i.e. 900' - 1500'W) which was thought to be related to mineralised zone II; from a mineral exploration viewpoint it is extremely significant that wide interval reconnaissance sampling along the central axis of peat bogs succeeded in locating this weak anomaly.

It is evident from table 50 that the Mo contents of anomalous peat profiles show a marked tendency to increase with depth. This is in agreement with profile data presented by Hvatum (1964) for a peat bog underlain by Cu-Mo mineralisation at Amdal, 60 miles north of Flottorp, and by Atkinson (1967) for peat bogs overlying Mo-rich black shales in County Limerick, Ireland, although Salmi (1967) records concentration of Mo in the surface layer of a peat bog overlying molybdenite mineralisation in Finland.

Table 50. Variation in Mo content (ppm) with depth for peat profiles

(a) Traverse II *

Depth (ins.)	350'E	400'E	500'E	625'E	650'E	675'E	700'E	725'E	750'E	775'E	875'E
6-12	-	-	40	-	-	-	-	14	48	-	-
18-24	3	2	160T	40	8	4	28	22	56	20	48
30-36	5	6		40T	2	2				28	
42-48						6					
54-60						4T					
Remarks.	Barren Rock		Zone II	Barren Rock					Zone I		

(b) Traverse I

Depth (ins.)	125'E	100'E	75'E	*900'W	950'W	1000'W	1150'W	1250'W	1500'W
6-12	3	2	5	NA	NA	NA	NA	NA	NA
18-24	4	NA		< 2	< 2	2	2	8	< 2
30-36	16	2		< 2	NA	NA	NA	NA	NA
42-48		10		< 2	< 2	2	2	8	2
54-60		14T		< 2	< 2	< 2	2	10	NA
66-72				< 2		< 2	2		2
76-84							5		2
Remarks	Zone I			Background Bog			Anomalous Section		

* = Offset from soil traverse line T = Underlying moraine

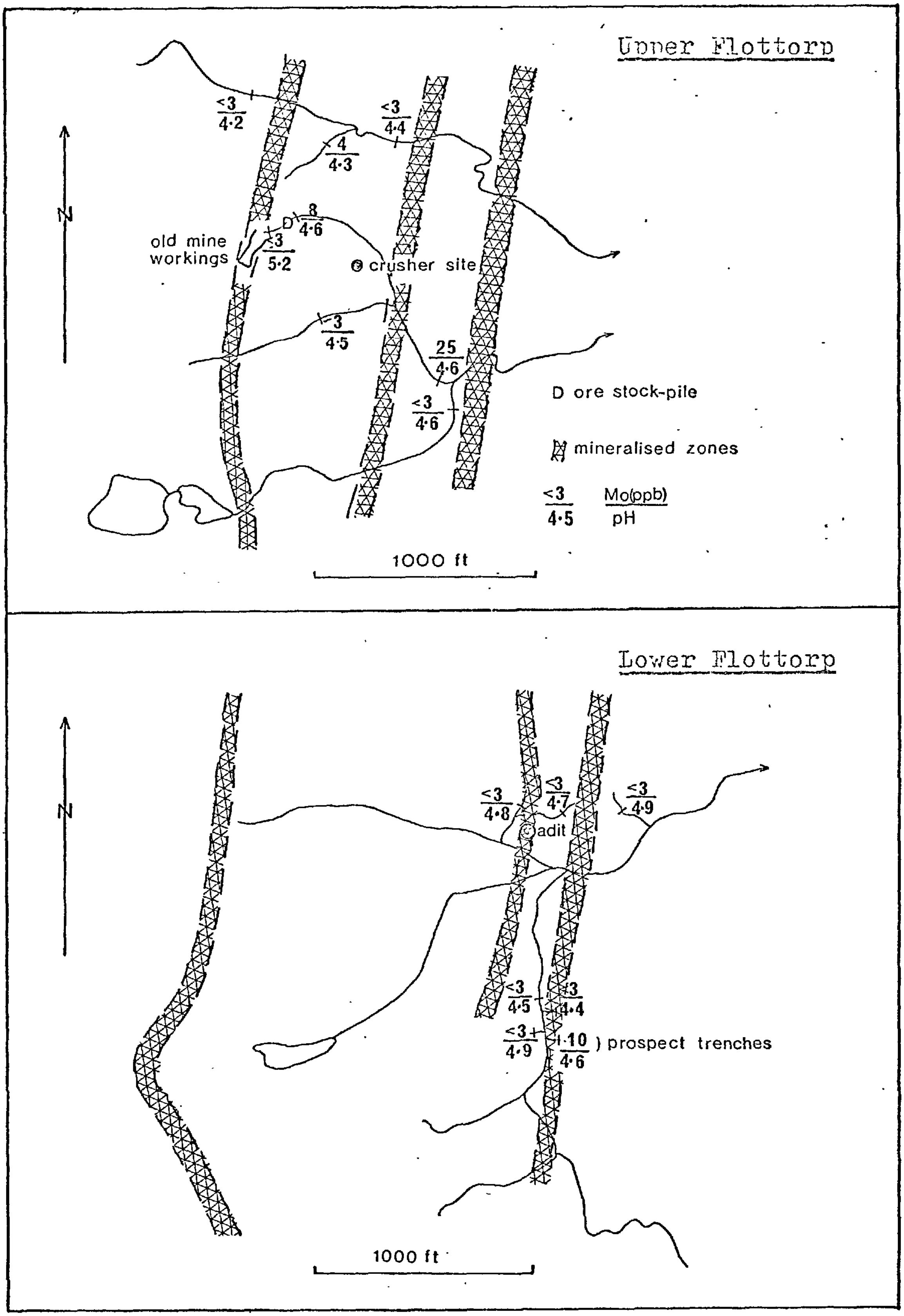


Fig. 49 Mo (ppb) in surface water, Flottorp.

(iv) Mo in surface waters

Data from a limited study of the distribution of Mo in surface waters at Flottorp are conveniently presented at this stage. Values given in the literature for the Mo content of surface waters draining unmineralised areas are <0.1 ppb(Tooms et al 1965), 1 ppb (Kuroda and Sandell 1954) and <3 ppb (Vinogradov 1957). Since the detection limit of the analytical method was 3 ppb (p.29) it was not possible to study the distribution of Mo in background waters and in the absence of background data, threshold is taken as 3 ppb (Vinogradov 1957).

Mo contents of surface waters are shown in fig. 49. Titley (1963) and Hansuld (1966) have related the solubility of Mo to pH and for this reason pH values are also given; it is evident however that there is little variation in the pH of surface waters at Flottorp.

At Upper Flottorp Mo contents of 8 ppb and 4 ppb occur in waters which have percolated through stockpiled ore near the mine workings, and the highest Mo content (25 ppb) occurs immediately downstream from the site of an old crushing plant; other water samples from Upper Flottorp have <3 ppb Mo. At Lower Flottorp water standing in a prospect trench in which rich molybdenite mineralisation was exposed had an Mo content of 10 ppb; waters draining relativley undisturbed mineralisation contain <3ppb Mo.

The data therefore indicate that anomalous Mo contents are restricted to surface waters draining areas where there has been local contamination of the environment by mining or exploration activity, and that background contents (i.e. <3 ppb Mo) occur in surface waters draining undisturbed mineralisation. It is also worthy of note that the level of Mo in anomalous water samples (4-25 ppb Mo) is low compared to the range of 10-10,000 ppb Mo cited for anomalous waters by Vinogradov (1957).

(c) Discussion - The formation of soil and peat anomalies

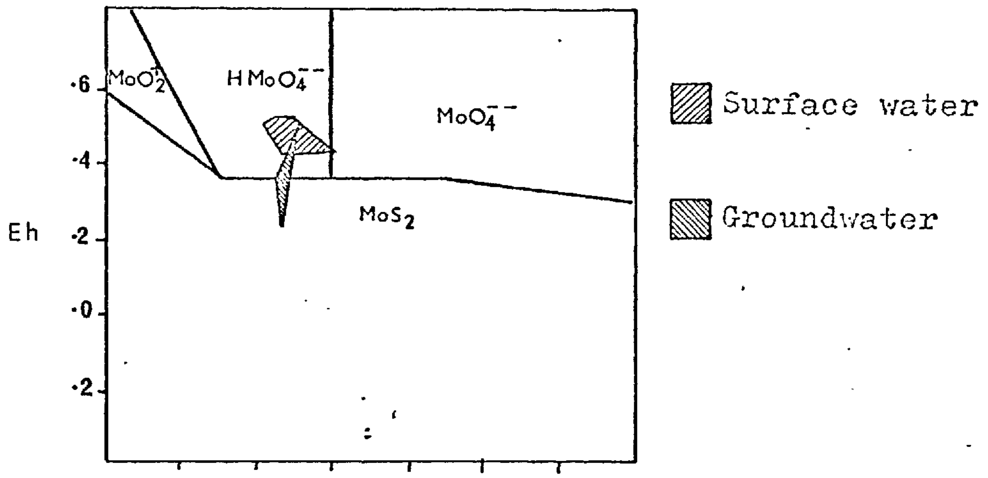
A knowledge of the processes governing the formation of anomalous dispersion patterns is clearly a pre-requisite for the successful interpretation of geochemical prospecting data. In glaciated areas mechanical transport is likely to be an important factor. Kauranne (1958) detected a fan-shaped Mo anomaly in the minus 0.012 mm fraction of till which extended a minimum distance of 3000 ft. from outcropping molybdenite mineralisation in the direction of ice-movement; an ore-boulder train was also found, confirming the glaciogenic origin of this dispersion pattern. However, as has been demonstrated at Mølland, saline dispersion may also be important and, depending on the mobility of the metal in question, may modify mechanical dispersion patterns (Pollock et al 1960, Canney 1965) or be the dominant process in the development of anomalies in the overburden (Dreimanis 1960, Yardley 1958, Mehrtens 1967).

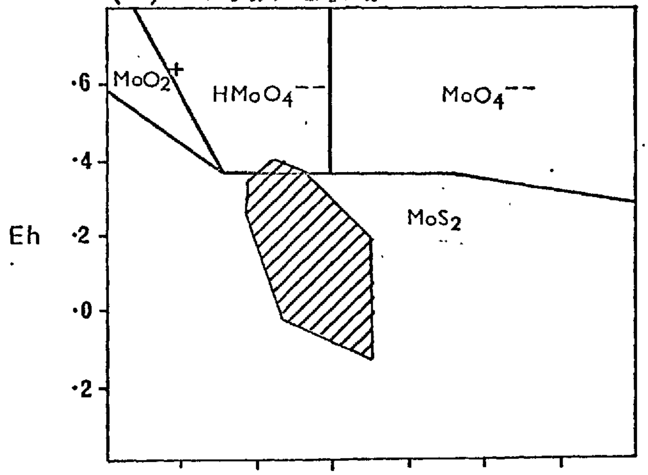
Vinogradov (1957) considered Mo to be mobile in the weathering environment, and suggested the use of hydrogeochemical surveys to locate molybdenite mineralisation. The absence of an oxidised zone at Flottorp probably accounts for the generally low Mo contents of the surface waters (fig. 49) but Vinogradov has shown that the rate of oxidation of molybdenite is such that high Mo contents can occur in aerated waters percolating through primary unoxidised ore (cf. the anomalous Mo contents in waters percolating through stockpiled ore and standing in an abandoned prospect trench, page 218).

The supergene mobility of Mo has been investigated by Titley (1963) and Hansuld (1966) and found to be affected by the Eh-pH conditions of the environment. Eh-pH fields for water, soil and peat bogs (data from fig. 2) together with stability fields for the system water-molybdenite (after Titley 1963) are given in fig. 50. The experimental data suggest that Eh is the most important factor governing the stability of molybdenite and that:

a) Molybdenite is unstable under the Eh-pH conditions of all surface waters, and of some groundwaters and soils;

b) Molybdenite is stable under the Eh-pH conditions shown by peat bogs and the majority of soil samples.


(a) Waters


(b) Peat Bogs

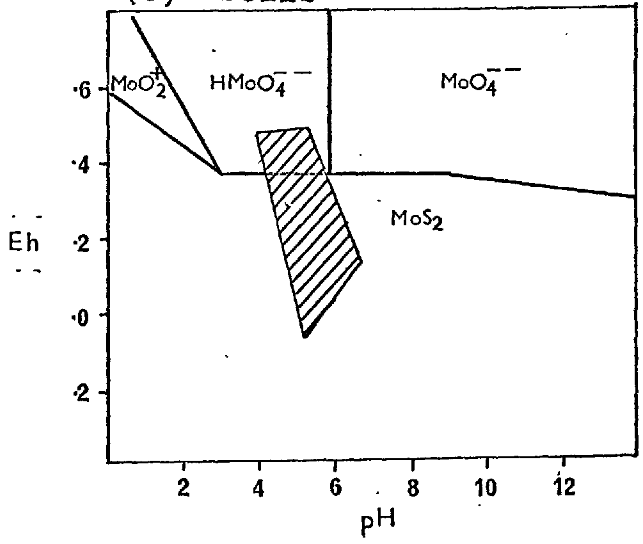

(c) Soils

Fig. 50 Eh–pH fields for water, peat bogs and soil (data from Fig. 2) and stability fields in the system water-molybdenite (after Titley 1963).

However, Sveshnikov et al (1964) considered that, in the absence of oxidation, electrochemical dissolution of the primary ore may be an important process in the weathering of polymetallic mineral deposits resulting, in the case of Cu-Mo mineralisation, in the preferential dissolution of molybdenite. The effect of biological activity and its products (Pauli 1968) on the solubility of molybdenite under low Eh conditions was also not taken into consideration and it is possible that, under natural conditions, the molybdenite stability field is more restricted than that suggested in fig. 50.

As Mo is an important plant nutrient the factors controlling its uptake by plants have been investigated by a number of workers (e.g. Barshad 1951, Davies 1956). It is generally considered that in moderately acid soils only a small proportion of the total Mo content is readily available to plants, the remainder being fixed in an insoluble form. Jones (1967) investigated this experimentally and concluded that adsorption by hydrous Fe oxides was the dominant mechanism by which Mo was fixed in acid soils, adsorption by clay minerals being less significant. Jones considered that in his experiments Mo was removed from aquaeous solution principally by surface adsorption, through anionic exchange of molybdate and hydroxyl ions.

Under the moderately acid conditions at Flottorp, and in view of the abundance of hydrous Fe oxides in the dominant podzols, it is to be expected that Mo will have low mobility in the secondary environment. Soil profile data support this observation, the non-systematic distribution of Mo through the mineral soil of anomalous profiles (table 49) suggesting that the soil forming process had little effect on the initial Mo content of the till. The high Mo content of the leached A_2 horizon is worthy of particular note and indicates that, even in the absence of hydrous Fe oxides, Mo is fixed in the soil, presumably by adsorption on to clay-size particles. It is concluded therefore that saline dispersion of Mo from bedrock mineralisation will be of limited importance and largely restricted to the till or soil immediately overlying the bedrock source.

Hansuld (1966) compared the supergene mobility of Mo and Cu under a variety of Eh-pH conditions, using both theoretical and empirical data. He concluded that Mo and Cu were antipathetic in their behaviour and in particular that under moderately acid, mildly oxidising conditions Cu is relatively mobile and Mo considerably less so. Data for the effect of weathering on mineralised samples (table 43) confirm the applicability of Hansuld's conclusions to the Flottorp area.

On the foregoing evidence it may be concluded that at Flottorp saline dispersion from bedrock mineralisation will be limited in the case of Mo (by fixation with hydrous Fe oxides or clay-size particles in the overlying till), but may be important in the case of Cu. The principal features of the soil and humus anomalies are in accord with this conclusion:

a) The broad B horizon Mo anomaly on Traverse II (fig. 47) which is wider than the underlying mineralisation and shows no sign of downslope displacement, is regarded as largely due to mechanical dispersion.

b) The broad zone of weakly anomalous B horizon Cu values is also regarded as due to mechanical dispersion. The peak Cu values, which for soil Traverse II were found to occur immediately over bedrock mineralisation, are regarded as due to saline dispersion.

c) The generally lower contrast shown by Cu in anomalies developed on well-drained as opposed to waterlogged soils (p. 211) is thought to be due to leaching of Cu from the well-drained soils (as was shown to occur for both Ni and Cu in the case of background soils, p. 126).

d) The broad humus Mo anomalies are regarded as due to the accumulation of vegetable debris containing anomalous Mo; high Mo contents have been reported from the leaves and twigs of a variety of plants growing on soils with a high content of Mo (Marmo 1958, Malyuga 1958, Warren et al 1953, 1965). The Mo content of the humus is generally lower than that of the mineral soil due to the restricted availability of soil Mo to plants under moderately acid conditions (p. 221), although locally high humus Mo contents may reflect increased plant uptake due to limited saline dispersion from bedrock mineralisation.

e) Humus Cu anomalies principally reflect the dispersion of Cu in groundwater and are, therefore, related to topography and the pattern of groundwater flow from bedrock mineralisation.

The accumulation of trace metals in peat bogs was considered by Kochenov et al (1967) to be due to two factors, (a) biogenic accumulation, and (b) sorption from groundwater. The restricted mobility of Mo under the moderately acid conditions at Flottorp suggests that biogenic accumulation may be the dominant factor in the development of the peat anomalies. The peat bogs at Flottorp are of the low moor type, however, and receive a large in-flow of groundwater and surface run-off; as Mo is readily adsorbed by peat humic acids under moderately acid conditions (Szigaly 1967), it is possible that significant Mo contents could gradually accumulate in the peat from groundwaters only marginally enriched in Mo.

The effect of the general pH status of the environment on the level of Mo in anomalous peat bogs may be well demonstrated by comparing the present data with the much higher Mo contents (50-2,000 ppm) reported from anomalous peat bogs in an alkaline environment (Atkinson 1967). Localised variations in pH (as shown to occur at Mølland, table 27) may similarly affect the tenor of Mo within individual anomalous peat bogs since, as already mentioned, pH is a critical factor in both the biogenic accumulation of Mo (Barshad 1951, Davies 1956) and its adsorption by peat humic acids (Szigaly 1967). The Mo content of anomalous peats may also be affected by local variations in moisture content, since the uptake of Mo by peat plants has been shown to increase with the level of water saturation (Terent'ev and Smirnova, 1966).

3. Drainage sediment investigations

The position of the Flottorp mineralisation with respect to the drainage system (fig. 51) provides almost ideal conditions for a drainage sediment orientation study. The Mo content of stream sediments from Flottorp was briefly mentioned in the section on the regional survey (p. 42); in the course of the orientation study additional stream sediment samples were taken to give complete coverage of the area of interest and in addition a limited number of lake bottom samples were collected.

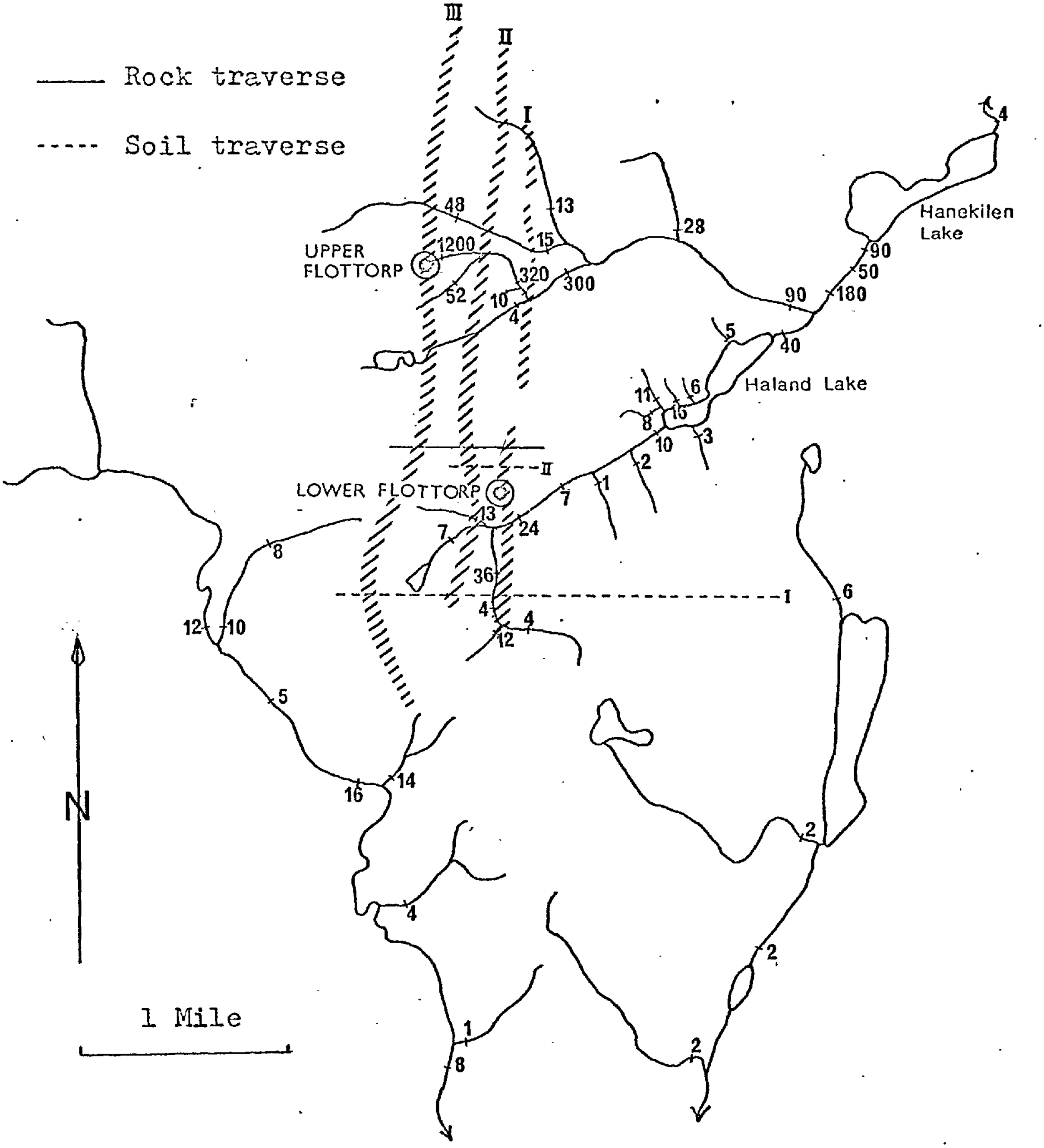


Fig. 51 Mo (ppm) in stream sediment, Flottorp.

Data for stream sediment and lake bottom samples are first presented, and are followed by a discussion of the effect of lakes on anomalous dispersion trains.

(a) <u>Mo in stream sediments</u>

Stream sediment Mo contents are shown in fig. 51. As only a limited number of background samples were collected threshold may be taken as the lowest Mo content for streams draining known mineralisation (i.e. 4 ppm Mo). The stream draining the Upper Flottorp mine workings is certainly contaminated; in other streams the maximum Mo contents are 48 ppm (Upper Flottorp) and 36 ppm (Lower Flottorp). The anomalous dispersion train at Lower Flottorp persists for at least 3000 yards downstream from mineralisation, and is still strongly anomalous at the confluence with the contaminated Upper Flottorp stream. The drainage system to the west of the mineralised zones is also anomalous, the principal stream being strongly anomalous (maximum 16 ppm Mo) for a distance of at least 6000 yards.

Anomalous tributaries enter the western drainage system south of the limit of known mineralisation; this may be due to a glacinogenic soil anomaly, or may indicate a continuation of the mineralised zones to the south (as was suggested from the regional survey data, p. 43).

A further feature emerging from fig. 51 is the manner in which background minor tributaries in the south and east serve to outline the position of the mineralised zones. It is interesting in this connection to speculate whether the anomalous minor tributaries north of Haland Lake indicate a fourth mineralised zone, en echelon with zones I, II and III.

It was earlier concluded (p. 223) that, at Flottorp, hydromorphic processes are of minor importance in the development of Mo anomalies in the overburden, saline dispersion of Mo being restricted to the till or soil immediately overlying bedrock mineralisation. In view of this limited mobility it is unlikely that saline dispersion is a significant factor in the development of stream sediment Mo anomalies at Flottorp and the latter are considered to result principally from the erosion of anomalous soils.

Limited data from the regional reconnaissance survey suggest however that saline dispersion may be an important factor in the development of stream sediment Mo anomalies in areas of extensive waterlogged soil, since a number of Mo anomalies were found to coincide with high contents of Fe, Mn, Zn, Co, Ni and Cu, interpreted as due to secondary enhancement processes (p. 59). The present work has not clearly demonstrated whether such Mo anomalies are related ultimately to molybdenite mineralisation;

Horsnail (1968) regarded fine-grained background rock fragments in the waterlogged soil as the principal source of Fe, Mn, Zn, Co and Ni in areas of secondary enhancement (p. 57) and since the degree of enrichment, relative to the average content of acid igneous rocks, is of the same order for Mo as for Fe, Mn, Zn, and Co (table 15), leaching from background rock fragments cannot be discounted as the source of Mo in these anomalies.

It is concluded that local conditions are of paramount importance in determining the supergene mobility of Mo, and hence the mechanism by which anomalies are formed in the overburden and stream sediment. In predominantly freely-drained areas, such as Flottorp, mechanical dispersion is the dominant process in the development of both soil and stream sediment anomalies, whereas from the regional survey data it appears that hydromorphic dispersion is the dominant process in the development of stream sediment Mo anomalies in areas with extensive waterlogged soils.

(b) Mo in lake bottom sediments

Perhaps the most striking feature of fig. 51 is the apparent continuation of the Lower Flottorp dispersion train through moderate-sized Haland Lake. Lakes, in general, act as effective barriers to the mechanical transport of stream sediment and, by truncating anomalous dispersion trains, may be expected to greatly limit the catchment area effectively represented by drainage sediment samples. A detailed investigation was conducted at Haland Lake to determine whether the anomalous dispersion train does in fact continue through the lake and, if so, to determine whether a generally applicable process is operative.

The principal features of the Haland Lake are shown in fig. 52; it is approximately 1200 yards in length, and consists essentially of two separate ponds joined by a narrow, shallow channel. The banks of the lower pond are formed by well-sorted terrace sands, which rise 30 ft. above lake level and appear to be primarily responsible for the narrow "waist" separating the two ponds. The upper pond, where sampling was concentrated, has banks formed by an extensive sphagnum bog.

Bottom samples were collected along traverses across the lake head, using a 15 ft. stainless steel scoop. As is apparent from fig. 52, distinct but narrow, deltas have been built up by the sediment discharged into the lake from the main stream and from a recently dug drainage channel, while between the two deltas the sediment consists of loose organic debris. At a distance of 60 ft. from the shore on the line of the principal delta the lake sediment consists entirely of organic matter,

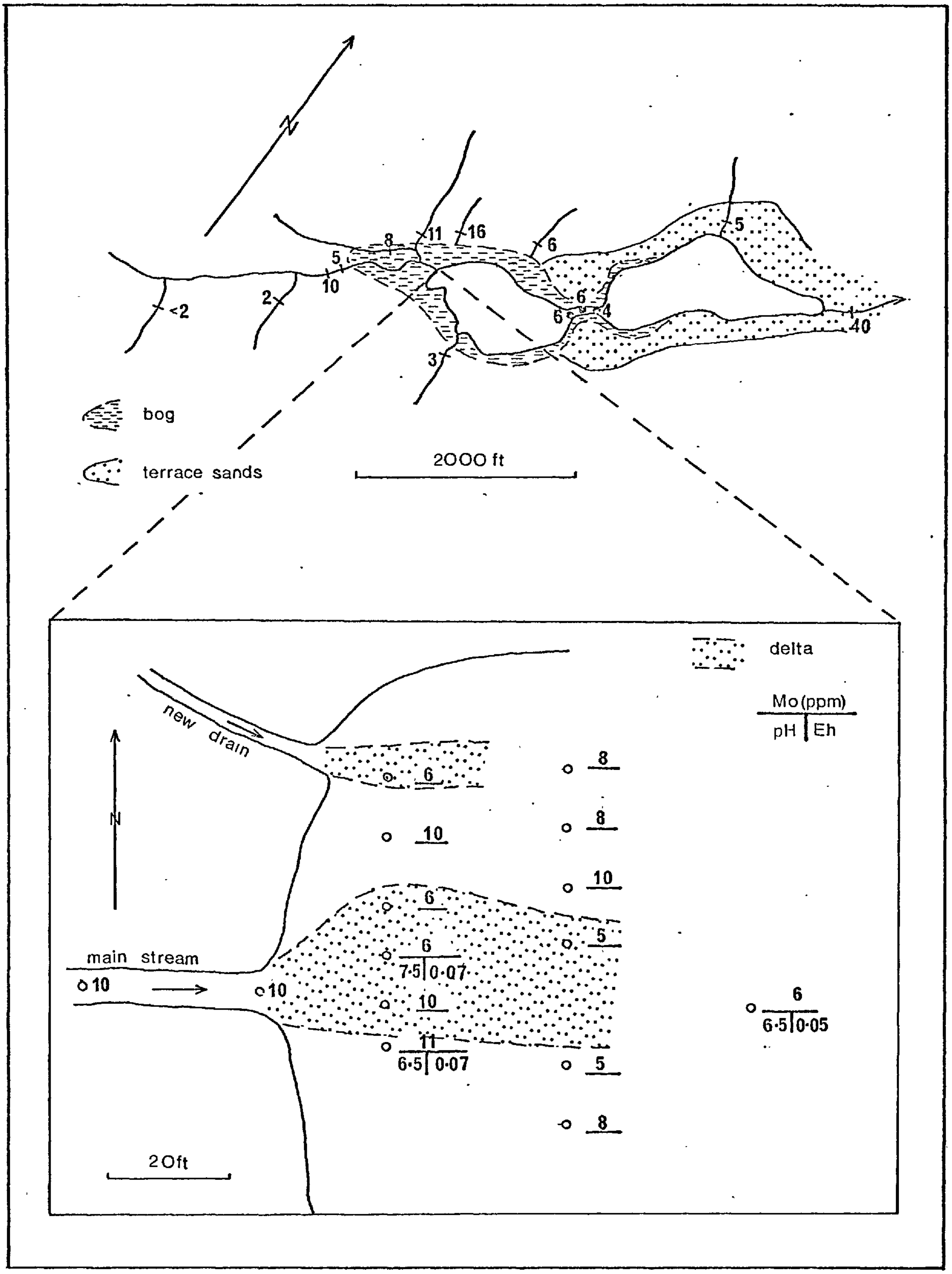


Fig. 52 Mo (ppm) in stream and lake sediments, Haland Lake, Flottorp.

indicating extremely limited transport of the stream sediment in the lake environment. Bottom conditions in the centre of the lake at a depth of 40 ft. were examined by SCUBA diver; the bottom was found to consist of loose organic debris, in a partially suspended state, forming a bottom ooze several feet thick, but cold and poor visibility prevented systematic sampling of this material.

In view of the absence of inorganic matter in lake bottom samples other than from the lake-head deltas, mechanical transport of the anomalous stream sediment through the lake may be discounted. An alternative explanation which must be considered is the possibility of a source of anomalous Mo existing downstream from Haland Lake. To check this,three sediment samples were taken from the channel connecting the two ponds and were found to be weakly anomalous (4-6 ppm Mo, fig. 52). The channel sediment consisted of coarse sand which, as mechanical transport through the lake has been discounted, can only be regarded as deriving from the terrace sand deposits on either side of the channel. Four composite samples of these sands, collected both north and south of the channel, proved to have background Mo contents (<2 ppm). The terrace sand deposit cannot therefore be the source of the anomalous Mo in the drainage channel sediment, and it must be inferred that dispersion of Mo has occurred through the upper pond by some process other than mechanical transport of anomalous stream sediment. With the available data the possibility that the high Mo content (40 ppm) immediately downstream from the lower lake is caused by a local Mo source (i.e. sub-outcropping mineralisation or a glacinogenic soil anomaly) cannot be discounted and the following discussion will initially be limited to dispersion through the upper pond.

(c) Discussion - Dispersion of Mo through Lake Haland

It has been stressed that mechanical transport of stream sediment discharged into the lake is extremely limited, the sediment being confined to a narrow, relatively short lake head delta. A grab sample of the organic bottom ooze from the centre of the lake contained recognisable deciduous leaves indicating that much of this organic matter has its origin outside the lake. A high proportion of allochthonous organic matter in the bottom sediment of Russian reservoirs has been noted (Kuznetsov, 1968); such sediments may be derived from peat bogs or from eroded humus or fallen leaves carried into the lake by influent streams (Hutchinson 1957). The organic load of in-flowing streams will be carried either in colloidal solution, in suspension or actually floating, and on entering the lake will be dispersed over a wide area, transported by minor currents in the surface waters of the lake.

By a process analagous to the development of anomalous Mo contents in the inorganic sediment of streams draining mineralised catchments, anomalous Mo contents may also be expected in the organic load; recent work has shown this to be so in the case of Pb (Antropova, 1969). Reference to fig. 52 reveals comparable Mo contents in the stream sediment immediately above the lake (10 ppm), in the delta sediment (5-10 ppm) and in the organic lake sediment (5-11 ppm). Although data is limited to the lake-head it seems reasonable, in view of the expected wide dispersion of introduced organic matter, to assume that similar anomalous Mo contents will occur in the organic bottom ooze throughout the lake.

Lakes in northern temperate regions undergo limited periods of complete circulation in the spring and autumn; during the remainder of the year circulation is restricted to a shallow upper zone (the epilimnion), while the essentially stagnant lower zone (the hypolimnion) may become stratified (Hutchinson 1957). Strongly reducing conditions may develop in the basal layer of the hypolimnion during the summer and winter stagnation periods, principally (in oligotrophic lakes such as Lake Haland) as the result of reduction of organic debris. During the spring and autumn circulation, on the other hand, oxygenated surface waters are brought into contact with the basal muds so that alternating circulation and stagnation bring about marked seasonal variation in the conditions of the lake bottom.

The concentration of minor elements in the basal waters of such dimictic lakes shows a cyclic variation related to the spring and autumn circulations (Hutchinson 1957). For predominantly inorganic muds these cycles have been related to diffusion across the mud/water interface by metals which are readily soluble under the reducing conditions developed during stagnation (Mortimer 1941/2, Hutchinson 1957, Hough 1959). Kuznetsov (1968), discussing the more relevant case of reservoirs with organic bottom sediments, considers that under such conditions the anaerobic breakdown of organic matter is the principal metal source and stresses the importance of micro-organisms in concentrating metals in the basal zone of the hyperlimnion. It is considered, therefore, that during periods of stagnation the anomalous organic bottom ooze of the Haland lake decomposes to produce a concentration of Mo in the basal lake waters; anomalous stream sediments accumulated in the lake-head deltas undoubtedly also lose Mo to the reduced basal lake water but it is thought that the organic bottom ooze, because of its much greater interface with the lake water, is the principal Mo source. In view of the importance of micro-organisms in anaerobic decomposition it is probable that Mo is present in the basal water as an organic complex, stable under reducing conditions, although the possibility of Mo occurring in ionic form cannot be discounted.

The influx of oxygenated waters into the lake bottom environment during the spring and autumn circulations results in a sharp decrease in metal content (Kuznetsov 1968); metals for which the solubility is strictly Eh dependent (e.g. Fe) may be precipitated, while others are circulated throughout the body of the lake and in part lost to the effluent flow. It is envisaged that the Mo concentrated in the basal lake water during stagnation is dispersed through the body of the lake by the spring and autumn circulations (either as an organic complex, unstable in the now aerated lake water, or as a coprecipitate with hydrous Fe oxide colloids circulating in suspension) and that stream water issuing from the lake during and after circulation has an enhanced content of Mo. Mackareth (1959) considered the distribution of Mn in lake water and sediments to be due to a similar process, and Gorham et al (1965) invoked the circulation mechanism to account for differences in the Mo content of lake bottom muds in the English Lake District.

In the aerated stream environment Mo may be lost from the effluent water by the precipitation of hydrous Fe oxide colloids suspended in the effluent water and containing adsorbed or occluded Mo, or by the oxidation of unstable organic complexes and the subsequent sorption of Mo by hydrous Fe oxides in the stream sediment. The channel connecting the two lakes at Flottorp is short, and it is likely that dispersion of Mo in the effluent water will continue into the second lake. If this is correct then the low anomalous Mo contents in the channel sediment (4-6 ppm Mo) may represent only partial removal of Mo from the aqueous phase, and the highly anomalous contents (40 ppm Mo) in the stream sediment below the lower lake may be more typical.

The mechanism suggested above should be of general application wherever dimictic lakes receive an in-flow of metal-enriched organic matter, provided reducing bottom conditions develop during the summer and winter stagnation periods; in large lakes however, where the anomalous stream is only part of the total in-flow, dilution may prevent the development of recognisable dispersion trains in the sediment of the effluent stream. Reducing bottom conditions are not so readily developed in lakes with predominantly inorganic bottom sediments and it is thought likely that lakes of this type, receiving a relatively low in-flow of organic matter, will effectively truncate anomalous dispersion trains. In this connection it is worthy of note that the anomalous Flottorp dispersion train is in fact terminated by a second, slightly larger lake (Hanekilen Lake, fig. 51), despite the much higher Mo content (90-180 ppm Mo) in the stream sediment above this lake compared to that above Haland Lake (10 ppm Mo).

4. Conclusions

(1) Anomalous Mo and Cu contents in the bedrock at Flottorp are confined to zones of low-grade sulphide mineralisation; the bedrock anomalies are sharply defined and there is no evidence that aureoles of primary dispersion extend into the granite gneisses adjacent to the mineralised zones. For exploration purposes the position and extent of zones of low-grade molybdenite mineralisation may be rapidly and satisfactorily outlined by the Mo content of weathered bedrock samples, the latter collected on a suitable grid pattern and analysed for Mo using rapid geochemical techniques; in the subsequent evaluation of such zones, however, a more rigid sampling and analytical procedure is essential to obtain reliable assay data.

(2) The weakly mineralised molybdenite-bearing fahlband zones at Flottorp are considered to be of syngenetic origin and to represent the high-grade metamorphic equivalents of molybdeniferous black shale horizons. Molybdenite present in minor intrusions (i.e. aplite, grey granite and vein quartz) within the mineralised zones is regarded as derived initially from these fahlbands, either by the incorporation of molybdenite-bearing inclusions or the migration of molybdenite towards areas of locally higher temperature.

(3) Detailed soil sampling showed that anomalous Mo contents occur in all horizons of the soil profile in the vicinity of known mineralisation. In freely drained, moderately acid soils saline dispersion of Mo from bedrock mineralisation is of limited importance, and glacial dispersion is the dominant process in the formation of Mo anomalies in the soil. At Flottorp Mo anomalies in the mineral soil are wider than the underlying bedrock mineralisation, due to the effects of glacial dispersion. Humus Mo anomalies are approximately the same width as those in the mineral soil, although the Mo content of the humus is generally lower, due to the restricted uptake of Mo by plants under moderately acid conditions.

(4) In contrast to Mo, saline dispersion is an important factor in the formation of soil Cu anomalies. Glacial dispersion gives rise to zones of weakly anomalous Cu contents in the B horizon but the peak Cu values within such zones are the result of saline dispersion from bedrock mineralisation. Humus Cu anomalies principally reflect the dispersion of Cu in groundwater and as such are related to the pattern of groundwater flow from bedrock mineralisation.

(5) Topographic variations appear to have little effect on the width or contrast of Mo anomalies in the mineral soil or humus. For Cu, on the other hand, topography has a marked effect on the contrast shown by anomalies in the B horizon, anomaly contrast being greater for poorly-drained localities than on freely-drained slopes, due to leaching of Cu from the latter. The effect of topography is most clearly shown by humus Cu anomalies which closely reflect the flow of Cu-rich groundwater from weathering bedrock mineralisation.

(6) Anomalous Mo contents occur in peat bogs overlying known mineralisation, the content of Mo showing a marked tendency to increase with depth in anomalous peat profiles. The available data indicate that in bog covered areas sampling of the basal peat layer, at intervals of approximately 100 ft., provides an effective method of locating

anomalous Mo dispersion trains in the underlying glacial deposits.

(7) The limited data available for surface waters indicate that at Flottorp anomalous Mo contents are restricted to areas where there has been local contamination of the secondary environment by mining or exploration activity.

(8) The drainage sediment survey revealed a strongly anomalous dispersion pattern in the active stream sediment, persisting at least 6000 yards downstream from sub-economic mineralisation. The maximum Mo content for streams draining relatively undisturbed mineralisation at Lower Flottorp is 36 ppm.

(9) At Flottorp, Mo anomalies in uncontaminated stream sediments result principally from the erosion of anomalous soils. Limited data from the regional survey suggest, however, that in areas of extensive waterlogged soil hydromorphic dispersion may be the dominant process in the development of stream sediment Mo anomalies. It is concluded that local conditions determine the supergene mobility of Mo and that while in predominantly freely-drained areas, such as Flottorp, saline dispersion of Mo is restricted to the soil or till immediately overlying bedrock mineralisation, it may be an important factor in areas with extensive waterlogged soil.

(10) Small lakes which receive a high in-flow of organic matter and which develop reducing bottom conditions during the summer and winter stagnations do not seriously affect anomalous Mo dispersion trains in the active stream sediment. The limited available data indicate however that anomalous Mo dispersion trains are truncated by lakes which for some reason do not develop reducing bottom conditions.

(11) On the evidence available from the orientation study the following procedure is recommended for exploration for Mo mineralisation in areas such as southern Norway:-

(a) In virgin areas rapid reconnaissance cover by means of widely-spaced stream sediment samples will allow the recognition of favourable localities for more detailed investigation. Samples should be collected from streams with catchment areas of 1-5 sq. mls. and should be analysed for Mo and Fe. In planning follow-up sampling programmes priority should be given to Mo anomalies unaccompanied by high Fe values, but all reconnaissance anomalies should be followed-up.

(b) In follow-up sampling it is recommended that active stream sediment samples be collected from all streams draining the area of interest, at intervals of approximately 1000 yards. Samples should be collected upstream from lakes in the drainage system wherever possible.

(c) The procedure for follow-up work on drainage sediment anomalies will depend on local conditions but the following guides are suggested:

(i) If a"cut-off" to the stream sediment anomaly is not obtained during follow-up sampling, reconnaissance soil traverses should be collected along both valley sides, at a sufficient elevation to avoid sampling alluvial material; a sample interval of 250 ft. is adequate to outline the position of Mo anomalies in the soil. Samples should be collected from the mineral soil, but for areas with a relatively thin cover of glacial material, similar to that at Flottorp, the sampling depth is not critical.

(ii) Once the general position of the soil anomaly is located, its form should be determined by systematic grid sampling at a sample interval of 100 ft., traverses being aligned at right angles to the direction of ice-movement, if known. In bog covered areas sampling of the basal layer of the peat profile provides an effective method of locating anomalous Mo dispersion trains in the underlying glacial deposits.

(iii) In favourable areas the source of the anomalous Mo may be more precisely located by close interval (25 ft.) soil sampling. Molybdenite is frequently accompanied by Cu-bearing sulphides and the position of mineralisation of this type will be defined more closely by peak Cu values in the overlying soil; if the detailed samples are to be analysed for Cu however, it is essential that only B horizon soils be collected. Alternatively, in areas of abundant outcrop, mineralisation may be sought by systematic sampling of the exposed bedrock.

(iv) In interpreting soil data it should be borne in mind that glacial dispersion is the dominant process in the formation of Mo anomalies in freely drained soils, but that hydromorphic processes may be important in extensively waterlogged areas.

CHAPTER VII. FOLLOW-UP INVESTIGATIONS

Preliminary follow-up surveys were carried out over selected anomalous zones revealed by the regional survey. The follow-up surveys were undertaken in order:

a) to confirm the regional survey results;

b) to check, if possible, the general applicability of the orientation survey conclusions in other areas;

c) to assess the economic potential of the anomalous zones.

For reasons of logistics priority was given to sites with easy road access in the eastern half of the survey area. Sediment samples were collected from all streams draining the potential anomaly, and rock exposures were examined for indications of the source of the anomalous metal. The samples were analysed wet chemically and the data interpreted in the light of experience gained from the Mølland and Flottorp orientation surveys. Data from reconnaissance soil surveys at two localities are also presented. The conclusions drawn from the follow-up investigations have already been briefly referred to in the section on the regional survey (pages 43 and 44).

1. Mo follow-up investigations

Regional survey data for the localities selected for follow-up investigations are summarised in table 51; locations are shown in fig. 11. In interpreting the

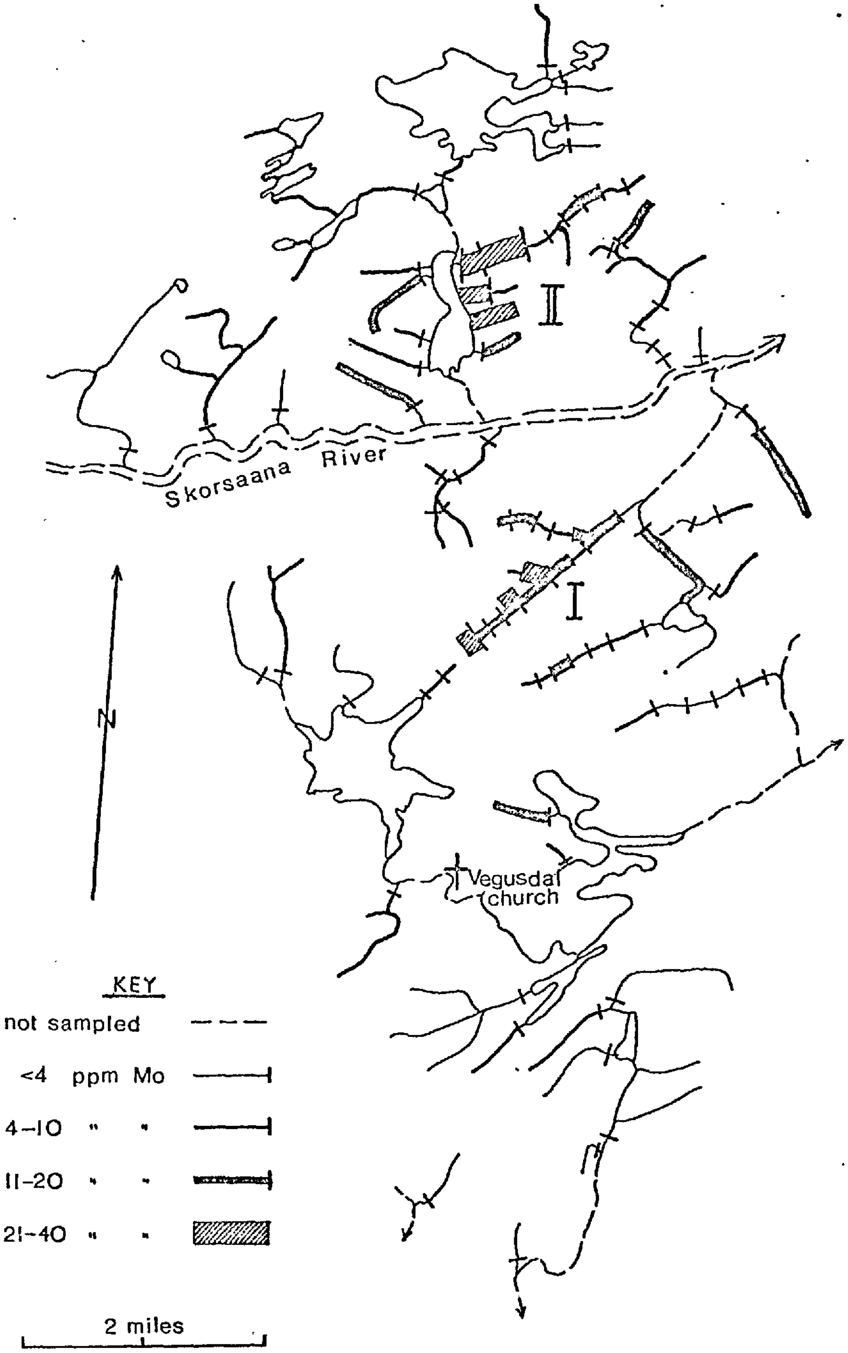


Fig. 53. Mo (ppm) in stream sediment, Vegusdal follow-up survey.

follow-up stream sediment data threshold was taken as 4 ppm (p. 226), Mo contents of 4-10 ppm are anomalous, while values in the ranges 11-20 ppm Mo and 21-40 ppm Mo are regarded as strongly and highly anomalous respectively.

Table 51. Summary of regional survey results for Mo follow-up localities (for locations see fig.11).

Locality	Peak Mo content (ppm)	Anomalous samples	Area (sq. mls.)
Vegusdal	30	7	50
Killand	40	10	50
Grovane	30	8	20

(a) Vegusdal

At the Vegusdal locality follow-up sampling confirmed the regional survey results and outlined a north-south trending anomalous zone with a length of 9 miles and a maximum width of 5 miles (fig. 53). Although the anomaly is bordered by background values to the south, west and north-east, it is possible that further sampling would reveal an extension to the east or north-west. Within the broad anomalous zone are two areas (I and II, fig. 53) where Mo contents compare favourably with uncontaminated streams at Flottorp (fig. 51); it is not clear if these form a single highly anomalous zone since, due to its size, the Skorsana River flowing between areas I and II was not sampled.

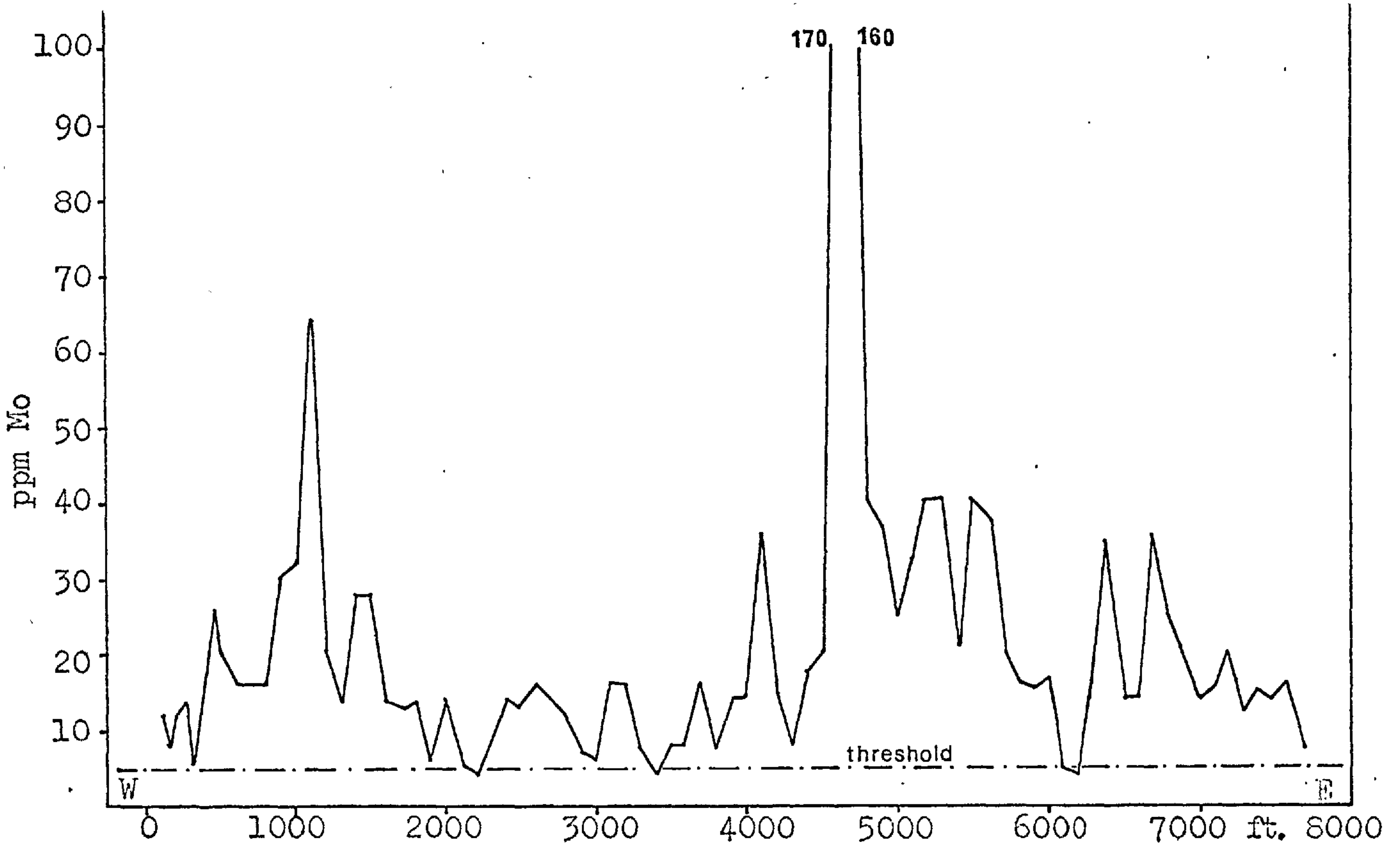


Fig. 54 Mo data for the initial reconnaissance soil traverse parallel to the principal anomalous stream at locality I, Vegusdal.

Reconnaissance soil samples were collected at locality I in an attempt to determine the source of the anomalous Mo. In view of the dominant north-south direction of ice-movement the more northerly locality would have been a preferable site for the soil traverse but, due to the timing of the various phases of the follow-up survey, soil sampling was completed prior to the discovery of locality II.

The soil traverses were aligned parallel to the principal anomalous stream and were sited on the well-drained north valley slope. In accordance with the conclusions of the orientation study a wide sample interval (100 ft.) was used for an initial traverse the full length of the valley (8000 ft.), run approximately 30 ft. above stream level to avoid sampling alluvial material. On the basis of the Flottorp threshold value (5 ppm Mo) the whole traverse is anomalous and there are two strongly anomalous zones (>25 ppm Mo) at 1000-1300 ft. and 4500-5700 ft. (fig. 54).

Detailed traverses (sample interval 25 ft.) were then collected across the two strongly anomalous zones, 100 ft. north (i.e. upslope) of the initial traverse. For the smaller western anomaly (fig. 55) the two traverses show the same broad high zone although the anomaly peaks do not coincide. Over the easternmost anomaly (fig. 56)

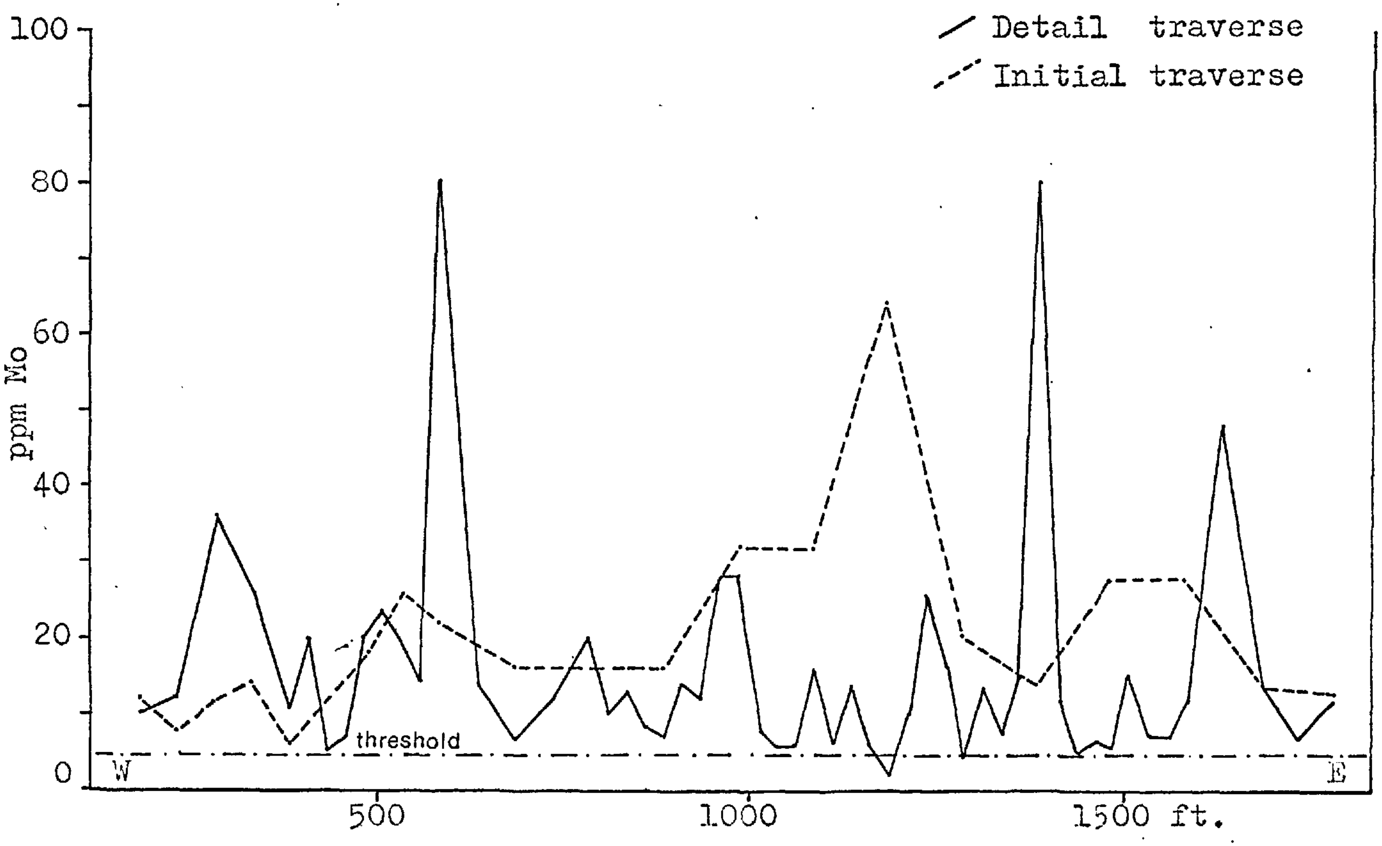


Fig. 55 Mo data for detailed soil traverse over westernmost soil anomaly, locality I, Vegusdal.

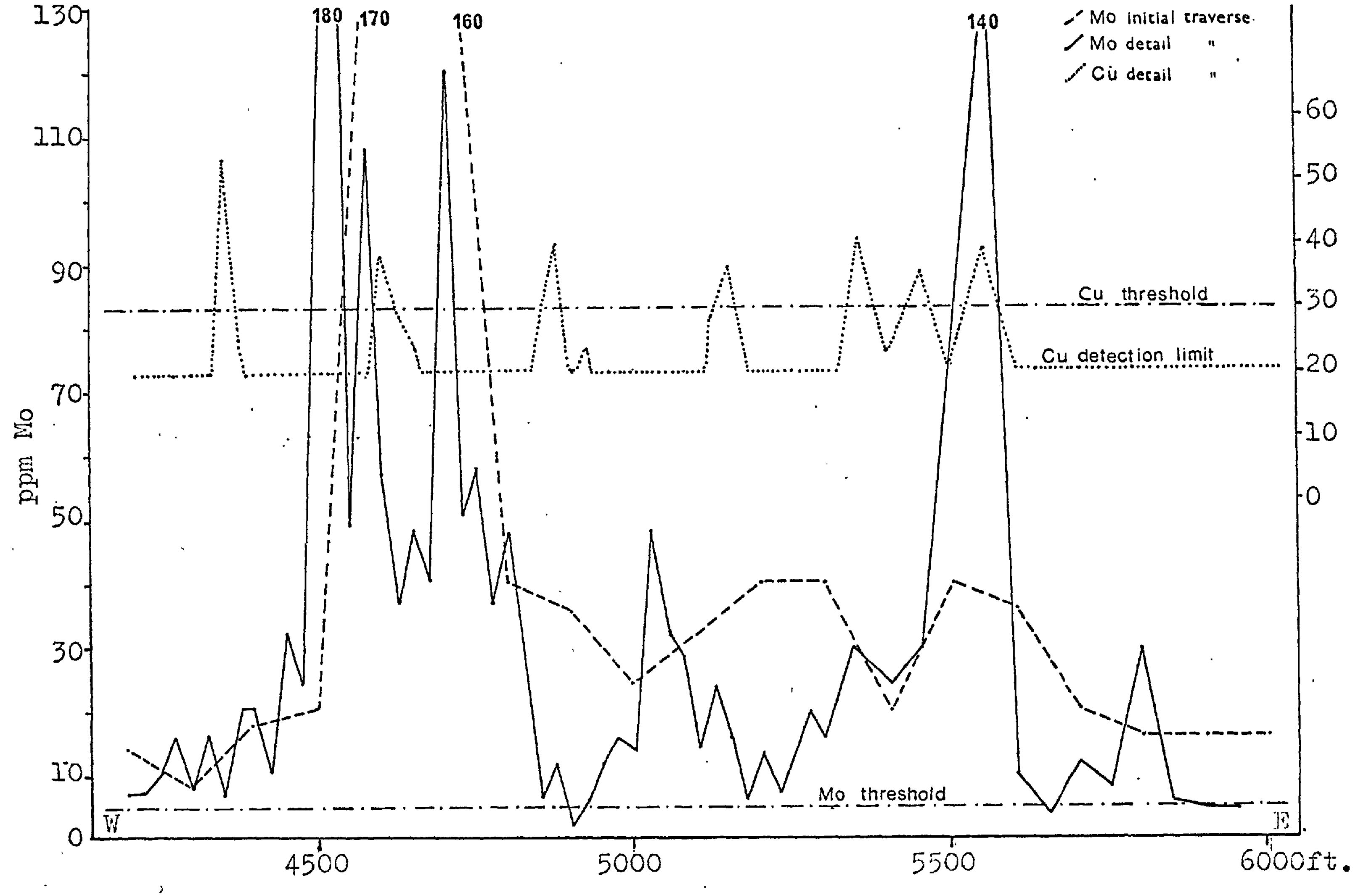


Fig. 56 Mo and Cu data for detailed soil traverse over eastern soil anomaly, locality I, Vegusdal.

there is a good correlation between the positions of peak values on the two traverses and it is noticeable that although the general level of Mo is slightly lower, almost the entire upslope traverse is anomalous (i.e. >5 ppm Mo).

Samples from this traverse were also analysed for Cu. Threshold is taken as 30 ppm (p. 205) and it is apparent (fig. 56) that although a number of isolated samples are weakly anomalous there is no broad zone of low anomalous Cu values similar to that noted at Flottorp (p. 207), suggesting that in this instance Cu and Mo mineralisation do not coexist.

18 rock samples were collected at intervals of approximately 20 ft. from 4500 - 4700 ft.; these showed a range from 2-6 ppm Mo and although non-anomalous (rock threshold = 6 ppm, p. 195), have a mean content of 4 ppm Mo, indicative of a locally high background. A molybdenite-bearing quartz vein found at 4400 ft. on the line of the initial traverse offers evidence for mineralisation in the area, but is far too small to be the principal cause of the anomaly.

Thus the source of the Mo was not located during the limited period of the follow-up survey but an anomalous zone with a strike length of at least 9 miles was outlined, and was shown to include an area of approximately 10 sq. miles where the stream sediments have strongly

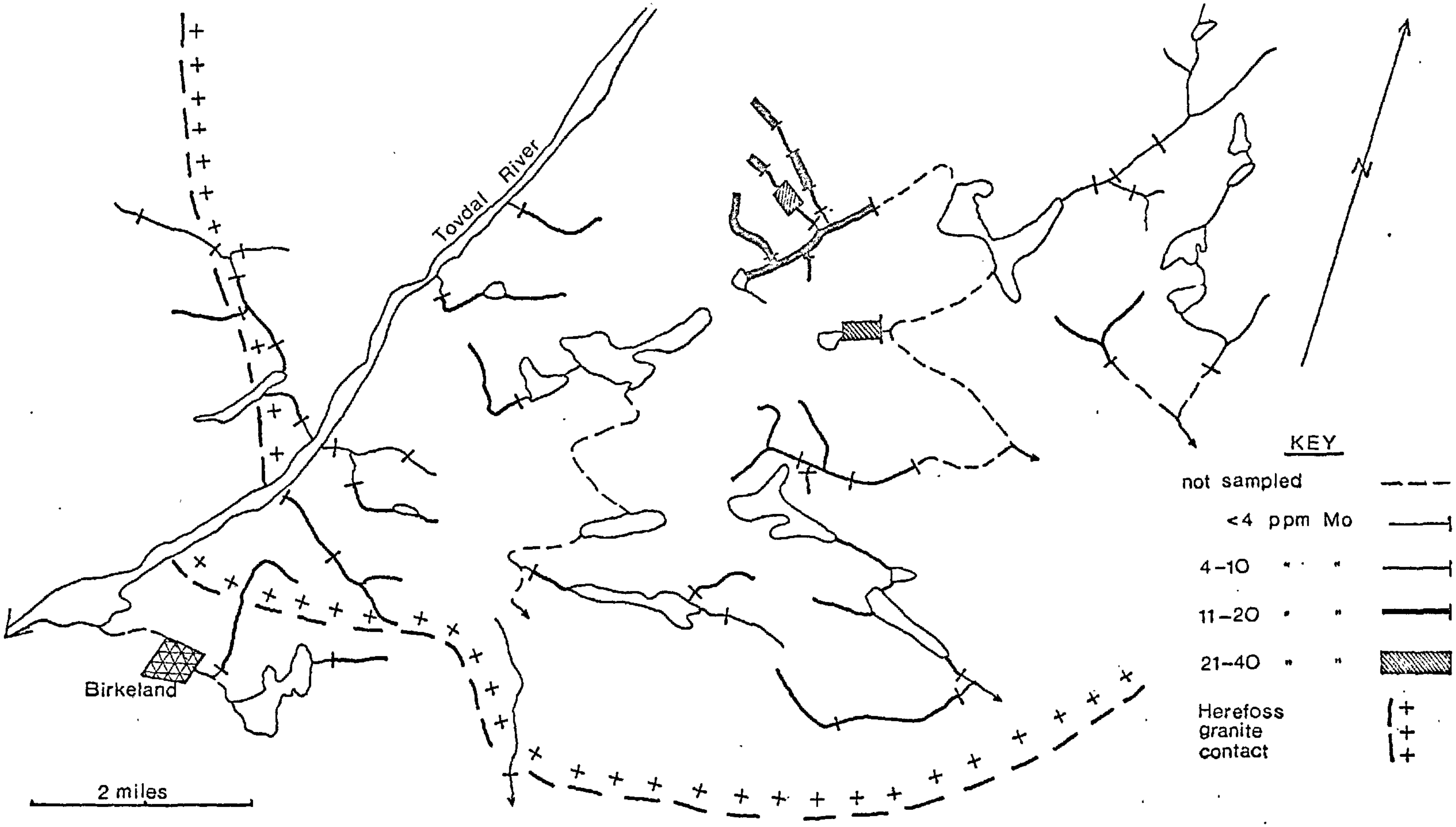


Fig. 57 Mo (ppm) in stream sediment, Killand follow-up survey.

anomalous Mo contents comparable to streams draining undisturbed mineralisation at Flottorp. Soil traverses at the single locality followed-up in detail revealed broad anomalous zones, comparable in width and intensity to those present over mineralisation at Flottorp. In view of the favourable results obtained during the follow-up survey the Vegusdal area is considered to warrant further work.

(b) Killand

At the Killand anomaly (fig. 57) follow-up sampling confirmed the regional survey results, outlining as anomalous an area of 45 sq. mls. largely coincident with the outcrop of the Herefoss granite. Within this broad zone is a smaller highly anomalous area where the Mo content of the stream sediment is similar to that below undisturbed mineralisation at Flottorp. Bugge (1963) briefly mentions the occurrence of molybdenite impregnations in the Herefoss granite, and in view of the encouraging follow-up results this locality is considered to have economic potential and to merit further work.

(c) Grovane

Preliminary sampling at Grovane (fig. 58) confirmed the presence of anomalous Mo in the stream sediment. In addition to the Mo anomaly the regional survey indicated high Fe, Mn, Ni, Zn, Co and Cu contents in the Grovane area and it was suggested (p. 59) that secondary

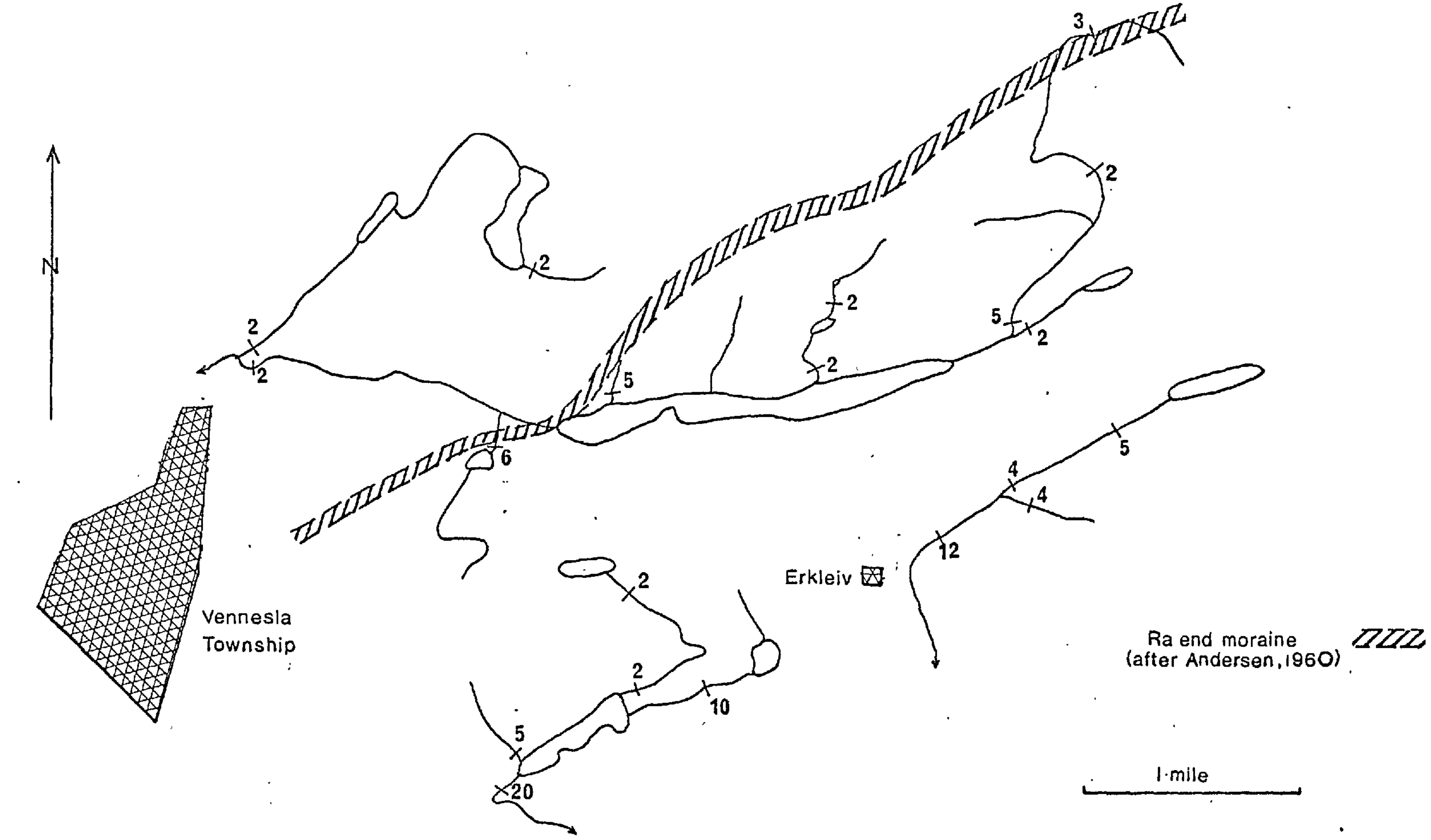


Fig. 58 Mo (ppm) in stream sediment, Grovane follow-up survey.

enhancement is responsible for such anomalies. This process is considered to be related to waterlogged soils developed on the generally deeper overburden to the south of the Ra end moraine belt (p. 60) and fig. 58 confirms that anomalous Mo contents occur only south of the Ra end moraine. Comparison with fig. 60 reveals, however, that while anomalous Ni contents occur throughout the Grovane area anomalous Mo values are largely confined to the N.W. - S.E. trending valley passing through Erkliev.

Jones (1957) showed that hydrous Fe oxides readily adsorb Mo from aqueous solution and this appears the most likely process by which anomalous Mo is accumulated in stream sediments affected by secondary enhancement. From the available data it is not certain whether the localisation of anomalous Mo contents in the Erkliev valley is due ultimately to a local bedrock Mo source or to some factor causing preferential accumulation of secondary hydrous Fe oxides in the stream sediment of this valley.

As mentioned earlier (p. 228), leaching from background rock fragments cannot be discounted as the principal source of Mo in stream sediment anomalies affected by secondary enhancement. If this is correct, however, high Mo contents are to be expected wherever secondary hydrous Fe oxides precipitate from groundwaters seeping from areas of waterlogged soil. Two such seepage precipitates were sampled during the follow-up investigation and the results, summarised in table 52, show that while hydrous Fe oxide from a known anomalous locality has a high content of Mo, similar material from a background locality is non-anomalous. The foregoing indicates molybdenite mineralisation to be the ultimate source of anomalous Mo in areas of secondary enhancement but a soil sampling programme is necessary to conclusively demonstrate this in the case of the Grovane anomaly.

Table 52. Comparison of the Mo content of hydrous Fe oxide precipitate samples collected from an anomalous locality (Vegusdal) and in a background area (Dalane).

	Vegusdal	Dalane
Locality description	Narrow drainage channel through valley bottom peat bog; highly anomalous Mo contents in sediment upstream.	Swampy valley in background area.
Sample description	Slimey hydrous Fe oxide precipitate in stagnant section of channel.	Slimey hydrous Fe oxide precipitate from a seepage area.
Mo	36 ppm	3 ppm

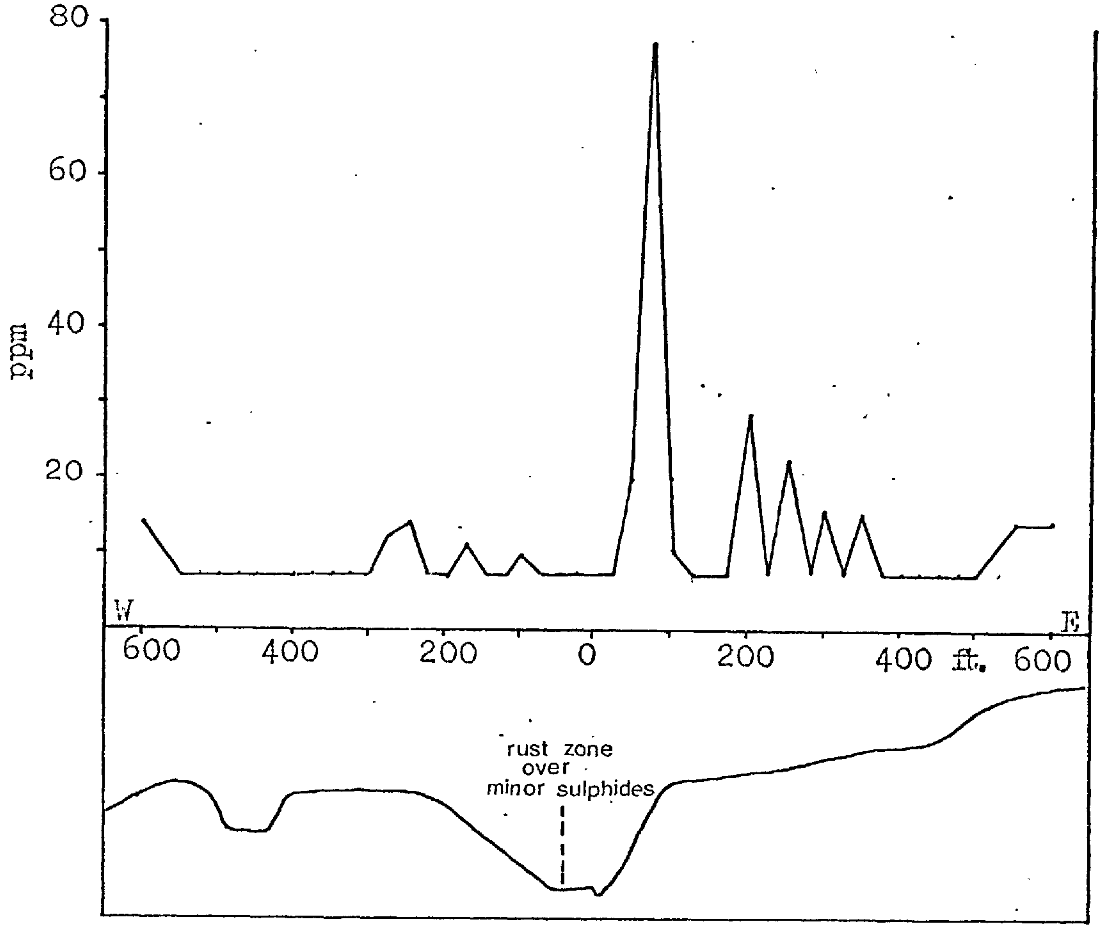
2. Ni follow-up investigations

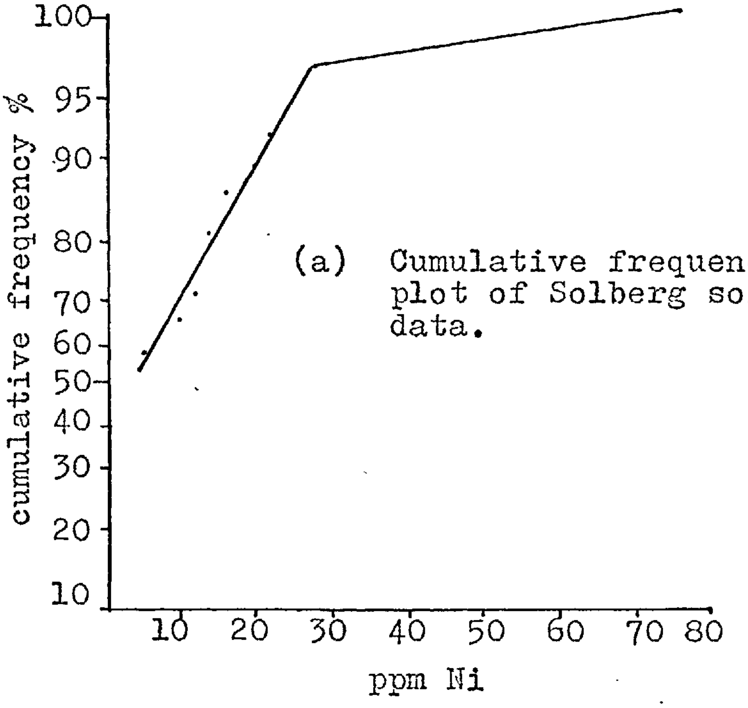
It is unfortunate that the timing of the various phases of the sampling and analytical programmes prevented the application of the technique recommended for Ni exploration (p. 188) to the present follow-up investigations.

The results of the most comprehensive follow-up study over 40 sq. mls. of the Iveland-Evje basic complex have already been presented and discussed (p. 156). This study confirmed the general findings of the regional survey, but demonstrated that close-interval stream sediment sampling is essential in order to detect anomalous dispersion patterns related to mineralisation. Only one locality (Solberg) within the detailed survey area was considered to warrant further work and data from a reconnaissance soil traverse at this locality are presented below. The results of preliminary follow-up surveys at two other localities (Grovane and Amli) are also given.

(a) Solberg reconnaissance

A detailed drainage survey of the Iveland area (p. 158) revealed an area of possible interest at Solberg; a narrow rust zone overlying am hibolite with very minor nickel-bearing sulphides was found in a road-cut, and a reconnaissance soil traverse was collected at this locality (fig. 54). The lower mean Ni content of background soil samples from Solberg compared to Mølland (table 26) suggests that threshold at Solberg may also be lower than at the orientation locality. A cumulative frequency plot of the Solberg data (fig. 59a) indicates a marked inflection at 30 ppm Ni, which is taken as threshold (Tenant et al 1959). One soil sample only is anomalous (75 ppm, fig. 59), and it is worthy of note





(a) Cumulative frequency plot of Solberg soil data.

Fig. 59 Ni (ppm) in B horizon, Solberg reconnaissance soil traverse.

that background soils overly the rust zone. The road is of recent construction and blocks of weakly mineralised amphibolite, blasted from the road-cut, have been dumped into the stream; the weakly anomalous Ni content of the stream sediment is thought to be due to the accelerated oxidation in the stream bed of the minor disseminated sulphides in these blocks.

(b) Preliminary follow-up surveys

Regional survey data for the Grovane and Amli localities are summarised in table 53. Only the Grovane area can be regarded as strictly anomalous, Amli being of interest as an area of moderately high Ni content outside the mafic belt.

Table 53. Summary of regional survey data for Ni follow-up localities (for locations see fig. 12).

Locality	Peak Ni content (ppm)	Anomalous samples	Area (sq. mls.)
Grovane	300	2	10
Amli	120	-	50

During the follow-up surveys sediment samples were collected from all streams draining the potential anomaly and rock exposures were examined for indications of the source of the anomalous metal. The samples were analysed wet chemically and the data interpreted in the light of

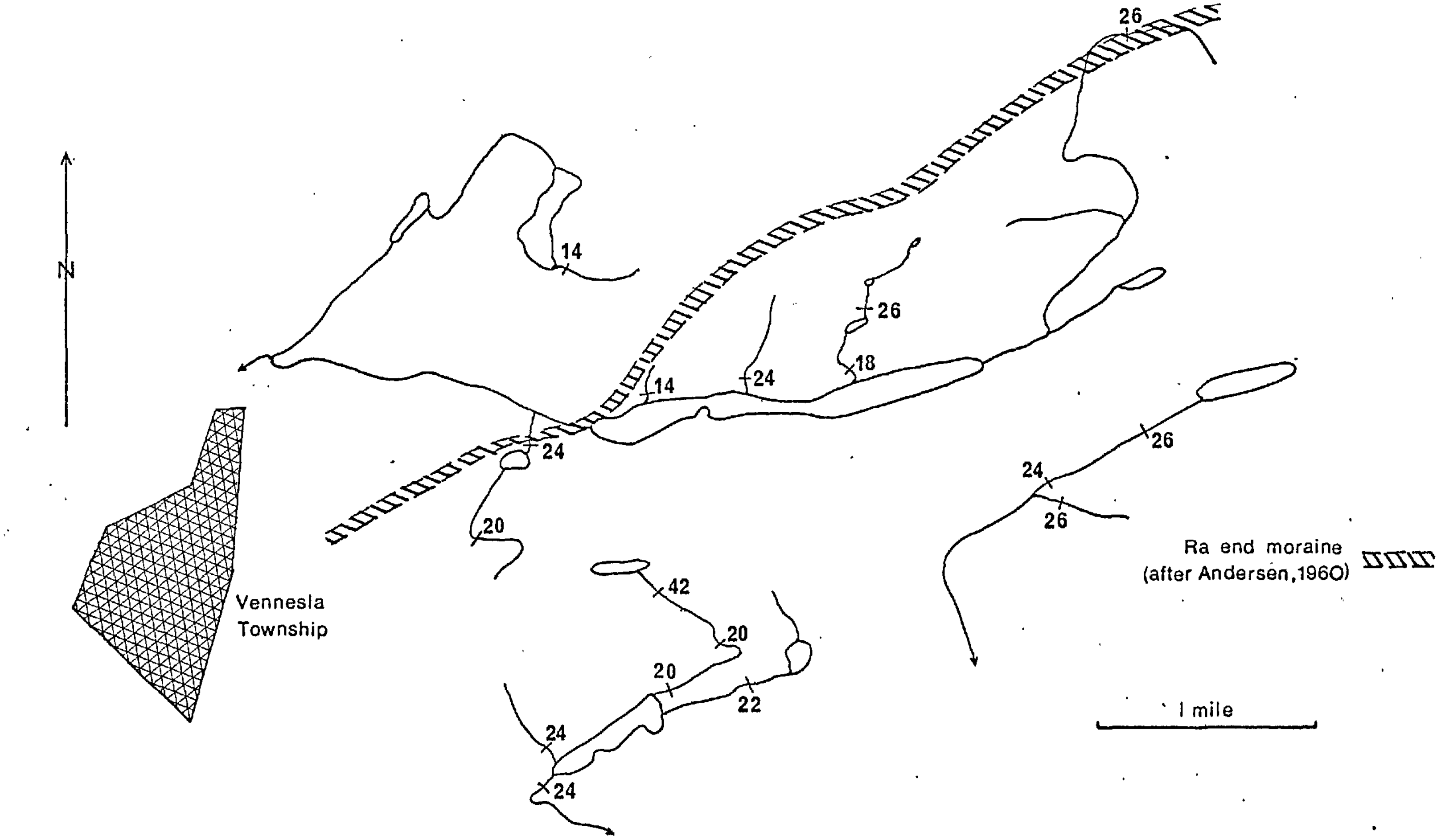


Fig. 60 Ni (ppm) in stream sediments, Grovane follow-up survey.

experience gained from the Mølland orientation survey, where threshold values for mafic and granite gneiss areas were established as 35 ppm Ni and 15 ppm Ni respectively.

The Grovane locality lies outside the Iveland-Evje mafic belt and only granite gneiss outcrops were observed during the follow-up sampling. The Ni content of the stream sediment ranges from 14-42 ppm (fig. 60) and with two exceptions is universally greater than the threshold value for granite gneiss areas (15 ppm Ni), confirming the regional survey anomaly.

The high content of Fe, Mn, Ni, Mo, Zn, Co and Cu in the stream sediment of the Grovane area revealed by the regional survey, and the spatial relationship of the Grovane Ni anomaly to the Ra end moraine belt have already been referred to (p. 247) and the suggestion made that the metal content of the stream sediment in this area has been affected by secondary enhancement processes. Examples of similarly enhanced stream sediment Ni and Co contents associated with high Mn were noted during the nickel orientation survey (pages 169 and 177).

Amli: Barth (1960) designates the rock type in the Amli area as mixed gneiss and local basic gneiss was observed in the field. The follow-up sampling (fig. 62) confirmed the regional picture of an area of moderate Ni contents (<10-30 ppm) and in the absence of high Mn values (fig. 16) it is concluded that the locally mafic bedrock

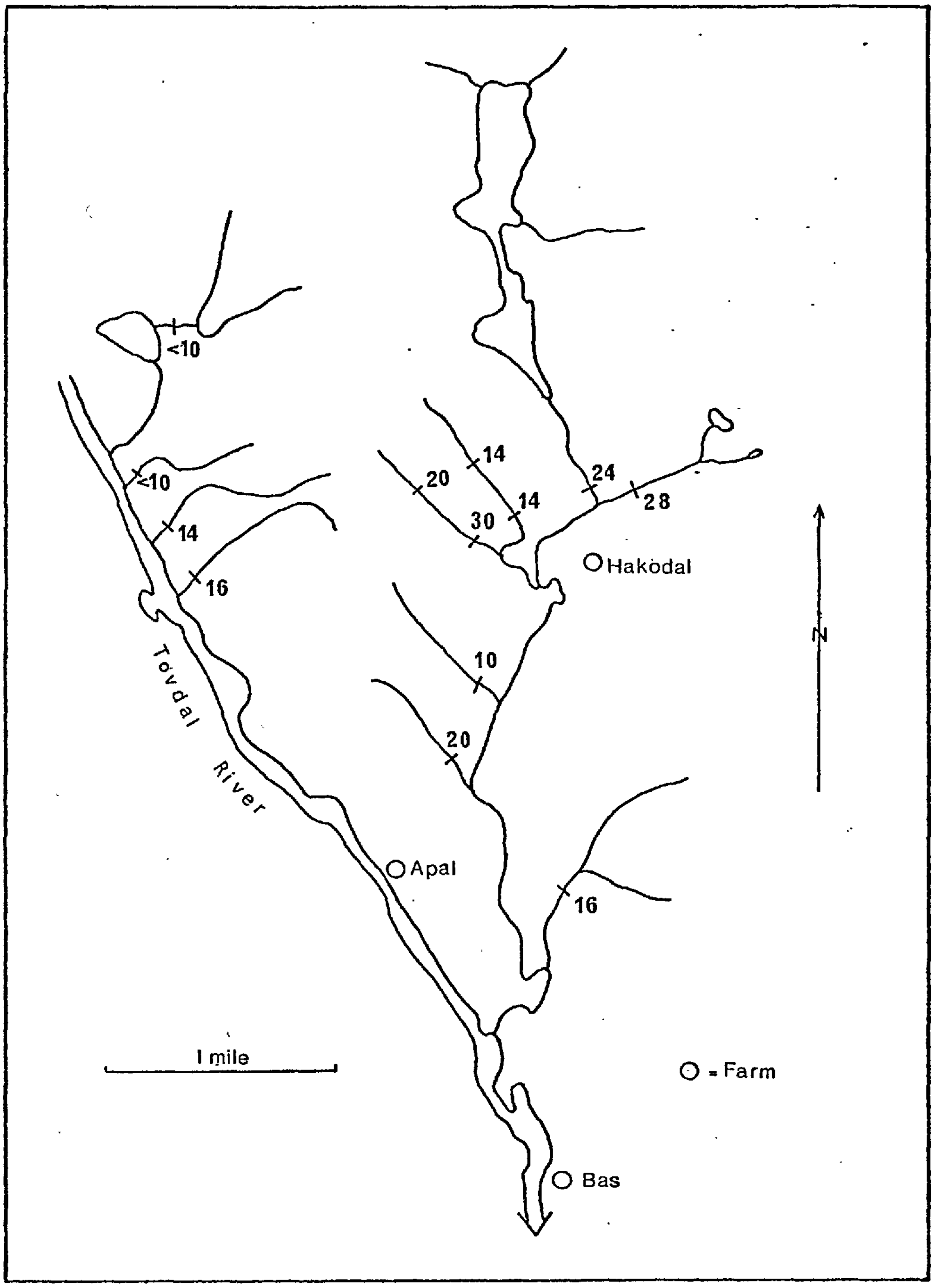


Fig. 61 Ni (ppm) in stream sediment, Amli preliminary follow-up survey.

is responsible for the moderate Ni values at Amli.

3. Conclusions

(1) Preliminary follow-up sampling has in each case confirmed the Mo or Ni anomaly revealed by the regional survey.

(2) At both Vegusdal and Killand preliminary follow-up sampling has outlined broad Mo anomalies and located areas where the stream sediments have strongly anomalous Mo contents, comparable to those below undisturbed mineralisation at Flottorp. Soil traverses at the single locality followed-up in detail revealed broad soil anomalies comparable in width and intensity to those present over mineralisation at Flottorp.

(3) In view of these encouraging follow-up results the Vegusdal and Killand localities are considered to have economic potential and to warrant further exploratory work to locate the source of the anomalous Mo. The favourable results obtained at these localities are also considered to justify preliminary follow-up sampling on the remaining Mo anomalies revealed by the regional survey.

(4) Of the regional survey Ni anomalies selected for preliminary follow-up sampling, only that at Solberg is related to sulphide mineralisation. The stream sediment Ni anomaly at this locality is, however, considered to be principally due to contamination from very minor sulphides

occurring in blocks of recently blasted amphibolite dumped in the stream bed during road construction.

CHAPTER VIII. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

(a) Regional reconnaissance

(1) From a mineral exploration viewpoint the purpose of a regional survey is to provide rapid reconnaissance cover over large blocks of country so that areas of low economic potential may be eliminated and favourable targets selected for subsequent more detailed exploration. The nature of the target areas depends on the type of mineralisation sought; thus, in the present survey, zones of weak mineralisation act as primary targets in the search for molybdenite deposits and areas of basic and ultrabasic rock are favourable initial targets for nickel sulphide mineralisation.

(2) The regional survey results indicate that in southern Norway reconnaissance by means of stream sediment samples collected at a mean density of 1 sample per 5 sq. miles adequately outlined the known areas of mafic bedrock and the zone of weak Mo mineralisation at Flottorp. It is also evident that distinct Mo anomalies are revealed related to individual molybdenite deposits. The lack of Ni or Cu anomalies related to mineralisation may be due to the low-grade and restricted size of the deposits since, to avoid contamination, samples were not collected down-drainage from Flat mine, the only Ni-Cu deposit of economic grade and size in the area.

(3) In areas with extensive waterlogged soils, secondary processes lead to enhanced contents of Mn, Fe, Co, Ni, Zn, Cu and Mo in the stream sediment. These may be distinguished from the broadly similar patterns related to mafic bedrock features (i.e. moderate to high Ni, Cr, Co, Mn and Fe) by the moderate to high Cr values associated with the latter. No such criterion is available for distinguishing between Mo anomalies related to secondary enhancement and those related to molybdenite mineralisation; in follow-up investigations priority should be given to Mo anomalies unaccompanied by high Fe contents, but follow-up sampling is justified on all Mo anomalies.

(4) No unambiguous evidence of glacial dispersion was found during the present regional survey. It is thought however that where glacial dispersion trains do occur they will favour the recognition of major bedrock features by wide interval reconnaissance surveys.

(5) It is concluded that rapid reconnaissance, by means of widely spaced stream sediment samples, is a valuable technique in the initial stages of mineral exploration programmes for Mo in glaciated terrain. In exploration for Ni the primary targets, areas of mafic and ultrabasic bedrock, are perhaps more easily recognised from aeromagnetic maps and where these are readily available reconnaissance surveys may have little application in the initial stages of mineral exploration for Ni.

(b) Ni orientation survey

(6) The three major rock units recognised in the field at Mølland (i.e. amphibolite, metagabbro and norite) have been shown on chemical evidence to be distinct rock types. A strong negative correlation exists between advancing fractionation stage (as indicated by $\frac{Fe}{Fe+Mg}$ ratios) and the content of Ni and Cr for all three rock units and it was concluded that all are of igneous origin and in particular that the amphibolites are ortho-amphibolites.

(7) The dominant amphibolites are the oldest rocks within the Iveland-Evje complex. The metagabbro cropping out at Mølland is regarded as belonging to a second distinct phase of igneous activity while the Mølland norite is the youngest basic intrusion in the area and is considered to have been emplaced along a line of weakness at the metagabbro-amphibolite contact. Both whole rock and mineral separate analyses indicate a distinct fractionation trend within the Mølland norite; it is concluded that the base of the norite intrusion is the eastern contact with the metagabbro, the sharp boundary with the amphibolites to the west being the upper contact.

(8) Mineralisation at Mølland has been shown to be genetically related to the norite intrusion. Nickeliferous sulphides occur throughout the norite body, but are concentrated in a distinct zone near the upper or western

contact. Anomalous Ni, Cu and Hg contents in the bedrock are confined to this zone.

(9) Available evidence indicates that the Flåt mineralisation is likewise associated with igneous activity post-dating the formation of the main body of ortho-amphibolites; other younger intrusions within the Iveland-Evje complex are therefore considered to be potentially favourable areas for Ni mineralisation, and to warrant detailed examination. On surface indications the ortho-amphibolites comprise approximately 90% of the Iveland-Evje complex and, as the individual younger intrusions appear of limited size, the economic potential of the area as a whole is regarded as relatively low.

(10) The mean Ni content (445 ppm) of unmineralised samples from the Mølland norite is much higher than that of the ortho-amphibolite (111 ppm) and metagabbro samples and reconnaissance bedrock sampling would clearly indicate Mølland as potentially nickeliferous. Unmineralised samples collected in the immediate vicinity of the Flåt mine have a low mean Ni content (142 ppm) however, and it is concluded that in the search for Ni mineralisation in the Iveland-Evje area bedrock sampling is not a reliable reconnaissance exploration method.

(11) At Mølland anomalous Ni and Cu contents occur in B horizon soils in the vicinity of known mineralisation; the soil anomaly outlined by detailed sampling coincides

broadly with the position of the mineralised zone although anomalous Ni contents occur in the soil south (or down-ice) of the most southerly known mineralisation. For Ni, contrast between anomaly peak and threshold is greater in the soil than in bedrock mineralisation. For Cu the reverse is true, contrast being greater in bedrock samples than in the overlying soil.

(12) Reconnaissance soil sampling at Flat revealed anomalous Ni and Cu in B horizon soils in an area where the orebody is blind at 900 ft. The anomalous metal contents in the soil are considered to be related to leakage anomalies in the bedrock above the Flat orebody and it is concluded that under favourable circumstances soil sampling may serve as an effective method of detecting blind orebodies.

(13) Anomalous soil profiles show a general decrease in Ni and Cu content with depth, both metals being significantly enriched in the B horizon. In background soil profiles Ni and Cu are uniformly distributed through the deeper levels of the soil and there is no significant accumulation of either metal in the B horizon. The content of both Ni and Cu is low in the eluvial A_2 horizon of background profiles and Ni alone is enhanced in the humus layer.

(14) The constituent size fractions of anomalous B horizon soils show a distinct increase in Ni, Cu, Co, Fe and Mn content with decreasing grain-size; a similar feature is shown by Fe and Cu in background samples. For size fractions coarser than 125 mesh the Ni content of anomalous samples is approximately twice that of background samples; this contrast increases slightly in the (-125 +200) fraction, but is an order of magnitude greater in the silt and clay fractions. For Cu, on the other hand, there is a negligible difference between anomalous and background samples in size fractions coarser than 200 mesh and anomaly contrast is low (<2) in the silt and clay fractions.

All size fractions of the soil contain quartz, plagioclase and hornblende, the principal mineralogical difference being the presence of vermiculite in size fractions coarser than 200 mesh while chlorite is present in the silt and clay fractions. No pedogenic clay minerals were identified in the clay fraction which is regarded as essentially weathered rock flour.

In the coarser size fractions of anomalous soils Ni is present largely through adsorption by vermiculite. On experimental evidence it was concluded that anomalous Ni occurs in the silt fraction as a result of adsorption by secondary hydrous Fe oxides; adsorption by high-Fe organo-mineralic colloids is the dominant process by which anomalous Ni is fixed in the clay fraction.

(15) The mean Ni and Cu content of background B horizon soils is markedly lower than that of the underlying bedrock. Comparative mineralogical studies of bedrock and soils from Mølland showed that a large proportion of the -80 mesh fraction of the soil is derived from granite gneiss bedrock transported a minimum distance of 2½ miles. It was concluded, however, that dilution by glacial smearing is only one factor in the discrepancy between soil and bedrock metal contents and that Ni and Cu are leached from the till during soil formation.

(16) The dispersion or accumulation of Ni in the soil is considered to be primarily a function of the form in which Ni migrates in the groundwater. Experimentally ionic Ni was shown to be readily adsorbed from solution by the silt and clay fractions of B horizon soils; Ni also forms soluble complexes with a constituent of the clay fraction organic matter, and it was found that these Ni-chelates were not adsorbed from solution. It is concluded that Ni derived from oxidising sulphides migrates in groundwater principally in ionic form and is therefore accumulated in the B horizon of the soil; weathering of till or bedrock, on the other hand, liberates Ni principally in the form of soluble Ni-organic complexes which are not fixed in the B horizon but tend to be dispersed in the drainage system.

(17) Anomalous Ni and Cu contents occur in peat bogs at Mølland in the vicinity of known mineralisation. The content of both metals tends to increase with depth in anomalous peat profiles. Ni shows no significant variation with depth in background profiles but the content of Cu increases markedly, and may locally be very high.

The relative concentration of Ni and Cu and their distribution in the peat profile offers a method of distinguishing superjacent and lateral peat anomalies. In superjacent anomalies the contents of both metals increase with depth; Ni is strongly anomalous throughout the profile but the content of Cu is lower and may be anomalous in the basal peat layer only. In lateral anomalies the relative concentration of Ni and Cu is reversed and peak anomalous values may occur at intermediate depths in the peat profile, dependent on the level at which the anomalous groundwater flow is channeled.

(18) Glacial dispersion was an important factor in the development of the Mølland soil anomaly, but due to the instability of the ore minerals under weathering conditions the intial syngenetic dispersion patterns have been largely modified by soil forming processes. Saline dispersion from weathering bedrock sulphides is also an important factor and it is concluded that the majority of soil anomalies overlying or adjacent to mineralisation are

of complex origin, developed by a combination of both glacial and saline dispersion.

(19) On the evidence of the Mølland orientation area, stream sediment anomalies related to Ni mineralisation are of restricted length and low contrast. Anomalous Ni contents in the stream sediment result principally from the erosion of anomalous soils; hydromorphic dispersion from weathering mineralisation, while important in the formation of stream sediment Cu anomalies at Mølland, is a minor factor in the case of Ni.

(20) Under normal circumstances marked climatic fluctuations do not give rise to significant variations in the Ni content of the -80 mesh fraction of anomalous or background stream sediments. The observed variation in the Ni content of the -80 mesh fraction of stream sediments from anomalous localities is attributed principally to the inhomogeneity of anomalous stream sediments; the more limited variation noted for background localities is attributed principally to analytical error.

(21) A detailed drainage survey over the southernpart of the Iveland-Evje amphibolite complex confirmed the findin of the regional survey regarding the distribution of Ni in this area. In addition to Mølland this survey revealed two weakly anomalous localities within the mafic rock outcrop. At the apparently more promising locality (Solberg) a reconnaissance soil traverse revealed only a

single anomalous sample, although minor Ni-bearing sulphides were found in a road cut adjacent to the stream and in large blocks of recently blasted material dumped in the stream bed; it was concluded that contamination from the latter was the most likely cause of the weakly anomalous Ni contents in the stream sediment. Anomalous Ni contents were also found in areas of granite gneiss bedrock at Dalane and Grovane; these occur in association with high Mn contents and are interpreted as due to secondary enhancement.

(22) On the basis of the present orientation survey results the following provides a satisfactory procedure for the location of Ni mineralisation in areas such as southern Norway:-

(a) Areas of basic and ultrabasic bedrock provide initial exploration targets. In the absence of prior geologic knowledge of the area aeromagnetic maps, if available, should provide the best method of identifying such targets. Areas of basic and ultrabasic bedrock may also be identified by multi-element wide interval reconnaissance stream sediment surveys; they are characterised by moderate to high contents of Ni, Cr, Co, Mn and Fe in the stream sediment.

(b) Favourable localities within the initial target areas may be readily outlined by detailed stream sediment surveys. The following procedure is recommended:-

(i) samples of the active sediment should be collected in duplicate from all streams draining the area of interest, at a maximum sampling interval of 1500 ft.;

(ii) samples should be collected upstream from any lakes occurring in the drainage system;

(iii) Ni analyses should be based on the -125 mesh fraction to improve anomaly contrast;

(iv) anomalous samples should be analysed for Mn to outline possible areas of high Ni content resulting from scavanging by secondary Mn oxide precipitates. In selecting areas for follow-up sampling priority should be given to anomalous localities with low Mn contents, but areas of anomalous Ni and high Mn should also be followed-up.

(c) Follow-up procedure will depend on local conditions but the following guides are suggested:-

(i) if a distinct 'cut-off' is obtained in the stream sediment anomaly reconnaissance soil traverses aligned perpendicular to the direction of ice-movement, if known, should be collected over the hill slopes on either side of the stream. Samples of the B horizon should be collected at intervals of approximately 25 ft. and -80 fraction analysed for Ni and Cu;

(ii) if a 'cut-off' is not obtained reconnaissance soil traverses should be collected along both valley sides, aligned parallel to the stream and at sufficient elevation to avoid sampling alluvial material;

(iii) if a soil anomaly is located by the reconnaissance sampling its form should be determined by systematic grid sampling, traverses being aligned at right angles to the direction of ice-movement, if known;

(iv) in bog covered areas systematic sampling of peat profiles at intervals of approximately 25 ft. is an effective method of locating Ni-Cu mineralisation. Profiles should be sampled at depth intervals of 1-2 ft. and if possible the underlying glacial deposits should also be sampled. Samples should be analysed for Ni and Cu;

(v) in interpreting follow-up data it should be borne in mind that soil anomalies related to Ni mineralisation are of complex origin and that both mechanical and saline dispersion are likely to have occurred. Pure hydromorphic dispersion patterns in the soil are restricted to poorly drained areas and in such anomalies it is likely that the content of Cu will exceed that of Ni.

(c) Mo orientation survey

(23) Anomalous Mo and Cu contents in the bedrock at Flottorp are confined to zones of low-grade sulphide mineralisation; the bedrock anomalies are sharply defined and there is no evidence that aureoles of primary dispersion extend into the granite gneisses adjacent to the mineralised zones.

(24) The weakly mineralised molybdenite-bearing fahlband zones at Flottorp are considered to be of syngentic origin and to represent the high-grade metamorphic equivalents of molybdeniferous black shale horizons. Molybdenite present in minor intrusions (i.e. aplite, grey granite and vein quartz) within the mineralised zones is derived initially from these fahlbands, either by the incorporation of molybdenite-bearing inclusions or the migration of molybdenite towards areas of locally higher temperature.

(25) Detailed soil sampling showed that anomalous Mo contents occur in all horizons of the soil profile in the vicinity of known mineralisation. At Flottorp, saline dispersion of Mo from bedrock mineralisation is of limited importance and glacial dispersion is the dominant process in the formation of Mo anomalies in the soil. Mo anomalies in the mineral soil are wider than the underlying bedrock mineralisation, due to the effects of glacial dispersion. Humus Mo anomalies are approximately the same width as those in the mineral soil, although the content of Mo in the humus is generally lower, due to restricted uptake of Mo by plants under moderately acid conditions.

(26) In contrast to Mo, saline dispersion is an important factor in the formation of soil Cu anomalies. Glacial dispersion gives rise to broad zones of weakly anomalous Cu contents in the B horizon but the peak Cu values within such zones are the result of saline dispersion from

bedrock mineralisation. Humus Cu anomalies principally reflect the dispersion of Cu in groundwater and are related to the pattern of groundwater flow from bedrock mineralisation.

(27) Anomalous Mo contents occur in peat bogs overlying known mineralisation, the Mo content showing a marked tendency to increase with depth in anomalous peat profiles. In bog covered areas sampling of the basal peat layer, at intervals of approximately 100 ft., provides an effective method of locating anomalous Mo dispersion trains in the underlying glacial deposits.

(28) Highly anomalous Mo dispersion patterns persist in the active stream sediment for a minimum distance of 18,000 ft. downstream from sub-economic molybdenite mineralisation. The maximum Mo content for streams draining relatively undisturbed mineralisation at Flottorp is 36 ppm, compared to a threshold level of 4 ppm Mo.

(29) At Flottorp Mo anomalies in uncontaminated stream sediments result principally from the erosion of anomalous soils. Limited data from the regional survey suggest, however, that in areas of extensive waterlogged soil hydromorphic dispersion may be the dominant process in the development of stream sediment Mo anomalies.

(30) The presence in the drainage system of small lakes which receive a high in-flow of organic matter and which develop reducing bottom conditions during the summer and

winter stagnations does not seriously affect anomalous Mo dispersion trains in the active stream sediment. The limited available data indicate, however, that anomalous Mo dispersion trains are truncated by lakes which for some reason do not develop reducing bottom conditions.

(31) On the evidence of the orientation study the following procedure is recommended for use in exploration for Mo mineralisation in areas such as southern Norway:-

(a) In virgin areas rapid reconnaissance cover by means of widely-spaced stream sediment samples will allow the recognition of favourable localities for more detailed investigation. Samples should be collected from streams with catchment areas of 1-5 sq. mls. and should be analysed for Mo and Fe. In planning follow-up sampling programmes priority should be given to Mo anomalies unaccompanied by high Fe values, but all reconnaissance anomalies should be followed-up.

(b) In follow-up sampling it is recommended that active stream sediment samples be collected from all streams draining the area of interest, at intervals of approximately 3000 ft. Samples should be collected upstream from lakes in the drainage system wherever possible.

(c) The procedure for follow-up work on drainage sediment anomalies will depend on local conditions but the following guides are suggested:-

(i) If a 'cut-off' to the stream sediment anomaly is not obtained during follow-up sampling, reconnaissance soil traverses should be collected along both valley sides, at a sufficient elevation to avoid sampling alluvial material; a sample interval of 250 ft. is adequate to outline the position of Mo anomalies in the soil. Samples should be collected from the mineral soil; in areas with a relatively thin cover of glacial material, similar to that at Flottorp, the sampling depth is not critical.

(ii) Once the general position of the soil anomaly is located, its form should be determined by systematic grid sampling at a sample interval of 100 ft., traverses being aligned at right angles to the direction of ice-movement, if known. In bog covered areas sampling of the basal layer of the peat profile provides an effective method of locating anomalous Mo dispersion trains in the underlying glacial deposits.

(iii) In favourable areas the source of the anomalous Mo may be more precisely located by close interval (25 ft.) soil sampling. Molybdenite is frequently accompanied by Cu-bearing sulphides and the position of mineralisation of this type will be defined more closely by peak Cu values in the overlying soil; if the detailed samples are to be analysed for Cu however, it is essential that only B horizon soils be collected. Alternatively, in areas of abundant outcrop, mineralisation may be sought by systematic sampling of the exposed bedrock.

(iv) In interpreting soil data it should be borne in mind that glacial dispersion is the dominant process in the formation of Mo anomalies in freely drained soils but that hydromorphic processes may be important in extensively waterlogged areas.

(32) It is concluded that geochemistry provides a rapid and effective exploration method for both Ni and Mo mineralisation in glaciated terrain such as that of southern Norway.

RECOMMENDATIONS FOR FUTURE RESEARCH

(a) The principal shortcoming of the suggested exploration procedure is that while areas affected by secondary enhancement processes can be readily recognised from stream sediment data, it is still necessary to conduct preliminary soil surveys over Ni or Mo anomalies in such areas to determine whether the anomalous metal content is derived in part from mineralisation, or is leached entirely from waterlogged background soils. An analytical or interpretive technique allowing the positive identification of the metal source from stream sediment data alone would clearly greatly reduce the amount of follow-up sampling necessary to completely evaluate a given exploration area. Probably the most fruitful approach to this problem would involve multi-element determinations on samples from such anomalies and the use of multivariate statistical techniques such as are currently being developed by the Applied Geochemistry Research Group at Imperial College for use in the interpretation of regional reconnaissance data.

(b) The present work has shown that under conditions of free drainage Ni and Cu are leached from the parent till during soil formation, and has indicated, in the case of Ni, that this was due to the formation of soluble organic complexes. Further experimental work could profitably be directed towards an understanding of the factors leading to the mobilisation of Ni, Mo, Cu and other metals under low Eh conditions, such as are found in waterlogged soils.

(c) The persistence of the Flottorp stream sediment Mo anomaly through Haland Lake has been related to the high in-flow of organic matter received by this lake and the consequent development of reducing bottom conditions during the summer and winter stagnation periods. An experimental investigation into the effect of reducing bottom conditions on the exchange of trace metals between lake sediments (both organic and inorganic) and lakewater would lead to a much clearer understanding of the effect of lakes on stream sediment anomalies.

SAMPLE NO	COORDS EAST	NORTH	MO PPM	CU PPM	ZN PPM	NI PPM	CO PPM	MN PPM	CR PPM	FE2O3 PERCENT
37	4409	4616	13	30	300	85	85	6000	130	11.
38	4407	4618	30	12	300	300	40	5000	50	15.
39	4449	4653	1	2	60	40	5	1000	50	3.
40	4449	4649	2	20	300	60	40	600	85	11.
41	4429	4645	2	6	200	50	40	600	100	6.
42	4431	4665	2	6	200	50	10	850	10	6.
43	4433	4666	10	20	300	60	60	1000	100	13.
44	4446	4708	1	6	100	80	30	3000	60	6.
45	4441	4723	5	8	300	50	30	4000	60	9.
46	4444	4735	5	10	300	85	60	4000	100	4.
47	4445	4823	1	4	80	60	20	6000	30	4.
48	4445	4812	2	2	200	100	40	1200	80	9.
49	4442	4782	1	10	180	100	20	2000	100	20.
50	4441	4770	12	12	300	60	30	1000	100	13.
51	4371	4801	5	13	200	50	30	500	60	5.
52	4358	4802	2	20	300	85	60	1600	200	13.
53	4351	4823	2	8	200	100	30	1000	50	8.
54	4355	4823	6	20	200	120	80	4000	100	15.
55	4358	4817	1	30	180	100	50	3000	100	12.
56	4364	4810	1	6	120	60	40	2000	30	4.
57	4381	4835	1	8	200	50	30	4000	100	5.
58	4403	4675	13	6	160	50	20	3000	60	8.
59	4378	4706	16	5	300	85.	60	3000	100	13.
60	4354	4714	1	4	40	20	13	1000	20	4.
61	4413	4704	16	8	300	40	40	2000	50	12.
63	4355	4762	1	2	40	400	30	6000	50	4.
64	4334	4745	2	5	40	300	40	3000	10	4.
65	4291	4833	2	10	50	30	20	1000	50	5.
66	4282	4818	1	5	200	30	4	600	10	3.
67	4294	4795	1	10	100	40	13	500	50	4.
68	4279	4763	1	10	100	50	20	60	10	2.
69	4282	4768	1	2	50	30	10	85	10	1.
70	4268	4716	16	2	300	40	30	1000	50	14.
72	4299	4662	1	1	200	4	16	100	5	1.
73	4303	4657	1	2	50	5	13	85	5	2.
74	4342	4672	16	20	300	200	40	600	300	11.
75	4339	4648	5	10	300	100	40	1300	50	11.
76	4583	4906	5	10	130	30	30	850	60	9.
77	4518	4652	1	8	300	40	20	1000	30	4.
78	4508	4658	5	3	300	30	20	600	20	4.
79	4517	4644	16	10	300	50	60	4000	50	15.
80	4480	4705	1	5	40	40	10	500	16	2.
81	4520	4632	13	5	300	60	40	1300	85	15.
82	4561	4694	20	8	300	60	40	3000	40	13.
83	4567	4719	6	6	300	13	5	500	5	4.
84	4519	4758	10	10	400	50	30	1000	30	5.
85	4575	4718	1	6	80	4	30	5000	4	2.
86	4600	4684	13	40	300	40	50	4000	10	9.
87	4667	4684	1	1	60	40	4	400	4	5.
88	4648	4715	12	12	40	50	12	300	50	3.
89	4685	4730	18	10	40	50	10	600	20	3.
90	4662	4762	40	2	40	200	30	400	50	3.
92	4662	4806	1	6	100	40	4	400	12	2.
93	4633	4750	18	1	100	20	18	300	20	4.
94	4660	4964	1	6	40	30	18	300	20	2.

96	4635	4907	1	12	200	40	30	850	30	8.
97	4631	4899	8	10	200	50	30	850	50	9.
98	4624	4872	2	18	300	50	30	500	60	7.
101	4613	4804	2	8	120	40	30	1000	18	7.
103	4557	4792	1	1	40	4	4	300	1	1.
104	4575	4825	1	8	120	60	30	850	100	7.
105	4551	4819	1	8	100	50	50	850	180	7.
107	4500	4836	30	6	120	30	20	600	40	1.
108	4500	4791	2	1	80	30	12	500	20	4.
109	4507	4935	20	12	100	50	20	800	30	12.
110	4510	4936	30	6	60	20	18	300	20	3.
111	4545	5008	1	4	40	40	4	500	1	2.
112	4571	4997	1	4	120	50	20	1000	50	9.
113	4573	4993	1	8	50	60	30	600	100	5.
114	4618	5008	1	1	40	30	20	400	1	1.
115	4619	4948	18	30	120	50	20	600	40	9.
116	4615	4943	20	1	100	40	20	500	18	8.
117	4650	4964	1	6	50	80	20	400	80	6.
118	4638	5050	50	40	300	100	40	600	80	11.
119	4622	5087	18	50	300	120	30	600	60	11.
120	4649	5099	2	2	60	50	18	500	18	5.
121	4675	5108	1	3	300	20	20	300	4	1.
122	4594	5098	1	1	40	80	20	600	1	1.
123	4455	5026	1	1	40	20	12	400	8	1.
124	4458	5023	4	8	120	30	20	400	40	5.
125	4494	5028	2	10	80	30	18	300	30	6.
127	4511	4958	20	8	40	20	4	300	8	4.
128	4451	4946	10	6	80	20	4	850	4	4.
129	4441	4939	1	12	300	50	20	600	40	7.
130	4425	4939	6	5	40	60	12	400	40	7.
131	4395	4936	20	3	300	100	40	1000	60	20.
132	4370	4937	2	5	200	50	20	1000	40	6.
133	4346	4941	1	10	100	100	30	1000	60	10.
134	4300	4973	20	12	300	200	50	3000	80	10.
135	4297	4984	1	1	80	50	20	500	20	3.
136	4295	4989	5	6	180	100	40	1200	60	20.
137	4301	5031	18	6	120	80	40	850	80	10.
138	4296	5043	1	10	80	40	20	400	40	6.
139	4205	4985	1	1	60	30	4	300	12	2.
140	4194	5018	2	6	120	50	20	500	30	8.
141	4263	4938	1	1	4	20	4	300	10	2.
142	4259	4895	5	10	120	50	30	600	60	15.
143	4217	4831	1	1	40	4	4	200	4	1.
144	4190	4824	2	5	100	20	4	400	10	4.
145	4185	4830	2	6	80	40	4	200	4	2.
146	4276	4861	1	2	200	160	10	600	10	4.
147	4318	4976	2	1	40	50	12	400	20	5.
148	4318	5031	1	4	100	50	18	500	40	9.
150	4363	4966	2	1	100	180	20	600	50	8.
151	4358	4964	1	1	40	20	4	400	18	2.
152	4352	4969	1	3	40	30	4	400	20	4.
154	4343	4976	1	1	40	12	12	300	4	3.
155	4338	4968	8	85	200	300	20	600	40	18.
156	4331	4960	1	8	80	40	20	600	40	11.
157	4325	4933	1	1	40	30	4	400	50	3.
158	4330	4899	1	12	300	100	50	600	180	13.
159	4325	4872	16	16	100	60	30	850	100	9.
160	4310	4857	1	20	200	100	50	850	200	15.
161	4306	4854	1	6	200	30	20	850	30	6.

162	4320	4835	1	10	300	120	40	1000	80	13.
163	4323	4869	2	2	100	40	20	400	40	3.
164	4344	4874	2	1	80	40	20	1000	60	11.
165	4374	4886	1	13	100	60	30	1000	100	6.
166	4388	4887	1	5	130	50	30	800	60	6.
167	4389	4881	1	2	50	40	4	600	20	4.
168	4405	4895	2	12	50	50	18	600	30	4.
170	4434	4877	2	8	100	120	30	500	180	9.
171	4435	4870	1	6	120	60	30	600	60	6.
172	4490	4946	1	8	100	40	20	300	50	4.
173	4463	4905	2	5	80	60	30	500	50	9.
174	4465	4907	10	10	180	80	30	600	60	8.
175	4443	4877	1	10	80	50	30	500	50	6.
176	4376	4848	8	13	300	160	60	3000	400	15.
177	4375	4847	10	50	200	160	40	1600	200	20.
178	4368	4847	1	10	130	85	30	600	160	5.
179	4363	4848	10	30	300	130	60	2000	160	14.
180	4362	4850	2	18	180	120	50	1000	100	20.
181	4373	4831	1	1	40	40	20	3000	40	6.
182	4371	4831	1	1	40	50	20	600	20	3.
184	4279	4859	1	5	300	20	30	4000	85	10.
186	4232	4895	1	1	40	4	4	200	6	1.
187	4171	4867	8	12	300	50	20	1000	50	13.
188	4155	4866	1	4	60	30	18	300	30	4.
189	3955	4811	1	18	180	40	12	600	4	7.
190	3949	4828	2	8	200	18	4	500	6	8.
191	3948	4830	1	1	40	20	4	300	8	2.
192	3963	4835	8	5	300	20	20	600	10	13.
193	3970	4820	13	5	100	30	20	1300	5	9.
194	3976	4805	3	6	180	18	30	1000	30	13.
195	3981	4740	10	6	200	30	30	600	20	7.
196	3981	4742	1	1	40	40	4	300	4	2.
197	3948	4731	1	2	400	5	4	400	4	1.
198	3936	4777	16	5	100	13	16	400	6	6.
199	3940	4769	1	12	180	20	4	400	1	3.
200	3939	4767	10	2	130	10	16	1600	10	13.
201	3960	4714	2	5	130	20	4	600	5	9.
202	3958	4698	2	2	130	4	10	2000	8	9.
203	3950	4670	1	6	100	18	4	400	4	3.
204	3955	4670	1	3	100	40	18	500	40	9.
205	3958	4662	4	6	60	50	4	600	4	9.
206	3955	4644	1	1	40	12	4	500	18	3.
208	3943	4593	1	2	100	60	10	400	10	4.
209	3938	4624	10	2	100	30	10	3000	5	13.
210	3954	4644	2	8	200	60	40	6000	60	15.
211	4166	4729	2	8	100	30	13	100	16	3.
212	4192	4790	8	6	80	30	20	400	50	10.
213	4167	4725	1	30	200	50	20	600	30	8.
214	4155	4705	3	30	200	40	30	1200	100	11.
215	4139	4742	1	5	50	40	5	400	16	2.
216	4138	4770	1	2	100	5	5	300	5	1.
217	4142	4795	1	6	160	40	30	600	10	3.
218	4109	4822	1	4	130	5	4	300	5	1.
219	4107	4843	1	3	85	40	10	400	20	3.
220	4111	4851	2	20	200	30	40	500	80	6.
221	4088	4902	10	13	50	40	16	600	3	5.
222	4081	4865	2	6	100	13	4	200	5	2.
223	4089	4871	1	2	100	5	4	400	2	1.
224	4088	4902	10	13	50	40	16	600	3	5.
225	4104	4927	1	20	40	18	18	500	6	6.

226	4130	4937	10	8	100	160	20	600	30	5.
227	4139	4943	30	10	100	60	40	1000	100	11.
228	4148	4939	2	12	200	80	40	800	100	9.
229	4128	4935	5	8	85	40	20	600	60	7.
230	4055	4918	13	5	100	30	5	300	10	3.
231	4044	4899	10	5	100	40	20	300	16	5.
232	4096	5011	16	8	50	50	30	1600	50	9.
233	4108	5041	6	8	100	60	4	300	13	5.
234	4101	5038	8	8	200	30	18	500	18	5.
235	4074	4984	10	6	130	20	30	850	10	11.
236	4073	4983	10	5	130	30	30	3000	40	15.
237	4070	4911	5	8	160	40	20	850	20	7.
238	4034	4866	13	6	130	40	20	600	20	5.
239	4025	4858	12	10	180	30	4	800	10	7.
240	4018	4848	6	8	130	30	30	1000	30	11.
241	4021	4821	10	6	100	20	20	400	16	6.
243	4034	4815	10	6	100	5	5	500	13	4.
244	4053	4815	13	6	100	16	13	500	10	4.
245	4054	4813	30	20	40	20	10	400	13	5.
246	4067	4820	10	6	100	20	10	400	13	4.
247	4082	4830	850	20	40	13	5	600	20	5.
248	4080	4806	1	6	100	130	4	300	5	1.
249	4046	4813	1	5	40	10	4	100	2	1.
250	4032	4814	13	6	100	5	20	600	2	4.
251	4045	4796	20	2	100	20	5	500	10	5.
252	4043	4796	20	1	40	60	4	400	1	3.
253	4046	4787	1	5	40	5	4	600	8	3.
254	4050	4775	1	6	50	30	13	130	16	5.
255	4048	4774	12	1	40	30	4	300	2	1.
256	4067	4771	2	4	50	20	13	100	6	3.
257	4076	4788	1	6	50	20	4	100	5	1.
258	4074	4783	1	5	50	20	10	100	10	2.
259	4078	4830	20	20	50	20	4	400	2	7.
261	4071	4835	20	13	100	50	20	1000	20	10.
262	4069	4837	1	8	50	40	12	300	30	5.
263	4061	4836	30	8	100	30	16	400	10	6.
264	4059	4832	160	300	100	20	20	1000	20	13.
266	4138	4719	1	8	40	18	4	600	2	6.
267	4135	4705	1	5	40	85	4	200	20	1.
268	4126	4675	10	30	200	100	40	3000	85	15.
269	4111	4639	18	18	200	12	20	1200	5	12.
270	4113	4633	10	50	100	300	30	1300	20	9.
271	4125	4636	13	13	100	85	40	2000	30	11.
272	4133	4592	10	13	100	85	30	1600	50	7.
275	4143	4662	10	10	100	85	20	1300	85	11.
276	4183	4683	13	8	40	50	10	400	10	13.
277	4172	4681	16	10	100	100	60	6000	40	13.
278	4205	4725	1	1	200	20	18	500	100	12.
279	4226	4726	1	6	80	30	12	600	6	3.
280	4204	4641	1	6	40	4	4	300	1	3.
281	4222	4629	2	6	200	20	4	600	60	6.
283	4093	4598	8	6	200	12	30	850	12	9.
284	4044	4616	1	12	180	30	40	3000	50	9.
285	4044	4618	1	40	200	50	30	600	80	11.
286	4043	4634	1	6	60	20	4	600	10	4.
288	4042	4659	10	20	300	50	30	600	60	13.
289	4046	4659	2	18	850	20	20	5000	12	8.
291	4017	4672	30	6	300	12	50	5000	4	15.
292	3994	4676	18	18	300	180	60	1000	100	8.
293	3993	4723	20	80	300	40	30	3000	12	10.

294	3984	4739	2	18	200	20	30	850	12	11.
295	4030	4699	1	20	80	4	4	500	4	2.
296	4029	4704	10	30	300	20	20	500	30	11.
297	4045	4723	2	18	200	20	18	600	40	13.
298	4043	4747	10	20	100	18	12	400	6	7.
299	4042	4751	12	12	40	4	50	5000	4	4.
300	4049	4763	20	40	300	40	18	5000	30	15.
302	4079	4765	12	20	300	20	40	3000	12	10.
303	4077	4761	20	60	40	40	12	600	60	3.
304	4052	4718	12	30	120	20	30	600	40	6.
306	4107	4718	5	20	300	30	30	500	40	9.
807	4054	4690	1	6	300	18	4	500	4	3.
308	3948	4682	12	6	300	18	10	850	12	15.
309	3910	4570	20	20	200	50	20	850	20	11.
310	3884	4580	20	10	300	50	50	5000	30	15.
311	3861	4596	5	6	40	60	30	1000	50	7.
312	3824	4586	1	12	200	50	20	600	50	80.
313	3833	4608	1	6	200	30	18	300	20	6.
315	3862	4688	20	8	40	4	1	1000	4	6.
316	3867	4690	2	2	80	6	1	400	4	6.
317	3855	4682	1	8	40	4	1	850	4	3.
318	3858	4751	12	50	300	80	3	850	50	9.
319	3861	4751	1	1	100	30	10	500	2	3.
320	3845	4733	2	1	40	50	1	200	4	1.
321	3832	4787	1	6	200	20	1	300	50	4.
322	3838	4817	2	6	200	40	1	600	5	2.
323	3858	4878	3	8	80	12	1	500	4	2.
325	3900	4884	12	1	120	60	1	3000	40	12.
326	3922	4861	1	1	100	40	10	600	4	5.
327	3927	4886	1	8	40	40	4	500	1	3.
328	3940	4856	6	5	200	13	20	2000	13	14.
329	3785	4838	5	4	40	20	10	1300	30	6.
330	3803	4844	2	400	50	50	13	200	13	2.
331	3782	4803	1	4	40	30	4	400	10	3.
332	3809	4779	1	5	40	10	10	200	8	1.
333	3795	4759	4	6	100	40	4	500	10	4.
334	3782	4768	1	5	100	30	4	200	8	9.
335	3807	4743	10	16	200	50	30	600	100	12.
336	3800	4723	6	10	300	40	20	3000	40	11.
337	3820	4719	1	5	300	100	4	400	13	4.
338	3816	4708	1	10	300	85	16	600	60	13.
339	3820	4612	5	6	100	50	4	600	16	8.
340	3793	4628	1	4	40	10	4	400	10	2.
341	3799	4637	1	10	100	60	4	1300	20	4.
342	3806	4645	6	4	100	50	4	600	30	5.
343	3809	4651	1	4	130	60	20	600	40	9.
344	3852	4705	1	2	100	40	40	1300	10	4.
345	4419	4652	3	8	300	50	60	3000	40	11.
346	4457	4603	12	20	400	80	400	10000	30	15.
347	4463	4620	5	2	100	40	4	600	5	4.
348	4501	4620	10	40	400	100	30	8500	60	13.
349	4547	4640	5	8	300	85	50	4000	85	13.
350	4560	4653	5	16	300	60	60	6000	85	15.
351	4605	4650	13	4	50	40	16	850	6	7.
352	4565	4693	18	10	600	200	500	10000	5	12.
353	4685	4690	5	5	200	40	20	1600	20	6.
355	4616	4817	16	60	300	40	85	6000	50	14.
356	4655	4842	1	1	100	60	20	850	40	4.
357	4683	4830	5	10	100	40	60	2000	30	7.
358	4408	4882	10	10	100	100	40	1000	60	11.

359	4312	5008	1	2	40	10	4	600	5	3.
360	4294	5002	10	5	100	30	30	850	30	5.
361	4258	4917	10	8	200	40	20	600	40	8.
362	4252	4843	1	1	100	40	10	500	30	3.
363	4284	4856	1	5	40	20	4	85	5	1.
364	4277	4750	1	5	100	30	13	200	30	4.
365	4220	4722	10	3	200	40	30	500	40	9.
366	4243	4695	1	6	40	13	20	85	5	3.
367	4232	4695	1	6	50	10	13	60	5	1.
368	4230	4658	5	5	300	40	20	200	20	5.
369	4315	4667	5	5	300	50	30	500	16	7.
370	4289	4622	5	2	300	50	30	600	20	6.
371	4257	4625	8	2	100	13	10	1600	5	8.
372	3795	4640	1	1	40	4	20	85	1	1.
373	3787	4636	1	3	100	5	20	60	5	1.
374	3772	4625	2	10	300	30	13	160	13	6.
375	3726	4664	1	5	50	30	20	85	10	2.
376	3704	4693	1	5	40	30	10	100	30	3.
377	3704	4703	1	10	200	60	30	850	85	8.
378	3719	4731	1	6	300	40	30	500	40	6.
379	3716	4745	5	6	300	100	30	2000	85	13.
380	3709	4769	2	10	300	40	10	1000	60	8.
381	3711	4773	1	5	400	30	5	200	20	3.
382	3752	4715	20	8	400	60	30	1000	20	9.
383	3746	4702	40	13	300	40	40	2000	20	12.
384	3748	4697	10	8	200	10	13	85	5	4.
385	3734	4748	2	20	200	40	20	60	20	4.
386	3739	4759	2	8	300	40	20	2000	40	11.
387	3735	4766	1	2	100	40	20	850	13	3.
388	3740	4780	1	1	50	400	4	300	10	2.
389	3741	4799	1	2	100	130	16	400	13	3.
390	3717	4788	2	3	40	10	4	500	10	2.
391	3714	4813	1	1	40	13	4	600	10	4.
392	3753	4851	1	3	50	10	4	300	10	2.
393	3758	4876	1	10	130	4	4	300	2	1.
394	3759	4880	13	5	100	10	5	400	8	3.
395	3783	4883	1	5	50	10	4	400	4	2.
396	3810	4891	1	2	50	4	4	400	5	1.
398	3831	4800	1	10	200	20	8	400	40	4.
399	3861	4868	30	20	200	400	30	1200	40	4.
400	3900	4908	18	6	300	12	12	3000	8	10.
401	3909	4869	1	1	40	80	12	1000	5	8.
402	3813	4850	1	20	300	180	30	1000	200	11.
403	3809	4843	1	3	40	50	4	300	40	2.
404	3795	4829	2	4	100	40	16	500	30	5.
405	3807	4912	1	1	180	30	4	1000	8	4.
407	3796	4914	1	1	40	4	4	300	4	1.
408	3649	4681	2	4	100	30	40	3000	6	4.
409	3668	4681	1	1	40	4	4	300	5	3.
410	3655	4729	1	12	100	30	30	600	60	5.
411	3674	4806	1	4	40	100	4	400	8	3.
412	3673	4771	18	6	300	40	30	1000	40	11.
413	3635	4774	1	4	40	12	4	300	12	4.
414	3630	4780	1	4	40	30	4	200	10	1.
415	3634	4815	18	20	200	50	30	500	100	6.
416	3634	4792	2	18	200	60	30	1200	80	11.
417	3639	4832	6	8	80	50	20	1000	60	7.
418	3634	4853	1	5	100	80	18	850	80	5.
419	3649	4897	1	4	40	12	4	400	8	2.
420	3650	4909		0	0	50		0		

421	3652	4928	1	4	40	4	4	300	4	1.
422	3635	4912	1	5	40	120	20	400	30	3.
423	3668	4615	1	3	40	40	4	850	40	4.
424	3745	4840	1	2	300	20	18	3000	12	6.
425	3743	4834	1	1	40	4	4	200	4	3.
426	3724	4838	1	1	40	12	4	600	4	2.
427	3695	4895	12	6	300	40	30	850	50	11.
428	3680	4965	6	6	200	50	30	600	60	10.
431	3690	4908	6	10	200	50	50	850	80	10.
432	3690	4883	1	5	40	20	20	300	30	5.
433	3701	4877	12	10	200	50	40	1200	40	13.
434	3614	4758	3	20	200	60	50	1000	180	11.
435	3606	4807	18	6	100	60	30	850	30	8.
436	3572	4814	2	5	160	30	30	1000	30	12.
437	3570	4792	1	5	200	20	16	1300	16	3.
438	3568	4785	1	5	160	30	30	1000	30	5.
444	3525	4755	1	1	40	18	4	500	4	3.
439	3542	4676	1	3	300	30	40	2000	40	13.
441	3584	4772	1	12	200	50	20	1200	20	10.
442	3573	4826	1	1	100	30	4	400	4	2.
443	3562	4779	2	2	300	40	30	2000	30	11.
446	3560	4719	1	18	200	100	50	1000	50	11.
445	3529	4760	6	8	200	20	20	600	85	7.
447	3563	4717	2	5	100	300	12	500	60	4.
448	3558	4757	30	8	100	200	20	850	80	10.
449	3568	4829	2	10	300	60	40	1200	40	12.
450	3500	4849	1	5	200	100	18	850	18	5.
451	3460	4851	2	8	300	100	50	2000	12	11.
452	3426	4855	2	4	300	20	12	1800	6	7.
453	3426	4822	2	2	50	10	12	850	5	6.
454	3410	4797	6	5	300	20	30	1000	10	11.
455	3401	4729	2	13	100	50	40	400	12	8.
456	3506	4785	1	2	130	50	30	500	1	6.
457	3500	4646	1	6	200	40	20	3000	50	5.
458	3546	4635	2	5	300	50	50	3000	10	15.
459	3597	4634	1	8	80	18	18	500	60	4.
460	3597	4641	1	8	40	50	20	850	50	6.
461	3610	4622	12	8	40	20	18	400	18	10.
462	3620	4653	1	18	200	50	30	1000	16	10.
540	3967	4831	1	1	40	4	12	400	1	2.
541	4054	4815	18	1	180	30	4	400	1	2.
542	4055	4813	40	18	100	50	20	850	20	5.
544	4067	4820	1	1	100	4	4	200	1	1.
545	4072	4823	10	6	120	30	20	1000	18	3.
546	4077	4828	6	4	40	100	4	1000	6	3.
547	4080	4829	18	8	200	20	4	2000	5	3.
548	4083	4833	16	60	100	16	13	300	16	5.
549	4095	4844	8	16	200	10	20	4000	30	14.

APPENDIX II Analytical data for whole rock and mineral samples from the nickel orientation survey. (Sample locations given with respect to bedrock traverses, see fig. 20.)

Table 1. Analytical data for Mølland norite samples (values in ppm unless otherwise shown).

Sample No.	Location	Fe %	Mg %	Cr	Ni	Cu	Hg (ppb)	S
	Traverse I							
490*	0'	5.9	8.6	859	480	105	46	S
491	20'	4.4	7.1	303	330	39	13	S
492*	40'	4.5	6.1	563	270	160	36	S
493*	60'	8.7	10.6	1413	850	160	70	S
494	80'	13.0	NA	1400	650	92	20	S
495	100'	6.1	NA	NA	570	258	145	S
496	120'	8.6	11.4	1752	530	118	13	S
497	140'	6.1	10.5	1774	350	110	13	S
498	160'	5.4	NA	1600	390	120	24	S
	Traverse II							
499	40'	3.9	6.8	685	320	120	24	
500	20'	7.5	7.0	800	3000	600	860	S
501	80'	5.8	10.6	824	630	130	46	
502	100'	6.4	10.9	1283	640	94	13	
503	120'	6.0	11.0	1354	520	95	13	
504	140'	5.8	10.9	1747	530	71	36	
505	160'	8.2	10.1	1099	1420	800	300	S
506	180'	6.4	11.3	1103	530	NA	41	
507	200'	7.2	10.2	1406	1650	660	300	S
508	220'	5.3	9.3	1396	690	226	56	S
509	260'	4.6	9.6	1676	470	116	24	
510	280'	5.5	10.9	1711	570	197	46	
511	300'	4.5	10.5	1511	440	115	24	
512*	320'	4.3	10.4	1494	440	126	13	
513*	340'	5.3	10.2	1259	480	271	90	
514*	360'	6.2	3.1	82	130	220	56	Z
515*	380'	3.6	5.5	270	170	100	10	Z
516*	400'	4.0	8.7	1189	280	64	10	
517*	420'	3.6	7.7	815	320	88	24	
518*	440'	3.6	6.9	715	200	105	13	
519*	460'	4.3	4.3	130	200	49	13	Z
520*	480'	4.3	4.8	410	150	136	10	Z
521*	660'	4.7	7.1	700	250	40	13	
529*	900'	4.3	7.5	844	290	100	13	
531*	1000'	5.1	7.8	999	260	142	13	

Continued .....

Table 1 Cont. Analytical data for Mølland norite samples (values in ppm unless otherwise shown).

Sample No.	Location	Fe %	Mg %	Cr	Ni	Cu	Hg (ppb)	S
	Traverse III							
567	100'	5.3	10.9	1163	620	150	46	S
568	80'	11.4	NA	NA	1040	600	165	S
569	60'	7.8	6.8	858	700	240	130	S
570	40'	5.3	7.5	984	400	66	20	
571	120'	10.4	8.9	1300	2300	1086	480	S
572	140'	5.8	8.9	1381	430	88	13	S
573	160'	5.6	9.9	972	470	192	10	S
574	180'	4.6	8.2	1500	350	70	13	S

S = visible sulphides Z = 'zenolith'

* = mineral separates prepared (see tables 4 and 5).

Table 2. Analytical data for metagabbro samples from Mølland (values in ppm unless otherwise shown).

Sample No.	Location	Fe %	Mg %	Cr	Ni	Cu	Hg (ppb)
	Traverse II						
522	680'	4.4	7.6	806	320	50	10
523	700'	3.7	6.3	670	370	50	13
525	740'	3.6	5.0	197	230	142	24
526	760'	5.1	6.0	419	170	34	13
527	800'	3.8	4.4	307	150	92	36
528*	850'	4.8	6.4	460	310	231	36
530*	950'	4.6	8.4	1014	290	143	24
532*	1050'	3.7	6.3	577	170	50	13
533	1100'	3.0	4.0	133	100	102	24
534	1150'	3.1	4.2	163	120	56	10
535	1200'	5.2	8.0	1362	300	140	46
536	1250'	4.6	7.6	1161	340	90	13
	Traverse III						
575	200'	6.7	5.4	288	170	188	210
576	220'	4.7	5.1	390	30	50	10
577	240'	4.1	NA	NA	75	58	10
578	260'	5.6	NA	NA	105	30	10
579	400'	4.7	5.2	266	200	57	10
580	420'	3.7	NA	NA	160	62	10
	Additional Grab Samples						
596		5.5	7.3	515	370	67	68
598		6.1	8.3	613	270	50	90
599		6.3	9.1	897	350	24	70

* = Mineral separates prepared (see table 4).

Table 3. Analytical data for amphibolite samples from Mølland (collected from road exposures along the west side of Lake Kjettevann).

Sample No.	Fe %	Mg %	Cr	Ni ppm	Cu	Hg ppb.
581	5.9	3.3	55	60	95	10
582	4.6	3.7	58	130	34	24
583	7.2	3.8	190	100	193	78
584*	6.3	4.2	249	120	119	54
585	5.5	2.9	104	80	79	10
586*	8.8	3.3	50	75	37	13
587*	6.8	3.7	60	96	33	10
588*	6.8	2.9	50	75	38	24
589*	7.5	3.9	125	170	96	46
590*	6.1	3.4	64	105	83	54
591	8.2	3.9	110	100	35	NA
592	6.3	6.6	1689	180	46	24
593	8.0	3.3	145	110	48	36
594	6.5	6.2	888	230	29	13
595	5.3	1.5	124	140	216	1040

* = Mineral separates prepared (see table 4).

N.B. Sample No. 595 contains abundant pyrrhotite.

Table 4.

Analytical data for hornblende, plagioclase and the strongly magnetic fraction of rock samples from the Iveland area.
(Values in ppm unless otherwise stated.)

Sample No.	HORNBLENDE									PLAGIOCLASE		MAGNETICS
	Fe%	Mg%	Ca%	Mn	Cr	Ni	Co	Cu	Zn	Ca%	Sr	Ni
NORITE												
490	7.3	10.4	6.80	1450	380	400	60	25	110	7.20	1650	9,500
492	8.1	9.9	5.75	1850	1025	335	65	65	150	7.20	1180	26,000
493	4.4	8.4	10.20	1050	1900	555	100	50	70	7.20	800	35,000
512	7.8	10.7	6.80	1500	1960	500	140	45	60	7.56	950	21,000
513	6.3	12.0	4.80	1600	1750	410	130	60	90	7.80	1080	30,000
516	3.7	8.9	9.80	950	1900	380	60	15	50	10.00	950	25,000
517	3.3	8.3	12.00	1000	1325	325	60	26	50	9.20	1300	21,000
518	5.9	9.1	8.25	1250	1250	355	63	30	90	8.00	1100	26,000
521	5.0	10.3	7.70	1250	1095	395	65	16	65	7.40	1100	1,500
Dykes												
529				no hornblende						10.40	950	740
531				no hornblende						8.00	1480	420
Zenoliths in norite and marginal facies												
514	7.4	8.1	7.35	2350	130	105	65	100	220	6.60	1300	125
515	6.2	8.9	9.20	1400	475	290	55	45	70	8.20	1150	25,000
519	7.5	5.4	7.40	1800	125	290	45	20	150	6.60	900	95
520	7.0	9.1	6.00	1800	465	230	45	75	180	6.60	2200	105

Table 4. continued

Sample No.	HORNBLENDE									PLAGIOCLASE		MAGNETICS
	Fe%	Mg%	Ca%	Mn	Cr	Ni	Co	Cu	Zn	Ca%	Sr	Ni
METAGABBRO (Mølland)												
528	11.7	8.8	7.40	1500	700	485	85	90	100	7.56	2000	275
530	7.3	9.1	6.50	1750	1200	355	70	45	110	6.10	2310	420
532	5.1	9.9	8.30	1350	910	410	75	17	50	8.00	1480	540
AMPHIBOLITE												
(i) Mølland												
584	19.0	7.3	4.50	2650	225	175	78	85	220	6.60	900	190
586				no hornblende						8.40	950	80
587	7.3	7.3	7.40	1750	50	110	65	16	65	10.60	-	32
588	7.9	6.3	7.40	1750	50	115	70	12	115	11.00	1200	70
589	10.6	6.6	6.80	1950	140	185	64	30	165	5.00	700	75
590	7.6	7.3	6.80	2150	100	260	75	26	105	8.30	1080	100
(ii) Solberg												
2449	10.3	6.2	7.50	2000	475	95	77	10	185	6.88	560	520
2450	14.0	4.7	1.00	4200	300	30	55	110	290	5.32	400	-
2451	9.0	6.3	7.65	2250	225	100	70	40	180	5.10	560	2,600
2452	11.7	6.1	7.40	2100	405	40	70	55	195	5.00	560	-
(iii) Flat												
1997	9.8	5.5	6.8	2350	50	45	35	30	385	9.60	1200	-

Table 4. continued

Sample No.	HORNBLENDE									PLAGIOCLASE		MAGNETICS
	Fe%	Mg%	Ca%	Mn	Cr	Ni	Co	Cu	Zn	Ca%	Sr	Ni
ORE DIORITE												
2371	11.0	7.7	5.0	1950	335	200	60	55	270	15.8	1000	140
2372	16.3	5.7	4.1	2050	795	5850	90	1300	295	11.0	600	48,000
2373	11.1	6.6	5.0	2400	450	240	50	85	280	13.6	1680	360
2374	14.0	6.3	5.5	2150	225	475	64	550	345	9.6	1680	320
OTHER MASSIVE ROCKS												
Skripeland												
(2453)	11.0	6.8	6.8	1900	200	165	105	45	95	4.1	310	176
Klepptjarn												
(2454)	12.3	5.8	5.0	3350	40	15	55	105	650	8.2	1200	46
Litjarn												
(2455)	10.2	6.6	7.4	2400	590	115	65	16	235	6.4	950	160

Table 5.

Analytical data for hypersthene separates from Mølland norite (values in ppm unless otherwise shown).

Sample No.	Fe%	Mg%	Ca%	Mn	Cr	Ni	Co	Cu	Zn
Norite Proper									
492	14.1	12.7	0.75	3100	1050	395	95	65	235
493	15.0	13.9	0.80	2800	1325	560	115	50	245
512	12.8	16.0	2.00	2200	1360	735	155	275	150
513	9.9	14.8	1.00	2200	1350	450	105	75	165
516	10.2	15.2	0.90	950	1250	380	120	15	150
517	10.5	23.3	1.15	1000	800	420	130	50	135
518	11.5	13.4	1.65	1250	800	370	140	30	170
521	9.5	14.0	2.50	2200	725	330	105	50	150
Dykes									
529	10.2	11.3	4.1	2100	760	480	95	30	100
531	9.2	12.4	3.6	1900	1625	420	90	115	150
Zenoliths in norite and marginal facies									
514	13.0	10.8	5.00	4200	100	85	95	75	300
515	18.0	13.4	3.10	1400	335	360	160	200	150
519	13.5	11.1	2.5	1800	100	250	135	60	280
520	12.7	12.4	2.00	1800	380	160	95	95	310

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