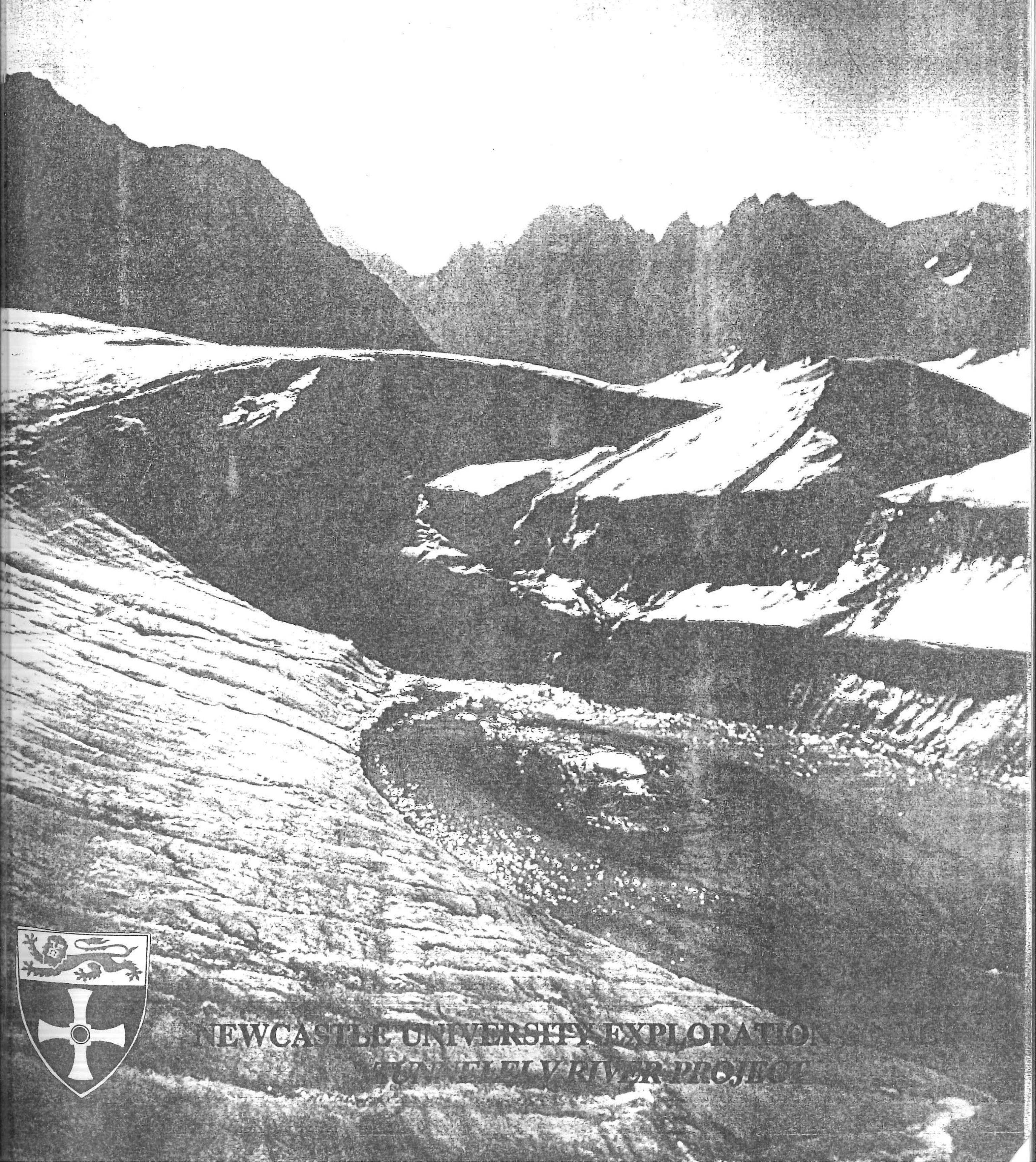
NORTH EAST
GREENLAND

EXPEDITION, MESTERS VIG & STAUNING ALPS, SUMMER 1989



NEWCASTLE UNIVERSITY EXPLORATION [illegible]

[illegible] ELV RIVER PROJECT

NEWCASTLE UNIVERSITY EAST GREENLAND EXPEDITION

1989 TUNNELELV RIVER PROJECT

FINAL REPORT

Steve Carver, David Sear, Jan Dick
Flemming Rune, Steve Naylor and Ella Brett

Newcastle University Exploration Society
Daysh Building
University of Newcastle upon Tyne
Newcastle upon Tyne
NE1 7RU

CONTENTS

List of figures
(❖ denotes a photograph)

List of tables

Acknowledgements

We would like to acknowledge the help and encouragement of all those people and organisations who made this expedition possible. This would amount to quite an expansive list and although it is not possible for us to mention all involved by name we feel obliged to mention a few whose assistance was particularly important. Firstly we would like to personally thank Professor Malcolm Newson, Dr Hal Lister and Mr Will Higgs for their encouragement and advice in organising the expedition. We would particularly like to thank Mr Watts Stelling for his labours and funny? jokes. Next we would like to thank those at the University of Newcastle upon Tyne, the Exploration Society, the staff and the students for help with fund raising, equipment, etc. Finally, for providing the essential financial assistance we would like to thank the Newcastle University Exploration Council, the Manchester Geographical Society, the Linnean Society and Mr John Hall.

1.0 INTRODUCTION

In 1989 members of the Newcastle University Exploration Society organised and successfully completed a scientific expedition to Mesters Vig in East Greenland. The aims of the expedition were multifaceted, but were centred around an investigation of the impact of lead and zinc mining operations in the Tunnelelv River valley. Other work carried out during the course of the expedition included observations of vascular plants and fungi and an assessment of two types of portable pH meters under field conditions. A detailed statement of the expedition aims is included in the next section.

Following the statement of aims and objectives the Leader's Report in section 3 gives an account of the expedition from its conception to its conclusion. Section 4 contains a description of the scientific research carried out, both in the field and upon return of the expedition from Greenland. In sections 5, 6, 7 and 8 expedition transport, food, medical and mountaineering aspects are respectively described. Finally, some conclusions are made in section 9, including both a reflection on the achievement of aims as laid out in section 2 and on the overall success of the expedition.

2.0 AIMS AND OBJECTIVES

The aims and objectives of the expedition, and in particular, the Tunnelelv River Project have been stated previously in both the expedition research proposal and preliminary report. The aims subsequent to field work and return to the UK differ slightly to those stated in the original research proposal due to modification once in the field (as a result of 'ground-truthing') and due to some difficulties in analysis back in the UK. However, the main objective to assess the impact of lead and zinc mining operations upon the sediments and floral communities within an Arctic river system and to compare results with those from the Tyne River basin, with particular regard to channel change and impact on bankside floral communities, remains the same. The aims and objectives as stated in the original research proposal (see appendix A) were as follows:

1. To measure concentrations of lead and zinc within river sediments associated with pre- and post-mining activity and to investigate the dispersal of contaminants through the river system;

2. To identify any downstream changes in the physical and chemical characteristics of sediment and water borne metals;

3. To assess the impact of metal pollution on local bankside floral communities;

4. To elucidate the rates of channel change within a dynamic arctic fluvial environment and to assess the implications for metal pollution dispersal;

5. To measure concentrations of molybdenum present within the Deltadal and Schuchert river systems through natural processes and, using results gained from the Tunnelelv, make a tentative assessment of the potential impact of Molybdenum mining at Malmbjerg and Mellempas; and

6. To assess the potential for the use of molybdenum mine spoil as a tracer for studying the transportation of surface glacier debris/sediments as a result of ice movement and surface meltwater.

Once the expedition had arrived in the field and as field work progressed, it became apparent that not all of the above aims and objectives were realistic and could not be realised with the limited time and resources available. Field work on the Tunnelelv River was completed successfully, but from this it was realised that the kind of detailed sediment sampling carried out in the Tunnelelv was not feasible in the Deltadal and Schuchert Dal given the constraints of time and resources (food, transport, etc.). As a result only a restricted number of spot samples were taken in the Malmbjerg/Schuchert region and the Mellempas/Deltadal making detailed conclusions on objectives 5 and 6 above impossible.

3.0 LEADER'S REPORT

The following Leader's Report is intended to provide an overview of the whole expedition and is written in an easy-to-read style as opposed to the more scientific reporting style of some of the subsequent pages.

3.1 Background

The expedition from conception, through fieldwork, to our safe return and subsequent analysis of samples and results has been, in my view at least, an absolute success. That is not to say that there has not been any problems, as they have been legion, but rather useful and interesting scientific research has been accomplished and above all everyone involved has thoroughly enjoyed themselves. From the very beginning there has been plenty of drive and enthusiasm making the whole project possible. Enough interest in the expedition and its scientific objectives was raised outside of the circle of expedition members during the organisational period prior to departure so as to attract sufficient funds to make the venture solvent. Once in the field, careful forward planning, good team work, experience and organisation ensured most went nicely to plan with no major mishaps.

The whole expedition stemmed originally from the desire of a number of people to travel to Antarctica; partly to carry out research on the potential impact of mining operations (which is a hot topic in environmental circles, especially given the recent debate on the Antarctic Mining Treaty) and partly because Antarctic is the only continent not yet visited by a Newcastle University Exploration Society expedition. The sheer cost and immense logistical problems in organising such an expedition, whilst given the time constraints of the university summer vacation, convinced us to do otherwise. Those people still interested in an expedition to make observations on actual or potential impacts of mining operations in an arctic environment decided to look elsewhere for a suitable location. The help of Dr Hal Lister (formerly of the Department of Geography at Newcastle University) and Mr Will Higgs (of Erskine Expeditions) is gratefully acknowledged in helping to pin-point the former Blyklippen lead and zinc mine at Mesters Vig in East Greenland. In the end this location provided us with an ideal and possibly unique opportunity to study both the impact of lead and zinc mining operations on an arctic river system and then compare results with those from work in the Department of Geography at Newcastle University on lead and zinc pollution resulting from mining in the valleys of the River Tyne.

After a few changes to the initial team line-up, the list of actual expedition members and their assigned duties was as follows:

1. Steve Carver, a postgraduate in the Department of Geography (now at Leeds University), as expedition leader and travel and freight co-ordinator;

2. Dave Sear, also a postgraduate in the Department of Geography, as the chief expedition geomorphologist and scientific officer (including procurement of scientific equipment, maps and air photographs);

3. Jan Dick, a postgraduate in the Chemistry Department, as the expedition secretary, treasurer, chemist and food co-organiser;

4. Flemming Rune, a Danish botanist from the Botanical Museum in Copenhagen, as the expedition botanist and mycologist;

5. Steve Naylor, an architecture student, as the expedition medic; and

6. Ella Brett, a Surveying/Geography student, as the expedition surveyor and food organiser.

3.2 Fund raising

As with most small expeditions, be they university or privately based, raising sufficient capital can be at best a headache and at worst a complete nightmare. It has already been mentioned briefly above that enough interest and finance had been generated before the planned departure date to make the expedition solvent. This passing reference belies the hard work of expedition members and the generosity of our sponsors. The list of people and organisations we must thank is long and so is included in appendix B. However, acknowledgement must made of financial support from Mr John Hall (of Cameron Hall Developments), the Manchester Geographical Society, the Percy Sladen Memorial Trust and the Newcastle University Exploration Council. A number of commercial companies contributed by providing goods free of charge or at special reduced rates. This assistance in keeping our outgoings to a minimum must also be acknowledged. Finally, we must thank the people of the North East and our fellow students for their small yet, in total, significant contributions made during several fund raising events.

3.3 Departure

A large amount of food and equipment in large boxes had to be freighted out to Greenland in advance since there are no shops at Mesters Vig. This was done for us by Safeair International who delivered it to Akureyri in northern Iceland from where it was to be flown on to Greenland Flugfelag Nordurlands; an air charter company. As it happened only a few of the smaller boxes went to Greenland ahead of us and the rest where squeezed into our plane along with our rucksacks and other luggage. A detailed description of the various transport and freight arrangements is given in section 5 for those who are interested.

Our own travel arrangements were slightly more complex. We set off from Newcastle in a borrowed minibus driven by my Father on the evening of the 14th July and drove to Glasgow Airport where we were due to board the 10am flight to Keflavik in Iceland. After a restless night spent in the airport packing and re-packing grossly overweight rucksacks in an attempt to distribute our weight allowance and avoid excess baggage charges, and trying (in vain) to get a good night's sleep on floor, we learnt that the flight had been delayed seven hours. This was due to bad weather in Iceland and the ensuing time at the airport was spent sun bathing and making the most of a free meal offered as compensation by the airline company.

Once in Iceland and after a bus ride from Keflavik to Reykjavik airport we discovered it was now too late to get a flight to Akureyri in the north, so we spent another night at an airport, this time camped out under the porch of the departure lounge (our tents had gone ahead in the boxes of freight). In the morning we caught the first flight north and about half an hour after we disembarked at Akureyri we were on our way east to Greenland in a small and very cramped 6 seater Piper Chieftain aircraft. The first view of our destination was of the mountains and wide fjord of Scoresbysund, heralded some time earlier by a patch work of pack ice on the sea below. Once over the coast of Greenland we headed north over the mountains and fjords of Jameson Land and Liverpool Land towards the magnificent Kong Oscars Fjord and the gravel airstrip at Mesters Vig. Upon landing we were given a warm welcome by two Danish soldiers manning the weather and radio station (these were Erling and Bent who were members of the Sirius Patrol) and by our Danish colleague and botanist, Flemming who had flown to Greenland from Denmark two weeks earlier.

3.4 Base camp

After making our base in the Washburn's Cottage, 3km up the valley from the airstrip, with its superb views across the fjord to the imposing cliffs and jagged peaks of Traill Island, the first two weeks were spent working in the Tunnelelv valley surveying cross-sections and taking sediment samples for later analysis. Washburn's Cottage was built in the 1960's by an American geographer, A.L.Washburn, as a base for his studies of periglacial phenomena and vegetation in the area and as such it also made an excellent base for our studies almost 25 years later (figure 3.1). The hut is spacious with 3 bedrooms, a large living area heated by a paraffin oil stove, and even a small laboratory. Indeed, we considered it the last word in luxury! However, the control tower at the airstrip were Erling and Bent lived was even more luxurious, with every modern convenience imaginable. Some evenings were inevitably spent visiting our two Danish soldier friends to avail ourselves of their company and hot showers!

With the main part of our work in the Tunnelelv completed, we prepared for the trek to Malmbjerg which was to take nine days. We planned to follow a circular route which brought us back via Deltadal, so a couple of days were spent carrying supplies of food and fuel to the Sortebjerg Hut which is located in this valley and which we planned to use on the return leg of the trek (figure 3.2). In this way we did not have to carry so much food and fuel on the outward leg. This hut, like those at Malmbjerg, was built by Nordisk Mineselskab in support of their mining and mineral survey operations in the area. Although they now represent a welcome break for weary expeditioners, we were disappointed to encounter many oil drums and other waste left lying about (figure 3.3).

Once in Iceland and after a bus ride from Keflavik to Reykjavik airport we discovered it was now too late to get a flight to Akureyri in the north, so we spent another night at an airport, this time camped out under the porch of the departure lounge (our tents had gone ahead in the boxes of freight). In the morning we caught the first flight north and about half an hour after we disembarked at Akureyri we were on our way east to Greenland in a small and very cramped 6 seater Piper Chieftain aircraft. The first view of our destination was of the mountains and wide fjord of Scoresbysund, heralded some time earlier by a patch work of pack ice on the sea below. Once over the coast of Greenland we headed north over the mountains and fjords of Jameson Land and Liverpool Land towards the magnificent Kong Oscars Fjord and the gravel airstrip at Mesters Vig. Upon landing we were given a warm welcome by two Danish soldiers manning the weather and radio station (these were Erling and Bent who were members of the Sirius Patrol) and by our Danish colleague and botanist, Flemming who had flown to Greenland from Denmark two weeks earlier.

3.4 Base camp

After making our base in the Washburn's Cottage, 3km up the valley from the airstrip, with its superb views across the fjord to the imposing cliffs and jagged peaks of Traill Island, the first two weeks were spent working in the Tunnelelv valley surveying cross-sections and taking sediment samples for later analysis. Washburn's Cottage was built in the 1960's by an American geographer, A.L.Washburn, as a base for his studies of periglacial phenomena and vegetation in the area and as such it also made an excellent base for our studies almost 25 years later (figure 3.1). The hut is spacious with 3 bedrooms, a large living area heated by a paraffin oil stove, and even a small laboratory. Indeed, we considered it the last word in luxury! However, the control tower at the airstrip were Erling and Bent lived was even more luxurious, with every modern convenience imaginable. Some evenings were inevitably spent visiting our two Danish soldier friends to avail ourselves of their company and hot showers!

With the main part of our work in the Tunnelelv completed, we prepared for the trek to Malmbjerg which was to take nine days. We planned to follow a circular route which brought us back via Deltadal, so a couple of days were spent carrying supplies of food and fuel to the Sortebjerg Hut which is located in this valley and which we planned to use on the return leg of the trek (figure 3.2). In this way we did not have to carry so much food and fuel on the outward leg. This hut, like those at Malmbjerg, was built by Nordisk Mineselskab in support of their mining and mineral survey operations in the area. Although they now represent a welcome break for weary expeditioners, we were disappointed to encounter many oil drums and other waste left lying about (figure 3.3).

3.5 Malmbjerg trek

When we set off on our trek on 1st August we left Flemming to concentrate on his botanical studies in the Mesters Vig area. The walk to Malmbjerg took us over the Gefion Pass at the head of the Store Blydal ('big lead valley') in which the Tunnelelv River flows, and down into Skeldal where we made our first nights camp. The route of the trek to Malmbjerg (and later trips into the Staunings Alper and to Kap Petersens is shown in figure 3.2). The Skeldal is a large valley running south to north into Kong Oscars Fjord which follows the line of an immense fault between the extremely old (Cambrian, Precambrian and granites) rocks of the Stauning Alper to the west and the younger Tertiary sedimentary rocks (Carboniferous and Permian) of the Mesters Vig area to the east. This site offered spectacular views over the Skel river to the Berserkerbrae glacier and the snowy peaks of the Stauning Alper. The following day we set off up the valley and onto the Skel Glacier. We were heading for the Skelpas which leads over into Schuchert Dal, a large valley whose waters flows eventually into Scoresbysund and whose upper reaches are occupied by a large glacier which flows out of the central Staunings. A large tributary glacier was 'explored' whilst trying to find the Skelpas (i.e. we got lost). After realising our mistake we retraced our steps and followed the correct route to a position just below the pass where we made camp for our second night away from Washburn's Cottage. Some time was spent levelling a small platform out of the snow for our two tents and melting ice for cooking and drinking water.

The following day was Ella's birthday and was spent negotiating the Skelpas and making the long walk down the motorway-like Schuchert Gletscher to the two Malmbjerg huts. These huts nestle together on a shoulder of rock at the junction of the Arcturus Gletscher with the Schuchert. Indeed, they are literally only a few feet from the wall of ice which is the snout of the Arcturus so at night when everyone lay quiet the sound of the ice creaking and cracking could be heard, together with the clatter of small stones falling from its surface, as it moved its way inexorably to join with the Schuchert. I wonder how long these huts will remain in their precarious position before the ice destroys them? Nevertheless, we spent three days and nights here taking spot samples of sediment, resting and exploring the glaciers and the mine workings. Again it was rather disappointing to find much general rubbish and mine equipment carelessly discarded at the glacier snout (figure 3.3) and on the top of the Arcturus (which obviously served as the mine's rubbish tip). I understand that it may have been too expensive to remove at the time, but more care could have been taken in disposing of it, say in one of the now disused mine shafts. Another black mark for Nordisk Mineselskab?

After our stay at Malmbjerg we made the journey up the Arcturus Gletscher and over the Mellempas onto the Mellem Gletscher which flows down into Deltadal. The pass itself is often described as 'easy', but we found it to be quite step and exposed on the Mellem side and with a number of deep bergschrund crevasses. These required great care to cross and more than one number of our party found the soft snow bridges, long strides across yawing gaps and the occasion jump (with heavy rucksack) rather disconcerting. The snow further down the Mellem had, when we reached it by late afternoon, turned into deep slush making the going rather unpleasant. It had been a long and tiring day when we stumbled across two huts in a small valley beside the terminal moraine of the Mellem. These were not on our map, but we gathered from the hut log book that they were called the 'Jacobs Bo'. However, we were grateful and again spent the night with a roof over our heads. Beats pitching the tents!

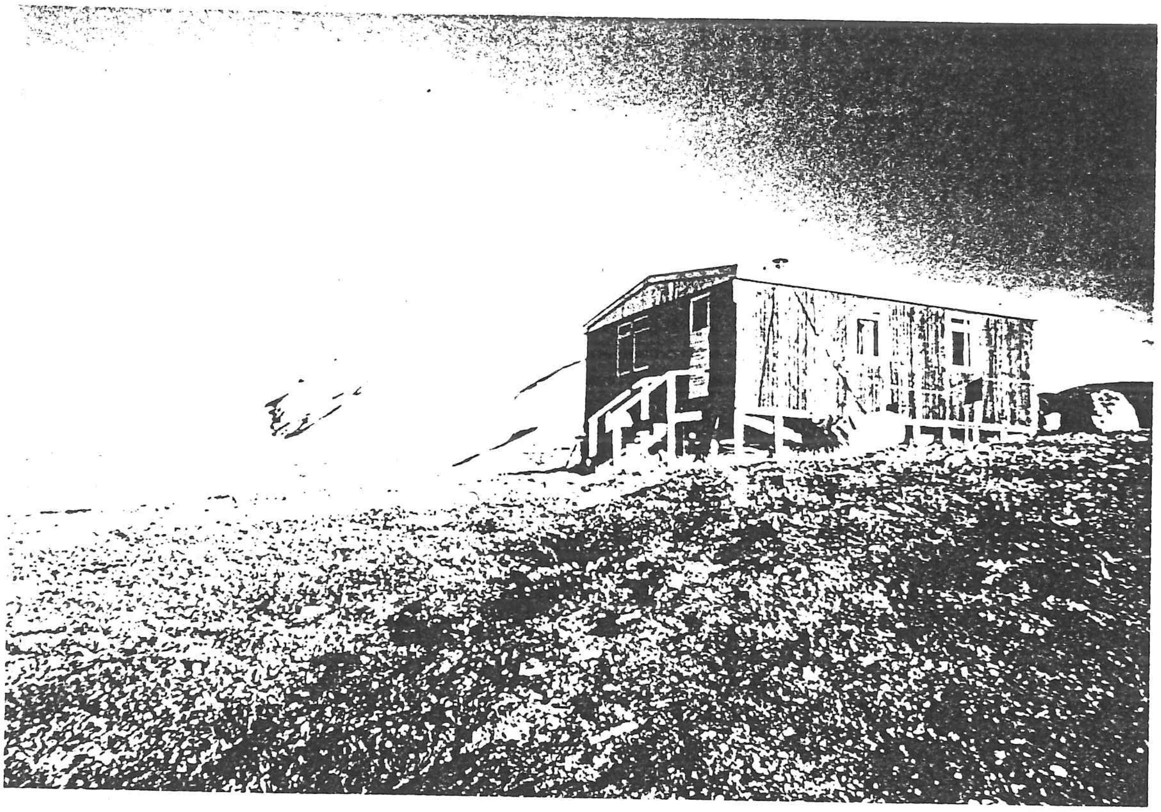


Figure 3.1: Washburn's Cottage

Figure 3.2: Deltadal

Figure 3.3: Rubbish left behind by mining operations at Malmbjerg

The next day we followed a rough track from the Jacobs Bo down the valley towards the Sortebjerg Hut, where we had left our supplies a week or so earlier. We found the hut occupied, to our surprise, by members of another expedition. These were people on a commercially run expedition organised by Erskine Expeditions. It was nice to see some fresh faces, but somewhat annoying to find our solitude invaded. And they had occupied all the beds so we had to sleep on the floor! However, our sense of one-up-manship prevailed and was upheld with stories of our glacier trek and by our luxurious and plentiful food rations. Eskimos had been to the huts where the Erskine group had stashed their food over the winter and they had helped themselves to all the goodies (such is their right and their custom)!

We left the Erskine group the next morning having split into two parties returning 'home' to Washburn's Cottage via slightly different routes. Dave and Steve wanted to cross over Deltadal and investigate some old Eskimo ruins which were marked on the map. In the end they could not find them but had some excellent views across the fjord and down the coast to Pictet Bjerg. They returned to Washburn's via Fundal, the route we had used earlier to ferry supplies to the Sortebjerg Hut. In the meantime, Jan, Ella and myself climbed Sortebjerg and then walked down Deltadal to the Mesters Vig inlet and the Pink Hut. This rather small hut with a leaky roof is painted a rather fetching shade of pink (hence the name) and is built on the site of the old Expedition Hut. This was the traditional landing place for expeditions arriving by boat in the days prior to mining and the construction of the airstrip. Here we met up with another member of the Erskine group; Bruce, a naturalist and painter who was spending some time alone painting some exquisite water-colours of migratory birds in their natural habitat. He too was short of food so after spoiling his solitude we made ourselves a little more welcome by sharing out our newly replenished rations, including some bilberries we had picked along the way.

The following day we left Bruce to his painting and climbed up Blyryggen; the mountain behind the Pink Hut. It was a wonderfully warm and sunny day and much time was spent collecting more bilberries, about 2lbs in all. We had left our rucksacks at the hut that morning so returned late in the afternoon to collect them and present Bruce with some more bilberries and leave him some of our excess rations. Traversing the coastline towards the airstrip, and yet another hut, the fog rolled up the fjord from the sea as it did most evenings. A detailed account of the weather conditions and records kept by Flemming is included in section 4.12. The fog made navigation slightly difficult as we have hitherto relied mostly on clear conditions and a basic idea of the terrain. With clear vision gone and the lack of detailed maps (the largest scale available for the area is 1:250,000) navigation was helped by a geology map and a good knowledge of the rocks we where walking over. By identifying basaltic intrusions and other geological features, which are marked clearly on the geology map and easily recognised on the ground, we found our way eventually to the Hamna Hut. The following morning saw us knocking at the door of the airstrip tower to say "Hello" to Erling and Bent. After 9 days on the move with no hot water they suggested we smelt and should take a shower!

3.6 Stauning Alper

Following two days R&R the four of us in the party who were experienced mountaineers (Jan, Ella, Steve and myself) spent nine days climbing in the Stauning Alper whilst Dave and Flemming did some more field work. A detailed account of our trip into the Staunings is given in section 8, so it is suffice to say here that we climbed two peaks; Harlech Fjeld and Dunottar in the Berserkerbrae region.

3.7 Kap Petersens

After returning from the Stauning Alper the remaining time in Greenland was spent on a short four day trip north along the shore of Kong Oscars Fjord to Kap Petersens. This took four days in all, stopping the first night at the diminutive Skel Hut. In fact this hut was so small only one of our team, and incidentally the smallest, could sleep in it. The rest of us slept outside in the tent and bivi bags. We intended to stay two nights in the Kap Petersens hut but arriving there after a pleasurable walk we found the stream issuing from the mouth of the Skoldungebrae glacier a raging torrent and too dangerous to cross. Another night was spent in tent and bivi bag so by this time we were pining for the luxuries of a hut! The weather too was getting noticeably cooler. We had been rained and snowed on in the Staunings and by now the sun had started to sink below the horizon for a few hours each night giving glorious sunsets/sunrises which lasted for hours. There was a definite feel of the approaching winter in the air, and hard frosts on the ground! The leaves of the dwarf willow, birch, heathers and bilberry too had all by now turned the ground into a colourful carpet of reds, yellows and browns.

In the morning the level of the river had receded and it was forded at a shallow point. The rest of the day was spent exploring the incredibly beautiful Kap Petersens (figure 3.4), with its views across the meeting of Kong Oscars Fjord and Segellsallskapets Fjord, and drying boots and socks in the hut. The geology in this area is of great interest, consisting of interbedded Cambrian and Precambrian rocks of brilliant colours (the Multicoloured Series); predominantly brick reds, yellows, pinks and dark grey-greens. Together with the autumnal shades, the deep blue-green of the fjord water, the occasional ice berg and the cloud streaked sky made this a truly wondrous place. All too soon however it was time to return to Washburn's Cottage one last time and pack our gear for the journey home.

3.8 Homeward

The same small plane arrived on time to take us back to Akureyri, but this time we were sharing it with Flemming and an American who had just arrived from Daneborg further up the coast via canoe. Back in Iceland we said our goodbyes to Flemming and took the scenic route from Akureyri to Reykjavik via the coastal bus rather than flying. This took eleven hours but provided better views and still left the last day of the expedition for some sight-seeing in Reykjavik (it was rather novel to see a town again).

Leaving Iceland behind we were soon at Glasgow airport again being met by my Father with his borrowed minibus. It seemed a shame that the expedition was over but good to be back in civilisation.

3.9 Analysis of samples

All that remained now was to analyse the hundreds of sediment samples we had so carefully taken whilst in the field and write our reports. This, however, has for one reason or another taken longer than planning the expedition in the first place. Nevertheless, the bulk of the laboratory work has been completed so that this report could be written. There is, however, still much analysis which could be done and this is outlined later in section 4. It is hoped that the work done will be of sufficient quality and interest to be published in scientific journals.

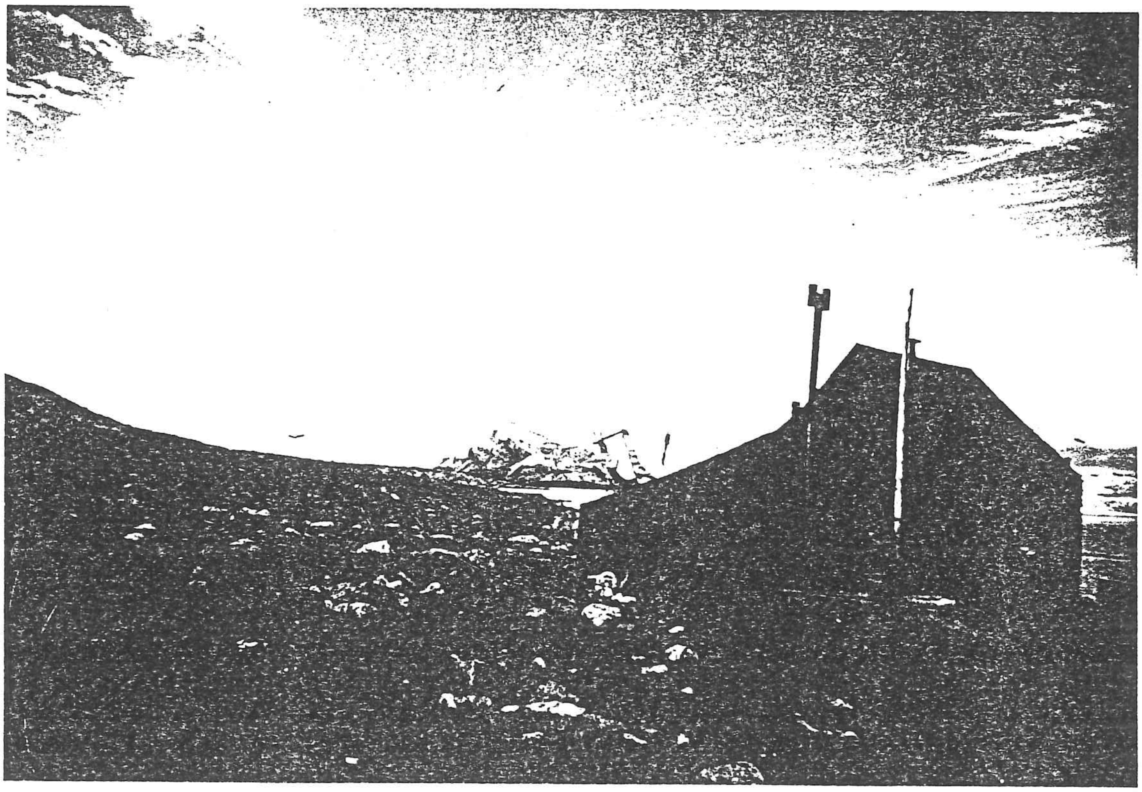


Figure 3.4: Kap Petersens

3.10 Summary

As I have said at the beginning of my Leader's report, I believe that the expedition has been a complete success. Everyone was enthusiastic, we were a good team, some useful and interesting work has been accomplished, we made new friends and had a great time. The weather in Greenland was good to us, and together with the dramatic scenery, the natural history and the company made the whole expedition an extremely rewarding and unforgettable experience. Thank you to all those who made it possible.

Steve Carver
Expedition Leader.

4.0 SCIENTIFIC REPORT

4.1 Introduction

The following sections in this chapter of the report deal solely with the various scientific aspects of the expedition. As already outlined in the leader's report (above), the first two weeks in the field were spent carrying out scientific work in the Store Blydal area. The main research project of the expedition is the investigation of the impact of lead and zinc mining operations on the Tunnelelv. Other (related) work carried out in the field included observations of vascular plants and fungi, an assessment of two types of portable pH meters and observations of climatic conditions. These are described in detail below.

4.2 Introduction to sediment analysis

4.2.1 Objectives

The scientific objective of the Tunnelelv River project was to assess the impact of mining for lead and zinc, upon the sediments and floral communities of an Arctic river system. Six specific objectives were outlined in the original project proposal (see appendix A), these were:

1. To measure concentrations of lead and zinc within river sediments associated with pre- and post-mining activity, and to investigate their dispersal downstream;

2. To identify any downstream changes in the physical or chemical characteristics of sediment and water borne metals;

3. To assess the impact of the metal levels and mining operation on the bankside floral communities;

4. To elucidate rates of channel change within a dynamic fluvial environment, and to discuss the implications for pollutant dispersal.

5. To measure concentrations of molybdenum within sediments in the Deltadal, and Schuchert river systems with a view to assessing the impact of mining operations for molybdenum at Malmbjerg; and

6. To assess the potential for the use of molybdenum rich mine spoil as a tracer for studying the transportation of surface glacier debris as a result of ice movement or meltwater action.

Whilst sufficient samples were collected for the realising of these objectives, laboratory time has proved difficult to obtain subsequently, and therefore the final dissemination of results will take longer than intended. Sampling from the Schuchert river proved impossible owing to the scale of the terminal moraines, and the lack of time whilst in that area.

4.0 SCIENTIFIC REPORT

4.1 Introduction

The following sections in this chapter of the report deal solely with the various scientific aspects of the expedition. As already outlined in the leader's report (above), the first two weeks in the field were spent carrying out scientific work in the Store Blydal area. The main research project of the expedition is the investigation of the impact of lead and zinc mining operations on the Tunnelelv. Other (related) work carried out in the field included observations of vascular plants and fungi, an assessment of two types of portable pH meters and observations of climatic conditions. These are described in detail below.

4.2 Introduction to sediment analysis

4.2.1 Objectives

The scientific objective of the Tunnelelv River project was to assess the impact of mining for lead and zinc, upon the sediments and floral communities of an Arctic river system. Six specific objectives were outlined in the original project proposal (see appendix A), these were:

1. To measure concentrations of lead and zinc within river sediments associated with pre- and post-mining activity, and to investigate their dispersal downstream;

2. To identify any downstream changes in the physical or chemical characteristics of sediment and water borne metals;

3. To assess the impact of the metal levels and mining operation on the bankside floral communities;

4. To elucidate rates of channel change within a dynamic fluvial environment, and to discuss the implications for pollutant dispersal.

5. To measure concentrations of molybdenum within sediments in the Deltadal, and Schuchert river systems with a view to assessing the impact of mining operations for molybdenum at Malmbjerg; and

6. To assess the potential for the use of molybdenum rich mine spoil as a tracer for studying the transportation of surface glacier debris as a result of ice movement or meltwater action.

Whilst sufficient samples were collected for the realising of these objectives, laboratory time has proved difficult to obtain subsequently, and therefore the final dissemination of results will take longer than intended. Sampling from the Schuchert river proved impossible owing to the scale of the terminal moraines, and the lack of time whilst in that area.

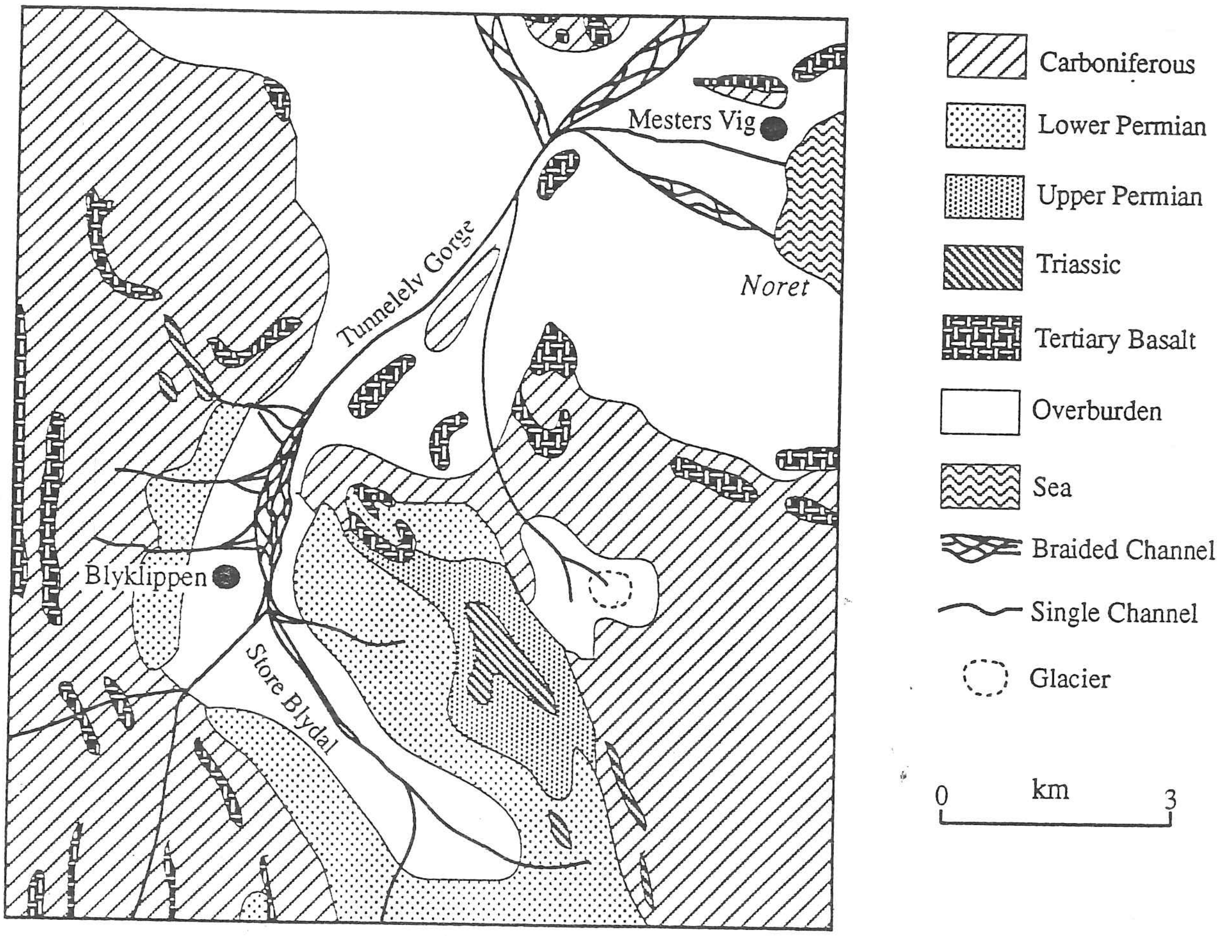


Figure 4.1: General Geology Map of the Tunnelelv Region, Mesters Vig.

4.2.2 Geology

The Tunnelelv catchment is composed of Tertiary sedimentary rocks of Carboniferous, Permian and Triassic age, these being mainly flaggy sandstones, conglomerates and interbedded shales and mudstones. Relief is controlled by numerous igneous intrusives, manifested as dyke and sill features in the valley sides (figure 4.1). Much of the valley floor and sides are covered by a layer of glacial drift and alluvium. Towards the coast, the deposits are dominated by Pleistocene raised beach and dune systems.

The mineralisation within the catchment (which provided the source for the mining operation) is generally assumed to be of Tertiary age, although this is open to speculation and (Harpoth et al., 1986) reports that the date could span from Upper Devonian to Tertiary. The mineralogy is associated with a sequence of dominantly quartz veins including baryte, galena and sphalerite (Harpoth et al., 1986) which dip at 60 - 80 degrees in a north-easterly direction. Both the galena and sphalerite have undergone deformation resulting in recrystallisation. Basalt dykes cut the veins in several places.

4.2.3 Geomorphology

The Tunnelelv river drains a catchment area of 115 km^2. Total mainstream length is 18 km, with a mean gradient of 0.010 (figure 4.2). Water is supplied from an average 400mm precipitation pa, mostly falling as snow (see climatic report in section 4.12). The snowmelt season begins in late May, and peaks in late June. From July to September discharge in the Tunnelelv river is maintained by the ablation of neo-glacial snow fields (located in sheltered valleys and at altitudes greater than 350m) and two small corrie glaciers at the head of the Rungstedelv (figure 4.2). Records made during the development of the Blyklippen mine in the early 1950's, document mainstream discharges of only 2.5 - 3.2 litres/s during the months of December to April. However, during the snowmelt, discharges are competent to move boulders of 500-1000mm in diameter.

Sediment is supplied from extensive, frost-shattered scree slopes, tributary gorges, and the reworking of glacial/periglacial colluvium and alluvial fans. Extensive in-channel deposits of fluvial sediments provide an immediate source of mobile material.

Since the construction and operation of the Blyklippen mine, (1952) a source of fine sediment in the form of mine waste tailings has been available to the Tunnelelv. It is the transport and dispersal of this material which forms the basis of this study.

Within the Mesters Vig region there exist, numerous examples of active glacial, periglacial and marine processes, including raised beaches, pingos, patterned ground, ice wedges and extensive solifluction features on the south facing hillsides. Further information on these features is recorded by Washburn (1973; 1969).

The Tunnelelv river can be divided into four distinct zones:

1. Steep headwater tributaries, characterised by confined valley floors, direct sediment input from steep slopes, and rapid sediment throughput with little storage (figure 4.3a). Significant knickpoints occur where the valleys are cut by igneous dykes.

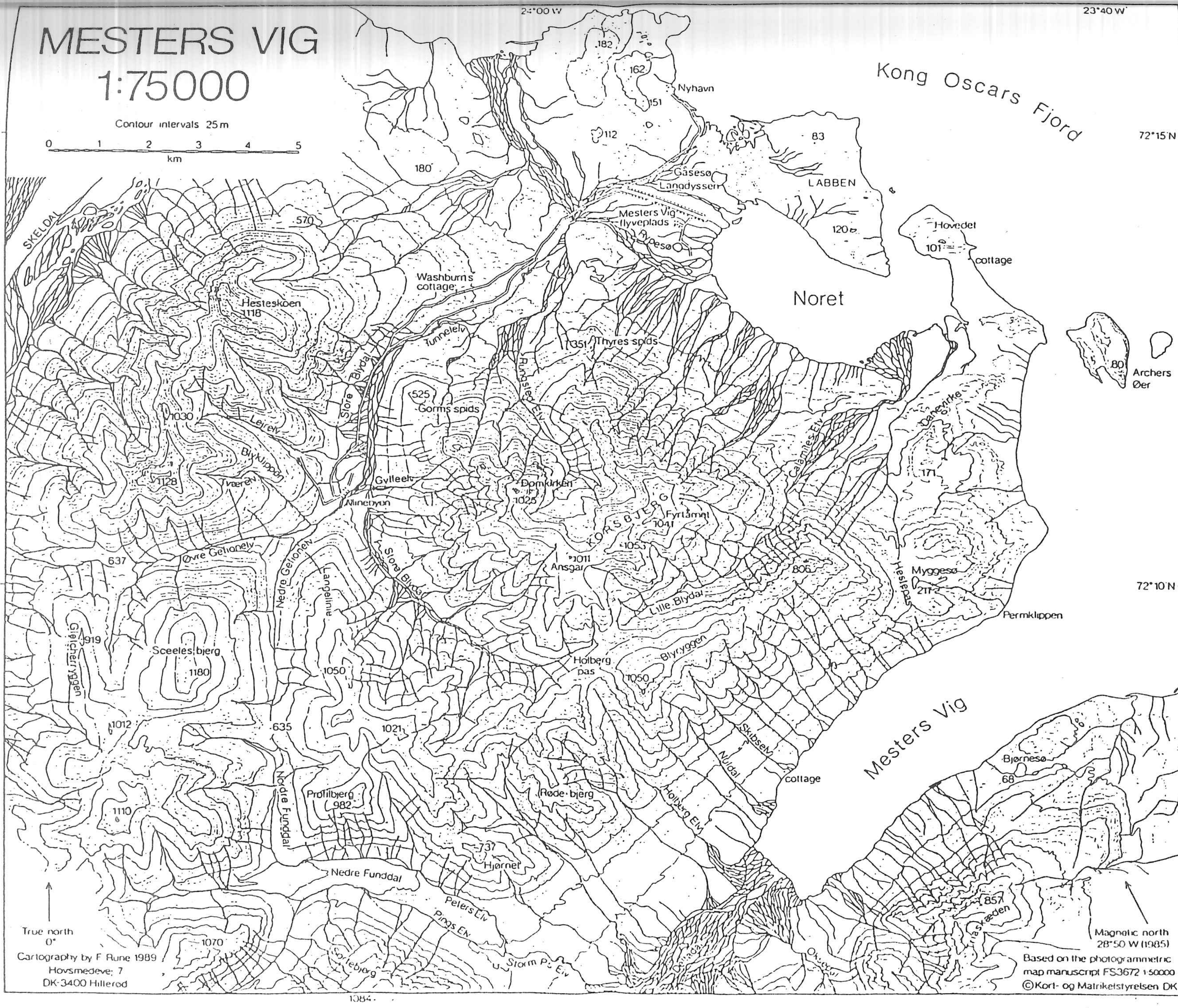

MESTERS VIG
1:75000
Contour intervals 25 m
0 1 2 3 4 5
km
24°00 W
23°40 W
72°15 N
72°10 N
Kong Oscars Fjord
Nyhavn
Gåsesø
Langdyssen
LABBEN
Mesters Vig flyveplads
Hovedet
cottage
Noret
Washburns cottage
Hesteskoen
1118
Tunnelelv
Thyres spids
Archers Øer
Rungsted Elv
Gorms spids
Store Blydal
Lerelv
Blyklippen
Tværelv
Gylleelv
Minebyen
Domkirken
1025
KORSBJERG
Fyrtårnet
1041
Ansgar
Calamites Elv
Danekirke
Myggesø
Hestepas
Permklippen
Øvre Gefionelv
Nedre Gefionelv
Langelinie
Gletcherryggen
Sceelesbjerg
1180
Lille Blydal
Holberg pas
Blyryggen
Skibselv
Nuldal
cottage
Mesters Vig
Bjørnesø
Røde bjerg
Holberg Elv
Profilbjerg
982
Nordre Funddal
Nedre Funddal
Hjørnet
Peters Elv
Pingos Elv
Storm P. Elv
Korlebjerg
True north
0°
Cartography by F Rune 1989
Hovsmedeve; 7
DK-3400 Hillerød
Magnetic north
28°50 W (1985)
Based on the photogrammetric map manuscript FS3672 1:50000
©Kort- og Matrikelstyrelsen DK

Figure 4.3(a): Headwater tributaries

Figure 4.3(b): Store Blydal braidplain (mine waste splay in foreground)

Figure 4.3(c): Tunnelelv gorge

Figure 4.3(d): Tunnelelv delta

2. Store Blydal, (Big lead valley) (figure 4.3b). A relatively shallow gradient, extensively braided channel within a wide valley, (300-500m width). Braiding results from the imbalance between high rates of sediment supply, and the low stream powers within the channel that are consistently under-capacity. Channel features include a range of active and inactive bars, braid channels exhibiting riffle-pool sequences, Boulder dumps, and a discontinuous terrace of palaeobars/channels on the North side of the valley floor. These latter features were abandoned sometime before 1949 as a result of the incision of the north bank channels, (see Sections D - G). Gross channel morphology is characterised by a slope from North to South across the valley floor, with a maximum height difference between north and south bank channels of 2.5m, (Section C). This results it is suggested, from the higher rates of sediment supply from the south facing slopes of the Hesteskoen massif. Asymmetry of alluvial valleys is a characteristic of periglacial regions, although the orientation of the steepest sides are variable, (Washburn, 1973). Nevertheless, the process of asymmetry involves an imbalance in the slope sediment supply which is in accordance with the observations from Mesters Vig (Washburn, 1973).

3. The Tunnelelv Gorge through which the Store Blydal plummets some 50m down a series of waterfalls (figure 4.3c). The gorge slopes are steep and where shallower angles permit, are covered with loose, weathered material. Sediment supply is directly to the channel and opportunities for storage within the channel are minimal. The bed morphology is characterised by bed-rock and a confused collection of boulder and gravel bars. At the downstream end of the gorge, the Tunnelelv is joined by the Rungstedelv. The confluence of these two streams occurs as the gorge widens towards the delta.

4. The Tunnelelv splits into three major distributary systems to form the delta plain (figure 4.3d). The majority of the flow is now channelised by the Danish Military into the Southern distributary branch which like the northern and eastern branches, ends in a complex of sand bars. The delta plain is built upon marine sediments. Raised beaches bound the fossil cliffline where the Tunnelelv gorge discharges onto the plain. Variations in sea level have initiated a succession of incision phases in the distributary channels, leading to at least three terrace levels (see Section J). The fall in sea level has in part created the Tunnelelv gorge through knickpoint recession as the channel adjusted to the new (lower) base level.

4.2.4 Research Methodology

The study was divided into 5 components:

1. An initial desk study involving aerial photographic (1:10000 scale) reconnaissance of the river catchment and assessments of channel changes between the available aerial photo coverages of 1949, 1968 and 1973;

2. Catchment familiarisation and ground truthing of the photo reconnaissance, involving mapping of bars and vegetated areas;

3. Surveying of cross sections and sampling and splitting of sediments across the sections. In addition, Ph and soil moisture were obtained for most sampling points;

4. Vegetation analysis involving pin-plot estimates of species abundance from quadrats sited at sediment sampling positions together with the collection of *Salix arctica* and *Chamenirium latifolium* specimens for heavy metal analysis; and

5. Laboratory analysis of sediment samples for Lead and Zinc content. Dendrochronological analysis of *Salix artica* was also attempted in order to date the sequence of relic bars.

At the time of writing the vegetation analysis has not been conducted and the data and specimens remain in store in Denmark.

4.3 Studies of metal contaminants in sediments

4.3.1 Heavy metal contamination of soils and sediments: the legislative viewpoint.

The study of heavy metal contamination of soils and sediments has recently received a fillip from the development of legislation in EC member nations regarding permissible levels of Pb, Zn and Cd in soils (ICRCL 1990; Dutch Ministry of Housing 1983). However, there is clearly still a need for more information on the mechanisms of heavy metal transport, storage and chemical synthesis within the fluvial and pedological systems. This is reflected in the paradox of official recognition of the problem (represented by Dutch indicator values) and the critical reaction of the scientific community to what it perceives to be over-simplistic and unsupported official decisions (Webber et al., 1984). The official reaction to an increasing database of information is demonstrated by the range of permissible, indicator and acceptable threshold levels available to the planning authorities (table 4.1). Many of these levels clearly reflect the highly variable values of contamination by Pb and Zn documented in the literature (table 4.1) and are specific to the individual nations concerned (Moen et al.,1986). Many of these levels are a product of the specific geologies of the study areas, thus a threshold value for soils in urban Tyneside for Pb is lower than agricultural soils in the west of England, whilst Maximum Permissible Levels (MPL) for Pb and Zn vary from 50-300 mg/kg while farmers in the Vistula basin Poland and on the Banks of the South Tyne customarily produce foodstuffs on land exhibiting metal levels over 3 times the MPL (Macklin and Klimek, 1992).

Table 4.1 indicates that for many large river systems in temperate Europe, heavy metal levels in alluvium far exceed officially acceptable levels. In order to effectively manage these polluted systems will require an analysis of the processes by which the contaminants are transported and stored in the sediment system and over what timescales the contaminated fluvial sediments can be expected to pose a problem for river and land managers (Macklin and Klimek, 1992 suggest 100 - 1000 years residence time for floodplain deposits). The results of the research published here go some way to identifying the fluvial processes of metal dispersion, storage and transformation within an ecologically sensitive Arctic fluvial system.

4.3.2 Heavy metals in fluvial systems

Table 4.1 lists a broad range of documented Lead and Zinc levels within fluvial sediments of differing ages. These largely reflect the different histories of metal mining within the study catchments. Thus Macklin and Klimek (1992) identify maximum metal contamination of alluvium post-1900 and pre 1988, and document relatively stable levels in the preceding 3000 years. Macklin et al., (1992) use the variation in recorded Pb and Zn levels in within-channel alluvial deposits in conjunction with metal mining output for the upstream catchment to tentatively date individual flood units. The importance of the preservation of metal polluted alluvial sediments lies in the wider distribution and continuity of the pollutant source far beyond the spoil heap. Thus Klien (1962) documents the reduction of aquatic species diversity (particularly fish and molluscs) following Lead/Zinc mining activity in Wales in the past 100 years. Importantly, 70 years after mining ceased, remobilisation of contaminated river sediments continues to maintain high levels of Lead and Zinc, with fish, molluscs and crustaceans still depleted. In addition, to the toxicity associated with mine waste, many channels exhibit morphological instability, which itself disturbs the ecological balance within the river system (Leopold & Dunne, 1979).

4.3.3 Chemical and physical processes and metal ion dispersion within fluvial systems

Once introduced to the river system which usually occurs during flooding, the mine waste is hydraulically sorted on the basis of particle size, density and chemical solubility (Jones, 1986; Macklin & Dowsett, 1989). The chemical and physical speciation of the original mine waste will correspondingly dictate the initial processes of dispersal. Subsequent concentration of metal ions in stream sediments will depend on a range of physio-chemical processes, though supply from secondary sources such as eroding stream banks or tributaries will provide considerable downstream variation (Macklin and Dowsett, 1989; Bradley and Cox, 1990; Axtmann and Luoma, 1991).

Physical processes controlling metal contaminant dispersal include concentration in regions of fine sediment deposition such as floodplains (Bradley and Cox, 1986), slackwater zones (Knox, 1987) or sediment transport processes associated with the migration of bedforms (Hubbell and Glen, 1973).

Dissanayake et al., (1984) identify the role of organic complexing in the subsequent concentration of metal ions within stream sediments. Humic and Fulvic acids are particularly effective in concentrating metal ions at the boundary of reducing and oxidating sedimentary environments such as occur in Estuaries. Li (1983) has shown that the dilution of Pb in streams is closely associated with suspended sediment concentrations and the presence of colloids and ligands. pH and reducing/oxidising conditions were also shown to affect the rate of dilution of Pb, with slightly Alkaline conditions (pH 8.5-9) favouring the dilution. Li (1983) concluded that the concentration of Pb in stream sediments was controlled by chemical conditions that promoted sorption/de-sorption onto sediments and suspended sediments. Zinc concentration in stream sediments is strongly controlled by pH (anon 1983), and its concentrations in fine overbank sediments is generally even throughout the grain sizes (< 1mm) (Macklin and Dowsett, 1989; see also discussion in section 4.5.4 of this report).

Table 4.1 **Documented Lead (Pb) and Zinc (Zn) levels in Sediments and Plants**

Environment	Sediment	Pb (mg/kg)	Zn (mg/kg)	Source
Background				
G.B. Agricultural	Soil <2mm	10.9-145	29 - 210	Archer & Hodgson (1987)
Nethlnd Loess	Soil <2mm	34	84	Rang et al (1987)
Sub-recent Rhine	Soil <2mm	30	115	Salmons & Furstner (1984)
Late Holocene	Alluvium <2mm	17	61	Macklin (unpublished)
Late Holocene	Alluvium <2mm	81	61	Macklin (unpublished)
Mid Holocene	Alluvium <2mm	7.2 - 60.2	32 - 196	Macklin & Klimek (1992)
U.K.	Soil <2mm	50 - 500	2.5 - 560	Webber et al (1984)
Germany	Soil <2mm	30	50	" " " "
River Alluvium	Alluvium <2mm	55	145	Bradley & Cox (1986)
Arctic Greenland (Tunnelelv River)	**Stream/Soil**	**30**	**50**	**Kunzendorf (unpublished)**
Threshold Values				
Agric Soils UK	Soil	108	---	Archer (1980)
Agric Soil W.Uk	Soil	90 - 116	---	Davies (1983)
Agric Floodplain	Soil	125	---	Lewin et al (1983)
Urban Soils Tyne	Soil <2mm	80	345	Aspinall et al (1986)
Soils	Soil <2mm	67	---	Macklin et al (1985)
Arctic Fluvial (Tunnelelv River)	**River Sed <2mm**	**70**	**135**	**Kunzendorf (unpublished)**
Official Levels				
ICRCL Threshold values (acceptable)				
Vegetable Gardens	All Sediments	550	---	ICRCL (1980)
Amenity Land	" "	1500	---	" "
Public Open Space	" "	2000	---	" "
Dutch I.L.:				
Class A	All Sediments	50	150	Dutch Ministry of Housing
Class B (Warning)	" "	150	500	" " " "
Class C (treatment)	" "	600	3000	" " " "
Dutch Signal values				
Consumer Crop	All Sediments	200	350	Leenaers (1989)
Pasture	" "	200	350	" "
Maximum Permissable Levels				
CEC Directive	Agric. Soils	50 - 300	150 - 300	Sauerbeck (1987)
UK	" "	550	560	Webber et al (1984)
France	" "	100	300	" " " "
Germany	" "	100	300	" " " "
MAFF Maximum Permissable Levels				
Agricultural Soil	" "	300	---	MAFF UK
Foodstuffs	-----------	1	---	" "
Mineralised Areas	River Sed <2mm	8 - 500	1- 1900	Thoms (1987)
Mining	River Sed <2mm	16 -8000	17 -6055	" "
Industrial Areas	River Sed <2mm	6 -1430	30 -6220	" "
Urban Areas	River Sed <2mm	1 -2100	5 -6114	" "
Urban Areas	Soil <2mm	80 -2000	300 - 345	Aspinall et al (1986)
Polluted Fluvial				
Temparate W.Allen	Flood Sed <2mm	98-3166	74 -1131	Aspinall & Macklin (1983)
Temparate " "	Moss	807-13369	823 -2305	" " "
Post-1988 Vistula	Alluvium <63	4.2 - 404	31 -7850	Macklin & Klimek (1992)
Post-1900 "	Alluvium <63	7.6 -1745	35 -11580	" " " "
Pre-1800 "	Alluvium <63	7.2 - 60	48 - 192	" " " "
2000-3000 BP "	Alluvium <63	8.8 - 33	123 - 196	" " " "
Temparate Geul	Alluvium <2mm	--- ---	500 -10000	Leenaers (1990)
Temparate Tyne	Flood Sed<2mm	500 -3000	1200-3000	Macklin & Dowsett (1989)
Temparate Twymyn	Alluvium <2mm	500 -6350	100 -7000	Lewin & Macklin (1989)
Temparate Ystwyth	Alluvium <2mm	150 -2200	100 - 900	" " " "
Temparate Towy	Alluvium <2mm	170 -5900	30 -3800	" " " "
Temparate Rea Br.	Alluvium <2mm	40 -6400	200 -11000	" " " "
Water				
Temparate W.Allen	Water	<0.5-2.5	0.03-0.64	Aspinall & Macklin (1983)
Guideline Levels	Water	2.0	2.0	Saunders (1990)
Arctic Greenland				

The relative chemical mobility of Zn in comparison to Pb is mentioned in a number of sources with respect to downstream rates of dilution (anon, 1983; Aspinall and Macklin, 1985; Macklin and Dowsett, 1989). Both Pb and Zn within overbank fines from the Tyne river system are associated with Fe/Mn complexes, though with an increase in organic matter a process of chemical sorption increases the levels of organic complexed Zn with respect to Fe/Mn complexes (Macklin and Dowsett, 1989). Lead also experienced a downstream decrease in the proportion attributable to Fe/Mn complexes, but Macklin and Dowsett (1989) attributed this more to the physical destruction of adsorped surface coatings of quartz grains than any chemical process. The importance of chemical sorption/de-sorption processes in the downstream (and lateral) dispersion of metals in river sediments calls into question the use of density/grain-size based models of dispersal (Marcus, 1987; Lewin and Macklin, 1989).

4.3.4 Metal contaminated sediments and morphological instability

Vertical distribution of metal contaminants can provide an important tracer for fluvial studies. Vertical distribution of metal contaminants also provides information on the vertical behaviour of the channel within the post-mining period. Correspondingly, Macklin et al., (1992) and Axtmann and Louoma (1991) identify subsequent incision of river channels following a period of mining. In both instances this has led to preservation of the vertical alluvium, and consequently a persistent secondary source of metal pollutants.

Lewin and Macklin (1989) identify two responses of the sediment system to injections of mine waste:

1. Passive dispersal, whereby the mine waste is routed through the system with little or no morphological change; and

2. Active dispersal, whereby morphological change of the valley floor results from mine waste injection.

The latter scenario can be temporarily extended by the subsequent retardation of stabilising vegetation growth on contaminated gravel shoals (Macklin and Smith, 1990). Consequently, the morphological response relates not only to the quantity of sediment released to the stream channel, but also the concentration of metal contaminants and their distribution and dilution downstream. The interpretation of morphological response is not always clear however; Rumsby (1991) has suggested that the morphological instability (both lateral and vertical) experienced by the South Tyne has resulted more from a series of geomorphologically effective floods than from the injection of mine waste alone. Nevertheless, aggradation of floodplain surfaces has been accelerated in part by an increased frequency of flooding, but also as a result of an increased supply of fine sediment from mine waste (Macklin et al., 1992).

4.3.5 Modelling contaminant dispersal in stream systems

Recent approaches to modelling metal contaminant dispersal within main stream channels have concentrated on the apparent exponential decay of sediment borne metal contaminants with distance from source (Marron, 1987; Lewin and Macklin, 1987). The three models most widely used are:

1. Semi logarithmic regression model(Wolfenden & Lewin, 1978) of the form..

$$\text{Log } C = b_1 D + a_1 \qquad (4.1)$$

2. Log-Log regression model(Marron, 1986; Macklin & Lewin, 1987) of the form..

$$\text{Log } C = b_1 \log D + a_1 \quad (4.2)$$

3. Log-Log regression (equation 2) incorporating a mixing model (Marron, 1986) of the form..

$$C_r = [(C_t . X_t)/(X_t + X_m)] + [(C_m . X_m)/(X_t + X_m)] \quad (4.3)$$

Where C = concentration of sediment related metal contaminants at a point downstream from source;
D = distance downstream from source of metal contamination;
a_1 and b_1 are empirical coefficients;
C_r = sediment related metal concentration below tributary inputs;
C_t = metal concentration in tributary sediments;
C_m = metal concentration in main channel upstream of the confluence;
X_m and X_t are the sediment yields (or basin areas) of main stream and tributary stream respectively.

Marron (1986) in a review of the application of these models, concluded that simple Semi-Logarithmic and Log-Log regressions failed to account for the differential capacity of tributary streams to dilute bed sediments. The application of the simple mixing model enabled the replication of sudden decreases (in the case of Marron's river) of metal ion concentration downstream of tributary streams. However, Marron (1986) and Lewin and Macklin (1987) note that differences in the bedload transport environment within the stream will produce regions of high and low concentration independently of tributary dilution effects. For example, Marron, (1986) describes increases in the concentration of metal ions within a heavily vegetated reach and concluded that bedload was being preferentially trapped in this reach. Aspinall and Macklin, (1985) record such a physical trapping mechanism associated with moss and lichen within the bed of the West Allen. Further evidence from these two studies refers to the effect of sediment size on the downstream dispersal (and efficacy of models to replicate the dispersal). Marron (1986) identifies bedload sized sediments with preferential trapping by vegetation or deposition in slackwater areas, whilst suspended sized sediments, exhibiting a more uniform dispersal through the channel network, are more influenced by tributary stream dilution and hence are modelled more effectively by the Log-Log and mixing model application.

Lewin and Macklin (1987) discuss the nature of the stream channel and type of metal contaminant and its effect on the application of Semi-Log, Log-Log and Linear models. Lewin and Macklin (1987) suggest that exponential models of sediment related metal dispersal apply most effectively to streams with a significant floodplain sediment storage component. This is because secondary contaminant sources caused by floodplain erosion, would maintain a lower rate of decline after an initially rapid decline as the mine waste was diluted in stream.

Differences in the rate of dilution between Pb and Zn have been attributed to either Hydraulic sorting on the basis of particle density or chemical dispersal through solution, adsorption or complexing. Lewin and Macklin (1987) conclude that regression models do not allow differentiation of the specific processes of dispersion to be elucidated and that more work is required to specify the relative effects of geomorphic and chemical processes which operate within individual or similar stream systems. The mixing model approach of Marron (1986) provides an improvement to the simple regression models of Lewin and Macklin (1987) but again only accounts for dilutions based on the assumption of dilution from uncontaminated bedload. Two further problems remain to be overcome, first the validity of the *apriori* assumption of the three models above, that spot samples of channel sediment represent the concentration at that point in the network, and secondly the effect (particularly in larger basins) of the climatic patterns prior to sampling. As Marron suggests, the effect of an isolated storm in a tributary stream may result in a temporary dilution of contaminated sediments as a wave of "fresh" tributary sediment is transported downstream.

Leenaers (1990) applied multiscale spatial modelling to values of Zn contamination in the river and floodplain of the River Geul, Netherlands. Leenaers identified three scales of spatially correlated metal contamination:

1. The River Valley (characterised by an exponential decline downstream with random spatially uncorrelated residuals);

2. The Floodplain (characterised by a significant correlation between metal concentration and floodplain morphology expressed as height above the main channel); and

3. The Geomorphological Unit; including channel, palaeochannel, levee (characterised by strong correlation between metal concentration and small scale elevation differences).

Leenaers (1990), by examining the individual covariograms of Zn concentration at a point and that concentration at points **x** and **x+h** distances from the point, was able to show that similar dispersal processes were operating at the scales of the floodplain and the individual geomorphological unit. The patterns of dispersal within the main channel, by inference, are controlled by different processes. The floodplain/geomorphological unit experiences concentration of metal contaminants largely in association with regions experiencing frequent inundation by overbank flows and slackwater. Nevertheless, Leenaers (1990) concludes that no one model of sediment related metal contaminant dispersion can be applied to fluvial systems owing to the complexity of concentration/dilution processes operating over a range of scales.

A final point of note is the vertical complexity of metal contamination within floodplain and in-channel deposits. Temporal variation in the rate of metal supply (e.g. longevity of mining) can result in variations in the metal concentration with depth of deposit (Macklin et al., 1992). This has implications both for lateral floodplain concentrations if the channel has migrated during or after the mining period, as well as for downstream patterns of dispersal if different ages of vertical sediment are being eroded at different locations. Thus the problem of modelling metal contamination dispersal has a physio-chemical, three-dimensional spatial component in addition to a temporal component. The conclusion to date must remain that none of the existing models approaches anything like the sophistication required to model metal contamination in fluvial systems.

4.4 Experimental procedure

4.4.1 Sediment sampling procedure.

In the section described here, samples were collected in the field from the top 5cm of sediment at every site identified. Each sample was approximately equivalent to 3kg, and these were left on polythene to air dry. Each sample was manually sieved through a 2mm sieve and the proportion of sediment <2mm calculated and returned to the laboratory. Some 126 surface samples were taken in total from 10 cross-sections. Where a bar face was revealed by erosion then, wherever possible, a sample was taken from the surface, middle and bottom of the exposure at a distance of 0.5-1.0m from the face itself. This precaution avoided any contamination of the lower samples by material collapsing from above or imported from other sedimentary units.

In addition to the above procedure, small wet samples of surface <2mm sediment were returned to the lab and weighed before and after air drying to establish their moisture content.

4.4.2 Geochemical analysis of Lead (Pb) and Zinc (Zn) in Tunnelelv valley floor sediments.

Sediment samples were returned to the UK for analysis for total and available metal ion concentrations. The procedure used for determining total metal ion concentration involves Nitric acid (HNO_3) digestion of weighed samples of sediment. Twenty-five ml of 0.25M HNO_3 are added to each 2.0g sample in a glass beaker and the solution slowly evaporated to dryness. The sample is then re-wetted with 20ml of 0.1M HNO_3, shaken for 10 minutes and the resultant solution filtered to remove the remaining solids. The solution is then combusted in an air/acetylene flame within a Phillips SP2900 double beam Atomic Adsorption Spectrophotometer (AAS) and the readings converted into metal ion concentrations (Mg/Kg). The procedure used for determining available metal ion concentrations involves shaking a solution of 2g of sediment and 25ml of 0.5M Acetic acid (C_2H_5COOH) for 12 hours, filtering and processing the solution through the AAS as above.

Information on this technique together with estimates of the accuracy of the analysis are given in Sinex et al., (1980) The accuracy obtained by Sinex et al., (1980) for acid digestion were comparable with those obtained by radioisotope energy-dispersive X-ray fluorescence analysis (EDX) analysis. This is important in the context of this study since the data for the Tunnelelv collected by Kunzendorf (unpublished) was processed using the latter technique.

Information on the sequential extraction for chemical speciation of particulate metals is contained in Tessier et al., (1979) and Macklin and Dowsett (1987). The procedure sequentially apportions the sediment related metal ions into five chemical categories:

1. exchangeable metal ions;
2. surface oxide and carbonate-bound metal ions;
3. Fe/Mn complexed ions;
4. organically bound metal ions; and
5. residual metal ions.

These phases broadly reflect the potential mobility of the metal ions within the environment, correspondingly exchangeable ions are those most easily mobilised (and therefore those most potentially available to components of the food chain) whilst residual metal ions are strongly bound to individual particles and do not easily enter solution. Macklin & Dowsett (1987) note that for environmental analysis, a knowledge of the chemical and physical speciation of the particulate metal ions provides a clearer picture of the potential role of the contaminants in the ecosystem than that provided simply by a consideration of total loadings.

In addition to the five chemical categories, each sample is split into size ranges prior to the chemical analysis. The size ranges equate to Coarse sand (0.5-1mm), Medium sand (0.5-0.25mm), Fine sand (0.25-0.063mm) and Silt & Clay (<0.063mm). This provides information on the size categories which contain the highest concentrations of which chemical species of metal ion. This has important implications in a fluvial system where the dominant sorting process occurs through hydraulic action (Macklin & Dowsett, 1989; Lewin & Macklin 1987).

The phase analysis was unavailable for all the samples returned by the expedition due to the limited laboratory resources, however, two samples of mine waste and bar sediments downstream of the mine were subjected to phase analysis for speciation: their results are discussed below.

4.5 Results of sedimentary analysis

4.5.1 Morphological changes associated with mining

Figure 4.4 depicts the morphological changes associated with the construction and operation of the Mine between 1954-1962. The data was obtained through planvariometric adjustment of 1:10000 scale aerial photographs for three dates, 1949; 1968 and 1973. All photographic sequences were taken in the summer when snow and ice cover are at a minimum and stream flow is just past maximum. The channel sequence downstream of the mine is typically braided before plummeting through the Tunnelelv gorge. Four active alluvial fans are shown entering the channel from the north side of the valley. These have steep channels descending from rocky canyons in the Hesteskoen massif. Considerable quantities of sediment have been supplied from these fans which elevate the north side of the Store Blydal relative to the south side, producing two distinct channel systems adjacent to each other (see below).

A sequence of abandoned palaeochannels and bars is evident immediately upstream of the Tunnelelv gorge section. The presence of these palaeochannels indicates a period of incision and channel migration towards the North. Analysis of tree rings from dwarf willow (*Salix artica*) stumps from the largest living plants give a minimum colonisation by dwarf willow of around 35 years BP (c.1954). The appearance of the palaeochannels on the 1948 aerial photographs indicates that they predate the tree ring ages by at least six years. In all probability the surfaces are of a significantly greater age since soil depth and species diversity have amongst the highest values recorded in the Store Blydal Valley and it is known that the processes of soil formation and plant colonisation are much slower in arctic environments than in temperate. A lichenometric survey from stone surfaces might provide a useful indication of general surface age.

Figure 4.4: Morphological changes associated with metal mining at Blyklippen, Mesters Vig, Greenland. Data derived from aerial photography.

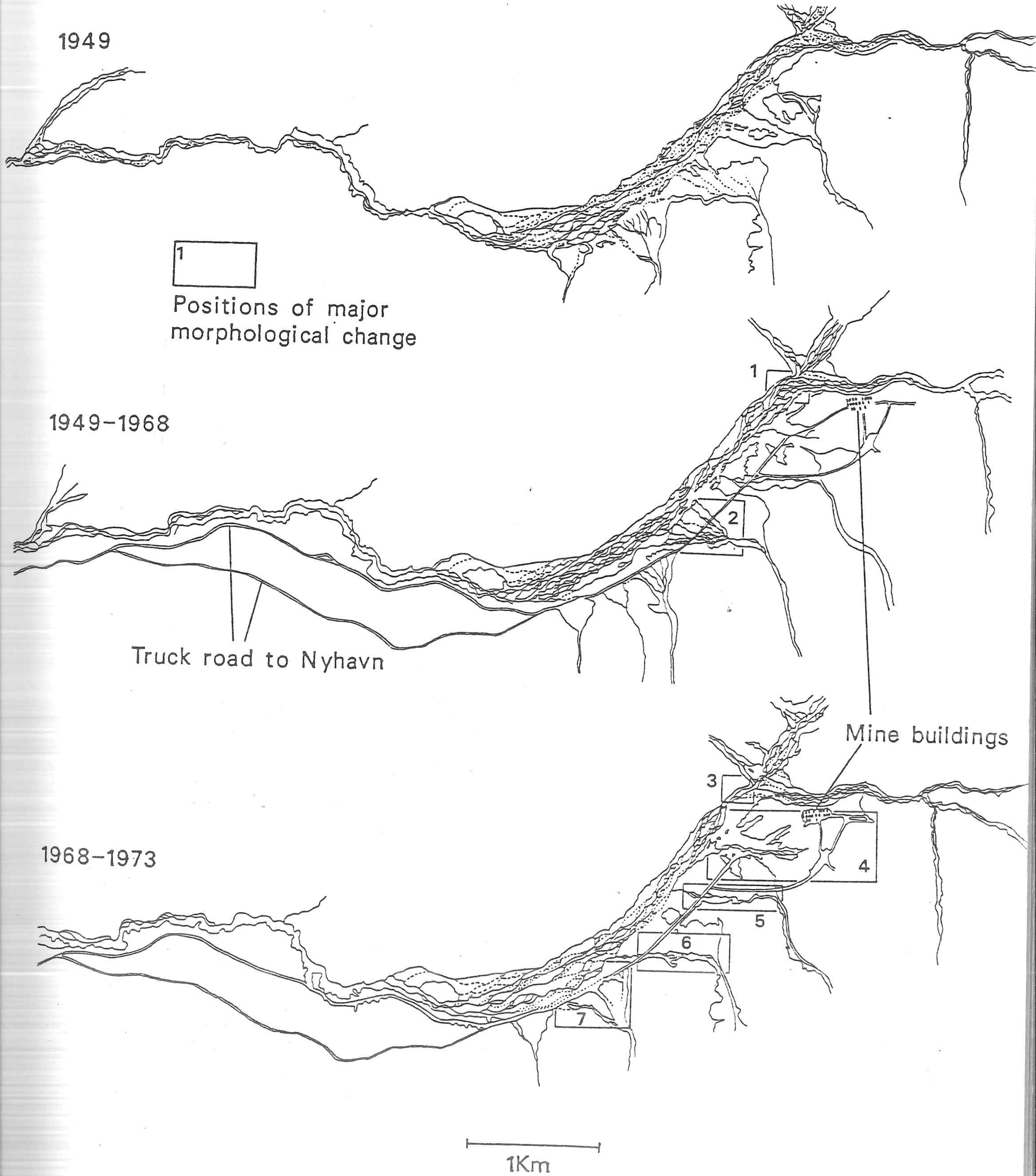


Figure 4.4 indicates that with the exception of the triple confluence adjacent to the mine buildings (No. 1), most of the morphological changes in the Store Blydal valley have resulted from the construction of access roads, the mine site and the disposal of mine tailings. The latter is evident in No. 4 in figure 4.4 which indicates that efflux from the mine (probably the result of the shut down of the milling operation) continued to eject material into the small stream draining the mine after production ceased in 1962.

Significant alterations have occurred to the drainage networks on the alluvial fans as a result of road construction. This is evident from figure 4.4 (No.s 5-7). Between 1968-1973 the channels of all four fans have been concentrated into single channels, with smaller distributaries activated only during large runoff events (e.g. spring snow melt). Two mine roads were constructed to take material from the Mine to the harbour at Nyhavn. The double roads enabled trucks returning from the harbour to pass those on their way down from the Mine. Drainage channels on the north side of these roads intercepts slope runoff and channels this into the Store Blydal via the major channels of the alluvial fans.

The land surface at the mine site has been completely churned up by bulldozer activity during the demolition of the mine buildings (figure 4.5) in the 1980's. The distinctive grey-white mine tailings have been spread over the site together with detritus from buildings and equipment. Locally the albedo has been increased, and the vegetation destroyed. On the Blyklippen hillside, two terraces of excavated rock dominate the landscape, whilst a large grey-white splay of mine waste forms benches on either side of the stream draining the mine. Locally the depth of these fine mine tailings (100% < 2mm grain size) reaches almost 3m, beneath which the cobble bed of the former stream is exposed. Thermal and fluvial erosion of these benches still provide a significant source of contamination for the Store Blydal/Tunnelelv (see below).

The complexity of the channel system downstream of the Mine precludes the identification of any channel changes specifically associated with the mining operation and the release of tailings. However, this in itself suggests that whatever the morphological change, it was not extensive and in fact was accommodated within the existing braidplain. Field "ground truthing" of this observation in fact revealed mine waste barforms extending 200m into the braidplain from the mine site, but mixing rapidly with fluvial material such that after 200m mine waste was evident only as small ephemeral deposits of grey-white sand in slackwater areas.

The morphological map shown in figure 4.6 identifies the region of mine waste immediately upstream of a network of relic palaeobars and active channels. The former are covered by vegetation and no longer play an active role in the sediment dynamics of the river system. Between these stable barforms the channel is actively eroding and depositing sediments as bars, riffles and pools. However the width of the active braidplain is controlled by the gross valley morphology so that in the reach opposite the palaeobars (Section G) upstream of the Tunnelelv gorge, the braidplain is constricted. Mine waste entering this reach will be mixed effectively with uncontaminated material from the valley sides, alluvial fans and from upstream. This is discussed further in section 4.5.3.

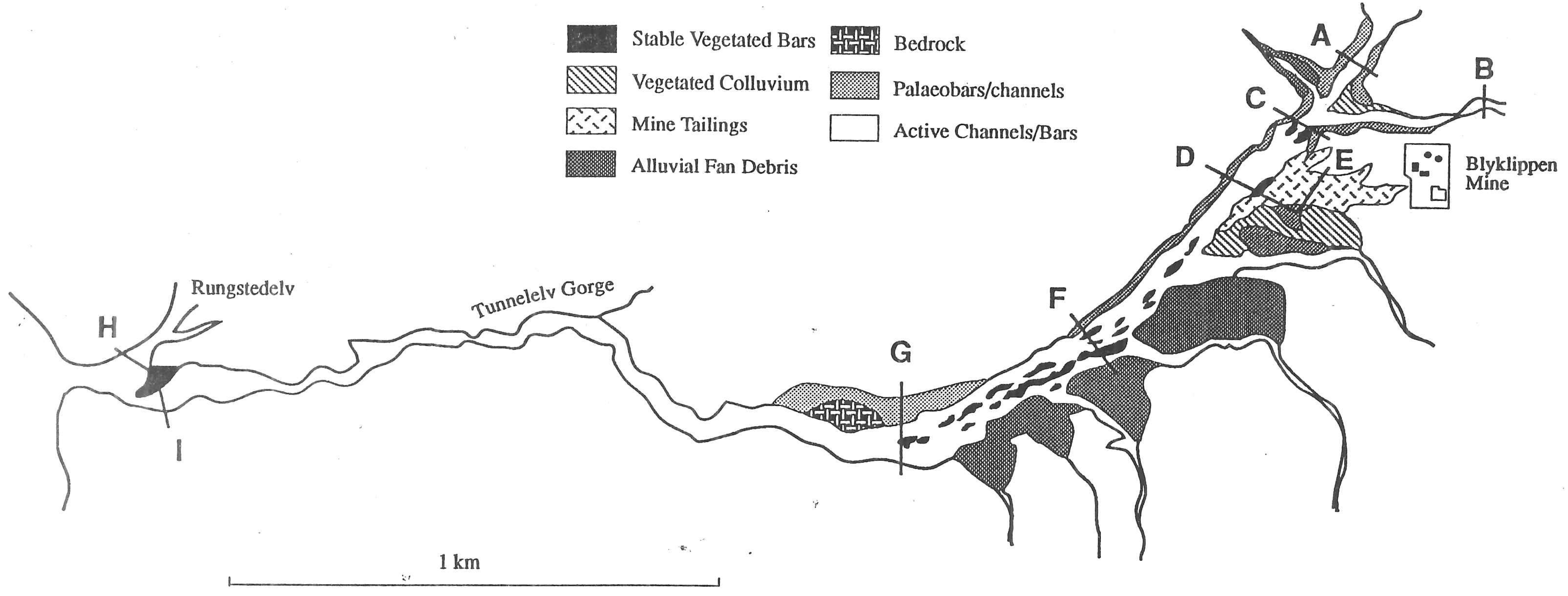
From The morphological evidence of aerial photographs and field reconnaissance, it is clear that the injection of mine tailings in to the Store Blydal braidplain resulted in localised morphological change but general passive dispersal within a system already accommodating excess sediment supply from active alluvial fans. The nature of this dispersal and how it is affected by the existing braided morphology of the river bed is investigated further in section 4.5.4.

Figure 4.5: Aerial photograph of Blyklippen mine

Figure 4.5: Aerial photograph of Blyklippen mine

Figure 4.6:

Morphological Map of the Store Blydal and Tunnelelv Gorge showing the mine site and tailings.



4.5.2 Chemical and physical speciation of Pb and Zn in mine waste and re-deposited river sediments.

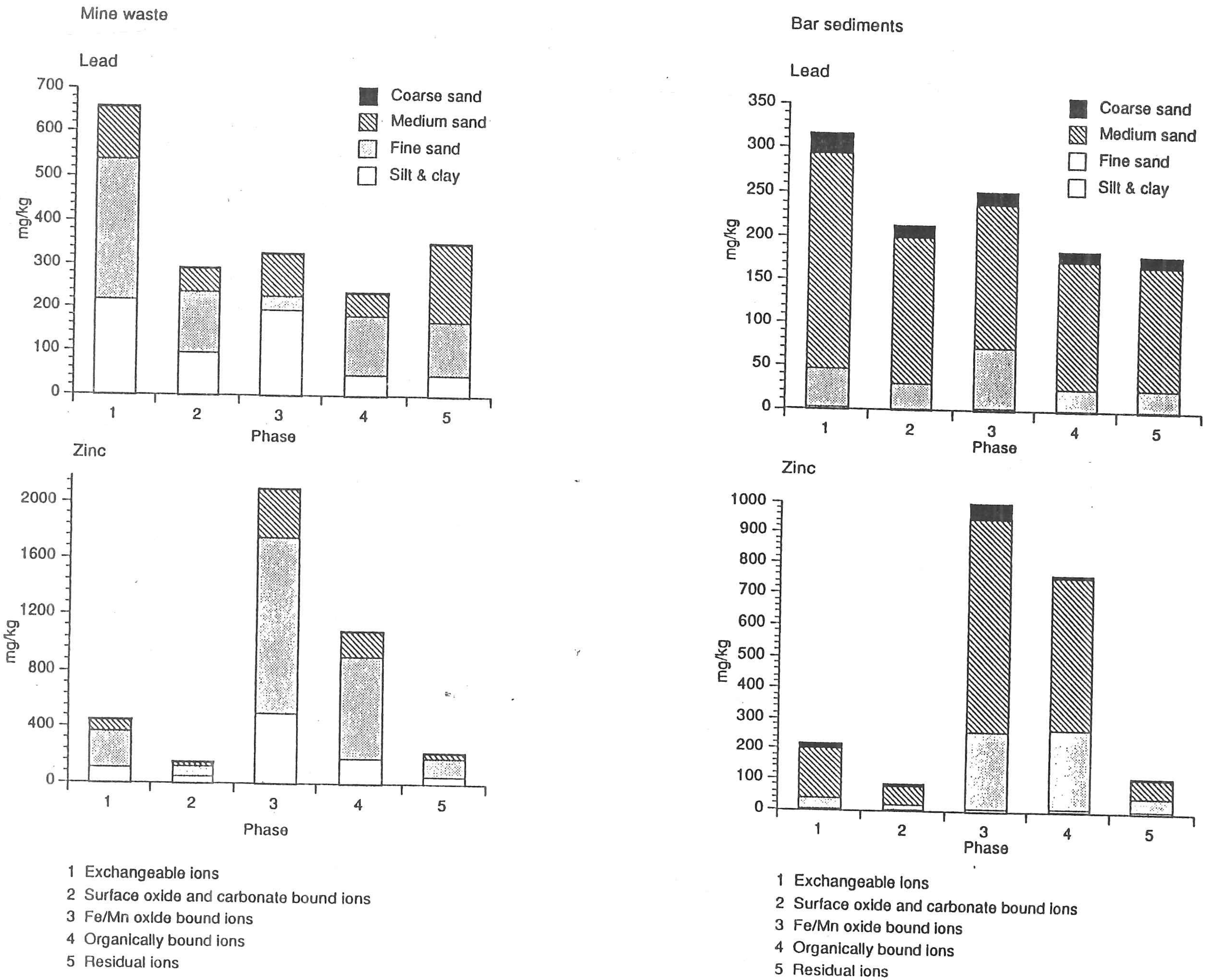
Figure 4.7 depicts the geochemical speciation of Pb and Zn for four sediment size classes from two samples; mine waste (Section E) and river bar sediments (Section G). The mine waste is comprised of tailings from the ore concentration process and is dominated exclusively by material < 2mm diameter. In contrast, the bar sediments have been subjected to physio-chemical processes and have a heterogeneous sediment fabric. Concentrations of Pb and Zn are many times greater in the mine waste than in the bar sediments, reflecting dilution by uncontaminated sediments in the 2km journey from the mine site to the bar sampled.

Figure 4.7 shows that Pb is primarily associated with the operationally defined exchangeable metal ion phase in the mine waste and bar sediments <2mm diameter, although in the latter environment the importance of the other phases is accentuated. This is important because it is the operationally exchangeable phase which most readily enters the environment in solution and therefore is available for take up by plants and animals. In contrast the majority of the Zn exists in the form of Mn/Fe or organically bound complexes. The chemical speciation is preserved in the bar sediments although the proportion of organically bound complexes has increased, reflecting the higher proportion of organic material available in solution within the stream system and the operation of chemical sorption/desorption processes (Macklin & Dowsett, 1989).

Chemical processes are clearly in operation within the fluvial environment of the Store Blydal. The increase in the proportion of phases 2, 4 and 5 within the bar sediments relative to the exchangeable phase 1, occurs independently of sediment size expressed as the proportion of each phase in the four size categories in the mine waste. Thus the Proportion of Fe/Mn complexed Pb increases although the proportion of silt/clay and fine sand (associated with this phase in the mine waste) decreases downstream. This suggests that the environment favours the preservation of the stronger chemically bonded phases and the loss of exchangeable ions in transit via chemical sorption-desorption. The same cannot be said of the Zn ions, whose proportion of chemical phases is retained though with accentuated organic complexed Zn ions.

Significant hydraulic sorting processes operate between the mine waste site and bar deposition, characterised by the preferential removal of fine sand and silt/clay from the original mixture. Correspondingly the Pb ions in the mine waste are dominated by fine sand and silt/clay fractions whereas medium sand dominates the chemical phases in the bar sediments. The same hydraulic sorting process also operates for Zn metal ions. The discrimination on the basis of size reflects the mode of transport; fine sand, silt and clay will be transported as suspended load, with little interaction with the stream bed, whilst medium and coarse sand will be transported as bedload and interacts repeatedly with the stream bed. and will thus be affected by the morphological environment within the channel. In a braided system such as the Store Blydal, the opportunities for bedload deposition are great and the sediment loads high. Consequently rapid dilution and comparatively local storage are to be expected. With the suspended load, much of the transport will be independent of channel morphology and it is probable that the majority of fine sediments are transported from the mine site to the Noret inlet during one snowmelt season. Nevertheless, the high concentrations of metals associated with the finest fractions of mine waste indicate that regions of slackwater where these fines can settle out, will be amongst the most contaminated.

Figure 4.7: **Chemical and physical speciation of Pb and Zn within mine waste (E) and bar sediments (F). Store Blydal, Mesters Vig, Greenland.**



Macklin and Dowsett (1989) report on a downstream change within the Tyne basin from physical (hydraulic) sorting of metal contaminated sediments in the headwaters to a process of chemical sorption-desorption associated with Fe/Mn oxides and organic complexes. The same processes are clearly operating in the Store Blydal system though in tandem. Further research will be required to identify if there is a change in emphasis from physical to chemical metal ion processes although at present it appears that this distinction is more a result of physical sorting into coarse and fine sediments than any fundamental change associated with chemical environment as suggested by Macklin and Dowsett (1989).

4.5.3 Downstream dilution of Pb and Zn in active channel sediments in the Store Blydal 1971-1989

In 1971 a comprehensive stream sediment sampling survey was conducted by RISO and Greenland Geological Survey (GGU) in order to provide a background database of sediment related metal concentrations. The initial results were documented in an internal RISO report (Kunzerndorf, unpublished). The survey included all the major tributaries of the Store Blydal, the Store Blydal, Tunnelelv and the Delta distributaries. The date of the survey in 1971 comes 10 years after production at the mine had ceased and after mining related sediments had been introduced to the fluvial system; this is recognised in Kunzerndorf's report. Statistically estimated threshold and background levels of Pb and Zn concentration in stream sediments are given in the report and shown in table 4.1 above.

Figure 4.8 illustrates the downstream distribution of sediment related Pb and Zn metal ions for sediments sampled from the same stream in 1971 and 1989. The effect of mining related metal contamination of sediments is graphically illustrated for both surveys. Figure 8 also shows the downstream Pb and Zn levels recorded in 1989 in relation to the ICRCL (1990) "action trigger" and "threshold trigger" values for Pb and Zn in soil. Action trigger values are those above which there is a very high probability of phytotoxic or zootoxic effects which may result in the death of grazing animals if the levels are continuously exceeded (ICRCL,1990). Threshold trigger concentrations are those levels below which metal concentrations will not be expected to give rise to phytotoxic or zootoxic effects.

The results show that for Pb, the 1989 levels recorded in alluvial soils and stream sediments were above the ICRCL "action trigger" in 66% of cases downstream of the mine, with most values being concentrated in the first 3500m downstream of the mine site (figure 4.8). The results indicate continuing severe contamination of alluvial soils and stream sediments by both Pb and Zn sediment related metal ions for at least 3500 m downstream of the Mine site. An improvement in Zn concentrations below the ICRCL (ATV) has occurred due to dilution since 1971, which appears to limit the region of maximum contamination to the Store Blydal braidplain upstream, of the Tunnelelv gorge. Further discussion will be made of the ecological effects of the Zn and Pb contamination in section 4.5.4 below.

A comparison of semi-log exponential models of the downstream dilution of Pb and Zn was carried out to assess both the relative rates of dilution between the two metals as well as to compare the dilution rates in 1971 (10 years after cessation of production) and 1989 (28 years after production ceased). In addition, values for the rate of dilution of Pb and Zn in other temperate stream systems were compared with the values recorded from the Store Blydal. Table 4.2 and figure 4.8 illustrate several key points:

Figure 4.8:

Comparative models of metal concentration decline with increasing distance downstream from the mine site, Mesters Vig, Greenland. ICRCL Action and Threshold values are shown.

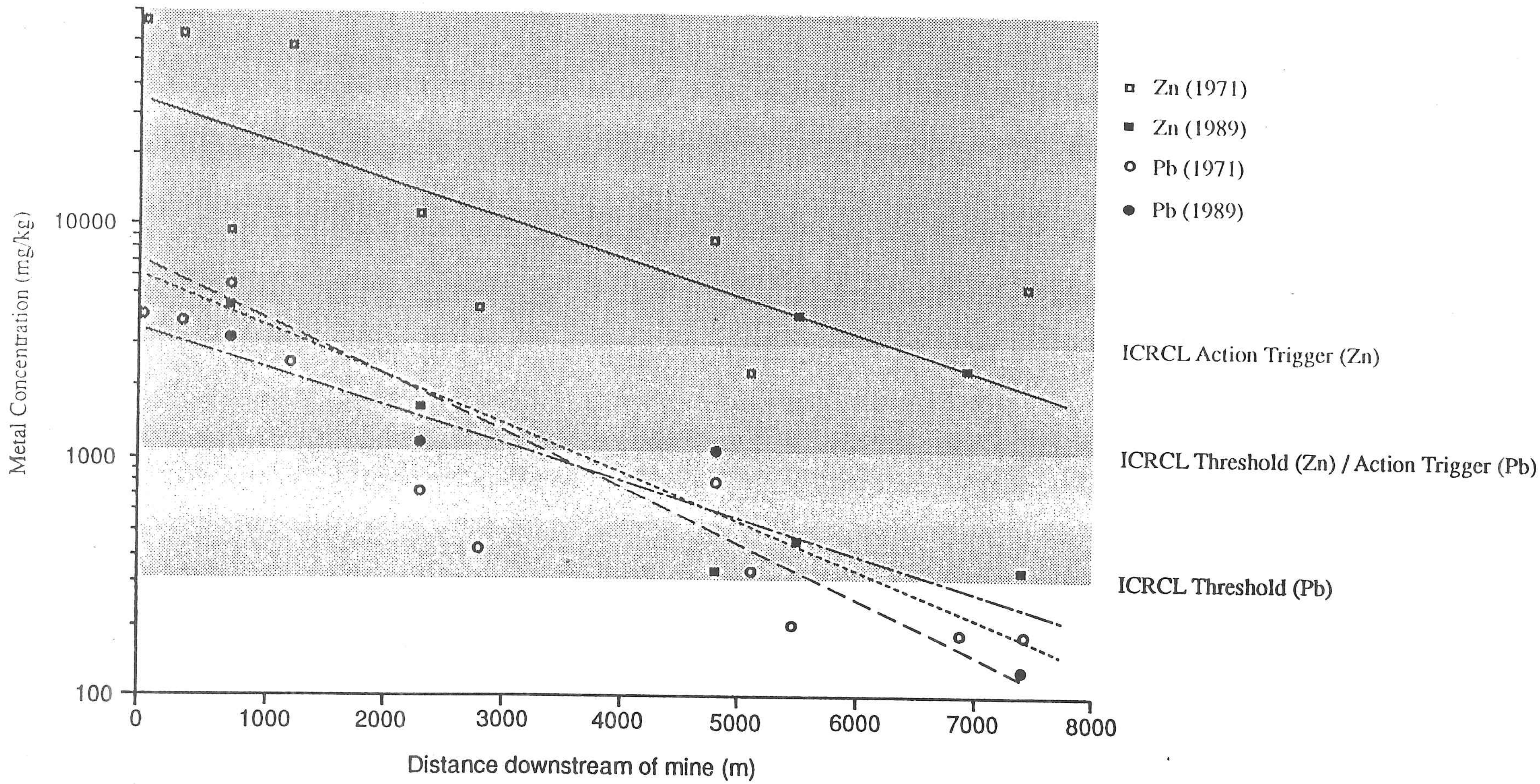


Table 4.2 Comparative models of Pb and Zn metal ion dilution with increasing distance from source.

River	*Pb*	*Zn*
Store Blydal (1971)	$y = e^{-0.37D} \times 3435$	$y = e^{-0.39D} \times 34067$
Store Blydal (1989)	$y = e^{-0.48D} \times 6778$	$y = e^{-0.56D} \times 6608$
Towy	$y = D^{-0.75} \times 2199$	$y = D^{-1.03} \times 1869$
Twywyn	$y = D^{-0.87} \times 8205$	$y = e^{-0.27D} \times 4386$
Ystwyth	$y = e^{-0.04D} \times 1419$	$y = 7.1D + 471$
Rea Brook	$y = e^{-0.13D} \times 3981$	$y = e^{-0.18D} \times 10396$
W.Allen	$y = 100D + 2580$	$y = 14D + 1056$
E.Allen	$y = D^{-0.49} \times 239$	$y = D^{-0.54} \times 147$
Geul		$y = e^{-0.06D} \times 3893$

y = metal ion concentration (mg/kg)
D = distance downstream from source of contamination (m)

1. For Pb. the rate of downstream dilution is more rapid in the Store Blydal than for other temperate river systems in Europe.

2. For Pb the rate of downstream dilution is most rapid in 1989; moreover the levels of Pb in stream sediments are generally higher than for the 1971 survey.

3. For Zn, the rate of downstream dilution is generally more rapid in the Store Blydal than for other temperate river systems in Europe.

4. The rate of downstream dilution of Zn is most rapid in 1989 although the concentrations of Zn are substantially lower than those recorded in the 1971 survey.

5. The rate of downstream dilution of Zn is more rapid than Pb for both surveys in the Store Blydal. This is supported by similar surveys of Pb/Zn downstream dilution in temperate European river systems.

The rapid rates of contaminant dilution are considered to be a function of the relatively high sediment delivery rates of uncontaminated sediments from the alluvial fan systems and tributary streams in the Store Blydal. The active braidplain is in itself indicative of a system conveying high sediment loads (Schumm, 1977) and it is this sediment sufficient system, peculiar to the Store Blydal, which also accounts for the high dilution rates relative to the single channel temperate stream systems documented for Europe. The Tunnelelv gorge is also considered to have a significant effect on increasing the rate of dilution of metal rich mining related sediments. During active sediment transport (mainly during the meltwater season, June-September) uncontaminated sediments and mine waste will be transported over the 50m falls at the head of the Tunnelelv gorge and through the narrow active bed of the river. This process will mix sediments efficiently, with little or no capacity for hydraulic sorting to operate. Consequently, values downstream of the gorge can be expected to be significantly lower than upstream. This is evident in both the 1971 and 1989 surveys. Despite this efficient "sediment mixer" the results for Zn indicate that gross loads of contaminated metals must effect the resulting mixing process, with much greater volumes (or higher concentrations of Zn) of Zn contaminated mine waste entering the Tunnelelv gorge in 1971 than in 1989.

The increase in Pb values in stream sediments in 1989 is explained by preferential storage of the denser and less soluble Pb in the braided system downstream of the mine, together with the re-exposure of Pb mining related sediments as part of the active fluvial processes occurring in the braidplain. However, it is difficult to reason why, if secondary sources are providing locally enhanced Pb levels, that Zn levels are not accentuated also. It should be remembered that there is an inherent error involved in spot sampling fluvial sediments and the lower Pb values recorded in 1971 may be more the result of sampling a transient uncontaminated sediment wave (Hoey, 1992) than a reflection of existing Pb levels at the time. The importance of potential secondary sources of metal contamination will be discussed in the following section.

4.5.4 Lateral patterns of metal contamination in the Store Blydal.

Figures 4.9 to 4.16 illustrate the cross section variation in metal contamination, soil moisture, floral species diversity and the percentage of sediment samples < 2mm diameter. Several studies have identified significant lateral variation in stream deposited metal contamination across floodplains (Leenaers, 1990; Marron, 1989; Lewin & Macklin, 1989). However, the majority of these studies have been conducted in temporal climate, single channel streams, where the lateral dispersal of fine sediments is dominated by overbank deposition during flood events. An exception is the historical studies of Macklin (1986) and Lewin and Macklin (1989) which record terrace sequences for a multichannel environment associated with high sediment loads from mining sources. However, no complementary study exists of metal mining contamination into an already braided system.

Figures 4.11 to 4.15 indicate that the channel network of the Store Blydal consists of two stream systems which maintain parallel courses until Section G. The stream sections from C to G display distinct asymmetry, with the northern stream system occupying a braided course some 4 m above the course of the southern stream system. The effect of this morphology is to concentrate the metal contamination into the northern stream system until by Section G, the majority of the braid plain is contaminated as the two systems combine.

4.5.4.1 Sections A-C

Sections A-C illustrate the distribution of naturally weathered Pb and Zn across the valley floor. Despite the absence of mine derived metals, the distribution is surprisingly variable, reflecting in part, the concentration of fine sediments in bar sequences. This is assumed to reflect concentration of Pb and Zn in fine sediments by a process of chemical sorption/desorption onto the proportionally larger surface areas of the fine sediment particles. Metal levels and the proportion of fine sediments are generally depressed in regions of active channels, and concentrated on bar surfaces and margins. The highest proportion of fine sediment particles are associated with soil development on the braidplain margins and lower valley side slopes. These areas also possess the highest species diversities, reflecting the age and stability of these surfaces. In Section A, colonisation of a bar surface has been facilitated by its height above the active braidplain. Soil has not developed and the dominant pioneering species are *Chamenerion latifolium* and *saxifrage oppositifolia*. In Section B, the confined channel and steep, unstable rocky walls of the valley sides inhibits colonisation by plant species. The valley floor is continually reworked by fluvial processes whilst the unstable valley sides support few niches for soil development and plant growth. In contrast the broad valley floor at Section C, and the narrow braidplain result in a diverse and extensive floral community. Where the channel system is concentrated on the North side of the valley, species diversity reaches $12/m^2$.

4.5.4.2 Section D

Section D runs from the margins of the mine site (samples 1-3) through the mine outwash deposits (4-9) and across the braidplain. The metal contamination is represented by two sources, in samples 2 and 3, the source is wind blown fines and bulldozed mine site waste, whilst in samples 4-9 the source is fluvially dispersed mine tailings. The concentration of metals is clearly higher in the mine tailings than in the bulldozed mine waste and air bourne material, this is likely to be the result of the incorporation of uncontaminated soil and debris within the latter. The stream draining through the mine waste (sample 5) unlike the channels in the rest of the section, is dominated by fine sediments (<2mm), and has a bed of mine tailings with a correspondingly high metal content. Sample 9, the stream nearest to the end of the mine waste outwash splay, is comparatively unaffected by the mine tailings, although metal levels are much higher than in streams further across the braidplain. Dilution is clearly rapid, with material from the mine outwash transmitted downstream, and diluted with uncontaminated material from upstream.

The contamination of alluvial sediments is spatially limited across the section, so that by sample 12, the Pb and Zn values are back to background levels. Stream channels (5) and (9) represent the transport routes for contaminants from the mine, whilst the channels further across the braidplain transfer water from the upper catchment.

The species diversity across the section is strongly affected by burial with mine outwash and by the dynamic and recent nature of the valley floor. The relatively high species diversity found at sample 1 reflects the undisturbed nature of this valley side site. The apparent colonisation of a mine splay terrace by *Chamenerion latifolium* and *Salix artica* (sample 6) in fact represents a thin covering of mine waste over a valley side soil. It is probable that mine waste has smothered other floral communities further up the valley side.

Figure 4.9: SECTION A

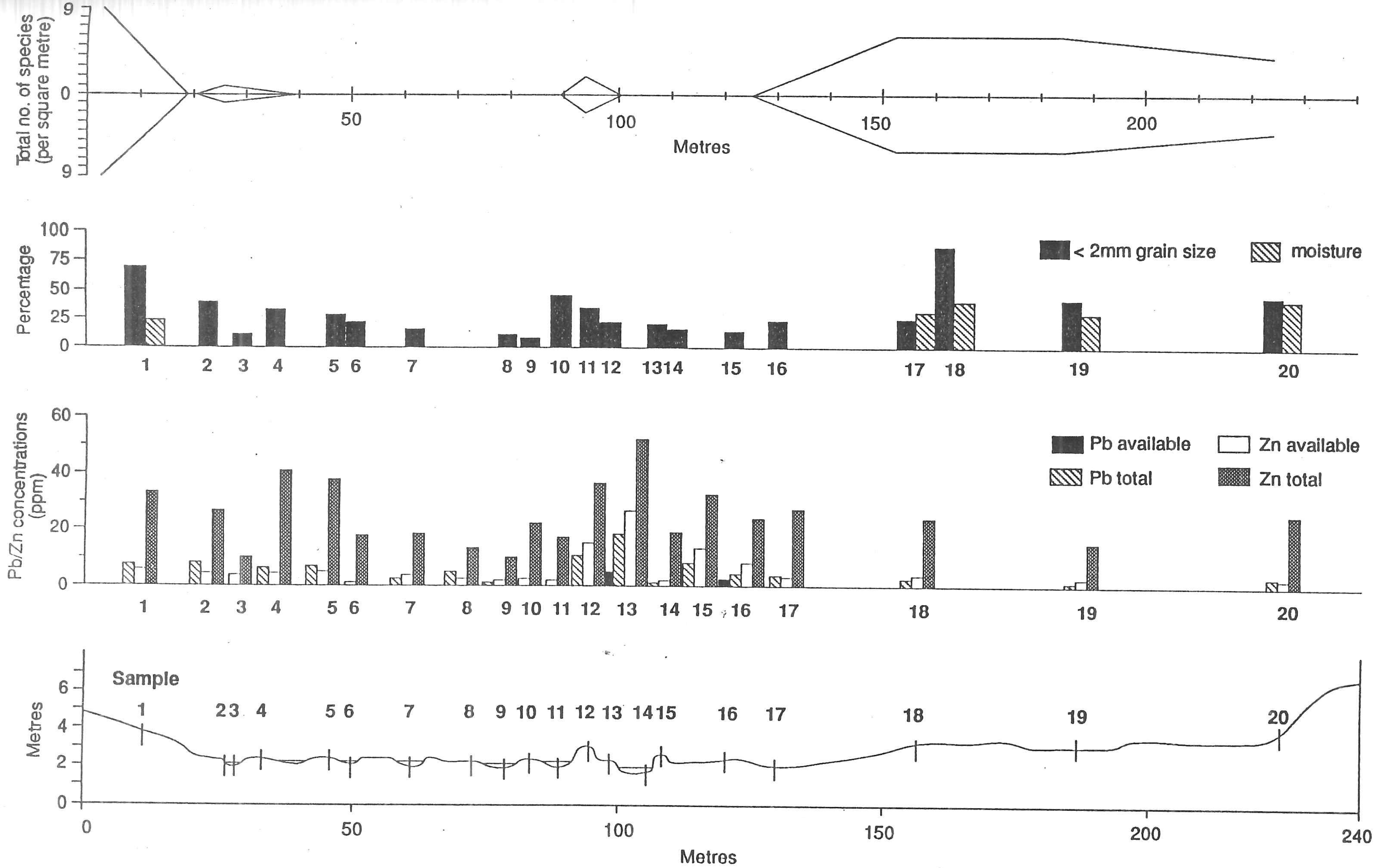


Figure 4.10: SECTION B

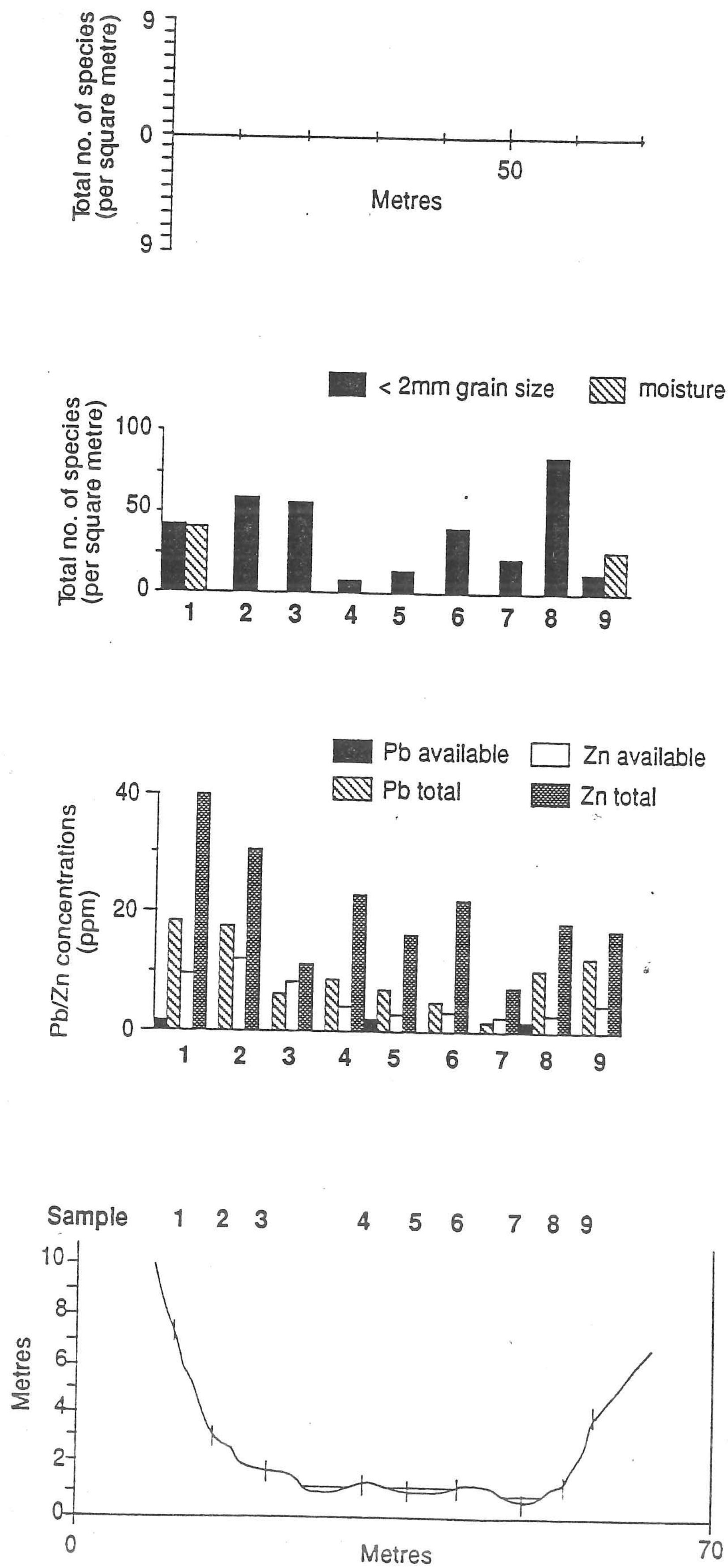


Figure 4.11: SECTION C

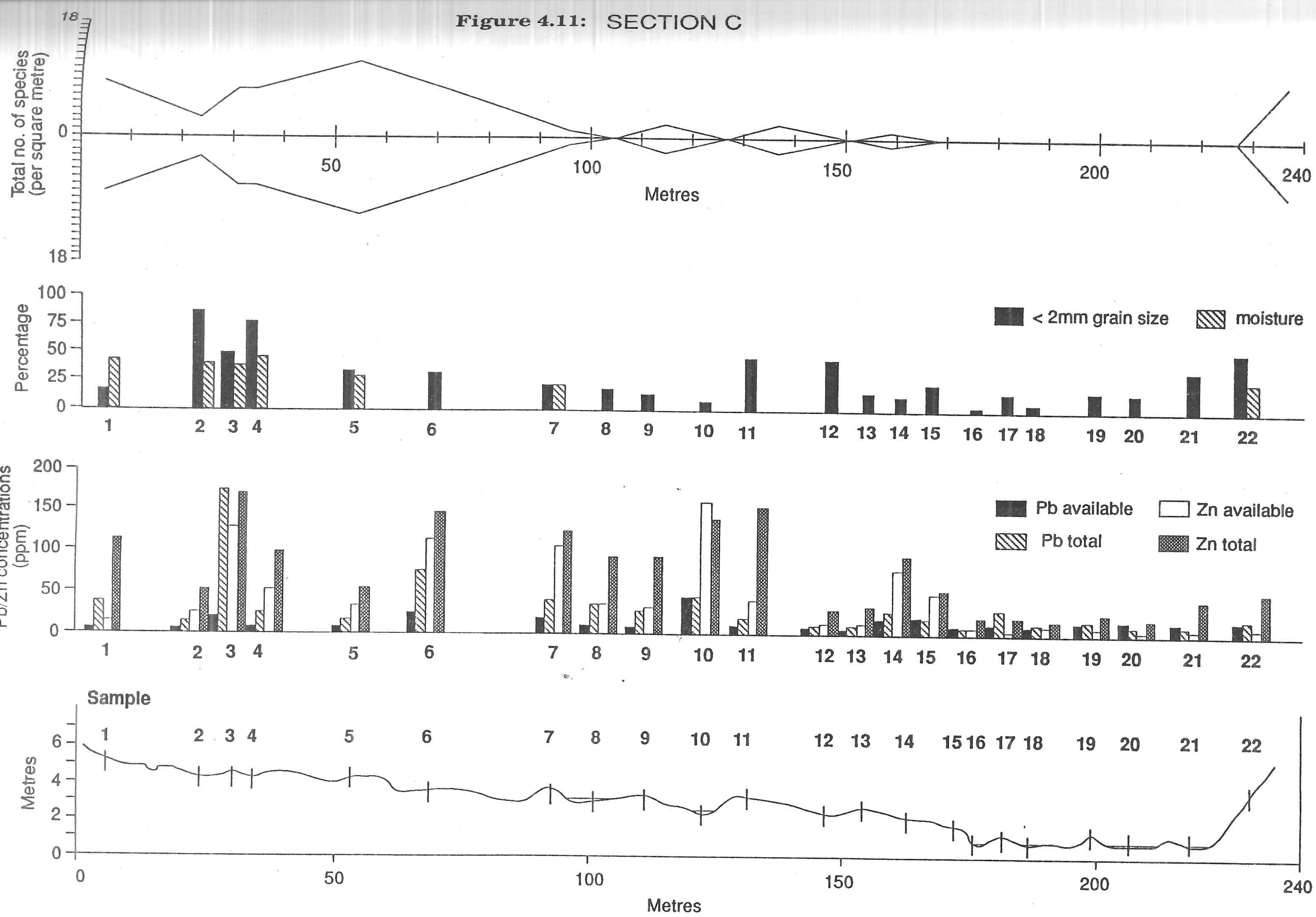
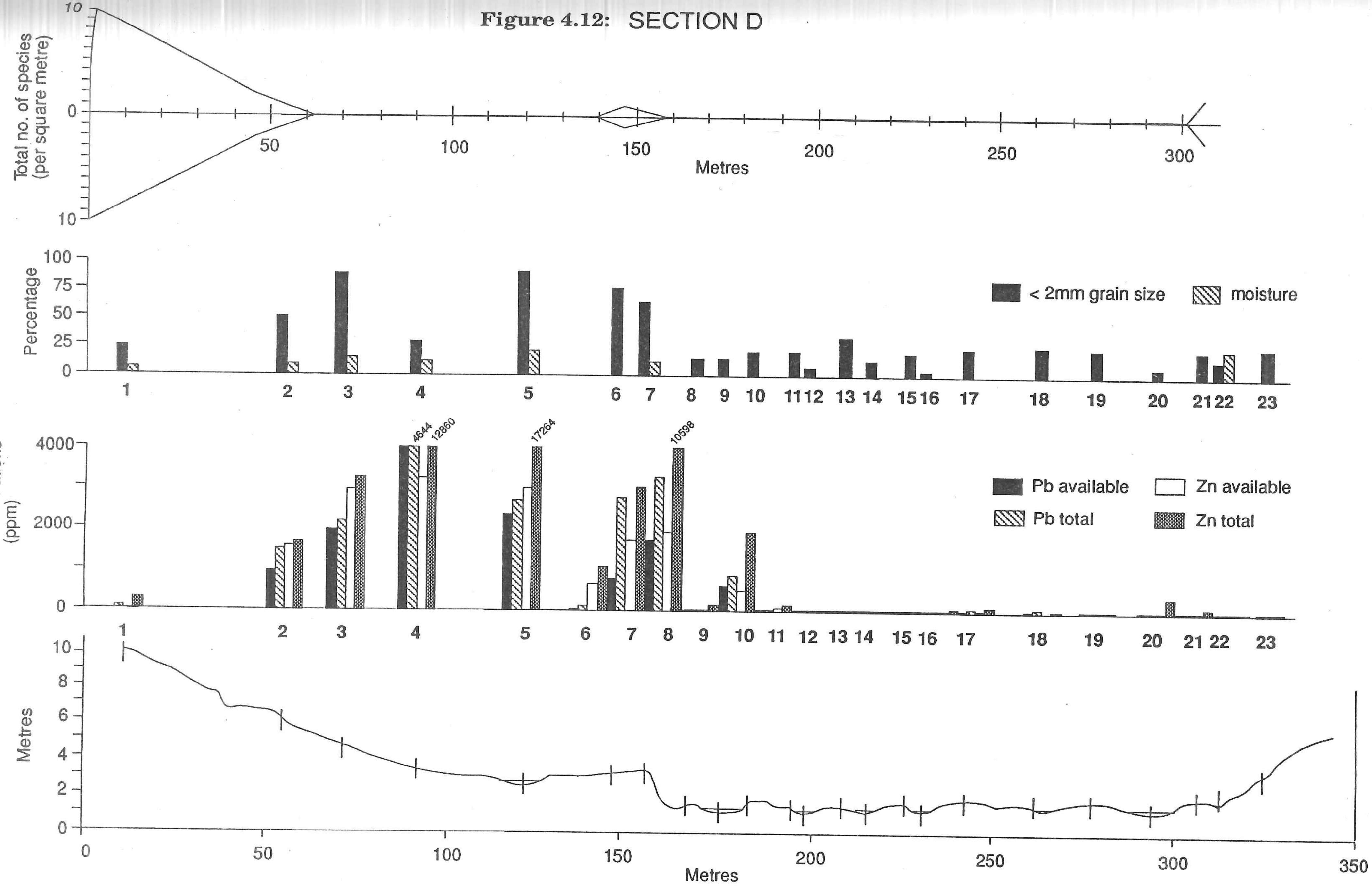


Figure 4.12: SECTION D



4.5.4.3 Section E

The burial of older sediments by mine waste rather than colonisation of mine waste itself is evident in Section E (samples 3 and 4). This section cuts across the mine outwash splay from the relatively undisturbed surface of the valley side (sample 1). The presence of mine waste is identified by the high Pb and Zn values in the surface soil as well as the high percentages of fine (<2mm) sediment in each sample. The majority of the mine waste is in the form of fluvially deposited sediments within the stream channel which drains the mine site. Some 2.7m of mine waste formerly infilled this stream as evidenced by the vertical section shown in figure 4.17. Much of this material has now been eroded following stream incision revealing vertical banks of stratified mine waste. These provide the major secondary source of pollution to the Store Blydal. The sequence of aggradation followed by post-mining incision has been described for streams draining china clay mines in Cornwall (Richards 1982) and in the Northern Pennines following cessation of mining and the incidence of large flood events (Rumsby, 1991). Samples 7-9 are taken from the mine waste splay and exhibit the highest Pb and Zn levels. Samples 10-11 although taken from contaminated ground, represent aeolian deposited mine waste overlying old valley side soils. Correspondingly some species are recorded, growing through the surface mine waste. Interestingly these species are dominated by arboreal taxa (*Salix arctica* and *Betula Sp.*) whilst the grasses and vascular plants evident in other undisturbed valley side soils are not present. A more detailed analysis of the metal concentrations in the vertical exposure are presented in section 4.5.5 below.

4.5.4.4 Section F

Section F is dominated by active and inactive braidplains. The inactive bars and channels are in several cases sufficiently old and removed from contemporary fluvial processes to have well developed floral communities (samples 5, 12 and 14). Lead and zinc levels on these old surfaces approximate to background levels observed for fluvial features upstream of the mine site and so clearly pre-date the mining operations. Dissecting these old bar and channel features are the active channel systems of the Store Blydal. These are clearly contaminated with mine waste, with high levels of Pb in particular associated with the northern valley side stream channels (samples 4, 11,13,15 and 19). Relatively uncontaminated stream channels are still found on the southern valley side (samples 21, 24 and 25) and though mine waste has entered these channels and locally elevates the Pb and Zn levels above background. The percentage of fine sediments no longer provides evidence of mine waste in the fluvial deposits, but is incorporated within a coarse framework of cobbles and pebbles. Moreover, there is a preferential concentration of Pb over Zn within the fluvial sediments in Section F which contrasts the uncontaminated sections (A-C) as well as the relatively undisturbed mine waste in Sections E and D. This is presumed to reflect the relative mobility of zinc over lead within fluvial systems and which has been reported above.

4.5.4.5 Section G

Section G is unique in possessing a suite of palaeobars and channels on the southern side (samples 16-20). The active braidplain narrows through this section of the valley, confined by a steep northern bluff and the palaeobraidplain on the southern side. Metal contamination is widespread throughout the active channels and recent bar surfaces though the levels are significantly reduced from Section F. In a distance of only 400m the levels of Pb and Zn in the stream channels has dropped from +1000 mg/kg to <700 mg/kg. A similar reduction has occurred on the bar sediments confirming that there is a general dilution of contaminated sediments.

Figure 4.13: SECTION E

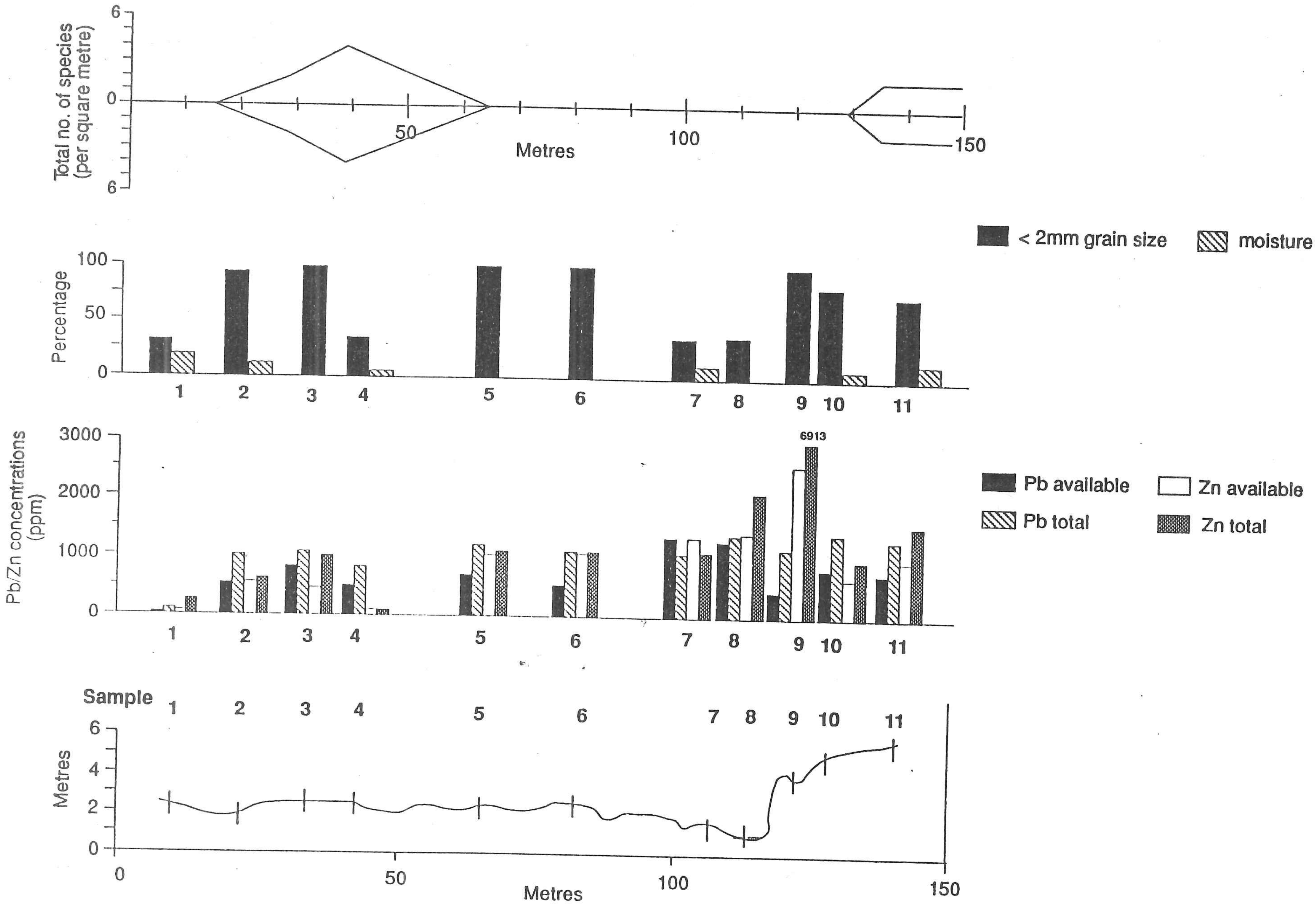


Figure 4.14: SECTION F

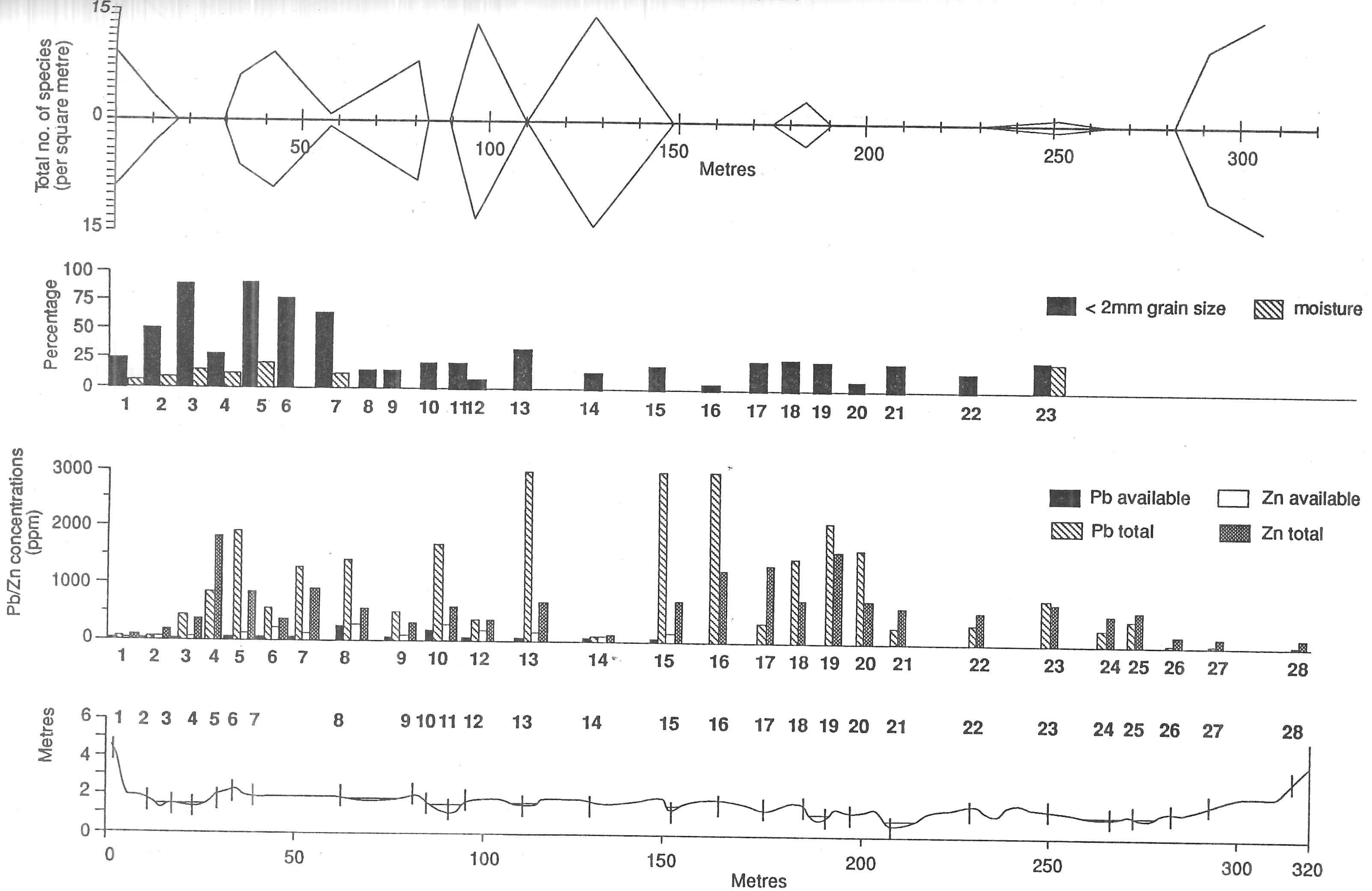


Figure 4.15: SECTION G

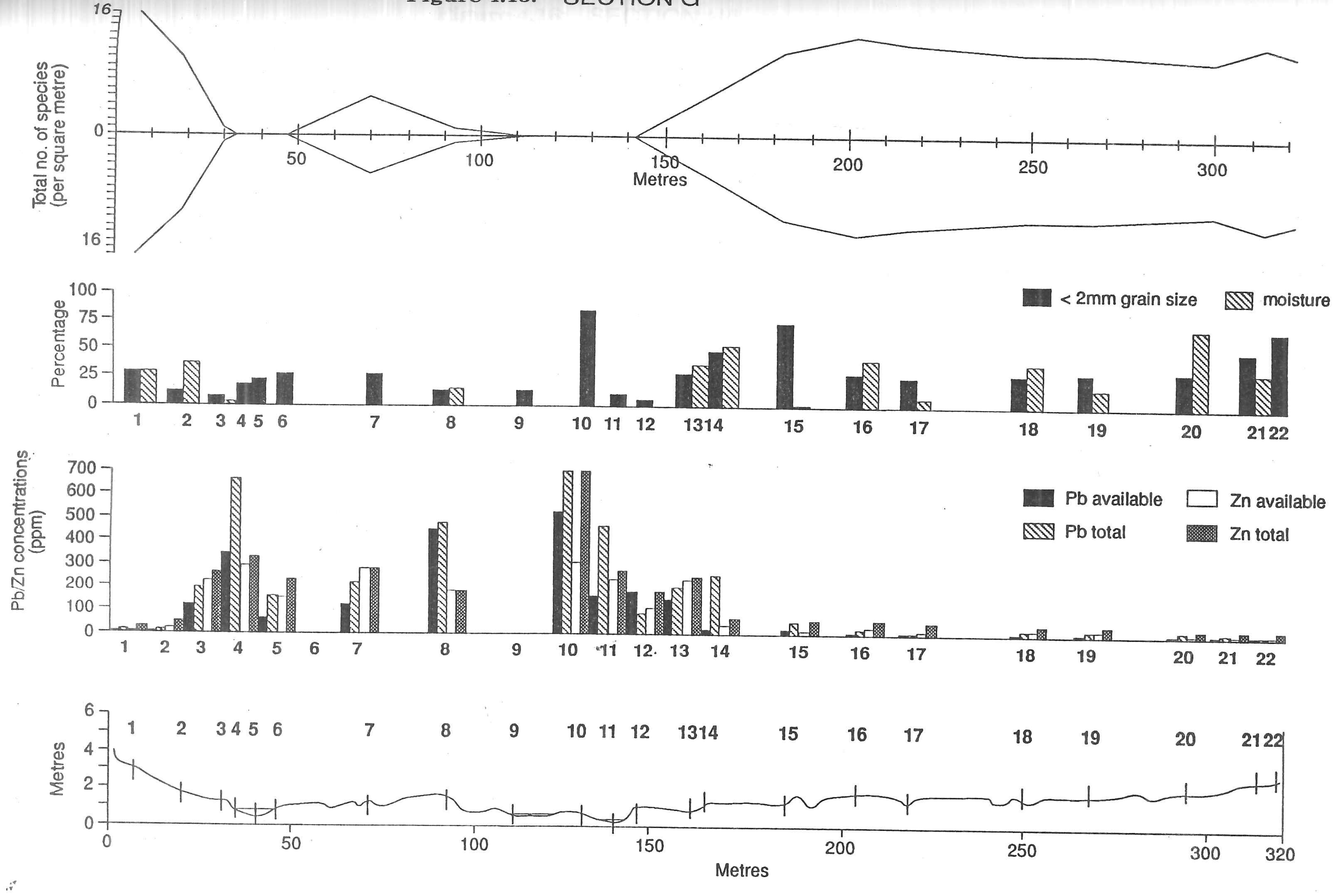
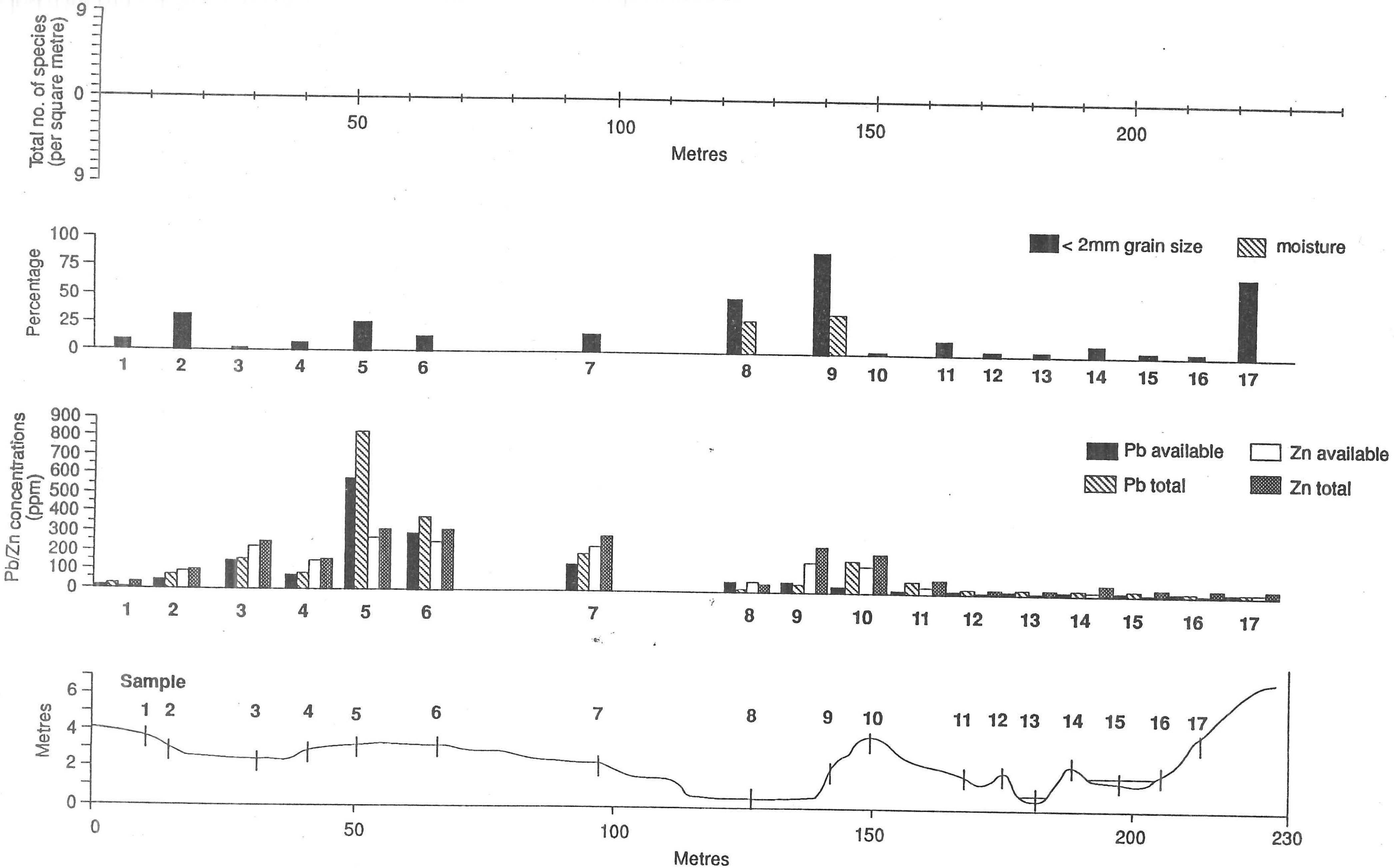


Figure 4.16: SECTION H/I



The metal levels on the palaeobars/channels fall below 100mg/kg which corresponds to the background levels recorded in Sections A-C. Floral communities are relatively rich with up to 12 species per square metre. in contrast, more recent bar surfaces (samples 7 and 8) record 5 and 2 species of plant per square metre respectively.

The age of the palaeobraidplain is difficult to determine without lichenometric or even radiocarbon dating. Samples of the largest boles of living willow (Salix arctica) were taken for dendrochronological dating. Five sections were cut and the annual growth rings counted. The age variation was only 4 years with a maximum age of 35 years (bole diameter 12 mm), giving a colonisation date of 1954. however, it is evident from the aerial photographs that these palaeobar surfaces were vegetated in 1949 and the high species diversity suggests a longer period of colonisation still. Assuming that the largest living willow (also the largest willow dead or alive) was sampled suggests that colonisation of deactivated fluvial bar surfaces by willow occurs significantly later on in the floral succession. More work is required to confirm this and so establish an exact date for the palaeobraidplain.

4.5.4.6 Sections H and I

Section H and I are located on the Tunnelelv and Rungstedelv confluence. Samples 10-17 cut across the Rungstedelv which drains the Rungstedgletsher on the northern face of the Korsbjerg massif. Levels of Pb and Zn are < 100 mg/kg in contrast to the Tunnelelv where locally levels reach 830Mg/Kg (Pb). Considerable mixing of fluvial sediments has occurred in the Tunnelelv gorge, however there is a distinct lateral variation in Pb and Zn levels across the Tunnelelv at Section I. Levels of Pb and Zn are highest on the bar surfaces and lowest in the active channels and channel margins. The presence of accentuated metal levels on the surface of the 4m high terrace remnant (sample 10) suggests considerable incision during the post-mining period. The incision is independent of the mining phase since similar incision is present in the bed of the Rungstedelv. This would infer a climatically driven phase of downcutting, possibly in response to a series of or one exceptionally large flood. The relative activity of this section of confined channel clearly does not allow colonisation of plant species.

4.5.5 Vertical distribution of metal contamination

The preceding sections described the longitudinal and lateral distribution of Pb and Zn contaminants within the Store Blydal river system. Considerable variation is experienced in both dimensions according to the rate of dilution and the morphology of the braidplain. However, this data refers only to the surface sediments as they were sampled in 1989. Consideration of the vertical differentiation is required to elucidate the relative magnitude of surface metal levels and to investigate the possibility that contaminated sediments lie buried within the barforms of the contemporary channel.

Figure 4.17 illustrates the vertical section through the mine waste outwash splay cut by Section E. The stratigraphy revealed in this section provides evidence for a highly variable supply of Pb and Zn to the Tunnelelv system during and after mining. For the purposes of this survey it is assumed that the deposition of fine mining related sediments began when production started at the mine. The tailings were generated as part of the separation/enrichment process for producing the Pb/Zn concentrate. Correspondingly, the particle size is dominated by sands and silt/clays. The stratigraphy of the section reveals some 2.6m of mine tailings overlying fluvial gravels, corresponding to the current level of the streambed (see Section E above). Above this layer, lies a thin organic band containing the roots of *Salix artica*. This suggests that the fluvial gravels represent a relic bar feature that prior to mining, was vegetated, much in the same way as the palaeobars in Section G. Considerably greater quantities of fine sediments and water were released down this stream during the mining operations in order for the bar to have been inundated. The sediment loads were also very high and deposition must have been immediate since there is no evidence of erosion of the bar surface.

The stratigraphy of the section reveals a pattern of alternating layers of sands and silt/clays of variable thickness. The boundary between each layer is clearly defined with no merging, indicating a sharp transition in sediment source and depositionary conditions. The sequence of sands and silt/clays is hypothesised to represent annual sediment yields, such that the coarser sand layer represents snowmelt and mining production whilst the silt/clay bands represent post production separation tank washings. Thus a single year is represented by a coarse layer and then a fine layer of sediments. Figure 4.18 depicts the Pb and Zn totals for each sequence. Problems in defining the layers were encountered at -0.74m from the surface due to the presence of permafrost and cryoturbation of the sediments. Nevertheless the resolution of individual layers is taken to be as accurate as possible under the field and equipment conditions available.

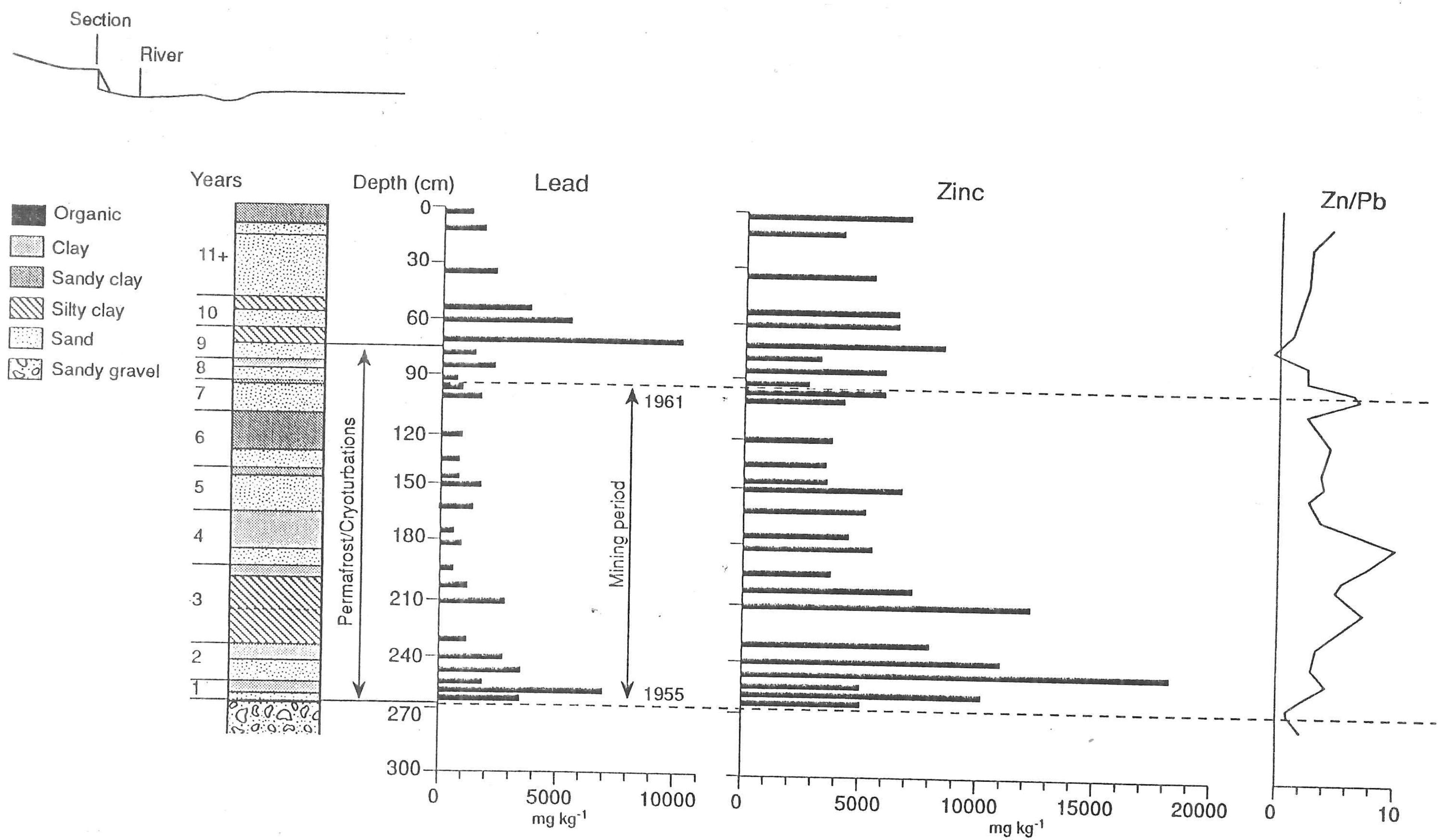
There is considerable vertical variation in Pb and Zn levels within the section. Lead totals peak at the bottom of the section and at the interface with the permafrost layer. Zinc also tends to increase in concentration down the profile, with again some evidence for enhanced values at the junction of permafrost and unfrozen sediments. It is possible that this represents some vertical mobility of metal ions in solution down the section, with concentrations occurring where further percolation is retarded by the permafrost. This hypothesis is not supported by the vertical sections recorded through barforms at other sections, neither by the lack of enhanced metal levels within the relic organic and fluvial gravels at the section base.

The lower levels of mine tailings date from c.1955 when ore concentrates were first produced. Levels of Zn are particularly enhanced with values reaching 18200 mg/kg. The preservation of these extremely high values in the lowest levels of the section illustrate the potential importance of secondary pollutant sources to the Store Blydal even though mining production has ceased. However, the presence of permafrost at this depth effectively regulates the quantity of contaminated sediment released from the lower layers into the stream system.

Figure 4.17: Vertical section through mine waste

Figure 4.18:

Section E Through mine derived tailings outwash
Store Blydal, Blyklippen Mine, Mesters Vig, Greenland August 1989



The stratigraphic record of metal contamination has been used in recent studies to date the sequences of overbank sediment deposition (Lewin and Macklin, 1987; Rumsby, 1991, Macklin et al., 1992). This has been facilitated by a knowledge of the annual outputs of Pb and Zn from the headwaters of the river catchment and by the assumption that peaks in the metal levels of the sedimentary record correspond to peaks in the mining output record. In an overbank alluvial sequence this stratigraphic cross-referencing is dependant upon the coexistence of mining production with flooding of sufficient capacity to inundate the valley floor, followed by channel incision to preserve the alluvial deposits (Macklin et al., 1992).

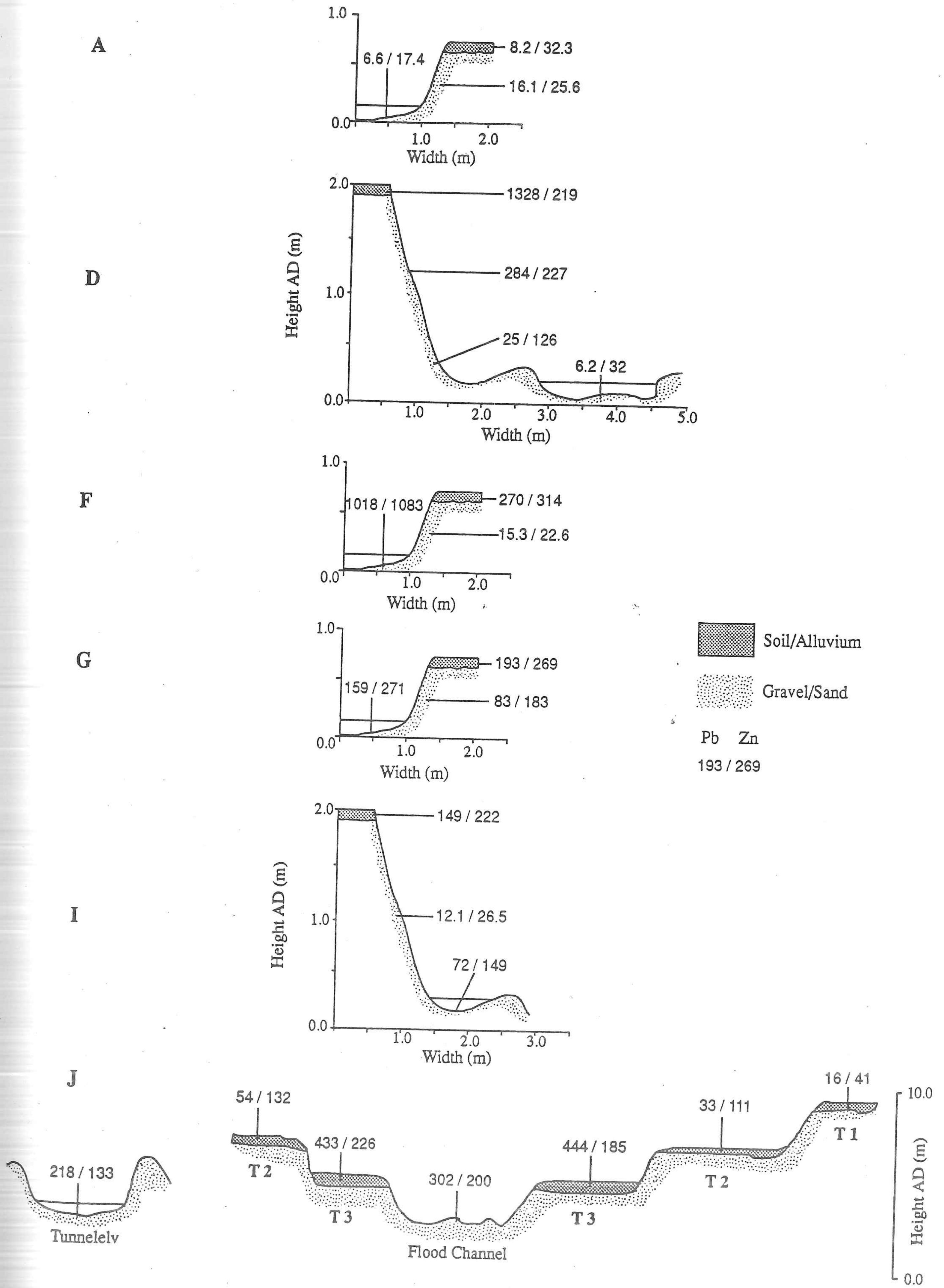
For the mine stream at Blyklippen, the deposition occurred in channel over a relatively short time period (assumed to be coincident with mining 1955-1961) followed by incision after the sediment supply was exhausted. Despite preservation, figure 4.18 shows that cross-referencing metal levels with mining output expressed as Zn/Pb ratios does not work in this instance. Some evidence for a relationship between Zn levels in the sediments and total Zn concentrate production exists, but this is not matched by Pb levels (figure 4.19). This probably results from a number of factors including vertical mobility of Pb and Zn (although the evidence for this is not conclusive; see above), cryoturbation involving up-section mixing of sediments (although stratigraphic evidence does not apparently support this) too coarse a sampling interval and the reality that the metal levels in the sediments reflect the efficiency of the separation process rather than total Pb/Zn production.

Analysis of the stratigraphic record reveals consistent grain size reversals that have been tentatively attributed to annual sediment production. On this basis the sediments were laid down over a period of 10-11 years, 1955-1965/6 (figure 18), after which sediment supply to the surface of the deposit was arrested by incision into the streambed. This assumption would place the active metal mining phase in the bottom 1.65m of the deposit which gives a sedimentation rate of 0.23m/yr, followed by a further four years of sedimentation at a rate of 0.15m/yr. These represent extreme sedimentation rates which reflect the volume of sediment released to the Store Blydal during and immediately after mining production. The incision of the stream into the mine tailings has produced a serious secondary pollutant source that can clearly be traced within the active channels of the Store Blydal downstream of the mine.

4.5.6 Vertical variation in metal levels within braidplain sediments.

Figure 4.19 documents the vertical variation in metal levels within barforms in the cross-sections sampled, including a traverse across terraced deposits in the outwash delta (Section J). In general the highest metal levels are associated with surface sediments. Finer resolution may reveal a layer of high Pb/Zn levels below the surface but there is little evidence to support an extensive vertical contamination of bar sediments. An exception to this is the bar sampled at Section D, where above background levels of Pb and Zn are found 0.75m below the surface. This may be the result of leaching, since the bar exhibits a buried soil immediately below the characteristic light grey veneer of mine waste.

Figure 4.19: The vertical distribution of Lead and Zinc within active bar sediments and delta terraces.



Section F and Section G illustrate that much of the mine waste is stored within the active channels and bar surfaces. From this it is supposed that much of the spatial contamination occurs during overbank fine sediment deposition and aerial transport of mine waste onto a pre-mining template of fluvial features. This scenario requires much of the current braidplain morphology to date from pre-1955, an observation supported by the colonisation of stable bar surfaces by vegetation. This model also suggests that the current system is undergoing incision across most of the stream network, a fact supported by the presence of accentuated metal levels on the surface of the Bar at Section I, some 3.1m above the present channel.

Evidence for a post-glacial history of incision within the Store Blydal is evident in the Terrace sequences identified in Section J. Three terraces are identified with the highest (T1) probably associated with marine deposition during a period of higher sea level immediately preceding the last glaciation. Metal levels decrease with terrace age, such that T3, immediately bordering recently active channels possess metal levels above background which are attributed to mining at Mesters Vig. Terrace 3 now lies some 1.7m above the bed of the Tunnelelv and active distributary channels. The Tunnelelv has been diverted and channelised to protect the airstrip and roads up the valley. Consequently the bulk of the Store Blydal water and sediments now run into Noret through a confined channel, rather than diluting the metal contaminated load over the distributary system. The effect of this channelisation is marked in the metal levels in the two delta branches. Metal levels in river sediments taken from the Tunnelelv where it discharges into Noret are 173 mg/kg (Pb) and 172 mg/kg (Zn) compared to levels of 33 mg/kg (Pb) and 115 mg/kg (Zn) for river sediments at the mouth of the northern delta branch.

4.5.7 Morphological distribution of Lead and Zinc enriched sediments.

The results of the sampling programme were analysed for association between morphological grouping and metal levels. This was undertaken to isolate the components of the arctic fluvial system that stored and transmitted mine waste. Eight morphological groupings were identified, and the values for each group per cross-section were averaged. The results are depicted in figure 4.20. As expected there is little morphological differentiation of metal levels above the mine associated with Sections A-C. Average values all fall below 50mg/kg. Section E, which is dominated by mine waste exhibits enhanced metal levels associated with the mine waste splay, vegetated alluvium and in active bars within the channel. The presence of accentuated metal levels within the vegetated alluvium reflects partial burial of vegetated ground by mine waste. The low levels of metals recorded in the active stream channel result from the recent flushing of the stream by snowmelt and the concentration of metals in sand bars.

Section D reveals a similar pattern to Section E, with most of the mine waste stored in active bars in the channel and as partially buried vegetated alluvium. The low values for active channels reflects the localised nature of the metal contamination in relation to the total cross section sampled. Sections F and G illustrate how the mine waste is preferentially stored in active channels and active bars though with some surface contamination of inactive bars and vegetated alluvium. Vegetated colluvium and palaeobars/channels are all associated with low metal levels.

Section H across the Rungstedelv, displays enhanced metal levels in association with the 3m inactive bar adjoining the Tunnelelv. Section I, in contrast to Section F and G displays accentuated metal levels in active bar sediments, with low values recorded for active channels and inactive bars.

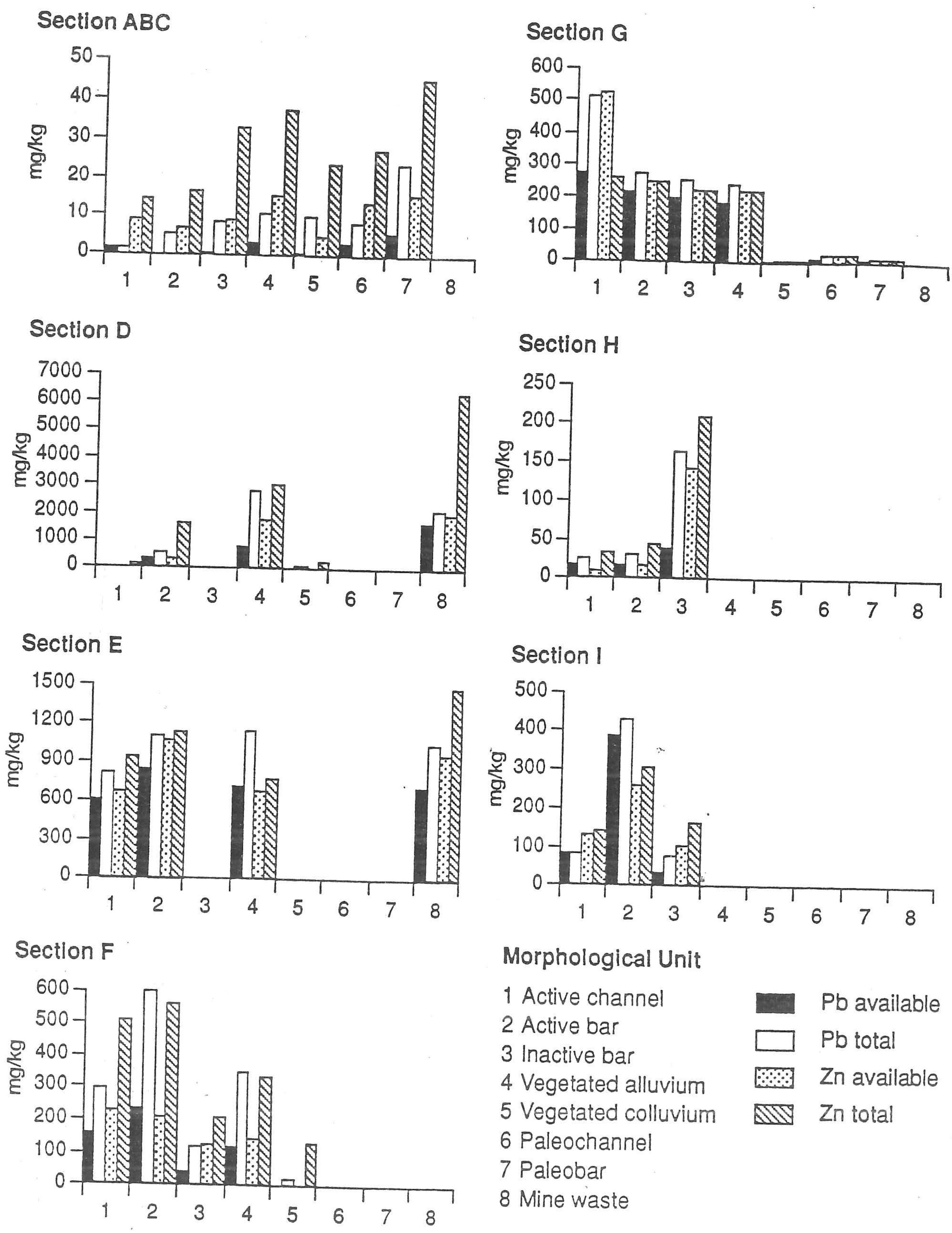


Figure 4.20: Metal concentrations associated with geomorphological units.

Figure 4.21 illustrates the morphological distribution of metals by grain size for Section F. In general, Pb and Zn totals are concentrated in the fine sand/silt and clay fractions of active channels and bars, whilst operationally determined available Pb and Zn are concentrated in the fine sand fraction of active channels and bars. Metal concentrations, particularly Zn tend to be more evenly distributed within the coarse sand fraction for different fluvial units. This latter point, together with the preferential concentration of metals within fine sediments in active channel areas suggests that much of the contaminated material is derived from reworked mine waste rather than reworked bar sediments, the former being a concentrated source of fine sand/silt and clay. This was visually confirmed by the white/grey colour of much of the fine sediments within the active channels and bars of the Store Blydal downstream of the mine.

4.6 Metal mining sediment dispersal and levels of contamination in the Store Blydal/Tunnelelv river system

4.6.1 Metal concentrations and the arctic ecology

The results of the analysis discussed above indicate that substantial contamination of the active braidplain and delta system of the Store Blydal/Tunnelelv river has occurred during and after the mining. The initial impact caused aggradation of separation tank tailings in the stream channel draining the mine, and a phase of contamination of channel and bar surfaces within the braidplain. Immediately after sediment supply ceased from the mine, the channel incised into the tailings, releasing substantial quantities to the river system downstream. Much of this sediment is currently stored as a veneer on bar surfaces and within the active channel. However, there is no evidence to suggest that any major morphological change was associated with the passage of mine waste through the braided river system. Rather, the braidplain morphology controls the movement of fine contaminated sediments. This is illustrated by the juxtaposition of contaminated and uncontaminated active channels within the Store Blydal valley until Section G, where the two systems combine.

The incision of the mine tailings has presented a significant and insidious source of secondary metal pollution. Continual collapse of the mine tailings into the mine stream, though regulated by the presence of permafrost, continues to supply highly contaminated fine sediment to the Store Blydal. The pattern of contamination is currently dominated by the transfer of fine sediment through the active channel network, with temporary storage along channel margins and on active bar surfaces. Mixing of the metal contaminated sediments with uncontaminated sediment occurs downstream of Section G, and within the Tunnelelv gorge. Metal levels are substantially reduced, though they remain above background levels up to the point of discharge into Noret.

The significance of metal levels on the floral and faunal communities of the Store Blydal valley cannot as yet be determined. Certainly the burial of plant communities by highly contaminated mine waste has eradicated all but some of the *Salix artica* from some sites, but little further conclusive evidence of an ecological impact can be established. However, the potential for ecological damage can be assessed according to the ICRCL threshold trigger and active trigger values for Pb and Zn contamination. The effect of metal contamination on livestock is dependant on the amount of soil ingested; this in turn depends on the percentage coverage of sward. The vegetation data collected during the expedition indicates that on vegetated and contaminated soils, the percentage of exposed soil averages 67%, which indicates that there is a high probability of soil ingestion should grazing occur.

Figure 4.21 illustrates the morphological distribution of metals by grain size for Section F. In general, Pb and Zn totals are concentrated in the fine sand/silt and clay fractions of active channels and bars, whilst operationally determined available Pb and Zn are concentrated in the fine sand fraction of active channels and bars. Metal concentrations, particularly Zn tend to be more evenly distributed within the coarse sand fraction for different fluvial units. This latter point, together with the preferential concentration of metals within fine sediments in active channel areas suggests that much of the contaminated material is derived from reworked mine waste rather than reworked bar sediments, the former being a concentrated source of fine sand/silt and clay. This was visually confirmed by the white/grey colour of much of the fine sediments within the active channels and bars of the Store Blydal downstream of the mine.

4.6 Metal mining sediment dispersal and levels of contamination in the Store Blydal/Tunnelelv river system

4.6.1 Metal concentrations and the arctic ecology

The results of the analysis discussed above indicate that substantial contamination of the active braidplain and delta system of the Store Blydal/Tunnelelv river has occurred during and after the mining. The initial impact caused aggradation of separation tank tailings in the stream channel draining the mine, and a phase of contamination of channel and bar surfaces within the braidplain. Immediately after sediment supply ceased from the mine, the channel incised into the tailings, releasing substantial quantities to the river system downstream. Much of this sediment is currently stored as a veneer on bar surfaces and within the active channel. However, there is no evidence to suggest that any major morphological change was associated with the passage of mine waste through the braided river system. Rather, the braidplain morphology controls the movement of fine contaminated sediments. This is illustrated by the juxtaposition of contaminated and uncontaminated active channels within the Store Blydal valley until Section G, where the two systems combine.

The incision of the mine tailings has presented a significant and insidious source of secondary metal pollution. Continual collapse of the mine tailings into the mine stream, though regulated by the presence of permafrost, continues to supply highly contaminated fine sediment to the Store Blydal. The pattern of contamination is currently dominated by the transfer of fine sediment through the active channel network, with temporary storage along channel margins and on active bar surfaces. Mixing of the metal contaminated sediments with uncontaminated sediment occurs downstream of Section G, and within the Tunnelelv gorge. Metal levels are substantially reduced, though they remain above background levels up to the point of discharge into Noret.

The significance of metal levels on the floral and faunal communities of the Store Blydal valley cannot as yet be determined. Certainly the burial of plant communities by highly contaminated mine waste has eradicated all but some of the *Salix artica* from some sites, but little further conclusive evidence of an ecological impact can be established. However, the potential for ecological damage can be assessed according to the ICRCL threshold trigger and active trigger values for Pb and Zn contamination. The effect of metal contamination on livestock is dependant on the amount of soil ingested; this in turn depends on the percentage coverage of sward. The vegetation data collected during the expedition indicates that on vegetated and contaminated soils, the percentage of exposed soil averages 67%, which indicates that there is a high probability of soil ingestion should grazing occur.

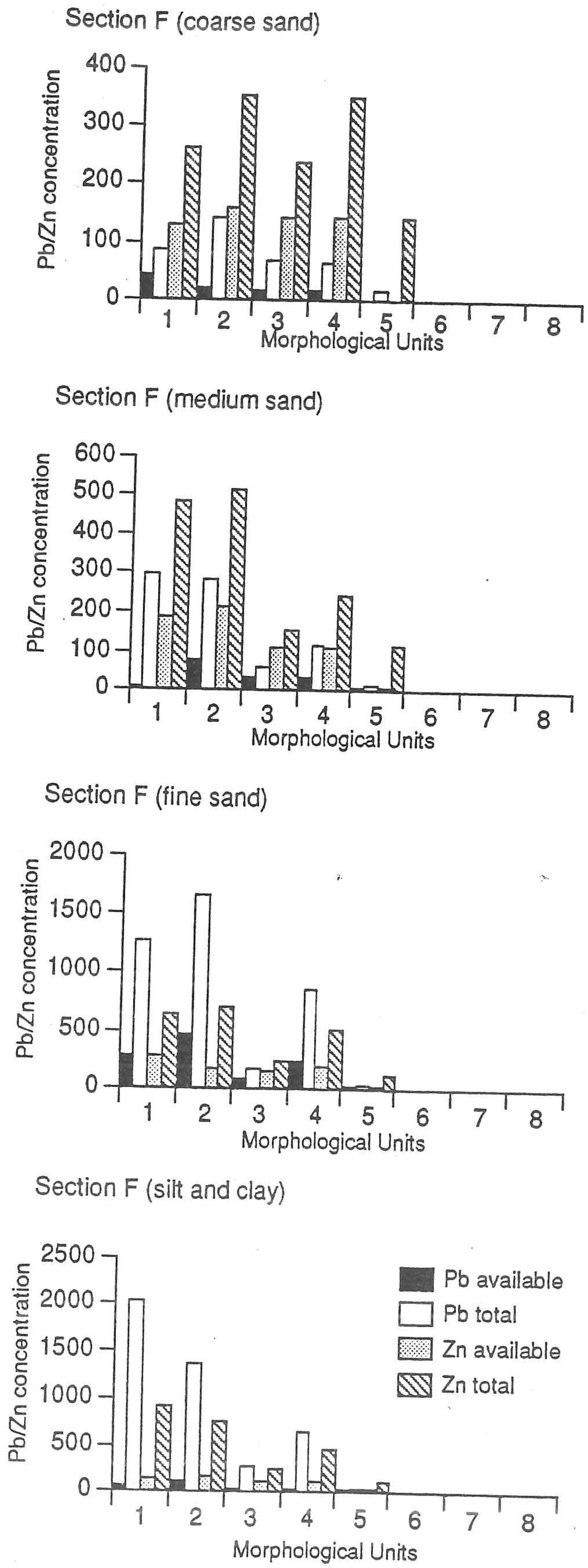


Figure 4.21: Metal concentrations in different grainsizes associated with geomorphological units. Section F

Table 4.3 records the percentage of samples per cross section that fall above or below the ICRCL values for threshold trigger and active concentrations of Pb and Zn.

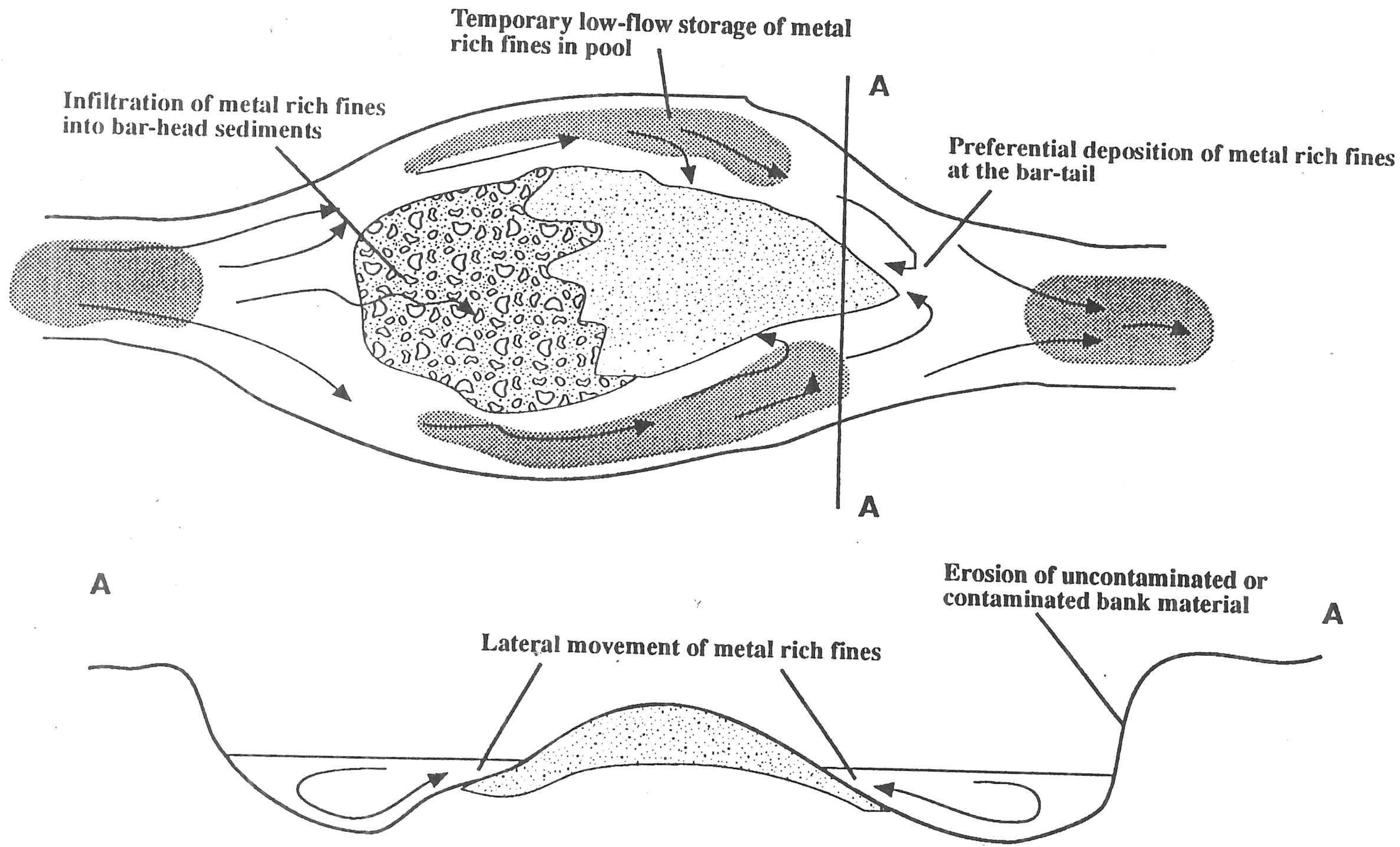
Table 4.3 The percentage of samples per section that exceed ICRCL Threshold and Action trigger values.

Sect	%>ICRCL Threshold	Pb%>ICRCL Action	Pb%>ICRCL Threshold	Zn%>ICRCL Action
ABC	0	0	0	0
D	30	26	35	22
E	91	73	55	9
F	68	36	36	11
G	14	5	5	0
H	0	0	0	0
I	22	0	0	0

Clearly there is potential for phytotoxic and zootoxic effects in up to 73% of samples taken across the mine outwash sediments with dilution taking this level down to 5% by Section G. Downstream of Section G, there are no samples that exceed ICRCL action trigger values for Pb or Zn, although 22% of samples in Section I exceed threshold trigger values for Pb. Although metal levels are generally below ICRCL metal values in the lower Tunnelelv system, this is not the area where vegetation is abundant. Potentially contaminated sources of vegetation are localised to areas around the mine waste splay and on some vegetated inactive bars. Observations of rutting Musk Ox on the mine splay surface, and on the braidplain margins suggests that ingestion of contaminated soil is possible although spatially limited. Other species that may be affected by the high metal levels are Lemmings (both through feeding and through excavation of burrows into contaminated soil) Ptarmigan and Arctic Hare. In turn these species are predated by Snowy Owls, Gyr Falcons and Arctic Foxes. More research is required to confirm or reject the uptake of Pb and Zn into the arctic food chains.

The future behaviour of the contaminated channels and bars within the Tunnelelv is of concern since the evidence suggests that incision into the braidplain has occurred and is occurring at present. Incision leads to abandoned areas of contaminated soil, which in some instances has already been colonised by *Chamenerion latifolium*. Consequently, there exists the potential for the development of highly contaminated areas of vegetated sward (assuming that phytotoxicity does not preclude colonisation) or if phytotoxic effects are revealed, then subtle alterations in the ecological succession of these regions may be observed (see Macklin and Smith, 1989) or even adaptive strategies adopted by plant species in response to the elevated metal levels.

Figure 4.22: Sedimentation processes associated with braid bar morphology that illustrate how metal rich fines are concentrated in pool, bar-tail and as infiltrated matrix fines.



It is clear that the development of metal contamination in Arctic river systems is dependant upon the activity of fluvial processes and their vertical direction; incision leading to preservation of and colonisation of abandoned contaminated bars and channels, or aggradation, leading to burial and/or dilution of contaminated sediments. In the short term, aggradation of the river system post-contamination leads to a deflected impact. but one which is potentially problematic in the long term following incision into the contaminated sediments. However, there is greater potential for sediment dilution. Incision effectively freezes the processes of fluvial dispersion, and allows relatively rapid access of metals into the food chain via the development of floral communities.

4.6.2 Evidence of fluvial dispersion processes for fine sediments.

Fluvial dispersion processes in braided river systems are strongly controlled by the bar morphology of the braidplain. This in itself indicates that much of the barforms are stable features, forming a morphological template around which fine sediments are transported. Investigations into the sorting processes in braided rivers (Ferguson and Ashworth, 1992; Ashmore, 1982) suggests that for fine sediments, preferential deposition (and therefore enhanced metal levels) occurs at the bar-tail where secondary flow cells in the channels initiate a transverse motion of sediment towards the bar form (figure 4.22). The surfaces of barforms are afforded relative stability by the development of bed structure during shallow high velocity flows over the gravel surface and by infiltration of fines into the gravel interstices (Sear, 1992a; Frostick et al., 1984).

Within the channel system, field evidence indicated that riffle-pool morphology is important for the short term storage of metalliferous fines within pools and particularly pool-tails (see Sear, 1992b). During high flow conditions the fines are routed from pool to pool, with lateral storage at the channel margins in association with slackwater areas or secondary flow patterns. Storage within the gravel-bed will also occur as a result of infiltration through surface interstices. Field evidence again indicates that the majority of fluvial gravels in the braidplain contained a high proportion of matrix fines within an otherwise gravel/cobble framework.

The realisation of the role of existing fluvial morphology in concentrating fine sediment dispersal has important implications for geochemical surveys. Sampling strategies based on simple point samples are likely to provide little useful information on the location and variation of metal concentrations; rather a morphologically based sampling strategy is recommended which seeks to identify regions of high and low metal content from consideration of the fluvial processes in operation.

4.7 Management considerations

4.7.1 Isolation of primary contaminant sources

Given the existence of over 2 meters of highly contaminated mine spoil through which an obviously actively eroding stream currently flows, a partial solution would appear to be the re-routing of this stream away from the mine spoil and the trapping of throughflow from the spoil heaps into settling lagoons. Whilst this will prevent the primary source of contamination proceeding to pollute the Tunnelelv, the secondary fluvial sources within the active braided floodplain will continue to provide accentuated metal levels to the system. Following a period of incision then many of these bars will develop flora over metal rich sediments. Values of metal contamination in 41% of the braidplain currently exceeds ICRCL levels for livestock grazing and whereby offal consumption from that livestock becomes hazardous for human consumption (it is a local delicacy for Inuit to eat the tongues of Musk Ox). Clearly a potential threat exists for herbivorous animals feeding on the Store Blydal floodplain with potential food chain concentration into the top carnivores.

4.7.2 Preservation of channelised river margins in the lower Tunnelelv

The channelisation of the lower Tunnelelv at the time of mining operations effectively reduced the metal contamination of much of the Delta system. However, there has been subsequent abandonment of distributary channels following a depletion in water and sediment supply following channelisation. Given the continual contamination of the Tunnelelv from sediments stored in the Store Blydal braidplain and mine waste splay, then preservation of the channelised river margins should be encouraged to prevent subsequent pollution of the northern delta system.

4.7.3 Removal or entrapment of contaminated river sediments

The vertically limited extent of the metal contamination within a well defined portion of the Store Blydal braidplain presents an opportunity for removal of contaminated surface sediments. This could be achieved by landscaping followed by restoration of the braided river system. The surface soil and sediments could be disposed of at the mine site away from surface and subsurface water sources. Alternatively, the contaminated portion of the braidplain could be isolated from the rest of the system and the channels diverted into a gravel trap located upstream of Section F. This would trap the majority of the grossly contaminated sediment which could be removed en masse at a future time.

4.7.4 Geomorphological characterisation prior to mining

The evidence from the Tunnelelv study suggests that it is important to establish the nature of the vertical direction of fluvial activity prior to mining. The release of metal contaminated sediments into an incising river system effectively confines the pollution to the channel, and provides opportunities for trapping. Release of contaminated sediments into an aggrading system leads to spatially extensive pollution and the potential for secondary pollution following incision into the mining related sediments. Once released into the braided system, incision isolates metal contaminated areas allowing colonisation by plants and the rapid inclusion of metals into the food chain. Aggradation following contamination leads to burial and dilution. It is clear that a geomorphological survey of the river system prior to mining is essential to determine the possible impact of the release of mining related sediments.

4.7.5 Post-mining surveys

The variability of metal concentrations in three dimensions brings into question the validity of spot sampling for assessment of contamination. For post-mining surveys sampling should be based around an initial geomorphological survey which would identify potential sinks for metal enriched sediment. Sampling should then be conducted on the basis of morphology, stream channels, active bars, inactive surfaces etc. This provides not only a wider coverage of the potential impact but also includes a process component to the sampling strategy. Careful consideration of the vertical component of contamination in river sediments should be built into the sampling programme. Wherever possible, the chemical speciation in relation to grain size should be established in order to resolve the effects of physical sorting from chemical synthesis.

4.8 Molybdenum mining and the potential use of mining related ore as a glacial tracer.

The collection of sediments from around the abandoned mine at the confluence of the Arcturus and Schuchert Glaciers was limited, owing principally to the lack of time available at the site and the tortuous nature of the Schuchert glacier terminal moraines. Nevertheless a field observation revealed substantial quantities of mining related debris which is currently being forced under the Schuchert glacier where the Arcturus glacier impinges. The majority of the mining related sediments are of a coarse nature, and are scattered as debris cones below the major mine entrances. Material from these spoil heaps has collapsed into the lateral supraglacial stream which drains under the snout of the Arcturus Glacier.

From the field observations it is concluded that there is sufficient metalliferous waste (Cans, boxes, pipes, machine parts) scattered around the mine site to provide a valuable tracer for supraglacial and englacial ice movements (see figure 3.3).

4.9 Future research in the Mesters Vig region

It is recommended that an ecological survey is conducted with the aim to measure the levels of Pb and Zn within plants and animals in the Tunnelelv river system and estuary.

The likely presence of a datable metal trace within the surface sediments of Noret provide the opportunity for estimating sediment production for the Tunnelelv over the past 35 years. Coring of the Noret inlet is anticipated to yield a relatively undisturbed post-glacial sediment record with evidence for vegetation colonisation and sea level changes.

A morphological mapping of the Mesters Vig area would be a viable and useful basis for future research into sea level change and periglacial features. In addition, given the accurate and extensive database of periglacial process rates recorded from the 1950 and early 1960's (Washburn, 1973) a resurvey of these sites together with a complementary experiment of process rates would provide evidence of a morphological response to climate change.

An accurate geodetic and photographic survey should be made of selected waste artefacts around the molybdenum mine site on the Schuchert Glacier. These could then form the basis for estimations of ice movement at the junction of the Arcturus and Schuchert Glaciers following re-surveys.

4.10 Surveying report

Stadia tacheometry was used to survey the 9 cross sections and positions of sample points described above. The following paragraphs describe survey work in greater detail including forward planning, equipment used, problems and results.

4.10.1 Survey methodology

Given the remote location of the field work site and the absence of an electrical supply (for recharging batteries for Electronic Distance Metering equipment), stadia tacheometry using a Kern 20" theodolite and lightweight aluminium tripod was used in the surveying of channel cross sections and sample point positions. This provided sufficient accuracy and a minimum of equipment.

Approximate targetting of likely cross sections was done prior to departure from aerial photographs taken in 1949, 1968 and 1973. This allowed rough identification of pre and post-mining sedimentation. Once in the field, careful reconnaissance work was carried out to identify those cross sections required to provide a representative sample for the Tunnelelv.

Cross sections were marked at each end by ranging poles and the section thus defined surveyed from stations located approximately 80m apart. Stations were located on the cross section by eye. Small errors in this positioning do not, however, cause significant errors in the resulting profile. Distances between stations were observed three times to increase accuracy. From the stations, detail in the form of breaks of slope, sample sites, waters edge, bank top and bank bottom, patches of ice and spot heights were observed. Each section was oriented using a compass.

Data was checked and cross sections computed each night for those cross sections completed during the days surveying work.

4.10.2 Problems

As might be expected when working in a braided river system such as the Tunnelelv, river crossing posed occasional problems during surveying. Only two days where lost to inclement weather conditions. Snow patches still surviving from the winter did occasionally obscure detail.

No problems were encountered with the surveying equipment after the carrying strap of the theodolite tripod broke on the first days work. The compact and lightweight nature of the theodolite and tripod were much appreciated in the rough terrain, whilst the theodolite itself proved easy to use (important for cold conditions and for the inexperienced).

4.10.3 Accuracy considerations

There were two purposes in surveying river cross sections. The first was to determine the shape of the section with particular reference to the relative heights of the various banks and terraces present. The second was to identify the location of sample sites on the cross section. The surveyed cross sections and sample locations are shown in figure.

Sample sites were not pin-point positions, but rather areas river sediment upto 1m in diameter from which sediment samples were obtained. Hence, the accuracy of the horizontal position of sample sites needed to be only within 50cm.

The accuracy of height measurements needed to be of greater accuracy and was specified as +/-5cm for this work. In general, it is accepted that stadia tacheometry methods as used here give distance measurements good to 1 in 500, and height difference to +/-40mm. This suggests that the method is ideal for our purposes. However, the method must be used with care to avoid unnecessarily large errors from a number of sources. These are:

1. Staff readings;
2. Non-verticality of the staff; and
3. Measurement of the vertical angle.

To avoid errors in staff readings the length of sight was kept below 100m. Over such a distance a 1mm error in staff reading only amounts to a 3mm error in height difference. Larger errors are possible if the staff is not held vertically. Care was therefore taken to ensure the vertical angle was kept within 5 degrees of vertical.

Overall it should be noted that this work was conducted in order to allow analysis of lead and zinc in river sediments. The final plotted sections show ample detail for this purpose.

4.11 Measuring pH using portable meters

pH is an important factor governing the accumulation of heavy metals in sediments. Measurements of pH are therefore necessary in assessing the likely rates of accumulation and are an important aid in speciation. All inorganic priority pollutants, other than antimony, will bioaccumulate and are found in suspended and bottom river sediments. Significantly more trace elements are found here, in the bottom and suspended matter, than in the dissolved phase (US Govt., 1985; DeGroot and Allersman, 1975).

The distribution of heavy metals in Arctic streams and snow melt water exhibit peculiarities unique to permafrost regions. After the spring thaw is complete, more exists in the river bed. Accumulation of salts (particularly carbonates and sulphates) occurs within the winter snow cover, which are then deposited in lakes and river beds, etc. as fine silt. The dominant factor which controls ion uptake is the snow pH. This is generally around 4 as a result of dissolved carbon dioxide (Jonasson and Timperley, 1975). Monitoring the pH of both the stream water and the suspended sediment at sample points along the river gives an indication of the likely form of the heavy metal species present.

Since the pH of samples taken in the field can be altered significantly during transportation it is important to be able to make quick and accurate measurements of pH in-situ. For this reason the aim here is to investigate the behaviour of several commercially available pH meters. These include combination electrodes and hand held portable pH meters. The majority of this work was carried out in the field and the problems associated with in-situ pH monitoring are discussed. Of these problems, 2 notable ones having an effect on pH readings are temperature and suspended materials.

4.11.1 The temperature effect

The pH reading obtained for a given solution is dependent on the environment in which the observation is made. From the Nernst equation (4.4) temperature effects response.

$$E = E \quad k \log(a \;) \tag{4.4}$$

where k is a constant: RT/nF
R = the universal gas constant
T = temperature in K
n = number of electrodes involved in electrode process
F = Faraday constant
a = activity of the primary ion, i

For a univalent cation, with no interference and at 25°C, the Nernst equation predicts a response of 59 mV dec^{-1}. In dilute solutions the change of the activity coefficient with temperature is negative and uniform over the whole pH range. Over small temperature changes the standard potential is proportional to temperature. (see table 4.4).

Table 4.4 Variation of the slope factor(k) with temperature

Temperature(°C)	*Slope factor(k)*
0	54.199
10	56.183
20	58.167
30	61.144
40	62.136
50	64.120
60	66.104
70	68.088
80	70.073
90	72.057

The slope factor(k) is defined by $k = RT.\ln^{10}/nF$

where R = the universal gas constant
T = the temperature (in K)
F = the Faraday constant

$$E + a + bT + R/zF \log c\ a \qquad (4.5)$$

where a and b are constants
z = the charge on the species of interest
c = the concentration of species i
a = the activity coefficient of species i

This thermal effect is reflected in the shift of neutral pH with temperature as follows:

at 0°C neutral pH = 7.5

at 60°C neutral pH = 6.5

Thus, as the temperature is increased, the observed value of pH decreases.

4.11.2 The suspension effect

A direct effect on pH, particularly relevant to sampling in the field, is that of suspended particulate matter. Variations in pH have been reported as the soil to water ratio changes (Marshall, 1961). In acidic systems, the pH of the solution containing suspended matter is lower than that of the supernatant liquid on its own. Marshall (1961) reports that slightly acidic systems show an alkaline error. This effect has been reported by Brezinski (1983) and Matock and Taylor (1961), whilst the British Standards Institute further states that 'when test solution(s) contain organic matter -suspended or dissolved- reproducibility may not be high.'

Table 4.4 Variation of the slope factor(k) with temperature

Temperature(°C)	*Slope factor(k)*
0	54.199
10	56.183
20	58.167
30	61.144
40	62.136
50	64.120
60	66.104
70	68.088
80	70.073
90	72.057

The slope factor(k) is defined by $k = RT.\ln^{10}/nF$

where R = the universal gas constant
T = the temperature (in K)
F = the Faraday constant

$$E + a + bT + R/zF \log c\ a \qquad (4.5)$$

where a and b are constants
z = the charge on the species of interest
c = the concentration of species i
a = the activity coefficient of species i

This thermal effect is reflected in the shift of neutral pH with temperature as follows:

at 0°C neutral pH = 7.5

at 60°C neutral pH = 6.5

Thus, as the temperature is increased, the observed value of pH decreases.

4.11.2 The suspension effect

A direct effect on pH, particularly relevant to sampling in the field, is that of suspended particulate matter. Variations in pH have been reported as the soil to water ratio changes (Marshall, 1961). In acidic systems, the pH of the solution containing suspended matter is lower than that of the supernatant liquid on its own. Marshall (1961) reports that slightly acidic systems show an alkaline error. This effect has been reported by Brezinski (1983) and Matock and Taylor (1961), whilst the British Standards Institute further states that 'when test solution(s) contain organic matter -suspended or dissolved- reproducibility may not be high.'

4.11.3 Design of pH measuring systems

Several commercially available pH meters were tested under standard laboratory conditions in Newcastle. Of these only two were taken on the expedition since models with high resistance electrodes are undesirable as they are more sensitive to noise and drift. Using large and thin glass membranes is recommended for reduced sensitivity to noise whilst the stability of the electrode can be improved by ensuring that the reference part is very close to the sensing part of the electrode, and that the liquid junction and the reference section of the electrode are in the same region of the solution.

A lightweight, water-tight buffer amplifier manufactured by the Department of Chemistry Electronics Workshop at Newcastle University, and a small Thandar digital voltmeter (model TM451) were used in conjunction with the electrodes described above.

As much of the work was to be carried out in the field, often with long approach walks involved to reach sample sites, the weight and the sturdiness of the instruments used was important.

The handheld portable meters have a more robust design. The sensing membrane of these electrodes is very small and a ceramic plug junction is the contact to the reference electrode. Although specifications state reproducibility of +/- 0.01 pH this seemed rather doubtful with such a small sensing region. The Piccolo pH meter incorporates a temperature compensation facility, as do most of the more recent models currently available, although the ATC meter also taken did not.

4.11.4 Pretreatment of sample storage bottles

It is stated above that very low concentrations of heavy metals exist in the dissolved phase. Since samples of stream water were taken for analysis, it was necessary to choose sample bottles of a material which would neither absorb or leach out ions of interest or ions which could interfere with the primary ions. In glass vessels, besides being rather fragile for field work, ion exchange may occur. Alkali metal ions may be leached from the glass surface and physical adsorption may also occur.

Low density polyethylene is the best material for sample storage. However, in order to reduce any errors introduced by the containers, the following cleaning procedure is recommended (Bock, 1979):

1. soak bottles in EDTA or 10% NaOH + 1-2% H_20 for 24 hours;
2. boil bottles in 6M HCl or 6M HNO_3 for several hours or soak in 1:1 HCl for 48 hours; and
3. rinse thoroughly with deionised water.

In steps 1 and 2 the second option was followed in both instances, whilst adsorption/desorption and pH changes incurred during storage in polyethylene bottles was measured in the laboratory prior to field work.

4.11.5 Designation of sample sites and experimentation

A six mile long reach of the Tunnelelv from the Blyklippen Mine to the rivers mouth at Kong Oscars Fjord was divided into 10 separate sections (those described above in section 4.4.1). At each site, in addition to sediment samples, pH measurements were made at a series of sample points along the section.

At each of the chosen sample points where water was present in significant quantities (i.e. mid-channel deposits, river bed material, etc.) the pH of the supernatant liquid was measured along with the pH of the river water itself (if present). The temperature of the water was noted to allow for thermal variation in pH readings.

River water samples were taken from each cross section and acidified to pH 2.0 using dilute hydrochloric acid. This prevents speciation due to biota.

The pH was measured using each of the pH meters as well as the Russell glass electrode versus Calomel reference electrode (3.5 mol dm^{-3} KCl). The response time, reproducibility and stability of readings was observed.

Although not strictly necessary, the ability of the pH sensors to make surface soil measurements was also tested. The electrodes were placed against the silt on the river banks and where consistency allowed, pushed into the medium.

The pH of subsurface soil samples at a number of discrete sample points within the Tunnelelv valley were made. These tests were carried out in the small laboratory at Washburn's Cottage. Thin pastes or suspensions were made of samples taken from 25, 100 and 225mm depths from each sample point. These were allowed to stand for 5-10 minutes before measuring their pH.

4.11.6 Results

From laboratory tests carried out in Newcastle prior to the expedition, it was found that the Russell glass electrode performed best with a good Nernstian response of 59.14 mV dec^{-1} at 25°C versus Calomel reference electrode (3.5 mol dm^{-3} KCl). Initial worries about the fragile nature of the electrode's glass bulb were overcome during a preliminary field test. Concern was expressed as to the necessity to recalibrate at each sample point which is very time consuming. In practice, the electrodes were calibrated whenever distinct changes in the samples were encountered.

The pH readings made for three discrete cross sections (G, D and E) with different characteristics are given in tables 4.5, 4.6 and 4.7, respectively. Although the values are important as regards the assessment of lead and zinc pollution, the objective of this project is to examine the performance of instrumentation with respect to suitability for use in the field.

Table 4.5 Variation of the physical properties of water with temperature

Temperature (° C)	*Dielectric constant (ε r)*	*Density (ρ /g.ml^{-1})*
0	87.74	0.99987
10	83.83	0.99973
20	80.10	0.99828
30	76.55	0.99568
40	73.15	0.99225
50	69.91	0.98807
60	66.82	0.98322
70	63.86	0.97779
80	61.03	0.97182
90	58.32	-----------

Table 4.6 pH values at sample sites in Section G

Site No.	*Description*	*pH ATC & Piccolo*	*Temperature(° C)*
G1	Left bank	7.2 & 7.15	9.2
G2	Lower left bank	7.8 & 8.03	9.1
G3	Foreshore	8.0 & 8.08	9.2
G4	Beach	8.0 & 8.19	9.2
G5	River slurry	8.2 & 8.00	7.5
G6	Bar slurry 45cm below	8.0 & 8.19	8.8
G7	Bar surface material	8.0 & 8.02	8.9
G8	Top of vegetated bar	8.0 & 8.10	8.9
G9	as above no organics	8.1 & 8.12	8.9
G10	Beach no organics	8.1 & 8.19	9.0
G11	Mid active bar	8.1 & 8.12	8.9
G11a	Mid river channel	8.1 & 8.20	7.5
G12	Bar	8.0 & 8.10	8.9
G13	Old flood channel	8.1 & 8.20	8.9
G14	Older flood terrace	8.0 & 8.17	9.0
G15	Bottom of terrace	7.6 & 7.75	9.0
G16	Top of terrace	7.8 & 7.94	8.9
G17	Old flood channel	7.6 & 7.94	9.0
G18	Top of old bar	7.5 & 7.68	9.1
G19	Old paleo bar	7.5 & 7.45	8.9
G20	Old paleo bar	7.5 & 7.57	9.0
G21	Paleo channel/mire	7.6 & 7.73	9.2
G22	Peri-glacial slope wash	7.7 & 7.81	9.1

Table 4.7 pH values at sample sites in Section E

Site No.	*Description*	*pH*	*Temperature(° C)*
E1	Vegetated bank	7.50	9.2
E2	Mine waste slurry over vegtn	7.63	9.3
E3	Mine waste no vegetation	7.81	9.3
E4	Mine waste with vegetation	7.88	9.2
E5	As E4	7.31	9.1
E6	Totally vegetated mine waste	7.57	9.1
E7	Unvegetated river bank	8.20	9.2
E8	River	8.30	7.5
E9	Lower right river bank	8.32	8.8
E10	Mid right river bank	7.92	9.1
E11	Vegetated river bank	7.56	8.8

The custom built unit with Russell electrode gave very good reproducable results. In tests carried out in silt the electrode performed well and no detrimental effects were observed. Despite this, due to the fragile nature of the equipment and the extra time required to assemble the buffer amplifier and digital volt meter, this system, not surprisingly, is not recommended for extensive use in the field. At a base camp laboratory, however, this equipment would be ideal.

The ATC pH meter, despite its lightweight and robust nature did not behave well in the field. The siting of the ON/OFF switch was poor as it allows dampness to enter the body of the electrode (this has now been changed by the manufacturers). Large fluctuations in readings were observed using this meter which may be attributed to water contamination. This ATC meter did not contain a temperature compensation facility, so pH readings obtained needed correcting. The accuracy of the instrument is described as +/- 0.1 pH units. In reality, however, it was found to be much less accurate giving readings accurate to +/- 0.5 pH units.

The Piccolo pH meter was found to be the most reliable. The built-in temperature compensation function and accuracy to +/- 0.01 pH unit under ideal conditions, rendered it superior to the ATC device. Readings obtained were reproducible and the instrument was robust enough to withstand rough field work conditions.

All the electrodes displayed unstable readings when immersed directly into the river itself. This is not to be unexpected since the river current causes streaming potential to occur at the electrode surface. When river water samples were removed from the river and the pH measured, much more stable readings were observed. Upon removal from the river, a drift in potential was observed with time as the temperature of the water increased causing an apparent decrease in pH. This was consistent with the equation 4.5.

All electrodes, when used for measuring the pH of river sediment directly behaved remarkably well and gave good reproducible results. However, the Piccolo meter is to be recommended because of its greater accuracy and more robust design.

4.11.7 Conclusions

The use of glass electrodes for field testing is suitable only if based in one location. Due to the larger setup these electrodes are both unwieldy and fragile. Of the two handheld pH meters the Piccollo pH meter was found to be a much better, watertight design, complete with temperature compensation and with overall better accuracy.

4.12 Notes on the Mesters Vig climate

A continuous climatological record was kept at the Washburn's Cottage by Flemming Rune for the period covering 30th June to 26th August 1989. Measurements included precipitation, evaporation and temperature, as well as general observations on prevailing weather conditions. Following is a detailed description of the climate at Mesters Vig and a record of climate for the above mentioned period.

4.12.1 Classification

The climate in the Mesters Vig area is indeed polar. According to the Koppen System (Koppen, 1963) the climate can be classified as tundra (where the mean temperature of the warmest month is less than 10°C), with a period of growth too short for the formation of forest. However, in the highly preferable Vahl System (Reumert, 1947), which is only poorly known outside Scandinavia (because it is published only in Danish), the climate may be classed as low-arctic polar climate (where the mean temperature of the warmest month is between 5 and 10°C), despite the fact that the area is situated more than 72° North.

4.12.2 Previous climatic records

Regular meteorological records were kept at the Danish Government station at the Mesters Vig airfield for a period after 1952, and a brief summary of the temperature, precipitation and wind records for the first decade is given by Washburn (1965). The mean annual temperature for the area was -9.7°C, with an annual range of monthly mean temperatures from -24.3°C in the winter to 5.9°C in the summer. The absolute minimum during the decade was -44.2°C whilst the absolute maximum was 21.0°C, a range of 65.2°C.

Usually most of July and the first half of August are frost-free, but frost may actually occur any night throughout the summer. The depth to the permafrost in the area is reported to range from 0.5 to over 2.0m. At the Blyklippen mine the thickness of the permafrost has been measured to about 125m (Muller, 1959).

The mean annual precipitation is a little less than 400mm, most of it falling as snow during the winter. The summers are usually fairly dry. Long periods of drought are quite common during the summer, and only at rare intervals will longer periods of rain occur in the summer. During most of year katabatic winds from the inland ice are channelled along Kong Oscars Fjord from west-north-west, but in summer the wind direction is reversed due to the heating of the ice-free coastal fringe. On most days during the summer a chill east-south-eastern sea breeze blows over lowland areas along the fjord. This occasionally brings extensive banks of sea-fog into the fjord from the outer coast (figure 4.23).

The summers at Mesters Vig are considerably colder than at Ella O further up Kong Oscars Fjord (2.6°C for the warmest month), but warmer than Scoresbysund further south (0.4°C for the warmest month). This is mainly due to the different degree of continentality, but special local topographical conditions will affect climate as well. For an overall discussion of the regional climate see Ahlmann (1941), Hovmoller (1947) and Washburn (1965).

4.12 Notes on the Mesters Vig climate

A continuous climatological record was kept at the Washburn's Cottage by Flemming Rune for the period covering 30th June to 26th August 1989. Measurements included precipitation, evaporation and temperature, as well as general observations on prevailing weather conditions. Following is a detailed description of the climate at Mesters Vig and a record of climate for the above mentioned period.

4.12.1 Classification

The climate in the Mesters Vig area is indeed polar. According to the Koppen System (Koppen, 1963) the climate can be classified as tundra (where the mean temperature of the warmest month is less than 10°C), with a period of growth too short for the formation of forest. However, in the highly preferable Vahl System (Reumert, 1947), which is only poorly known outside Scandinavia (because it is published only in Danish), the climate may be classed as low-arctic polar climate (where the mean temperature of the warmest month is between 5 and 10°C), despite the fact that the area is situated more than 72° North.

4.12.2 Previous climatic records

Regular meteorological records were kept at the Danish Government station at the Mesters Vig airfield for a period after 1952, and a brief summary of the temperature, precipitation and wind records for the first decade is given by Washburn (1965). The mean annual temperature for the area was -9.7°C, with an annual range of monthly mean temperatures from -24.3°C in the winter to 5.9°C in the summer. The absolute minimum during the decade was -44.2°C whilst the absolute maximum was 21.0°C, a range of 65.2°C.

Usually most of July and the first half of August are frost-free, but frost may actually occur any night throughout the summer. The depth to the permafrost in the area is reported to range from 0.5 to over 2.0m. At the Blyklippen mine the thickness of the permafrost has been measured to about 125m (Muller, 1959).

The mean annual precipitation is a little less than 400mm, most of it falling as snow during the winter. The summers are usually fairly dry. Long periods of drought are quite common during the summer, and only at rare intervals will longer periods of rain occur in the summer. During most of year katabatic winds from the inland ice are channelled along Kong Oscars Fjord from west-north-west, but in summer the wind direction is reversed due to the heating of the ice-free coastal fringe. On most days during the summer a chill east-south-eastern sea breeze blows over lowland areas along the fjord. This occasionally brings extensive banks of sea-fog into the fjord from the outer coast (figure 4.23).

The summers at Mesters Vig are considerably colder than at Ella O further up Kong Oscars Fjord (2.6°C for the warmest month), but warmer than Scoresbysund further south (0.4°C for the warmest month). This is mainly due to the different degree of continentality, but special local topographical conditions will affect climate as well. For an overall discussion of the regional climate see Ahlmann (1941), Hovmoller (1947) and Washburn (1965).

4.12.3 Recording the climate during summer 1989

The snow melt in the spring 1989 began in the last days of May. On the 31st May the ice in the Tunnelelv broke up, and during the first half of June the temperature rose rapidly. On the 18th June the last night frost occurred, and even though most of the landscape was still covered with snow drifts up to a thickness of 0.5m, the snow was melting very rapidly and then, a fortnight later, most of it was gone (Ib Kristensen, Sirius Patrol, pers. comm.). The foliation of most dwarf shrubs took place in the first days of July.

During the period 30th June to 26th August climatic records were made at Washburn's Cottage in Store Blydal, 2m above the ground at an altitude of 225m. The potential evaporation was measured as the evaporation from a 180cm^2 water surface in a polished highly reflective 9cm deep aluminium pot. This as well as the precipitation was measured every 24 hours with an accuracy of 1mm. The minimum and maximum temperature was measured daily with an accuracy of 0.5°C, and the relative air humidity was measured 6-10 times daily using a high precision hygrometer (less than +/- 1% accuracy). The results are shown in figure 4.24, the relative humidity being stated as saturation deficit (100 - relative humidity%).

4.12.4 Special climatic conditions in Mesters Vig 1989

The hot dry and cloudless weather from the last half of June lasted until the 9th July. The daily solar irradiance during the period was very high, causing day temperatures up to 18°C, and temperatures at midnight (local time) of about 13°C due to the midnight sun. This caused a large saturation deficit (about 40%) in the air even throughout the nights, which is different from what is known in most of the low-arctic parts of Greenland, south of the polar circle, where the midnight sun does not appear. There the saturation deficit falls to zero on most nights during the summer (Petersen, 1977).

Spot checks showed that there was often a remarkable difference between the temperature at Washburn's Cottage and the temperature at the former government station (the airfield) just 5km away. The area around Washburn's Cottage is partly sheltered from the chilly sea-breeze blowing over the low plain at the airfield by the hillsides in the Store Blydal. On a rough estimate the difference between albedo might be 50% and 15% and the differences in air temperature registered was up to 5°C, in the afternoon just after the climax of solar irradiance, between Washburn's Cottage and the airfield respectively. This implies that great care should be taken when comparing climatic records from meteorological stations along the coast of Greenland. Small local distances may cause climatic changes as large as several degrees of latitude, the altitude being unchanged, as already implied by Sorensen (1941).

Late in the day on 9th July a heavy rainfall started giving 35mm of rain in just 14 hours. Even though showers of that intensity are quite unusual in the Mesters Vig area, occurring not more than one or two times each decade in the summer, the amount of water could not compensate for the large evaporation from the soil during the previous weeks. The drying out of the soil actually went on throughout the summer, the longest spell with no rain being 20 days (22nd July to 11th August). This made itself felt at Washburn's Cottage by the discharge of the small stream used as a water supply slowly getting less and ending up as only a trickle by the end of August. However, the saturation deficit and the potential evaporation gradually decreased due to the disappearance of the midnight sun, and the overall weather became more changeable, though it most often kept dry. During most of August the saturation deficit fell to zero in the nights.

Figure 4.23: Anabatic convection fog (Washburn's Cottage in foreground)

Figure 4.24: The climate during the growing season in 1989 at Mesters Vig 72 13' N.

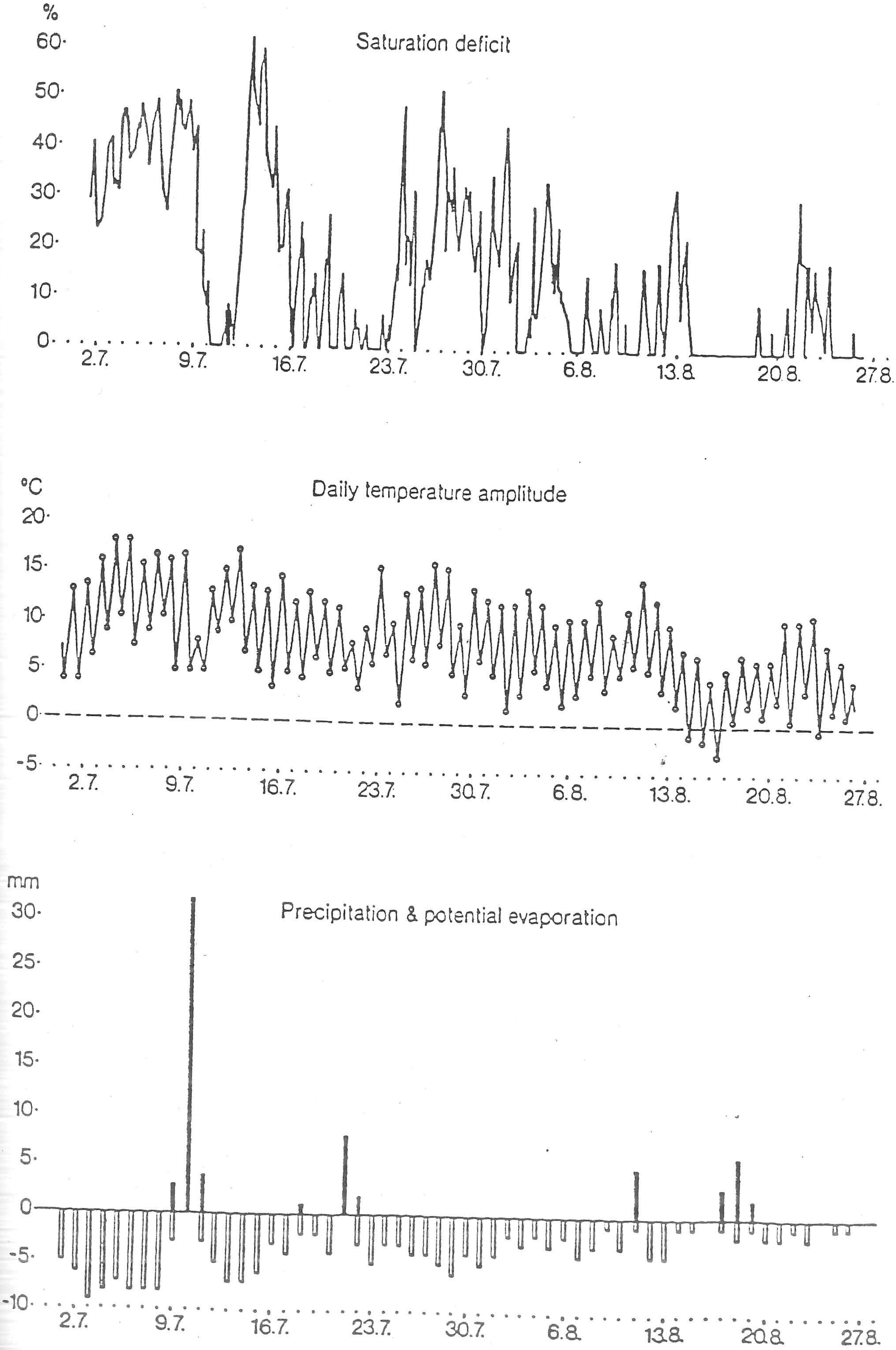
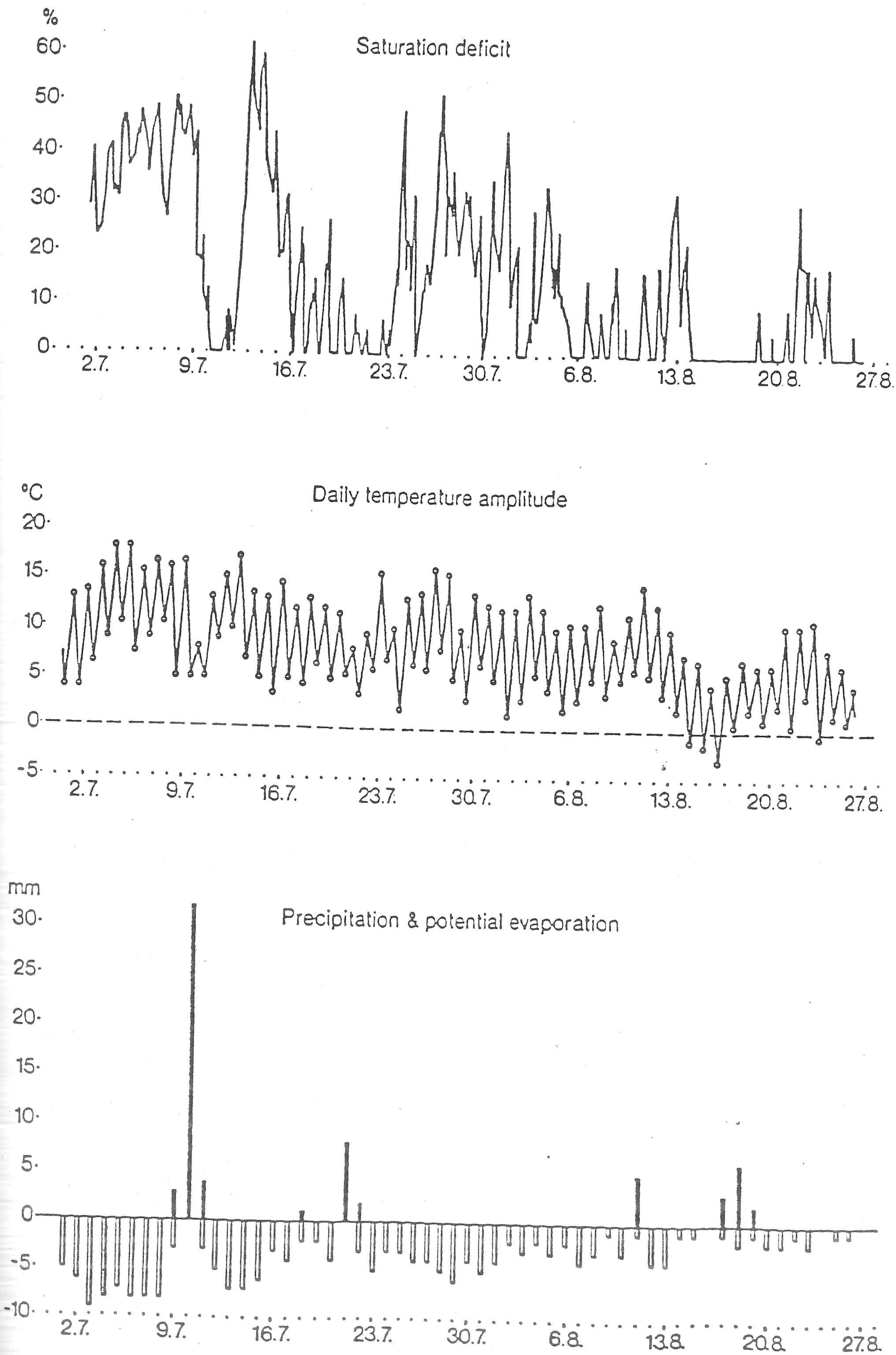


Figure 4.24: The climate during the growing season in 1989 at Mesters Vig 72 13' N.



4.12.5 The approaching autumn 1989

On the 14th August a four day period with extensive sea-fog began, ending up with 2-3 days of steady light rain. During the sea-fog period night frosts returned after a long frost-free period of nearly two months. This was the start of autumn with the foliage of the dwarf shrubs turning red, brown and yellow, and in the last week of August the growing season could be regarded as over, having lasted about 8 weeks.

All in all the growing season (30th June-26th August) included about 25 days of sunshine, 22 days of overcast skies, 5-6 days of rain and 5-6 days of sea-fog. This is however only valid for the area around Store Blydal around Washburn's Cottage. In August the low plain around the airfield at Kong Oscars Fjord was often shrouded in fog, at least until midday, while Store Blydal above 150-200m altitude had clear weather.

The is no doubt that the designation 'The Arctic Riviera', which has long been a name applied to the Mesters Vig area, suits the Store Blydal better than the low plains at the coast of Kong Oscars Fjord.

5.0 EXPEDITION TRAVEL AND FREIGHT

Getting to Mesters Vig in East Greenland can be problematic. Before even setting foot on a plane a permit to enter the North-East Greenland National Park is required from the Danish Polar Institute. To get a permit the expedition must be of a scientific nature, though a few purely mountaineering/canoeing expeditions have been allowed. It is, however, necessary to apply for the permit a good year in advance.

Travel to Mesters Vig is also expensive. There are no scheduled flights to the gravel airstrip so it is necessary to charter your own. We used a company called Flugfelag Nordurlands who operate out of Akureyri. They have a good reputation and are used frequently by the Danish Sirius Patrol, though it may be possible to get cheaper flights from smaller companies. In addition the airstrip is officially no longer in operation since the main airstrip serving the area has moved further south to Nerlerit Inaat (Constable Pynt). However, Mesters Vig is still used by the Danish military and planes can still land there for the time being. Having flown from Glasgow to Keflavik and from Reykjavik to Akureyri on scheduled Icelandair flights, we chartered a light aircraft (Piper Chieftain) to take us to Mesters Vig and back. It is necessary to pay for two return journeys since the plane will usually have to fly back empty. Once in the field, of course, the only means of transport is 'Shank's Pony', unless you are rich enough to be able to afford helicopter charter prices. Having said that, we were lucky enough to enlist the help of the Sirius Patrol in transporting our freight from the airstrip to base camp via Unimog.

Following is the travel itinerary (and approximate costings) we used in getting to and from Mesters Vig:

Table 5.1 Travel itinerary and costs

Date	*Place and destination*	*Transport*	*Cost(£)*
Outward:			
14.7.89	Newcastle to Glasgow	Minibus	nil
15.7.89	Glasgow to Keflavik	Icelandair flight	490.00
15.7.89	Keflavik to Reykjavik	Bus	25.00
16.7.89	Reykjavik to Akureyri	Icelandair flight	250.00
16.7.89	Akureyri to Mesters Vig	Charter flight	1450.00
16.7.89	Mesters Vig to Washburn's	Land Cruiser	1ltr. Whisky
Return:			
26.8.89	Mesters Vig to Akureyri	Charter flight	1450.00
28.8.89	Akureyri to Reykjavik	Bus	120.00
29.8.89	Reykjavik to Keflavik	Bus	25.00
29.8.89	Keflavik to Glasgow	Icelandair flight	490.00
29.8.89	Glasgow to Newcastle	Minibus	nil
		Total	**4300.00**

N.B. All costings are for one-way journeys for 5 people with the exception of the Glasgow to Keflavik flight for which return tickets were bought where it assumed for the purposes of the above table that the cost of the outward and return journeys, respectively, was half the total fare paid.

Freighting of food and equipment to Mesters Vig is also a major consideration in terms of cost and planning. Because there are no shops of any kind in Mesters Vig it is necessary to take everything needed with the expedition from the UK. This necessitates the sending of much gear by freight. We used a company called Saferair International who have an office in the Newcastle University Students Union. They offered reasonable rates and were able to get all our freight to the airport at Akureyri. From there to Greenland it was necessary to pay the charter company we were flying with to transport it before our arrival. As it happens, much of the freight boxes were squeezed onto the plane we flew in and only a few boxes had been sent on ahead. This made for a cramped journey but saved us money. Overall freight cost were in the region of £1500.

Steve Carver
Expedition Leader

6.0 FOOD REPORT

All the food requirements for the expedition were freighted from the UK to Greenland prior to the expedition departure since there are no shops at Mesters Vig. Apart from the odd meal and a beer at the airstrip, local bilberries, etc ., this was all we ate during our time in Greenland. The rations proved more than adequate and some of us actually put on weight. Following is a description of how we fed 6 hungry people during the expedition.

6.1 Planning, preparation and packing

It is difficult to know where to start planning six weeks food supply for 6 people knowing that everything must be taken into the field from the UK. The whole process was never short of extremely complicated, but the huge effort put in whilst still at home inevitably paid off once in Greenland with an organised, well packed and varied diet.

There are many important factors to consider including weight, bulk, cost, calorific and nutritional value, cooking time and variety. There was also peoples personal preferences to consider. This is very important as food is closely linked to expedition morale. In the event a questionnaire was compiled which everyone filled in as an aid to menu planning. Two members of the expedition are vegetarian and so to avoid over complicated rations the other members agreed to go vegetarian for the most part of the expedition.

Both freeze dried and specially dehydrated meals are usually expensive and often better meals can be made up of the cheaper and more widely available supermarket goods. I spent many hours compiling a list of possible suppliers, almost 100 in all. Letters were sent to these asking for support. Of the 100 companies identified, nearly 60% replied and about 20% agreed to help by either a straight forward donation of their product or by offering discount prices. This no doubt saved us a considerable amount of money. The donations ranged from 11 boxes of Extra-Strong mints (phew!), to tubes of mustard, honey and Jif Lemons, through to boxes of fruit and nut bars and flapjacks. The rest of the food was ordered from BCB International Ltd. and bought in cash and carry supermarkets.

All the food on the menu was chosen so as be easy to cook as it was thought that we would be spending much of our six weeks in Greenland in tents. The type of food and the manner in which it was packed was based on a rough itinerary of the expedition. The food was therefore packed as follows:

4 days travelling rations:
including rations for setting up base camp, packed as self contained food packs for 6 people.

7 days base camp rations:
for use when doing field work etc. at Washburn's Cottage, included more variety and heavier items such as tins, packs of fruit juice and other luxuries.

25 days 'mobile' rations:
for use when doing field work in remote locations and whilst on treks, packed as self contained units but retaining some choice.

7 days mountaineering rations:

again packed as self contained units but using mainly freeze dried foods.

4 days contingency rations:

same as mobile rations.

All the food once split into the ration packs outlined above was further divided into drinks packs, meal packs, pudding packs, etc. and carefully bagged and labelled. An inexhaustible supply of plastic bags was important and the loan of a heat-sealer also proved useful in the packing process. This all took many days but it meant that once in Greenland little organisation of food stores was required leaving the maximum amount of time for field work, etc.

In addition to the 7 types of main meal and 9 types of dessert included in the base camp and mobile rations, luxuries were included at base camp to add variety and enjoyment. These included:

herbs and spices
pickles
cheese
sauce mixes
extra vegetables
tinned meats
tinned fruit
cake mixes (suitable for pressure cooker)
mung beans for sprouting (successful)
fruit juice
snack foods
whisky (inevitably!)

All the food was sent out in the freight 5 weeks prior to our own departure, with the exception of some perishable items in our own luggage.

6.2 Food in Greenland

For the duration of the expedition base camp was the Washburn's Cottage in the Tunnelelv valley where we did the bulk of our field work. This made the cooking and storage of food considerably easier than if we had been based in tents as originally planned.

Interesting local delicacies included eating the leaves of sorel and arctic willow-herb (Greenland's national flower). These are rich in vitamin C. There was also a plentiful supply of mushrooms and with Flemming's expertise in this area we were able to enjoy a couple of mushroom stews without fear of being poisoned! Our favourite natural source of food had to be bilberries which can be found on most south facing hillsides. We occasionally feasted on such culinary delights as bilberry pancakes, bilberry and apple crumble, and chocolate bilberry sponge cake.

In general the food was a success, with enough variety to keep us all happy and plenty to go round (as indicated by certain members of the expedition actually putting weight on during our stay in Greenland)! As an example, a typical day would look something like the following:

Breakfast.: Muesli (homemade and very tasty)
Hot drink and fruit juice (powdered)

Lunch: 'Healthy Life' biscuits
Honey (in tube)
Cereal bar
Chocolate
Boiled sweets

Evening meal: Soup
Stroganof pasta with tuna
Mousse
Chocolate biscuits
Hot drink
(and perhaps a wee dram)

The honey in tubes donated by Ratcliffes of Oxford was absolutely ideal for us and very tasty. We ate it with practically everything, including muesli, oatcakes, *'Kalvi'* crisp breads, and *'Healthy Life'* biscuits. Pancake mixes from Greens of Brighton were popular and Flemming proved a dab hand and making them. Del Monte donated a large amount of tinned fruit which we used as base camp rations and made welcome treats after returning from treks and climbing. The huge amount of flapjacks which we consumed was kindly donated by Dunelm Wholefoods proved to be both filling and packed with valuable energy that we could not have done without. On the down side, the least satisfying foods we had were the specially designed freeze dried meals that you just add boiling water to. We used these extensively whilst climbing in the Staunings, but they were not very filling. Their redeeming feature is that they are very light and are quick to prepare.

At the end of our time in Greenland we were left with an excess of bread substitutes (i.e. oatcakes, crisp breads etc.), biscuits, sweets and some chocolate, together with small bits and pieces such as tea bags, sugar, mustard, etc. These we left in Washburn's for future visitors use.

Finally we would like to express grateful thanks to the following companies (in alphabetical order):

BCB International Ltd.
Beecham Bovril Brands
Colmans of Norwich
Del Monte Foods Ltd.
Dunelm Wholefoods Ltd.
Greens of Brighton
Kalvi Ltd.
Lyons Bakery Ltd.
Manley Ratcliffe Ltd.
St Ivel Ltd.
Simmers Biscuits
Shepherdboy Ltd.
Trebor Ltd.

Ella Brett
Surveyor and Food Organiser

7.0 MEDICAL REPORT

As none of the expedition members were trained medics, although a few of us had first aid courses under our belts, our medical strategy, if anything happened requiring more than the most basic of medical attention, was to administer emergency first aid and then hope for a speedy evacuation of the casualty. In this respect, we carried two Locat emergency radio beacons capable of sending a continuous distress signal to satellites and air traffic. Word was also left with the Danish soldiers at the Mesters Vig airstrip of our intended route and time away from base camp. Full medical and search and rescue insurance was provided by the British Mountaineering Council.

My own medical training, as the expedition medic, consisted of first aid course attended six years previously and a refresher course by the St John's Ambulance prior to our departure. So with this meagre experience just compiling the medical kit and knowing how to use its various contents was a daunting enough task. Fortunately many friends and contacts in the medical and pharmaceutical professions helped out here and we soon had quite a comprehensive kit.

The listed cost of many of the drugs we intended taking was quite considerable. However, by contacting the manufacturers and sales reps many of these were acquired free of charge whilst most other items were procured on a sale-or-return basis. Prescriptions were required for many items, and these were obtained from the head of the Newcastle University Health Service, Dr K.A. Norbury. We are all indebted to him for his patience and advice in sorting out our medical problems. Further advice was also obtained from friends who were doctors and dentists (generally along the lines of *'you must be joking!'* etc.).

Prior to departure for Greenland we all attended dental and general medical check-ups in order to reduce the risk of any conditions developing whilst in the field. An invaluable book, 'Medicine for Mountaineers', was also carried at all times whilst in Greenland. This gives detailed advice on improvised treatment under expedition conditions, as well as making helpful suggestions for the contents of the medical kit.

Three major hazards (excluding physical injury) were identified by our friends in the medical profession. These were:

1. Appendicitis;
2. Chest infection; and
3. Abscess of the tooth.

In extreme cases all three of the above could require evacuation from the field.

Problems actually encountered in the field were thankfully minor. General painkillers for headaches and muscle pain, decongestants for colds, antihistamines for mosquito bites and the use of tubigrips for muscular support were all that was required.

The main medical kit consisted of two BDH containers (watertight plastic containers used for storing chemicals) and a *'Gregson Kit'*. These contained most of the drugs, dressings, antiseptics, etc. (a complete list is given below in table 7.1). In addition, each member of the expedition carried their own emergency kit consisting of Bupromorphine tablets (strong analgesic), assorted dressings, paracetemol, antisceptic and insect repellent.

Table 7.1 Contents of main medical kit

Quantity	*Description*
Bandages, dressings, etc.	
9	Plain wound dressing No.15 BPC
6	Plain wound dressing No.14 BPC
3	Plain wound dressing No.13 BPC
10	Triangular bandage
10	Melolin (non adsorbent bandage) 10*10cm
5	Melolin (non adsorbent bandage) 10*20cm
50	Assorted elastoplast
3	Strips band aid 1m lengths
4	Rolls zinc oxide plaster 2.5cm*5m
6	Crepe bandages 15cm*4.5m
6 pkt	Cotton wool
30	Cotton buds
4	Sterile wound dressings 20*20cm
2	Rolls bandage 7.5cm*4m
2	Eye pads No.16 BPC
3	Tubigrips size C
3	Tubigrips size D
4pkt	Steristrips
Drugs:	
100	Paracetamol 500mg tablets
10	Bupremorphine 0.3mg ampoule
50	Bupremorphine tablets
120	Penicillin V 250mg tablets
120	W-Trimoxazole tablets
10	Diazipam 5mg tablets
100	Chlorpheniramine 4mg tablets
50	Senna 7mg tablets
100	Codine Phosphate 15mg tablets
30	Amethocane eye drops 1% single dose units
5	Flouroscein eye drops single dose units
60	Chloramphenicol eye drops
2	Chloramphenicol eye ointment, tubes
2	Vioform hydrocortisone cream 20g tubes
1	Bottle dental tincture lignocane & cloves of olives
1	Ovitrine nasal spray
48	Bisacoytl suppositories
60	Benzalkonium lozenges
28	Erythroped A 500mg tablets
2	Tubes deep heat
1	Tube pile ointment
1	Tube athletes foot cream

cont'd.

Table 7.1 Contents of main medical kit (cont'd)	
Syringes, etc:	
50	Injection swabs
10	2ml syringes
20	Syringe needles (38 x 0.8mm)
2	10ml syringes
Miscellaneous:	
3pr	Scissors
15	Savlon sachets (concentrate)
2pr	Sterile plastic dressing forceps
10pkt	Gauze swabs 2.5cm
2	Thermometers
1pr	PR splinter forceps
1	Emergency dental kit
2pkt	Plastic gloves

Steve Naylor
Medic

8.0 MOUNTAINEERING REPORT

The main mountaineering objective of the expedition was a 9 day trek into the Berserkerbrae region of the Staunings Alper. During this period two peaks were climbed, Harlech Fjeld (1900m) and Dunottar (2524m). During the course of the expedition all the major peaks in the area immediately surrounding our base camp at Washburn's Cottage were also climbed.

8.1 The Staunings Alper

The Staungings Alper is a group of mountains upto 2900m in height composed igneous rocks (mainly granitic intrusions into Cambrian and Precambrian rocks). The mountains are typically arctic alpine in character, and though not very high are very spectacular, offering superb alpine climbing. Their northerly location gives them a high mountain 'feel' as the summer snowline is low with many glaciers, some of which reach almost to sea-level. The range is enclosed roughly by Kong Oscars Fjord to the north, Nordvestfjord to the south, Skeldal and Schuchert Dal to the east and Nathorst Land to the west. All the major peaks in the range have been climbed. most during a period of high activity during the 1970's.

The length of the approach march from base camp at Washburn's Cottage to an advanced camp on the Berserkerbrae, a distance of approximately 15 miles over rough terrain, is a severe limiting factor governing mountaineering objectives in the Staunings. As a result, expeditions to the area are now fairly rare. If any length of time is to be spent here, particularly in the more remote locations, then helicopter transport of food, equipment and personnel is desirable, or alternatively, transport by boat around the coast if peaks and glaciers in the Alpefjord area are the objective. Since we had neither of these and that time was limited, we were restricted to the most easily accessible area to Mesters Vig. Nevertheless, walking into the Staunings carrying all the food and climbing gear needed for 9 days is by no means easy.

8.1.1 Approach and the Berserkerbrae

The Berserkerbrae is a veritable highway into the centre of the northern half of the Staunings, yet can only be reached from Mesters Vig by climbing the Ovre Gefionpas and by crossing Skeldal. The bottom of Skeldal is occupied by a wide river fed by the meltwaters from several large glaciers. This has to be forded to reach the Berserkerbrae if a long detour (approximately 5 miles) over the snout of the Skebrae is to be avoided. We crossed over the Gefionpas and forded the river in one days walk from Washburn's Cottage. Dave and Flemming who were not coming climbing graciously helped carry some of our gear to the top of the pass from where we continued down into Skeldal.

We had considered camping on near bank and crossing early next morning when the water in the Skel would be lower. After a bankside reconnaissance, however, we decided it was safe to try and cross that evening. Using ropes for safety and zig-zagging across sand banks and gravel bars we struggled across through the freezing water before collapsing wet and exhausted on the opposite bank. Here there are large flat areas of sand and gravel terraces above the level of the river which make excellent camp sites, although a supply of good drinking water can be difficult to find. The tents were pitched and a meal cooked before we collapsed into a deep sleep only to be awoken by the sound of wind and rain in the early morning.

The next day was wet with low cloud obscuring the peaks. Undaunted, however, we walked on up through the lateral moraine on the south side of the Berserkerbrae with the aim of making camp somewhere on the glacier. Quite a few expeditions visited this area in the 1970's and early 1980's so there is a good path up this side, skirting the heavily crevassed icefall where the glacier flows into Skeldal. The path eventually leads you out onto the surface of the glacier and we had a miserable time trudging up the glacier in the rain and cold looking for a suitable camp site. Jan's crampon broke necessitating some hasty repairs, but it still kept falling off. In the end we gave up trying and so carried on holding hands four abreast to support Jan in the middle on the slippery ice. We must have looked a real sight!

Eventually we found somewhere to pitch the tents. A large boulder on a medial moraine provided some shelter from the wind and rain and after clearing a level area of rocks pitched the tents and once again settled down to cook a meal and catch some sleep. The Whisper-lite multifuel stove was playing up and the ice under the tent cold and hard. We had convinced ourselves *'tommorrow would be better'*.

8.1.2 Harlech Fjeld

Breakfast saw us revelling in clear skies and warm sunshine and later that morning we set off from our camp to climb Harlech Fjeld. The mountain seen from the hills to the north east above Mesters Vig resembles a huge whale back ridge and is quite distinctive. From the Berserkerbrae it looks totally different, its south face is formed by two large corries bounded by aretes which form the whale back as seen from the north and split by a wide central ridge (figure 8.1). The ridge dropping down to the Berserkerbrae was climbed to the summit. The rock was heavily frost shattered but easy going once over some horrendous screes and unstable moraines its foot. A spectacular descent onto the Harlech Glacier was made by a long standing glisade down the snow chute which occupies the centre of the wide ridge splitting the two corries. This is clearly shown on the map (1:250,000 sheet 72 O.2) and probably the best means of descent if conditions allow.

Once onto the Harlech Glacier, a tributary of the Berserkerbrae, we were witness to the remarkable phenomena of 'roll waves' in a surface meltwater channel. Pulses of water were rushing down the channel at intervals of 6-7 seconds. In between waves the channel was completely dry such that we could easily step down into it and climb out onto the opposite side without getting wet or being swept away by the next wave! The following day the waves had subsided into normal flow but we spent the morning in the interest of science surveying the channel with the rudimentary equipment that we had available. A scientific paper has been written for the *Journal of Glaciology* (Carver, et al., in press), a copy of which is included as appendix C.

When we had returned from our work on the Harlech Glacier we struck camp and made our way further up the Berserkerbrae to the *'Sunny Valley'* camp. This site is situated at the junction of the Berserkerbrae and the Dunottar Glacier and has often been used in the past as a camp for scientific and climbing expeditions. Small, tent-sized patches of level ground have been made in the otherwise impossible jumble of rocks and boulders of the lateral moraine. A number of food and equipment dumps also scatter the area. These were investigated for additional rations and spare parts for Jan's broken crampons. Some food had obviously been there since the early 1980's and had been spoilt. The bad food was sorted out and burnt before the caches were resealed.

8.1.3 Dunottar

The following day we decided to make an attempt on Dunottar, the peak at the head of the twin forks of the Dunottar Glacier. This provided the longest mountaineering day of the expedition. The approach was made from the Sunny Valley site along the north fork of the glacier. The lower snout of the glacier where it joints with the larger Berserkerbrae is heavily crevassed and this was avoided by keeping on the lateral moraine of its northern flank. Once past the crevasses we crossed the glacier to its southern flank just above where it forks. After roping up and drinking our fill from the last meltwater stream encountered we made our way up this side overlooked by huge cliffs and gendarmed ridges. Again the weather was superb with clear blue skies and only light wind, our position providing breathtaking views back across the Berserkerbrae as the backcloth to our ascent.

The route up the peak of Dunottar itself remained hidden until the glacier curved abruptly round to the south above an icefall (complete with towering seracs and huge crevasses disappearing into inky darkness). This gave us our first glimpse of the summit and the north face route we had chosen. About 700 feet of 40-45 degree snow and ice led to the summit ridge. This was generally easy going (F+/D) with a final steep section above a small bergschrund leading to the summit. Our high point was on one of the rocky pinnacles along the ridge about 100 feet lower than the summit proper. Its dramatic position perched on the edge of the 2000 foot vertical rock wall of the south face provided amazing views out across a sea of snowy peaks and glaciers. It was a great feeling, especially knowing we where the only people for many miles with these magnificent mountains all to ourselves (figure 8.2).

With time getting on, and the temperature dropping well below freezing as the sun crept lower and shadows lengthened, we decided it was time to retrace our steps down the mountain and back along the glacier. We eventually reached camp a full 16 hours after setting off that morning. The next day we slept, dozed, sunbathed, read, ate and general did nothing. With a unanimous decision we had decided on a day of rest.

8.1.4 Over Glamis Col

Our exit route from the Staunings lay not back down the Berserkerbrae, but up the Beaumaris Glacier and over the Glamis Col to the Kishmul Glacier. This leads down to the Skelbrae and hence the Gefionpas and 'home' to Washburn's Cottage. The Beaumaris Glacier is quite heavily crevassed and these had to be negotiated before getting up to the Glamis Col. This is supposed to be an easy snow pass, but when we got there we found the opposite (Kishmul) side snow free and a horrendous mess of shattered butresses and steep scree chutes (figure 8.3). After investigating one of these we thought it would lead safely down onto the Kishmul Glacier. However it was difficult to say whether we could actually see the bottom so we scrambled down with great caution ever conscious of the fact that it may end in a cliff. In the end the scree lead safely out onto the glacier and so we made camp for the last time on ice.

Figure 8.1: Setting off to climb Harlech Fjeld (1900m)

Figure 8.2: On Dunottar (2524m)

Figure 8.3: Scree slopes on Glamis Col

8.1.5 Return to Washburn's Cottage

In the morning it was cloudy and threatening to turn nasty so we hurried on down the Kishmul. Once on the Skelbrae the past 5 days of brilliant sunshine and light winds broke and it rained heavily from low cloud. Camp was made on the Mesters Vig side of Skeldal, thankful that we did not have to ford the Skel river again but subdued by the down turn in the weather.

The last of our nine days mountaineering jaunt saw us climbing over the Ovre Gefionpas for the last time, having close encounter with a large unfriendly looking Musk Ox, and staggering tired but happy in Washburn's Cottage looking forward to seeing our companions Dave and Flemming again and to eating real food.

8.2 Other Peaks and climbs

During the course of the expedition a number of mountains were climbed in the Mesters Vig area. The five main peaks surrounding Washburn's Cottage are Hesteskoen (1118m), Scheele Bjerg (1180m), Sortebjerg (1084m), Dormkirken (1025m) and Blyryggen (1050m). These were all climbed on various occasions and by various members of the expedition.

Washburn's Cottage is sited on the slopes of Hesteskoen (meaning horse shoe in Danish) and so this was an obvious target for early walks in the immediate vicinity. The summit of the mountain provides good views of Kong Oscars Fjord, lower Skeldal and the snout of the Berserkerbrae. The summit also has a remarkable example of stone stripes and polygons caused by frost action on two different types of rock. Dormkirken is the central peak of the Korsbjerg massif on the opposite side of the Tunnelelv and Store Blydal and was climbed after a particularly heavy drinking session with Erling and Bent at the airstrip. Erling accompanied on this climb, ostensibly to clear the 'timbermen' from his head (timbermen = Danish colloquism for a hang-over!). The summit provides an excellent vantage point overlooking the Tunnelelv valley and Blyklippen mine but its upper slopes and ridges are heavily frost shattered and extremely loose, making for quite an exciting ascent. Scheele Bjerg was climbed whilst returning from a supply trip over the Nedre Gefionelv/Nodre Funddal pass to the Sortebjerg hut. The summit of this mountain gives magnificent surprise views across Skeldal and into the Staunings Alper. The Sortebjerg (black mountain) was climbed on the return leg of the Malmbjerg trek. The summit is marked by a basaltic dyke which stands about 5 metres proud of the surrounding softer conglomerate and sandstone rocks as a wall of almost man-made quality. Superb views of Deltadal, Mesters Vig inlet, the Kolossen nunatak and the Mellem and Ostre Glaciers are gained from this vantage. Blyryggen (lead ridge) was climbed the day after Sortebjerg. It south facing slopes are well vegetated and yielded a good crop of bilberries, whilst its wide flat summit, like that of Hesteskoen, provides a good example of large stone polygons.

Finally, a few rock climbs were done on the cliffs of some of the basalt intrusions near the airstrip. These were visited with Erling and Bent who were interested in trying their hand at rock climbing and abseiling. A number of routes were climbed ranging from easy chimneys to hard crack lines. These provided great sport, especially against the backdrop of fjord and mountains.

Steve Naylor and Steve Carver
Expedition Medic and Leader

9.0 CONCLUSIONS

9.1 General

In general we believe that the expedition has been a great success, despite the final report being a little late in materialising. The expedition has been a worthwhile experience for all those involved and some good science has been produced, some of which has already been published. It is hoped to publish the expeditions main findings in the near future. The detailed conclusions of this report dealing with the scientific aspects of the expedition are given below.

9.2 Impacts on the environment

Impacts on the environment from metal mining at Blyklippen can be categorised into three groups. These are:

1. Primary impacts associated with mine construction and operation including top soil removal, surface structures, poor waste management, etc;

2. Secondary impacts associated with site clearance including spoil dumping, insensitive or absent landscaping, etc; and

3. Tertiary impacts associated with the long-term release and dispersal of contaminated tailings into the river system.

9.3 Metal mining pollution

The levels of Pb and Zn within the river sediments of the Store Blydal and Tunnelelv continue to remain above recommended levels despite mining operations having ceased nearly 30 years ago. However, contamination is spatially limited by the braidplain morphology of the Store Blydal before mixing in the Tunnelelv gorge. Downstream dispersal in this instance is more rapid than has been recorded for single thread channels in temperate climates. This is a function of the high sediment loads and the relative activity of the channel processes.

The dispersal of metal mining wastes is at present characterised by the movement of contaminated fines through the existing channel network. Storage on barforms is commonly limited to lateral and bar-tail regions and within the channel is limited to infiltration of fines into the bed material and temporary low flow storage of fines in channel pools.

The presence of a large primary source of contaminated fines is confirmed in the form of the mine waste splay in Section E. However, in channel storage and the reworking of contaminated river deposits may be regarded as important secondary sources. Management of the Store Blydal should focus on the control of the primary source of contaminated material, either through removal or isolation from active processes.

Metal mining pollution at the Malmbjerg mine is not a problem. Mining of molybdenum at the Malmbjerg was limited to a small scale trail operation and as such did not produce large amounts of contaminated tailings. The small amount of mined material that exists is deposited as small debris cones below mine entrances similar in form to the surrounding scree material. Molybdenum contaminated material deposited onto the glacier through mining operations at Malmbjerg may therefore be considered little different to that deposited via natural processes. This makes molybdenum contaminated mine waste unsuitable for tracer experiments to determine glacier movement. A more suitable tracer may be the huge amounts of other waste (pipes, tin cans, machinery, oil drums, etc.) left by Nordisk Mineselskab when the ceased mining operations (see figure 3.3).

9.4 Areas for future research

A number of recommendations are made regarding potential areas of future research in the Store Blydal and Tunnelelv. The main two areas are identified. These are a full ecological survey of the river valley and a sediment survey of the Noret inlet. It is expected that these would yield information regarding the take up of Pb and Zn into plants and animals and further evidence of the movement of metal contaminated sediments, respectively. In the case of the latter, deeper sediments deposited in Noret may reveal evidence of post-glacial vegetation colonisation and sea-level changes.

9.5 Implications for mining operations in other arctic regions

The work presented here presents evidence of how metal mining pollution is dispersed and concentrated within an arctic river system. This is used in suggesting possible management solutions to the contamination of the Store Blydal and Tunnelelv. It is clear that such conclusions can be exported to other mining operations, past, present and future, in other arctic areas and in particular the Antarctic (given recent developments in this area of the world). The simple answer may be not to mine at all. However, political and economic considerations will often dictate that mining in arctic regions is a viable proposition and so we must be careful to implement appropriate management practices in order to minimise impacts on these fragile environments. These include isolation of mine tailings from river systems, sensitive siting of mine buildings, careful landscaping and long term monitoring. For future mines the mining company must carry out detailed environmental surveys before commencing operations so informed management decisions can be made to minimise impacts.

Bibliography

Ahlmann, H.W., (1949) Studies in North-East Greenland 1939-1940. PartII, Glacial conditions in general, and on Clavering Island in particular. in Geografiske Annalar 23 (3-4), p.183-209.

Archer, F.C. and Hodgson, I.H. (1987). 'Total and extractable trace element contents in soils of England and Wales'. *J. Soil. Sci.*, 38, 421-432.

Ashmore, P.E. (1982). 'Laboratory modelling of gravel braided stream morphology'. *Earth Surf. Proc. Landforms*, 7, 201-225.

Aspinall, R.J., Macklin, M.G. and Openshaw, S. (1987). 'Heavy metal contamination in soils of Tyneside: a geographically-based assessment of environmental quality in an urban area'. *University of Newcastle-upon-Tyne Dept. of Geography Seminar paper* No. 50, 10pp.

Aspinall, R.J. and Macklin, M.G. (1985). 'Heavy metal transport and storage in an upland catchment: A case study from the River West Allen, Northumberland'. *University of Newcastle-upon-Tyne Dept. of Geography Seminar paper* No. 41, 18pp.

Astlind, B. and Fahlstrom, P.H. (1957). 'Greenland Lead-Zinc Mine Beats Elements with Underground Mill'. *Mining World*, November Edition, 46-50.

Axtmann, E.V. and Luoma, S.N. (1991). 'Large scale distribution of metal contamination in the fine grained sediments of the Clarke Fork River, Montana, USA'. *Applied Geochemistry*, 6, 75-88.

Bock, R., (1979) A handbook of decomposition methods in analytical chemistry. (translated by J. Marr), International Textbook Co.

Bradley, S.B. and Cox, J.J. (1986). 'Heavy metals in the Hamps and Manifold valleys, North Staffordshire, U.K.: Distribution in floodplain soils'. *The Science of the Total Environment*, 50, 103-128.

Brezinski, D.P., (1983) Talanta 30, p.347.

British Standards Institute (1984) B.S. 1647, Part 1.

Carver, S., Sear, D. and Valentine, E., (in press) 'An observation of roll waves in a supragalcial meltwater channel, Harlech Gletscher, East Greenland'. in *Journal of Glaciology*.

Davies, B.E. (1983). 'Trace element pollution'. in Davies, B.E. (Ed), *Applied soil trace elements*, Wiley, London.

DeGroot, A.J. & Allersman, E., (1975) Heavy metals in the aquatic environment. Pergamon Press.

Diserens, A.P. and Delo, E.A. (1990). 'Heavy metal transport and dispersal by maintenance dredging: a study of the River Tees and the Inner Disposal Site'. iHydraulics Research Report SR 235, 38pp.

Dissanayake, C.B., Kritsotakis, K. and Tobschall, H.J. (1984). 'The abundance of Au,Pt, Pd and the mode of heavy metal fixation in highly polluted sediments from the Rhine River near Mainz, West Germany'. *Int. J. Env. Studies*, 22 (2), 109-119.

Dunne, T. and Leopold, L.B. (1978). 'Water in Environmental Planning'. W.H.Freeman, San Francisco.

Ferguson, R.I. and Ashworth, P.E. (1992). 'Sediment transport in Braided Rivers', in Hey, R.D., Billi, P., Thorne, C.R. & Tacconni, P. (Eds), '*Dynamics of gravel-bed rivers*', J.Wiley & Sons, Chichester, U.K.

Frostick, L.B., Lucas, P.M. and Reid, I. (1984). 'The infiltration of fine matrices into coarse-grained alluvial sediments and its implications for stratigraphical interpretation'. *J.Geol. Soc. London*, 141, 955-965.

Harpoth, O., Pedersen, J.L., Schonwandt, H.K. and Thomassen, B. (1986). 'The mineral occurrences of central East Greenland'. *Meddelelser om Gronland*, 17, 7-16,81-85.

Hoey, T. (1992). ' Temporal variations in bedload transport rates and sediment storage in gravel-bed rivers'. *Progress in Physical Geography*, 16 (3), 319-338.

Hovmoller, E., (1947) Climate and weather over the coast of NorthEast Greenland and the adjacent sea. in Meddelelser om Gronland 144(1) p.1-208.

Hubbell, D.W. and Glenn, J.L. (1973). 'Distribution of radionuclides in bottom sediments of the Columbia River estuary'. *USGS Prof. Paper*, 433-L, 63pp.

Interdepartmental Committee on the Redevelopment of Contaminated Land (1990). 'Notes on the restoration and aftercare of metalliferous mining sites for pasture and grazing'. ICRCL Guidance Note 70/90.

Jonasson, I.R., & Timperley, M.H., (1975) in Heavy metals in the aquatic environment. A.J. DeGroot and E. Allersman (eds), Pergamon Press.

Jones, K.C. (1986). 'The distribution and partitioin of silver and other heavy metals in sediments associated with an acid mine drainage system'. *Environmetal Pollution*, (Series B), 12 (4), 249-263.

Klien, P. (1962). 'River Pollution 2: causes and effects'. Butterworths, London.

Knox, J.C. (1987). 'Historical valley floor sedimentation in the upper Mississippi Valley'. *Annals of the Association of American Geographers*, 77 (2), 224-244.

Koppen, W., (1936) Das Geographische System der Klimate. in Handbuch der Klimatologie. Berlin.

Kunzerndorf, H. (unpublished) 'Geochemical exploration in the MEsters Vig area, central East Greenland'. RISO.

Leenaers, H. (1991) 'Multiscale spatial modelling of metal pollution in the fluvial environment'.

Lewin, J. and Macklin, M.G. (1987). 'Metal mining and floodplain sedimentation in Britain'. in Gardiner, V. (Ed) *International Geomorphology 1986 Part 1*, J.Wiley & Sons, Chichester, U.K., 1009-1027.

Li, B. (1983). 'A study on the mechanism of Pb-, Cd- transportation and purification in streams'. *Geochemica*, 2, 205-212.

Macklin, M.G. (1986). 'Channel and floodplain metamorphosis in the River Nent, Cumberland'. in Macklin, M.G. and Rose, J. (eds), *Quaternary River Landforms in the Northern Pennines, England, A Field Guide*. BGRG/QRA.

Macklin, M.G. and Klimek, K. (1992). 'Dispersal, storage and transformation of metal-contaminated alluvium in the Upper Vistula basin, southwest Poland'. *Applied Geography*, 12, 7-30.

Macklin, M.G., Rumsby, B.T. and Newson, M.D. (1992). 'Historic overbank floods and vertical accretion of fine grained alluvium in the lower Tyne Valley, northeast England'. in Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P. (Eds), *Dynamics of gravel-bed rivers*, J.Wiley & SOns, Chichester, U.K.

Macklin, M.G. and Smith, R.S. (1990). 'Historic vegetation sucession of alluvial metallophyte plant communities in the Tyne Basin, north-east England, UK'. in Thornes, J.B. (Ed), 'Vegetation and Erosion', J.Wiley & Sons, Chichester, UK.

Macklin, M.G. and Dowsett, R.B. (1989). 'The chemical and physical speciation of trace metals in fine grained overbank flood sediments in the Tyne basin, north-east England'. *Catena*, 16, 135-151.

Macklin, M.G. and Lewin, J. (1989). 'Sediment transfer and transportation of an alluvial valley floor: the River South Tyne, Northumbria, U.K.'. *Earth Surf. Proc. Landforms*, 14, 233-246.

Marcus, W.A. (1987). 'Copper dispersion in ephemeral stream sediments'. *Earth Surf. Proc. Landforms*, 12, 217-228.

Marron, D.C. (1989). 'Physical and chemical characteristics of a metal-contaminated overbank deposit, west-central South Dakota, USA.'. *Earth Surf. Proc. Landforms*, 14, 419-432.

Marshall, C.E., (1961) Physical chemistry and mineralology of soils. Volume 1. Wiley & Sons, New York.

Mattock, G. & Taylor, R., (1961) pH measurement and titration. Macmillan Co., New York.

Ministry of Housing (1983). 'Leidraad Bodemsanering'. Leidschendam. The Netherlands: Ministry of Housing, Physical Planning and Environment.

Muller, F., (1959) Beobachtungen uber Pingos. Detailuntersuchungen in Ostgronland und in der Kanadischen Arktis. in Meddelelser om Gronland 153(3) p.1-127.

Petersen, P.M., (1977) Investigations on the ecology and phenology of the Macromycetes in the Arctic. in Meddelelser om Gronland 199(5) p.1-72.

Rang, M.C., Kleijn, C.E. and Schouten, C.J. (1987). 'Mapping soil pollution by application of classical geomorphological and pedological field techniques'. in Gardiner, V. (Ed) *International Geomorphology 1986 Part 1*, J.Wiley & Sons, New York, 1029-1044.

Reumert, J., (1947) Vahls Klimainddeling. in Geografisk Tidsskrfit 48.

Rumsby, B.T. (1991). 'Historic floods and sedimentation in the Tyne Basin'. Unpublished PhD dissertation, Dept. of Geography, University of Newcastle-upon-Tyne.

Saunders, I. (1990). 'Testing the waters of Greenland'. *Laboratory Equipment Digest*, May Edition.

Schumm, S.A. (1977). 'The Fluvial System'. Wiley, New York.

Sear, D.A. (1992a). 'Sediment transport processes and the riffle-pool sequence within a regulated river'. in Hey, R.D., Billi, P., Thorne, C.R. & Tacconni, P. (Eds), *'Dynamics of gravel-bed rivers'*, J.Wiley & Sons, Chichester, U.K.

Sear, D.A. (b992a). 'Sediment transport processes in riffle-pool sequences and the effects of river regulation for hydro-elecrtic power within the North Tyne'. Unpublished PhD dissertation, Dept. of Geography, University of Newcastle-upon-Tyne.

Sinex, S.A., Cantillo, A.Y. and Helz, G.R. (1980). 'Accuracy of acid extraction methods for trace metals in sediments'. *Anal. Chem.*, 52, 2342-2346.

Sorensen, T., (1941) Temperature relations and phenology of the North-East Greenland flowering plants. in Meddelelser om Gronland 125(9) p1-305.

Tessier, A., Campbell, P. & Bisson, M. (1979). 'Sequential extraction procedure for the speciation of particulate trace metals'. *Analytical Chemistry*, 51, 844-851.

Thoms, M.C. (1987). 'Channel sedimentation within the urbanised River Tame, U.K.'. *Regulated Rivers*, 1,229-246.

US Government Printing Office (1985) A primer on trace metal sediment Chemistry.

Washburn, A.L., (1965) Geomorphic and vegetational studies in Mesters Vig. in Meddelelser om Gronland 166(1) p.1-60.

Washburn, A.L. (1969). 'Patterned ground in the Mesters Vig district, Northeast Greenland'. *Biuletyn Peryglacjalny*, 18, 259-330.

Washburn, A.L. (1973). 'Periglacial Processes and Environments'. Edward Arnold, London.

Wolfenden, P.J. and Lewin, J. (1978). 'Distribution of metal pollutants in active stream sediments', *Catena*, 5, 67-78.

Wright, D.A. (1975). 'Heavy metals in animals from the North East Coast'. *Marine Pollution Bulletin*, 8, 36-38.

Appendix A

Original research proposal

NEWCASTLE UNIVERSITY

EAST GREENLAND EXPEDITION

3 King John Street, Heaton, Newcastle upon Tyne, NE6 5XR. (091)2328511 x8016

1989 TUNNELELV RIVER PROJECT

Patron: Sir Vivian Fuchs, FRS

RESEARCH PROPOSAL

An assessment of the concentration and distribution of metal mining waste within the Tunnelelv River sediments of the Mesters Vig region, Scoresby Land, East Greenland.

INTRODUCTION

The objective of the Tunnelelv River research project is to assess the impact of lead and zinc mining operations upon the sediments and floral communities within an Arctic river system and to compare results with those from the Tyne River basin, particularly with respect to historical channel change and the impact upon bankside floral commuinities (Macklin 1986a, 1986b, Macklin & Lewin 1989, and Macklin & Smith 1989).

BACKGROUND

Lead and zinc were mined at Mesters Vig from 1956 until 1962. A total of 545000 tons of ore (9.3% Pb, 9.9% Zn) was extracted (Harpøth et al. 1986). On site concentration provided 585000 tons of lead concentrate (82.7% Pb) and 74600 tons of zinc concentrate (63.7% Zn). Such activity, and recent lanscaping, is assumed to have released quantities of metal rich fine sediment into the Tunnelelv river system.

Numerous glacio-fluvial deposits occur on both sides of the Store Blydal valley and provide most of the sediment for the Tunnelelv river. In the reaches around the Blyklippen mine, and for 4km downstream, the Tunnelelv river exhibits a braided morphology. This is a characteristic planform of a river that is conveying a high sediment load, (and supply) a significant source of which maybe metal mining spoil (Map 1).

Of interest in terms of future mining activity is the occurrence of molybdenum bearing rocks at Malmbjerg and Mellempas in the Werner Bjerge (Map 2). Amounts of molybdenum have been detected in moraine material at the head of the Deltadal river which flows northeast into Mesters Vig Fjord (Bearth 1959). Extensive investigatory drilling has been carried out by AMAX and Nordisk Mineselskab A/S. An ore body 150 million tons (0.23% MoS_2 and 0.02% WO_3 has been proven (Harpøth et al. 1986). Mining rights for the Malmbjerg deposit have been purchased and presumably this will commence when it is profitable to do so.

NEWCASTLE UNIVERSITY

EAST GREENLAND EXPEDITION

3 King John Street, Heaton, Newcastle upon Tyne, NE6 5XR. (091)2328511 x8016

1989 TUNNELELV RIVER PROJECT

Patron: Sir Vivian Fuchs, FRS

RESEARCH PROPOSAL

An assessment of the concentration and distribution of metal mining waste within the Tunnelelv River sediments of the Mesters Vig region, Scoresby Land, East Greenland.

INTRODUCTION

The objective of the Tunnelelv River research project is to assess the impact of lead and zinc mining operations upon the sediments and floral communities within an Arctic river system and to compare results with those from the Tyne River basin, particularly with respect to historical channel change and the impact upon bankside floral commuinities (Macklin 1986a, 1986b, Macklin & Lewin 1989, and Macklin & Smith 1989).

BACKGROUND

Lead and zinc were mined at Mesters Vig from 1956 until 1962. A total of 545000 tons of ore (9.3% Pb, 9.9% Zn) was extracted (Harpøth et al. 1986). On site concentration provided 585000 tons of lead concentrate (82.7% Pb) and 74600 tons of zinc concentrate (63.7% Zn). Such activity, and recent lanscaping, is assumed to have released quantities of metal rich fine sediment into the Tunnelelv river system.

Numerous glacio-fluvial deposits occur on both sides of the Store Blydal valley and provide most of the sediment for the Tunnelelv river. In the reaches around the Blyklippen mine, and for 4km downstream, the Tunnelelv river exhibits a braided morphology. This is a characteristic planform of a river that is conveying a high sediment load, (and supply) a significant source of which maybe metal mining spoil (Map 1).

Of interest in terms of future mining activity is the occurrence of molybdenum bearing rocks at Malmbjerg and Mellempas in the Werner Bjerge (Map 2). Amounts of molybdenum have been detected in moraine material at the head of the Deltadal river which flows northeast into Mesters Vig Fjord (Bearth 1959). Extensive investigatory drilling has been carried out by AMAX and Nordisk Mineselskab A/S. An ore body 150 million tons (0.23% MoS_2 and 0.02% WO_3 has been proven (Harpøth et al. 1986). Mining rights for the Malmbjerg deposit have been purchased and presumably this will commence when it is profitable to do so.

AIMS AND OBJECTIVES

The objectives of the study are sixfold:

(1) To measure concentrations of lead and zinc within river sediments associated with pre- and post-mining activity and to investigate the dispersal of contaminants through the river system;
(2) To identify any downstream changes in the physical and chemical characteristics of sediment and water borne metals;
(3) To assess the impact of metal pollution on local bankside floral communities;
(4) To elucidate the rates of channel change within a dynamic arctic fluvial environment and to assess the implications for metal pollution dispersal;
(5) To measure concentrations of molybdenum present within the Deltadal and Schuchert river systems through natural processes and, using results gained from the Tunnelelv, make a tentative assessment of the potential impact of molybdenum mining at Malmbjerg and Mellempas; and
(6) To assess the potential for the use of molybdenum rich mine spoil as a tracer for studying the transportation of surface galcier debris/sediments as a result of ice movement and surface melt water.

Although quite an extensive list much of this research can be completed on return of a relatively small number of samples in the field.

METHODOLOGY

The sampling strategy in the Tunnelelv system will consist of three parts: pre-expedition map and aerial photographic targetting of sample areas; field surveys and sampling; and post-expedition processing of samples and collation and publication of results.

(1) Pre-expedition map and aerial photographic targetting:
In the Tyne basin survey, the use of serial maps and aerial photographs enabled minimum dates to be fixed to discreet sedimentary units. This allows targetting of sampling sites prior to field surveys. For the Tunnelelv system, aerial photographs exist for pre-mining (1954) and post mining (1968, 1973) and 1:250,000 maps from 1980. These will enable the approximate identification of mining associated sedimentation.

(2) Field surveys and sampling:
The fieldwork will involve the collection of sediment samples from previously targetted locations. Survey transects across the floodplain will be made at several locations to determine the spatial distribution of metals and plants. The transects will be located at sites above and below the mine, at positions that reflect the depositional history contemporary with mining activity.The samples will be sieved in the field and a known proportion of fine material (< 2mm diameter) would be return for analysis.

The lead and zinc content present within river water as dissolved load will be determined using portable metal-specific probes. Water pH will also be measured in the field using a portable probe.

Some samples from the Tunnelelv have been brought back from the field this summer (1988) by a commercial expedition. Results from their analysis have enabled a preliminary assessment of the mine waste pollution to be made. As expected this increases dramatically downstream of the mine (see Map 1 & Table A). Given such ready detectable quantities no problems are forseen in carrying out the above research, even in such a dynamic river system.

Sediment samples will be collected from channels within the Deltadal and Schuchert river systems. Samples will aslo be taken from surface moraines and melt water deposits on the Schuchert, Arcturus and Mellem glaciers. These will be again sieved in the field and analysed later in the UK for molbdenum content.

Observation of plant communities will be made along survey transects across the floodplain and specifically on areas identified as being associated with pre- and post-mining sedimentation to allow comparisons to be made. Species will be identified in the field. Photographs will be taken of each species encountered to allow positive identification in the UK.

(3) Post-expedition analysis:
Sediment samples will be analysed using atomic absorbtion spectrophotometry (AAS) on return to the UK to determine their metal content. This method requires very little sediment (0.25g) which might otherwise prevent its return.

OTHER RESEARCH

A number of smaller research projects are also planned for our time in the field. Certain areas of the sandstone rocks in the Mesters Vig area contain some potentially interesting fossil records of early land vertebrates (tetrapods). It is hoped to visit these sites and spend some time collecting there to follow up work done by Clack (1986, 1987). In addition to planned work on succession of floral communities it is intended to keep a detailed record of the local fauna observed during field work including time and location of sighting and where appropriate, numbers observed, sex, number of young and direction of travel. The expedition hopes to make use of existing huts in the area. Remedial maintainence will be carried out on these when and wherever it is required so that others may find them in good condition.

REFERENCES

BEARTH, P. (1959) On the alkali massif of the Werner Bjerge in East Greenland. Meddr Gronland 153,4: 63pp. Copenhagen 1959.

CLACK, J.A. (1986) Report of the Cambridge Geological Expedition to East Greenland 1986.

CLACK, J.A. (1987) Report of the Anglo-Danish Expedition to the Upper Devonian of East Greenland 1987

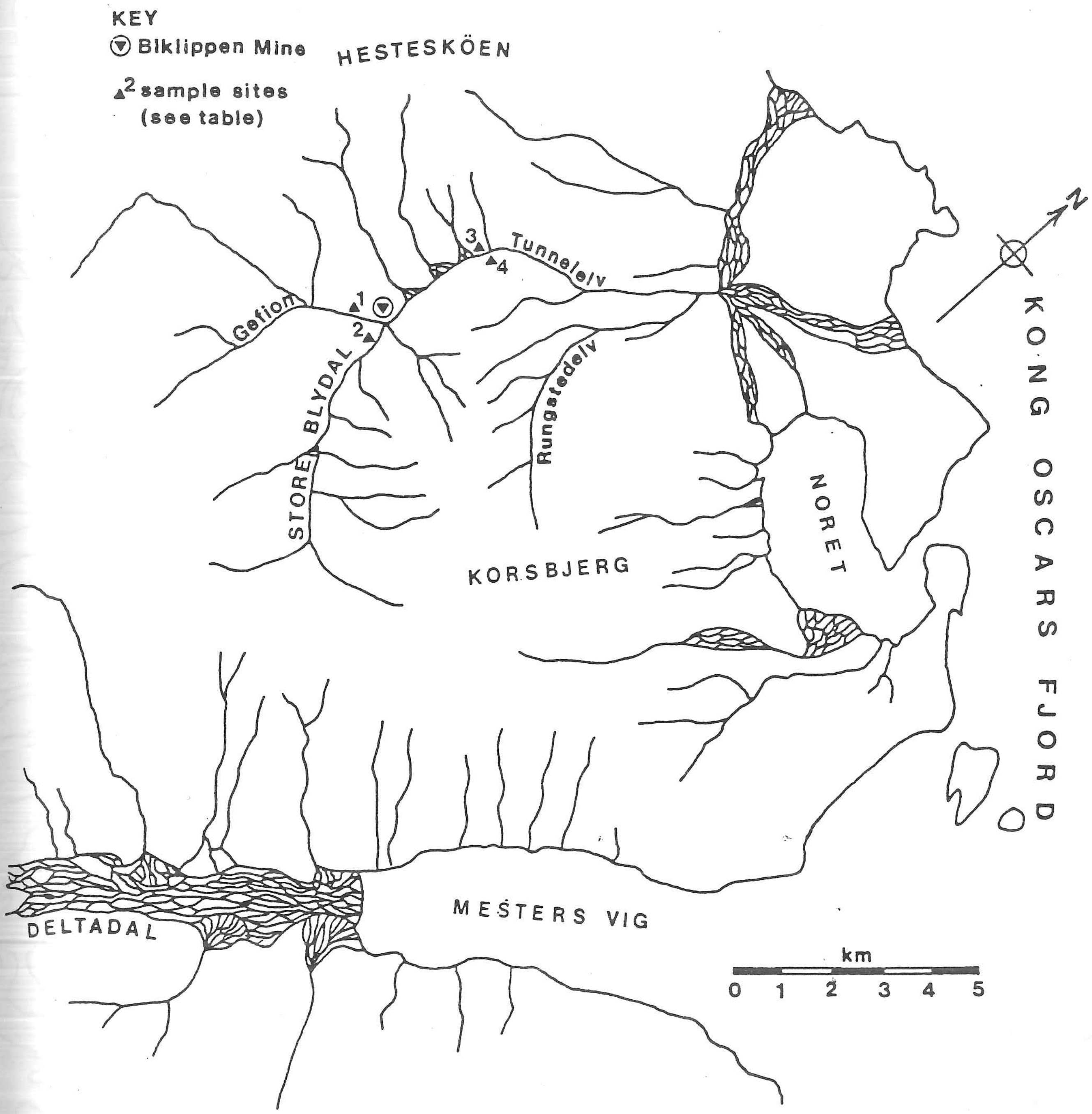
HARPØTH, O. et al (1986) The mineral occurences of central East Greenland. Meddr Gronland Geosci. 17: 139pp. Copenhagen 1986.

MACKLIN, M.G. (1986a) Recent channel change and floodplain development in the Nent, South Tyne, and West Allen Valleys, and alluvial fills of post-glacial and historic age. Quaternary river Landforms and Sediments in the Northern Pennines, Macklin, M.G. and Rose, J. (eds) BGRG & QRA, 1986.

MACKLIN, M.G. (1986b) Channel and floodplain metamorphosis in the River Nent, Cumberland. Quaternary River Landforms and Sediments in the Northern pennines, Macklin, M.G. & Rose, J. (eds) BGRG & QRA, 1986.

MACKLIN, M.G. & LEWIN, J. (in press) Sediment transfer and transformation of an alluvial valley floor: the river South Tyne, Northumbria, UK. Earth Surface Processes and Landforms

MACKLIN, M.G. & SMITH, R.S. (in press) Historic vegetation succession and conservation of alluvial metallophyte plant communities in the Tyne basin, north east England, UK. Vegetation and Geomorphology, Thornes, J.B. (ed) Wiley.



MAP 1

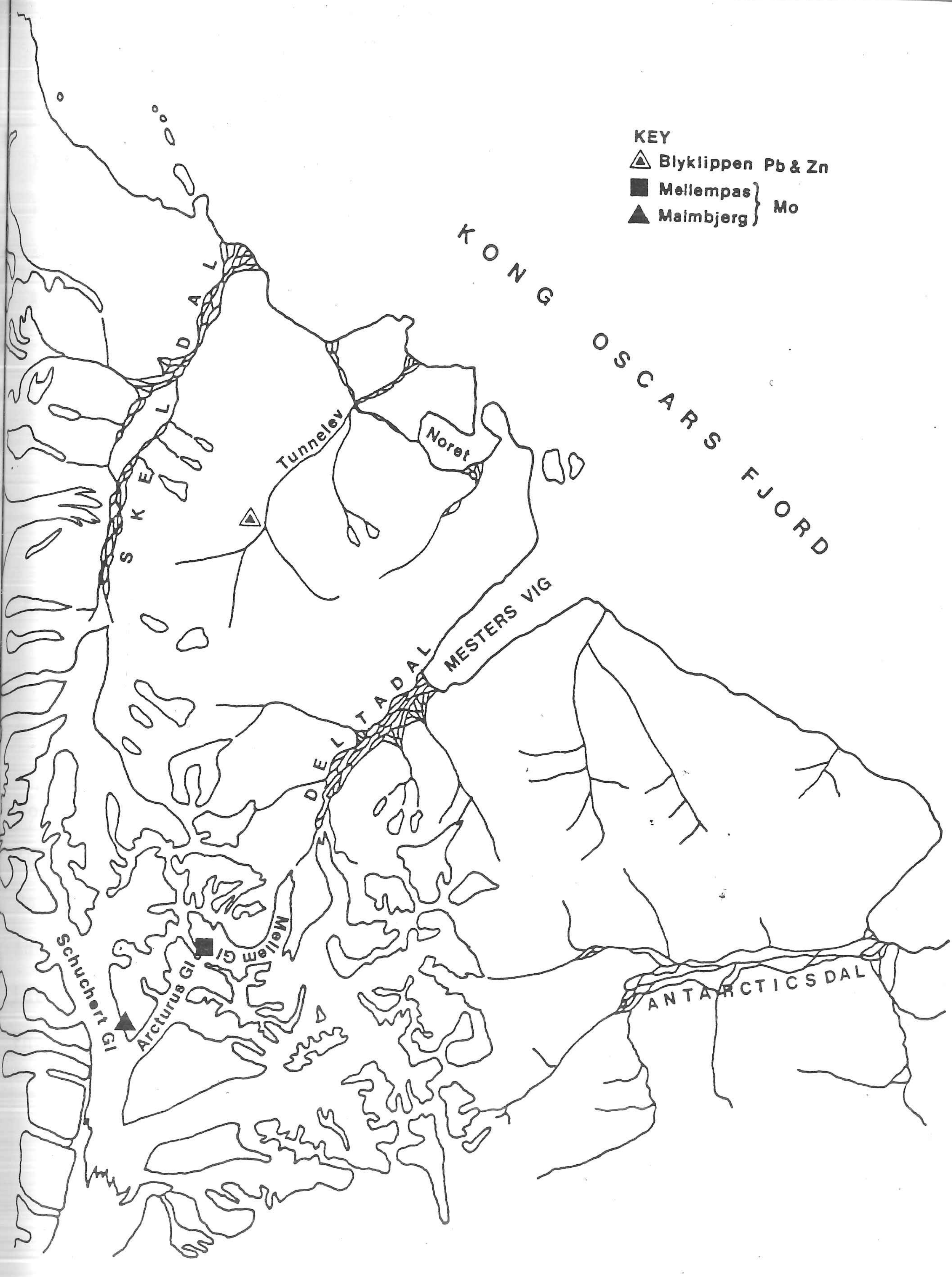
Tunnelelv River & 1988 sampling sites

	1.Store Blydal	2.Gefion	3.Tunnelelv #1	4.Tunnelelv #2
Lead (Pb^{++})	13.2	14.0	84.8	217.8
Zinc (Zn^{++})	75.8	75.0	298.5	366.5

(all values in $mg.kg^{-1}$)

TABLE A

Downstream increases in lead and zinc levels within contemporary channel sediments from the Tunnelelv river system



MAP 2

Location of the Malmbjerg and Mellempas molybdenum deposits relative to the main field work area

EXPEDITION BUDGET

			£000.00p
Pre-Expedition Expenses:			
Administration (postage etc.)			250.00
Equipment			
Scientific	100.00		
Photographic	150.00		
Maps & Air Photos	50.00		
Medical	100.00		300.00
Transport			
Newcastle to Glasgow (BR)		150.00	
Glasgow to Reykjavik (Icelandair)		740.00	
Reyk. to Akureyre (Flugfelag Nordurlands)		300.00	
Akur. to Mesters Vig (Flugfelag Nordurlands)		2900.00	
(all return journeys for 6 people)			4100.00
Freight			
Newcastle to Glasgow		20.00	
Glasgow to Reykjavik (Icelandair)		550.00	
Reyk. to Mesters Vig (Flugfelag Nordurlands)		550.00	
Mesters Vig to Reyk. (Flugfelag Nordurlands)		200.00	
Reyk. to Glasgow (Icelandair)		200.00	
Glasgow to Newcastle		20.00	
(weight calculated as 500kg)			1540.00
Food			400.00
Insurance			700.00
Post-Expedition Expenses:			
Administration (Report etc.)			100.00
Laboratory Analysis			750.00
Photographic (developing)			120.00
		SUB TOTAL:	8260.00
		15% contingency:	1240.00
		TOTAL:	9500.00
		Less £800 members contribution:	4800.00
		TOTAL REQUIRED:	4700.00

EXPEDITION BACKING & APPROVAL

Approval and funding secured:
Newcastle University approved and funded (£425 from exploration council)

Approval and funding applied for or pending:
Newcastle University Students Union (approval and funding pending)
Royal Geographical Society
Royal Society (20th Int. Geogl. Congress & Dudley Stamp Memorial Fund)
Auto Carto/RCIS Education Trust
Scott Polar Research Institute (Gino Watkins & Edward Wilson Funds)
Scientific Exploration Society
Adrian Ashby-Smith Memorial Fund
Springboard Trust
Edinburgh Trust No.2
British Ecological Society
Manchester Geographical Society
27 Foundation
Rev DJ Streeter Charitable Trust

CONTACTS & ADVISORS

General:
Dr Hal Lister
(formerly Department of Geography, Newcastle University)
Will Higgs
(Field Leader, Erskine Expeditions)

Metal mining and sediment contamination:
Dr Mark Macklin & Prof. Malcolm Newson
(Department of Geography, Newcastle University)

Vegetation succession:
Prof. Arne Strid & Dr Bent Fredskild
(Greenland Botonical Survey, Copenhagen, Denmark)
John Richards
(Department of Biology, Newcastle University)
Roger Smith
(Department of Agricultural Biology, Newcastle University)
Judith Maizells
(Department of Geography, Aberdeen University)

Palaeontology:
Dr Alec Panchen
(Department of Zoology, Newcastle University)
Jennifer Clack
(Asst. Curator, University Museum of Zoology, Cambridge)

PROJECT: NEWCASTLE UNIVERSITY EAST GREENLAND EXPEDITION

YEAR: 1989

TASK	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT–DEC
RESEARCH PROPOSAL		PRELIMINARY		FINAL REV.										
BROCHURE		PREPARE	ASSEMBLE	FINAL REV.										
PATRONS ?				WRITE										
FINANCE				OPEN ACCOUNT										
HOST COUNTRY PERMSN			APPLY TO DANISH AUTHORITIES			REPLY ?								
FOREIGN CONTACTS			APPROACH DANISH UNIVERSITIES											
EXPEDITION TEAM			SELECTION											
INSURANCE					ARRANGE INSURANCE									
TRAVEL ARRANGEMENTS	PRELIMINARY INQUIRIES				PRELIM. BOOKING		FINAL BOOKING							
FREIGHT	PRELIMINARY INQUIRIES				PRELIM. BOOKING		FINAL & SEND - - - - → ?							
FUND RAISING					← - - - - - - - - - - - - - - → (JAN–JUL)								← - - - - → ?	
TRAVEL											OUT	BACK		
FIELD WORK (6 WKS)											← - - - - → (JUL–AUG)			
EQUIPMENT		REQUIREMENTS?			← - - - ASSEMBLE - - - → (JAN–APR)									
FOOD		REQUIREMENTS?			← - - - ASSEMBLE - - - → (JAN–APR)									
TRAINING WEEK ENDS						*		*						
APPLICATIONS FOR APPROVAL & SUPPORT...														
ROYAL GEOG'L SOCIETY					FORM 31ST.									
ROYAL SOCIETY					FORM 31ST.									
M'CHESTER GEOG'L SOC.						FORM 1ST.								
AUTO-CARTO/RECS						FORM 1ST.								
EDINBURGH TRUST #2					LETTER 31ST									
E. ASHBY-SMITH MEM. TRUST									FORM 1ST.					
EXPLORERS CLUB					FORM 31ST.									
BRITISH ECOLOGICAL SOC.					LETTER 31ST									
SCIENTIFIC EXPLORATN SOC.							LETTER 31ST							
SPRINGBOARD CH. TRUST														
REW STREETER CH. STTLMNT							LETTER 1ST.							
27 FOUNDATION														
GINO WATKINS (SPRI)							FORM 1ST.							
EDWARD WILSON (SPRI)							FORM 1ST.							
REPORTS													PRELIMINARY	FULL
LECTURES & SLIDES													← - - - - - - → (SEPT–OCT–DEC)	

EXPEDITION MEMBERS

NAME & DUTY	EXPERIENCE
ELLA BRETT Surveyor/Food	Course: Jnt Hons Surveying/Geography yr2 Age: 19 Newcastle University Peru Expedition 1988 (treasurer, food manager and geographical project leader) Mountaineering (hillwalking, rock and snow & ice climbing) experience in UK and Peru. Gold Duke of Edinburgh Award
STEVE CARVER Geomorphologist Travel & Freight	Course: PhD Geography (Geogr. Info. Systems) yr3 Age: 23 Mountaineering, especially rock climbing & hill walking. President of university Exploration Society Research interests in fluvial geomorphology and hydrology.
JANICE DICK Analytical Chem. Eqpt. & Secretary	Course: PhD Chemistry (Phys) yr3 Age: 24 Mountaineering, experience in UK and Alps. Queens Scout Award MSc Analytical Chemistry Research interests in concentrations of heavy metals in river sediments.
SIMON MUNRO Leader & Medic Treasurer	Course: BSc (Hons) Geophysics & Planetary Physics yr2 Age: 20 Newcastle University Peru Expedition 1988 (deputy leader and asst. Geophysical project) Mountaineering, experience in Peru, the Alps and Scotland. Canoeing
DAVE SEAR Geomorphologist Maps & Air Photos Scientific Eqpt.	Course: Phd Civil Engineering yr2 Age: 23 Experienced hill walker BSc (Hons) Geography & Environmental Studies Research interests in metal mining and fluvial systems

UK HOME CONTACT:
Prof. Malcolm D Newson
Dept of Geography, Newcastle University,
Newcastle upon Tyne. NE1 7RU.
Tel: (091) 2328511

Appendix B

List of supporting bodies

We would like to thank the following individuals, organisations, institutions and companies who supported the 1989 Newcastle University East Greenland Expedition.

Academic

The University of Newcastle upon Tyne
The Exploration Council, University of Newcastle upon Tyne
The Newcastle University Exploration Society
Prof Malcolm Newson, Department of Geography, University of Newcastle upon Tyne
Dr Hal Lister, formerly of Department of Geography, University of Newcastle upon Tyne
Mr Watts Stelling, Department of Geography, University of Newcastle upon Tyne
The staff and students of the University of Newcastle upon Tyne

Grant-giving organisations

The Manchester Geographical Society
The Percy Sladen Memorial Trust, c/o The Linnean Society
The Gino Watkins Memorial Fund, c/o The Scott Polar Research Institute

Other organisations

The Royal Geographical Society

Commercial companies

Mr John Hall, Cameron-Hall Developments
BCB International Ltd.
Beecham Bovril Brands
Colmans of Norwich
Del Monte Foods Ltd.
Dunelm Wholefoods Ltd.
Greens of Brighton
Kalvi Ltd.
Lyons Bakery Ltd.
Manley Ratcliffe Ltd.
St Ivel Ltd.
Simmers Biscuits
Shepherdboy Ltd.
Trebor Ltd.

General

Our Patron, Sir Vivian Fuchs
Mr Will Higgs of Erskine Expeditions
Our friends and parents
The people of Tyneside

Appendix B

List of supporting bodies

We would like to thank the following individuals, organisations, institutions and companies who supported the 1989 Newcastle University East Greenland Expedition.

Academic

The University of Newcastle upon Tyne
The Exploration Council, University of Newcastle upon Tyne
The Newcastle University Exploration Society
Prof Malcolm Newson, Department of Geography, University of Newcastle upon Tyne
Dr Hal Lister, formerly of Department of Geography, University of Newcastle upon Tyne
Mr Watts Stelling, Department of Geography, University of Newcastle upon Tyne
The staff and students of the University of Newcastle upon Tyne

Grant-giving organisations

The Manchester Geographical Society
The Percy Sladen Memorial Trust, c/o The Linnean Society
The Gino Watkins Memorial Fund, c/o The Scott Polar Research Institute

Other organisations

The Royal Geographical Society

Commercial companies

Mr John Hall, Cameron-Hall Developments
BCB International Ltd.
Beecham Bovril Brands
Colmans of Norwich
Del Monte Foods Ltd.
Dunelm Wholefoods Ltd.
Greens of Brighton
Kalvi Ltd.
Lyons Bakery Ltd.
Manley Ratcliffe Ltd.
St Ivel Ltd.
Simmers Biscuits
Shepherdboy Ltd.
Trebor Ltd.

General

Our Patron, Sir Vivian Fuchs
Mr Will Higgs of Erskine Expeditions
Our friends and parents
The people of Tyneside

Appendix C

An observation of roll waves in a supra-glacier meltwater channel
Journal of Glaciology
(Paper in press)

AN OBSERVATION OF ROLL WAVES IN A SUPRA-GLACIER MELTWATER CHANNEL

Steve Carver, Dave Sear and Eric Valentine
University of Newcastle upon Tyne
Newcastle upon Tyne
NE1 7RU

Abstract

Observations of pulsating flow conditions in a supra-glacier meltwater channel on the Harlech Gletscher, East Greenland are reported. Measurements taken at the time are given together with calculations supporting the authors hypothesis of roll waves in a natural ice channel.

1. Introduction

Whilst traversing the Harlech Gletscher in early August 1989 after an ascent of the Harlech Fjeld (1900 metres) in the Berserkerbrae region of the North Staunings Alper, East Greenland, marked pulsating flow conditions were observed in a supra-glacier meltwater channel. The time between discharge peaks at the point of observation (estimated at between 0.5 and 1.0 cumecs) was measured at 6-7 seconds, in between which discharge was zero. It is suggested that this was due to the formation of roll waves in response to channel morphology and prevalent discharge conditions. The following paper gives a short description of the phenomenon as observed, basic measurements made at the time of observation, an outline to the theory of roll wave formation, supporting calculations and a brief discussion.

2. Location and description of the Harlech Gletscher

The Harlech Gletscher is located approximately 72 degrees 10 minutes North, 24 degrees 40 minutes West in the north east corner of the Stauning Alper were it forms a tributary of the Berserkerbrae (see figure 1). The Staunings Alper comprises an area of mainly granitic intrusions into Cambrian and Precambrian rocks enclosed roughly by Kong Oscars Fjord to the north, Nordvestfjord to the south, Skeldal and Schuchert Dal to the east and Nathorst Land to the west. These mountains can be described as being typical Arctic alpine in character.

The Harlech Gletscher lies between 700 and 1300 metres above sea level with a west-east orientation in direction of flow. The glacier is approximately 5 kilometres long and is fed by two main cirque glaciers at its head. The glacier surface has a relatively even gradient at the point of observation, with little evidence of crevassing.

3. Observations of pulsating flow

At the time of observation pulses of meltwater (estimated at between 0.5-1.0 cumecs peak discharge) were passing rapidly downstream at intervals of 6-7 seconds between peaks. At minimum discharge between peaks the channel was completely dry (with the exception of a small amount of runoff from the channel banks and sides together with the water retained in channel pools), such that it was possible to climb down into the channel and up onto the opposite bank in between the passage of waves. The wave front of each pulse was noted to be turbulent. The turbulent wave front and dry channel immediately in front of the advancing wave are clearly shown in figure 2.

The channel itself was noted to be gently sinuous (sinuosity = 1.43) and of near uniform cross-section. The longitudinal section was marked by a smooth undulating bedform analogous to pools and riffles. This is shown in figure 3. The time of observation was 18.00 hours local time (roughly at the peak in diurnal fluctuation of discharge due to solar heating). Investigation of the channel and catchment area upstream revealed no obvious siphon feature and furthermore, the 'pulsating' effect decreased with distance upstream such that zero discharge between peaks was no longer observed.

The following morning basic measurements of channel morphology were made using the rudimentary equipment available. Proper equipment for surveying and hydrological measurements was not available since the time spent by the expedition in the Staunings Alper was purely for the achievement of mountaineering objectives.

Arriving at the point of the previous days observations approximately 1.5 kilometres from the junction with the Berserkerbrae, pulsating flow had ceased and normal flow conditions resumed. Measurements were made using a 45m climbing rope (divided along its length in the manner of a surveying chain) and ice axes of known shaft length (65 and 55cm) and the ruled scale on a Silva-type compass for finer measurements. Overall channel gradient was measured by taking several measurements of the angle of slope using an improvised plumb-bob and the protractor on a Silva-type compass. Flow velocity was calculated by timing the passage of floating markers over a known distance. These measurements are summarised in figure 3. Although approximate, due to the nature of their measurement, these are used as the basis of tentative calculations given below.

4. Theory and calculations supporting roll wave formation

Roll waves are more or less regular surges of water, each somewhat like a section of a gradually varied flow profile ending in a bore (Townson, 1991). These form when uniform flow in inclined channels becomes unstable due to very high flow velocities and/or a very steep channel gradient. This instability is characterised by the formation of a series of roll waves as uniform flow breaks down into travelling waves or pulsating flow (Chow, 1973). Thomas (1940) describes pulsating flow as consisting of 2 parts, a turbulent head or wave front and a smooth tail section. This can be clearly seen in figure 2. This turbulent wave front is a result of the velocity of the wave being greater than that of the surface flow adjacent to the channel bed and sides giving rise to a breaking wave.

Roll waves were first reported by Cornish (1910) and have been studied experimentally and analytically by Jeffreys (1925). Attention has been focused on roll waves mainly in artificial channels such as inclined flumes and spillways, partly on account of their liability to overtop channel sides (Mayer, 1961). Most of these studies therefore relate to rectangular sections.

The following calculations and reasoning are presented in support of roll wave formation in natural ice channels. The friction slope may be expressed as:

$$(K\,Fr)^2$$

where K = relative roughness for ice channels ($k/R = 0.1$)
k = roughness height
R = hydraulic radius (where R approximates to d)
Fr = Froude Number ($U/\sqrt{gd}$)
U = calculated velocity (m/s)
g = acceleration due to gravity (9.82 m/s^2)
d = water depth (m)

Consequently, the condition for amplification of a disturbance which would lead to the formation of a roll wave is not only that the condition $Fr > 2$ is satisfied, but also that:

$$K2 > So/Fr^2$$

where So = channel slope

Taking the lower limit of Fr as 2, this gives $K < So/4$, as shown by Stoker (1957). For non-rectangular sections, the requirement for roll waves is expressed as:

$$U >= \alpha\, c$$

where α = the Escoffier coefficient (usually > 2)
c = wave (disturbance) celerity ($\sqrt{gd}$)

It follows that the maximum resistance for amplification is lower than for a rectangular section and so, for a particular slope, the band of velocities within which roll waves might form is evidently narrower in the case of non-rectangular channels.

Considering the ice channel described here, where a likely range of values of roughness would be 1 - 3mm and flow depths 0.2 - 0.5m then K would be approximately 0.0005 - 0.0006. Thus for the observed channel slope of So = 0.05, the criterion that $K2 < So/Fr^2$ is satisfied.

If the range of values of Manning's n for ice of 0.01 - 0.012 (Chow, 1973) is applied to the possible flow depths 0.2 - 0.5m then the calculated velocity, U, falls in the range 3.5 - 5.25m/s. This use of the Manning equation is an approximation for a steep channel but it does agree with the range of observed discharges. The wave celerity, c, for this range of depths is 1.4 - 2.21m/s. Therefore, the second criterion that $U >= 2c$ is also satisfied. It is also noted that the Froude Number would lie in the region of 2.37 - 2.5, thus $Fr > 2$, supporting the hypothesis of roll wave formation in a natural ice channel.

5. Discussion and conclusions

From the numerical analyses above, together with direct observation in the field, it is concluded that the phenomenon observed was roll waves. The critical conditions controlling roll wave formation are channel slope, flow velocity and depth. These are satisfied for the channel in question. The steep nature of the channel and the very low Manning's n for ice give rise to high flow velocities, whilst the time of observation at peak discharge due to solar heating provided sufficient depth of water in the channel for uniform flow to become unstable.

The behaviour of roll waves is strongly three dimensional and once conditions allow their formation, their spatial frequency seems to be strongly linked with that of upstream disturbances. In this instance it is likely that channel morphology in terms of its gently sinuous planform and smooth pool-riffle longitudinal section together with prevalent discharge conditions had a significant effect in accentuating wave formation. It is also possible that a progressive steepening of the Harlech Gletscher as it descends to meet the Berserkerbrae may have an effect both in increasing the channel slope and flow velocity giving rise to unstable flow conditions.

It is suggested that conditions in channels commonly found on glaciers in the lower ablation zone mitigate against the formation of roll waves. These include an increase in sinuosity, brought about by an increase in slope, and a strong variation in the longitudinal profile (i.e. deep pools, waterfalls, crevasses, etc.) causing increased resistance (accentuated by the presence of ice and rock debris) and reduced flow velocity. Conditions favouring the development of roll waves therefore decline downstream as several factors compound to reduce the Froude number of the channel to $Fr < 2$.

References

Chow, V.T., (1973) Open-channel hydraulics. McGraw Hill, London. Cornish, V., (1910) Waves of the sea and other waves. Fisher Unwin, London.

Jeffreys, H., (1925) The flow of water in an inclined channel of rectangular section. in Phil. Mag. 6(49), May 1925, p.793-807.

Mayer, P.G.H., (1961) Roll waves and slug flows in inclined open channels. in Trans. ASCE. 126, p.505.

Stoker, J.J., (1957) Water waves. Interscience, New York.

Thomas, H.A., (1940) The propagation of waves in steep prismatic conduits. in Proc. Hydraulic Conf. State University of Iowa, Studies in Engineering Bulletin, 20, p.214-229.

Townson, J.M., (1991) Free surface hydraulics. Unwin Hyman, London.

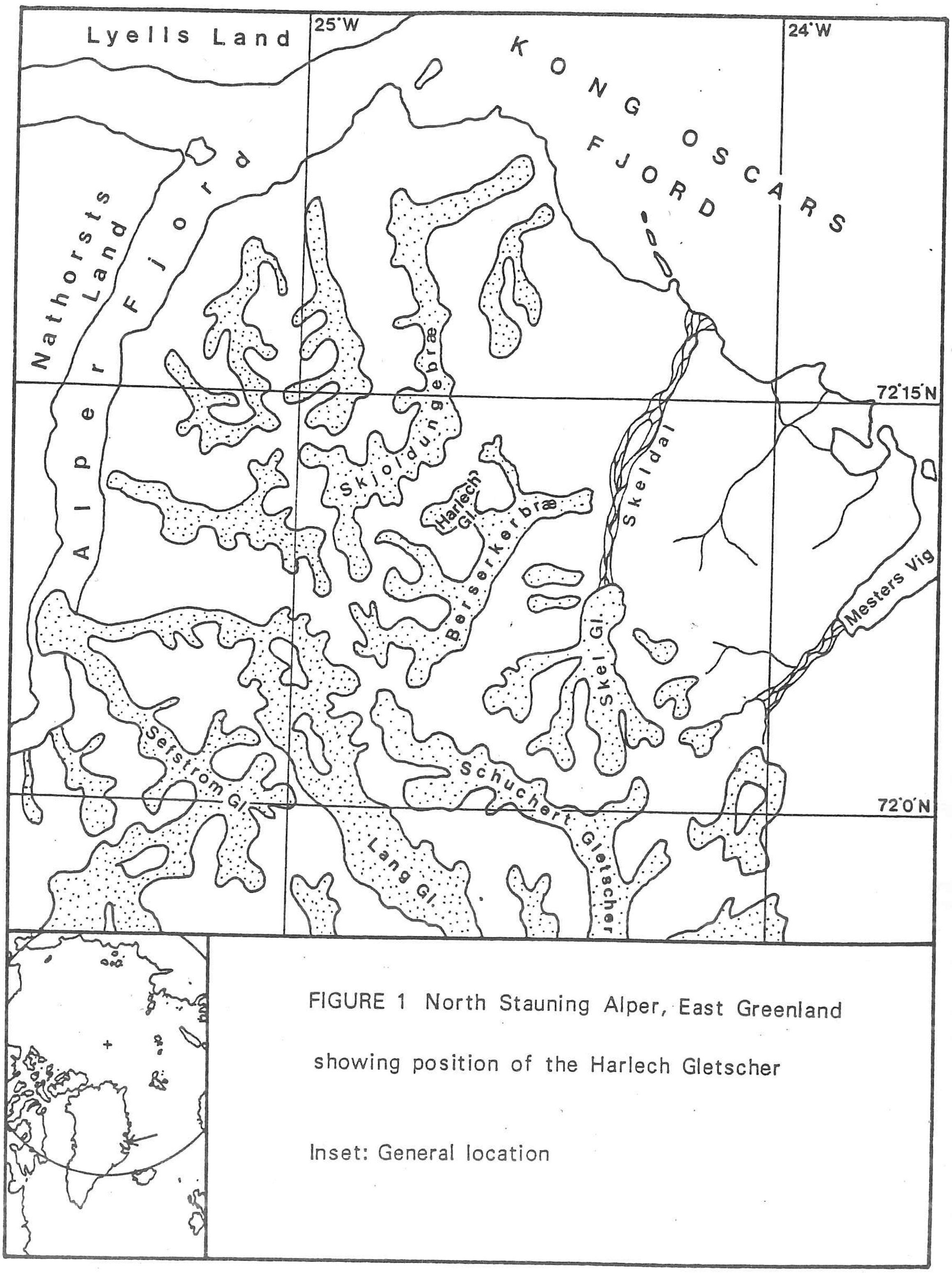
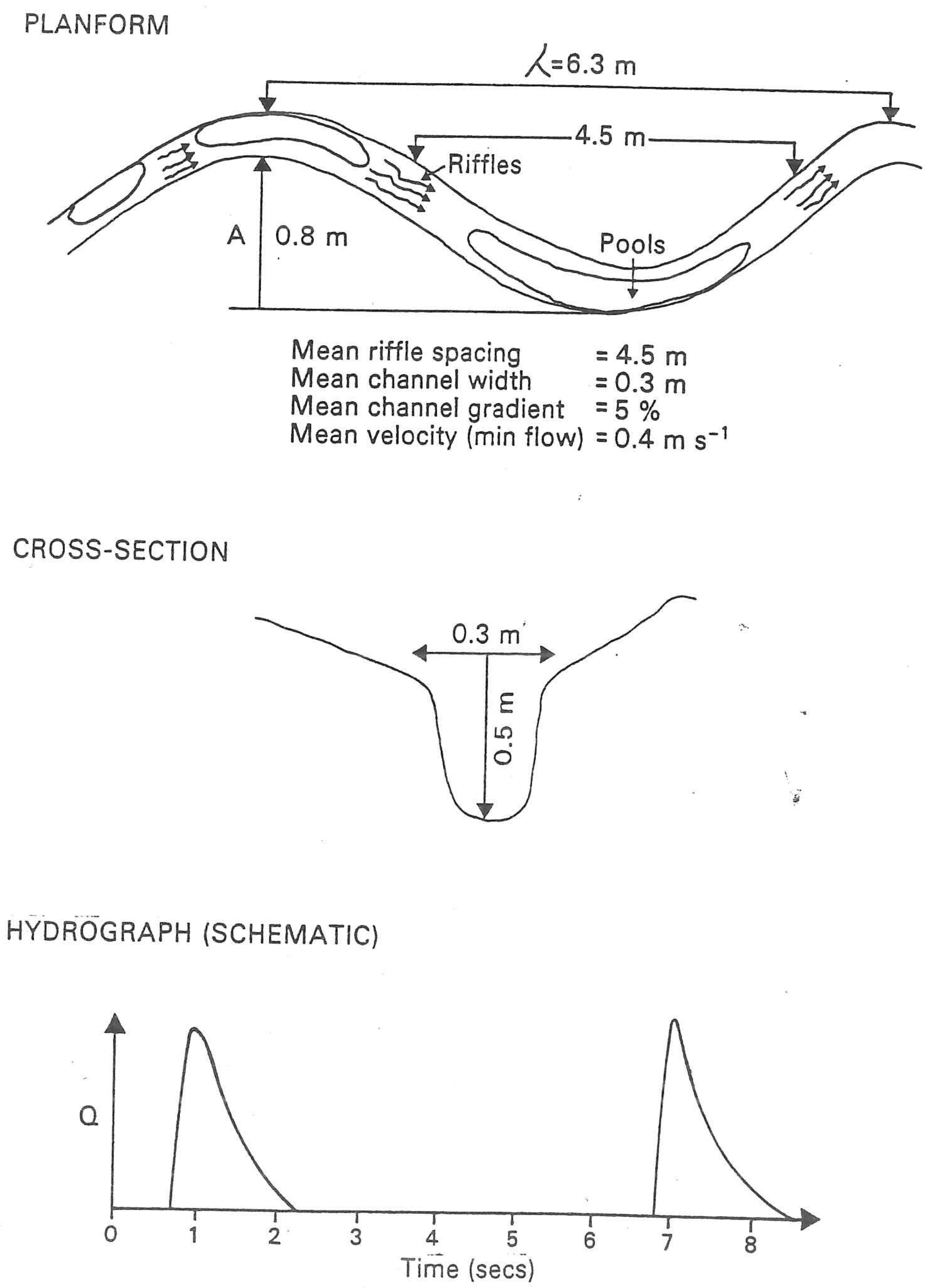
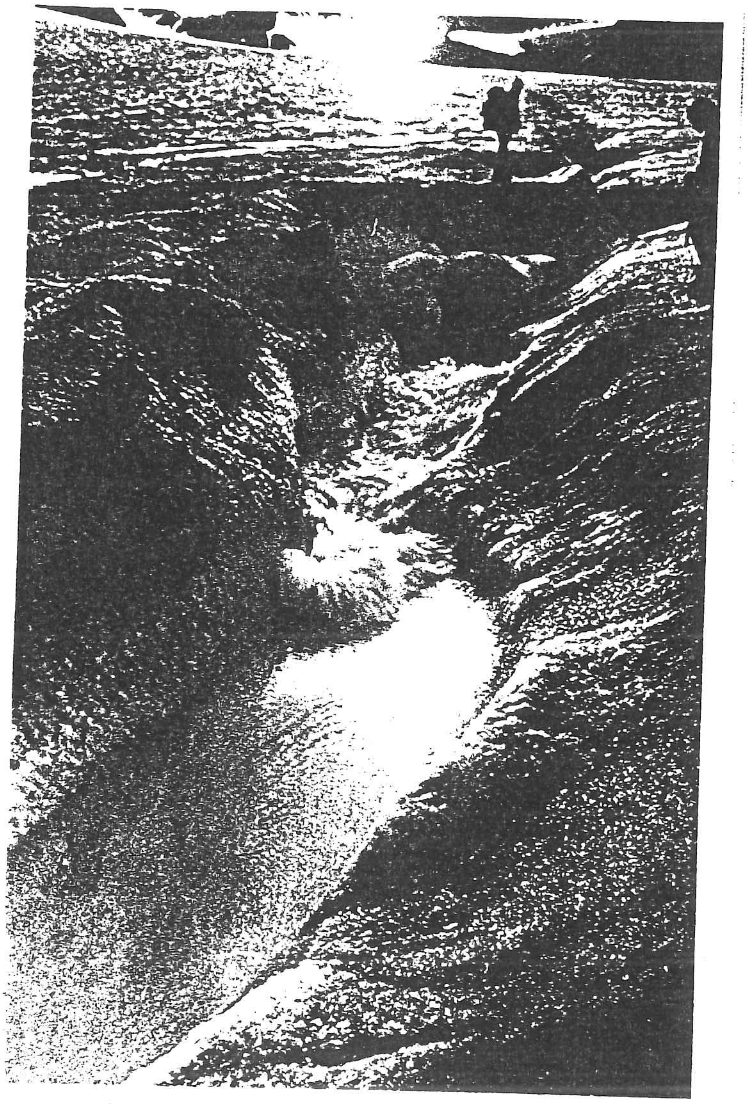


FIGURE 1 North Stauning Alper, East Greenland showing position of the Harlech Gletscher

Inset: General location

FIGURE 2 Channel morphology and schematic roll wave hydrograph.





NEWCASTLE UNIVERSITY
EAST GREENLAND EXPEDITION

1989 TUNNELELV RIVER PROJECT

FINAL REPORT

Steve Carver, David Sear, Jan Dick
Flemming Rune, Steve Naylor and Ella Brett

Newcastle University Exploration Society
Daysh Building
University of Newcastle upon Tyne
Newcastle upon Tyne
NE1 7RU

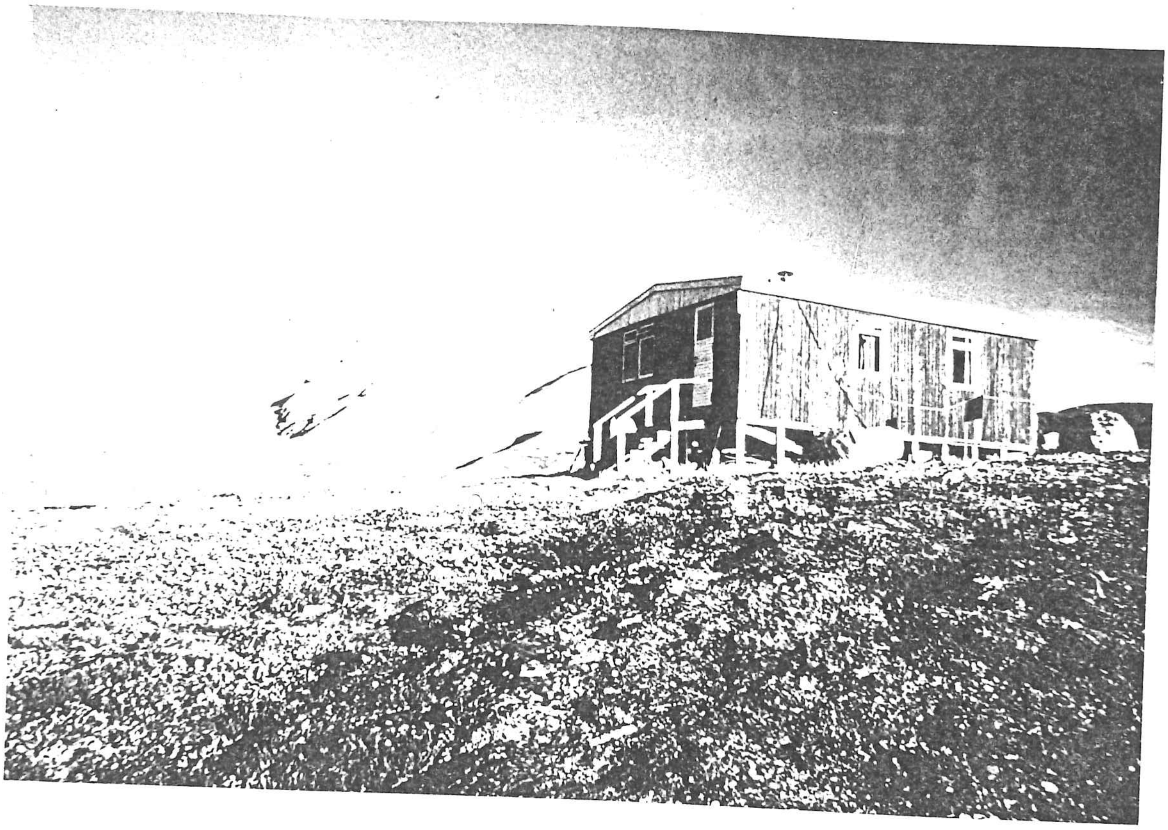


Figure 3.1: Washburn's Cottage

Figure 3.2: Deltadal

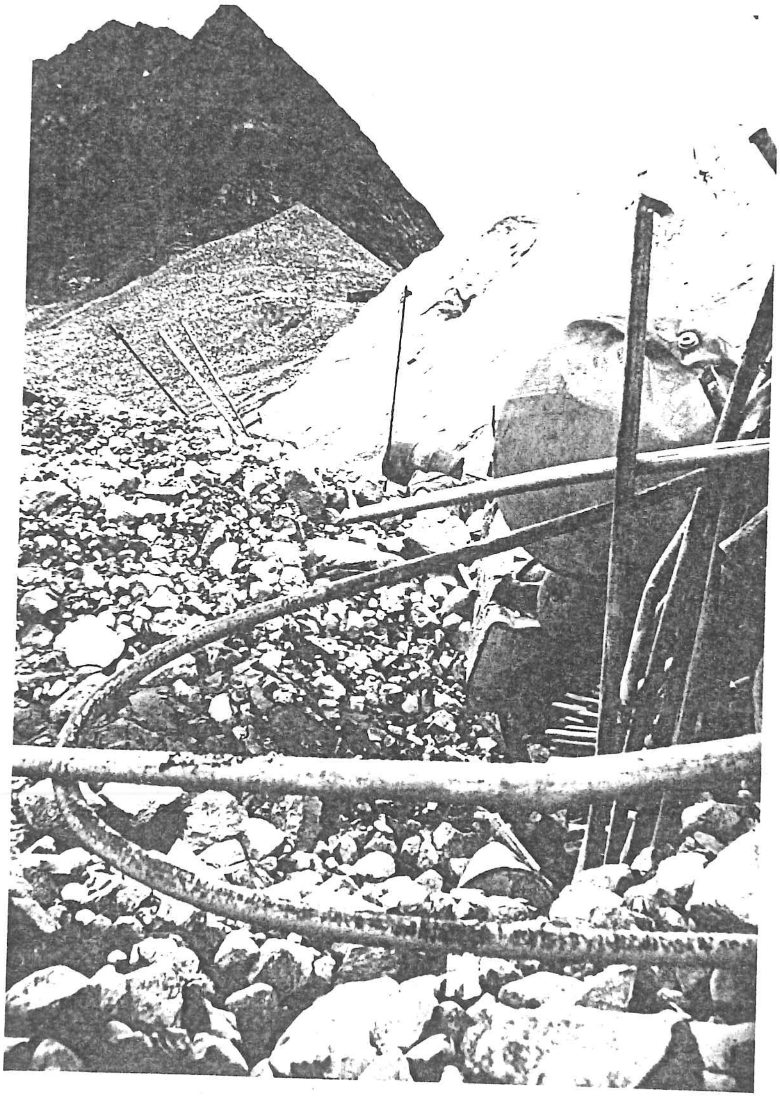


Figure 3.3: Rubbish left behind by mining operations at Malmbjerg

Figure 3.4: Kap Petersens

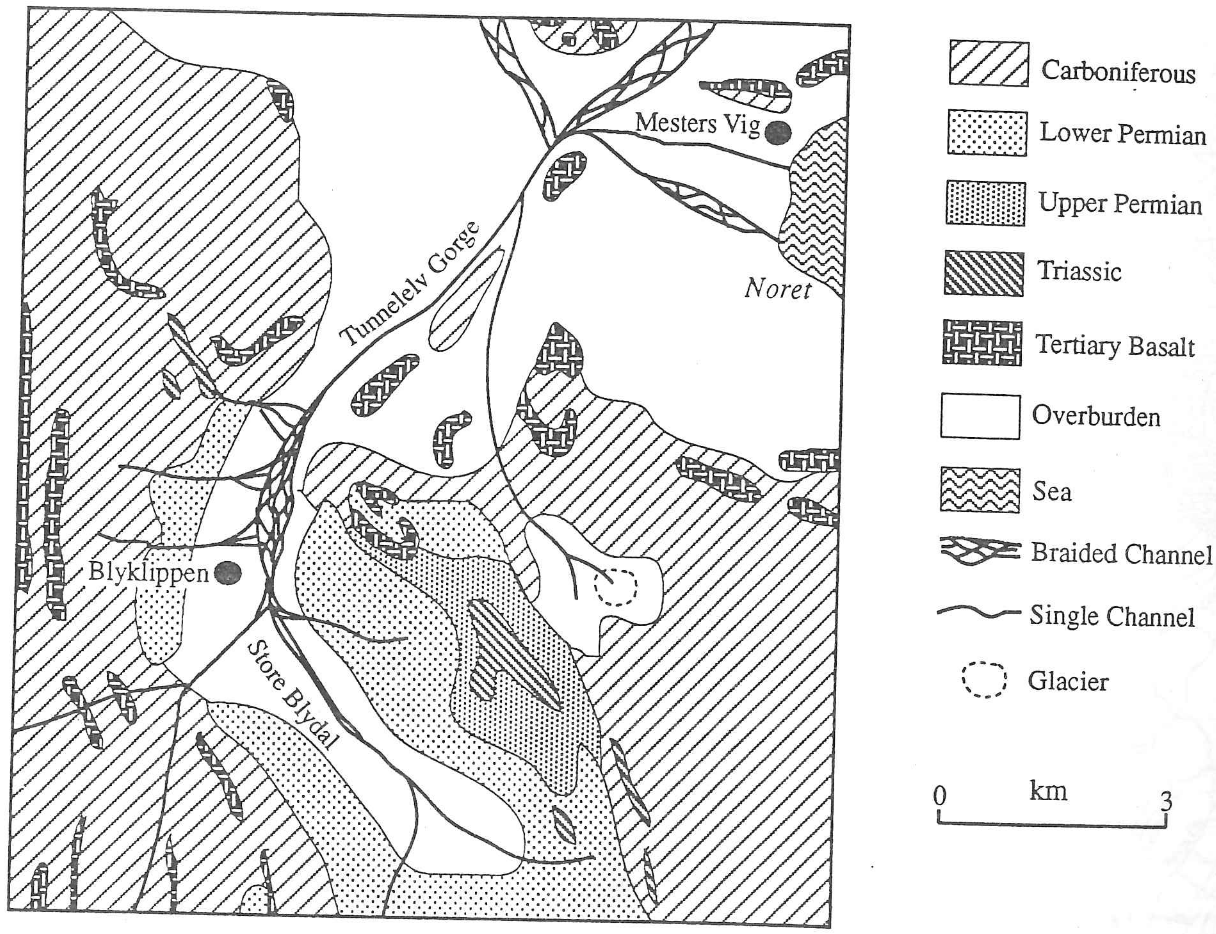
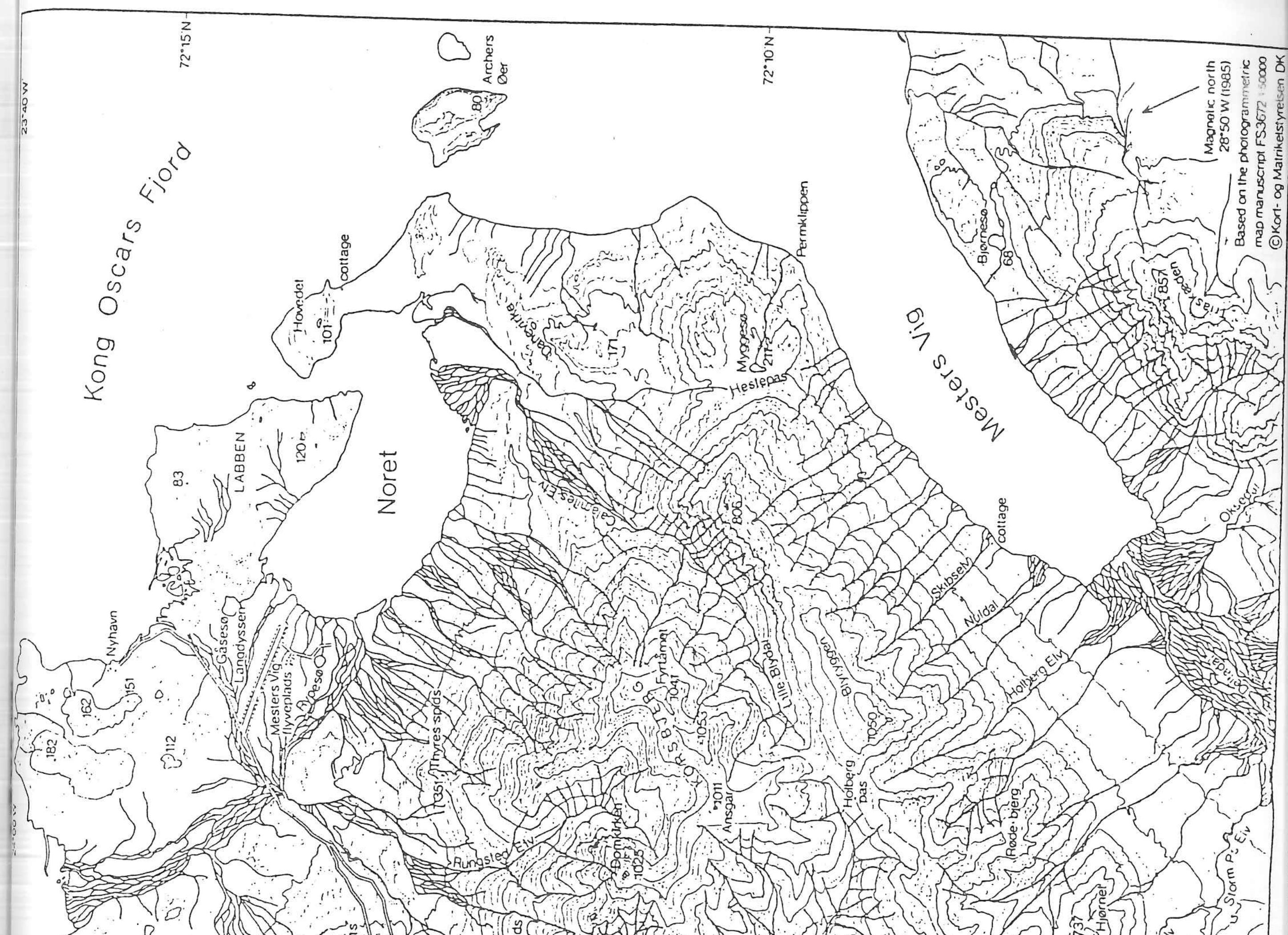


Figure 4.1: General Geology Map of the Tunnelelv Region, Mesters Vig.



MESTERS VIG
1:75000
Contour intervals 25 m
0 1 2 3 4 5
km
Kong Oscars Fjord
Archers Øer
72°15'N
72°10'N
Hovedet
cottage
LABBEN
Noret
Mesters Vig
Permklippen
Hestepas
Nyhavn
Gåsesø
Langdyssen
Mesters Vig flyveplads
Thyres spids
Rungsted Elv
Domkirken
Ansgar
Fyrtårnet
Lille Blydal
Blyryggen
Holberg pas
Holberg Elv
Nuldal
Skibselv
cottage
Washburns cottage
Tunnelelv
Gorms spids
Store Blydal
Minebyen
Langelinie
Nedre Gefionelv
Øvre Gefionelv
Hesteskoen
Blyklippen
Gletcherryggen
Nordre Funddal
Nedre Funddal
Profilbjerg
Hjørnet
Peters Elv
Pings Elv
Bjørnesø
SKELDAL
Magnetic north 28°50 W (1985)
Based on the photogrammetric map manuscript FS3672 1:50000
©Kort- og Matrikelstyrelsen DK
True north 0°
Cartography by F Rune 1989
Hovsmedevej 7
DK-3400 Hillerød

Figure 4.3(a): Headwater tributaries

Figure 4.3(b): Store Blydal braidplain (mine waste splay in foreground)

Figure 4.3(c): Tunnelelv gorge

Figure 4.3(d): Tunnelelv delta

Table 4.1 Documented Lead (Pb) and Zinc (Zn) levels in Sediments and Plants

Environment	Sediment	Pb (mg/kg)	Zn (mg/kg)	Source
Background				
G.B. Agricultural	Soil <2mm	10.9-145	29 - 210	Archer & Hodgson (1987)
Nethlnd Loess	Soil <2mm	34	84	Rang et al (1987)
Sub-recent Rhine	Soil <2mm	30	115	Salmons & Furstner (1984)
Late Holocene	Alluvium <2mm	17	61	Macklin (unpublished)
Late Holocene	Alluvium <2mm	81	61	Macklin (unpublished)
Mid Holocene	Alluvium <2mm	7.2 - 60.2	32 - 196	Macklin & Klimek (1992)
U.K.	Soil <2mm	50 - 500	2.5 - 560	Webber et al (1984)
Germany	Soil <2mm	30	50	" " " "
River Alluvium	Alluvium <2mm	55	145	Bradley & Cox (1986)
Arctic Greenland (Tunnelelv River)	**Stream/Soil**	**30**	**50**	**Kunzendorf (unpublished)**
Threshold Values				
Agric Soils UK	Soil	108	---	Archer (1980)
Agric Soil W.Uk	Soil	90 - 116	---	Davies (1983)
Agric Floodplain	Soil	125	---	Lewin et al (1983)
Urban Soils Tyne	Soil <2mm	80	345	Aspinall et al (1986)
Soils	Soil <2mm	67	---	Macklin et al (1985)
Arctic Fluvial (Tunnelelv River)	**River Sed <2mm**	**70**	**135**	**Kunzendorf (unpublished)**
Official Levels				
ICRCL Threshold values (acceptable)				
Vegetable Gardens	All Sediments	550	---	ICRCL (1980)
Amenity Land	" "	1500	---	" "
Public Open Space	" "	2000	---	" "
Dutch I.L.:				
Class A	All Sediments	50		
Class B (Warning)	" "	150	150	Dutch Ministry of Housing
Class C (treatment)	" "	600	500	" " " "
			3000	" " " "
Dutch Signal values				
Consumer Crop	All Sediments	200	350	
Pasture	" "	200	350	Leenaers (1989)
				" "
Maximum Permissable Levels				
CEC Directive	Agric. Soils	50 - 300	150 - 300	
UK	" "	550	560	Sauerbeck (1987)
France	" "	100	300	Webber et al (1984)
Germany	" "	100	300	" " " "
				" " " "
MAFF Maximum Permissable Levels				
Agricultural Soil	" "	300	---	MAFF UK
Foodstuffs	-----------	1	---	" "
Mineralised Areas	River Sed <2mm	8 - 500	1- 1900	Thoms (1987)
Mining	River Sed <2mm	16 -8000	17 -6055	" "
Industrial Areas	River Sed <2mm	6 -1430	30 -6220	" "
Urban Areas	River Sed <2mm	1 -2100	5 -6114	" "
Urban Areas	Soil <2mm	80 -2000	300 - 345	Aspinall et al (1986)
Polluted Fluvial				
Temparate W.Allen	Flood Sed <2mm	98-3166	74 -1131	Aspinall & Macklin (1983)
Temparate " "	Moss	807-13369	823 -2305	" " " "
Post-1988 Vistula	Alluvium <63	4.2 - 404	31 -7850	Macklin & Klimek (1992)
Post-1900 "	Alluvium <63	7.6 -1745	35 -11580	" " " "
Pre-1800 "	Alluvium <63	7.2 - 60	48 - 192	" " " "
2000-3000 BP "	Alluvium <63	8.8 - 33	123 - 196	" " " "
Temparate Geul	Alluvium <2mm	--- ---	500 -10000	Leenaers (1990)
Temparate Tyne	Flood Sed<2mm	500 -3000	1200-3000	Macklin & Dowsett (1989)
Temparate Twymyn	Alluvium <2mm	500 -6350	100 -7000	Lewin & Macklin (1989)
Temparate Ystwyth	Alluvium <2mm	150 -2200	100 - 900	" " " "
Temparate Towy	Alluvium <2mm	170 -5900	30 -3800	" " " "
Temparate Rea Br.	Alluvium <2mm	40 -6400	200 -11000	" " " "
Water				
Temparate W.Allen	Water	<0.5-2.5	0.03-0.64	Aspinall & Macklin (1983)
Guideline Levels	Water	2.0	2.0	Saunders (1990)
Arctic Greenland				

Figure 4.4: Morphological changes associated with metal mining at Blyklippen, Mesters Vig, Greenland. Data derived from aerial photography.

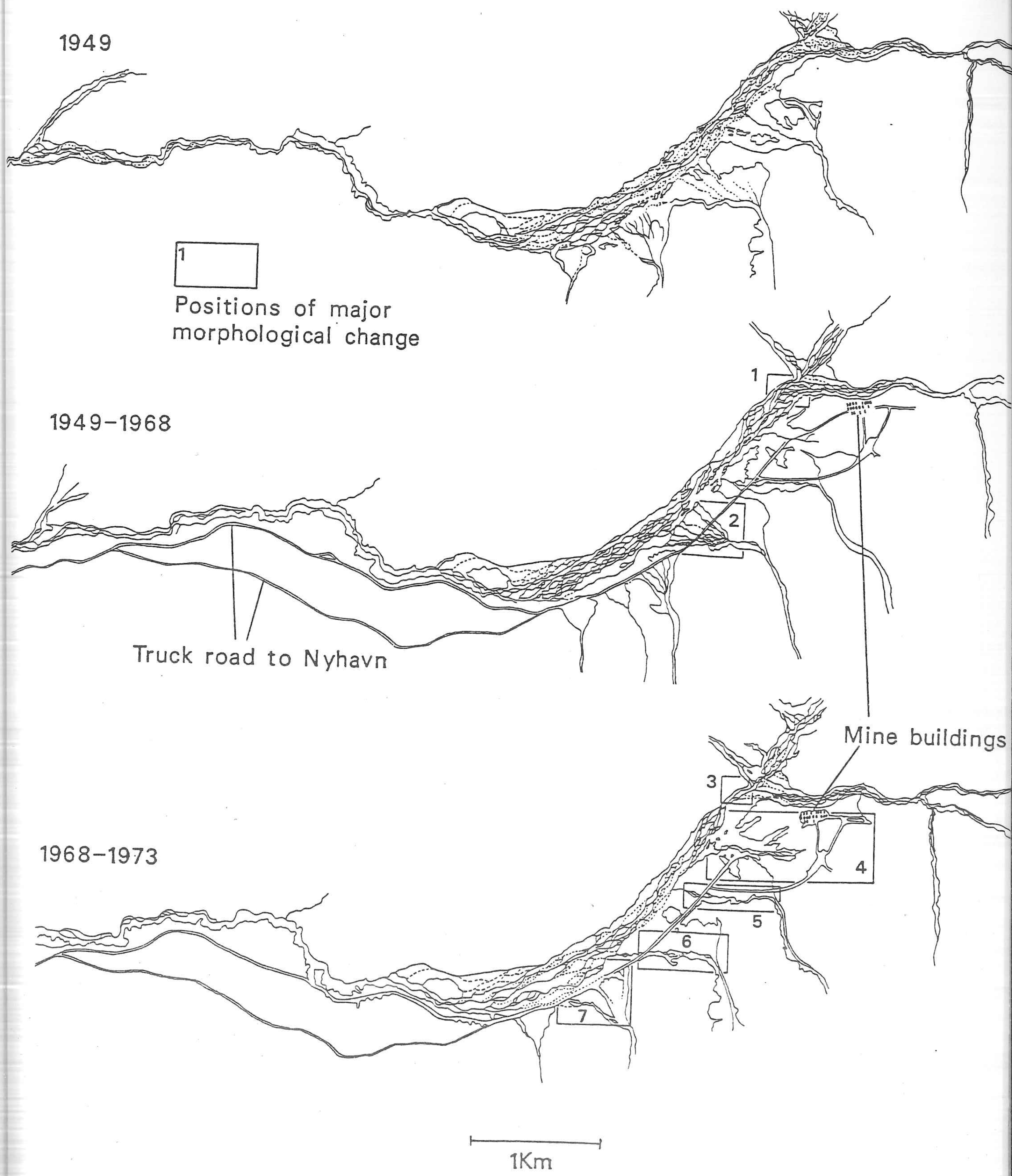


Figure 4.5: Aerial photograph of Blyklippen mine

Figure 4.6:

Morphological Map of the Store Blydal and Tunnelelv Gorge showing the mine site and tailings.

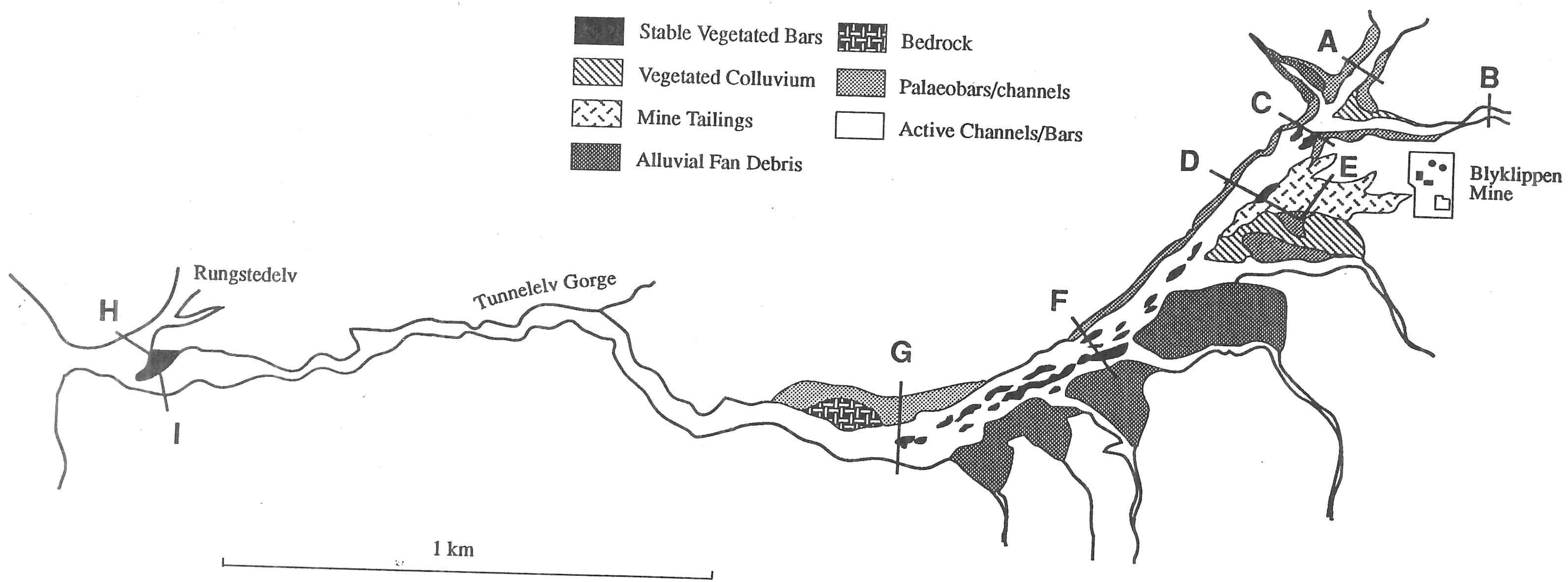


Figure 4.7: **Chemical and physical speciation of Pb and Zn within mine waste (E) and bar sediments (F). Store Blydal, Mesters Vig, Greenland.**

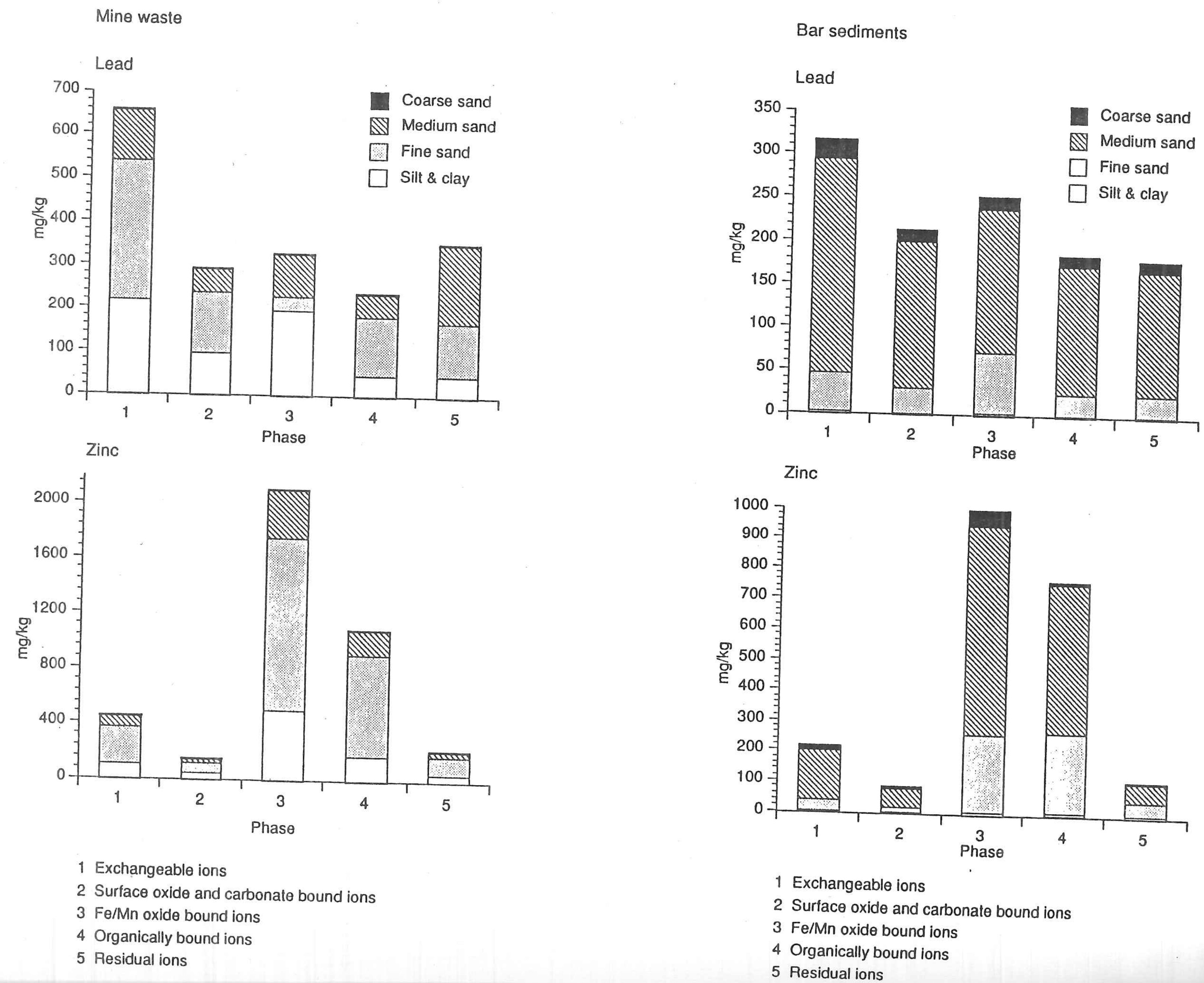


Figure 4.8:

Comparative models of metal concentration decline with increasing distance downstream from the mine site, Mesters Vig, Greenland. ICRCL Action and Threshold values are shown.

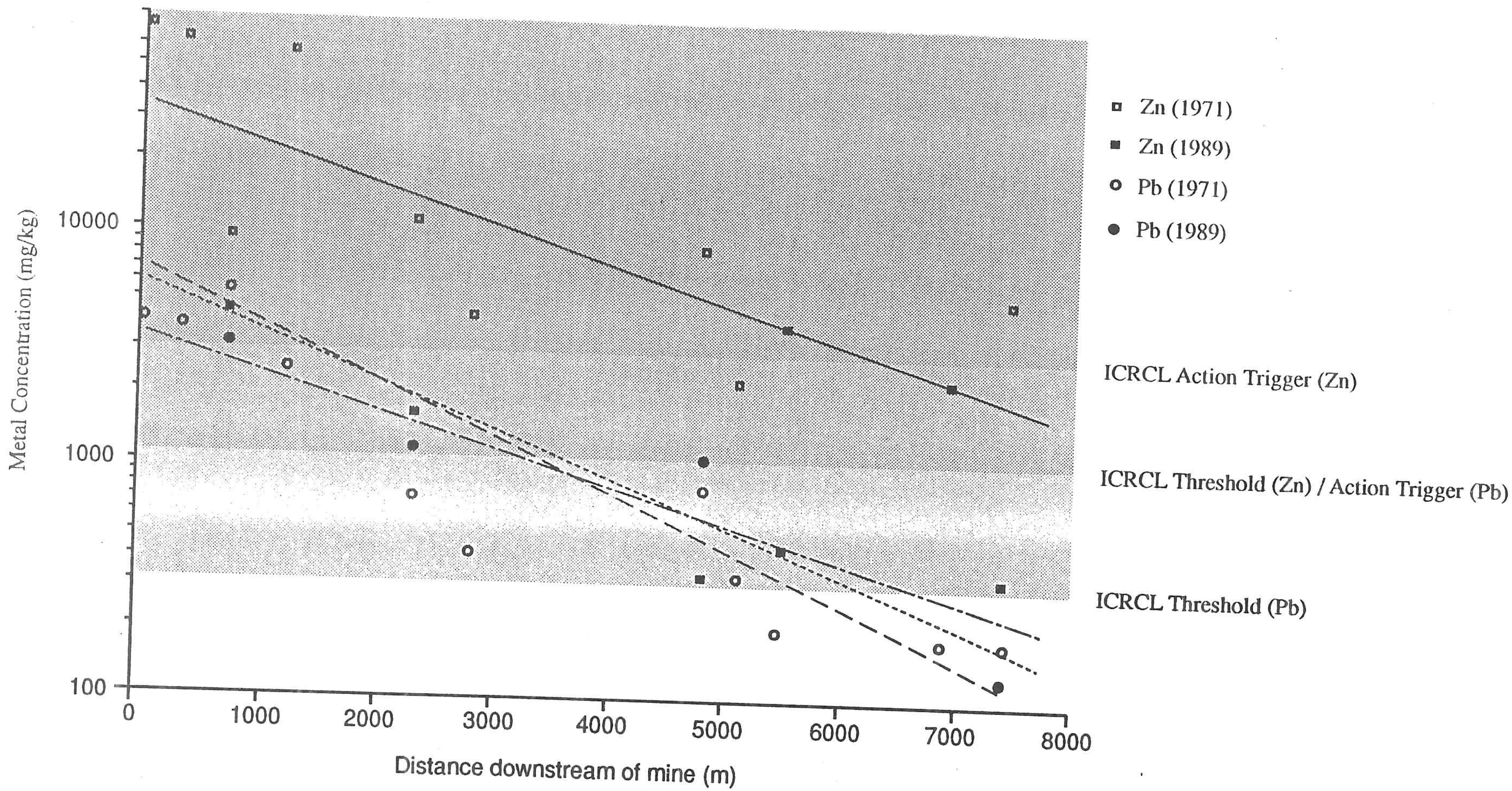


Figure 4.9: SECTION A

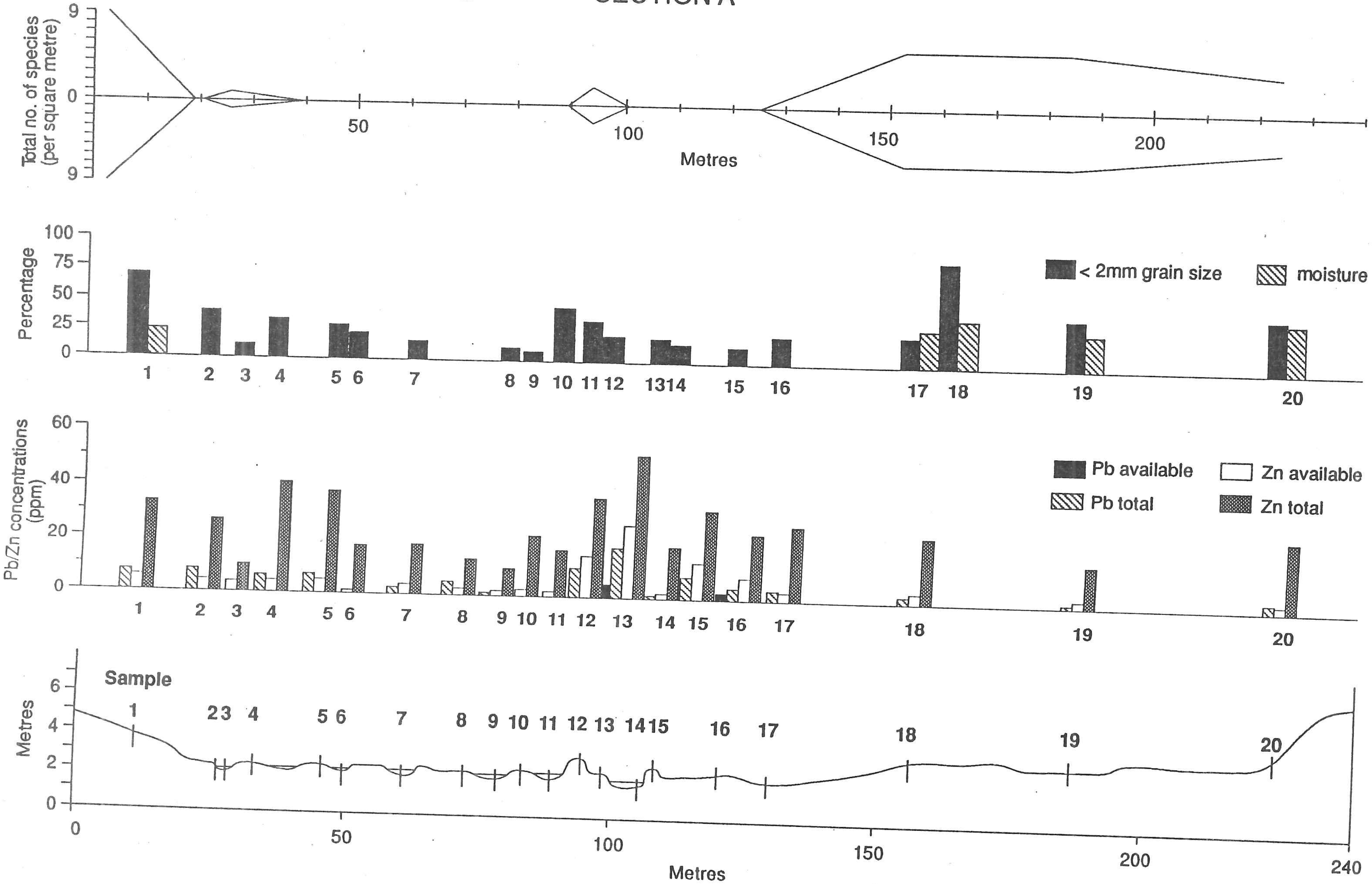
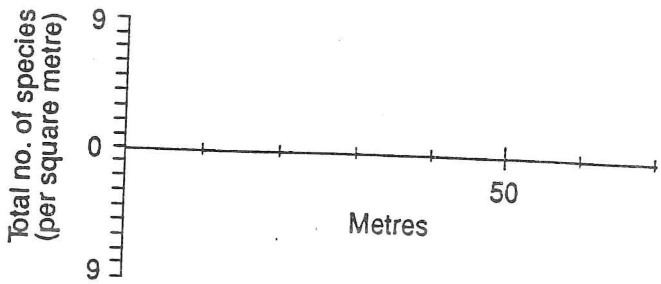
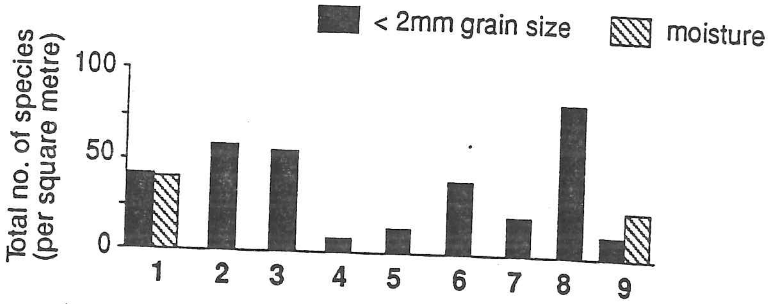
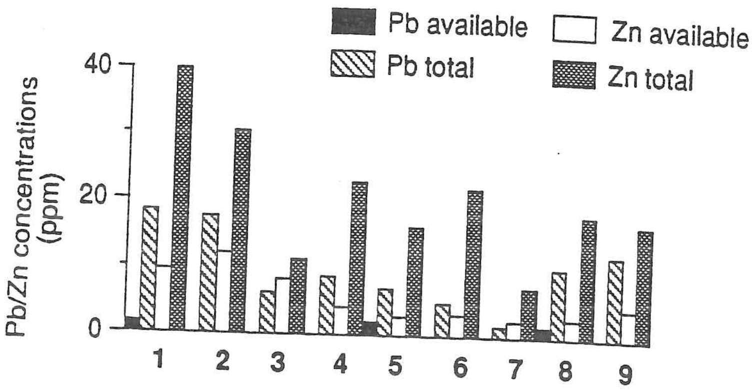


Figure 4.10: SECTION B







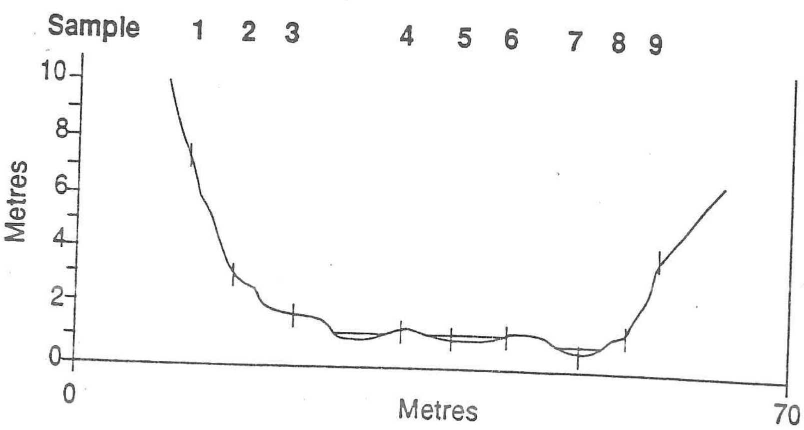


Figure 4.11: SECTION C

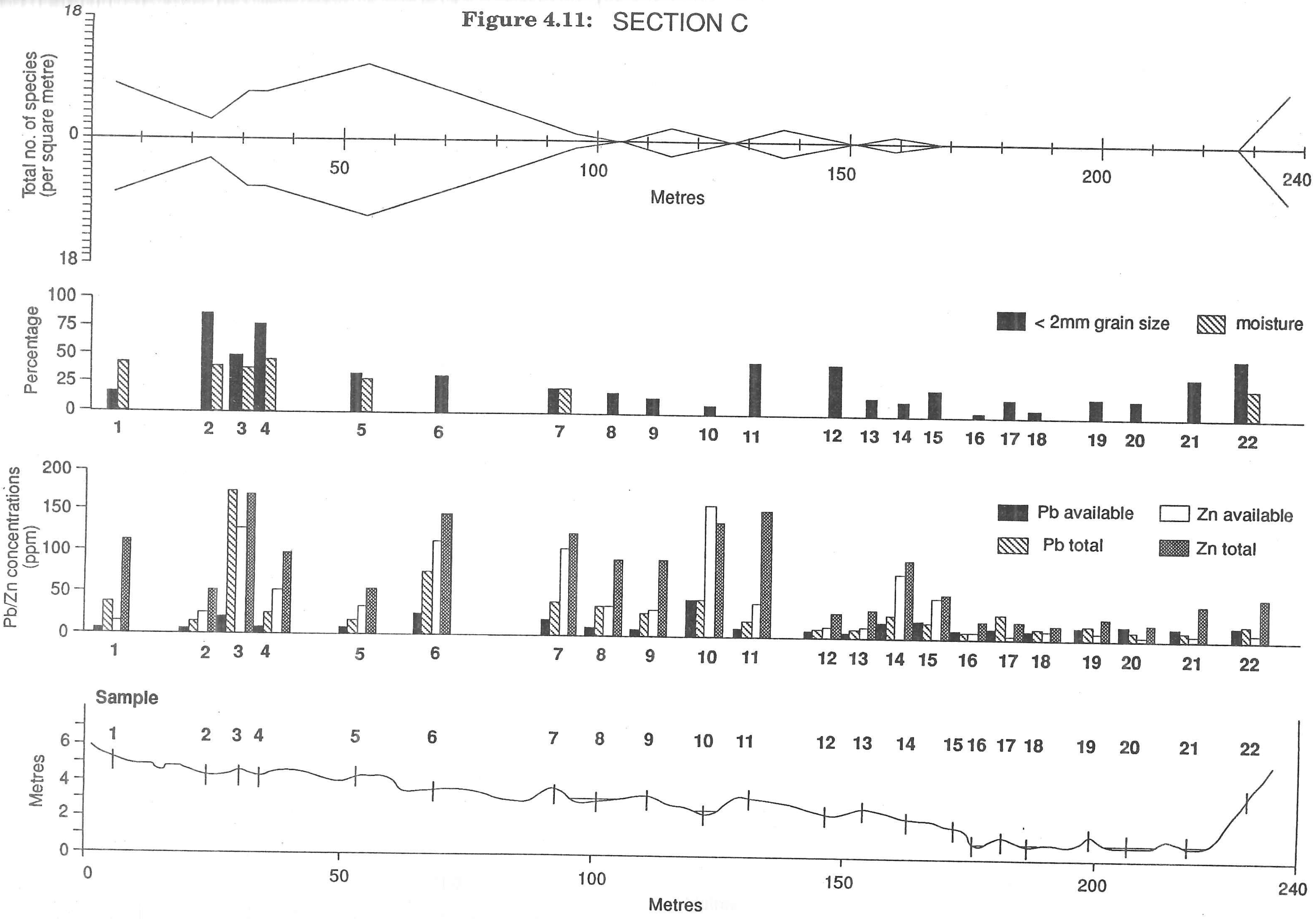


Figure 4.12: SECTION D

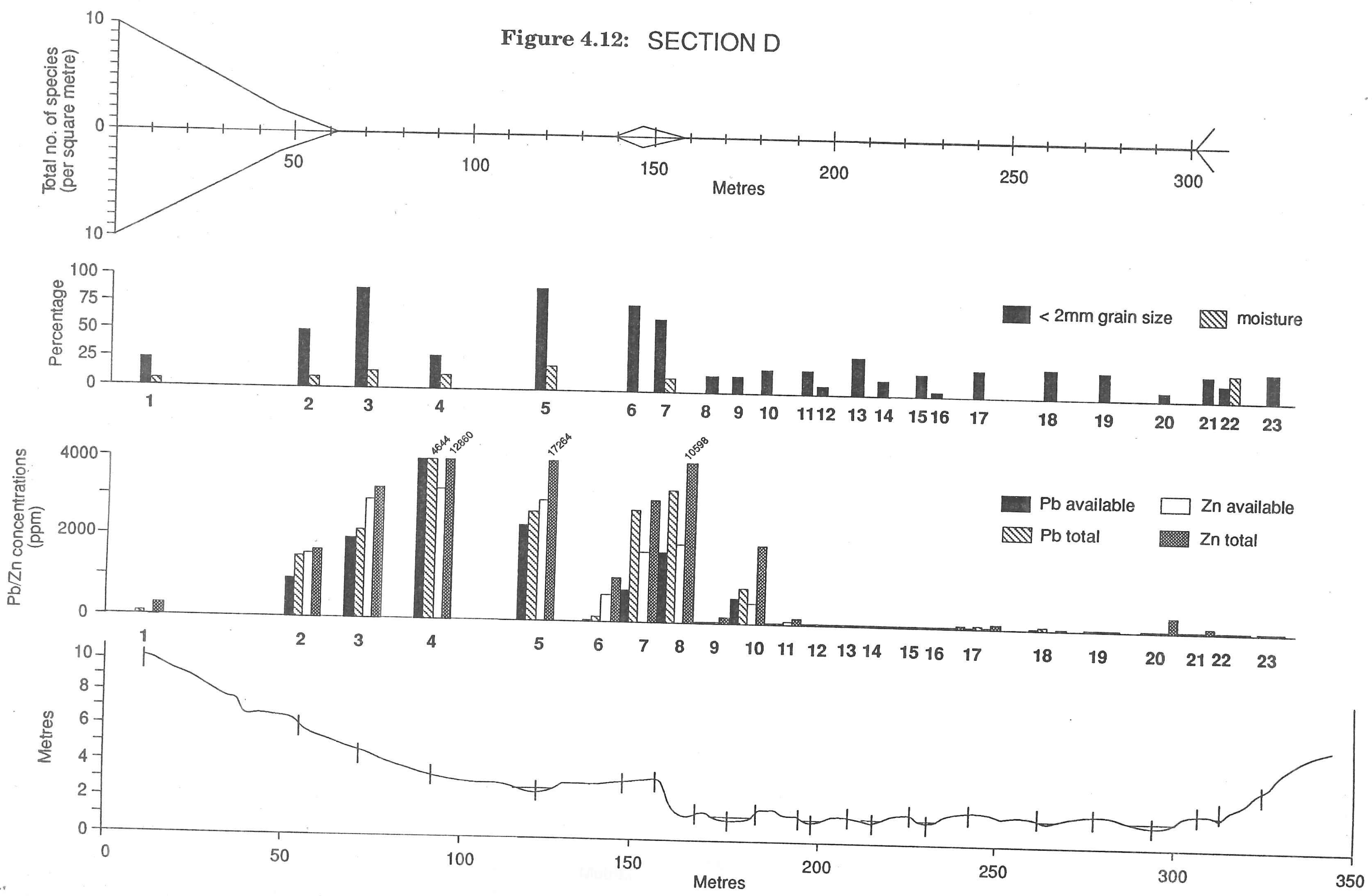


Figure 4.13: SECTION E

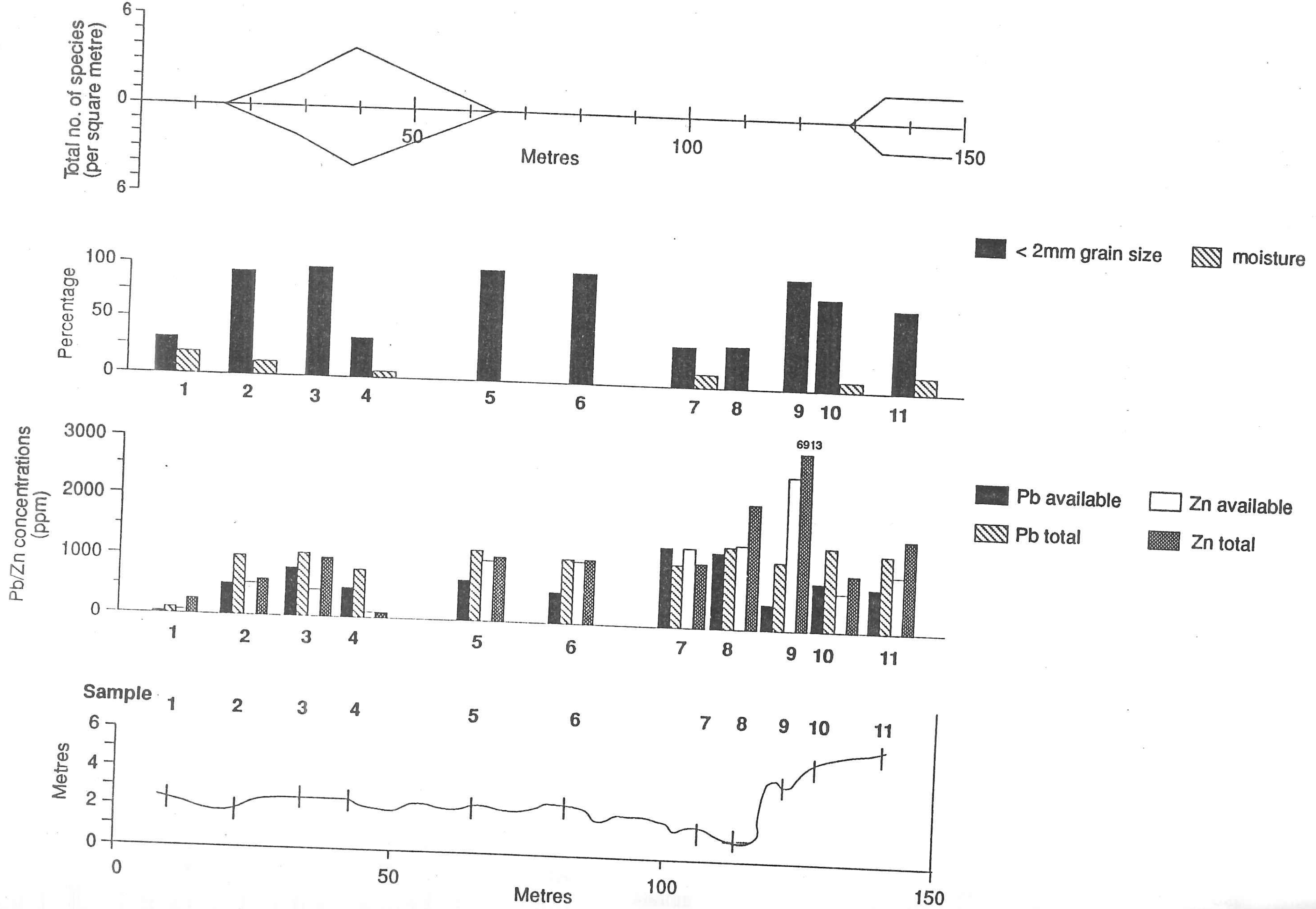


Figure 4.14: SECTION F

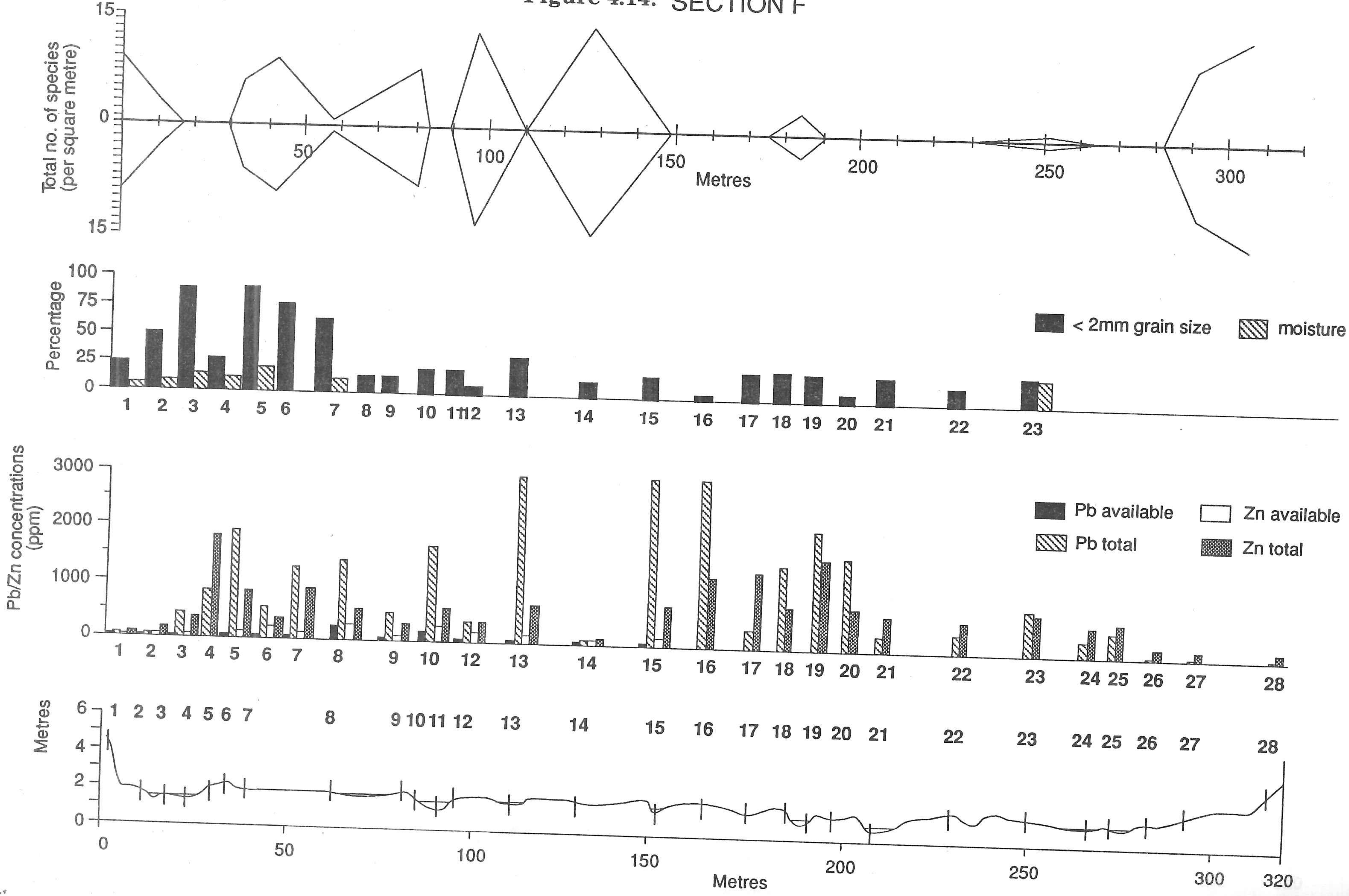


Figure 4.15: SECTION G

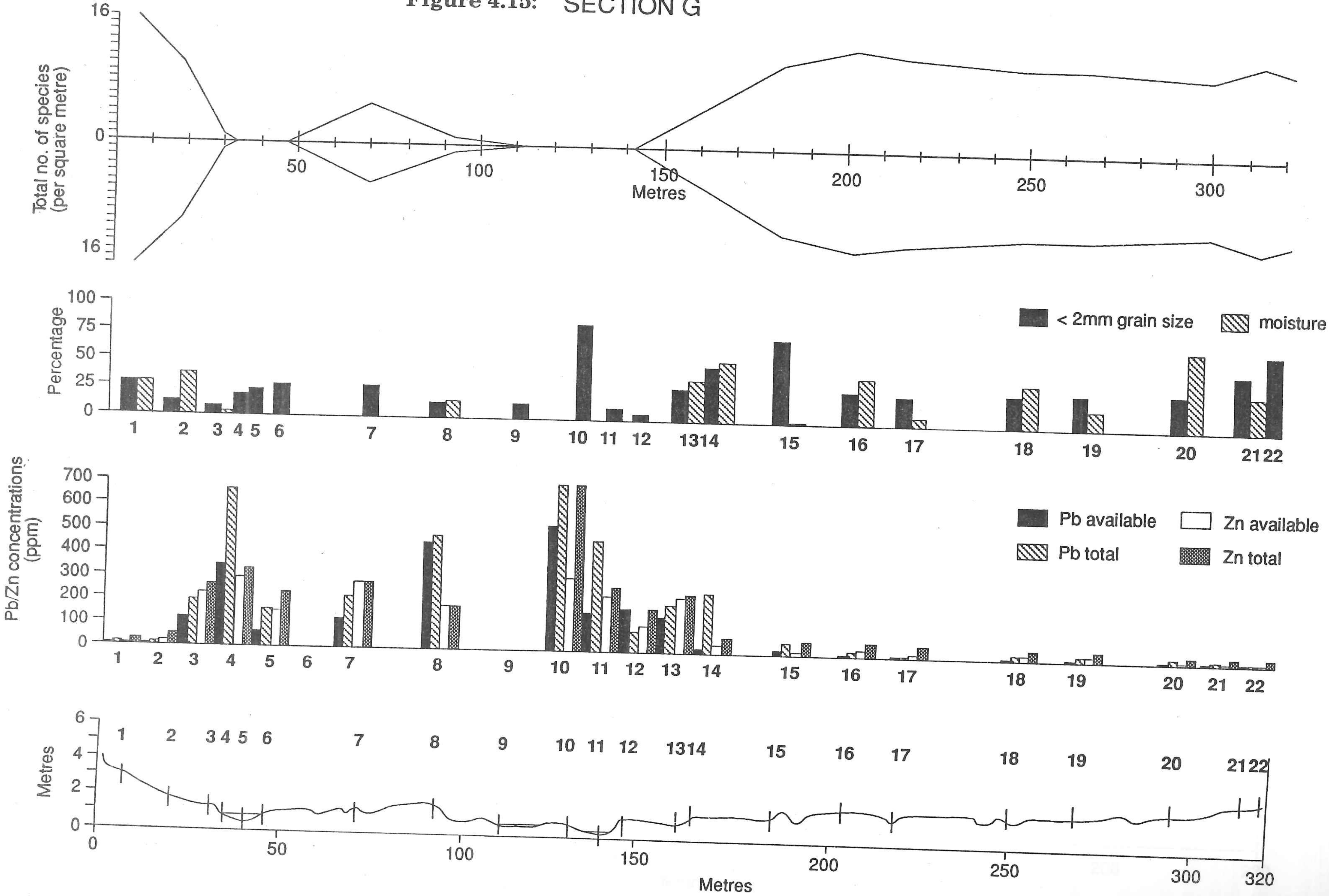


Figure 4.16: SECTION H/I

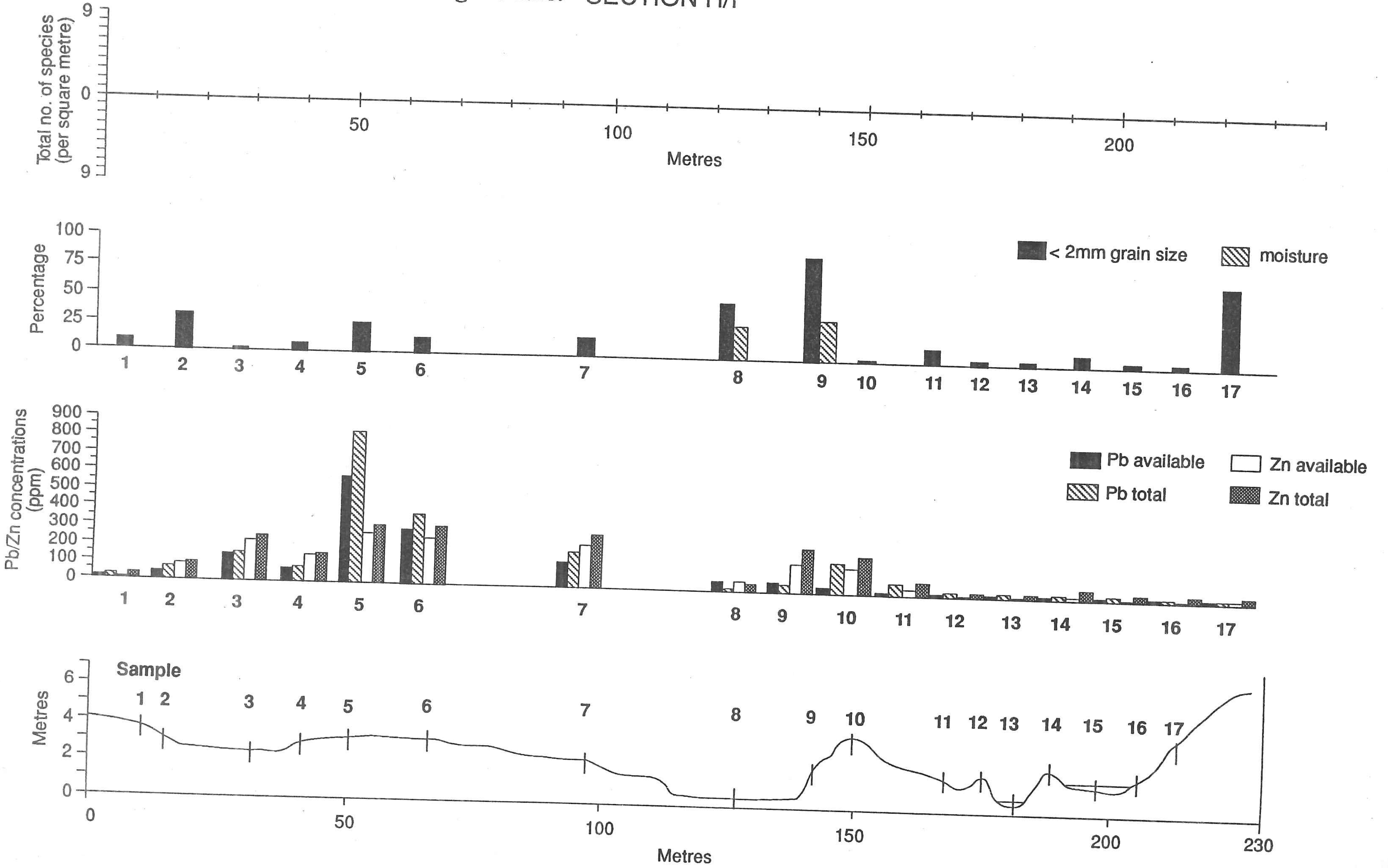


Figure 4.17: Vertical section through mine waste

Figure 4.18:

Section E Through mine derived tailings outwash
Store Blydal, Blyklippen Mine, Mesters Vig, Greenland August 1989

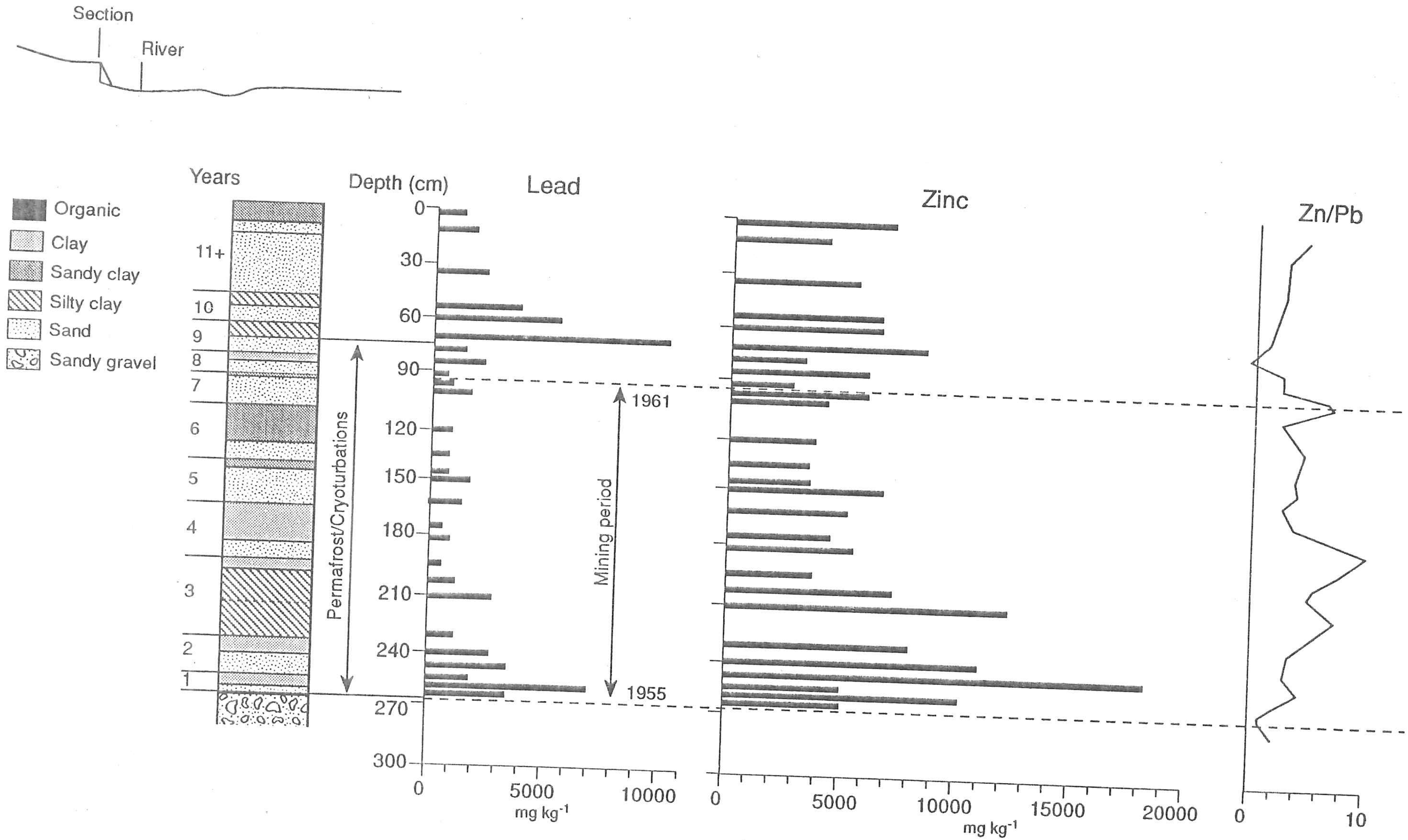
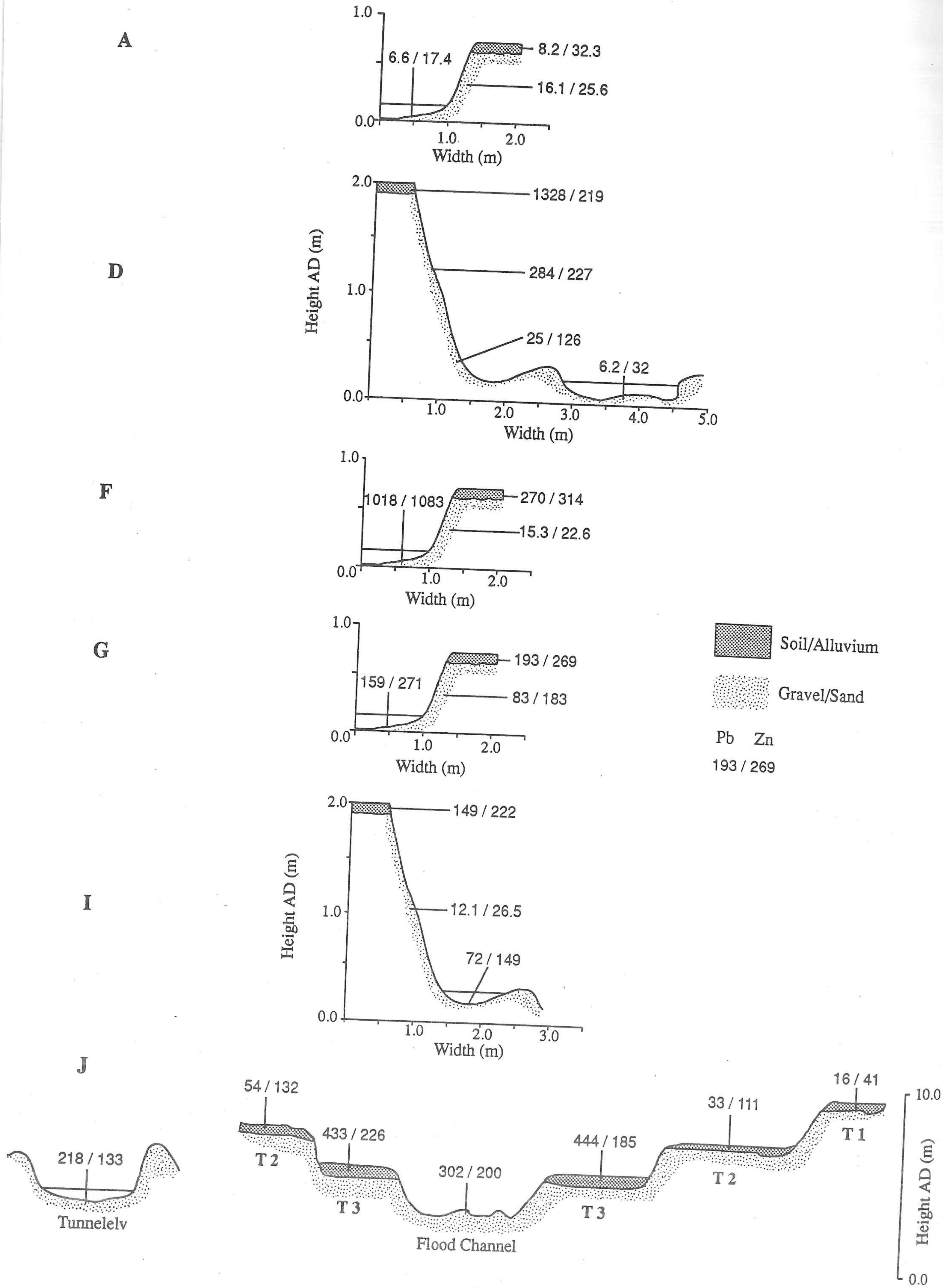


Figure 4.19: The vertical distribution of Lead and Zinc within active bar sediments and delta terraces.



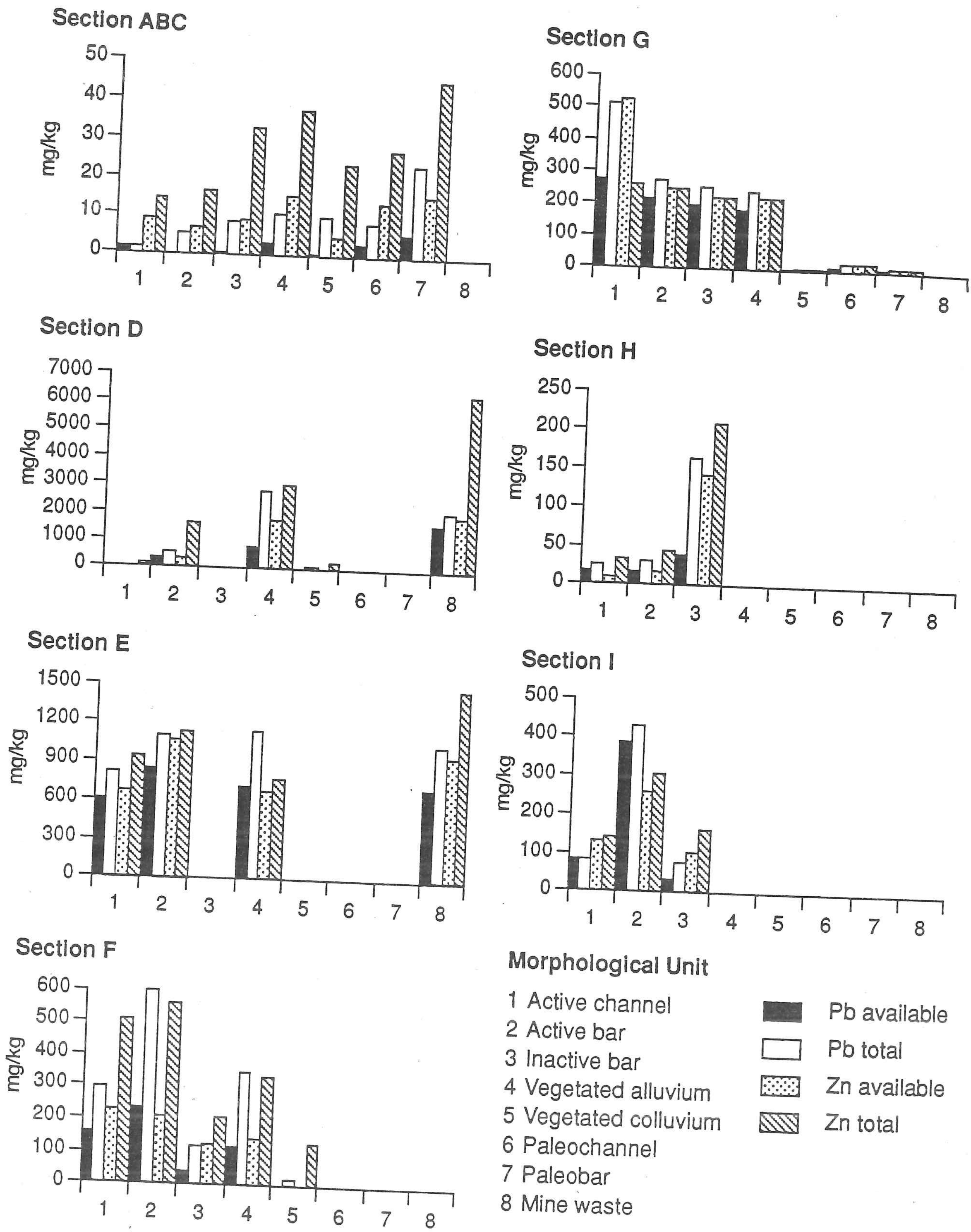


Figure 4.20: Metal concentrations associated with geomorphological units.

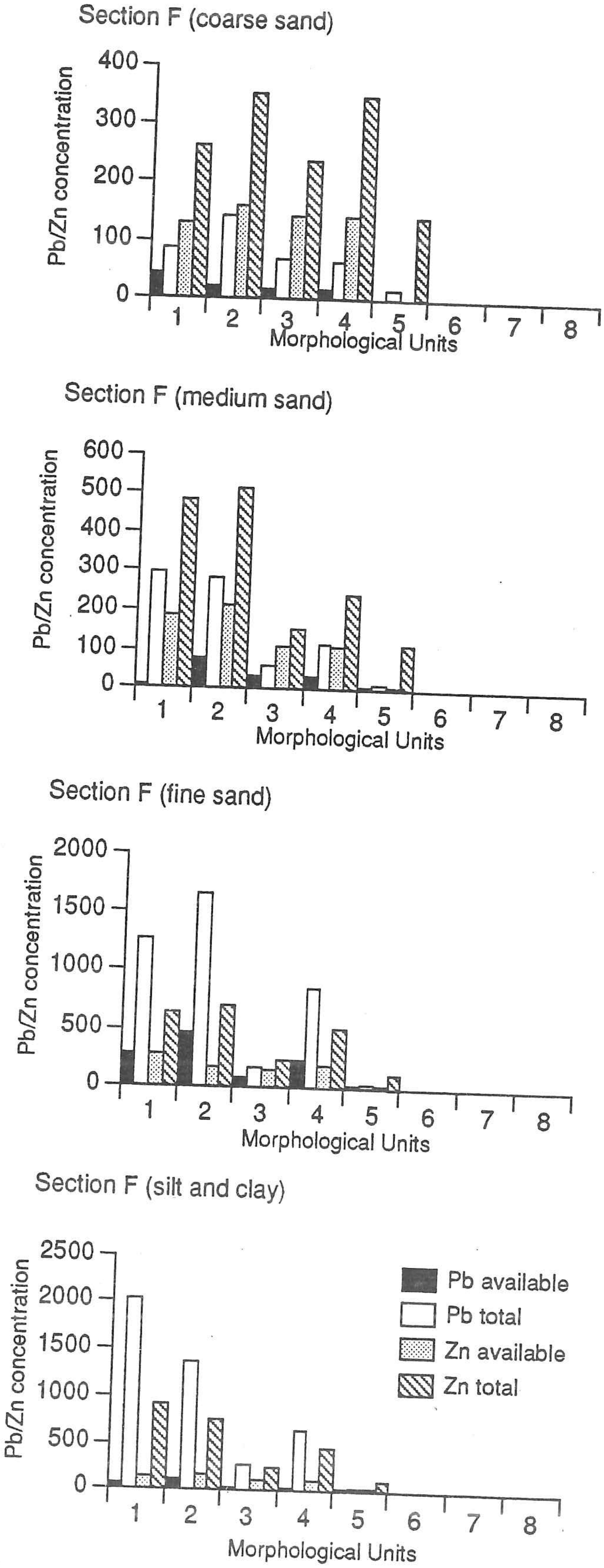


Figure 4.21: Metal concentrations in different grainsizes associated with geomorphological units. Section F

Figure 4.22: Sedimentation processes associated with braid bar morphology that illustrate how metal rich fines are concentrated in pool, bar-tail and as infiltrated matrix fines.

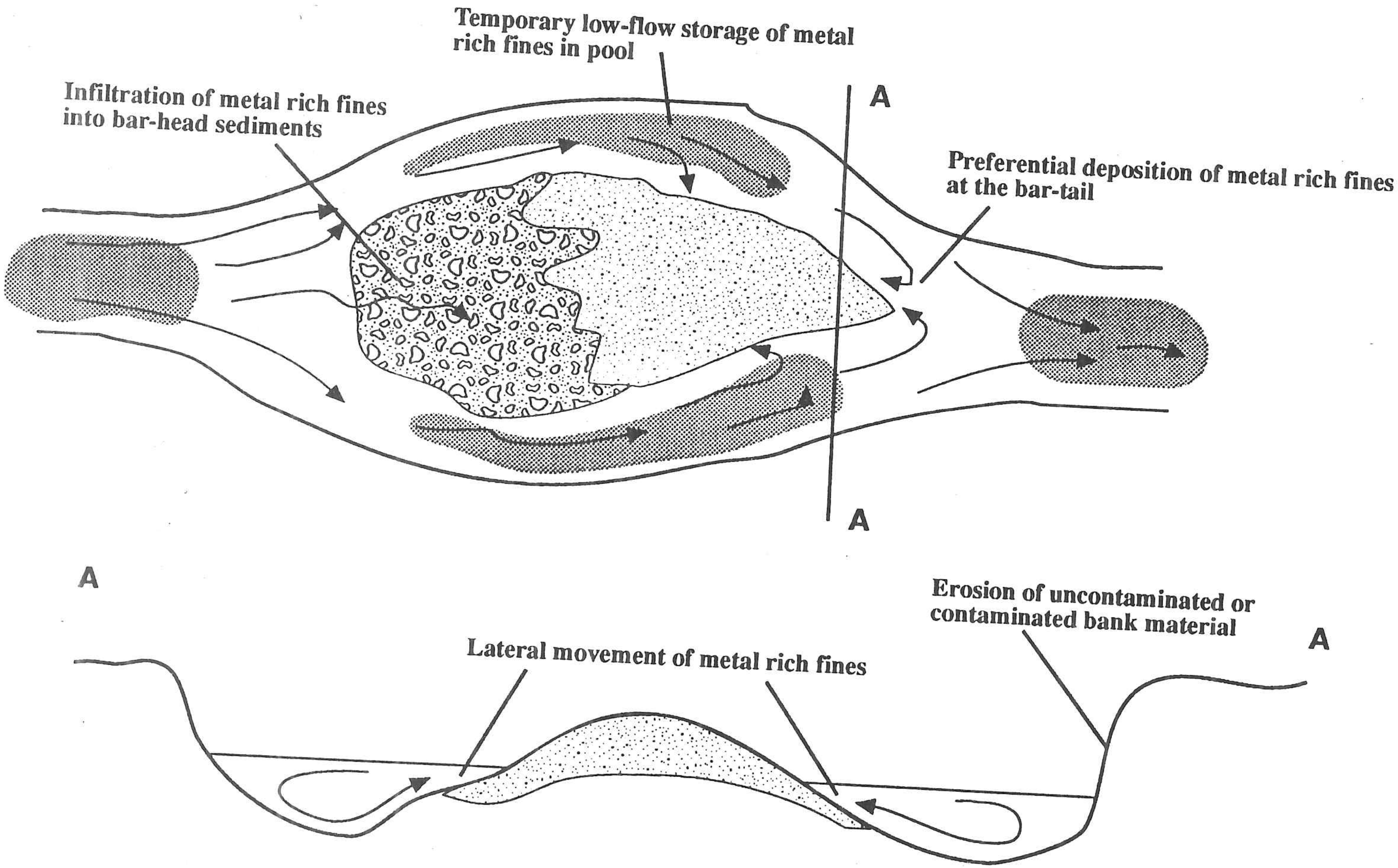
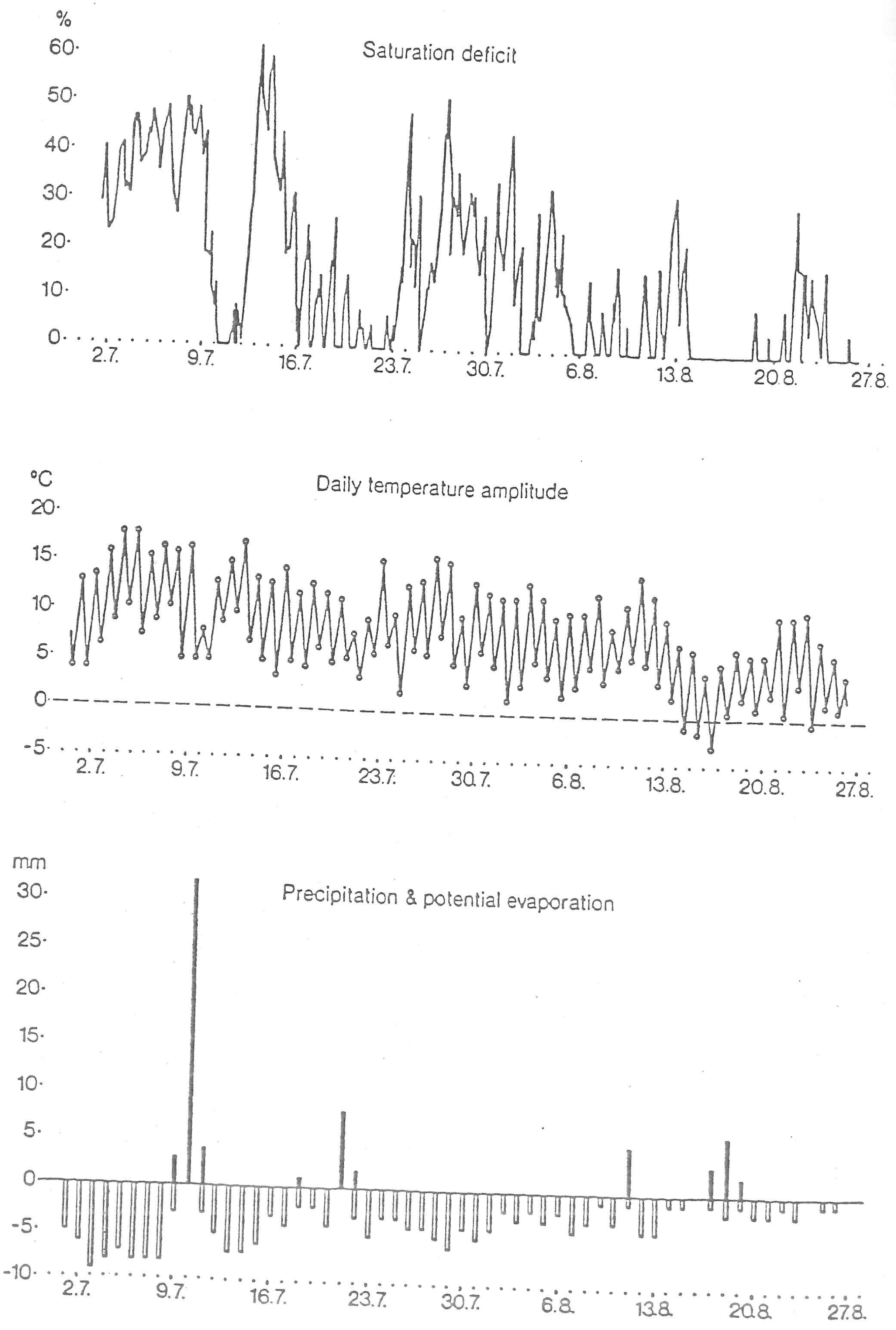


Figure 4.23: Anabatic convection fog (Washburn's Cottage in foreground)

Figure 4.24: The climate during the growing season in 1989 at Mesters Vig 72 13' N.



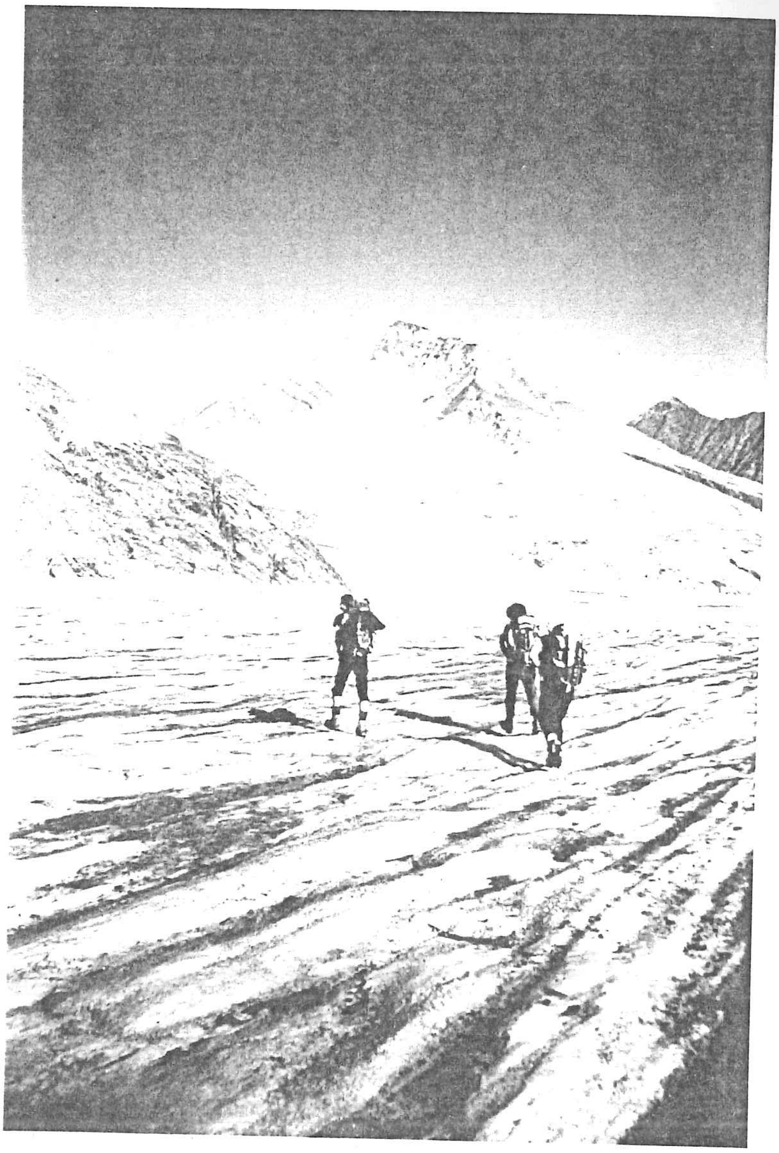


Figure 8.1: Setting off to climb Harlech Fjeld (1900m)

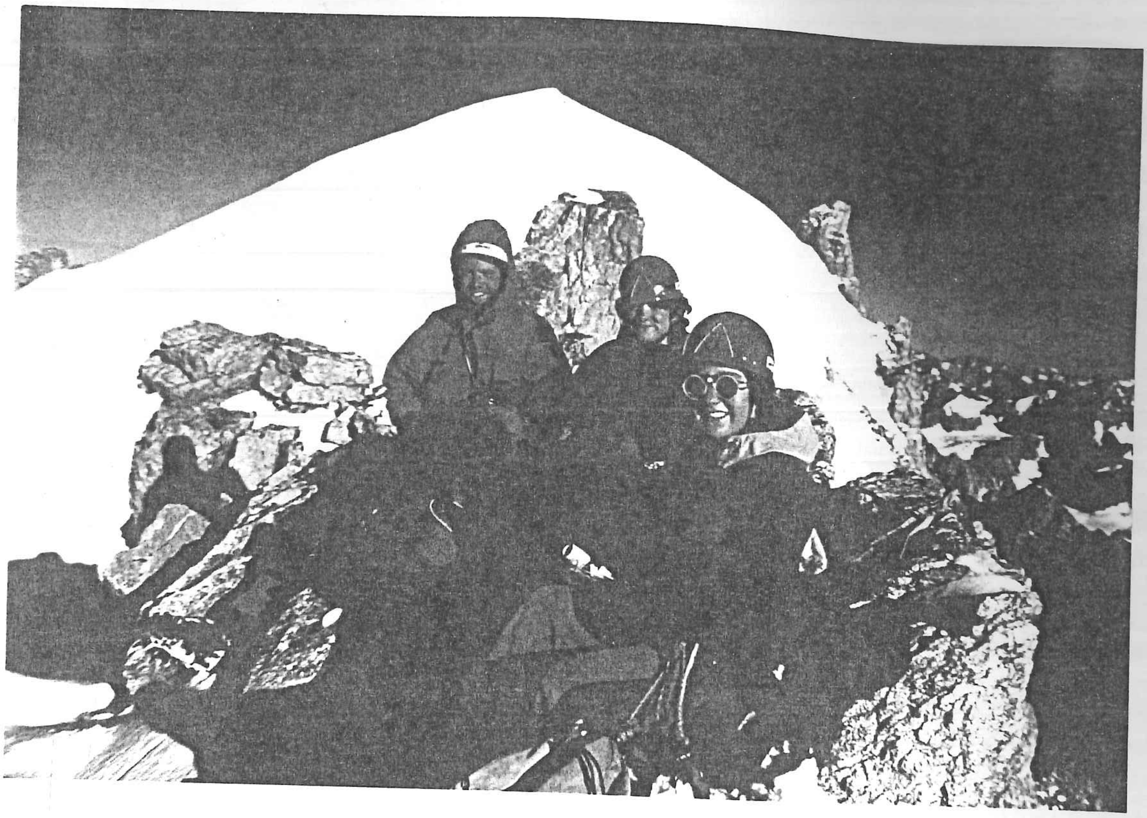


Figure 8.2: On Dunottar (2524m)

Figure 8.3: Scree slopes on Glamis Col