A

THESIS

entitled

# REGIONAL GEOCHEMICAL PATTERNS RELATED TO MINERALISATION IN CENTRAL SIERRA LEONE

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ABSTRACT.

The application of regional geochemical mapping in Sierra Leone was studied in the mineralised schist belt of the Sula Mountains and Kangari Hills.

Samples of active stream sediment were collected from an area of 450 square miles at a density of 4 per square mile. The concentrations of 22 elements were estimated by a semi-quantitative spectrochemical method and 2 elements were estimated by colourimetric methods. Geochemical maps were prepared for the 11 minor elements which displayed significant geochemical patterns.

The data were interpreted with reference to the influence of geology and other environmental factors on the broad scale geochemical patterns. Those patterns related to mineralisation received special attention.

The results demonstrate that the regional geochemical patterns are, in general, closely related to regional differences in the composition of the bedrock. Local variations in the minor element content of the stream sediments are normally correlated with major variations in the bedrock lithology. However, both regional and local variations may be, in part, related to pedological and geomorphological influences.

In areas of granitic rocks differences in the concentrations of the elements in the stream sediments are closely related to variations in the composition of the bedrock. By contrast, in certain areas of basic and ultrabasic rocks there are marked regional differences in the geochemical drainage patterns which are unrelated to the composition of the bedrock. These differences result from regional variations in the nature of the soil profiles and from regional variations in the rate of erosion which influences the nature of dispersion.

In relation to mineralisation, the regional patterns demonstrate the presence of a well defined geochemical province of arsenic which is related to bedrock gold deposits. Of the other elements of economic interest molybdenum is anomalous in widely separated areas and copper forms an isolated anomaly of unknown origin.

The study demonstrates that regional geochemical mapping provides data of fundamental and economic importance and is complimentary to regional geological mapping.

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# INTRODUCTION

This research study is concerned with the application of regional geochemical mapping to a mineralised schist belt in Central Sierra Leone, together with the interpretation of the data in terms of the geology and regional geochemistry with particular reference to the mineral potential.

Regional geochemical mapping has been used to describe a number of different operations, and it is therefore necessary to define the exact meaning attached to this term as used by the Geochemical Prospecting Research Centre. The term, 'regional geochemical mapping' is employed here to describe broad scale geochemical surveys for a wide range of elements, aimed at delimiting geochemical provinces, as distinct from reconnaissance surveys undertaken to discover specific deposits. Geochemical provinces are defined as wide tracts of country where the bedrock has distinctive contents of specific trace elements or distinctive ratios of a number of elements. Characteristically these provinces may include a number of lithological units which may also be present in adjacent provinces. The geochemical provinces of Perel'man and Saukov (1957) which are related to the physiochemical conditions of weathering and dispersion will be referred to as 'geochemical dispersion provinces'.

## PREVIOUS WORK

Broad scale geochemical prospecting surveys covering thousands of square miles have been carried out over the last two or three decades, particularly in the U.S.S.R. (Ginzburg, 1957) but also in other territories, as for example, Central Africa. These surveys have largely been aimed at discovering discrete mineral deposits, rather than at producing geochemical maps showing geochemical provinces. Thus in 1941, Fersman stated that "The methods of geochemical mapping remain undeveloped even up to this time, and in reality, we have nothing systematic even now, by way of experimentation, that would give us a genuine geochemidal map", and subsequently, in 1957 Ginzburg wrote, "... there has been no definite solution or formalisation for procedures of preparation of the genuine geochemical map".

It was only in 1956 that the concept of 'delimiting regional geochemical provinces unrelated to provincial differencos in the trace element content of the bedrock', by broad scale sampling and analysis of this material for a wide range of elements, was proposed by Webb (1956). At the same time an example of cold extractable heavy metal provinces in New Brunswick was given in a paper by Hawkes, Bloom, Riddell and Webb (1956). Similar provincial distribution of specific elements has been noted during other extensive reconnaissance surveys, as for example Holman's studies (1959) in Nova Scotia and by Bell and Overstreet(1960) in Carolina, but it is only recently that regional geochemical mapping aimed primarily at delimiting provinces has been undertaken.

Trial regional geochemical maps, are also being produced in a number of other areas of the Western World, but few have been published to date. These have in general, been carried out by Geological Survey organisations as predicted by Webb (1958), when he stated that, "It was believed to be only a matter of time before Geological Survey organisations must also accept responsibility for providing regional geochemical maps".

For example, a recent but unpublished report by Holman (1962), of the Geological Survey of Canada, describes the systematic bedrock sampling of 43,000 square miles of the Red Lake-Lansdowne House area of Ontario. Ten thousand samples of fresh rock, mainly granites and granodiorites, have been collected from a peneplain area drained by lakes of glacial origin and sluggish rivers. The sample density, excluding the area covered by lakes and rivers, is one sample to 3.5 square miles. It is understood that the samples are being analysed spectrochemically, but to date only zinc and copper have been determined using a partial attack. These results show variations in the copper concentration closely related to the lithology, (acid rocks containing 10 ppm. Cu., as compared to 50 ppm. in the basic rocks), but it is not known whether regional patterns unrelated to rock type also exist.

The Geological Survey of South Australia (1962), in an unpublished report, describe a regional geochemical survey of mineralised Cambrian rocks. Twelve hundred composite rock samples

were analysed spectrochemically for copper, lead, zinc, cobalt, nickel, chromium, vanadium, and silver. The results show that there is a marked association of copper, lead, and zinc with sedimentary facies, but there are also regional variations in trace element concentration probably indicating a primary sedimentary environmental control. Low grade mineralisation was found as a result of this investigation.

In Ghana the Geological Survey (unpublished report, 1962) has collected samples of active stream sediments, panned concentrates, banks and fresh rock at 0.8 mile intervals along the stream, which according to their geological environment were analysed by chemical methods for copper, nickel, arsenic, lead, molybdenum, tungsten, beryllium, tin, cadmium and chromium. The results of this work have shown regional concentrations of arsenic to be persistently associated with gold deposits of hydrothermal origin. Concentrations of copper, nickel, chromium and molybdenum have also been found to be associated with certain lithological facies, but it is not stated in the report whether there are also pronounced variations in the concentrations of elements other than arsenic within the lithological units.

Since 1956, a series of experimental surveys has been carried out by the G.P.R.C. of Imperial College in Africa and South East Asia to test the hypothesis that geochemical provinces unrelated to

bedrock lithology or topography do in fact exist, and that they can be related, at least in some instances, to metalliferous provinces.

During the research studies on the dispersion of cobalt and uranium in the Northern Rhodesia Copperbelt and Solwezi district, made by Jay (1959), and the dispersion of niobium from pyrochlore bearing carbonatite near Feira, Northern Rhodesia, by Watts (1960), additional samples were collected in the vicinity of the mineralisations and in barren areas. These samples were analysed spectrochemically and demonstrated that the concentrations of many elements, even in the pre-mineralisation basement rocks, differed significantly between the areas. Following these results and similarly encouraging results in Malaya and other areas of Northern Rhodesia, a phased programme of research was commenced in association with the Geological Survey of Northern Rhodesia, culminating in the production of regional maps of 3000 square miles of the Namwala Concession, which it is expected will be published shortly by the Geological Survey of Northern Rhodesia.

## Previous geochemical work in Sierra Leone

Several previous geochemical studies have been undertaken by the Geochemical Prospecting Research Centre in collaboration with the Geological Survey of Sierra Leone and the results have found considerable application in Sierra Leone, Ghana, and elsewhere.

Most of this work was confined to limited areas, but Tooms (reported by Wilson and Marmo, 1958) demonstrated that arsenic was widely distributed in the alluvial gold areas of central Sierra Leone.

Holman (1956) studied the dispersion of nickel in soils relative to bedrock geology. He found that the optimum geochemical contrast in soils was obtained at a depth of four feet and that the lateral dispersion of nickel was limited to only a few feet in residual soils.

Mather (1959) followed up previous results reported by Webb (1955) from an arsenical gold mineralisation and also investigated the dispersion of molybdenum. This work demonstrated the presence of widespread secondary dispersions in soils overlying the sub-outcropping mineralised rock. Mather only made a very cursory investigation of the dispersion in the drainage, but the results obtained were encouraging. Accordingly, Elliott (1962) investigated in detail the behaviour of arsenic and molybdenum in the drainages.

Although neither of these studies was concerned with regional geochemical mapping the results did show that drainage samples would reflect variations in the arsenic, molybdenum and probably other trace element contents of the bedrock of the catchment areas. It was therefore considered, subject to confirmation during the

preliminary stages of the investigation, that a regional geochemical map based on the analysis of stream sediment samples would reflect the regional distribution of the trace elements in the bedrock.

## ACKNOWLEDGEMENTS

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## PRESENTATION OF THE THESIS

This thesis is presented in two parts: Part 1 containing the text and Part 2, a folio containing the geochemical maps and larger diagrams.

The text is divided into 8 sections. Following the general introduction in Section 1, the field sampling techniques, and the analytical and data presentation techniques employed in this study are reported in Section 2.

In Section 3, the regional geochemical patterns are described (figs. 12 to 21), and discussed in relation to the broad outlines of the geological map. Under the heading 'Multi element patterns', the broadly similar distributions of several elements are discussed. This is followed by a brief account of the individual patterns of the separate elements.

The factors affecting the distribution of the geochemical patterns, as for instance the effect of variations in the bedrock mineralogy, pedology, and sedimentation, are discussed in Section 4.

In Section 5, the economic significance of the geochemical patterns is considered. The regional geochemical patterns of arsenic and molybdenum are reviewed in relation to the known occurrences of gold, and attention is drawn to the geochemical associations of other elements with known mineral occurrences.

The conclusions obtained from the results of this study of regional geochemical patterns are summarized in Section 6, whilst in Section 7 suggestions are made for future research.

The bibliography, Section 8, and an Appendix, containing detailed procedures for the analytical methods used in this work complete the thesis.

## SECTION 1

## DESCRIPTION OF THE FIELD AREA

### LOCATION

Only a part, approximately 450 square miles of the 1000 square miles, of the Sula Mountains - Kangari Hills schist belt of Central Sierra Leone and the immediately adjacent gneisses, was studied during the writer's field work (figs. 1 and 2). The remainder of the schist belt is being investigated as a separate project.

The area included by the present study is located between 9°04'30"N. and 8°30'30"N. latitude, and from 11°50'W. to 11°30'W. longitude.

### GEOLOGY

The general geology of Sierra Leone has been described by Dixey (1925) and Pollett (1951). The geology and mineral resources of the area covered by the regional geochemical map have been described by Wilson and Marmo (1958) and by Marmo (1962b), and the following brief account is largely taken from these publications.

Sierra Leone can be conveniently divided into two parts. The south western half of the country forms a vast plain underlain mainly by pre-Cambrian rocks, bounded on the south-west by a narrow belt of Recent and Pleistocene deposits of marine and estuarine origin. By contrast, the eastern half of the country

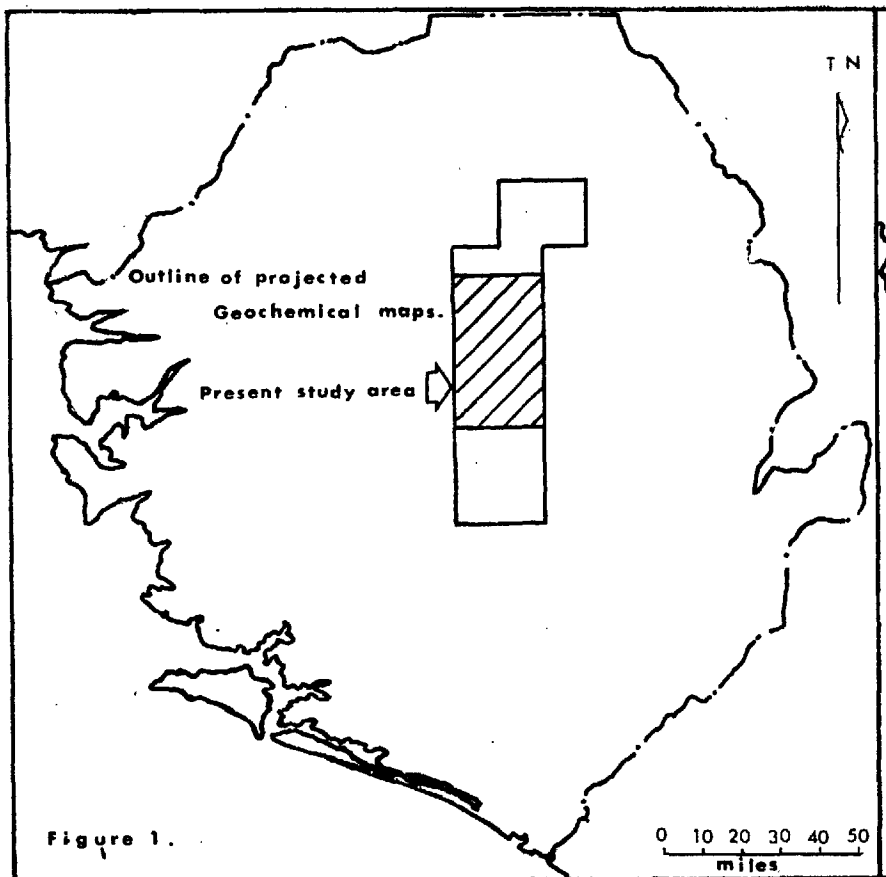



Figure 1.

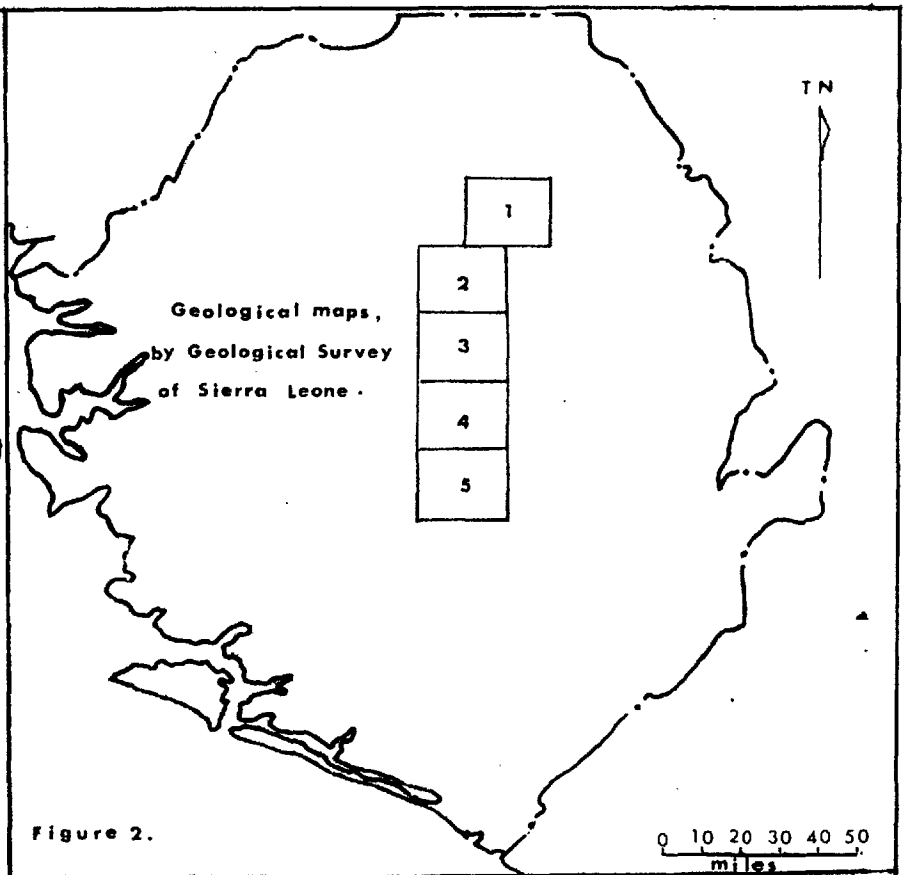
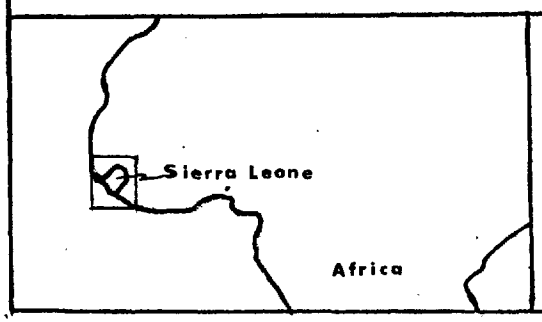



Figure 2.




## SIERRA LEONE

LOCATIONS OF GEOCHEMICAL AND GEOLOGICAL MAPS.

**FIGURES 1 and 2**

is dominantly granitic but also includes large lenticular masses of pre-Cambrian metamorphic rocks with the collective name of 'Kambui schists', (fig. 3 and table 1).

Sula Mountains - Kangari Hills schist belt

The 'Kambui schists' which form the schist belt are of early pre-Cambrian age and from radiogenic age determinations on lead isotopes, they appear to be older than $2.9 \times 10^9$ years. They include metamorphosed sediments, acid, basic, and ultrabasic rocks which are intruded by pegmatites whose frequent association with the known mineralisation has been discussed by Marmo (1962a, b).

Surrounding the schist belt proper are a variety of granitic rocks which have been classified as synkinematic or late-kinematic types.

The structure of the schist belt is complex, but in the Sula Mountains outcrops of banded ironstones show that the metasediments, flanked by amphibolites, are tightly folded and that the fold axes strike in a north-east to south-westerly direction. In the Kangari Hills the strike of the metasediments gradually changes towards a north-west direction and is interrupted by a large mass of basic and ultrabasic rocks. These basic and ultrabasic rocks at the southern margin of the area have been intensely folded with associated metamorphosed acid volcanics, and have been further distorted by large scale tear faults. To

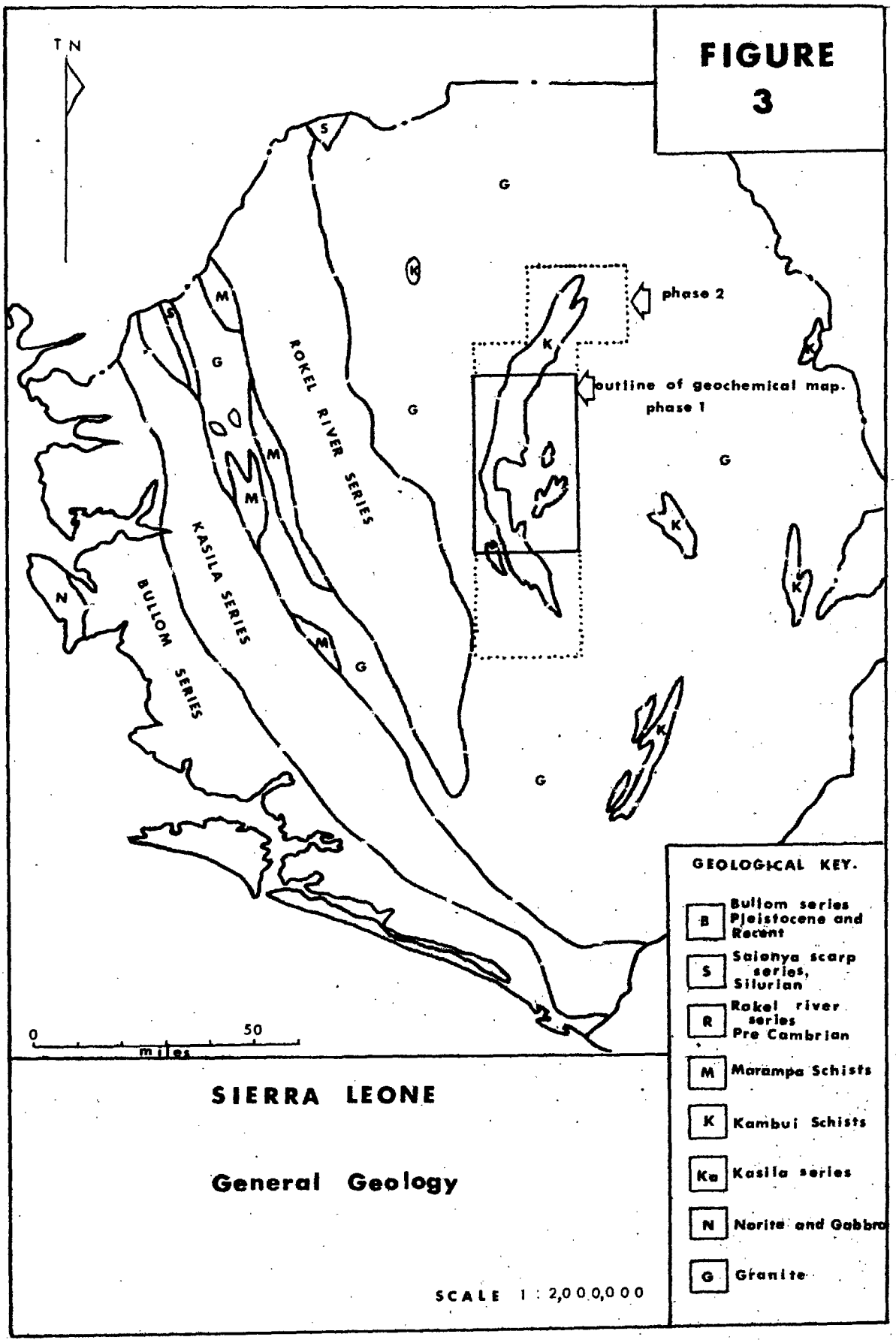
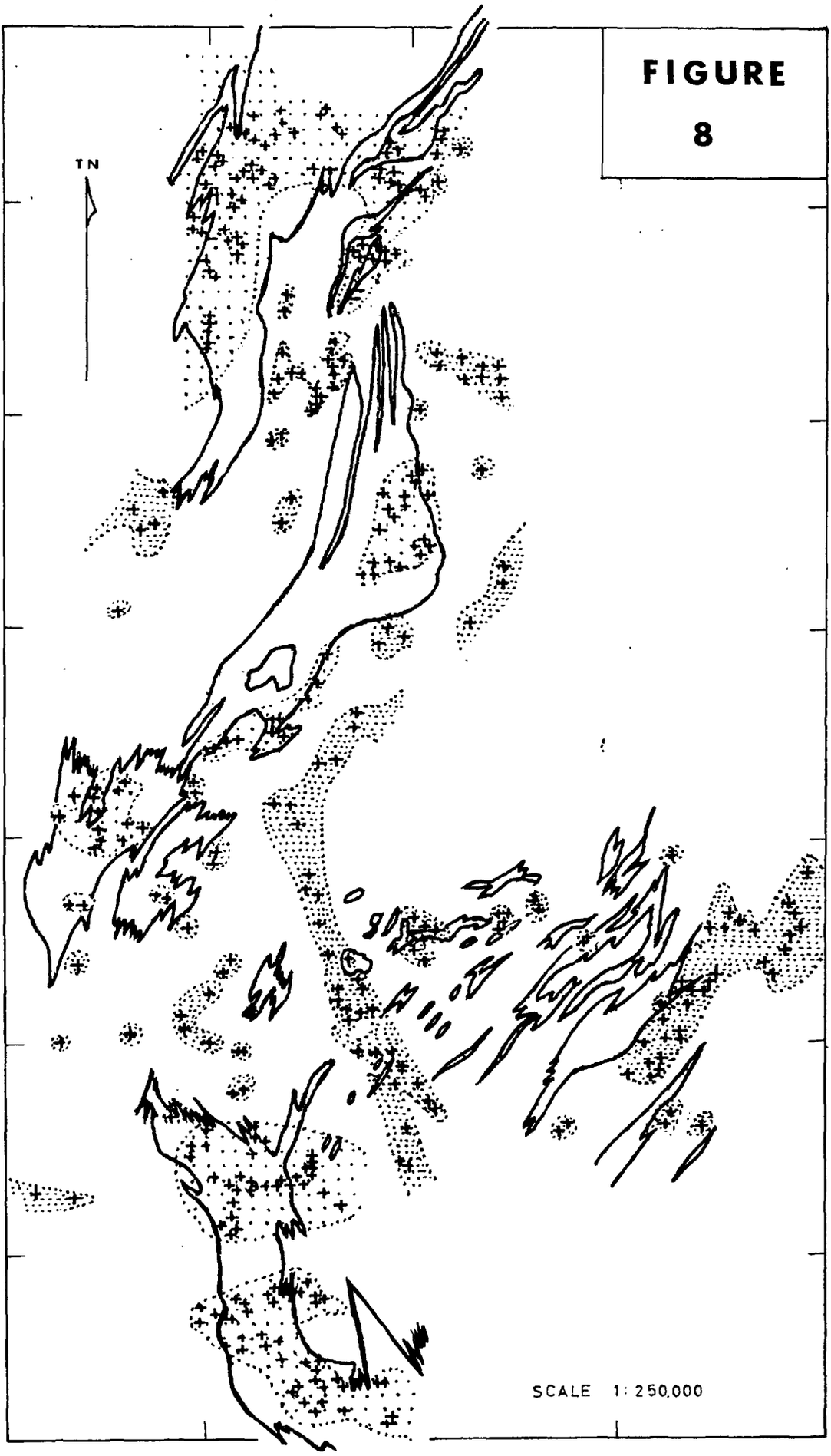

FIGURE 3
TN
phase 2
outline of geochemical map. phase 1
ROKEL RIVER SERIES
KASILA SERIES
BULLOM SERIES
0
50
miles
SIERRA LEONE
General Geology
SCALE 1 : 2,000,000
GEOLOGICAL KEY.
B Bullom series Pleistocene and Recent
S Salonya scarp series, Silurian
R Rokel river series Pre Cambrian
M Marampa Schists
K Kambui Schists
Ka Kasila series
N Norite and Gabbro
G Granite

Table 1. General Stratigraphic Column for Sierra Leone (after Wilson and Marmo, 1958)

| Period | Geological Formation | Description |
|---|---|---|
| Recent | Coastal sediments | Sands and gravels. |
| Cenozoic | Bullom Series | Pleistocene sediments of the coastal plain. |
| Palaeozoic | Saionya Scarp Series | Horizontally bedded arkoses, grits and flagstones, assumed mid-Silurian age. |
| | Unconformity | |
| | Rokel River Series | Folded arenaceous and argillaceous sediments with intercalated volcanic lavas and ashes. |
| Pre-Cambrian | Marampa Schists | Dominantly metamorphosed sediments with subordinate orthoschists. |
| | Kambui Schists | Very varied metamorphics of igneous and sedimentary origin, often deeply weathered and mineralised. |
| | Kasila Series | Crystalline basement rocks, gneisses, schists, granulites. |
| Intrusives | Synkinematic Granites | Foliated migmatite with diffuse contacts. No proven economic mineral associations. |
| | Late-kinematic Granite | Intrusive into schists possibly late Pre-Cambrian age. Associated with mineralisations. |
| | Basic Intrusives | Colony gabbro mass and numerous dolerite dykes and sills. |

# FIGURE 8




EXPLANATION

outcrops of Fe rich rocks

Apparent concentration of Ge.
> 640 p.p.m.

400 - 640 ppm. Ge.

< 400 p.p.m. Ge.

Sample locations in which Ge. shows extreme variation in apparent concentration from the true content of 400ppm Ge.

## THE SULA MOUNTAINS - KANGARI HILLS SCHIST BELT

THE DISTRIBUTION OF THE SPECTROCHEMICAL INTERNAL STANDARD GERMANIUM RELATED TO THE OUTCROPS OF IRON RICH ROCKS

the east and north-east of the tear faults numerous attenuated outcrops of ultrabasic rocks strike in a north-easterly direction (fig. 4).

A brief description of the principal rock types is given below:

## Metasediments

The metasediments have been divided by Wilson and Marmo (1958), into boulder and pebble conglomerates, quartzites, ferruginous quartzites, micaceous and amphibolitic quartzites, and micaceous and amphibolitic schists. The banded ironstones are also believed to be of sedimentary origin.

The amphibolitic metasediments are thought to be mainly composed of metamorphosed pyroclastic material and form a complete gradation with the true amphibolites so that these mapped boundaries are somewhat arbitrary.

The micaceous metasediments are frequently garnetiferous and grade into cordierite, tremolite and cummingtonite schists and include banded concentrations of magnetite (Marmo, 1956a).

Sillimanite, staurolite, andalusite and anthophyllite are present, particularly in the argillaceous facies.

## Basic rocks

Three groups of amphibolitic rocks are recognised: porphyroblastic, even-grained and vesicular or pillow textured.

Chemical analyses show that the composition of these rocks is in general basaltic and without much variation. The rocks are recrystallised and contain mainly hornblende and plagioclase. Pyroxene, biotite and quartz are also frequently present as minor constituents. Pyrite and pyrrhotite are sparsely disseminated and chalcopyrite and arsenopyrite are only rarely present.

A younger group of post-metamorphic dolerite dykes are scattered through the schist belt.

## Ultrabasic rocks

Ultrabasic rocks occur throughout the schist belt, but have only been divided into separate species in the more dissected areas where indurated laterite is not present.

Olivine, tremolite, talc and chlorite are important constituents of the ultrabasic rocks, whilst anthophyllite (Marmo, 1957) and spinel are less frequently present. Marmo (1958) has noted that calcareous serpentinites occur in areas of hydrothermal alteration.

## Acid igneous rocks

A wide range of granitic rocks are present and these are classified by Marmo (1955b) on petrochemical and mineralogical characteristics as syn-kinematic and late-kinematic.

The syn-kinematic group is believed to be the result of granitisation of the country rock and ranges in texture from

gneissic to porphyroblastic, and in composition from quartz diorite to granite. The characteristic feature of the syn-kinematic granite is a $K_2O/CaO$ ratio of less than one, but the ratio is greater than one in granites which are believed to have been subjected to potassium metasomatism (Marmo, 1955c).

The felspars are typically oligoclase and microcline. The latter is normally a minor constituent except in those rocks where microcline forms porphyroblasts, when it also forms a major component of the ground mass. Biotite is the most common mafic mineral and muscovite is frequently present. Pyroxene is also widely distributed but hornblende is confined to the diorite rocks in the eastern part of the area.

Within the part of the schist belt included by this thesis, the late-kinematic granite has only been recognised in a small area near Bumbuna (Marmo, 1955a). The late-kinematic granites are typically intrusive, and are distinguished by a $K_2O/CaO$ ratio of more than one, and frequently of two and even four.

Metamorphosed acid volcanics occur throughout the area.

Pegmatites are associated with both types of granites, but the economic minerals have only been discovered in pegmatites associated with late-kinematic granite.

## OUTLINE OF MINING HISTORY

Alluvial deposits are the main source of the economic minerals within the area and concentrations of gold, columbite

(containing 1-2 per cent $WO_3$), ilmenorutile, monazite, and cassiterite have been discovered by officers of the geological survey.

Alluvial gold was first discovered by N.R. Junner in 1926, and in 1936 gold production over the whole schist belt reached a maximum of 40,764 ozs. bullion, after which it gradually declined to 199 ozs. in 1946. During the period from 1947 to 1954, a dredge in the Pampana river rapidly boosted the output to an annual average of 2850 ozs. gold, but in 1954 operations on a commercial scale ceased, and the subsequent diminutive outputs have been obtained by small groups of Africans.

Lode prospecting was only partially successful and resulted in the discovery of gold bearing quartz veins at Yirisen (accompanied by arsenic, antimony, copper, lead, and zinc sulphides), Baomahun (arsenopyrite), and Makong (pyrite). Minor amounts of gold were discovered in the Mapoko river near Makele, with molybdenum, copper and nickel sulphides (Fowler-Lunn 1933, Marmo 1962b), and at Dalakuru with molybdenite, lead, copper and zinc sulphides, (Wilson and Marmo 1958, Mather 1959, Elliott 1962, Marmo 1962a).

No other metals have been produced from the schist belt on an economic scale but molybdenite occurrences have been reported in a number of places and those at Dalakaru and Makele have been drilled. Iron deposits have also been investigated at Farangbaia, but have proved to be of sub-economic grade.

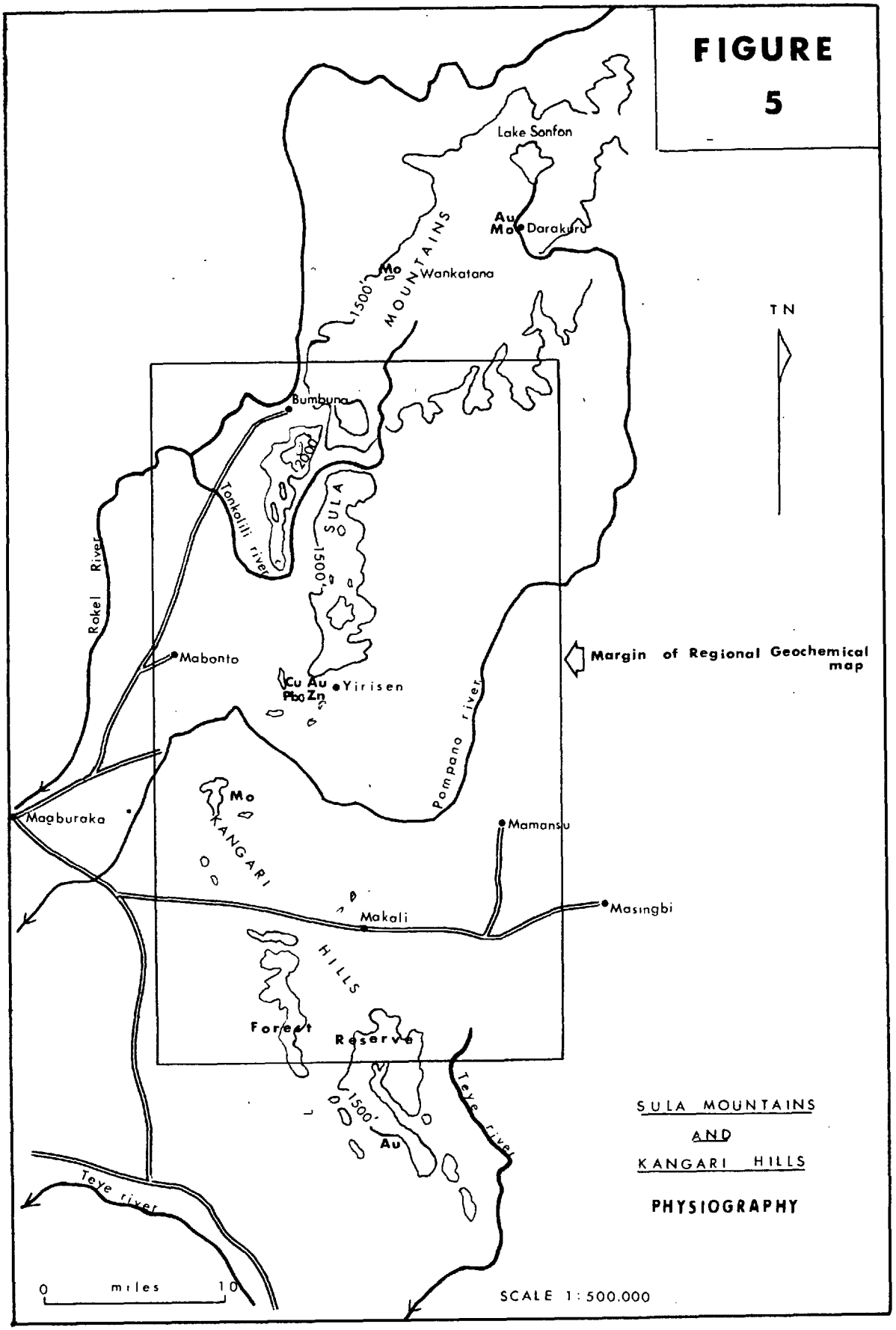
The metasediments and amphibolitic rocks contain certain minor and separate disseminations of arsenopyrite, pyrite, and chalcopyrite, which, wherever observed, are unaccompanied by concentrations of other metals.

## TOPOGRAPHY AND DRAINAGE

The Sula Mountains and Kangari Hills schist belt rises out of the Central Sierra Leone plain and is bounded by steep scarps except in the south west, where granite foot hills abutt the schists (fig. 5).

In general, the schist belt stands some 2000 feet above the granite plains, but the absolute altitudes decrease from north to south due to the overall slope of the country. Thus in the north, the average altitude of the crests of the Sula Mountains is about 3000 feet, while to the south, in the Kangari Hills, the hill crests rarely exceed 1750 feet. Similarly the altitude of the granite plain decreases from 1500 feet in the north to 450 feet in the south.

Much of the northern Sula Mountains is a plateau representing an old land surface, which is commonly lateritised. The drainage on the plateau is of low density and is normally mature or senile except along the major rivers where some rejuvenation is apparent. The probability that much of the drainage is subterranean is supported by the frequency of seeps


FIGURE 5
Lake Sonfon
Au Mo
Darakuru
Mo
Wankatana
1500'
MOUNTAINS
TN
Bumbuna
2000'
Tonkolili river
SULA
1500'
Rokel River
Mabonto
Cu Au Pbo Zn
Yirisen
Margin of Regional Geochemical map
Pompano river
Mo
KANGARI
HILLS
Magburaka
Mamansu
Masingbi
Makali
Forest Reserve
1500'
Au
Teye river
Teye river
SULA MOUNTAINS
AND
KANGARI HILLS
PHYSIOGRAPHY
0 miles 10
SCALE 1:500.000

and landslides on the slopes of the rejuvenated valleys and scarps. However, in most of the writer's field area, covering the southern Sula Mountains and northern Kangari Hills, this surface has been deeply dissected producing a strong relief with a high density of juvenile tributary streams and a superimposed trunk drainage. The old land surface still exists however, in the north of the field area, as isolated flat-topped hills and concordant peaks.

The lithology of the bedrock has a strong effect on the character of the streams in the dissected terrain. Over granite bedrock, the upper reaches of the tributaries are sluggish with much underground flow, whilst in the schist country the streams tend to be swift flowing and are often precipitous. In the eastern part of the field area bands of resistant rock alternate with granite and the stream valleys are steep sided, but flat-bottomed.

There are many wind gaps, particularly in the northern Sula Mountains, and from their distribution, Marmo and Wilson (1958) have deduced that the land surface was subjected to an intermittent uplift and subsequent tilting towards the north-west.

## PEDOLOGY

The soils of the Sula Mountains - Kangari Hills schist belt are dominantly latosols (Mather 1959; Elliott 1962, adopting the nomenclature proposed by Kellog 1949), and exhibit the following characteristic properties:-

1. Low silica / sesquioxide ratios of clays.
2. Medium to low cation exchange capacity of the mineral fraction.
3. Low activity of clays.
4. Low content of primary minerals, excepting the very highly resistent ones.
5. Low content of soluble minerals.
6. A relative degree of aggregate stability.
7. Red or reddish shades of colour.

The nomenclature used to describe soil profiles in this report is that used by the United States Department of Agriculture, (1951) and is summarized in table 2.

Table 2. Abbreviations used in the description of soils by the United States Department of Agriculture (1951)

| | |
|---|---|
| $A_{oo}$ | Organic debris not decomposed. |
| $A_o$ | Organic debris, decomposed. |
| $A_1$ | Dark coloured horizon, mixed organic and mineral matter. |
| $A_2$ | Light coloured horizon of maximum eluviation. |
| $A_3$ | Transitional to B. |
| $B_1$ | Transitional to A. |
| $B_2$ | Maximum accumulation of silicate clay minerals, and of iron. |
| $B_3$ | Transitional to C. |
| C | The weathered parent material, including horizon G for gleyed layers as in hydromorphic soils. |
| D | Any stratum beneath the soil such as hard rock or layers of clay or sand, that are not parent material, but which may have significance to the overlying soil. |

Residual latosols are most fully developed on the more iron rich rocks in the Sula Mountains where soil thicknesses of more than twenty feet are common. Typically these profiles are dominantly composed of rounded ferruginous concretions, which, when firmly cemented together to form a hard vermiform mass, are described as indurated laterite or, when exposed at surface, as 'duricrust' (a term suggested by Woolnough, 1927, and currently used in Sierra Leone for indurated mature latosols).

The most extensive development of duricrust is at an elevation of 2000 feet, i.e. on the old land surface. Indurated laterite is currently being deposited in the stream beds of the northern Sula Mountains, as for instance at Dalakuru, but it has been suggested (Woolnough, 1927) that much of the duricrust outcrop represents a B horizon, indurated following the lowering of the water table by rejuvenation of the drainage, and erosion of an original A horizon. The $A_1$ horizon, erratically present on the duricrust, is considered to be due to the activities of soil organisms and accumulation of mixed blown dust by the scanty vegetation (table 3).

Table 3. A typical indurated latosol profile of the Central Sula Mountains

| Soil horizon | Thickness | Description |
|---|---|---|
| $A_o$ } frequently absent | 1 inch | Plant ash and blown dust. |
| $A_1$ } frequently absent | 5 " | Loose grey loam bound by shallow roots. |
| $B_2$ | 8 feet | Vermiform mass of indurated limonite; dark reddish brown. |
| | 5 " | Limonite nodules less strongly cemented and enclosing deeply weathered remnants of amphibolite which become more frequent with depth. |
| $B_3$ | 3 ft. 6 ins. | Clay, containing laterite nodules. |
| $C_1$ | 11 feet | Clay, enclosing deeply weathered fragments of amphibolite. |
| $C_2$ | 7 " | Deeply weathered amphibolite including frequent seams of reddish brown clay. |

In the Kangari Hills removal of the duricrust capping has exposed the unconsolidated weathering products to erosion, and soils are commonly juvenile or truncated. In the latter, relicts of the original mature profile are frequently observed in the form of laterite nodules (table 4).

Table 4. A truncated latosol soil profile

| Soil horizon | Thickness | Description |
|---|---|---|
| $A_o$ and $A_1$ | $1\frac{1}{2}$ inches | Humus and polished laterite nodules. |
| $B_2$ | $10\frac{1}{2}$ " | Abundant laterite nodules and deeply weathered boulders of rock. |
| $B_3$ | 2 feet | Deeply weathered boulders, cavities between slabs filled by nodular laterite. |
| C | | Is developed only as leached surfaces on weathered boulders whose core is of fresh tremolite serpentinite. |

The relatively thin immature soils somewhat impoverished in sesquioxides are typical of the granitic rocks and quartzites in the field area (table 5). However, even on these rocks ferruginous soils may be present near the contacts with basic and ultrabasic rocks, no doubt due to migration of sesquioxides in solution.

Table 5. A typical latosol profile on granite bedrock

| Soil horizon | Thickness | Description |
|---|---|---|
| $A_o$ and $A_1$ | 2 inches | Light grey sand interspersed by organic debris. |
| $A_2$ | 7 " | Light grey sand, non organic with a blocky fracture. |
| $A_3 - B_1$ | 4 " | Light brown sand, compact. |
| $B_2$ | 5 " | Greyish brown sand, abundant quartz pebbles and some limonite nodules. |
| C | 2 feet | Yellowish brown clay enclosing deeply weathered boulders of granite and separated clusters of mineral grains. |

In several exposures of colluvial soil in the Kangari Hills laterite nodules become more frequent towards the top of the B soil horizon and, in the Sula Mountains, massive accumulations of indurated limonite concretions, presumably of detrital origin, occur in the flood plain areas of some rivers. These observations suggest that the process of accretion is active even under the present climatic and erosional conditions.

## VEGETATION

Major differences of vegetation in the field area are related to the soil types. The patchily distributed, thin,

unconsolidated soil on duricrust and granite monadnocks surfaces, supports only grass and a few stunted trees. Where unconsolidated soil is absent from the duricrust, no visible vegetation is present and on the granite outcrops, vegetation is confined to scattered rock plants.

The non-indurated soils, including latosols and colluvium are covered by dense secondary vegetation which has resulted from the activity of the rice farmers, except in the forest reserves and small patches of sacred, primary forest.

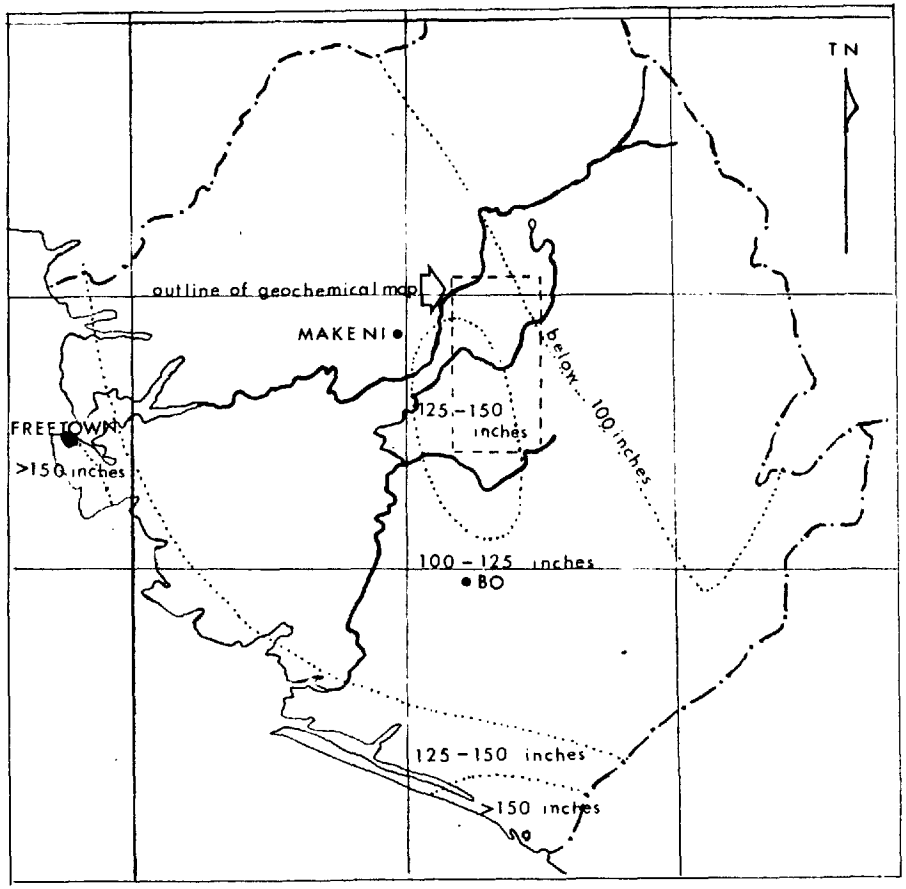
Swamps are rare except in some granite areas where the drainage channels meander through waterlogged masses of decaying vegetation interspersed with alluvium. It is not known whether these swamps are entirely related to the bedrock lithology or whether they may be due, at least in part, to tilting of the land surface during orogenic uplift. These swamps are covered by grass and stunted palm trees. They seldom exceed one hundred yards in width and from the profiles sections examined, the organic matter rarely exceeds four feet in depth.

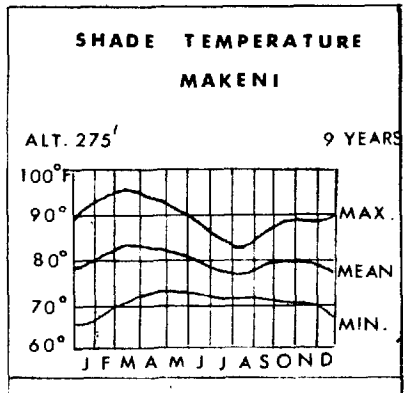
## CLIMATE

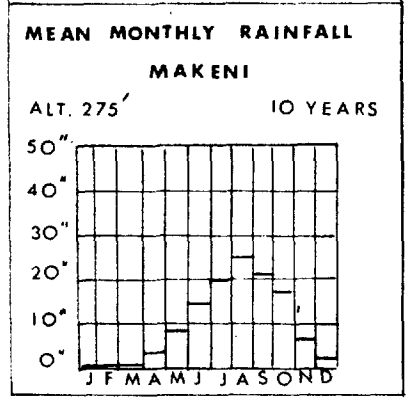
Climatic data is not available for the Sula Mountains and Kangari Hills, the major meteorological stations being situated at administrative centres on the plains. Accordingly, figures quoted below relate to areas of lower elevation than the field area and

can only be considered as a general guide to climatic conditions on the schist belt (fig. 6).

The climate of Sierra Leone is typical of the monsoon tropics. Most of the rain falls in the period from June to September but only the months of December, January, and February are entirely free of heavy rain storms. At Makeni the average annual rainfall is 125 inches, which is probably somewhat lower than the mountains and hills of the schist belt. Mean shade temperatures at Makeni vary between 77°F. and 83°F. with an average humidity of 60 to 90 per cent.




**SIERRA LEONE**

**CLIMATE.**

From Atlas of Sierra Leone, 1953.

**FIGURE 6**

## SECTION 2

# TECHNIQUES

## FIELD, ANALYTICAL AND DATA PRESENTATION

### Sample collection

Stream sediments were selected as the initial sample material in the prep ration of the geochemical map. Soil and rock samples were collected, however, in type areas, to obtain confirmation that the stream sediment reflected variations in the trace and major element content of the bedrock in the catchment areas, and during the subsequent investigation of certain regional geochemical patterns illustrated by the geochemical map. No water samples were collected, as analysis of water was considered impracticable in a broad geochemical mapping survey. This decision was based on the work of Elliott (1962), who demonstrated the extremely low salt content of the surface water resulting in considerable difficulties in estimating individual elements.

### Stream sediment samples

Samples of active stream sediments were collected in duplicate from the middle of the watercourse, care being taken to avoid excessive dilution from adjacent, collapsed, bank material. The sediment was placed in previously numbered kraft paper envelopes and allowed to dry in the sun. The average weight of sample was

50 grams, collected from sample sites whose density averaged four per square mile. Bulk samples of 500 grams were collected in areas of special interest.

### Soil samples

Individual soil horizons were sampled from channels cut in the cleaned face of the pits. On soil traverses and grids, one sample was collected at each sample site, from the $B_2$ horizon. As this horizon is rarely more than six inches below the surface it was usually found adequate to dig a small pit with a cutlass.

### Rock samples

Apart from samples collected from stream outcrops, the majority of the rock specimens were collected, during detailed investigations, at the corners of mile or half mile grids.

## Sample preparation

### Sieve analysis

The sample fraction analysed during the broad scale mapping was selected from the results of an investigation into variations of chemical content in the dry sieved fractions of stream sediment samples, which were collected from type areas (see discussion p. 163).

The samples were separated into five fractions by a partial mechanical analysis. Each sample was passed through a 6.35 mm aperture stainless steel wire sieve and 100 gm of the minus

6.35 mm-mesh material was mechanically agitated for a period of five minutes, in a nest of nylon sieves. The aperture sizes of the sieves approximate to those of the International system, but with additional subdivisions similar to those of the former British and American systems, (table 6).

Table 6. Description of sieved sample material related to sieve aperture sizes (Piper, 1950)

| Approx. aperture mm | Mesh | Convention employed | International convention |
|---|---|---|---|
| - | - | Gravel | |
| 6.35 | - | Fine gravel (greater than 1 mm) | Gravel |
| 2.0 | | | |
| 1.0 | 20 | Coarse sand | |
| 0.5 | 38 | | Coarse sand |
| 0.2 | 82 | Medium sand | |
| 0.1 | 125 | Fine sand | |
| 0.05 | 197 | Very fine sand | Fine sand |
| 0.02 | - | Coarse silt | |
| 0.002 | - | Silt | Silt |
| | - | Clay | Clay |

The separated fractions were stored in new paper envelopes and each sample was analysed by chemical and spectrochemical methods which are reported below.

### Routine sieving procedure

Samples of stream sediment and soil were sieved through 82-mesh nylon bolting cloth held in a perspex frame, and were stored in new paper envelopes. Samples which included abundant coarse material were passed through a 6.35 mm aperture sieve, and where necessary the material smaller than 6.35 mm was mixed, coned, quartered, and the soil structures destroyed in a porcelain pestle and mortar, prior to sieving.

### Preparation of rock samples

Rock samples weighing between 50 and 100 gm were crushed by hand in a tungsten carbide pestle and mortar, until all of the material passed through a 20-mesh sieve. This material was coned and quartered and approximately 10 gm was reduced to minus 200-mesh in a ceramic ball mill.

## Sample analysis

### Physical analysis

#### MEASUREMENT OF pH

Measurements of the hydrogen ion concentration (pH) were made using a portable meter manufactured by Analytical Instruments Ltd., and also by estimation, using 'Narrow Range Indicator Papers', supplied by British Drug Houses Ltd. Observations were made at the stream sediment sample sites.

MEASUREMENT OF Eh

A few measurements of the redox potential were made using the same meter as for the pH measurements, but fitted with a modified, platinum tipped, calomel electrode. The Eh observations were converted to the equivalent hydrogen electrode values using the equation:

$$Eh_{(H)} = (0.43 - Eh_{(Cal)} \text{ standard sol.}) + Eh_{(Cal)} \text{ sample.}$$

where $Eh_{(H)}$ is the redox potential with reference to the hydrogen electrode; $Eh_{(Cal)}$ is the redox potential with reference to the calomel electrode, i.e. the observed potential.

## Chemical and spectrochemical analysis

CHEMICAL ANALYSIS

Chemical methods used are the standard rapid colorimetric techniques currently employed at the Geochemical Prospecting Research Centre, excepting those analyses involving hydrofluoric and percloric acid sample attacks, and those incorporating the autoanalyser for the estimation of zinc (Stanton and MacDonald, in prep.). A detailed description of these methods is given in the appendix.

ANALYTICAL PRECISION

The analytical precision of the chemical (and spectrochemical) analyses was determined using a statistical sample series as

described by Craven (1954). By this method two bulk samples, one of which contains a high concentration of the element sought, and the other a low content of the same element, are mixed together in different proportions to make a series of 10 mixtures. The two original bulk samples provide the end members of the series, to make a total of 12 samples. These samples are included at regular intervals (every 10th sample in the chemical analysis, and every 14th sample or one per plate in spectrochemical analysis) amongst the unknown samples. The precision of the analytical method is obtained from a statistical analysis of the chemical results of the 12 samples. In general the precision of the chemical methods is superior to that of the spectrochemical methods (compare table 7, on page 32 and fig. 7, in Part 2).

Determinations of total cobalt and nickel were made to estimate the accuracy of the spectrochemical analyses. Nineteen samples were analysed using a hydrofluoric and perchloric acid sample attack followed by an alkaline fusion of the residue (see appendix). The precision of these results, as determined by replicate analysis of a control sample, in which the cobalt and nickel contents average 93 ppm. and 230 ppm. respectively, is estimated to be 6 per cent. In addition, 25 samples were analysed for potassium by a flame photometric method, and 10 samples were analysed for total lead by acid leach and alkaline fusion. No data was obtained on the precision of these results.

Table 7. The mean precision of chemical analyses of the statistical control samples (at the 95% confidence level)

| Element | Mean precision | Range of concentration in control samples ppm. | | No. of determinations | Range of concentration in Sierra Leone samples ppm. | | No. of analyses | Source of analytical method |
|---|---|---|---|---|---|---|---|---|
| As | ±25% | 5 | 125 | 240 | 5 | 100 | 2500 | Almond, 1953 |
| Sb | ±20% | 15 | 205 | 24 | 0.5 | 100 | 75 | Stanton & McDonald, 1961 |
| Zn | ±20% | 2 | 115 | 48 | 10 | 500 | 500 | Lakin et al 1949 |
| Mo | ±40% | 2 | 100 | 14 | 2 | 30 | 150 | North 1956 |

## OPTICAL SPECTROCHEMICAL ANALYSIS

Samples of rock, soil, and stream sediment were analysed by a simple semi-quantitative spectrochemical method which permits the simultaneous determination of some twenty elements. The method, which is fully described in the appendix, was developed at the G.P.R.C. from the method recommended by Kerbyson (1960), and that employed by Messrs. Chartered Exploration Ltd., of Lusaka, Northern Rhodesia.

## BRIEF DESCRIPTION OF THE METHOD

A high energy source unit is employed, and the sample, previously mixed with a buffer (lithium carbonate and carbon), is volatilised at the anode for a period of 20 seconds. The spectra are analysed by a Hilger Large Quartz spectrograph. The chemical content is estimated using a Hilger J.A.Co. comparator, and the following elements are estimated in all of the samples:- Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, Mo, Ag, Cd, Sn, Ba, Pb, Bi, and Na, Mg, Al, K, Ca, and Fe. Molybdenum is re-analysed by a modified and more sensitive method (see appendix).

The spectrochemical standards are at concentrations of 1, 2 and 5 units for trace elements and major elements with the following exceptions; barium: 0.1, 0.3, 1.0 units, and sodium and potassium: 0.15, 0.5, 1.5 units. The limits of detection, and the wavelength of the spectral lines used in analysis, are shown in table 8.

Table 8. Limits of detection and wavelengths of lines used in spectrochemical analysis

| Element | Limit of detection | | Wavelength of line in Å | Element | Limit of detection | | Wavelength of line in Å |
|---|---|---|---|---|---|---|---|
| | Low | High | | | Low | High | |
| | ppm | | | | ppm | | |
| Ag | 0.1 | 1000 | 3382.9 | Sn | 1 | 10,000 | 2840.0 |
| Ba | 10 | 10,000 | 4554.0 | Ti | 50 | 10,000 | 3377.6 |
| Bi | 10 | 10,000 | 3067.0 | V | 5 | 10,000 | 3185.0 |
| Cd | 50 | 10,000 | | Zr | 100 | 10,000 | 3438.0 |
| Co | 5 | 10,000 | 3453.5 | | per cent | | |
| Cr | 2 | 10,000 | 4254.0 | $Al_2O_3$ | 5 | 20 | 3064.3 |
| Cu | 1 | 200 | 3274.0 | CaO | 0.1 | 20 | 4425.4 |
| Ga | 2 | 10,000 | 2944.0 | $Fe_2O_3$ | 0.1 | 20 | 3225.8 |
| Mn | 1 | 10,000 | 4034.0 | $K_2O$ | 0.1 | 5.0 | 4044.0 |
| Mo | 5 | 10,000 | 3170.0 | MgO | 0.2 | 20 | 3336.7 |
| Ni | 2 | 1000 | 3414.8 | $Na_2O$ | 0.1 | 5.0 | 3302.0 |
| Pb | 1 | 10,000 | 2833.0 | | | | |

By the spectrochemical method outlined above, two operators are able to maintain a productivity of 52 samples for 15 elements per 7 hour day.

The buffer

Following the observations of Scott (1945) and Makitie and Lappi (1958) upon marked variations in the intensity of individual spectra related to base composition, Kerbyson (1960) investigated the possibility of reducing the bias, or matrix effect, to be expected from reading samples of varying composition against a single set of standards. The samples he used consisted mainly of synthetic mixtures simulating the composition of a wide range of igneous rocks and natural soils.

Kerbyson demonstrated that the effect of variation in base composition upon the spectral line intensity was markedly decreased by using lithium carbonate as a buffer; this was mixed with carbon and the sample in the proportion 1:1:2. This technique continued to be employed following the introduction of the high energy source unit, and proved to be satisfactory in areas of mature soils (Fortescue, 1962) and on the rock samples G.1. and W.1. (table 9).

In Sierra Leone, however, a marked base composition effect was observed despite the presence of the buffer (see analytical bias, below).

Table 9. Data on the performance of the spectrochemical method (Fortescue, 1962)

| Standard Rock | Cu | Pb | Cr | Co | Ni | Mn | Mo | Sn | Ga | V | Ti | R.S.M. Replicate Nos. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| G.1. | 20 | 40 | 8 | - | - | 120 | 5 | 3 | 25 | 10 | 1500 | 1 |
| | 15 | 70 | 10 | - | - | 120 | 8 | 3 | 30 | 10 | 1500 | 2 |
| | 10 | 70 | 10 | - | - | 150 | 5 | 3 | 25 | 10 | 1500 | 3 |
| | 18 | 70 | 10 | - | - | 180 | 10 | 3 | 30 | 10 | 1500 | 4 |
| | 20 | 40 | 10 | - | - | 180 | - | 3 | 25 | 10 | 1200 | 5 |
| | *13 | 55 | 22 | 2.2 | 1.2 | 210 | 7 | 2 | 18 | 21 | 1440 | U.S.G.S. |
| W.1. | 120 | 5 | 120 | 60 | 100 | 1500 | - | 3 | 20 | 350 | 7000 | 1 |
| | 150 | 6 | 150 | 60 | 80 | 2000 | - | 2 | 20 | 400 | 7000 | 2 |
| | 120 | 7 | 150 | 40 | 80 | 1500 | - | - | 15 | 400 | 7000 | 3 |
| | 120 | 5 | 100 | 40 | 70 | 1500 | - | - | 18 | 300 | 5000 | 4 |
| | *100 | 7 | 120 | 51 | 80 | 1300 | 0.5 | 3 | 16 | 240 | 6430 | U.S.G.S. |

* Contents from Stevens, R.E. (1960).

PRECISION OF THE SPECTROCHEMICAL METHOD

If variations in the estimated element content of samples are to be interpreted accurately, it is essential to have some knowledge of any bias that may be present in the analytical method, and also to know the precision of the estimations. To obtain this information, statistical control samples were included in each analytical batch, and an internal standard (germanium), was added to the buffer.

The analytical precision for the separate elements was estimated from scatter diagrams, in which replicate analytical results of the statistical control samples are compared with the mean value of all of the determinations. These diagrams (figure 7, in Part 2. ) show that the analytical precision is generally ± 50 per cent, but that it varies for different elements. Thus, the analytical precision is better than

± 50 per cent for:- Mn, Ge, Cr, Co, Ni, Mo, Cu, Fe, Ti, V, and;

± 65 per cent for:- Ba, Ca, Pb, and K.

The precision of aluminium, sodium and magnesium analyses were not estimated, as these elements were not used in this phase of the study. Only trace amounts of sodium are present in the control samples, and the concentration range is also considered to be inadequate in the case of lead, potassium, calcium, and manganese for the determination of the analytical precision.

ANALYTICAL BIAS

Analytical bias related to sample composition

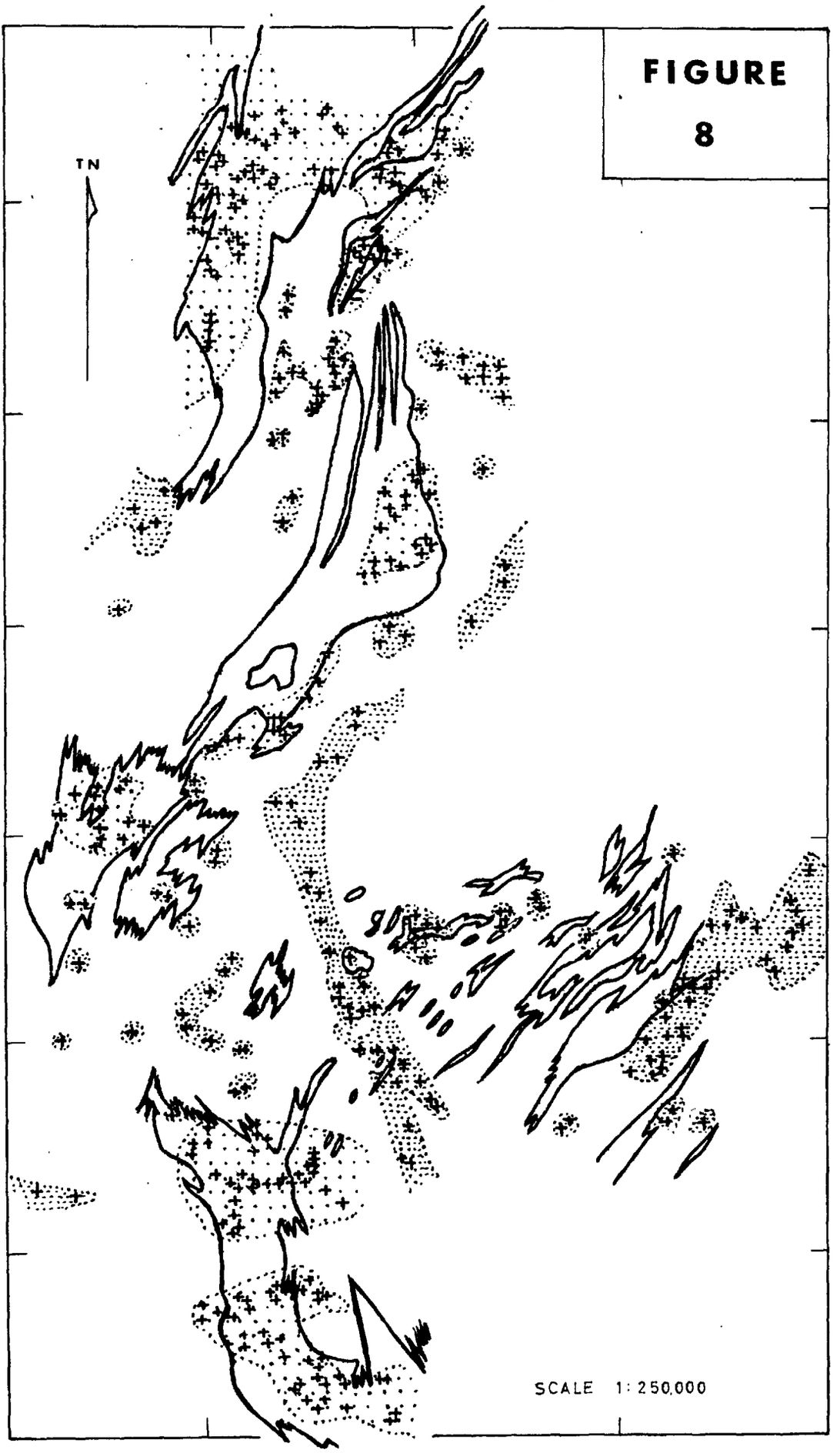
The principle of internal standardisation in spectrochemical analysis was introduced by Gerlach (1925), and has since been extensively used to control a variety of inherent analytical defects (Ahrens and Taylor, 1961).

Germanium was selected as the internal standard in the present method, because of its medium volatility and favourable excitation characteristics, as it was only expected to occur in minor quantities in the Sierra Leone samples. In practice, germanium oxide is added to the carbon buffer mixture, so that 100 mg. of the sample contains about 400 ppm. of germanium.

The content of germanium in the Sierra Leone samples as estimated spectrographically varied considerably more (-75 to +150 per cent) than that to be expected on the basis of the analytical precision (±50 per cent), calculated from replicate analyses. Furthermore, apparent low germanium concentrations were found to be associated with samples from iron rich rocks, in particular amphibolites, serpentinites and banded ironstones (fig. 8) and high germanium concentrations were associated with samples from iron poor, silica rich rocks.

Confirmation that the large variations in estimated germanium content are related to differences in the base composition was

**FIGURE 8**




EXPLANATION

- outcrops of Fe rich rocks
- Apparent concentration of Ge. > 640 p.p.m.
- 400 - 640 ppm. Ge.
- < 400 p.p.m. Ge.

+++ Sample locations in which Ge. shows extreme variation in apparent concentration from the true content of 400ppm Ge.

## THE SULA MOUNTAINS - KANGARI HILLS SCHIST BELT

THE DISTRIBUTION OF THE SPECTROCHEMICAL INTERNAL STANDARD GERMANIUM

RELATED TO

THE OUTCROPS OF IRON RICH ROCKS

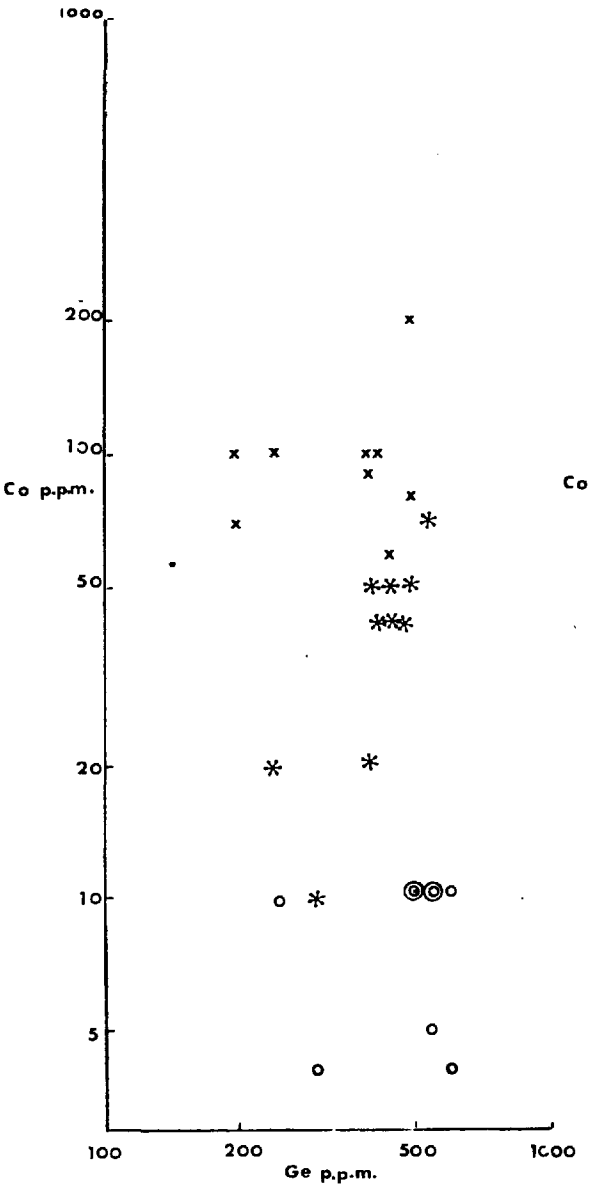
obtained by Nichol and Henderson-Hamilton (1962) working on synthetic mixtures (table 10). They also showed that the influence of the base composition was much greater on germanium than on most other elements. However, their experiments did not cover the whole range of bulk composition detected in the writer's samples and accordingly somewhat greater bias effects than their maxima can be expected to be present in the Sierra Leone data.

It is shown on fig. 9 that in the statistical sample series using visual estimation techniques, the visually estimated germanium and cobalt are not consistent, and therefore no attempt has been made to correct the analytical results. However, the results of replicate analyses of germanium and cobalt, in the statistical sample series, obtained by using the photo-densitometer, vary sympathetically, and show that germanium does in fact behave as an internal standard, and can be used in quantitative estimations of the metal content (fig. 9).

Bias related to visual estimation of the chemical content

The presence of a spectrum estimation bias is demonstrated by a comparison of germanium results obtained by a visual estimation of the spectra with those obtained by using a densitometer (fig. 10). With visual estimation there is a marked tendency for results to be grouped towards the standards. This fact must be considered in grouping results, and interpreting small variations in the trace element content (see page 43 ).

# FIGURE 9




Visual estimation.

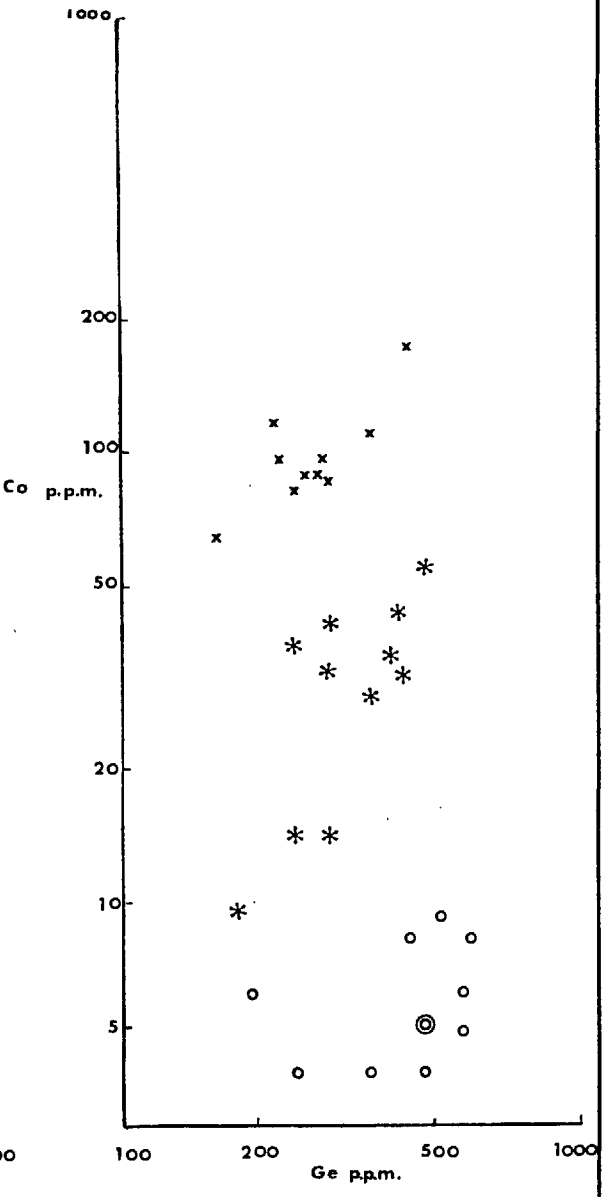
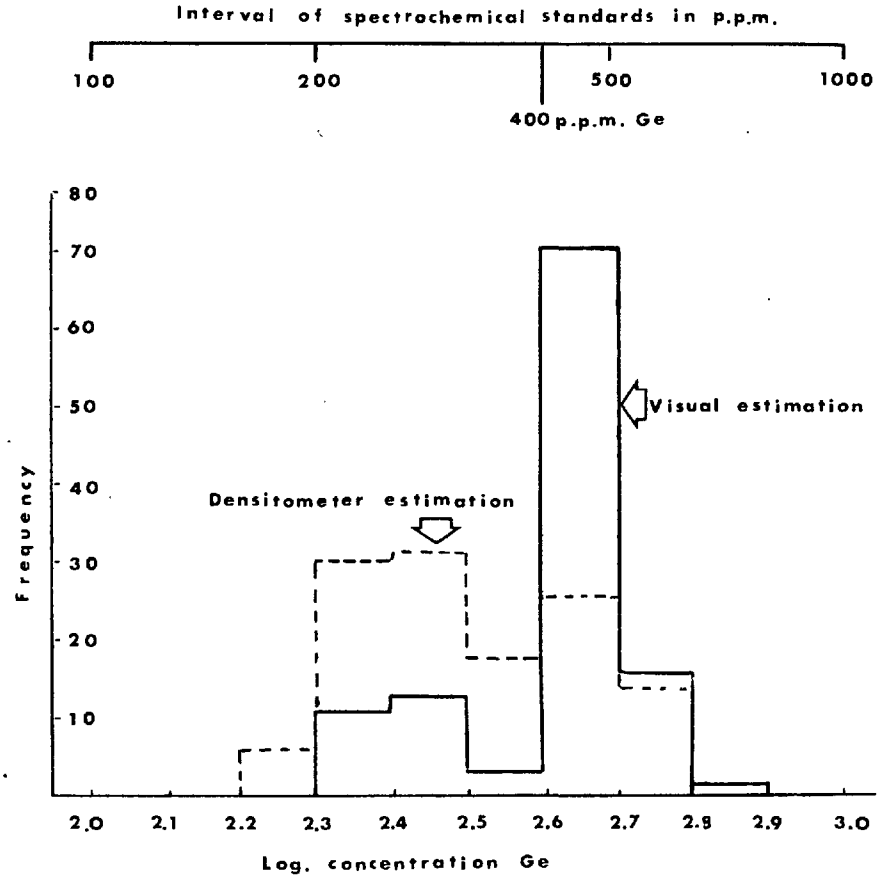



Photo densitometer estimation.

**Sympathetic variation of germanium and cobalt in the statistical control samples.**

6919 - x
6924 - o
6922 - *

# FIGURE 10




**The Internal Standard Germanium.**

COMPARISON OF VISUAL AND PHOTO DENSITOMETER ESTIMATIONS, IN THE STATISTICAL CONTROL SAMPLES.

Table 10. The effect of major element composition upon the apparent concentration of the trace elements, in synthetic mixtures
Adapted from Nichol and Henderson Hamilton (1962)

Trace metal content 150 ppm.; germanium content 950 ppm.

\+ positive; $\frac{\text{spectrochemical result}}{\text{true content}}$ — negative; $\frac{\text{true content}}{\text{spectrochemical result}}$

| Major element composition % | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | $Fe_2O_3$ | $M_2O_3$ | CaO | MgO | Ti | V | Cr | Mn | Co | Ni | Cu | Ga | Ge | Mo | Ag | Cd | Sn | Pb | Bi |
| 100 | - | - | - | - | +4.1 | +2.6 | +3.3 | +2.0 | +4.1 | +5.3 | +6.6 | +4.0 | +2.1 | +4.0 | +2.6 | +2.6 | +3.3 | +4.0 | +2.6 |
| 98.6 | 0.1 | 0.1 | 0.1 | 0.1 | +4.0 | +2.6 | +2.3 | +1.3 | +4.1 | +4.1 | +3.3 | +2.5 | +1.2 | +4.0 | +2.0 | +2.0 | +2.0 | +2.0 | +2.0 |
| 99.2 | 0.2 | 0.2 | 0.2 | 0.2 | +2.6 | +1.3 | +2.0 | +1.3 | +2.6 | +4.0 | +1.3 | +2.5 | +1.1 | +2.6 | +1.2 | +2.0 | +2.0 | -1.0 | +1.3 |
| 98.0 | 0.5 | 0.5 | 0.5 | 0.5 | +3.3 | +2.0 | +2.0 | +1.3 | +2.6 | +4.0 | +3.3 | +2.6 | +1.2 | +3.3 | +2.0 | +2.0 | +2.0 | 1.0 | +1.3 |
| 96.0 | 1.0 | 1.0 | 1.0 | 1.0 | +2.6 | +1.2 | +2.0 | +1.2 | +2.0 | +2.6 | +1.3 | +2.0 | +1.1 | +2.0 | 1.0 | +2.0 | +2.0 | -1.5 | 1.0 |
| 92.0 | 2.0 | 2.0 | 2.0 | 2.0 | +3.3 | +1.3 | +1.6 | +1.4 | +2.0 | +2.6 | +2.6 | +2.0 | +1.1 | +2.6 | +2.0 | +2.0 | +2.6 | +2.6 | +2.6 |
| 80.0 | 5.0 | 5.0 | 5.0 | 5.0 | +2.0 | +1.3 | +1.6 | +1.3 | +2.0 | +2.0 | +2.0 | +1.6 | -1.3 | +1.3 | 1.0 | +1.6 | +2.0 | +1.3 | 1.0 |
| 60.0 | 10.0 | 10.0 | 10.0 | 10.0 | +1.3 | 1.0 | +1.3 | +1.6 | +1.3 | +1.2 | +2.0 | +1.6 | -1.3 | 1.0 | +1.2 | +2.0 | +2.0 | +2.6 | +2.0 |
| 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 1.0 | -1.5 | -1.2 | +2.0 | 1.0 | 1.0 | +1.3 | +1.3 | -2.6 | -1.5 | -1.2 | +1.6 | +1.3 | +3.3 | +3.3 |
| 10.0 | 35.0 | 35.0 | 10.0 | 10.0 | -2.1 | -2.1 | -1.5 | +2.6 | -1.5 | -1.2 | +1.3 | +1.3 | -3.8 | -2.1 | -1.9 | 1.0 | +1.3 | +2.6 | +2.6 |

Comparison of spectrochemical and chemical analyses

The accuracy of the spectrochemical analyses would be expected to vary according to the major element composition of the sample, as seen from the results of the investigation into this effect in synthetic matrices (table 10). To investigate this possibility in a series of natural samples, with a wide range of major element composition, the end members of the statistical control samples, and fifteen Sierra Leone samples were analysed by a chemical method (see appendix) for total cobalt and nickel.

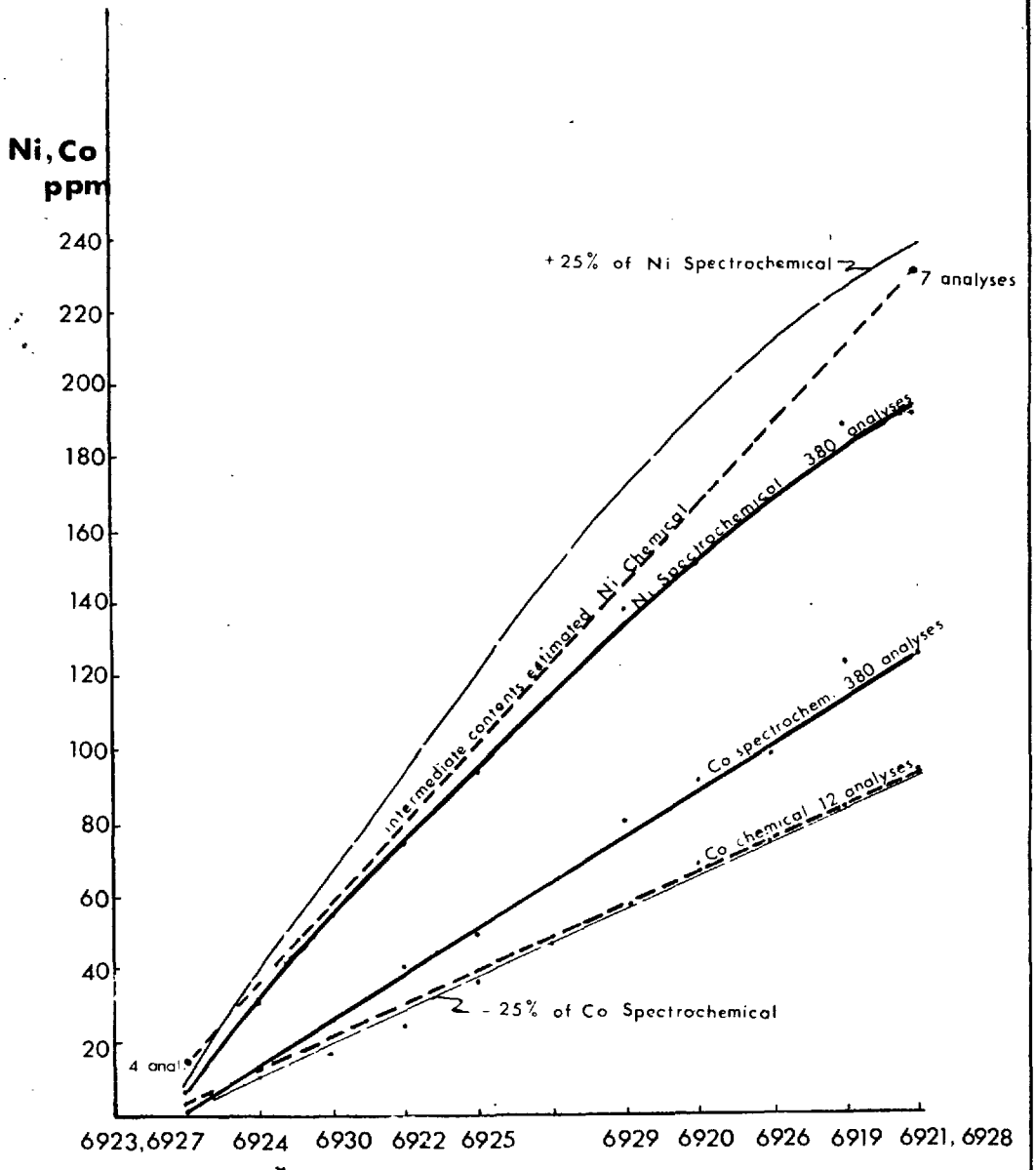
A comparison of the chemical and spectrochemical results of the control samples shows that (accepting the chemical results to be correct) the accuracy of the spectrochemical results is $\pm 25$ per cent of the chemical results (fig. 11). The bias is apparently positive for cobalt and negative for nickel, and increases concordantly with the iron content of the samples.

In the Sierra Leone samples (table 11), comparisons of the chemical and spectrochemical results (read by densitometer) show a generally similar bias to that of the control samples, except that there appears to be a slight positive bias in the results of the iron poor samples (i.e., the spectrochemical results are enhanced relative to the chemical results).

Conclusion

It will be apparent from the tables 10 and 11, that the analytical results from areas of silliceous rocks (granites and

**FIGURE 11**




**COMPARISON OF CHEMICAL AND SPECTROCHEMICAL ANALYSES OF COBALT AND NICKEL SHOWING THAT THE SPECTROCHEMICAL BIAS IS LESS THAN 25% OF THE CHEMICAL RESULTS.**

Table 11. Comparison of analytical results of Sierra Leone samples by chemical and spectrochemical analyses. Cobalt and nickel results only, were obtained by using the photo lensitometer

| Sample No. | Ce | $Fe_2O_3$ | $Al_2O_3$ | MgO | CaO | $Na_2O$ | $K_2O$ | Chemical Nickel | Spec. Nickel | Chemical Cobalt | Spec. Cobalt |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ppm | % | % | % | % | % | % | ppm | ppm | ppm | ppm |
| 173 | 600 | 0.2 | 5.0 | - | 1.0 | 4.0 | 5.0 | 12 | 20 | 8 | nd |
| 2281 | 800 | 0.5 | 6.0 | - | - | - | 0.15 | 12 | 29 | 8 | 6 |
| 146 | 1000 | 0.5 | 15.0 | 0.2 | 2.0 | 3.0 | 5 | 30 | 40 | 12 | 5 |
| 2043 | 800 | 0.6 | 10.0 | 0.5 | 0.4 | 4.0 | 5 | 5 | 30 | 12 | 8 |
| 2286 | 800 | 1.0 | 20.0 | - | 0.15 | 0.5 | 5 | 20 | 36 | 8 | 8 |
| 2238 | 400 | 2.0 | 5.0 | 0.5 | 1.0 | 0.5 | 0.3 | 62 | 50 | 12 | 11 |
| 434 | 450 | 8.0 | 15.0 | 1.5 | 1.2 | - | 0.5 | 124 | 270 | 56 | 58 |
| 438 | 450 | 8.0 | 15.0 | 1.5 | 1.0 | - | 0.5 | 164 | 200 | 32 | 56 |
| 2237 | 400 | 10.0 | 15.0 | 20.0 | 1.0 | - | 1.0 | 111 | 130 | 8 | 27 |
| 2236 | 400 | 20.0 | 10.0 | 1.5 | 2.0 | - | 0.5 | 94 | 35 | 16 | 35 |
| 983 | 150 | 20.0 | - | 5.0 | 1.8 | - | 0.4 | 1708 | 2000 | 132 | 290 |
| 2788 | 150 | 15.0 | 10.0 | 4.5 | 0.6 | - | 0.2 | 1032 | 450 (vis) | 68 | 95(vis) |
| 2700 | 150 | 20.0 | 15.0 | 10.0 | 2.5 | - | 0.2 | 1120 | 1000 | 52 | 95 |
| 2786 | 150 | 20.0 | 15.0 | 4.0 | 0.5 | - | 0.3 | 876 | 600 | 48 | 100 |
| 3058 | 150 | 20.0 | 20.0 | 1.5 | 1.5 | 0.5 | 0.4 | 148 | 190 | 16 | 60 |

quartzites) are likely to be enhanced, and that those for samples from iron rich rocks will tend to be suppressed. In practice, the lowest element concentrations were observed in areas of siliceous rocks (except for lead, barium and potassium), and it can therefore be concluded that:

a) the bias due to variation in bulk composition will tend to suppress geochemical patterns, and therefore

b) the geochemical provinces detected are not ascribable to analytical bias.

X-RAY SPECTROCHEMICAL ANALYSIS

Fifty samples were analysed for: Rb, Sr, Yt, and Zr, by a method whose precision is estimated to be ±20 per cent.

Presentation of the analytical data

To facilitate the interpretation of the analytical data, the results were grouped into a series of 'classes', and each 'class' is represented as a distinct symbol on the geochemical maps.

The range of concentration represented by a class is based upon the precision of the analytical method. The classes extend from mid point to mid point between the standards. The spectrochemical standards are spaced at approximately logarithmic intervals, and therefore the classes are also logarithmically spaced. Since a marked spectrum reading bias has been observed in which the results are biased towards the spectrochemical standards, this system

of grouping the analytical results will not only partly allow for the reading bias, but will also include the variations of analytical results to be expected from analytical precision (±50 per cent). It is only the results which are reported at the concentrations of the standards which will be invariably grouped into the correct class. Results which are reported from between the standards are equally subject to the analytical precision and it follows that these results are likely to be grouped into an adjacent, and possibly incorrect class.

To facilitate the grouping of the results into classes, the numerical equivalents of the logarithms were rounded off to form whole numbers (table 12). This results in the redistribution of a small number of analytical results close to the limits of the classes. In fact, it is the results in the classes grouped around the spectrochemical standards at the 10, 20, 100, 200, 1000 and 2000 ppm. levels of concentration which are affected, whereas these classes grouped around the 5, 50, 500 and 5000 ppm. standards are unaffected by the redistribution.

The effect of this redistribution upon the interpretation of the geochemical map is likely to be small, because the primary concentrations of the elements in the bedrock are frequently represented, due to their secondary dispersion characteristics, by a much wider range of concentration in the stream sediments than in the fresh rock. Such a distribution will result in a

Table 12 . Grouping of the analytical results.

| Intervals of Spec. Standards ppm. | Log. of Mid Points Between Standards | Numerical Equivalent | Numerals Rounded off | Frequency of analytical results | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Ti | V | Cr | Mn | Ca | Ni | Cu | Pb |
| 1 | | | | | | | | | | 12 | 341 |
| | 0.2 | 1.6 | 1.5 | | | | | | | | |
| 2 | | | | | | 12 | | | 27 | 84 | 30 |
| | 0.5 | 3.2 | 3.0 | | | | | | | | |
| 5 | | | | | 134 | 35 | | 485 | 95 | 288 | 558 |
| | 0.85 | 7.8 | 7.0 | | | | | | | | |
| 10 | | | | | 176 | 75 | 5 | 362 | 153 | 347 | 307 |
| | 1.15 | 14.2 | 15 | | | | | | | | |
| 20 | | | | | 173 | 86 | 12 | 307 | 144 | 256 | 147 |
| | 1.5 | 32 | 30 | | | | | | | | |
| 50 | | | | | 338 | 273 | 66 | 233 | 273 | 320 | 80 |
| | 1.85 | 78 | 70 | | | | | | | | |
| 100 | | | | | 379 | 369 | 133 | 92 | 568 | 162 | 12 |
| | 2.15 | 142 | 150 | | | | | | | | |
| 200 | | | | 33 | 233 | 318 | 221 | 9 | 140 | 17 | 2 |
| | 2.5 | 320 | 300 | | | | | | | | |
| 500 | | | | 58 | 51 | 290 | 420 | | 66 | | |
| | 2.85 | 780 | 700 | | | | | | | | |
| 1000 | | | | 195 | 3 | 89 | 460 | | 36 | | |
| | 3.15 | 1420 | 1500 | | | | | | | | |
| 2000 | | | | 190 | | 54 | 121 | | 6 | | |
| | 3.5 | 3200 | 3000 | | | | | | | | |
| 5000 | | | | 529 | | 19 | 50 | | | | |
| | 3.85 | 7800 | 7000 | | | | | | | | |
| 10000 | | | | 498 | | | 1 | | | | |

geochemical pattern which would be expected to include a range of element concentration represented by more than one class interval.

Individual maps are drawn for each of the elements studied, and they show the analytical results represented as symbols located at the sample sites in the stream drainage. The use of symbols to represent figures has obvious advantages when large numbers of analytical results are to be represented in the form of a map.

## SECTION 3

## THE GEOCHEMICAL MAP

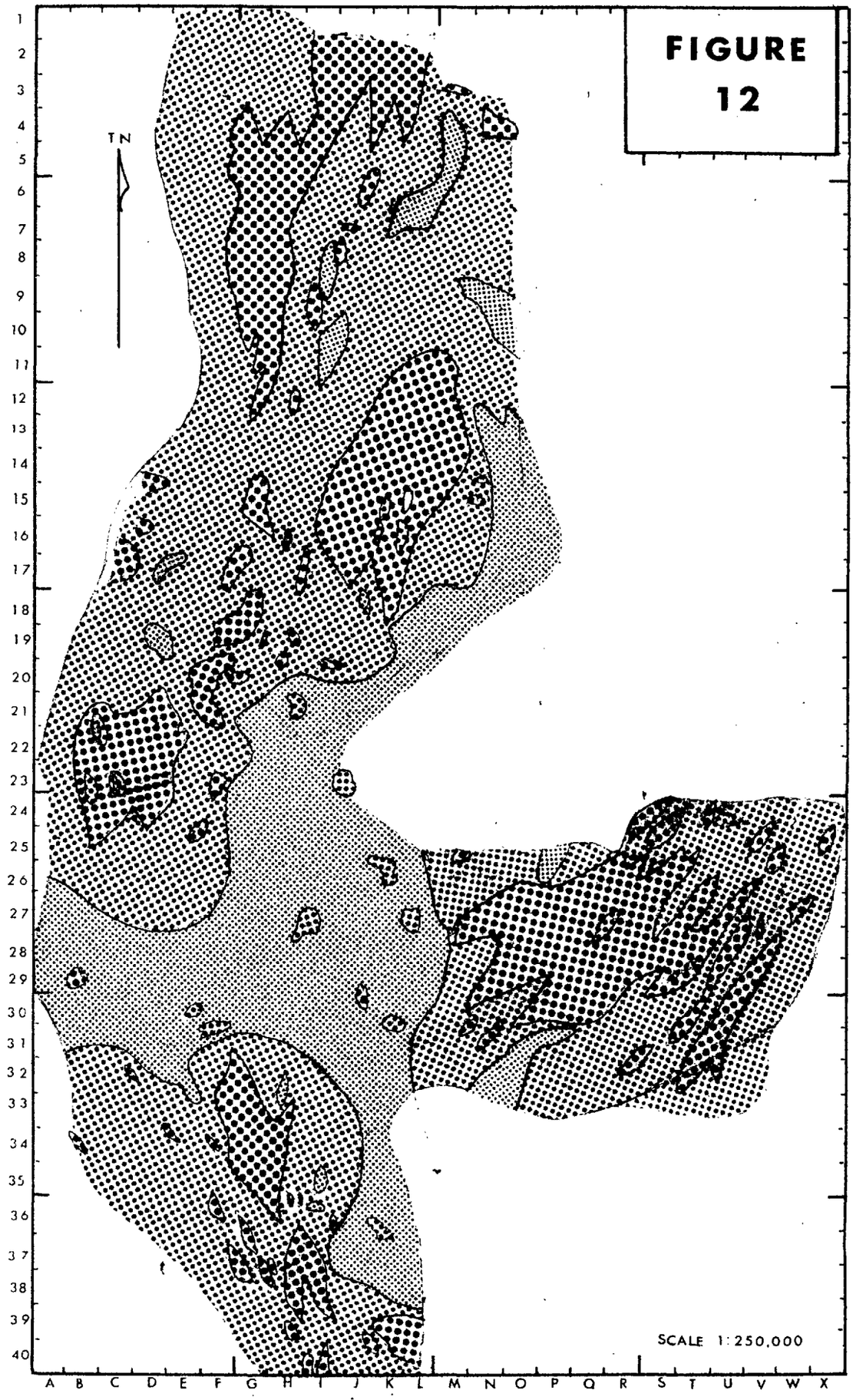
### GENERAL DESCRIPTION OF THE GEOCHEMICAL PATTERNS

In the following pages, the regional variations in the distribution of the elements are frequently described in terms of the 'geochemical topography'. The topography is an expression of the geochemical relief, and this is determined by variations in the concentration levels of the elements. Following Hawkes and Webb (1962), the "geochemical relief is defined not only by the contrast between high and low values, but also by the homogeneity of their distribution."

The regional geochemical patterns of the elements (figs. 12 to 21) are broadly similar in distribution except for those of lead. The geochemical patterns of the elements titanium, vanadium, chromium, manganese, cobalt, nickel, copper, and zinc show their highest concentrations in two areas; one covers the arcuate form of the Sula Mountains and Kangari Hills schist belt in the western part of the field area, and the other, the region of interfingering outcrops of ultrabasic and acid igneous rocks which occur in the eastern part of the field area.

Between the two extensive areas in which the minor elements (excluding lead) are most concentrated is an area in which only low contents of the minor elements were detected. An area of low

# FIGURE 12




EXPLANATION.

Ti P·P·M·

<1500

1500 – 7000

>7000

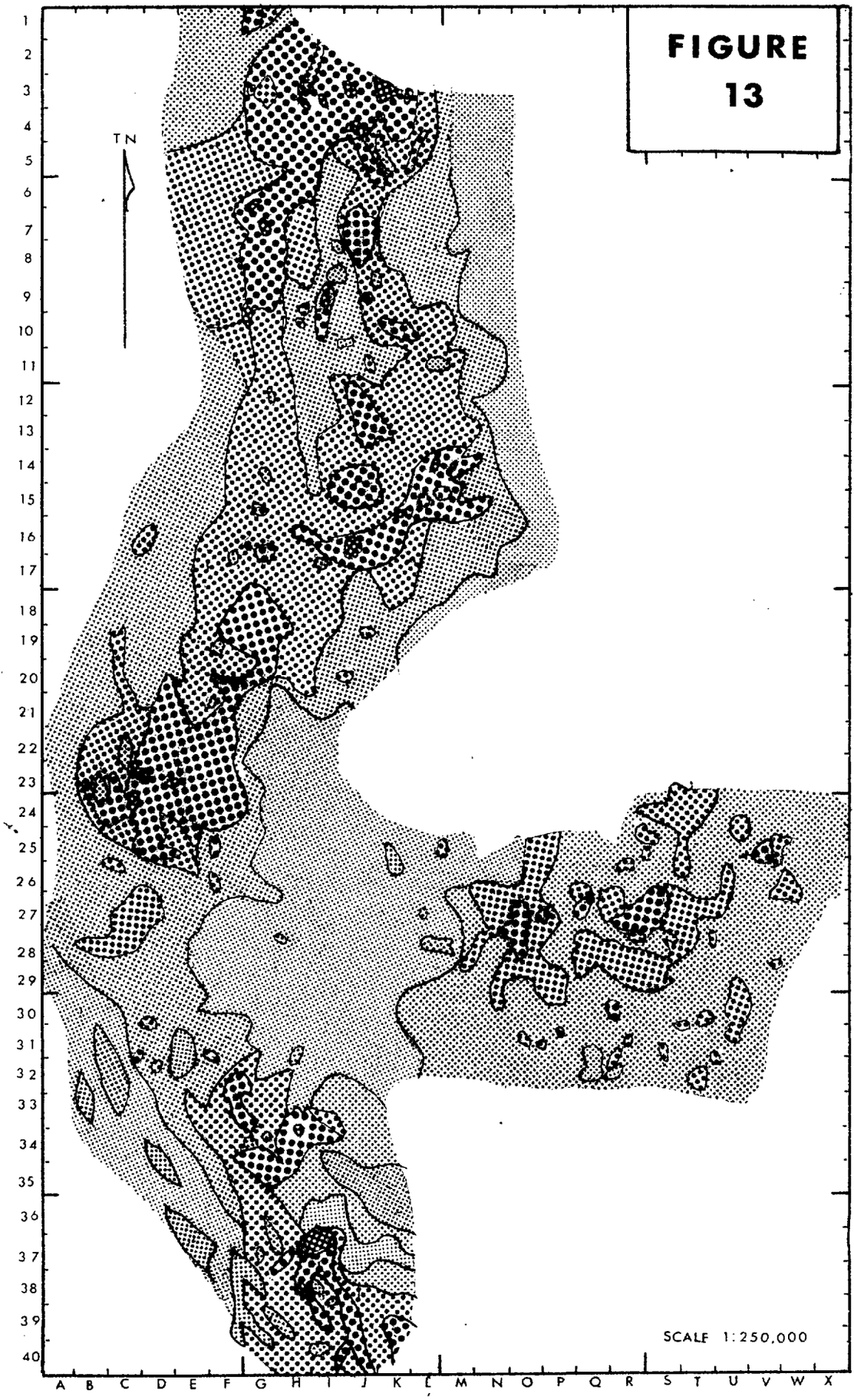
## REGIONAL GEOCHEMICAL PATTERNS

**Sula Mountains – Kangari Hills Area**

**Sierra Leone.**

## TITANIUM

# FIGURE 13




EXPLANATION.

V p.p.m.

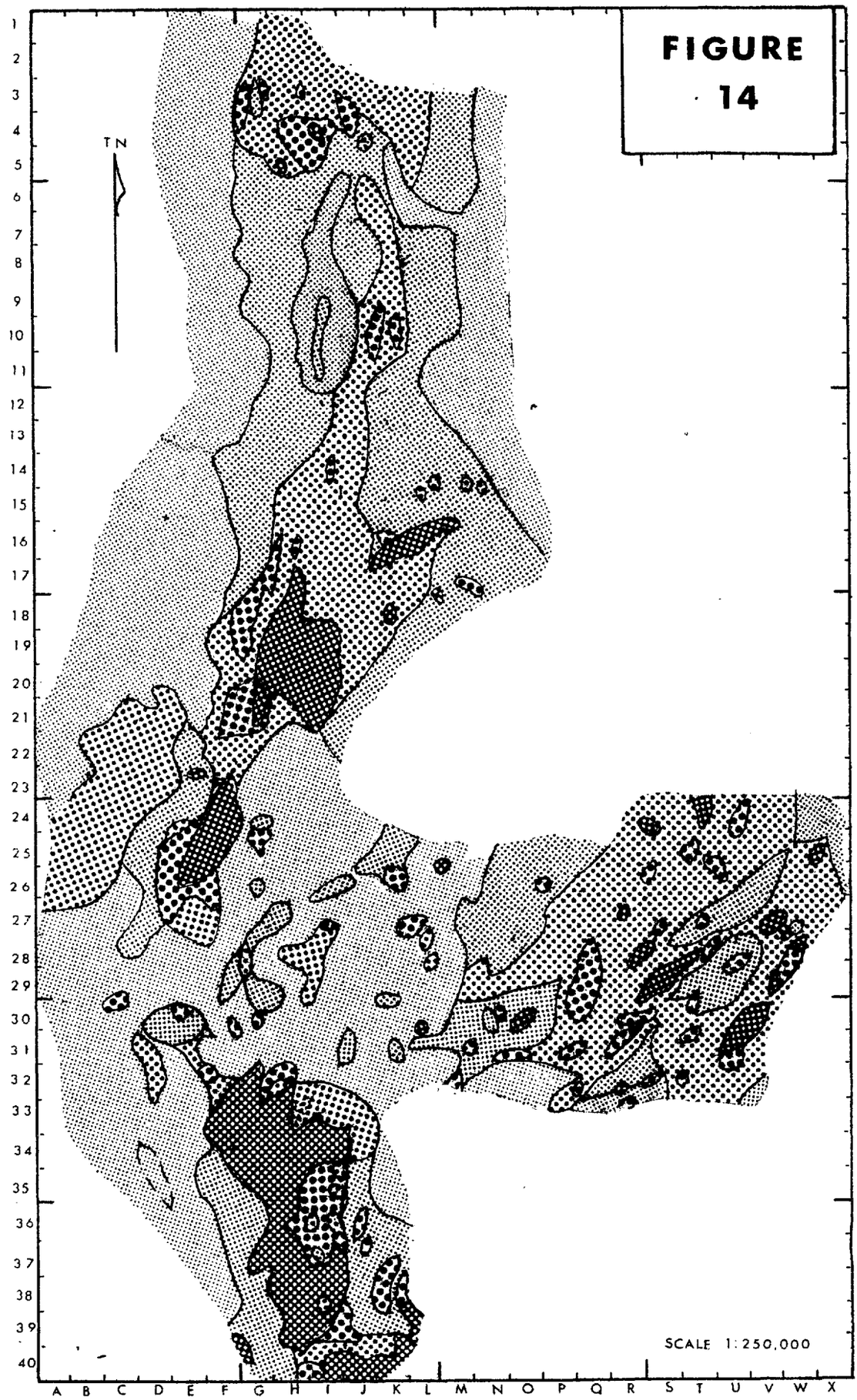
- < 30
- 30- 70
- 70–150
- 150 – 300
- >300

## REGIONAL GEOCHEMICAL PATTERNS

**Sula Mountains – Kangari Hills Area**

**Sierra Leone.**

## VANADIUM




EXPLANATION.

Cr p.p.m.

< 70

70 – 150

150 – 300

300 – 700

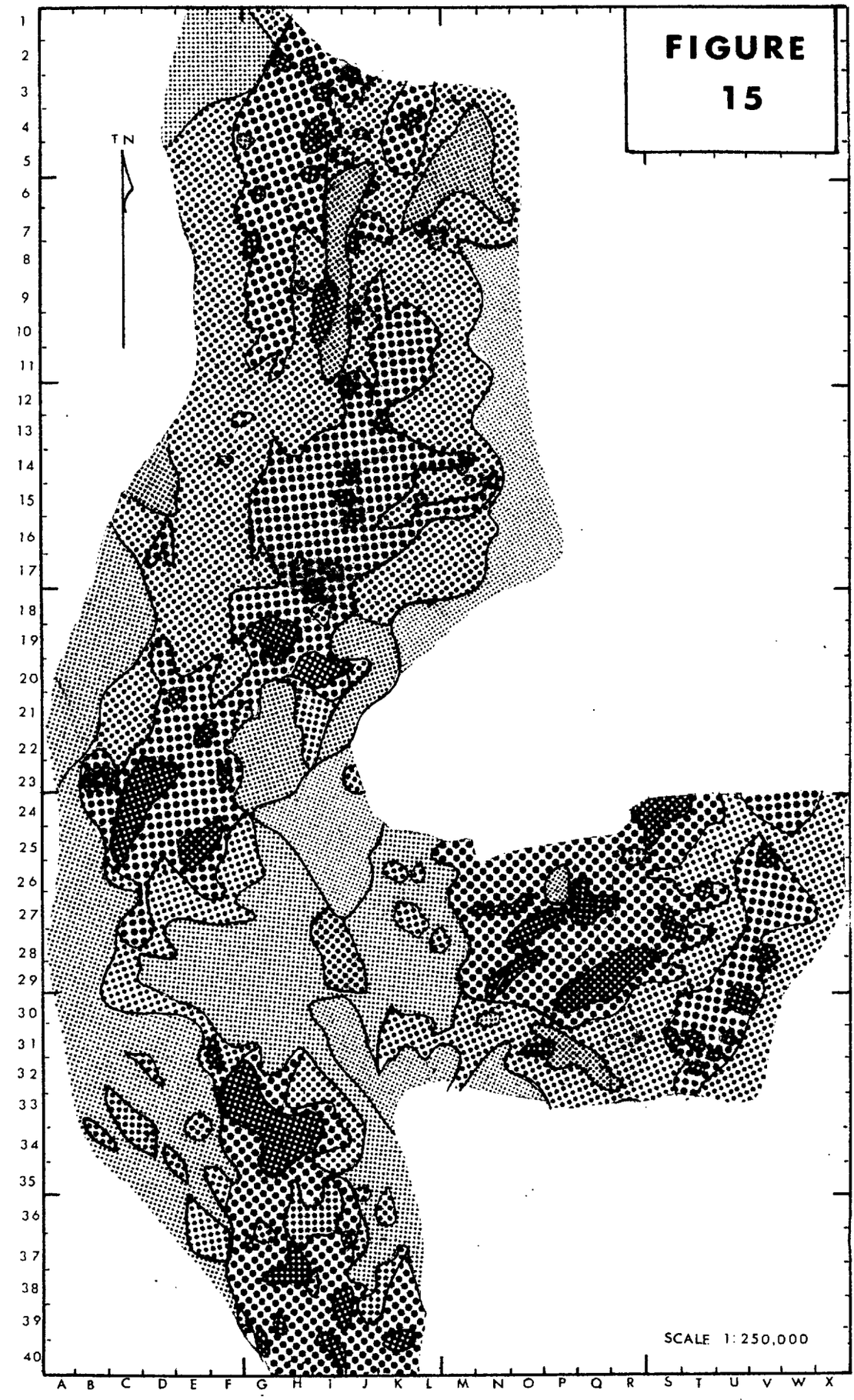
> 700

## REGIONAL GEOCHEMICAL PATTERNS

### Sula Mountains – Kangari Hills Area

### Sierra Leone.

### CHROMIUM




EXPLANATION.

Mn p.p.m.

- < 150
- 150 – 300
- 300 – 700
- 700 – 1500
- > 1500

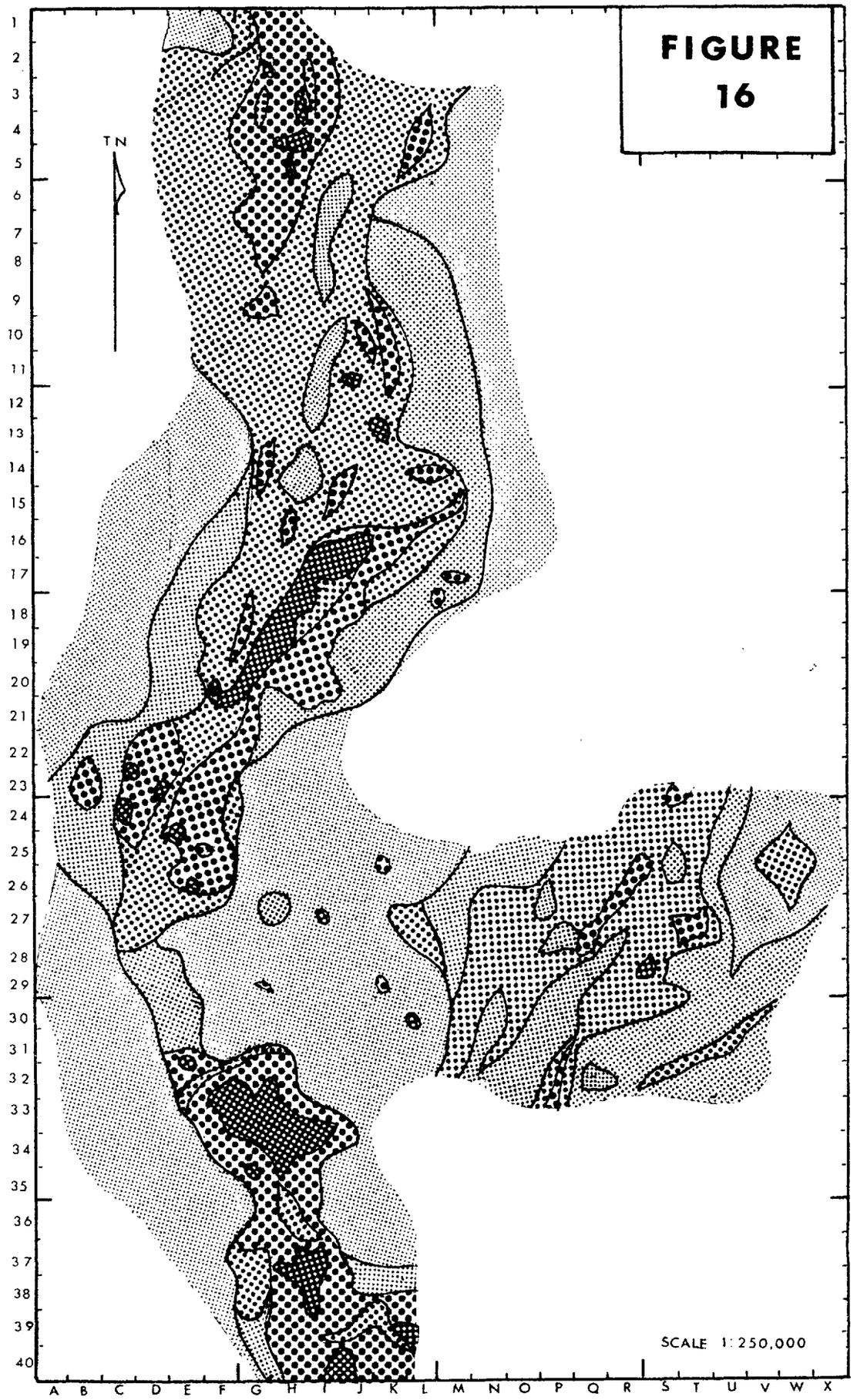
## REGIONAL GEOCHEMICAL PATTERNS

**Sula Mountains - Kangari Hills Area**

**Sierra Leone.**

## MANGANESE

# FIGURE 16




EXPLANATION.

Co p.p.m.

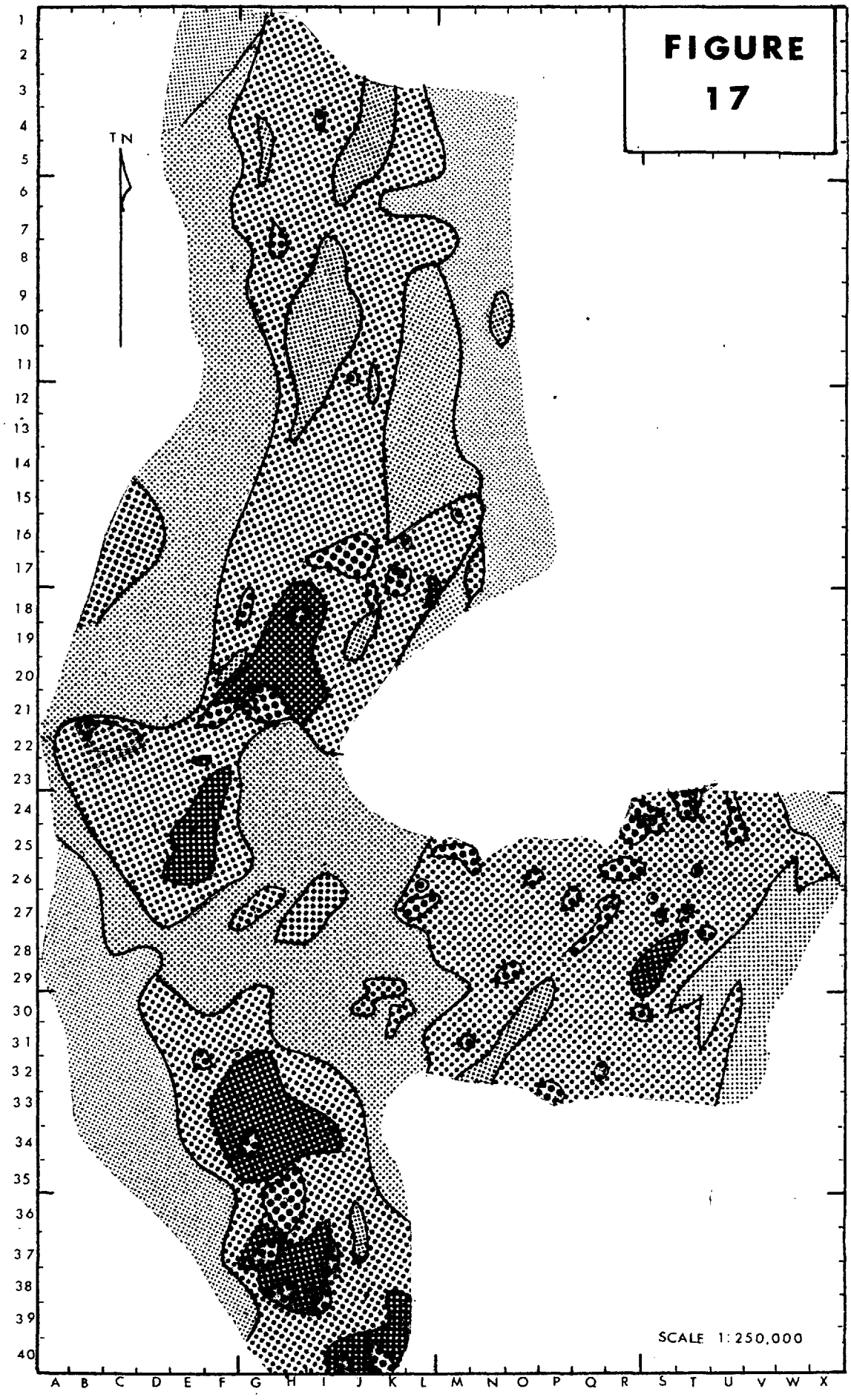
- < 7
- 7 – 15
- 15 – 30
- 30 – 70
- > 70

## REGIONAL GEOCHEMICAL PATTERNS

**Sula Mountains – Kangari Hills Area**

**Sierra Leone.**

**COBALT**




EXPLANATION.

Ni p.p.m.

<30

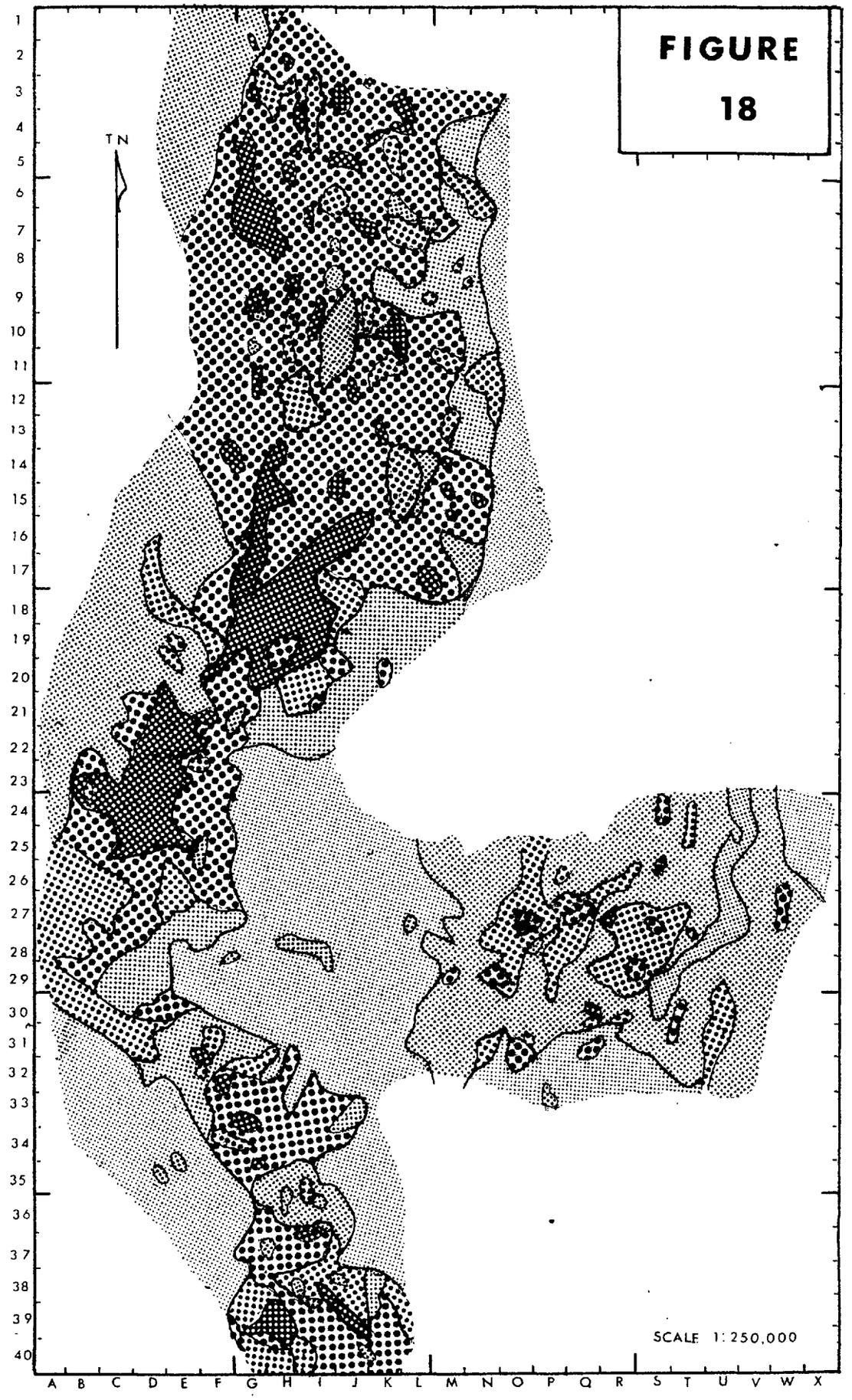
30 – 70

## REGIONAL GEOCHEMICAL PATTERNS

### Sula Mountains – Kangari Hills Area

### Sierra Leone.

## NICKEL




EXPLANATION.

Cu p.p.m.

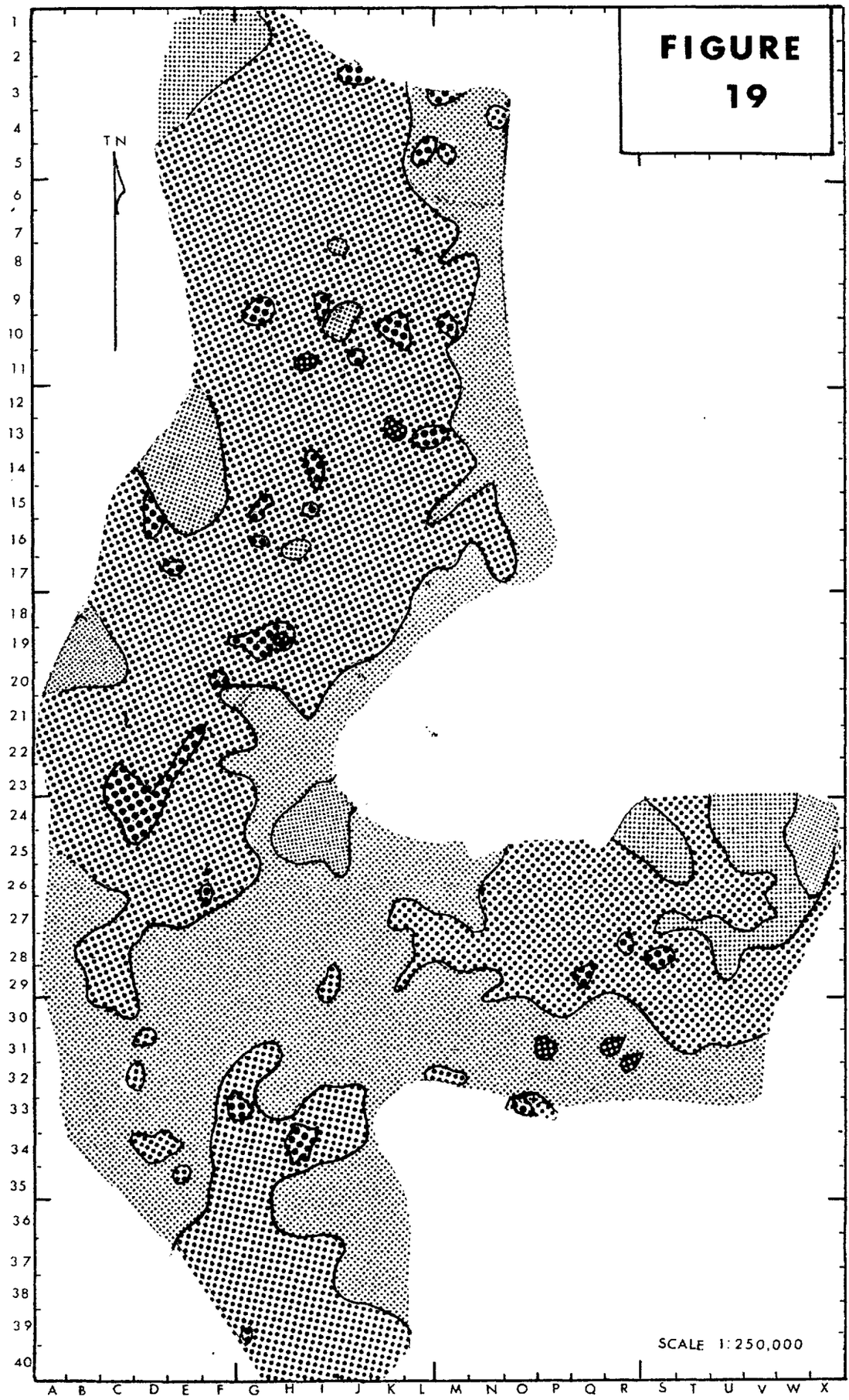
- < 7
- 7 – 15
- 15 – 30
- 30 – 70
- > 70

## REGIONAL GEOCHEMICAL PATTERNS

**Sula Mountains - Kangari Hills Area**

**Sierra Leone.**

**COPPER**




EXPLANATION.

Zn p.p.m.

- < 15
- 15 – 30
- 30 – 70
- 70 – 150
- >150

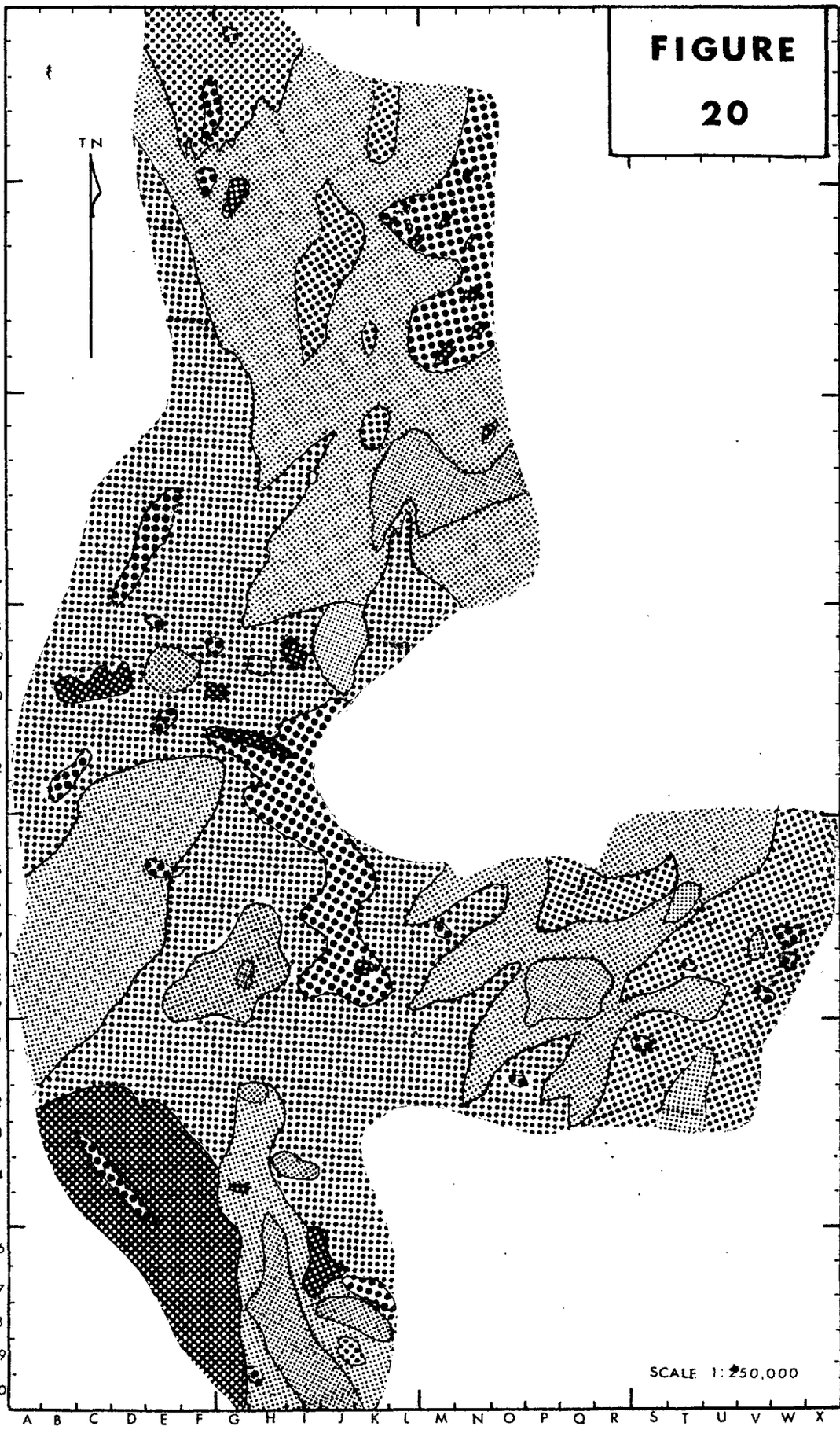
## REGIONAL GEOCHEMICAL PATTERNS

**Sula Mountains - Kangari Hills Area**

**Sierra Leone.**

**ZINC**

# FIGURE 20




EXPLANATION.

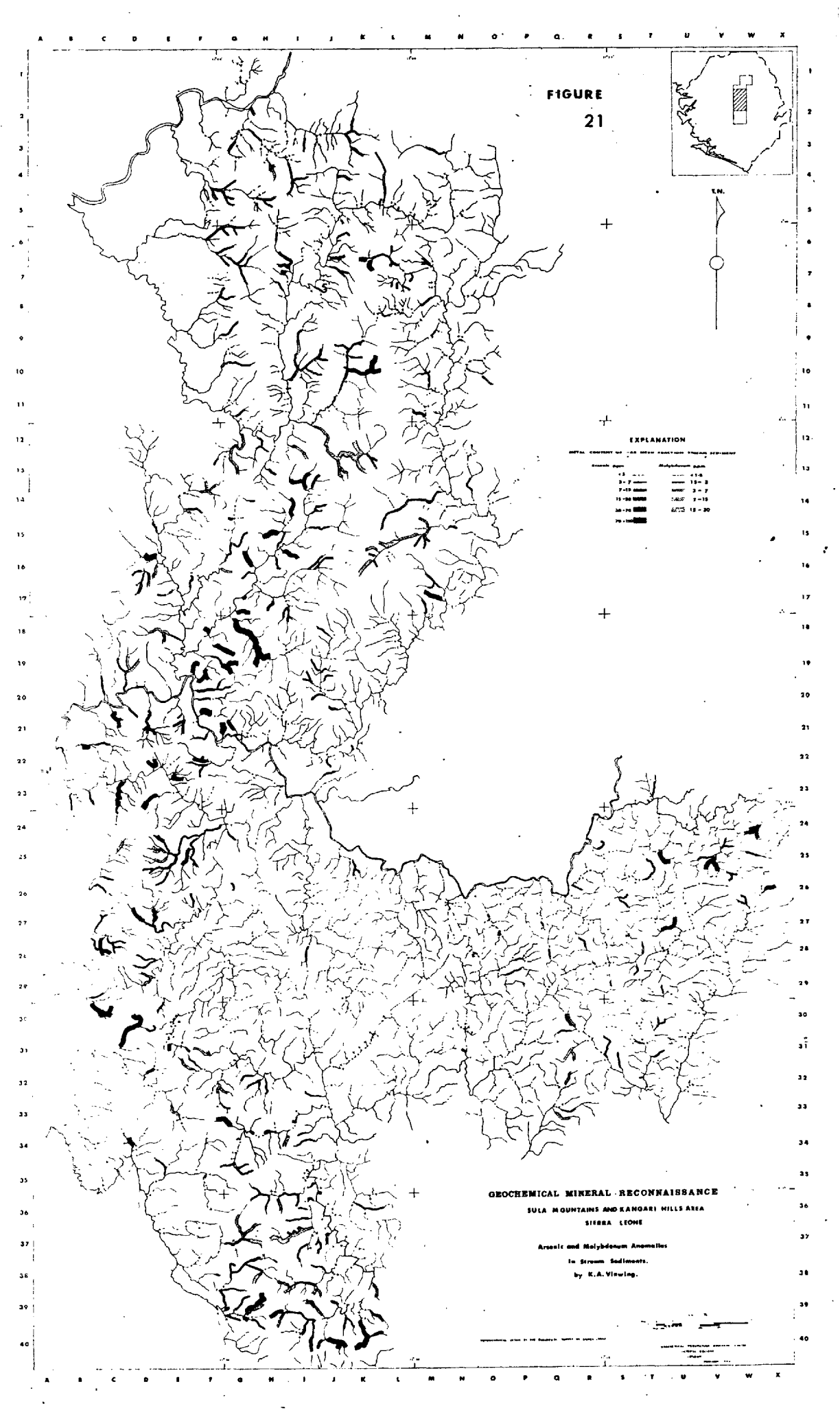
| Pb p.p.m. | |
|---|---|
| <3 | |
| 3 – 7 | |
| 7 – 15 | |
| 15–30 | |
| >30 | |

## REGIONAL GEOCHEMICAL PATTERNS

**Sula Mountains – Kangari Hills Area**

**Sierra Leone.**

**LEAD**


FIGURE
21
T.N.
EXPLANATION
GEOCHEMICAL MINERAL RECONNAISSANCE
SULA MOUNTAINS AND KANGARI HILLS AREA
SIERRA LEONE
Arsenic and Molybdenum Anomalies
in Stream Sediments.
by K.A. Viewing.

element concentration between two regions of high concentrations, such as the above, could be described in terms of regional geochemical topography as a 'trough', separating the alternating ridges and troughs to the east from the broad linear zone of strong relief at high levels of concentration to the west. Both areas of high relief are flanked by an intermediate and frequently low relief (at low levels of concentration) which extends in an east to west direction to the limits of the sample coverage.

The western zone of strong relief at high levels of concentration which extends over the Sula Mountains and Kangari Hills schist belt, is divided by a saddle which is represented by a number of samples at low levels of concentrations. The saddle is of varying width and level for the different elements. For example, the central titanium trough extends to the west and effectively divides the schist belt ridge (fig. 12), whilst for manganese and cobalt a narrow tenuous saddle connects the regions of high concentration to the north and south (figs. 15 and 16).

Within each of the main trough and ridge patterns there are a number of minor variations of relief. One of the most dominant of these minor patterns is situated in the northern part of the map, approximately in the centre of the schist belt. Here, the high peaks which are frequently situated on the axial area of the schist belt, give way to a deep trough which is well illustrated by the nickel patterns (fig. 17). The chromium and vanadium patterns

also show a trough in the same area as that of nickel, but unlike nickel, the chromium and vanadium troughs include a centrally situated peak which rises to the level of the surrounding topography.

The geochemical distribution of lead is very different to that of the other elements studied, and in general, the areas of high concentration are situated on the granite areas which are marginal to the schistose rocks. Not all of the granite areas are covered by regions of high concentration. For example, on the north east margin of the geochemical map a plateau of high values surrounds several tall peaks, and is clearly distinguished from an area of low values, also on granitic rocks, which forms the southern margin of the plateau.

## REGIONAL GEOCHEMICAL PATTERNS RELATED TO GEOLOGY

A study of the geochemical topography in relation to the geological map shows that in areas where the geology is simple, as on the granites, the ultrabasic rocks in the south part of the map, and the basic rocks in the central part of the map, the geochemical patterns are simple and display small ranges of concentration. In areas of mixed rocks the geochemical patterns show a normally wide range of concentration according to the geochemistry of the bedrock. In the eastern part of the map where acid and ultrabasic rocks interfinger, the distribution patterns of some elements, as for instance cobalt, are at lower levels of concentration than the

simple patterns of high concentration on areas of only ultrabasic rocks. Other elements, as for example chromium, provide a few results of high concentration (at levels equivalent to those observed on ultrabasic rocks), but most of the analyses show only low levels of chromium. The chromium patterns include, therefore, a wide range of concentration on mixed acid and ultrabasic rocks, when compared to the small range of concentration on ultrabasic rocks.

The range of minor element concentration for each major rock type is given in table 13. The mean value of the range is not given as it is believed that the mean would have little significance due to the wide regional variations in concentration shown by many of the elements.

Table 13. The range of minor element concentration in stream sediments derived from the major rock types

Minor element concentration in ppm.

| | Ti | V | Cr | Mn | Co | Ni | Cu | Zn | Pb |
|---|---|---|---|---|---|---|---|---|---|
| Metasediments | | | | | | | | | |
| Arenaceous | 5000-<br>>10,000 | 5-<br>200 | 5-<br>150 | 50-<br>2000 | ND-<br>20 | 10-<br>100 | 5-<br>150 | 25-<br>75 | ND-<br>30 |
| Argillaceous | 1000-<br>10,000 | 10-<br>200 | 20-<br>300 | 200-<br>1000 | ND-<br>50 | 5-<br>150 | 5-<br>100 | 30-<br>75 | ND-<br>50 |
| Igneous Rocks | | | | | | | | | |
| Basic Rocks | 8000-<br>>10,000 | 80-<br>450 | 70-<br>250 | 600-<br>5000 | 10-<br>100 | 10-<br>150 | 5-<br>200 | 40-<br>110 | ND-<br>10 |
| Ultrabasic | 2000-<br>>10,000 | 50-<br>400 | 450-<br>6000 | 600-<br>6000 | 20-<br>200 | 150-<br>2000 | 30-<br>120 | 30-<br>110 | ND-<br>20 |
| Granites | 200-<br>9000 | ND-<br>70 | ND-<br>300 | 50-<br>700 | ND-<br>10 | ND-<br>100 | 2-<br>20 | 10-<br>60 | ND-<br>50 |

Most of the geochemical patterns appear to be closely related to the distribution of the major rock types, but within this broad correlation there are numerous examples of regional variations of minor element concentration.

Elements which normally occur at high levels of concentration in resistant mineral forms, such as titanium in ilmenite, and chromium in chromite, provide geochemical patterns which are closely related to the geological units. For instance, titanium patterns at high levels of concentration (greater than 7000 ppm. Ti) cover large areas of the basic and ultrabasic rocks throughout the field area, whilst the chromium patterns at concentrations of more than 700 ppm. Cr, are confined to the areas of ultrabasic rocks.

Elements which frequently occur in the less resistant minerals, such as nickel in olivine, amphibole and pyroxene show regional variations in concentration which are particularly noticeable on areas of basic and ultrabasic rocks. In the southern part of the field area the nickel patterns, at different ranges of concentration, closely correspond to the areas of basic and ultrabasic rocks, which are here covered by thin colluvial latosols. In the northern part of the field area the nickel patterns on basic and ultrabasic rocks are at lower ranges of concentration than the patterns which occur on lithologically similar rock types in the south. Whilst this difference in minor element concentration in the patterns on basic and ultrabasic rocks could result from a

regional variation of the nickel concentration in the bedrock, the soils covering the basic and ultrabasic rocks are mainly indurated latosols and duricrust, and it is possible that the observed variations of concentration are related to regional variations of the pedology.

Arsenic and molybdenum are the only elements which are widely distributed at abnormally high concentrations. The patterns of theseelements appear to be related to a series of rock type and to geochemical provinces. Other elements, such as copper and lead, display regional variations of concentration, which are closely related to the bedrock geology over large areas of the geochemical map. However, these elements also occur in several samples at abnormally high levels of concentration. These occurrences may possibly be related to geochemical sub-provinces, or micro-provinces, but this is regarded as unlikely for there is no apparent regional enrichment of these elements.

It is evident from this brief description therefore that there are likely to be several factors which influence the distribution of the geochemical patterns.

## Multi-element patterns

In the following description of multi-element and individual geochemical patterns the words 'anomaly' and 'anomalous' are frequently used to describe areas of abnormally high contents of one or more

elements resulting from any one or more of the factors which affect the distribution of the geochemical patterns, including mineralisation. Following the terminology introduced by Hawkes and Webb (1962) geochemical anomalies which are proved to be related to ore and mineralisation are termed 'significant' anomalies. Anomalies that are proved to be unrelated to ore are termed 'non-significant' anomalies.

## Metasediments

The overall geochemical patterns associated with the metasediments typically display a flat topography with occasional variations in geochemical relief. It is not possible to distinguish the argillaceous from the arenaceous facies on the basis of the geochemical patterns, except in the case of chromium and nickel which occur in higher concentrations in the argillaceous facies. Other minor variations in relief occur along the strike within each facies, for example the geochemical troughs situated at Sangbari, Simbili, Furia and Numbara (map refs. D29, L7, I10 and L4 to 5 respectively) are demonstrated by the distribution of the majority of elements. In the central part of the area, between the troughs at Simbili and Sangbari, the geochemical topography displays a 'hummocky surface' for the elements titanium, vanadium and chromium, whereas the copper patterns display a long, low, ridge-like form.

Isolated high concentrations of cobalt, nickel, lead and zinc occur over this area. The areas covered by the trough, hummock and ridge topography are of variable size for the various elements (figs. 12 - 21).

The ranges of the minor element concentration of the geochemical patterns which have been described in topographical terms above are given in table 14.

The reasons for the regional variations of minor element concentration in the geochemical patterns over the metasedimentary rocks noted above have not been investigated. It seems possible that the development of the geochemical troughs at Sangbari, Simbili, Furia and Numbara (map ref. D29, L7, I10 and L4 to L5 respectively) is related to variations of the minor element content of the bedrock.

Over the area covered by the geochemical trough at Sangbari, the metasediments are largely composed of a quartz biotite garnet assemblage, whilst on the northern margin of the trough they are predominantly composed of cummingtonite and magnetite. Although no confirmatory analyses are available, it seems probable that the development of the geochemical trough is related to the mineralogical and associated variations in the minor element content of the bedrock.

The troughs at Simbili, Furia and Numbara (map ref. L7, L10, L4 to L5) are also believed to result from a relative impoverishment of the minor element concentration in the bedrock. The large accumulations of lateritic iron ore which are present in the drainage

R = range

A = average

NS = no. of samples

Range and average value of minor elements in ppm.

Table 14. Ranges and average values of minor element concentration of geochemical patterns on metasediments

| | Map Reference | R Ti | A/NS Ti | R V | A/NS V | R Cr | A/NS Cr | R Mn | A/NS Mn | R Co | A/NS Co | R Ni | A/NS Ni | R Cu | A/NS Cu | R Zn | A/NS Zn | R Pb | A/NS Pb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Background | | | | | | | | | | | | | | | | | | | |
| Arenaceous<br>Argillaceous | | | 7000 | | 150 | | 100<br>300 | | 700<br>800 | | 20 | | 30<br>150 | | 60 | | 50 | | 5 |
| Numbara trough ridge | L4 - 5 | 2000-<br>6000 | 1500/<br>10 | 70-150<br>200-300 | 110/2<br>250/2 | | 200/<br>2 | 1000 | | ND-<br>10 | | 50-<br>150 | | 15-<br>20 | 17/<br>2 | | 22/1<br>94/1 | 4-<br>5 | 4/<br>22 |
| Simbili trough | L7 | 1000-<br>3000 | 1800/<br>12 | 10-<br>150 | 55/<br>21 | 20-<br>95 | 42/<br>10 | 80-<br>300 | 130/<br>16 | ND-<br>10 | 2.5/<br>16 | 5-<br>50 | 11/<br>13 | 6-<br>20 | 12/<br>14 | 45-<br>47 | 46/<br>2 | ND-<br>50 | 24/<br>11 |
| Furia trough | I10 | 400-<br>1500 | 1000/<br>12 | 10-<br>120 | 48/<br>26 | 5-<br>100 | 50/<br>33 | 20-<br>300 | 1120/<br>17 | ND-<br>30 | 7/<br>31 | ND-<br>100 | 30/<br>38 | 5-<br>25 | 12/<br>13 | 22-<br>25 | 23/<br>2 | ND-<br>20 | 9/<br>14 |
| Furia peak | I10 | 10,000-<br>>10,000 | >10,000/<br>3 | 25-<br>450 | 260/<br>4 | 60-<br>150 | 100/<br>7 | 2000-<br>4000 | 3000/<br>4 | | | 50-<br>100 | 75/<br>2 | 70-<br>100 | 90/<br>4 | 75 | 75/<br>1 | | |
| Hummock and ridge patterns | K10 | 5500-<br>7000 | 6000/<br>3 | 150-<br>180 | 170/<br>3 | 300-<br>400 | 340/<br>4 | | | 40-<br>50 | 45/<br>3 | 100-<br>150 | 125/<br>4 | 80-<br>100 | 95/<br>3 | 71 | 71/<br>1 | 6-<br>8 | 7/<br>3 |
| | J11 | 3000-<br>5500 | | 200 | 200/<br>2 | 50-<br>300 | | 1000-<br>1500 | 1200/<br>3 | 20-<br>30 | | 70-<br>150 | | 90-<br>120 | 105/<br>2 | 50-<br>78 | 65/<br>3 | ND-<br>5 | |
| | H12 | 8000 | 8000/<br>1 | 100 | 100/<br>1 | 80 | 80/<br>1 | 500 | | 5 | | 160 | 160/<br>1 | 30-<br>20 | 25/<br>2 | 40 | 40/<br>1 | ND-<br>8 | |
| | G14-15 | 8000-<br>>10,000 | > 8500/<br>3 | 50-<br>300 | | 55-<br>200 | | 800 | | 50-<br>70 | 60/<br>2 | 10-<br>100 | 65/<br>6 | | | 40-<br>102 | 62/<br>5 | | |
| | F17 | 8000-<br>10,000 | 9000/<br>2 | 150-<br>150 | 85/<br>4 | 40-<br>100 | 65/<br>4 | 300-<br>600 | 420/<br>4 | ND-<br>10 | 7/<br>4 | 20-<br>150 | | 80-<br>150 | 97/<br>15 | 38-<br>60 | 51/<br>3 | Tr-<br>55 | |
| | G18-19 | >10,000 | >10,000/<br>6 | 200-<br>300 | 225/<br>6 | 100-<br>550 | 333/<br>6 | 800-<br>1500 | 1000/<br>6 | 50-<br>70 | 60/<br>4 | 120-<br>400 | 200/<br>4 | | | 47-<br>77 | 62/<br>2 | | |
| | F20 | 8000-<br>>10,000 | > 8500/<br>3 | 150-<br>200 | | 100-<br>400 | | 100-<br>1000 | 600/<br>8 | 20-<br>80 | | 20-<br>400 | | | | 113 | 113/<br>1 | | |
| Sangbari trough | D29 | 500-<br>2000 | 1400/<br>17 | 10-<br>100 | 40/<br>13 | 30-<br>80 | 50/<br>9 | 50-<br>700 | 330/<br>13 | ND-<br>20 | 6/<br>25 | 5-<br>150 | 35/<br>19 | 5-<br>20 | 10/<br>9 | 12-<br>38 | 26/<br>9 | ND-<br>30 | 8/<br>11 |

catchments of these areas appear to have little effect on the composition of the stream sediments, although, in the vicinity of the Numbara Hill lateritic iron deposit some minor elements do show a slightly higher level of concentration than in the surrounding area.

Within the Furia trough, an island, represented by the elements vanadium and chromium, is elongated in a north-south direction. The vanadium content rises well above the background content at 150 ppm. (trough level 50 ppm.) to a peak of 450 ppm., whereas the chromium peak of the island barely exceeds the background level (table 14). In the case of titanium, manganese, copper and zinc, the island abutts the western margin of the trough. A relatively high concentration of titanium and manganese and a low peak for copper and zinc occur within the island. When the minor element concentrations of the patterns which form the island are compared with the ranges of element concentration detected in sediments derived from basic rocks (tables 13 and 14) a fair correlation is apparent, and it seems probable that the island pattern is due to detritus from a horizon of basic composition within the quartzose facies of the metasediments.

The hummock and ridge-like surface of the geochemical topography in the area between the Simbili and Sangbari troughs was briefly described in the review of the general geochemical features. The distribution of titanium is particularly uneven and in several areas

(table 14), the concentration rises above the background level of 7000 ppm., to minor peaks of between 8000 ppm. and greater than 10,000 ppm. It is noticeable that where the titanium level is more than 8000 ppm., as at map references H12 and F17, the chromium content is low (65 and 80 ppm. respectively) compared to the background level of 100 to 300 ppm. The opposite relationship exists at map reference K10, where three samples contain an average of 6000 ppm. Ti and four samples an average of 340 ppm. Cr. This antipathetic relationship of the concentration of titanium and chromium is a common feature of the area (table 13), and might be taken to indicate changes in the facies and mineralogy of the metasediments.

A low geochemical ridge formed by the copper patterns extends from map ref. H14 to F20 over the hummocky topography of the titanium and chromium distribution. The background level of copper is about 60 ppm. and the average level of the ridge, on the basis of 15 samples, is about 100 ppm., rising in a few instances to 150 ppm. The copper ridge is accompanied, at map references G18 to 19, and F20, by isolated peaks for the elements zinc, lead and cobalt, or nickel, whilst at map reference G15 it is accompanied by lead. At map reference J11, the elements cobalt and nickel are concentrated at levels higher than the background.

Whether these anomalous occurrences of high contents of the elements titanium, chromium, and particularly cobalt, nickel, copper, zinc and lead are associated with mineralisation is not known, but

it seems possible that some of these occurrences on the metasediments may be found to be related to significant anomalies.

## Basic rocks

Marked regional variations in concentration and geochemical relief are shown by the minor element patterns of sediments in the three study areas of basic rocks situated near Bumbuna (map ref. I4 and G10), Basaia (map ref. L15) and Makele (map ref. D23; see fig 24).

The geochemical topography as shown by the titanium and vanadium distributions in the three areas is relatively flat, but the average contents at Makele (greater than 10,000 ppm. Ti and 380 ppm. V) are higher than those at Bumbuna and Basaia (7000 ppm. Ti and 240 ppm. V). In the case of chromium, the distribution at Bumbuna displays strong geochemical relief, with average contents of 360 ppm. over monadnocks, as opposed to 85 ppm. over duricrust. Although chromium shows a greater relief in the Basaia area (70-500 ppm.) than at Makele (100-250 ppm.), in both areas the mean content is 200 ppm.

The elements manganese, cobalt, nickel, and copper show a strong relief in the three areas. The highest concentrations occur in the Makele area and the lowest at Basaia. The levels at Bumbuna are slightly below those at Makele (table 15). For example the average nickel content of the sediments at Makele is 125 ppm., compared to 30 ppm. at Basaia and from 60 to 110 ppm. in

different areas at Bumbuna. The lead content of sediments derived from basic rocks is frequently below the limit of detection so that it was not possible to observe regional variations in concentration. There is insufficient data available to compare the regional distribution of zinc in basic rocks.

A number of factors individually, or a combination, could account for the regional variations in the distribution of minor elements in sediments derived from basic rocks. The two most probable are:

that regional variations of the minor element concentration which occur in the bedrock are reflected by similar variations in the associated stream sediments, or

that the variations noted in stream sediments are largely unrelated to the bedrock and are primarily the result of regional variations in the effects of erosion.

It is apparent from the geological map (in PART 2) that duricrust extends over the Basaia and Bumbuna areas, but does not occur at Makele. Furthermore it is evident that in the area of high geochemical relief at Bumbuna, the lowest element contents were obtained from an area situated below the margin of the duricrust (map ref. G10), whilst the highest contents were observed in an area where monadnocks rise through the duricrust and indurated latosols (map ref. I4). In addition, there is little difference between

Table 15. Range and average values for minor element concentration of geochemical patterns on basic rocks

R = range

A = average

| | Map Reference | R Ti | A Ti | R V | A V | R Cr | A Cr | R Mn | A Mn | R Co | A Co | R Ni | A Ni | R Cu | A Cu | R Zn | A Zn | R Pb | A Pb | No. of Samples |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Basic Rocks | | | | | | | | | | | | | | | | | | | | |
| Bumbuna monadnock | I4 | 5000–8000 | 7000/ | 180–400 | 300/ | 150–800 | 360 | 800–3000 | 1380 | 20–150 | 70 | 30–150 | 110 | 40–150 | 75 | - | 46 | ND–5 | 1 | 9 |
| duricrust | G10 | 8000–>10,000 | > 9300 | 120–450 | 260 | 40–180 | 85 | 800–2000 | 1300 | 10–55 | 30 | 10–120 | 60 | 8–100 | 60 | - | 62 | ND–25 | 7 | 6 |
| Basaia duricrust | L15 | 7000–>10,000 | > 9000 | 80–400 | 240 | 70–500 | 200 | 400–1500 | 910 | 10–70 | 26 | 10–50 | 30 | 5–120 | 40 | - | - | ND | ND | 12 |
| | Sample No. 3147 | - | 2000 | - | 70 | - | 80 | - | 80 | - | ND | - | 5 | - | 10 | - | - | - | 10 | 1 |
| Makele colluvial latosols | D23 | > 10,000 | > 10,000 | 250–500 | 380 | 100–250 | 200 | 600–6000 | 3750 | 20–200 | 90 | 50–150 | 125 | 100–200 | 150 | 60–110 | 85 | ND–25 | 6 | 10 |

Table 16. Range and average values for minor element concentration of geochemical patterns on ultrabasic rocks

R = range

A = average

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ultrabasic Rocks | | | | | | | | | | | | | | | | | | | | |
| Basaia duricrust | L16 | 7000–>10,000 | > 7500 | 80–300 | 185 | 800–1500 | 1100 | 400–1500 | 750 | 20–80 | 45 | 70–200 | 160 | 30–100 | 50 | - | - | ND–15 | 3 | 7 |
| colluvial latosols | I20–21 | 1000–8000 | 4000 | 20–100 | 50 | 600–3000 | 1300 | 700–4000 | 1850 | 50–100 | 60 | 450–1800 | 860 | 8–55 | 27 | - | 42 | ND–25 | 10 | 7 |
| Makele colluvial latosols | F23–E25 | 2000–>10,000 | > 7000 | 120–250 | 170 | 400–2000 | 1050 | 800–5000 | 2200 | 20–100 | 55 | 150–1800 | 590 | 45–150 | 65 | 56–68 | 60 | ND–25 | 4 | 7 |
| Makong colluvial latosols | F32–H37 | 5000–>10,000 | > 9000 | 90–450 | 260 | 1500–10,000 | 3000 | 700–10,000 | 3780 | 20–550 | 110 | 150–2000 | 970 | 25–120 | 60 | 48–107 | 70 | ND–20 | 5 | 16 |

the mean values for the elements titanium, vanadium, cobalt, nickel, and copper in the two areas of duricrust-covered basic rocks at Bumbuna (G10) and at Basaia (table 15).

From the above correlations of geochemical patterns at low concentrations with areas of duricrust, and patterns at high concentrations in other soil types, it is probable that the dispersion at the minor elements is largely influenced by the nature of the overburden. The secondary dispersion of elements from the bedrock to the overburden and stream sediments is considered in SECTION 4.

The geochemical relief of the Basaia area is varied, and in the case of chromium is no doubt strongly affected by the wide range of minor element concentration in the basic and ultrabasic rocks which have been traced under the duricrust by Wilson and Marmo (1958). Within this area an isolated sample contains very low amounts of all minor elements except lead. As the sample is largely composed of quartz with minor quantities of felspar and muscovite, it is probably derived from a granitic rock whose outcrop is obscured by the duricrust.

## Ultrabasic rocks

Ultrabasic rocks outcrop over large areas of the geochemical map in the vicinity of Makong, Makele and Basaia (fig. 24). Within this major rock type a variety of mineralogical facies have been

recognised wherever the bedrock is well exposed (Wilson and Marmo, 1958). Several mineralogical units have been mapped in the Makong and Makele areas but not near Basaia, where the bedrock is largely obscured by duricrust.

In terms of the geochemical topography, and compared to the minor element content of the granites as a background, the geochemical relief is very strong over the ultrabasic rocks. Within this topography the dominant features are the peaks of chromium and nickel which occur at much higher levels on the ultrabasic rocks than on any other major rock type.

Amongst the three study areas, the strongest geochemical relief and highest levels of concentration occur in the Makong area (table 16). At Makele, the topography is slightly less rugged and the peaks do not attain the same levels as at Makong. Farther to the north, the topography over the Basaia area shows strong variations of relief and two distinct forms are identified. In the southern part of the Basaia area, where colluvial latosols predominate, chromium and nickel occur at higher levels of concentration than in the northern, and duricrust-covered, part of the Basaia area. By contrast, titanium and vanadium occur at higher levels of concentration in the northern duricrust area than in the south.

The geochemical patterns at Makong include areas of low values which probably result from the dilution of ultrabasic

detritus, by predominantly siliceous material derived from the granite porphyry outcrops in the central part of the area (map ref. H36). Two of the drainage catchment areas (map ref. F32 and H33) include dominantly ultrabasic rocks, and although several of the drainage channels in these areas are shown, on the basis of the geological map, to drain particular mineral assemblages, no striking differences of trace element content were detected in the geochemical patterns. This indistinct reflection of the bedrock mineralogy by the trace element content of the associated sediments could well be due to the sample density, for the geochemical patterns in soils show differences of level related to the mineralogy of the underlying bedrock.

Different mineralogical assemblages have also been observed in the ultrabasics at Makele, but here the drainage catchments frequently include outcrops of such rocks as granite migmatite, acid volcanics, metasediments and amphibolites, and the stream sediments are likely to reflect this mixed derivation. In addition, molybdenite has been discovered in the biotite schists exposed in the bed of the Mopoko river (Fowler-Lunn, 1933) at map reference E25, and from the location of the peaks of the geochemical patterns, it is possible that copper, and lead are associated with the molybdenite mineralisation.

Variations of the minor element concentration between the two areas of different soil types near Basaia have been noted

above. In the area of duricrust soils to the north (map ref. L16) the average value of titanium and vanadium is high (greater than 7500 ppm. Ti/and 185 ppm. V) compared to the levels of these elements in the area of colluvial latosols (4000 ppm. Ti and 50 ppm. V) to the south (table 16). In contrast, the average chromium, manganese and nickel contents in the south (1300 ppm. Cr; 1850 ppm. Mn; 860 ppm. Ni) are higher than in the duricrust area to the north (1100 ppm. Cr; 750 ppm. Mn; 160 ppm. Ni).

This variation of the minor element distribution between the two areas of different soil type is taken to indicate a variation in the geochemistry of the bedrock. However, it is possible that the low average values of nickel in the northern area at Basaia (map ref. L16) are related to the minor element composition of the duricrust, which forms a scarp-like feature at the margin of the drainage catchments.

## Acid igneous rocks

### SYNKINEMATIC GRANITE

The distribution of the minor elements on areas of synkinematic granite shows regional variations in geochemical relief which can in general be correlated with textural features shown on the geological map. The textures vary from even-grained (GE) to gneissic (GN), and porphyroblastic (GP), and are not necessarily related to the mineralogical composition which ranges from granite to granodiorite.

The even-grained granites (except where they are associated with porphyroblastic granite in the south west part of the map) and the gneissic granites (except in the eastern area of interfingering ultrabasic and granitic rocks) are characteristically covered by geochemical patterns of low relief and low levels of concentration. The porphyroblastic granites typically display higher levels of concentration of lead, titanium, vanadium, and manganese, than the gneissic and even-grained granites (table 17, and figs. 28, 12, 13 and 20).

The geochemical topography in the Mabendu area of porphyroblastic granite is of special interest. The relief for the elements cobalt, nickel and copper is gently undulating and there are no outstanding geochemical features. For the elements titanium, vanadium, and manganese the relief is more variable and for each element a number of small hills rise out of the background. The hills are elongated in a north west to south east direction and coincide with a trough-shaped depression which is a feature of the lead distribution (figs. 12 to 20). This generally linear hill and trough relief is situated over a gneissic zone in the porphyroblastic granite, and includes a discontinuous series of amphibolitic lenses which outcrop over a total strike length of about 4 miles. In the zone of gneissic granite the concentration of titanium and manganese, and depletion of lead in the stream

Table 17. Range and average values of minor element concentration of geochemical patterns on granitic rocks

R = range

A = average

| | Map Reference | Textural Type | Range Ti | A Ti | R V | A V | R Cr | A Cr | R Mn | A Mn | R Co | A Co | R Ni | A Ni | R Cu | A Cu | R Pb | A Pb | No. of Samples |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nunkekoro | N5 | GP | 2000–5000 | 3500 | ND– | 15 | ND–75 | 23 | 150–700 | 400 | – | ND | ND–40 | 8 | ND–20 | 7 | 10–50 | 39 | 6 |
| Kalifaiya | D17 | " | 3000–> 10,000 | > 7700 | 15–150 | 65 | 5–75 | 40 | 350–1500 | 670 | ND–35 | 6 | 3–100 | 45 | 3–20 | 8 | 6–30 | 18 | 6 |
| Kalmoro | C19 | " | 1000–6000 | 3400 | 10–100 | 37 | 15–80 | 35 | 150–400 | 240 | ND–5 | 3 | 3–80 | 18 | ND–20 | 12 | 10–120 | 63 | 7 |
| Makema | X24 | " | – | 80 | – | 70 | – | 20 | – | 200 | – | ND | – | 10 | – | 20 | – | 30 | 1 |
| Mabendu | E34 | " | 5000–> 10,000 | > 6000 | ND–70 | 43 | 5–300 | 33 | 100–1000 | 508 | ND–5 | 1 | ND–50 | 10 | 3–10 | 5 | 20–60 | 55 | 16 |
| Makong | J36 | " | – | – | 5–150 | 47 | 70–1500 | 510 | 150–1800 | 925 | ND–55 | 20 | 60–550 | 225 | 6–45 | 16 | 6–75 | 30 | 11 |
| Dandaya | N13 | GN | 800–10,000 | 2100 | ND–20 | 8 | 5–50 | 13 | 50–200 | 100 | ND | ND | ND–40 | 8 | 2–8 | 5 | ND–6 | 2 | 7 |
| Mabutaw | V28 | " | 2000–> 10,000 | > 7375 | 5–50 | 18 | 30–1500 | 490 | 30–1000 | 500 | ND–40 | 5 | 20–100 | 50 | 4–40 | 9 | ND–20 | 6 | 9 |
| Makele | H24 | GE | 300–700 | 500 | 5–10 | 6 | 5–15 | 8 | 80–350 | 200 | – | ND | 5–6 | 5 | 3–8 | 5 | 5–25 | 12 | 3 |
| Acid Volcanic | H36 | | 1800–10,000 | 7100 | 20–50 | 34 | 250–950 | 445 | 500–2000 | 1000 | 5–55 | 32 | 120–300 | 175 | 6–25 | 12 | ND–6 | 2 | 7 |
| " | I38–39 | | 600–10,000 | 3400 | 80–200 | 130 | 120–550 | 300 | 450–5000 | 1800 | 20–60 | 31 | 100–750 | 210 | 8–150 | 80 | ND–8 | 6 | 6 |
| Ultrabasic | H37 | | 5000–10,000 | 9000 | 90–450 | 260 | 1500–10,000 | 3000 | 700–10,000 | 3780 | 20–550 | 110 | 150–2000 | 970 | 25–120 | 60 | ND–20 | 5 | 16 |

GP = Porphyroblastic Texture; GN = Gneissic Texture;
GE = Even Grained Texture

sediments is believed to reflect the presence of amphibolitic and gneissic granite included by the porphyroblastic granite.

A somewhat similar geochemical pattern to that described above is developed on the interfingering ultrabasic and granitic rocks in the eastern part of the field area near Mabutaw (map ref. V28). The gneissic granite, about one mile to the south and to the west of Mabutaw, surrounds several attenuated outcrops of ultrabasic rocks, which are mapped largely as tremolite serpentinites. To the north of Mabutaw, the rocks are obscured by poorly drained latosols and gley soils. The geochemical relief in this area is very rugged and is well illustrated by chromium (fig. 14), whose concentration ranges between 30 ppm. and 1500 ppm. In several sediment samples from the gneissic granites the chromium content ranges between 1500 ppm. and 5000 ppm. These levels are high compared to contents of 1000 ppm. or less detected in sediment samples derived from ultrabasic rocks which outcrop in the vicinity. The peak concentrations of chromium, and also those of titanium and manganese, are situated on the north strike projections of the attenuated outcrops of ultrabasic rocks.

These concentrations of chromium (and other elements) were not investigated, but from the pedology of the area it is possible that the anomalously high levels reflect residual accumulations of chromium, possibly as chromite, in soils overlying a chromium rich bedrock, such as tremolite serpentinite.

In other areas, for example at Kalifaiya and Makong (map refs. D17 and J36), the high concentration of titanium, chromium, manganese, cobalt, and nickel are probably derived from amphibolites (at Kalifaiya) and ultrabasic rocks (at Makong) which outcrop in the drainage catchments. The same explanation is probably tenable for the high levels of the minor elements detected in sediment samples from the granitic inlier at Kalmoro (map ref. I19), where a ridge of ultrabasic rocks encircles a swampy area underlain by granite.

RECRYSTALLISED GRANITE PORPHYRY

These rocks have been located throughout the field area, but only in the south, near Makong (map refs. H36, I38, J39), do they form outcrops which are sufficiently large to form a distinctive geochemical pattern. The patterns for most of the elements are at very low levels of concentration, relative to the high levels of the surrounding ultrabasic rocks (table 17).

The geochemical pattern over the granite porphyry at map reference I38 to J39 is unusual because of the high level of the copper concentration (95 to 150 ppm; based on five samples) compared to the lower levels (60 ppm.) on the areas of ultrabasic rocks. This anomalous concentration was not investigated, but from the linear distribution of the results it is more probable that they are associated with a significant anomaly than with abnormally high copper contents in the recrystallised granite porphyry.

LATE-KINEMATIC GRANITE

Outcrops of late-kinematic granite included by the present geochemical map are restricted to an area of about 2 square miles near Bumbuna (map ref. G1). The late-kinematic granite is intrusive into the synkinematic granite and is described as a plug partly surrounded by a ridge of amphibolite hills (Marmo, 1955a). The amphibolitic hills form a watershed, and the larger drainages on the late-kinematic granite contain amphibolitic and granitic detritus. The mixed derivation of the detritus is reflected by the stream sediments, so that no geochemical pattern characteristic of the late-kinematic granite was obtained.

The late-kinematic pegmatites are too small in outcrop area to produce a discernable and characteristic geochemical pattern in the sediments.

Mixed ultrabasic and acid igneous rocks

The complex geochemical patterns over the area of interfingering ultrabasic and granitic rocks in the eastern part of the field area have been noted above. In general the geochemical patterns of titanium, chromium, and manganese at high levels of concentration (greater than 7000 ppm. Ti, 300 ppm. Cr, and 700 ppm. Mn) reflect the larger outcrop areas (and some possible sub-outcrop areas) of the ultrabasic rocks. At lower levels of concentration (greater than 1500 ppm. Ti, 150 ppm. Cr, 300 ppm. Mn) the patterns extend to the margin of the mixed rocks area.

The levels of the geochemical patterns over drainage catchments which include only ultrabasic rocks are almost invariably high compared to the patterns on the granitic rocks. For example, at map reference S29 the chromium content ranges from 300 to 1500 ppm. whilst the nickel content is 300 to 1500 ppm. and the cobalt and zinc content is from 70 to 150 ppm. Although the zinc content is high (70 to 150 ppm.) compared with the more usual range of 30 to 70 ppm. on ultrabasic rocks, the levels of the other elements are not unusual, and it is unlikely that this and similar patterns are related to significant anomalies.

Geochemical patterns at low levels of concentration, of the elements cobalt and copper, and particularly for vanadium and manganese, are situated at map reference Q31 to 32. The levels of the geochemical patterns are unusually low for drainage catchments which include ultrabasic rocks, and although this pattern was not investigated, it is very probable that it reflects an abundance of siliceous material in the stream sediments.

The geochemical patterns on the diorite gneiss are distinguished from those on the ultrabasic rocks by the chromium concentration, which is generally relatively low (70 to 150 ppm.) compared to the levels over most of the ultrabasic rocks (greater than 150 ppm.). Although the chromium content is frequently low titanium, vanadium, and manganese are, in some places, concentrated

in sediments derived from drainage catchments which include outcrops of diorite gneiss (map refs.027 to 28, R27). These irregularities of the minor element distribution were not investigated.

## Individual patterns of the minor elements

Most of the regional geochemical patterns illustrated by the regional survey are, to some extent, reflected by several elements, but there are many patterns which appear to be entirely individual in character, and these are described below. Patterns which are believed to be due to mineralisation are described in SECTION 5.

### Titanium

There are few titanium patterns which are not reflected by the geochemically related elements, vanadium, and chromium. The dominant feature of the titanium patterns is their close correlation to the basic and ultrabasic rocks at concentrations of greater than 7000 ppm. (Fig. 12).

The distribution of titanium on granitic rocks is particularly interesting, for there are distinct regional variations of concentration, ranging from less than 1500 to greater than 7000 ppm. over the areas of porphyroblastic synkinematic granite, and also over the area of mixed granite and ultrabasic rocks in the eastern part of the field area.

At concentrations of less than 1500 ppm. the titanium patterns extend over large areas of gneissic and even-grained granite in the central part of the field area and largely cover the granite which flanks the eastern wall of the Sula Mountains, as far north as Basaia (map ref. M13). The geochemical topography of titanium on the granitic rocks is broadly similar to that of lead, for both elements occur at higher levels on the porphyroblastic granite compared to the even-grained and gneissic granites. Regional variations in the titanium content of synkinematic granites are to be expected, for a wide range of acid igneous rocks, from hornblende rich granodiorites to microcline rich granites, are included under this name (Wilson and Marmo, 1958). Furthermore, the geochemical map shows that titanium is more concentrated over basic rocks than over acid rocks.

The high concentrations of titanium associated with the metasediments were not investigated, but might possibly be derived from detrital or other accumulations of titanium-rich minerals in the bedrock. Alternatively, these concentrations could result from some feature of the secondary dispersion of this element. If the former explanation is valid, then the concentration of titanium could be a useful guide in determining whether co-existing concentrations of copper and other chalcophile elements are likely to be related to significant or non-significant anomalies. From the geological map, the metasediments, particularly the argillaceous

facies, are known to endorse lenses of basic rocks, and it is possible that concentrations of titanium with copper and other elements are related to these outcrops of basic rocks.

The restricted dispersion of titanium is well illustrated by the single sample pattern at map reference C23, in which stream sediments derived from mixed amphibolites and metasediments contain less than 1500 ppm. in contrast to the surrounding patterns on amphibolites, with concentrations of more than 7000 ppm. This example is a special case, but a comparison of the titanium patterns (fig. 12) with the generalised geological map (fig. 4) shows the close correlation of high concentrations of titanium (greater than 7000 ppm.) with areas of basic and ultrabasic rocks. At lower levels of concentration, between 1500 and 7000 ppm., the patterns are indistinct and it is for this reason that on fig. 12, two groups of analytical results, from 1500 to 3000 ppm. and from 3000 to 7000 ppm. are represented as one (1500 to 7000 ppm.).

## Vanadium

The geochemical patterns of vanadium are somewhat similar in distribution to those of titanium, but are at a lower range of concentration. The maximum content recorded is 1500 ppm. Relatively high concentrations of vanadium extend over the non-duricrust covered basic and ultrabasic rocks at levels of greater than 150 ppm. Where deeply truncated latosols are present on

basic rocks, as in the Pampana river valley (map ref. D23) and to the south east of Bumbuna (map ref. G7), the vanadium contents in some scattered samples increase to between 150 and 300 ppm.

The vanadium patterns on granitic areas show interesting regional differences of concentration. In the central part of the field area the vanadium content is, in general, less than 30 ppm., but increases to 70 ppm. in some small areas which are situated over, or adjacent to, the outcrops of ultrabasic rocks in the central granitic area (map ref. I28, L29). In the south west part of the field area the vanadium patterns on the porphyroblastic granite are in the same range of concentration as in the central granite, but there are several comparatively large lenticular areas in which the vanadium content is between 30 to 70 ppm. These concentrations appear to be related to a linear zone of gneissic granite which includes a discontinuous series of amphibolitic lenses.

The geochemical patterns in the eastern part of the field area are generally indistinct, and are only poorly related to the outcrops of the ultrabasic rocks. This distribution could result from regional variations in the concentration of vanadium in the bedrock, but it is more likely to be due to the combined effects of dilution of the ultrabasic detritus by granitic material and to the greater, possibly saline, dispersion of vanadium, compared to titanium. The mechanism of the vanadium dispersion was not investigated.

A wide variation of vanadium concentration was detected in stream sediments principally derived from banded ironstones, and residual accumulations of lateritic iron. For instance at Numbara (map ref. K3) four samples collected from an area of less than one square mile, contain between 500 and 1500 ppm. (average 900 ppm.). This range of vanadium concentration is very much higher than that detected in drainages from other banded ironstones. For example at Simbili, Kapfaia and Sokoya (map refs. L7, E17 and I10) where the vanadium contents average 60 ppm.

The Numbara vanadium concentration is also high when compared to the average content on areas of basic and ultrabasic rocks (about 500 ppm.).

The reason for the high level of vanadium concentration at Numbara was not investigated, but it is of interest that the titanium content of the vanadium rich samples is greater than 10,000 ppm. The titanium content of the vanadium poor samples from the other areas of banded ironstone mentioned above seldom exceeds 2000 ppm. It is possible therefore, that titanium and vanadium are both strongly concentrated in the Numbara banded ironstone.

## Chromium

The chromium patterns are closely related to the outcropping geology, and most of the major rock types can be identified on the basis of the chromium content of their stream sediments.

The highest chromium concentrations (1000 to 10,000 ppm.) occur in the south part of the area over the ultrabasic rocks to the west of Makong. Here fifteen samples collected from three drainage catchments contain an average of about 5000 ppm. Cr. This concentration is high compared to the average chromium content of dunite of 3400 g/ton quoted by Rankama and Sahama (1950). In addition a few scattered samples in the eastern part of the field area contain similarly high levels of chromium.

The present results could be taken to indicate a strong regional enrichment of chromium in some of the ultrabasic rocks, especially those which outcrop to the west of Makong (map ref. H37). However, there is the possibility that the high results are due to a sampling bias. Chromium, in the mineral form of chromite, is likely to concentrate with other heavy and resistant minerals in natural riffles in the stream bed, and sediment samples collected from the fast flowing streams on the ultrabasic rocks are likely to be largely composed of resistant and comparatively heavy detritus.

The chromium concentrations over the granitic areas show a different distribution to those of titanium and vanadium. Whereas high concentrations of titanium and vanadium occur as lenticular patterns in the south west porphyroblastic granite area, chromium is evenly distributed at concentrations of less than 70 ppm., except in a lenticular area (indicated by a dashed line in fig. 14) where the concentrations are between 15 and 30 ppm. In the central

area of even-grained and gneissic granite the chromium range is similar to that in the south west porphyroblastic granite, being from the limit of detection to 70 ppm. However, there are several small areas in the central granite where the chromium concentration exceeds 70 ppm., and ranges up to 700 ppm. These results no doubt reflect the numerous small outcrops of ultrabasic rocks which are rarely illustrated by the titanium and vanadium results. The different distributions of titanium, vanadium, and possibly chromium, in the south-west and central granite areas, could be taken to reflect a geochemically "basic affinity" for the south west porphyroblastic granite, and to an "ultrabasic affinity" for the central, even-grained and gneissic granite.

## Manganese

Manganese shows a distribution which is broadly similar to that of titanium, vanadium, and chromium, being concentrated in basic and ultrabasic rocks, and only occurring in small quantities in most of the granitic areas.

Manganese, over large areas of basic and ultrabasic rocks, ranges in concentrations between 700 and 1500 ppm. over the main schist belt, and in the eastern part of the field area. Drainage catchments which include only small amounts of siliceous detritus and large areas of basic and ultrabasic rocks frequently reflect manganese contents of more than 1500 ppm. Exceptions occur in the

area of duricrust soils to the west of Basaia (map ref. N15), where the level is reduced to between 300 and 700 ppm. Mn.

The concentration of manganese on granitic rocks is generally less than 300 ppm. In the central granite the outcrops of ultrabasic rocks do not significantly affect the manganese concentration of the sediments, and these rocks are reflected as a few isolated results in the range 300 to 700 ppm. In the south western porphyroblastic granite the small outcrops of amphibolite, which occur in the gneissic zone, are also reflected by manganese contents of between 300 and 700 ppm.

Patterns in the range 300 to 5000 ppm., cover almost the whole of the eastern part of the area and illustrate a widespread distribution of manganese in an environment of mixed acid and ultrabasic rocks. In this area, the peak manganese contents (1500 ppm. or more) were invariably detected on areas in which the catchments include only ultrabasic rocks.

## Cobalt

The geochemical distribution of cobalt is simple and at much lower ranges of concentration (less than 200 ppm.) than the elements which are described above.

Large areas of granitic rocks are covered by patterns in which the cobalt content is less than 7 ppm., and in general the concentration only increases from 7 to 15 ppm. where the stream

sediments are partly derived from the schistose rocks. In the central granite area, however, four widely scattered samples (represented on fig. 16) contain high levels of cobalt (50 to 80 ppm.) compared to the background (less than 7 ppm.).

The origin of these high cobalt contents (map refs. I27, G29, K29, L30) was not investigated, but it is possible that they are related to detritus of basic or ultrabasic composition. Cobalt contents of between 60 and 90 ppm. frequently occur on areas of basic rocks and ultrabasic rocks, and it is significant that the high cobalt contents are supported by high levels of titanium, chromium and nickel. This geochemical association of minor elements at high levels of concentration (at map ref. L30:- 1500 ppm. Ti; 5000 ppm. Cr; 300 ppm. Ni) is typical of the geochemical patterns on ultrabasic rocks (table 13).

The cobalt distribution on areas of basic and ultrabasic rocks on the main schist belt shows a wide range of concentration from 15 to more than 200 ppm. Concentrations of between 30 and 100 ppm. are present on basic rocks overlain by colluvial latosols near Makele (map ref. C23) and by mainly indurated latosols to the south east of Bumbuna (map ref. H4). Much higher concentrations (100 to 200 ppm. Co) are frequently present over the ultrabasic rocks in the southern part of the area (map refs. H34, 37), but the level falls to about 70 ppm. on the ultrabasic rocks at Makele (map ref. F25). Some three miles to the north east of Makele, a

linear pattern, in which the cobalt content ranges from 80 to 250 ppm., covers an area of mainly ultrabasic rocks. It is situated between map refs. F20 and J16 and lies on the west side of the Kalmoro granite inlier. At the north-east extremity, this anomalously high pattern extends over a part of the interdigitation of basic and ultrabasic rocks. To the south west, it projects as a narrow tongue over the metamorphosed sedimentary rocks. This cobalt anomaly is of special interest because the Yirisen gold prospect is situated at about the centre of the anomalous area, but there is, however, no record of cobalt mineralisation. The high cobalt contents might result from prospecting activity, but as the anomaly extends at high levels of concentration over lithologically different rock types to the north-east and south-west of Yirisen, it could possibly be associated with mineralisation.

On the Farangbaia quartzite facies of the metasediments, three areas of low cobalt content extend from map reference I6 in the north to H14 in the south. An interesting feature of the central area is that the northern extremity terminates against a faulted strip of amphibolite about 500 yards in width. The headwater runnels of a small stream drain both rock types separately and it is possible to distinguish cobalt contents of 10 ppm. on amphibolitic rocks from a 'not detected result' on the quartzites.

In the eastern part of the field area the cobalt contents range between 15 - 30 ppm., and reflect areas of predominantly

ultrabasic rocks which interfinger with lenses of granitic rocks. Slightly higher contents from 30 to 70 ppm., outline drainage catchments which include ultrabasic rocks only. At map reference W26, there is a diamond-shaped area in which the cobalt contents of a few samples range from 15 to 50 ppm. These results are anomalously high and are partly substantiated by increased levels of chromium and nickel. These concentrations of cobalt, chromium and nickel possibly reflect suboutcropping ultrabasic rocks obscured by latosols in this area.

## Nickel

The regional geochemical patterns of nickel are clear and simple in comparison to those of the other elements studied. The ultrabasic rocks of the main schist belt are associated with contents from 300 ppm. to a maximum of 2000 ppm., except over areas of duricrust and indurated latosols where low levels of nickel, between 70 and 150 ppm., are present. The nickel content of sediments derived from basic rocks also shows regional variations which can be partly correlated with the pedology. A range of 70 to 150 ppm. Ni is widespread in areas of dominantly colluvial latosols, whilst in areas of duricrust the results on basic rocks all fall between 30 and 70 ppm.

Nickel contents between 70 and 150 ppm. are distributed over a large area in the eastern part of the map where ultrabasic

rocks interfinger with granites. A few anomalously high results, between 300 and 1000 ppm. Ni, are situated on the larger outcrops of the ultrabasic rocks.

The nickel distribution over granitic rocks seldom exceeds 70 ppm. Where higher contents were detected they are believed to be derived from outcrops of ultrabasic rocks which are surrounded by granite. On the central, north-west, and extreme eastern granite, the nickel contents are between 30 and 70 ppm. This is high compared to the level on the south-west and north-east granite where the nickel contents seldom exceed 30 ppm. A geochemically 'basic affinity' for the south-west porphyroblastic granite, and an 'ultrabasic affinity' for the central granite has been proposed largely on the basis of the titanium, vanadium, and to a slightly less extent the chromium distributions. The nickel distribution is more concentrated on the central granite, than on the south-west granite, and is taken to support this hypothesis.

## Copper

The regional distribution of copper forms complex geochemical patterns whose interpretation is made difficult by the wide range of concentration detected in the stream sediments derived from most of the major rock types.

Copper contents of less than 7 ppm. were detected in sediments derived from the large areas of granitic rocks which skirt the

main schist belt. In drainage catchments which include both acid and ultrabasic rocks, as, for example, in the eastern part of the area, the concentration ranges between 7 and 70 ppm. It is only in comparatively small areas that levels of greater than 30 ppm. are found.

The highest levels of copper are generally found in areas of basic rocks. To the west of Makele, where colluvial latosols overlie basic rocks, the copper content frequently exceeds 80 ppm. and is often in the range 120 to 200 ppm. To the south-east of Bumbuna (map ref. G3), the geochemical patterns show a wide range of concentration from 30 to 120 ppm. Cu, but the highest levels were detected over the amphibolitic monadnocks which protrude through the indurated latosols and duricrust in this area.

Slightly lower concentrations in the range 30 to 70 ppm. Cu cover large areas of the ultrabasic rocks, on the main schist belt.

High copper contents extend over two or three rock types whose copper concentrations normally differ. Thus the large 'V' shaped area in which the copper contents frequently exceed 70 ppm. extends from map reference G20 in the south to H13 and J16, at the northern extremities of the western and eastern limbs respectively. This area of anomalously high copper extends over basic, ultrabasic and metamorphosed sedimentary rocks of both arenaceous and argillaceous facies, and could be regarded as a

geochemical sub-province. The Yirisen gold prospect is situated in ultrabasic rocks within the anomalous area, and it is possible that the high results are partly related to the copper sulphides, although only small quantities have been reported to accompany the gold mineralisation (Wilson and Marmo, 1958). The high copper contents recorded on the other rock types, particularly the metasedimentary rocks, are of special interest since it is possible, from their high level, that they are related to mineralisation. Another anomalously high pattern is situated near the Mapoko molybdenite occurrence (map ref. E25). Here, copper contents of between 80 and 150 ppm. cover both the basic rocks and the ultrabasic rocks close to the molybdenite mineralisation.

Several small anomalous patterns, in which the copper concentration is between 80 and 150 ppm., are present on the predominantly ultrabasic rocks in the southern part of the map (at map refs. G33, I36, H39, J39) where the background level is about 55 ppm. Only the concentrations at map reference J39 are, from their geological environment, likely to be related to mineralisation (see page 68).

## Zinc

The geochemical distribution pattern of zinc is based on analyses at a sample density of one per square mile, and is simple compared to the distribution patterns of the other minor elements; these are based on a sample density of about four per square mile.

The zinc content of the samples from granitic sediments is less than 30 ppm., and falls to less than 15 ppm. in a few small areas. Zinc contents in the range 30 to 70 ppm. cover large areas of the schistose rocks. Concentrations which exceed 70 ppm. are anomalously high, but in one area near Makele (map ref. D23) contents between 70 and 110 ppm. are probably related to the basic rocks, which outcrop in this vicinity. High concentrations of zinc (between 150 and 490 ppm.) were detected in several samples which are widely separated, and are not confined to outcrops of a particular rock type (fig. 19). At these high levels of concentration, it seems possible that the zinc is related to mineralisation. For instance, at the Yirisen gold prospect (map ref. H19), 415 ppm. was detected in stream sediments probably contaminated by spoil from the prospect workings.

## Gallium

The gallium content of most of the analytical results ranges from 3 - 70 ppm., and no significant regional geochemical patterns appear to be present.

## Arsenic and molybdenum

The regional geochemical patterns of these elements are described in SECTION 5.

## Silver, cadmium, tin and bismuth

The concentration of these elements seldom rises above the limits of analytical detection, and regional patterns were not obtained. However, a few samples contained more than 0.1 ppm. of silver, and these results are considered in SECTION 5.

## Lead

Only lead, of the elements studied, is concentrated in granitic rocks, and the geochemical distribution shows striking regional differences of level, ranging from the limit of detection to about 50 ppm. (see SECTION 4).

The basic and ultrabasic rocks in the south, central, and eastern parts of the area are covered by results in which the lead content is generally less than 7 ppm. In the north-east, and north-west areas of basic and ultrabasic rocks, a boundary between the geochemical patterns of less than 7 ppm. Pb, and more than 7 ppm. cuts across the strike of the schistose rocks. This distribution could be taken to illustrate the northern margin of a geochemical sub-province, in which the lead contents exceed 7 ppm. The southern margin of this sub-province is outlined by a large area (map ref. E23) in which the lead contents seldom exceed 7 ppm., except near Mopoko (map ref E 25 ). Here, lead contents of up to 20 ppm. were detected. The sub-province includes several small areas of high lead concentration. One of these, at Yirisen

(map ref. I19), is probably related to the gold mineralisation for more than 1000 ppm. was detected in sediments downstream from the prospect workings.

Another area in which high levels of lead were detected is situated in the drainage to the east of Simbili (map ref. L7). The area of high lead results extends across the contact of the granitic rocks onto the quartz-mica schists which enclose the banded ironstones forming Simbili hill. The lead contents of most of the samples range from 15 to 45 ppm. The origin of the lead is obscure, but of the many possible origins of these lead values, the two most probable explanations are that they are related to mineralisation, or to weathered granite rocks which might be concealed by overburden in the drainage catchments. In support of the latter explanation the maximum lead contents on both the granites and quartz-mica schists are at about the same level (40 to 50 ppm.). From some points of view the former explanation is more attractive, because alluvial gold has been recovered from the stream gravels of the lead high drainages to the east of Simbili, and it is possible that in this area, as at Yirisen, lead could be a pathfinder to gold mineralisation.

High levels of lead were also detected in samples from the vicinity of Makong (map ref. J37). The high values are mainly situated over granites, but also extend onto the ultrabasic rocks. Whether these concentrations are related to the granite, or to

mineralisation accompanying the rich alluvial gold deposits (or even to contamination) is not known. However, the level of the results is about 50 ppm. Pb, which is similar to the level in the south-west area of porphyroblastic granite.

## SUMMARY

### General

The regional geochemical patterns are described in relation to the geology. Features of the distribution displayed by more than one element are termed 'multi-element patterns' whilst 'single element patterns' are those displayed by individual elements.

The regional geochemical patterns of the elements (figs. 12 to 21) are broadly similar in distribution except for those of lead. The geochemical patterns of the elements titanium, vanadium, chromium, manganese, cobalt, nickel, copper and zinc show their highest concentrations in two areas; one covers the arcuate form of the Sula Mountains and Kangari Hills schist belt in the western part of the field area and the other, the region of interfingering outcrops of ultrabasic and acid igneous rocks which occur in the eastern part of the field area. The granitic rocks are characterised by generally low levels of these elements except for lead, which is concentrated in some granites.

The individual element patterns show a number of minor variations in the geochemical relief, but in general, in areas where the geology

is simple, as on the granites, the ultrabasic rocks in the south part of the map and the basic rocks in the central part of the map, the geochemical patterns are simple and display small ranges of concentration. In areas of contrasting rock types the geochemical patterns show a wide range of concentration according to the geochemistry of the bedrock.

Most of the geochemical patterns appear to be closely related to the distribution of the major rock types, but within this broad relationship there are numerous examples of regional variations of minor element concentration which may be related to either variations in the geochemistry of the bedrock or to the effects of the many environmental factors affecting dispersion.

The geochemical patterns of arsenic and molybdenum are widespread and although probably related to concentrations in the bedrock they do not conform to the geological boundaries and are considered to be related, in the case of arsenic, to a geochemical province and in the case of molybdenum, to a geochemical sub-province. Other elements such as copper and lead are closely related to the geology over large areas of the map, but in some small areas display anomalously high levels of concentration.

## Multi-element patterns

Amongst the many multi-element patterns, interesting regional variations in the concentrations of the minor elements occur in the areas of the metasediments, particularly on the argillaceous facies.

Variations also occur on the arenaceous facies. The cause of these variations was not investigated but some, particularly of copper on the arenaceous facies, may be related to mineralisation.

In areas of basic and ultrabasic rocks there are marked regional variations in the concentration of several elements. In general the highest concentrations occur in areas of thin colluvial latosols, whilst the lowest concentrations occur in areas of duricrust. Of the elements studied, cobalt and nickel show the widest range in concentration in areas of both basic and ultrabasic rocks.

Other differences in the regional distribution of the patterns amongst basic rocks are ascribed to variations of the geochemistry of the bedrock and amongst ultrabasic rocks, to dilution of ultrabasic detritus by quartzose rocks.

In areas of granitic rocks there are regional variations in the concentrations of several elements which can be correlated with the textural varieties of the granites. Of these elements, the distribution of lead is the most distinct and high contents occur in areas of the porphyroblastic synkinematic granite. On the basis of the minor element distribution in granite areas it is suggested that the porphyroblastic granite in the south-western part of the field area displays a geochemically 'basic affinity', whilst the gneissic and even-grained granite in the central part of the area displays a geochemically 'ultrabasic affinity'.

Geochemical patterns characteristic of the late-kinematic granite could not be obtained due to contamination of the stream sediments by amphibolite detritus.

In areas of complex geology and chemically different rock types, as in the eastern part of the field area, the geochemical patterns are not closely related to the geological contacts except for titanium, chromium and manganese. Of these elements, chromium is the least dispersed.

Individual patterns of the minor elements

The individual patterns of the minor elements show many small scale variations in distribution. The dominant feature of the titanium patterns is their close correlation with the basic and ultrabasic rocks at concentrations of greater than 7000 ppm.

The distribution of vanadium is somewhat similar to that of titanium, but at lower levels of concentration. In the eastern part of the field area the vanadium patterns are diffuse and poorly related to the geological boundaries.

In contrast to vanadium, the chromium patterns are closely related to the outcropping geology and most of the major rock types can be identified on the basis of the chromium content of their stream sediments. The close correlation of the chromium patterns to the geology and particularly the ultrabasic rocks is taken to indicate that the chromium occurs in these areas in the mineral form of chromite.

Manganese displays a distribution which is more closely related to the geology in the eastern part of the field area, than is the case with vanadium. Like vanadium, manganese only poorly reflects the ultrabasic rocks in the central granite area.

The geochemical patterns of cobalt are simple and at much lower ranges of concentration than those of Ti, V, Cr and Mn. Marked regional variations of concentration occur in areas of basic and ultrabasic rocks, the higher levels occurring in areas of thin colluvial latosols and the lower levels in areas of duricrust. Small, anomalously high concentrations of cobalt may be related to mineralisation.

Like cobalt, nickel shows regional variations of concentration in which high levels can be correlated with areas of basic and ultrabasic rocks in areas of thin colluvial latosols, whilst lower levels occur in areas of duricrust covered basic and ultrabasic rocks, and in areas of siliceous rocks. Nickel also shows a regional variation in granites, slightly higher levels being detected in the central granite area than in the south-west granite area.

Copper forms complex geochemical patterns over most of the major rock types, probably resulting from the wide ranges of concentration detected. The most interesting feature of the copper distribution is the V shaped anomaly situated over the schist belt to the north of the Pampana river. The western limb of this anomaly is possibly related to mineralisation, while the eastern limb is probably related to the high background levels of copper in basic and ultrabasic rocks.

The geochemical patterns of zinc, based on a sample density of one per square mile, are simple compared to those of the other elements studied which are based on a sample density of four per

square mile. Several widely separated concentrations of zinc were detected which are possibly associated with mineralisation.

The distribution of arsenic and molybdenum is reported in SECTION 5.

Gallium does not form significant geochemical patterns.

Silver, cadmium, tin and bismuth seldom rise above the limit of analytical detection and regional patterns were not obtained.

Only lead, of the elements studied, is concentrated in granitic rocks. In distribution, lead shows striking regional differences of level, the higher levels being detected in areas of porphyroblastic synkinematic granites. Some of the lead concentrations may be associated with mineralisation.

## SECTION 4

## FACTORS AFFECTING THE DEVELOPMENT OF THE GEOCHEMICAL PATTERNS

The following description of the factors affecting the distribution of geochemical patterns is illustrated by reference to specific patterns which were investigated in detail. Mineralisation, as a factor affecting the distribution of the geochemical patterns, is considered separately in SECTION 5.

The chemical composition of the bedrock appears to be the most important factor governing the distribution of the geochemical patterns. Other environmental factors, such as the pedological variations and the variable composition of stream sediments also affect the patterns. Biological factors have little recognisable effect.

In the rugged topography of the field area, the minor element composition of the bedrock is strongly reflected in stream sediments especially in areas where the soil cover is comparatively juvenile. The geochemical distribution patterns are, for several elements, considerably modified where duricrust and indurated latosols form a large proportion of the stream sediment. The bedrock geochemistry is, however, the dominant factor affecting the distribution of the patterns.

### BEDROCK GEOCHEMISTRY

#### Geochemical patterns related to the major rock types

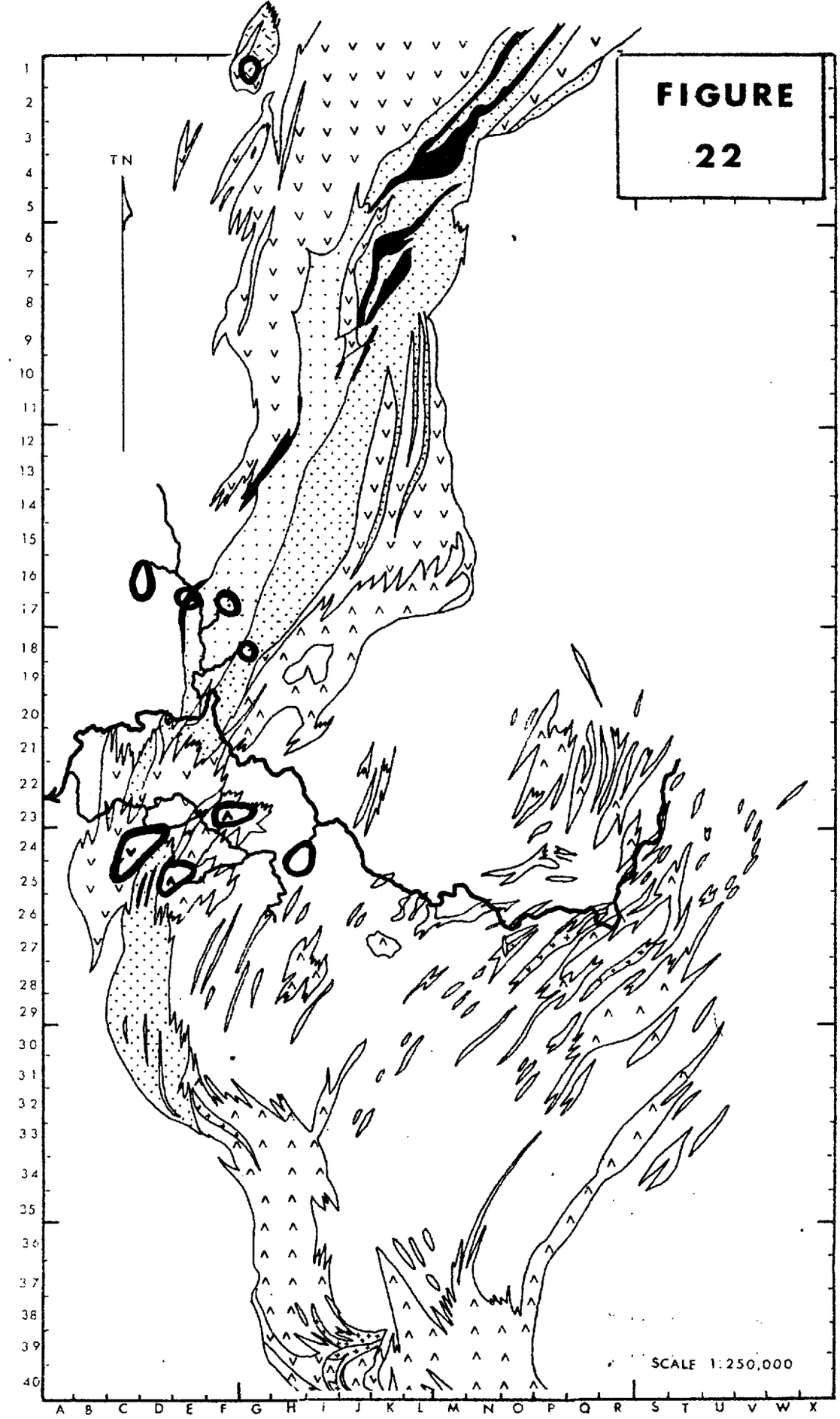
Although the geochemical maps show a correlation of trace element distribution with geology, it is necessary to establish that the geochemical patterns are directly related to the

geochemistry of the bedrock. Several drainages were therefore selected to provide 'type' geochemical patterns. The selected drainages had, in each case, been previously mapped by officers of the Geological Survey of Sierra Leone. The bedrock was well exposed and the soils in the drainage catchments were largely colluvial latosols (fig. 22). Each of the selected drainages was approximately one mile in length, and the stream sediment samples were collected at quarter mile intervals.

The analytical results of the minus 80-mesh fraction of the stream sediments show that tremolite-serpentinites are distinguished by the ratios of Cr/V = greater than 1, and Ni/Co = approximately 10. In contrast, amphibolitic sediments provide ratios of Cr/V = less than 1, and Ni/Co = approximately 1.

Granitic sediments were found to contain characteristically low concentrations of all the elements studied, except for lead.

The minor element contents of detritus derived from the metasediments could not be easily distinguished from the concentrations detected in sediments derived from the other major rock types. From the present data the metasediments contain low concentrations (but generally high compared to the granites) of the elements Ti, V, Cr, Mn, Co and Ni. The ratio of Cr/V = approximately 1, and the ratio Ni/Co = approximately 1 (fig. 23).

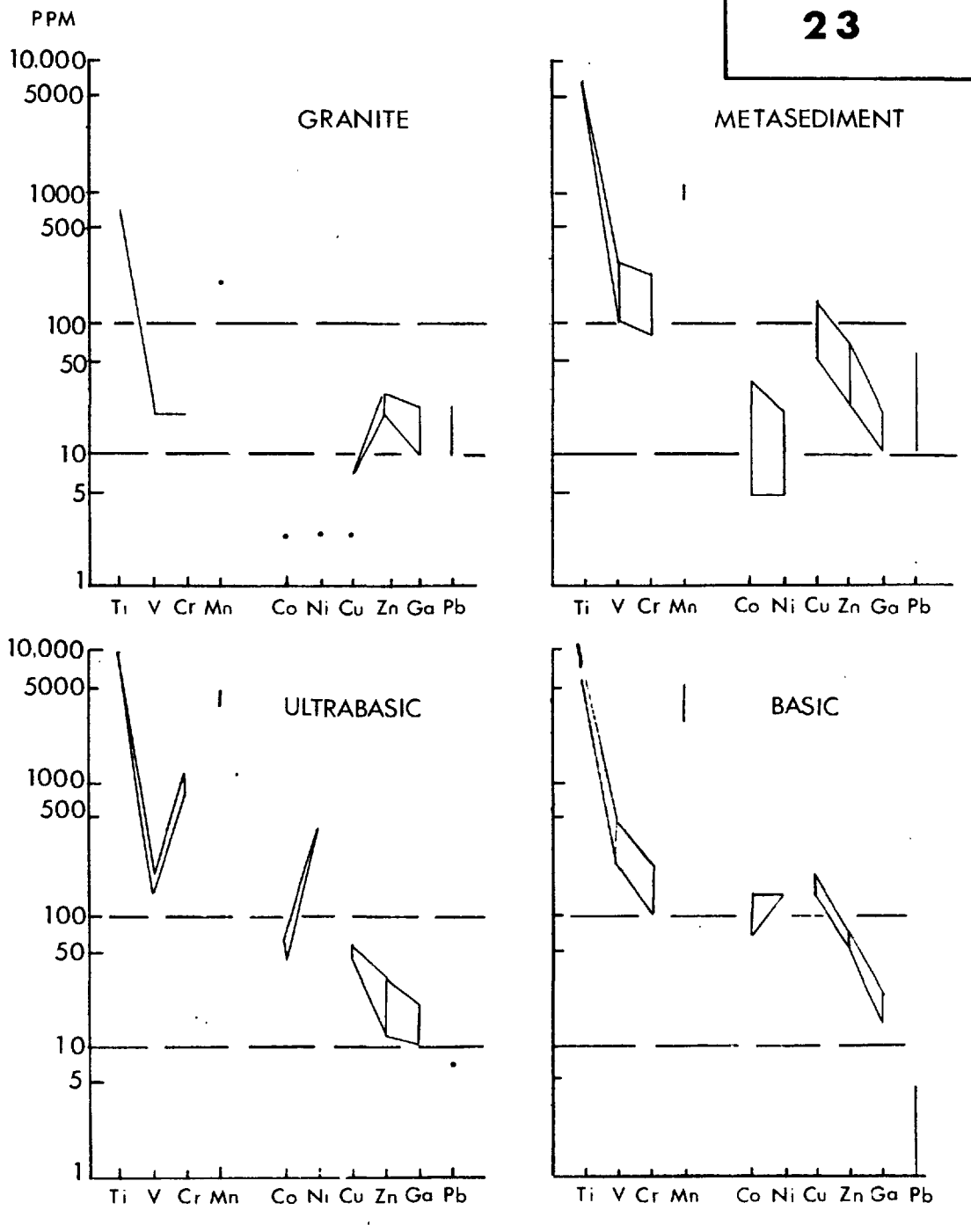



**Sula Mountains - Kangari Hills Area**

**Sierra Leone.**

Location of selected drainage systems on major rock types.

**FIGURE 23**




Each diagram is based on 3 samples

**DISTRIBUTION OF THE MINOR ELEMENTS IN THE MINUS 80-MESH FRACTION OF STREAM SEDIMENTS DERIVED FROM THE MAJOR ROCK TYPES.**

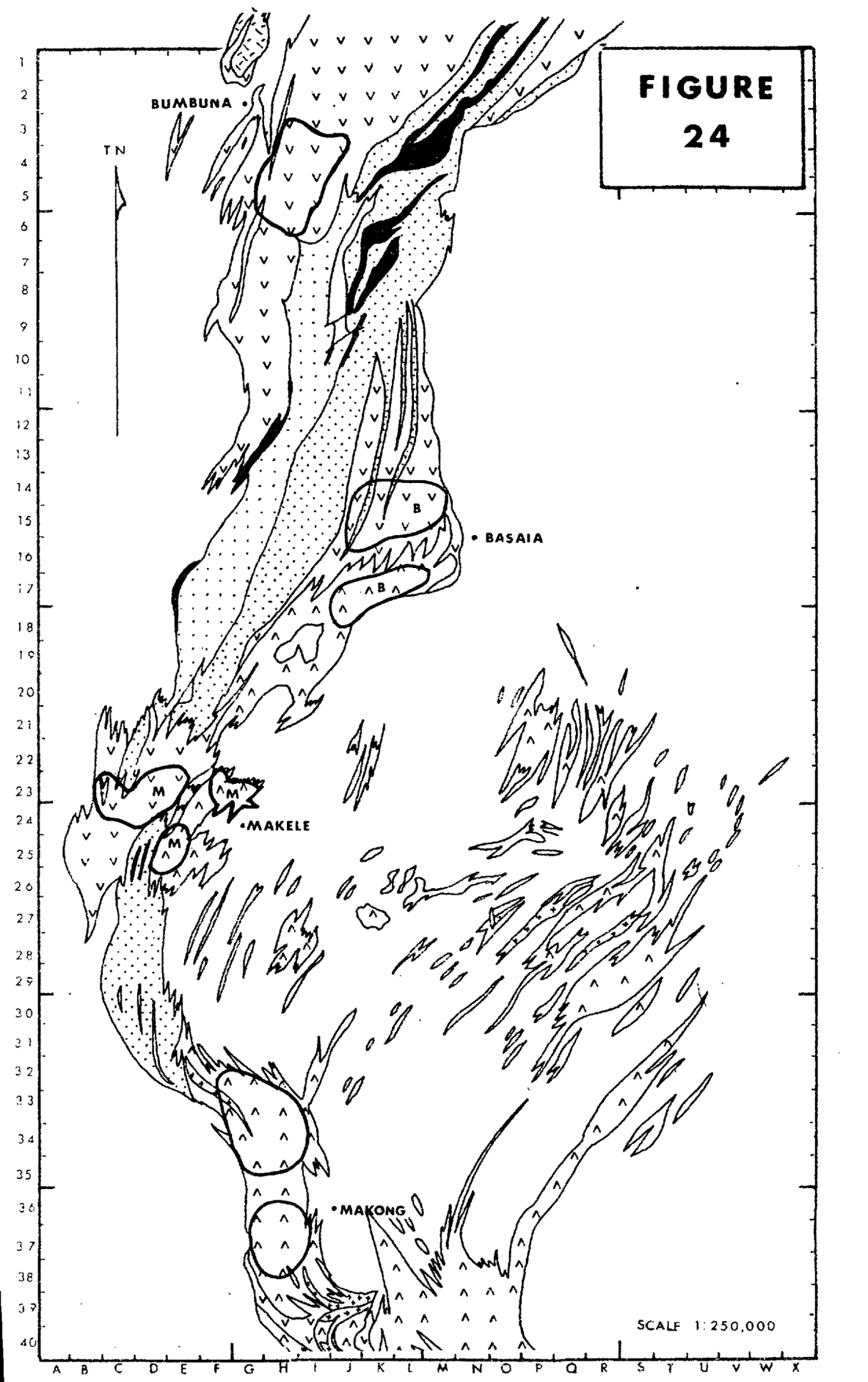
## Regional variations in the geochemistry of basic and ultrabasic rocks

The strong regional variations of the trace element patterns in the stream sediments derived from basic and ultrabasic rocks has been discussed (tables 15, 16), and it is possible that these patterns result from the combined effects of two factors: a regional variation of the minor element distribution in the bedrock; and a regional variation of the minor element concentration between comparatively juvenile latosols, and mature indurated laterite and duricrust.

The field areas in which the regional variations of geochemical patterns were investigated cover a large proportion of the total outcrop of the basic and ultrabasic rocks (fig. 24). They were primarily selected from the distribution patterns of cobalt and nickel.

### BASIC ROCKS

Within the limits of analytical precision, the results of the rock samples show that there is very little regional variation in the minor element content, except in the Bumbuna area, where chromium and manganese are more concentrated than in the Makele and Basaia areas. Nickel is more concentrated in the Bumbuna and Basaia areas compared to the Makele area. The increased concentration of these elements in the Bumbuna area is illustrated by a comparison of the averages of the minor element contents (table 18).




EXPLANATION

- Arenaceous meta-sediment.
- Argillaceous meta-sediment.
- Banded ironstone.
- Metamorphic acid volcanics.
- Metamorphic basic rocks
- Metamorphic ultra basic rocks.
- Late kinematic granite
- Syn kinematic granite

**Sula Mountains - Kangari Hills Area**

**Sierra Leone.**

LOCATION OF STUDY AREAS

BASIC AND ULTRABASIC ROCKS

Table 18. Average contents of minor elements in basic rocks in ppm.

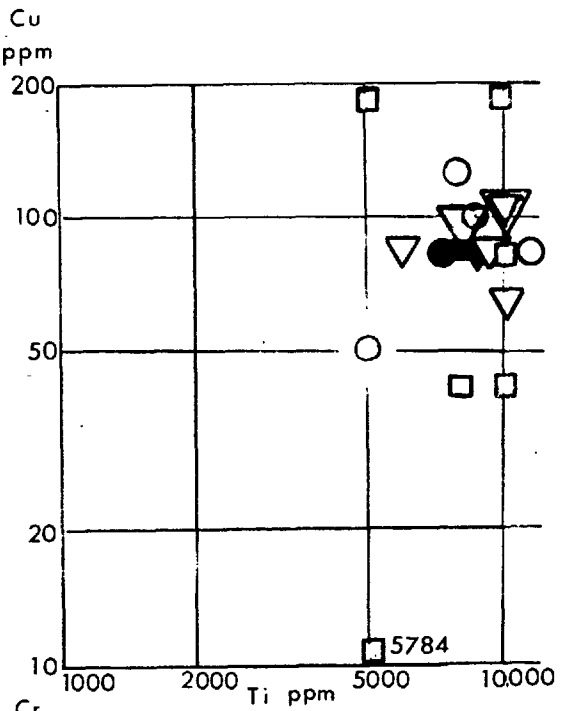
| | Ti | V | Cr | Mn | Co | Ni | Cu | No. of Samples | |
|---|---|---|---|---|---|---|---|---|---|
| Bumbuna | >8000 | 260 | 290 | 1500 | 60 | 170 | 85 | 6 | |
| Basaia | > 7800 | 310 | 140 | 1020 | 65 | 160 | 85 | 5 | |
| Makele | > 8800 | 400 | 150 | 980 | 65 | 115 | 85 | 5 | |
| Average world abundance | - | - | 170 | - | 48 | 130 | - | | Turekian and Carr, 1960 |
| | 9000 | 200 | 300 | 2200 | 45 | 160 | 140 | | Hawkes and Webb, 1962 |

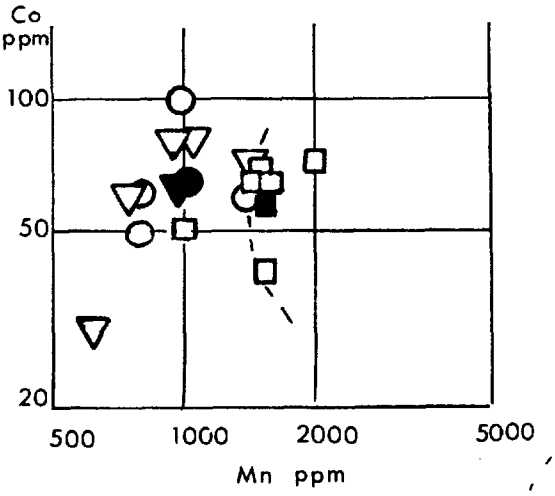
Although the average minor element contents of the rock samples only show small variations (about 2 fold, or less) of level amongst the three areas, the individual results show a wider scatter for chromium, nickel, and copper, than for titanium, vanadium, manganese and cobalt. The range of the chromium content in basic rocks is particularly wide and extends from 15 to 600 ppm. (fig. 25).

ULTRABASIC ROCKS

The minor elements show a wide range of concentration in rocks which have been mapped as ultrabasics. The average minor element contents (solid symbols, fig. 26a) show that the Makong area has a high content of cobalt and vanadium, and a low content

**FIGURE 25**

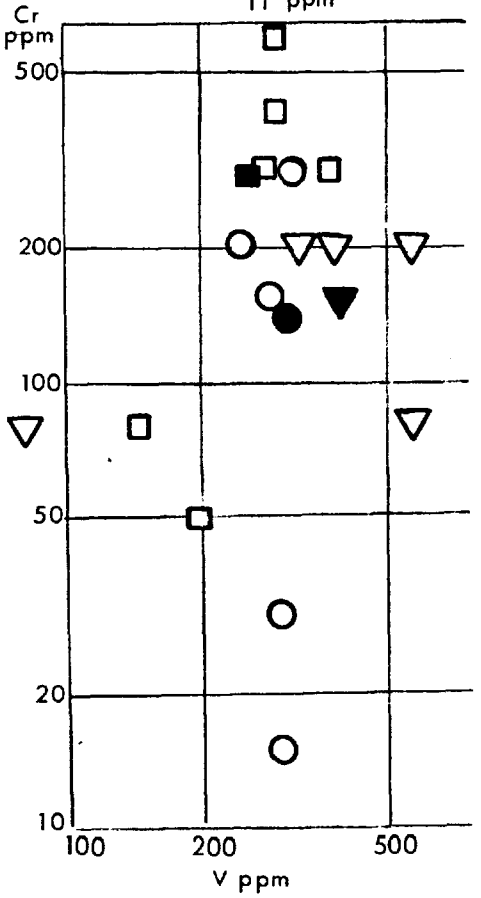


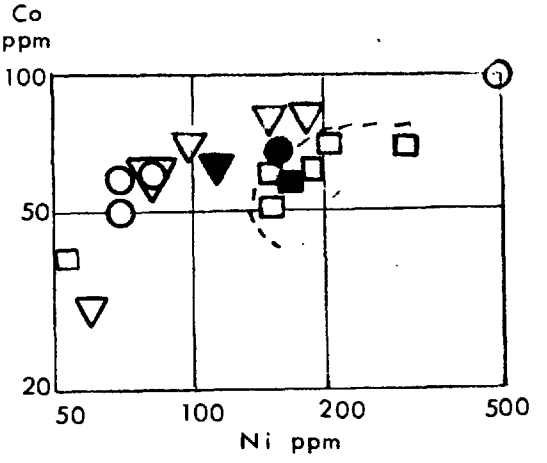




EXPLANATION

- Bumbuna
- Basaia
- Makele

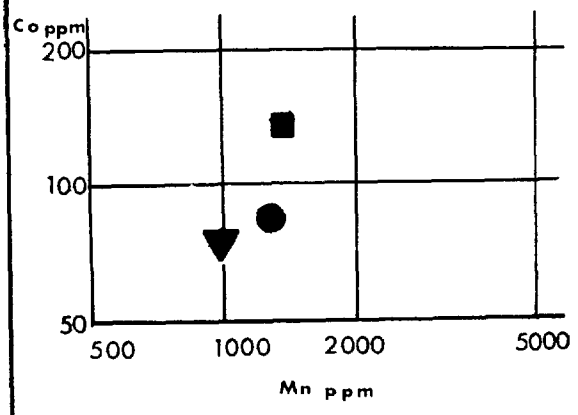
Solid symbols are average results.

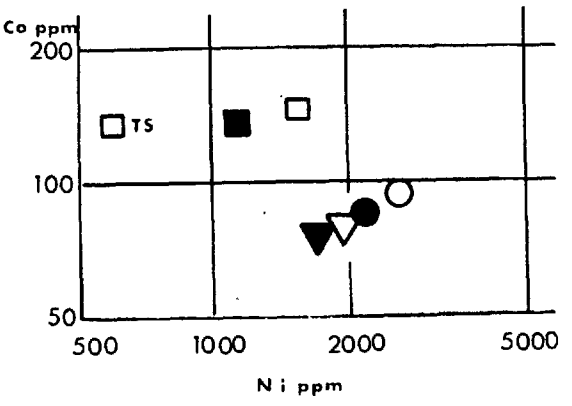



**MINOR ELEMENT DISTRIBUTION IN BASIC ROCKS**

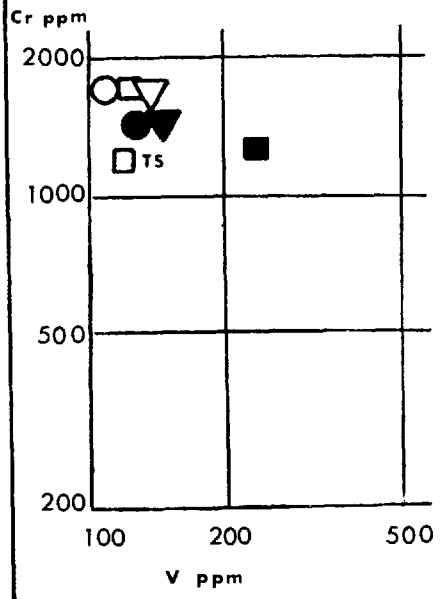
**FIGURE 26 a**

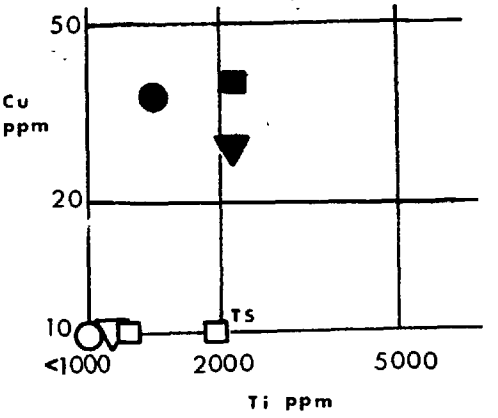


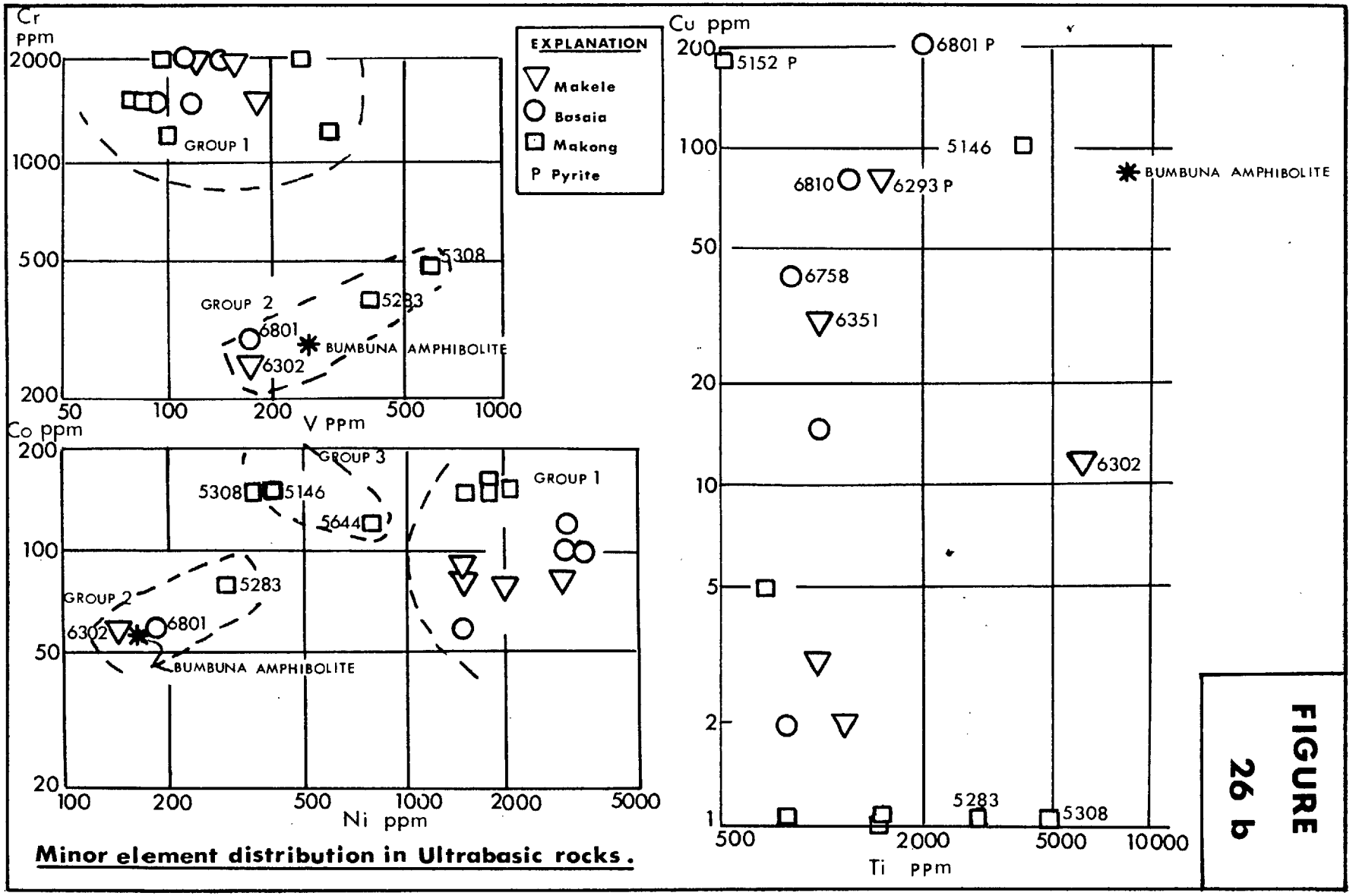

**Explanation**

| Averaged analyses No: | | Amphibolitic types subtracted No: | | Field Area |
|---|---|---|---|---|
| ● | 5 | ○ | 4 | Basaia |
| ▼ | 5 | ▽ | 4 | Makele |
| ■ | 8 | □ | 4 | Makong |
| | | □ TS | | Tremolite Schist |




**Average contents of minor elements in areas of dominantly ultrabasic rocks.**




**Minor element distribution in Ultrabasic rocks.**

**FIGURE 26 b**

of nickel, compared to the Makele and Basaia areas. The concentrations of titanium, chromium, manganese and copper are approximately the same in each of the areas investigated.

From the analyses of the individual samples (fig. 26b) there are, on the basis of the chromium, vanadium, cobalt and nickel results, at least two, and possibly three, distinct groups of results. The majority of the results (group 1) from each of the study areas show chromium contents of greater than 1000 ppm., and nickel contents of greater than 1500 ppm. A second group of results contains between 200 and 500 ppm. Cr and 150 and 300 ppm. Ni. The third group of results are distinguished by their nickel contents which are intermediate between those of groups 1 and 2 (table 19).

Table 19. Ranges of minor element concentration in ultrabasic rocks, in ppm.

| | Cr | V | Co | Ni | No. of samples |
|---|---|---|---|---|---|
| Group 1 | 1000-2000 | 70-300 | 60-150 | 1500-3000 | 12 |
| Group 2 | 200- 500 | 170-600 | 50- 70 | 150- 300 | 3 |
| Group 3 | - | - | 110-150 | 300- 800 | 3 |

The results which fall into group 2 were detected in a sample of tremolite schist (No. 5283 Makong), and two samples of serpentinite (nos. 680 Basaia, 6302 Makele). The chromium and nickel contents

in these rock samples (Group 2) are typical of the contents in basic rocks. The same samples show, however, a wide variation from the characteristic titanium and copper contents of basic rocks (compare fig. 25 with fig. 26b).

The results which constitute group 3 are distinguished on the basis of their nickel contents, and are intermediate between the ranges of concentration typical of the ultrabasic rocks (group 1), and those typical of amphibolite rocks (group 2). The rock samples (Nos. 5308, 5146 and 5644, Makong) from which these results were obtained have the appearance of tremolite schists.

## DISCUSSION

### BASIC ROCKS

The minor element analyses of the basic rocks show that the average concentration of chromium, manganese, and nickel is higher in the rocks of the Bumbuna area than at Basaia and Makele. It is possible that this enrichment partly accounts for the higher concentrations in the stream sediments of the Bumbuna area (map ref. I4, Figs. 14 and 17). However, the regional differences of minor element concentration in the rock samples are small compared to the markedly different concentrations of the geochemical patterns observed in the stream sediment analyses (table 20).

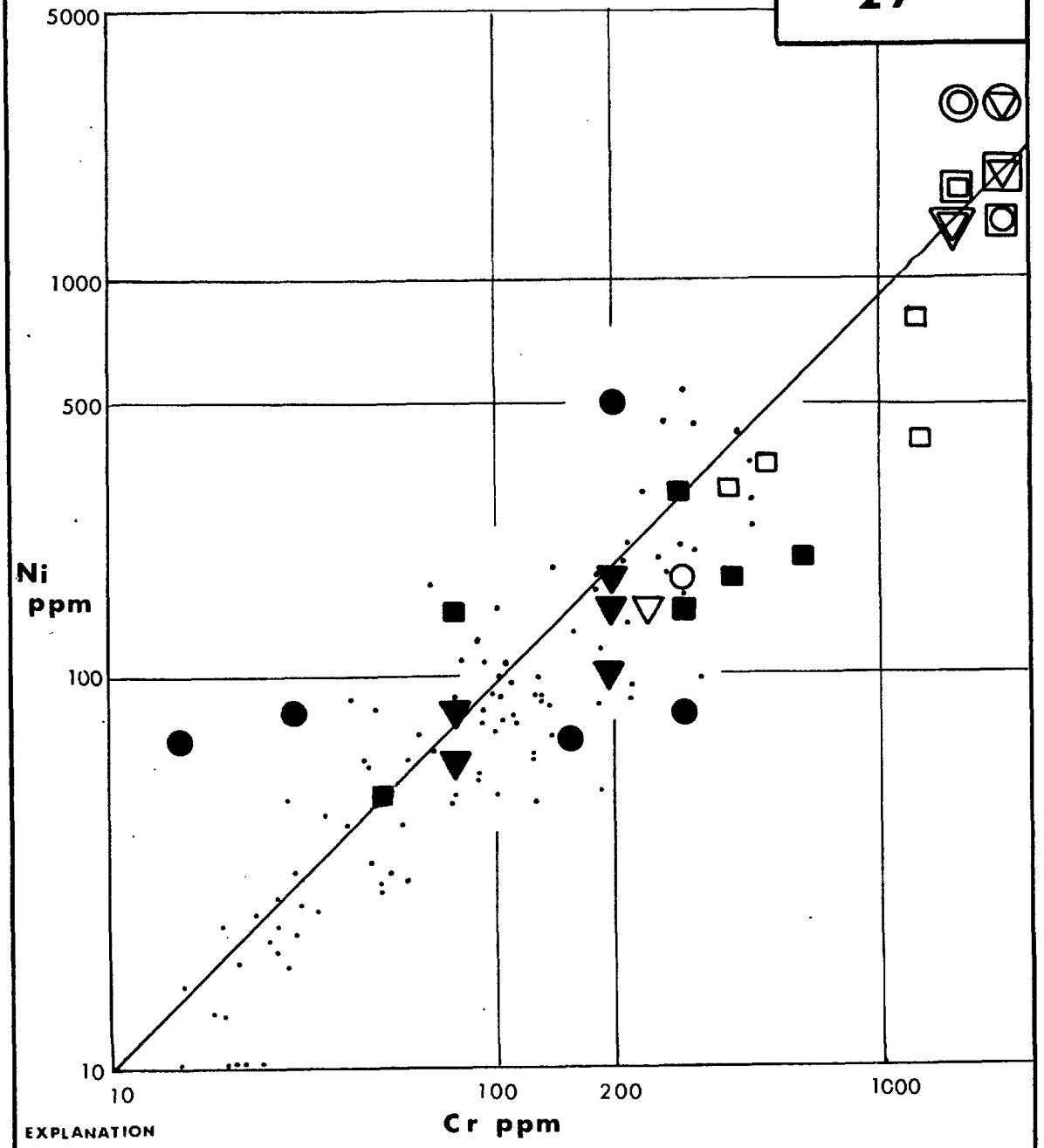
Table 20. Average values (in ppm.) of minor element concentration in basic rocks compared with average values in stream sediments

| Area | Ti | V | Cr | Mn | Co | Ni | Cu | No. of Samples |
|---|---|---|---|---|---|---|---|---|
| Rocks | | | | | | | | |
| Bumbuna | > 8000 | 260 | 290 | 1500 | 60 | 170 | 85 | 6 |
| Basaia | > 7800 | 310 | 140 | 1020 | 65 | 160 | 85 | 5 |
| Makele | > 8800 | 400 | 150 | 980 | 65 | 115 | 85 | 5 |
| Sediments | | | | | | | | |
| Bumbuna Monadrock | 7000 | 300 | 360 | 1380 | 70 | 110 | 75 | 9 |
| Duricrust | > 9300 | 260 | 85 | 1300 | 30 | 60 | 60 | 6 |
| Basaia Duricrust | > 9000 | 240 | 200 | 910 | 26 | 30 | 40 | 12 |
| Makele Colluvial latosols | > 10,000 | 380 | 200 | 3750 | 90 | 125 | 150 | 10 |

In the Bumbuna and Basaia areas, where indurated laterite and duricrust are the dominant soil types, there are wide variations between the averaged results of the rocks and the sediments. For the elements cobalt and copper the variations is about two fold, whilst for nickel it is between three and five fold (table 20).

According to Turekian and Carr (1960) the abundances of nickel and chromium are covariant in basaltic rocks, and varying concentrations of these elements may illustrate progressive differentiation. Most of the present results lie within the limits of scatter shown by Turekian and Carr (fig. 27). The

**FIGURE 27**




EXPLANATION

Ultrabasic Basic Area

BASAIA

MAKELE

BUMBUNA

MAKONG

Data from TUREKIAN and CARR.

## COVARIANCE OF NICKEL AND CHROMIUM IN BASIC AND ULTRABASIC ROCKS

COMPARED WITH DATA FROM BASALTIC ROCKS, FROM TUREKIAN AND CARR (1960).

higher chromium and nickel contents in some of the Bumbuna samples compared to the Makele and Basaia samples is demonstrated by the solid symbols on figure 27.

ULTRABASIC ROCKS

The distribution of nickel and chromium is also covariant in the ultrabasic rocks (fig. 27). Most of the present results are at distinctly high levels of concentration compared to those of the basic rocks, but there are exceptions. Two of the Makong samples and one each from the Basaia and Makele areas lie well within the scatter of the results of the basic rocks. Two other samples from the Makong area lie between the basic and ultrabasic results. This wide distribution of nickel and chromium in the ultrabasic rocks at Makong could be taken to illustrate a progressive differentiation of these elements in the rocks of this area.

The distribution of copper in ultrabasic rocks

The copper content of rocks collected from the ultrabasic study areas ranges from 1 ppm. to greater than 200 ppm. From figure 26b there are several samples (Nos. 6758, 5159, 6810, 6293, 6351) in which the titanium, vanadium, chromium, nickel, and cobalt contents are characteristic of the ultrabasic rocks of the field areas. The copper contents of these samples are greater than

20 ppm. and are anomalously high. In addition, sample No. 6801 (which is on the basis of the chromium and nickel contents, of amphibolitic affinity) contains a greater concentration of copper than the average contents of the basic rocks. It is possible that the high copper contents of these samples are associated with segregations of sulphide minerals. In this connection disseminated crystals of pyrite were observed in samples nos. 5159, 6801, 6293 collected from the Makong, Basaia and Makele areas respectively.

Minor element distribution in ultrabasic rocks related to the regional geochemical patterns

The analytical results show that in each of the areas where ultrabasic rocks outcrop, there are rocks which have the physical appearance of serpentinite, or tremolite schist, but have chromium, and nickel content which is more characteristic of basic rocks.

Of the distinct mineralogical types which have been recognised by officers of the Geological Survey, only the tremolite schists in the Makong and Makele areas can be distinguished geochemically from the other rocks of ultrabasic type. The tremolite schists are identified by a nickel content of less than 1000 ppm., compared to more than 1500 ppm. in the other types of ultrabasic rocks. From these results it appears that the ultrabasic rocks may, possibly characteristically, display a wide range of minor element concentration.

The regional variations of minor element concentration detected in the stream sediments of the three areas could be strongly influenced by variations in the element content of the associated ultrabasic rocks. This possibility could be investigated where the ultrabasic rocks are well exposed, but would be very difficult in areas of duricrust, as at Basaia.

In table 21, the average values of the minor element contents of the ultrabasic rocks are compared to the average values of the stream sediments.

Table 21. Average values, in ppm., of minor element concentration in ultrabasic rocks compared with average values in the stream sediments

| Area | Ti | V | Cr | Mn | Co | Ni | Cu | No. of Samples |
|---|---|---|---|---|---|---|---|---|
| Rocks | | | | | | | | |
| Basaia | 1150 | 125 | 1450 | 1250 | 85 | 2150 | 35 | 5 |
| Makele | 2150 | 150 | 1450 | 1000 | 75 | 1830 | 26 | 5 |
| Makong | 2120 | 240 | 1290 | 1350 | 135 | 1120 | 37 | 8 |
| Sediments | | | | | | | | |
| Basaia Duricrust | >7500 | 185 | 1100 | 750 | 45 | 160 | 50 | 7 |
| Makele Colluvial | >7000 | 170 | 1050 | 2200 | 55 | 590 | 65 | 7 |
| Makong Colluvial | >9000 | 260 | 3000 | 3780 | 110 | 970 | 60 | 16 |

The data show wide regional differences in the concentration of several minor elements which are clearly much larger in the stream sediments than in rocks. For example, the average content of nickel varies between 1120 and 2150 ppm. in the ultrabasic rocks of the three areas; the highest level occurs in the Basaia area and the lowest in the Makong area. The average nickel content of the stream sediments at Basaia (160 ppm.) is, however, very much less than in the Makong area (970 ppm.), despite the higher nickel content of the bedrock at Basaia.

Evidently regional variations in the minor element concentration of the ultrabasic (and basic) bedrock is not closely reflected by the distribution of the elements in stream sediments. From tables 20 and 21 the widest variations of minor element distribution in rocks compared to stream sediments occurs in areas of duricrust soils, and the least variations in areas of colluvial latosols.

The influence of soil type upon the distribution of the geochemical patterns is considered under the heading "Pedology".

## COMPARISON OF THE MINOR ELEMENT CONTENT IN BASIC AND ULTRABASIC ROCKS

The distribution of chromium and nickel in basic and ultrabasic rocks has been discussed above (fig. 27). The ranges and average values for the other important minor elements in basic and ultrabasic rocks are given in table 22.

Table 22. Range and average value of minor element content of basic and ultrabasic rocks

| | Ti | | V | | Cr | | Ma | | Co | | Ni | | Cu | | No. of Samples |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Range | MV | Range | MV | Range | MV | Range | MV | Range | MV | Range | MV | Range | MV | |
| Basic Rocks | 5000–10,000 | > 8200 | 80–600 | 320 | 15–600 | 200 | 600–2000 | 1150 | 30–100 | 65 | 50–500 | 150 | 10–180 | 85 | 16 |
| Ultra-basic Rocks | 500–5000 | 1800 | 80–300 | 170 | 250–2000 | 1400 | 600–2000 | 1200 | 60–150 | 100 | 50–3000 | 1700 | ND–200 | 35 | 18 |

The ranges of concentration are wide for all of the elements, and there is an overlap in the ranges of titanium, chromium, and nickel in basic and ultrabasic rocks. The average values are, however, widely separated. In addition the ratios Cr/V = less than 1, and Co/Ni = 1 to 5, are possibly characteristic of basic rocks, whilst the ratio of Cr/V=greater than 1, and Ni/Co = 20 are characteristic of ultrabasic rocks.

## Regional variations in the geochemistry of granitic rocks.

Regional variations in the distribution of several minor elements have been observed in areas of granitic rocks. It has been shown (SECTION 3) that high levels of titanium and lead, and low levels of nickel, occur in sediments derived from the south western porphyroblastic granites, whilst on the central even grained and gneissic granites, the titanium and lead levels are low but the nickel contents are high. The south western granite is covered by patterns which have a lenticular form. These patterns contain high levels of titanium, vanadium, manganese, but low levels of chromium and lead. From the geological map, they can be correlated with a zone of gneiss including discontinuous outcrops of amphibolite (map ref. D33).

To determine the influence of the geochemistry of the granite bedrock upon the minor element composition of the stream sediments, six widely separated field areas were selected for investigation.

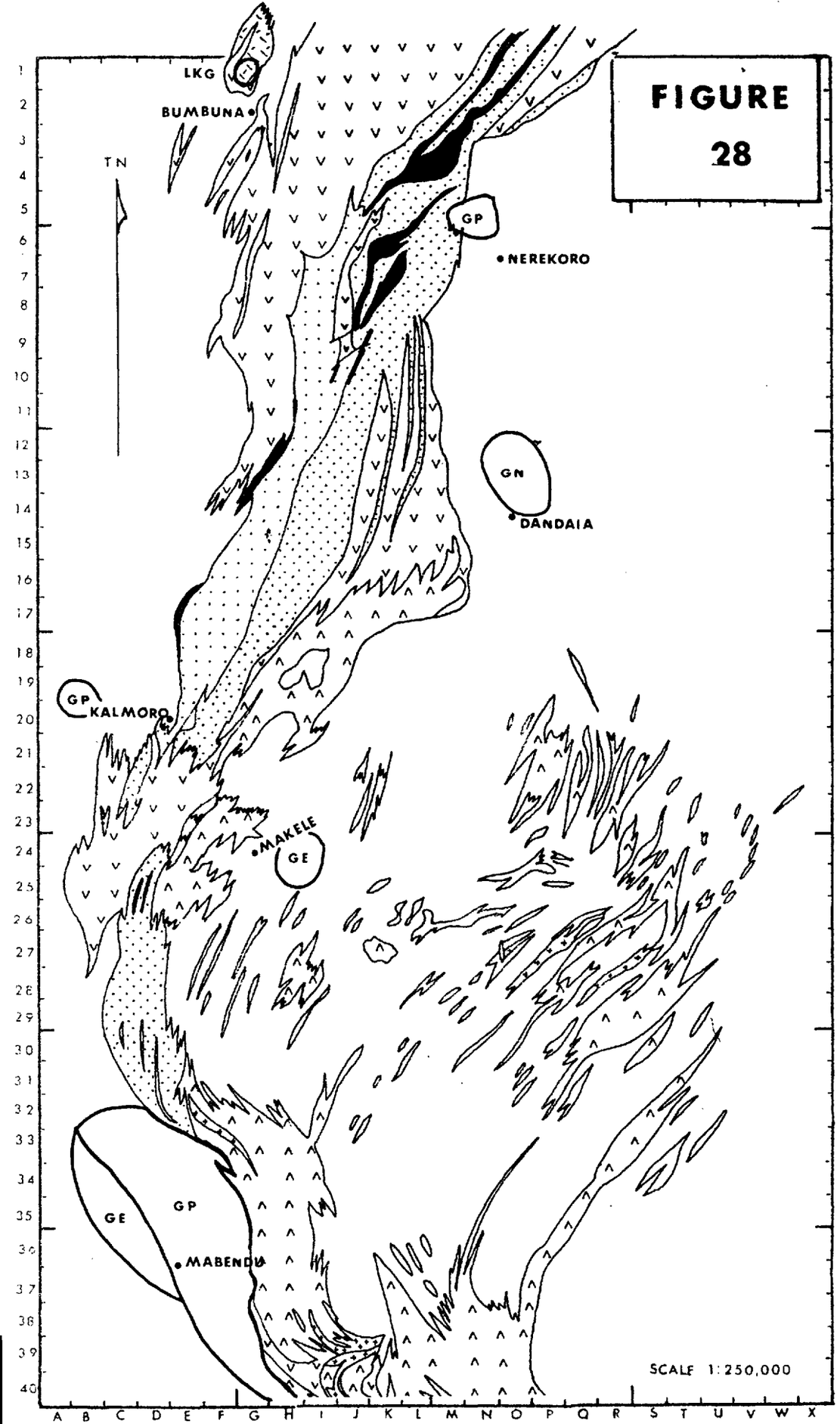
The field areas were chosen on the basis of the lead distribution, bedrock texture and topographic features. One of these areas included the outcrop of late-kinematic granite at Bumbuna (map ref. G1) to provide a comparison with the other, synkinematic granites (fig. 28).

## THE DISTRIBUTION OF LEAD

A comparison of the average values of the lead contents of the granite bedrock with the lead contents of the stream sediments shows that there is little difference between them (table 23).

It is only in the Dandaya area (map ref. N13) that lead is impoverished in the stream sediments (2 ppm.) compared to the rock samples (15 ppm.). This depletion could be correlated with a topographical feature, as for example the swampy nature of the drainage catchment, where the chemical dispersion of lead might be more active than the mechanical dispersion. At higher levels of lead concentration, however, there is little or no depletion of the lead contents in stream sediments from a swampy environment, and in the south-west granite near Mabendu the stream sediments contain 53 ppm. and the rocks 41 ppm.

It is concluded that, in general, the content of lead in granitic rocks is closely reflected by the stream sediments. It follows that the regional variation in the lead content of the stream sediments closely reflects regional variations of the lead content of the granite bedrock.




EXPLANATION

- Arenaceous meta-sediment.
- Argillaceous meta-sediment.
- Banded ironstone.
- Metamorphic acid volcanics.
- Metamorphic basic rocks
- Metamorphic ultra basic rocks.
- Late kinematic granite
- Syn Kinematic granite

LKG – late kinematic
GP – porphyroblastic
GE – even grained
GN – gneissic

**Sula Mountains – Kangari Hills Area**

**Sierra Leone.**

LOCATIONS OF THE GRANITE STUDY AREAS

Table 23. Average lead contents of stream sediments and rocks from granites

| Area | Map Ref. | Texture | Topography | Sediments | | Rocks | | No. of Samples | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Range | Mean | Range | Mean | Sediments | Rocks |
| Bumbuna | G1 | LKE | In amphitheatre of amphibolite hills | 6-30 | 16 | 20-21 | 20 | 4 | 2 |
| Nunkekoro | N5 | GP | Undulating to hilly; exfoliating granite slabs | 30-40 | 32 | 29-38 | 34 | 4 | 2 |
| Dandaya | N13 | GN | Flat, swampy areas | ND- 6 | 2 | 12-19 | 15 | 7 | 5 |
| Kalmoro | C19 | GP | Pampana river flood plain | 57-70 | 13 | 43 | 43 | 2 | 1 |
| Makele | H24 | GE | Undulating, swampy channels | 10-25 | 12 | 15-17 | 15 | 5 | 4 |
| Mabendu | E34 | GP | Rounded hills, exfoliating slabs | 30-70 | 55 | 30-52 | 38 | 16 | 6 |
| | B34 | GE | Undulating, swampy valleys | 30-65 | 53 | 35-46 | 41 | 5 | 3 |

## THE DISTRIBUTION OF LEAD AND OTHER MINOR ELEMENTS

The regional distribution of lead is compared with the average values for the other minor elements studied in table 24.

The results show that high levels of rubidium occur in synkinematic granite rocks and stream sediments which also contain high levels of lead. Thus, the mean rubidium content of the porphyroblastic and even-grained lead rich granites varies between 170 and 205 ppm. In the lead poor granites the average rubidium level is between 50 ppm. (Makele area) and 80 ppm. (Dandaya area).

In the late-kinematic granites, the lead content of the rock samples is low (20 ppm.) and little more than the levels detected in the lead poor synkinematic granites (15 ppm. Pb). The rubidium content, however, is high (170 ppm.) and within the concentration range of the lead rich synkinematic granites (110 to 240 ppm.).

In areas of synkinematic granites, certain regional differences in the concentration of minor elements (apart from lead) were observed between the south-west porphyroblastic granite and the central even-grained granite (SECTION 3).

The stream sediments of the south-western granite contain high levels of titanium and low levels of nickel, compared to the central granite. In addition, the elements titanium, vanadium,

Table 24. Mean values of minor element contents (in ppm.) of granitic rocks and stream sediments

| Area | Map Ref. | Texture | Pb | | Ti | | V | | Cr | | Mn | | Co | | Ni | | Cu | | Ba | | No. of Samples | | Rb | | Sr | | No. of Samples | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Sediments | Rocks | Sediments | Rocks | Sediments | Rocks | Sediments | Rocks | Sediments | Rocks | Sediments | Rocks | Sediments | Rocks | Sediments | Rocks | Sediments | Rocks | Sediments | Rocks | Sediments | Rocks | Sediments | Rocks | Sediments | Rocks |
| Bumbuna | G1 | LKE | 16 | 20 | 4250 | 425 | 82 | 1 | 48 | 3 | 462 | 60 | ND | 25 | 10 | 2 | 16 | 1 | 1875 | 70 | 4 | 2 | 145 | 170 | 180 | 50 | 4 | 1 |
| Nunkekoro | N5 | GP | 32 | 34 | 3500 | 1050 | 15 | 2 | 23 | 2 | 400 | 125 | ND | 32 | 8 | ND | 7 | 2 | 1625 | 1000 | 6 | 2 | 180 | 210 | 51 | 130 | 3 | 1 |
| Dandaya | N13 | GN | 2 | 15 | 2100 | 1240 | 8 | 8 | 13 | 6 | 100 | 168 | ND | 23 | 8 | ND | 5 | 3 | 350 | 910 | 7 | 5 | 8 | 80 | 40 | 460 | 3 | 2 |
| Kalmoro | C19 | EP | 63 | 43 | 3400 | 1500 | 37 | 15 | 35 | 7 | 240 | 300 | 3 | 40 | 18 | 5 | 12 | 3 | 1900 | 2000 | 7 | 1 | - | 200 | - | 690 | - | 1 |
| Makele | H24 | GE | 12 | 15 | 500 | 350 | 6 | 2 | 8 | 2 | 200 | 132 | ND | 37 | 5 | ND | 5 | 2 | 3000 | 1687 | 3 | 4 | 43 | 50 | 200 | 450 | 3 | 2 |
| Mabenda | E34 | EP | 55 | 38 | 6785 | 1666 | 43 | 38 | 33 | 10 | 508 | 283 | ND | 24 | 8 | 14 | 5 | 14 | 6687 | 4416 | 16 | 6 | 135 | 170 | 242 | 330 | 4 | 4 |
| | B34 | GE | 53 | 41 | 6400 | 1133 | 3 | 10 | 5 | 3 | 360 | 123 | ND | 3 | ND | 1 | 2 | 1 | 4400 | 3333 | 5 | 3 | 156 | 205 | 45 | 195 | 3 | 2 |

and manganese were concentrated in lenticular shaped patterns on certain areas of the south-west granite, whilst lead and chromium were impoverished over somewhat smaller areas. From table 24, it is seen that variations in the concentrations of titanium, vanadium, and manganese detected in the stream sediments are broadly related to the distribution of these elements in the bedrock, and that the concentration of these elements in the stream sediments is frequently high compared to the average value of the rock samples. Thus the mean titanium content of the south-western porphyroblastic granite is 1666 ppm. compared to 6785 ppm. in the associated stream sediments.

The nickel and chromium distribution in stream sediments is less clearly related to the bedrock contents.

Cobalt, when compared to the reported world abundance, is distributed at abnormally high levels in the central Sierra Leone granites. The average cobalt values from each of the study areas ranges from 3 to 40 ppm., and the mean of these results is 26 ppm. (based on 15 samples). The average content of cobalt in acidic rocks is reported to be 11 ppm. (Rankama and Sahama, 1950). In granitic stream sediments, however, cobalt is seldom detected.

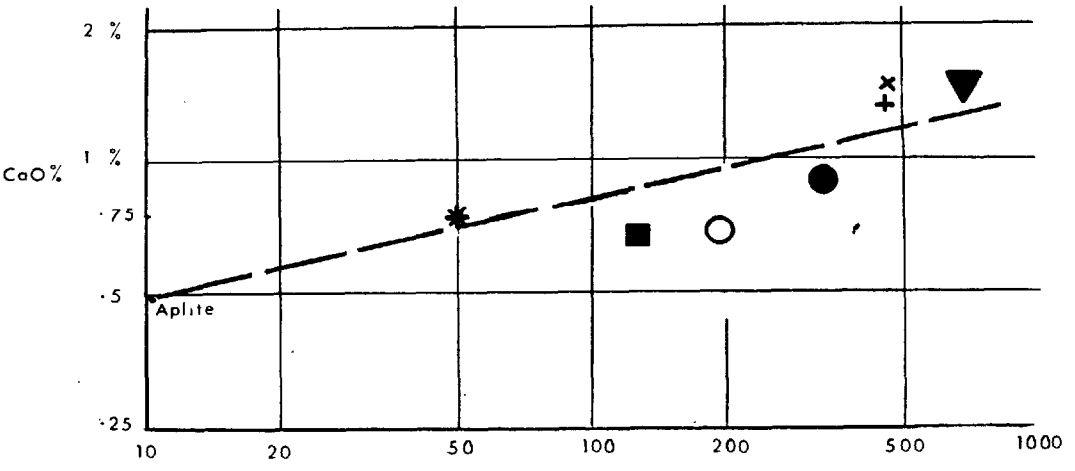
Barium and strontium occur at lower levels in the late-kinematic granites, 70 ppm. and 50 ppm. respectively, than in the synkinematic granites, 910 to 4416 ppm. and 690 ppm. respectively,

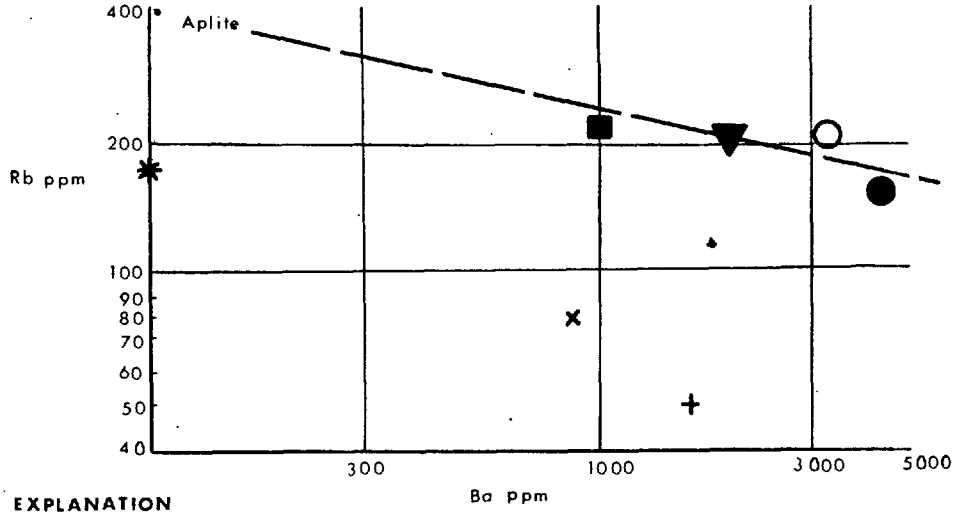
except in the aplite where only very low levels of both elements are present (fig. 29). These differences are poorly reflected in the stream sediments, and barium occurs at much higher levels in the stream sediments than in the rock in all of the granite areas except for Dandaya. At Dandaya the reverse is true and barium is impoverished in the sediments, as is the case with lead. Strontium occurs at lower levels in stream sediments than in the rock in the majority of the granite areas.

In conclusion, regional differences in the concentration of the elements lead, rubidium, titanium, vanadium and manganese in granitic rocks are reflected in the stream sediments. The present results do not prove that the same is true for chromium and nickel, but the regional distribution patterns of chromium, and particularly of nickel are well defined, and for this reason are believed to reflect their distribution in the bedrock. The distributions of cobalt, copper, barium and strontium in granites are poorly reflected in the associated stream sediments.

It is of interest that higher contents of rubidium and lead were detected in the porphyroblastic synkinematic granites, than in even grained (except at Mabendu) and gneissic granites. The late-kinematic granite characteristically contains a high level of rubidium, and a low level of lead (170 ppm. and 20 ppm. respectively).

# FIGURE 29




**EXPLANATION**

- Nunkekoro GP
- Kolmoro GP
- Mabendu GP
- Mabendu GE
- Dandaya GN
- Mokele GE
- Bumbuna LKG

## GRANITIC ROCKS

**DISTRIBUTION OF CALCIUM, RUBIDIUM, STRONTIUM AND BARIUM.**

## THE DISTRIBUTION OF POTASSIUM AND CALCIUM

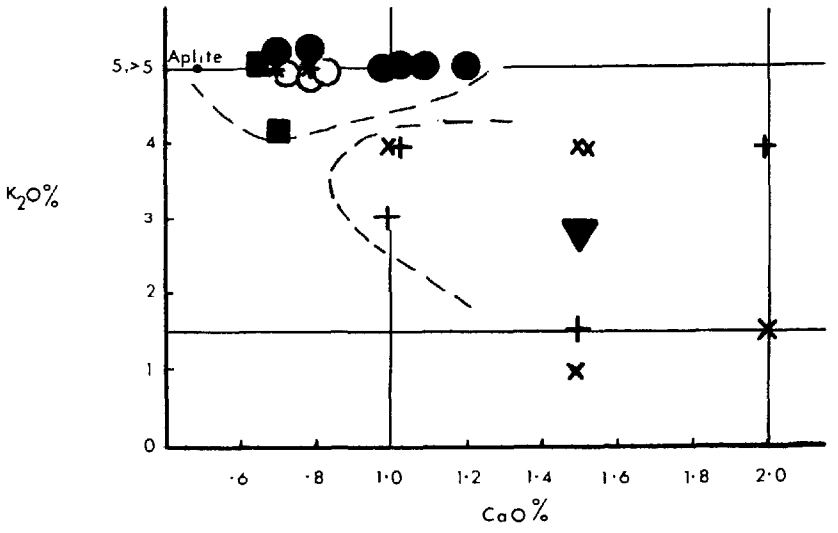
The results of the potassium and calcium analyses (reported as oxides) are shown in figure 30. The lead rich porphyroblastic and even-grained granites of the Mabendu and Nunkekoro areas are grouped with the late-kinematic granite, at concentrations of frequently more than 5 per cent $K_2O$ and less than 1.2 per cent CaO.

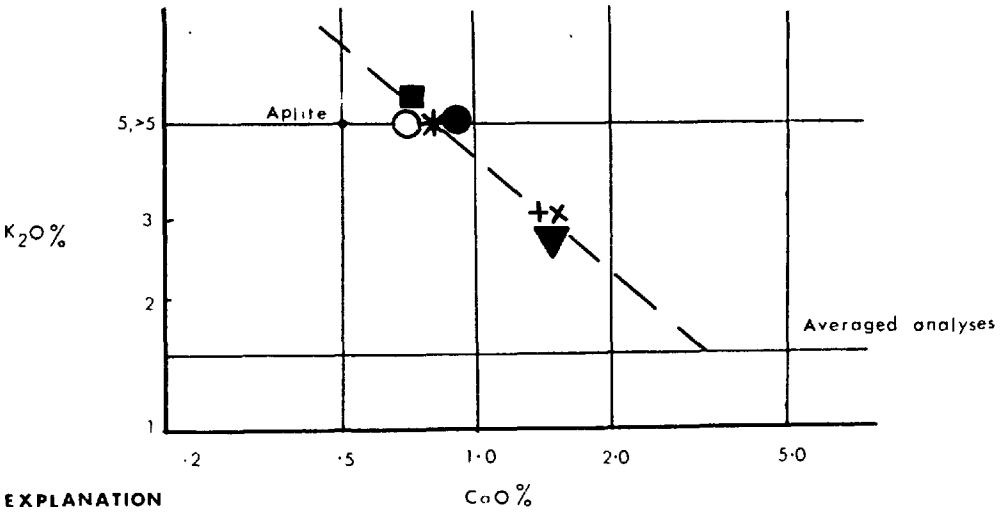
The results of the Makele and Dandaya (lead poor) samples are grouped around the Kalmoro (lead rich) sample at low levels of $K_2O$ (4 per cent or less) and slightly higher levels of CaO concentration (average 1.5 per cent). Little importance is attached to the results of the Kalmoro sample because the stream sediments in this area contain characteristically high contents of $K_2O$ and lead, and low contents of CaO. For this reason the low content of $K_2O$ and high content of CaO in the Kalmoro rock sample are not believed to be representative of the rocks in the drainage catchment.

## DISCUSSION

The influence of the geochemistry of granitic rocks upon the distribution of the geochemical patterns has been shown above (table 24), and it is clear that for many elements, regional differences in the distribution of the minor elements in the bedrock are reflected by the geochemical patterns. The secondary

**FIGURE 30**




**EXPLANATION**

- Nunkekoro GP
- Kalmoro GP
- Mabendu GP
- Mabendu GP
- Dandaya GN
- Makele GE
- Bumbunu LKG

**Distribution of $K_2O$ and CaO in Granitic rocks.**

dispersion of these elements was not investigated, but from their broadly similar concentration in the bedrock and stream sediment, the dispersion is probably mainly mechanical. From the very low contents of cobalt detected in granitic sediments, compared to the higher levels in the bedrock, it is possible that cobalt is chemically dispersed in granitic drainages.

In the following discussion, some of the analytical results are interrelated and applied to the problem of the classification of the granites and to the detection of significant anomalies of lead in granitic sediments.

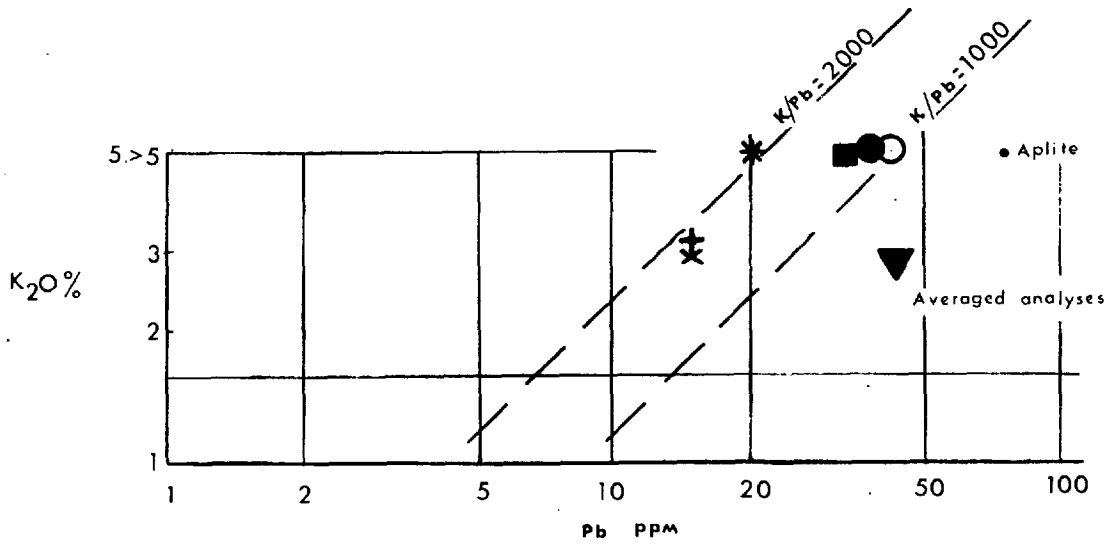
## THE RELATIONSHIP OF LEAD AND RUBIDIUM WITH POTASSIUM

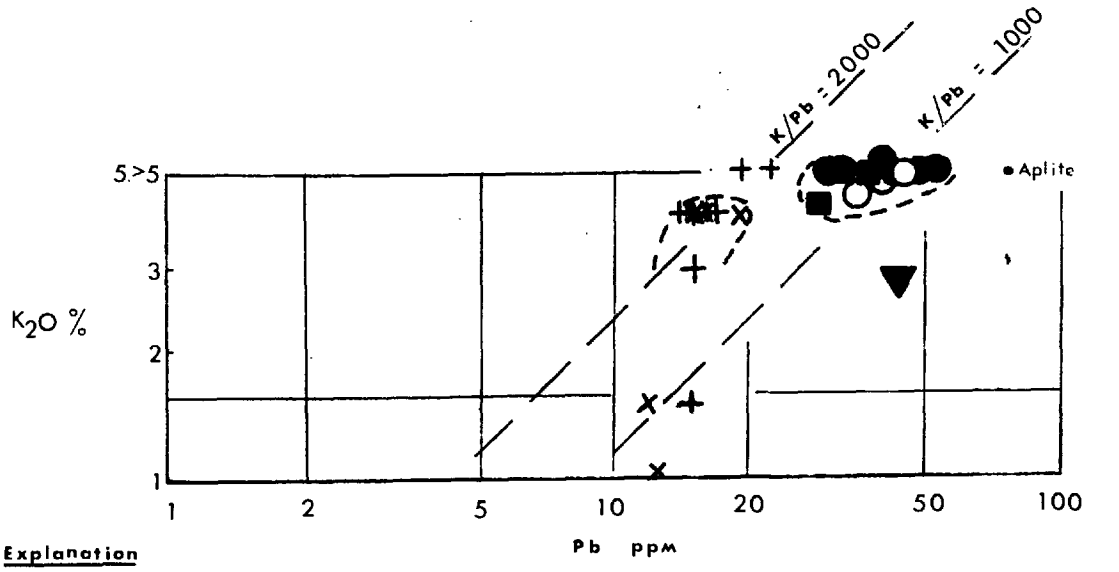
The results presented above show that synkinematic granites which contain high levels of lead and rubidium also contain high levels of $K_2O$ with low levels of CaO. The reverse is also true and lead-rubidium poor granites are rich in CaO, but poor in $K_2O$. The distribution of lead and $K_2O$ is illustrated in figure 31.

An examination of thin sections of the lead and potassium rich granites showed that they contain abundant microcline, both as porphyroblasts, and in the groundmass. The lead poor granites contain only small quantities of potash felspar.

No mineral separations were made during the course of this research, but from the generally log linear variation of potassium and lead (fig. 31), it is probable that lead is evenly distributed

# FIGURE 31




**Explanation**

- Nunkekoro GP
- Kalmoro GP
- Mabendu GP
- Mabendu GE
- Dandaya GN
- Makele GE
- Bumbunu LKG

**The distribution of $K_2O$ and lead in granitic rocks .**

Results are compared with the potassium/lead ratio.

with potassium in the granites. It follows that the lead is likely to occur mainly in the potassium rich minerals, such as microcline.

The occurrence of lead in potassium rich minerals is well known (Rankama and Sahama, 1950). Taylor and Heir (1960), in a study of the trace element variation in some alkaline felspars of Southern Norway, have shown that there is no simple relationship of lead to potassium, or any other element studied. They conclude that lead may be incorporated in plagioclase as well as in potash felspars. Nockolds and Mitchell (1948), investigating the geochemistry of the Caledonian plutonic rocks found notably higher contents of lead in potash felspars (100 ppm.) than in plagioclase felspars (10 ppm.). The average lead contents of felspars quoted by Wedepohl (1956) also show that lead is more frequently found to be concentrated in potash felspars (27 ppm.), and especially pegmatites (100 ppm.), rather than in the plagioclase felspars (10 ppm.).

It is concluded therefore, that the bulk of the lead is likely to be concentrated with potassium in the potash felspars.

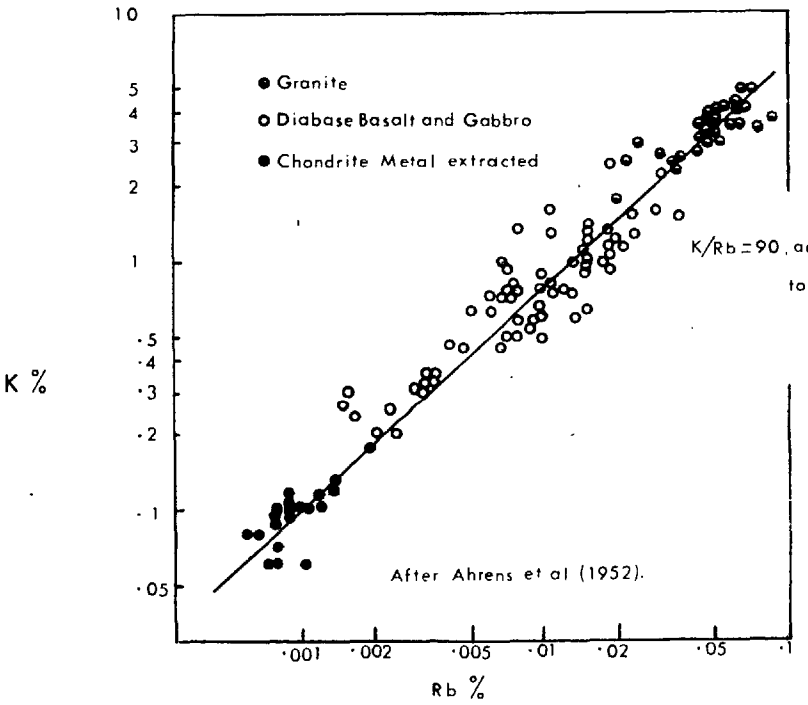
The association of rubidium and potassium in common igneous rocks and meteorites, has been studied by Ahrens, Pinson and Kearns (1952). They found that the ratio K/Rb = 90 was virtually unchanged in different rock types, and that there was no systematic

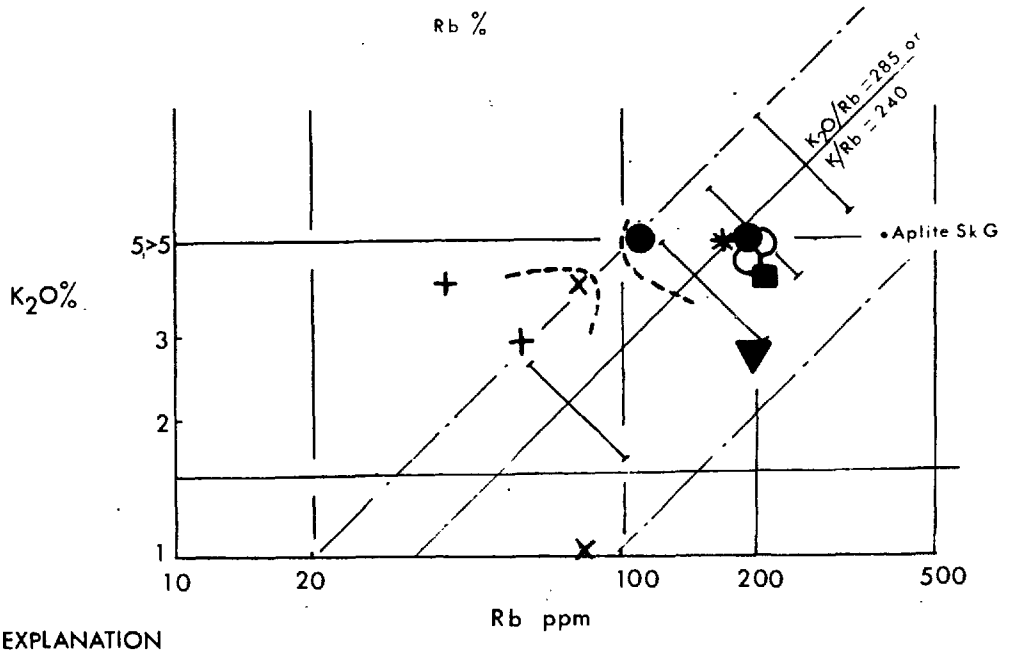
variation of the ratio in calc alkaline granites, due to different modes of origin. Taylor, Emeleus and Exley (1956) on the basis of new analytical data revised the ratio K/Rb = 90 reported by Ahrens, to K/Rb = 240. Taylor et al, reported anomalous ratios of K/Rb which were attributed to the enrichment of rubidium in extremely differentiated magmas.

Butler, Bowden and Smith (1962) investigated the distribution of potassium and rubidium in the younger granites of Northern Nigeria. They found that late stage rocks, such as albite riebeckite granites, have ratios below 30, while early stage rocks, such as calcium amphibole bearing granites, have ratios of up to 330.

The K/Rb ratio as determined from the present results is 240 (fig. 32). Most of the results fall within the limits of scatter shown by Ahrens' data, as modified by Taylor et al, but several lie outside these limits. Of the results which lie outside the limits of scatter, four could be accounted for by the analytical precision. One of the samples from the Makele area is, however, believed to be anomalous. The significance of this result was not investigated. The ratio K/Rb = 240 in the Sierra Leone samples is consistent with the data obtained by Ahrens et al (1952) as modified by Taylor et al (1956). It follows that these granites do not contain abnormally high or low quantities of rubidium with respect to potassium.

# FIGURE 32




EXPLANATION

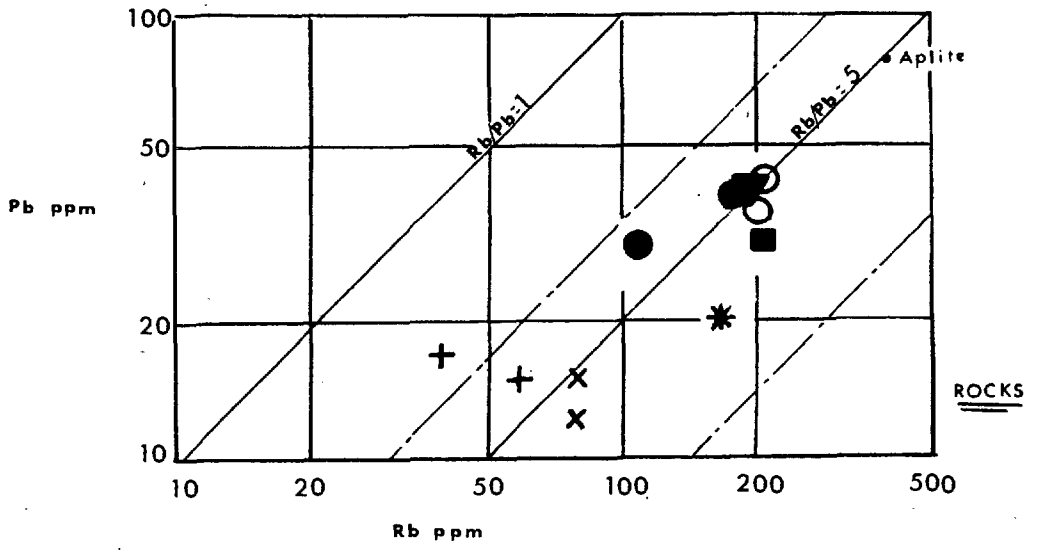
- ■ Nunkekoro
- ▼ Kalmoro
- ● Mabendu
- ○ Mabendu
- × Dandaya
- \+ Makele
- ✱ Bumbuna

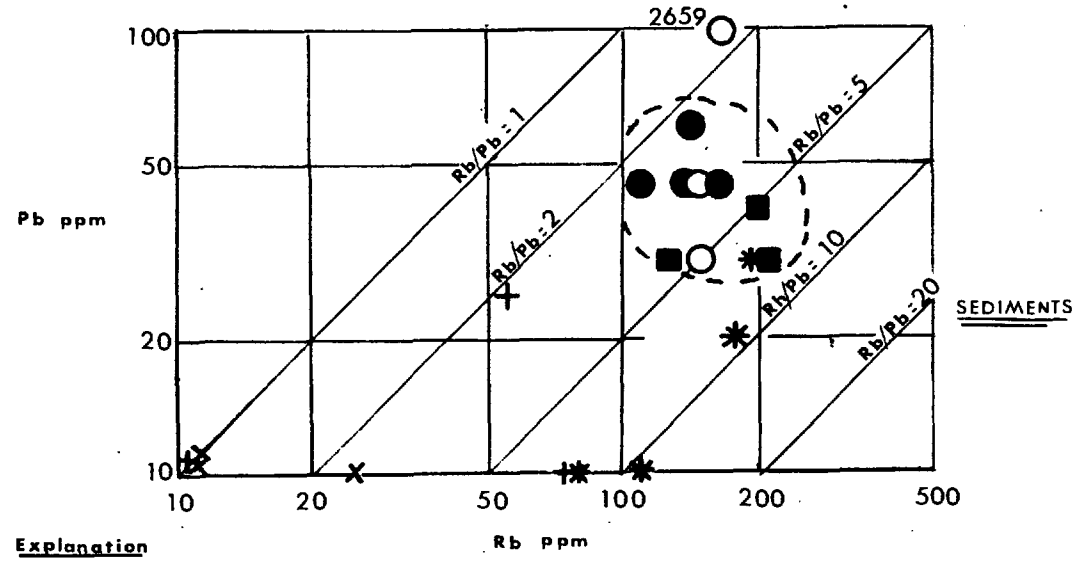
——·——·—— Limits of analytical precision $K_2O$

Limits of scatter, after Ahrens 1952

**Distibution of $K_2O$ and Rubidium in granitic rocks.**

# FIGURE 33




Explanation

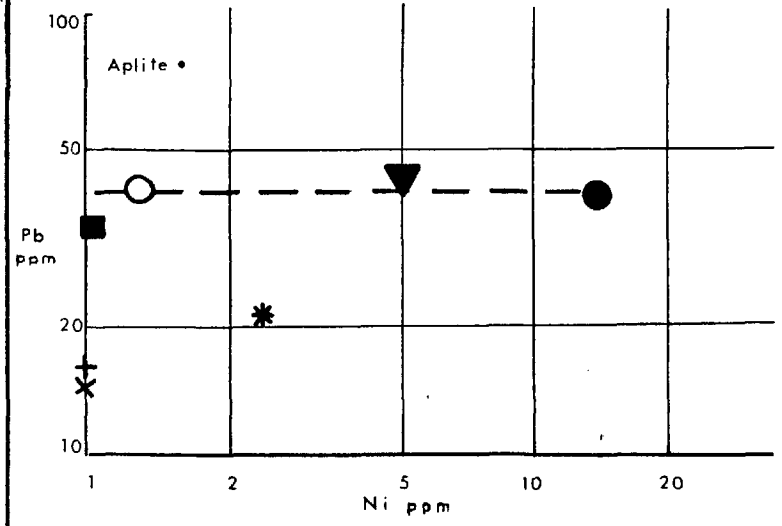
- Nunkekoro GP
- Kalmoro GP
- Mabendu GP
- Mabendu GE
- Dandaya GN
- Bumbuna KG
- limits of analytical precision
- Makele GE

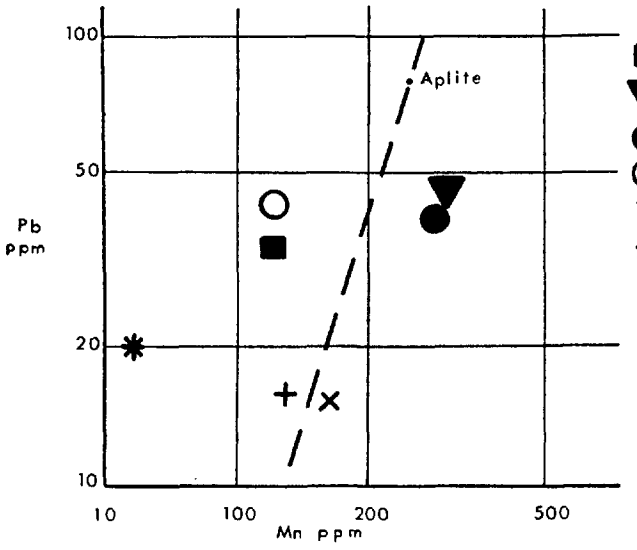
**The distribution of lead and rubidium in granitic rocks and stream sediments.**

The variation of rubidium and lead is also log linear (fig. 33), and the ratio Rb/Pb = 5 from the present results is possibly constant. It is noticeable that the ratio Rb/Pb = 5 is also applicable to the results of the synkinematic granite aplite, in which both lead and rubidium are enriched (80 ppm. and 400 ppm. respectively).

To conclude, potassium, rubidium and lead appear to be regularly distributed in the synkinematic granites. From an examination of thin sections, these elements occur at higher levels in rocks which contain large quantities of microcline felspar. It follows therefore that potassium, lead and rubidium are probably largely located in the microcline felspar. From the ratios K/Rb = 240 and Rb/Pb = 5 (figs. 32, 33), it is unlikely that either lead or rubidium is concentrated relative to potassium in the porphyroblastic granite, compared to the even-grained and gneissic granite. The rubidium and lead contents of the synkinematic granites are likely, therefore, to vary according to the proportion of potash felspar .

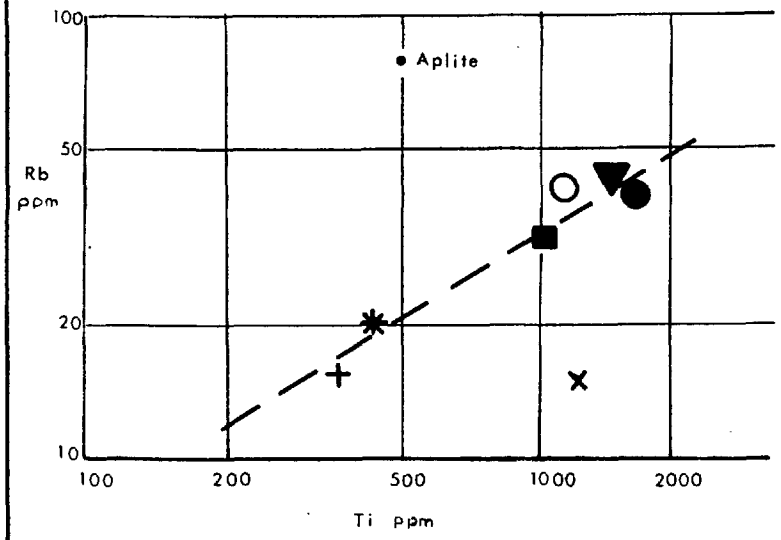
The constant distribution of lead, rubidium and potassium on a regional scale in potassium rich synkinematic granites is not shown by any other of the minor elements studied except titanium (fig. 34). For this reason it is possible that high levels of potassium, rubidium and lead, detected in some granites, have been imposed on the regionally variable geochemistry of a pre-existing rock type, as for example the gneissic synkinematic granites.










**Distribution of titanium and rubidium; and manganese and nickel related to lead in granitic rocks.**

**FIGURE 34**

## THE CLASSIFICATION OF THE GRANITES

The synkinematic and late-kinematic granites of Sierra Leone have been distinguished by a large number of both physical and petrochemical criteria. These are described in a series of publications by Marmo (1955a, b, c, d; 1956b, c; 1962b), and Wilson and Marmo (1958).

Dr. Marmo, in his most recent publication describing the granites of the Kangari Hills area (1962b), uses a chemical classification of granites first proposed by Wahl (1936). Marmo has adopted Wahl's classification to the nomenclature suggested by Eskola (1932). In this classification the late-kinematic granites have a $K_2O/CaO$ ratio of greater than 2 or even 4. The synkinematic granites have a $K_2O/CaO$ ratio of less than one.

The analytical results of the present study show that the $K_2O$ content of the lead rich synkinematic granites is frequently greater than 5 per cent. This level is similar to that of the late-kinematic granites (fig. 30).

The CaO contents of the same samples are plotted against $K_2O$ in figure 30. These results show that the lead rich porphyroblastic and even grained granites of the Mabendu and Nunkekoro areas are grouped with the late-kinematic granites. On the basis of the $K_2O$ and CaO contents of the Mabendu and Nunkekoro samples, according to Wahls' classification, these granites should be classified as late-kinematic.

Marmo (1956b), whilst discussing the emplacement of granites, has stated that potassium rich synkinematic granites are a 'separate problem'. He agrees with Eskola (1954) that such rocks are essentially granitised granodiorites in which potassium has been introduced by metasomatic processes. Evidence for this hypothesis was obtained from a petrochemical examination of the Sierra Leone porphyroblastic synkinematic granites. Marmo found that the porphyroblasts were of microcline, and that they were younger than the ground mass.

The geochemical results of the present work are taken to substantiate Marmo's conclusion. In addition, the potassium rich porphyroblastic synkinematic granites of central Sierra Leone can be identified on the basis of their lead and rubidium contents. This is in the range of 30-70 ppm. Pb and greater than 100 ppm. Rb, as compared to less than 20 ppm. Pb and less than 100 ppm. Rb in the non-metasomatised or potassium poor synkinematic granites. This observation is true for samples of both rock and stream sediment.

## THE DETECTION OF SIGNIFICANT LEAD ANOMALIES IN STREAM SEDIMENTS DERIVED FROM GRANITIC ROCKS OF THE SULA MOUNTAINS AND KANGARI HILLS AREA

Oftedahl (1954), and Slawson and Nackowski (1959) have investigated the regional variations of the lead content in the potassium felspars. Oftedahl, working on the granites of

Southern Norway found that there was no increase in the lead content of potassium felspars close to lead mineralisation. Slawson and Nackowski obtained a similar conclusion from their study of the potassium felspars in the intrusive monzonites of Nevada and Utah. However, Slawson and Nackowski's results also showed that each of the districts sampled belongs to a different lead population. They found that the potassium felspars from the lead mining districts have a higher trace lead content than those from areas where there is no lead production, or where lead production is insignificant; as below:

major lead producing areas; 29-61 ppm. Pb in potassium felspars.

minor or nil producing areas; 14-15 ppm. Pb in potassium felspars.

average lead content of potassium felspars is 27 ppm. (Wedepohl 1956).

In the Sierra Leone field area the regional enrichments of lead in granitic stream sediments are not believed to be associated with lead mineralisation. These areas were not individually prospected, and the fact that no lead mineralisation has so far been discovered does not rule out the possibility of its existence. In this connection it is important to distinguish significant from non-significant lead anomalies. From figure 31,

the scatter of the $K_2O$/Pb ratios is wide , and in stream sediments there is a larger variation, so that it is doubtful whether potassium and lead are dispersed in the same form. For these reasons the K/Pb ratio is believed to be unsuitable as an aid to the interpretation of anomalously high concentrations of lead. The ratio Rb/Pb = 5, however, appears to be constant in unmineralised granites, and in the associated stream sediments the ratio is always greater than one (fig. 33). It is reasonable to assume therefore, that an Rb/Pb ratio of less than one (or even Rb/Pb = less than two, at rubidium concentrations of greater than 100 ppm.), will indicate an abnormally high content of lead.

## OTHER FACTORS AFFECTING THE DEVELOPMENT OF THE GEOCHEMICAL PATTERNS

### Pedology

The various types of soil which occur in the field area have been described in the introduction (see page 18) and attention has been drawn to the presence of large areas of duricrust which cover parts of the schist belt to the north of the Pampana river. The margin of the duricrust is drawn on the geological maps of the Sula Mountains (in Part 2). In the area of basic rocks to the south-east of Bumbuna, monadnocks rise out of the duricrust at the 2000 feet elevation to attain heights of slightly less than

3000 feet. Monadnocks are, however, not present in the duricrust covered area of basic and ultrabasic rocks to the west of Basaia.

In areas other than those covered by duricrust, the soils developed on ferruginous rocks are normally indurated latosols. Residual profiles are often deeply truncated and covered by colluvium. The soils over siliceous rocks, particularly the granites, are generally thin and sandy, and ferruginous concretions are scarce.

In view of the varying nature of the soils it is most probable that their distribution will have an effect upon the development of the geochemical patterns in the stream sediments. This feature was investigated by studying the minor element distribution in soil profiles associated with the different rocks.

In the following account of the minor element distribution in the different soil types, the analytical results were obtained on the minus 80-mesh fraction of dry sieved sample. This fraction was found to be the most suitable for the analysis of the stream sediment samples (see below).

## Iron poor latosols

The iron poor latosols were only studied on granitic bedrocks. As noted previously, the granites show regional variations in the distribution of several of the minor elements, particularly lead, titanium, vanadium, manganese, and nickel (page 63). Soil

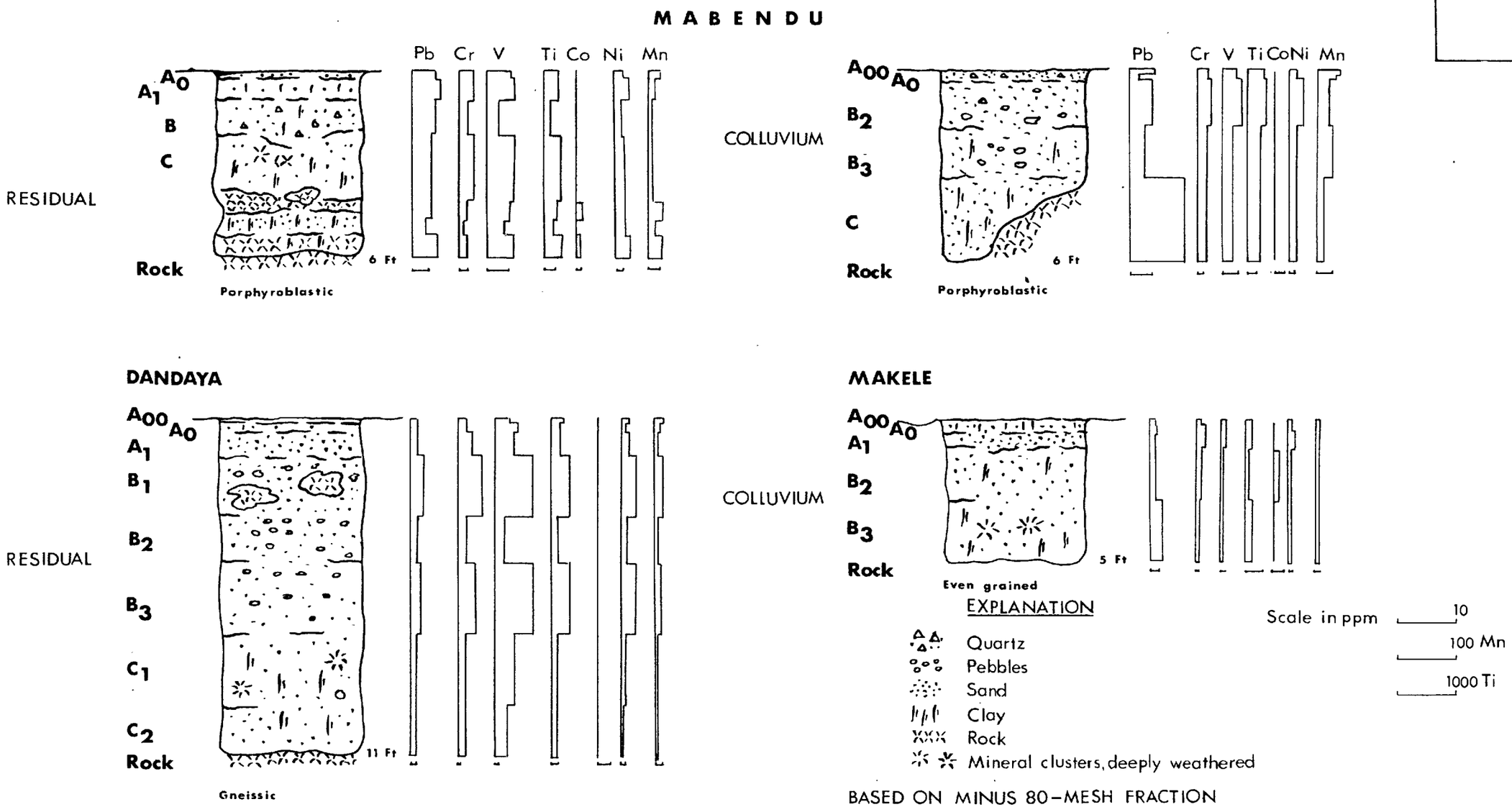
profiles were examined in areas which displayed the most strongly contrasting geochemical patterns.

The distribution of the elements Ti, V, Cr, Mn, Co, Ni, and Pb within the soil profiles of residual and colluvial soils over different types of granite, is presented in figure 35.

The analytical results show that in the profiles examined, the minor element content of the residual and colluvial soils is generally similar to that of the underlying rocks. Notable exceptions are the relative concentration of vanadium in residual soils over gneissic granite and the slight accumulation of lead in residual soils over porphyroblastic granites. Cobalt is impoverished in soils relative to the bedrock, and is seldom detected in the soils, whereas in rocks the cobalt content ranges between 3 and 47 ppm. with a mean content of 26 ppm.

In each of the soil profiles studied the minor elements show a variable distribution which can be correlated with the different soil horizons. The outstanding feature of the residual soil profiles examined, however, is a zone of relative impoverishment of the metals in the B horizon. This impoverishment extends through the entire B horizon in the porphyroblastic granite, but is restricted to the $B_2$ zone of the gneissic granite profile. In the latter case, the $B_1$ and $B_3$ zones display the normal concentration associated with the B horizon. Both of the residual soil profiles which display an impoverishment of the minor

**FIGURE 35**




**Distribution of minor elements in soils overlying synkinematic granites.**

elements in the B horizon are located within 100 yards of stream beds, and it is possible that the present distribution of the elements has resulted from varying levels of the water table.

In the residual soil profile on porphyroblastic granite there is an unusual distribution of the minor elements. Near the base of the profile, relatively high contents coincide with a thin (exfoliated) raft of granite, and low contents with a thin horizon of pallid sandy clay, which separates the granite raft from the bedrock.

It is of interest that lead, which is often accumulated by vegetable material, particularly some types of grass, in the surface soils near mineralisation in tropical and temperate areas (Webb, Millman 1951; Webb 1958; Ledward 1960) is not so concentrated in the Sierra Leone field area. This may be due to either the mineral form in which the lead is held and poor availability to vegetation, or to the weak accumulative characteristics of the vegetation and of the humus in the soils of the area. These possibiliies were not investigated.

It is concluded that the distribution of the minor elements in the minus 80-mesh fraction of the samples from the A horizon of granitic soils shows no consistent accumulation or impoverishment of the elements, except for cobalt which is normally depleted relative to the content of the bedrock, and so gives a fair indication of the minor element content of the bedrock. Since

the stream sediments are likely to be largely derived from the surface soils by the erosive effects of sheet wash, soil creep, etc., it follows that the stream sediment patterns are likely to reflect the concentrations of the minor elements in the bedrock.

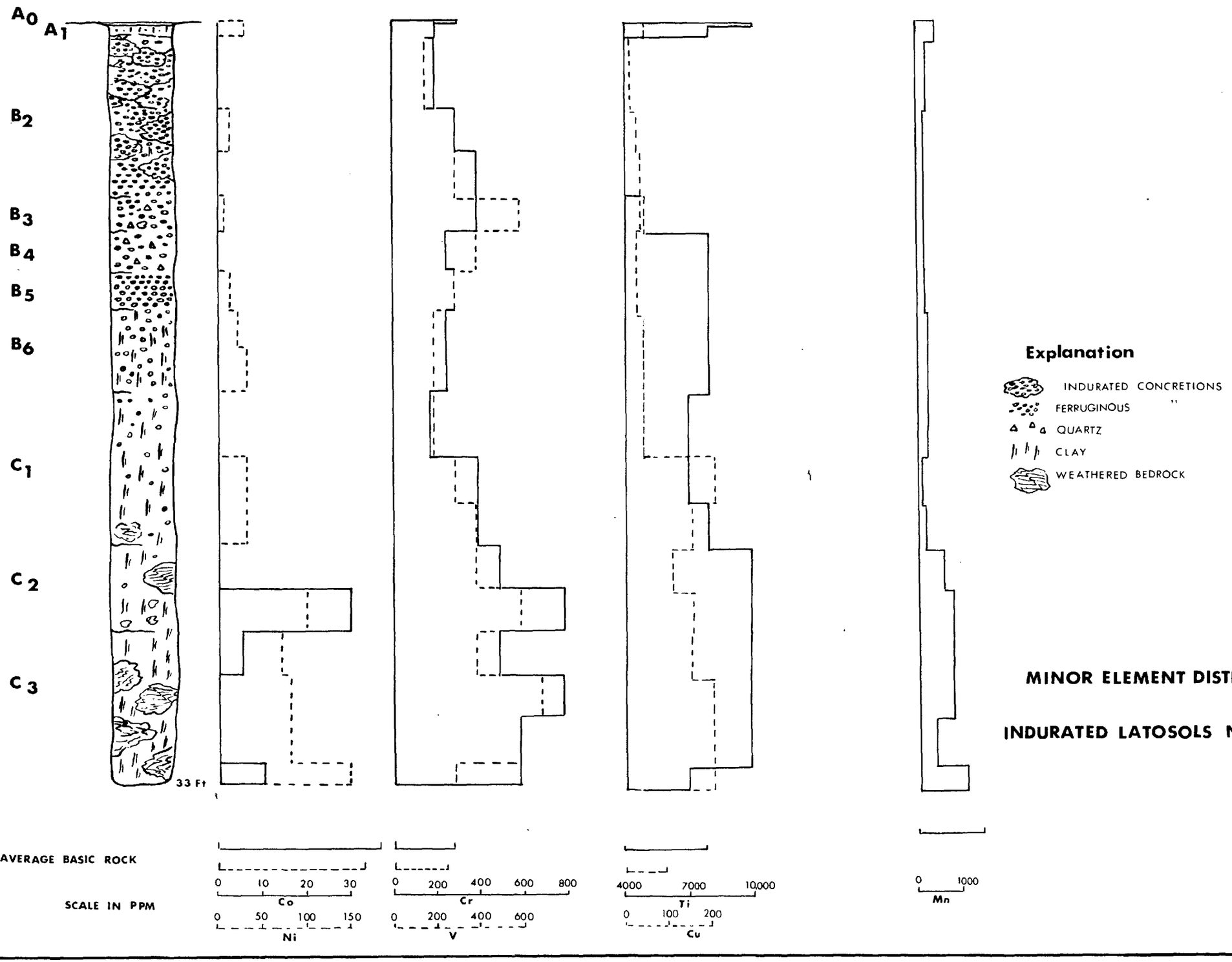
## Indurated latosols and duricrust

To investigate the minor element distribution in a duricrust profile, a pit was sunk into the duricrust on the basic rocks to the south-east of Bumbuna (map ref. I4). The pit was discontinued at a depth of 35 feet from surface after entering a deeply weathered rock whose texture resembled amphibolite.

The analytical results are plotted as a vertical profile (fig. 36), and are compared with the average minor element content of the basic rocks from the Bumbuna field area, the latter being chromium-manganese rich compared to the rocks of the Makele and Basaia areas.

The distribution of the minor elements in the vertical profile show a wide variation of content between the different horizons. In general, the highest contents occur in the $C_3$ and $C_2$ zones of the C soil horizon which contain numerous fragments of the weathered bedrock. Above the $C_3$ and $C_2$ zones the contents for most of the elements are gradually depleted towards the surface, except for chromium and vanadium which display a concentration in the $B_3$ zone relative to the $C_1$ zone.

**FIGURE 36**




**MINOR ELEMENT DISTRIBUTION IN**

**INDURATED LATOSOLS NEAR BUMBUNA .**

Some of the elements, notably titanium, vanadium, chromium and copper, occur at higher concentrations in the $C_3$ zone than in the average bedrock. All of the elements studied occur at lower concentrations in the $C_1$ zone than in the rock. These differences may not be significant, however, because of possible discrepancy between the minor element composition of the fresh bedrock below the pit, and the average value of the basic rocks, with which the profile is compared.

In the B horizon the distribution of the minor elements is somewhat irregular, but all of the elements studied occur at very low levels of concentration in the upper parts of the $B_2$ zone of massive and indurated ferruginous concretions. In the lower part of the $B_2$ zone, the vanadium and chromium contents gradually increase in depth until they reach a peak in the $B_3$ zone. Below this level they are progressively impoverished as far down as the $C_1$ zone. The distribution of titanium in the B soil horizon is different to that of vanadium and chromium, for the highest contents of titanium in the B horizon occur from the $B_4$ to the $B_6$ zones, and only very low contents occur in the $B_3$ zone in which vanadium and chromium are concentrated.

Titanium, manganese, cobalt, nickel and copper all show a progressive depletion towards surface when compared to the levels in the $C_3$ zone. This depletion of the minor elements is most marked for cobalt, which is undetected in the A soil horizon.

The elements titanium, manganese, nickel and copper are more concentrated in the upper six inches of the A soil horizon than in the $B_2$ zone, but the concentrations detected are very low compared to the $C_3$ zone and the average basic rock of the area. In the $A_o$ zone only titanium, and chromium occur at levels higher than, or equivalent to, the average basic rocks.

## Colluvial and truncated latosols

From the differential distribution of the minor elements within a profile on a residual indurated latosol (fig. 36), it is likely that varying depths of truncation in residual latosols will affect the distribution of the geochemical patterns in the associated sediments. This effect could be important if there are strong regional differences in the depth of truncation.

The extent to which this factor might explain regional differences in the geochemical patterns was investigated by analysing samples of colluvial latosols collected from each of the basic and ultrabasic study areas at Bumbuna, Basaia, Makele; and Basaia, Makele and Makong, respectively. In the Bumbuna area of basic rocks, and Basaia areas of basic and ultrabasic rocks, the colluvium is largely derived from the residual indurated latosols and the duricrust. In contrast, the basic and ultrabasic rocks of the Makele area, and the ultrabasic rocks of the Makong area, are largely covered by/thin colluvial latosols and only small areas

of residual latosols remain. In all of these areas the colluvial latosols frequently include fragments of fresh rock. In the Bumbuna and Basaia areas it was possible to divide the soils into two groups according to the presence or absence of weathered rock in the overburden.

The analytical results of the soils were averaged arithmetically for the purpose of comparison with the minor element contents of the bedrock and the geochemical patterns obtained from the stream sediments (figs. 37, 37a, 38 and 38a).

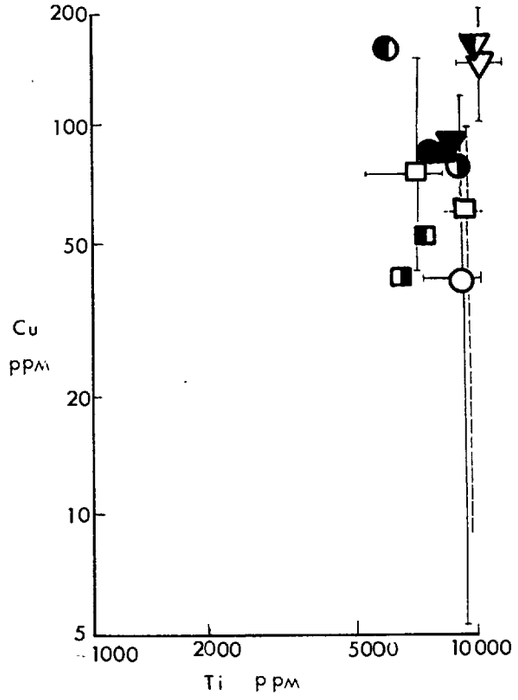
AREAS OF BASIC ROCKS

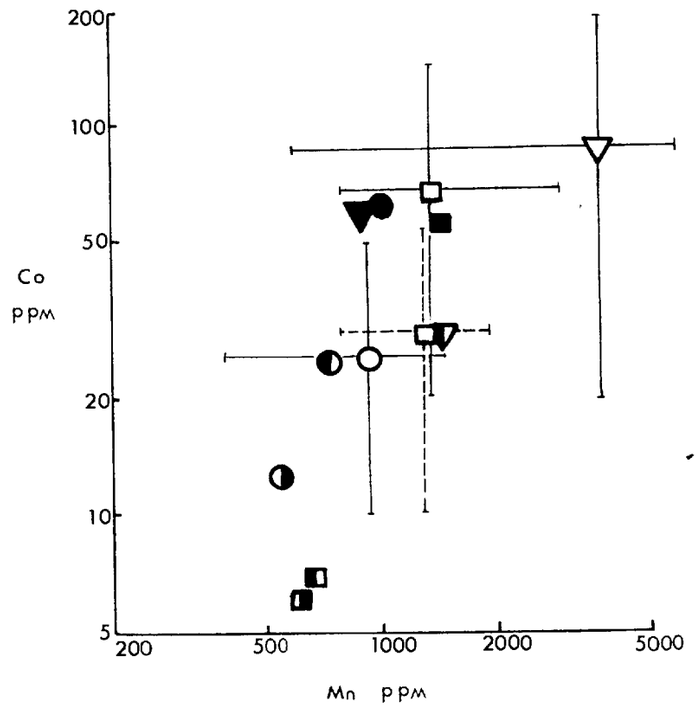
The distributions of the minor elements in soils overlying the basic rocks conform to some broadly similar trends.

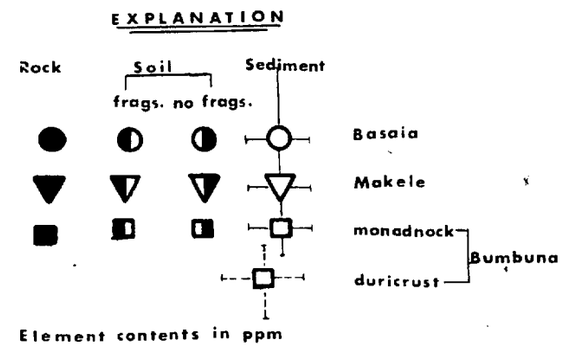
In general, the average contents of the elements cobalt, nickel and manganese in the soils are low compared to those of the rocks. The distributions of titanium, vanadium, chromium and copper are different according to the soil type in the various study areas. It is interesting to note that the soils from the Bumbuna area, and not the Basaia area, as might be expected from the stream sediment patterns (SECTION 3), show the lowest concentration for all of the minor elements except chromium.

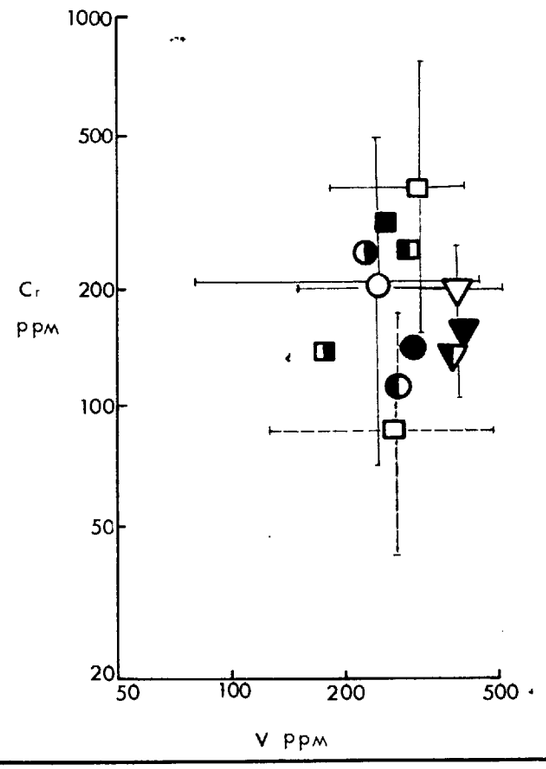
The average titanium contents of the soils are remarkably similar to the average level of titanium in the rock samples. The range of the titanium content in the soils varies between

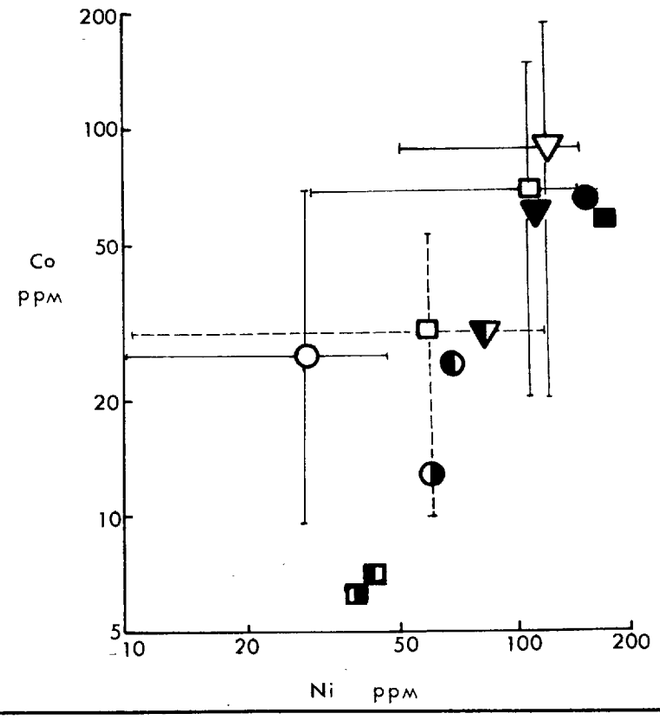
**FIGURE 37**



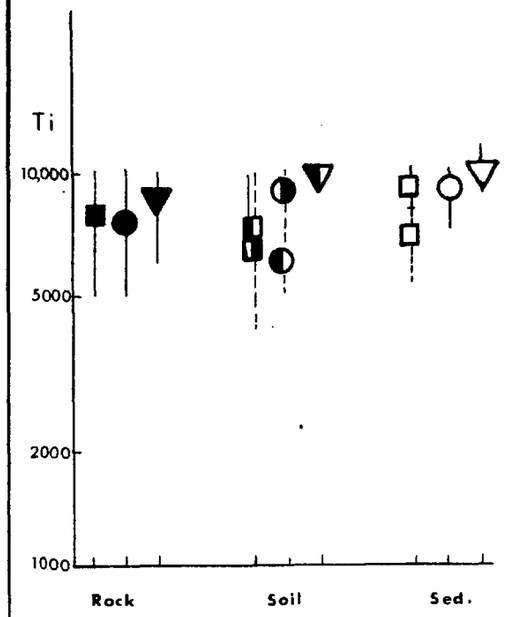



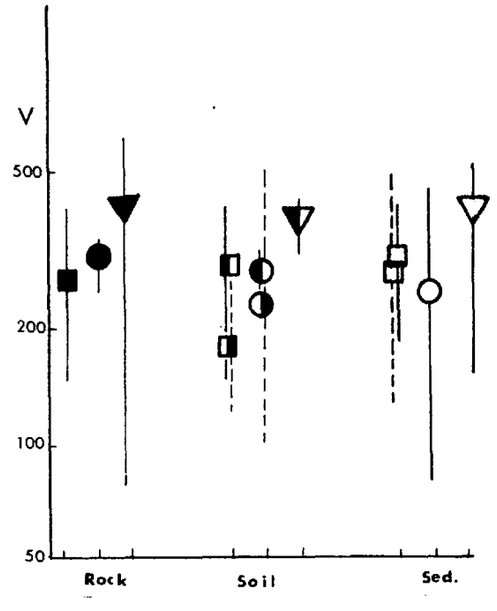



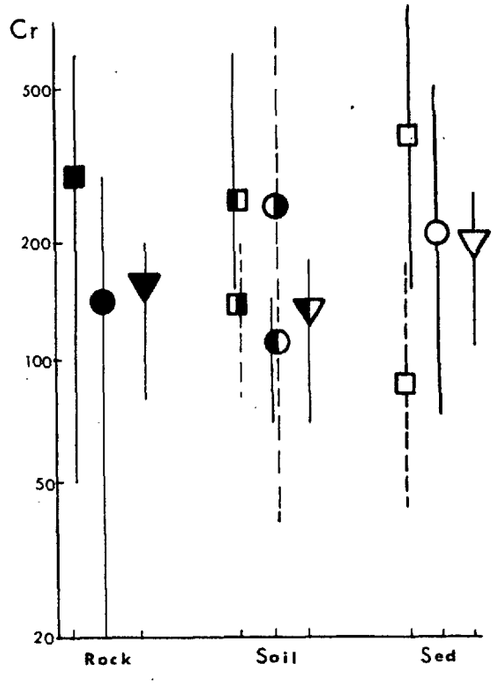

**DISTRIBUTION OF MINOR ELEMENTS**

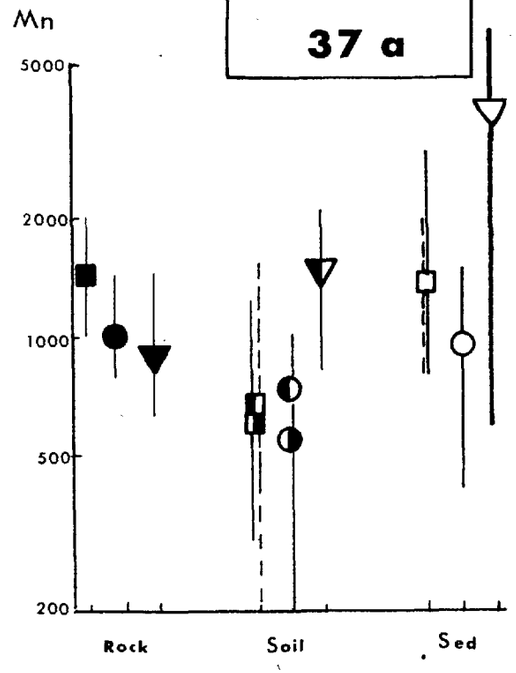
**IN AREAS OF BASIC ROCKS.**

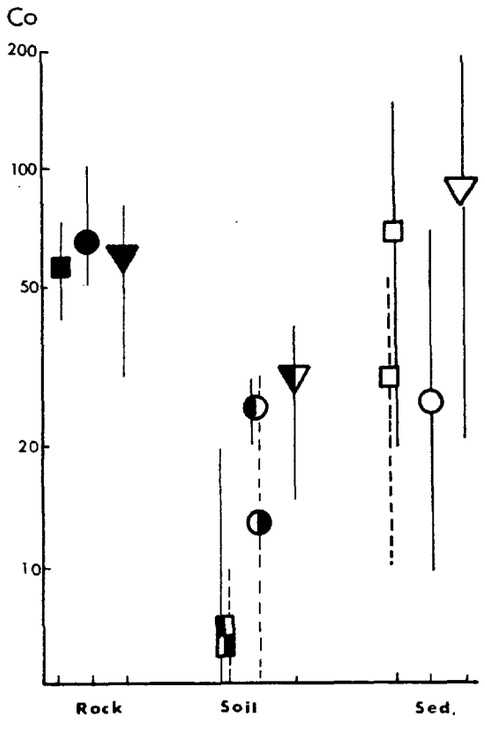
**FIGURE 37 a**

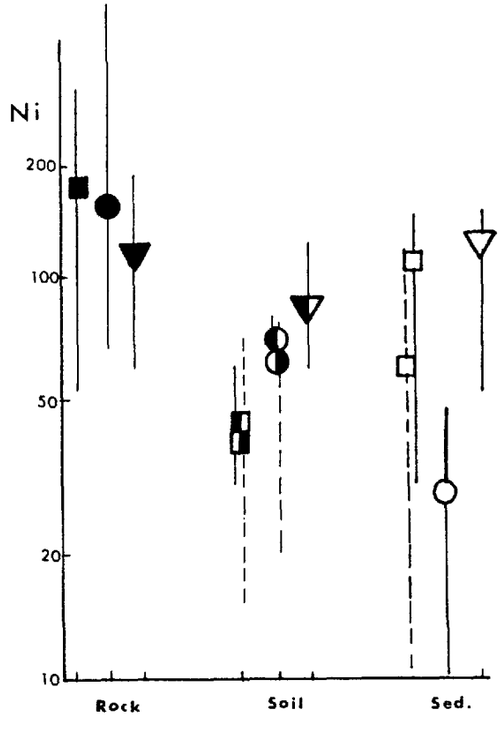


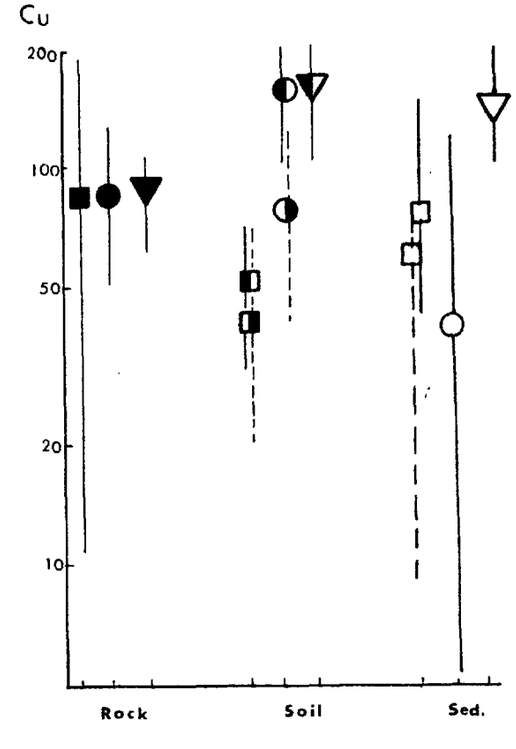




EXPLANATION

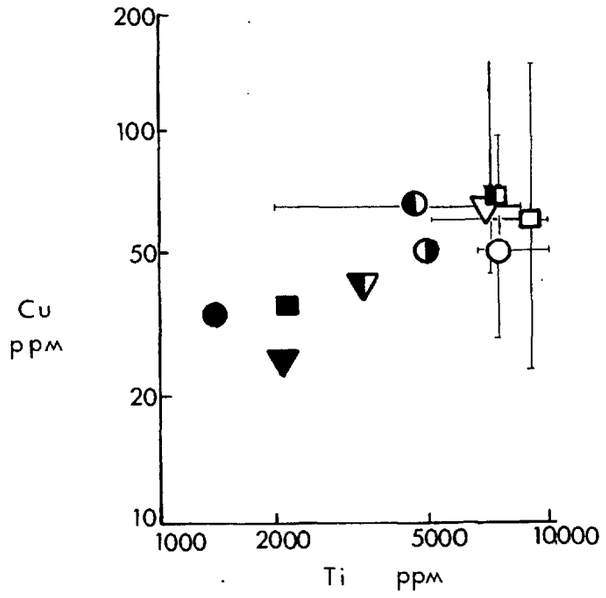
| ROCK NS | SOIL frags NS | SOIL no frags NS | SEDIMENT NS | |
|---|---|---|---|---|
| 5 | 2 | 7 | 12 | Basala |
| 5 | 5 | | 10 | Makele |
| 6 | 7 | 5 | 9 | monadnock |
| | | | 6 | duricrust |

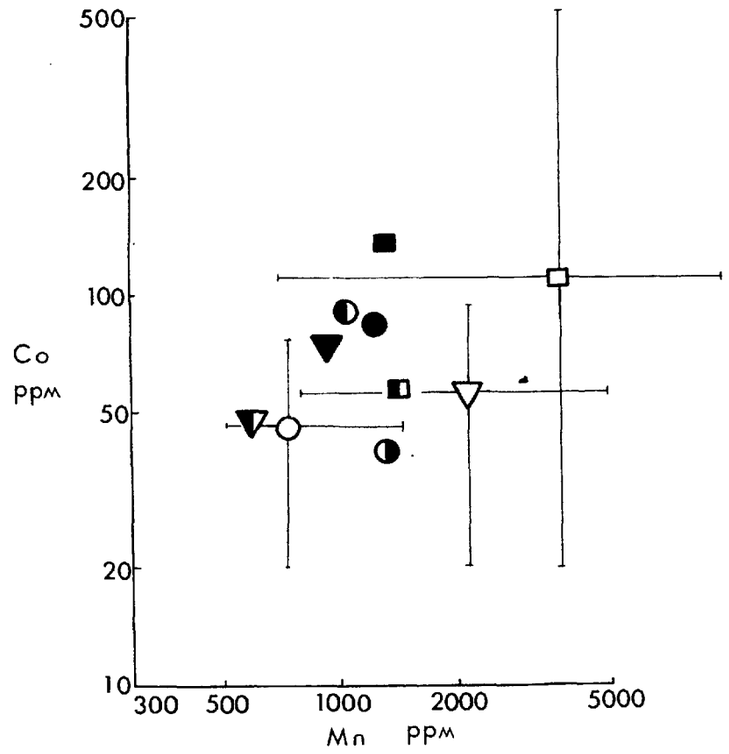
(Basala)

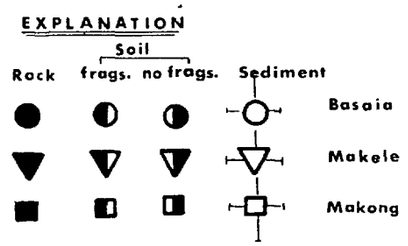
**Distribution of minor elements in areas of basic rocks.**

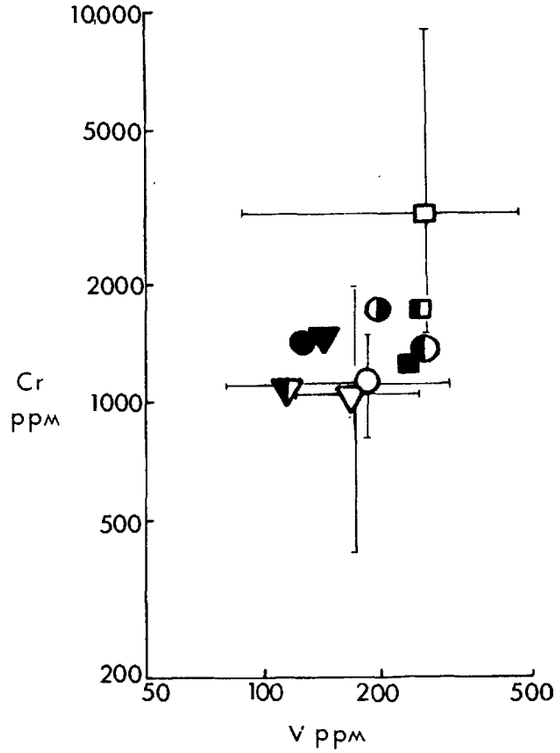
Element content in ppm.

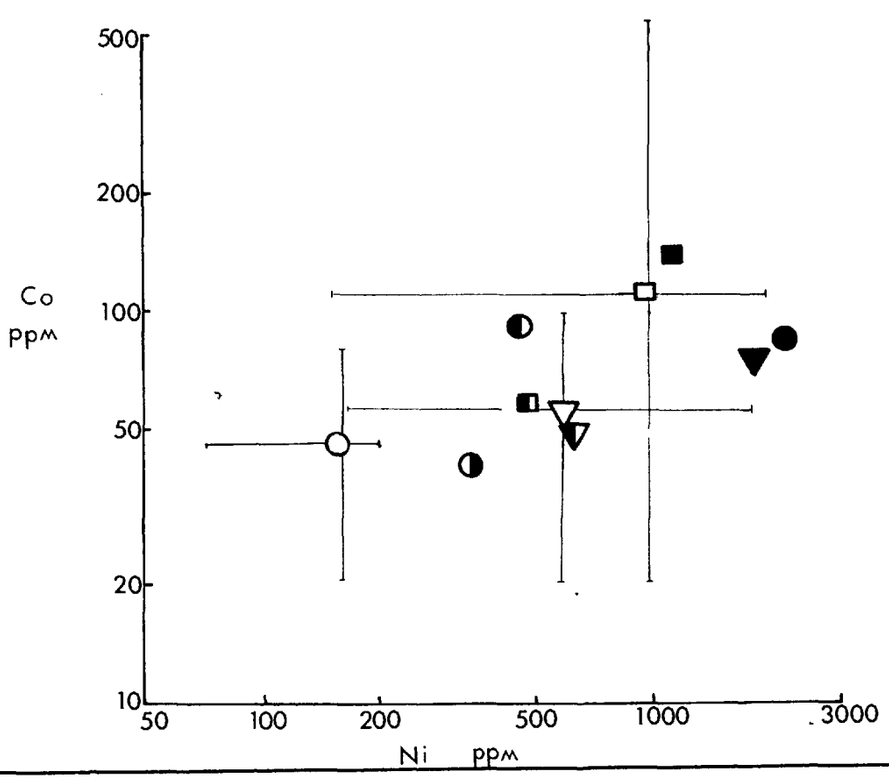
**FIGURE 38**



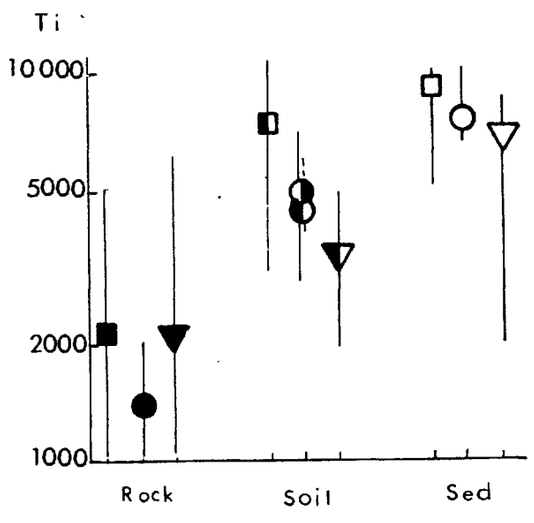



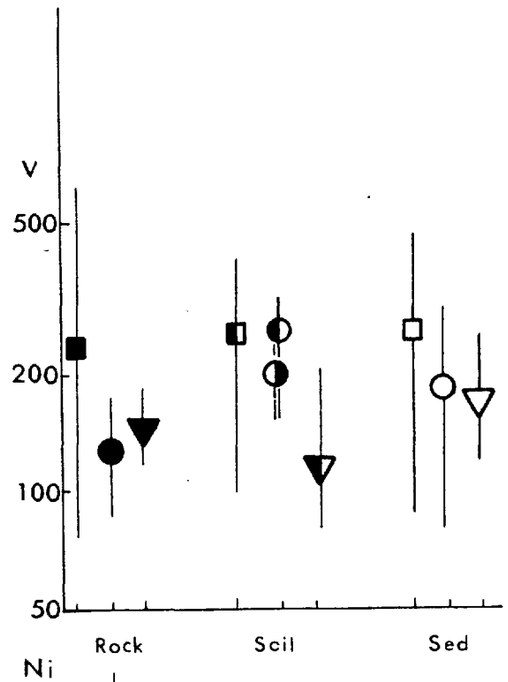



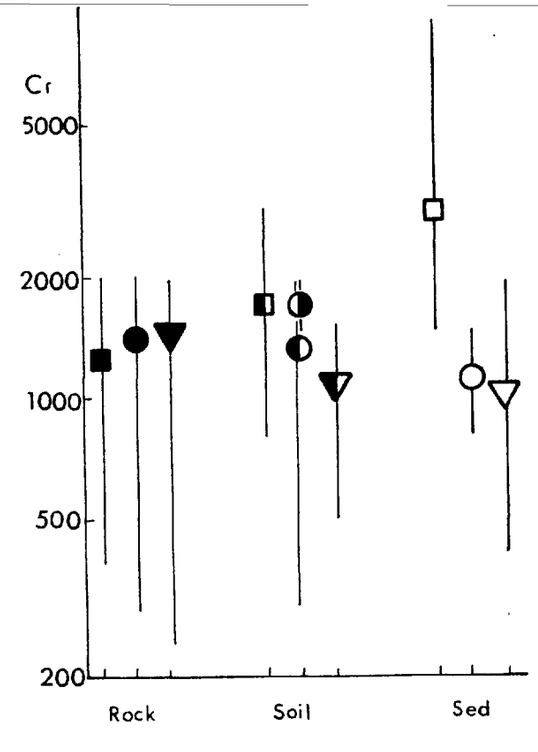



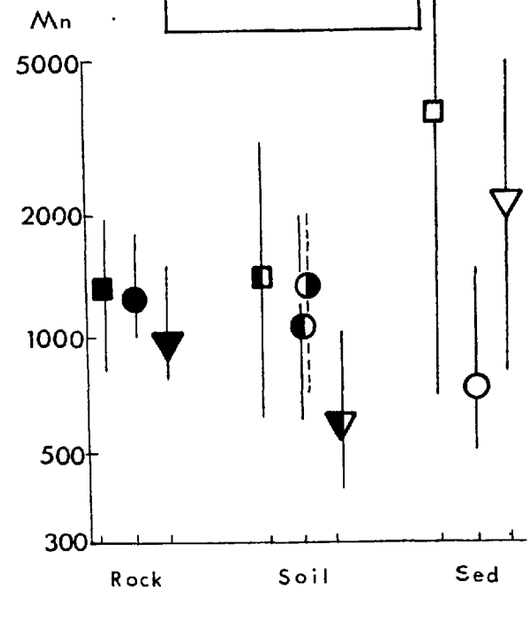

**DISTRIBUTION OF MINOR ELEMENTS IN AREAS OF ULTRABASIC ROCKS .**

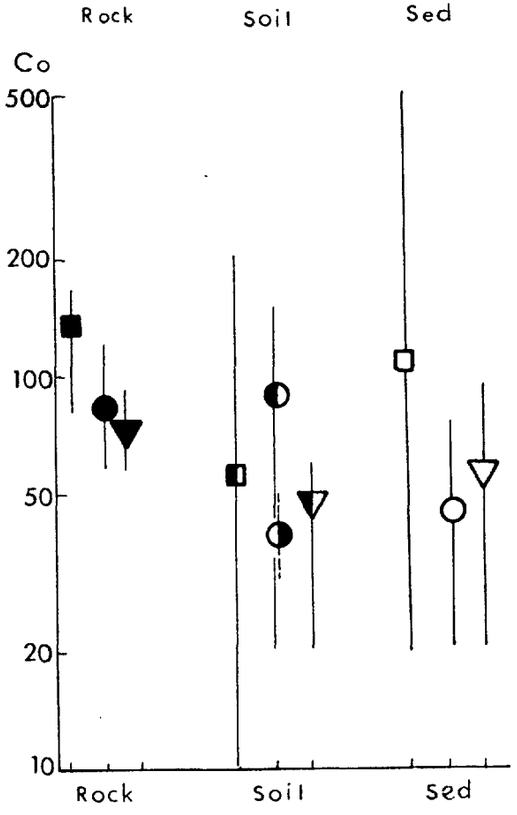
**FIGURE 38 a**

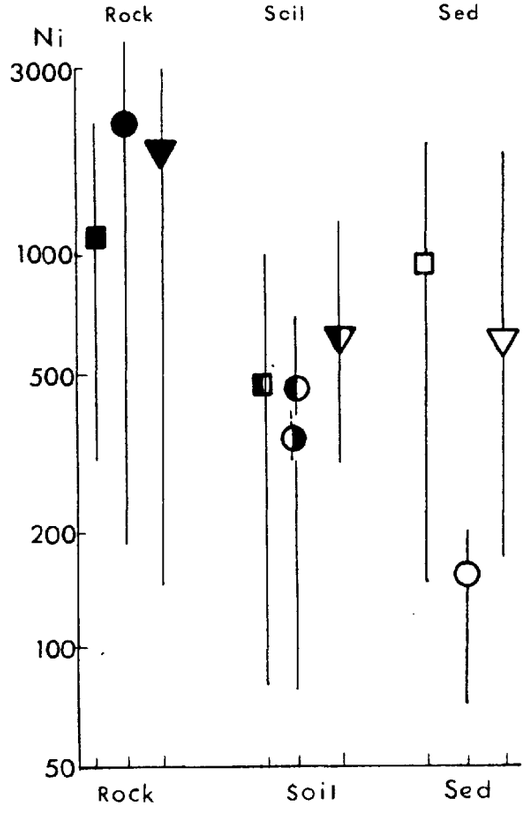


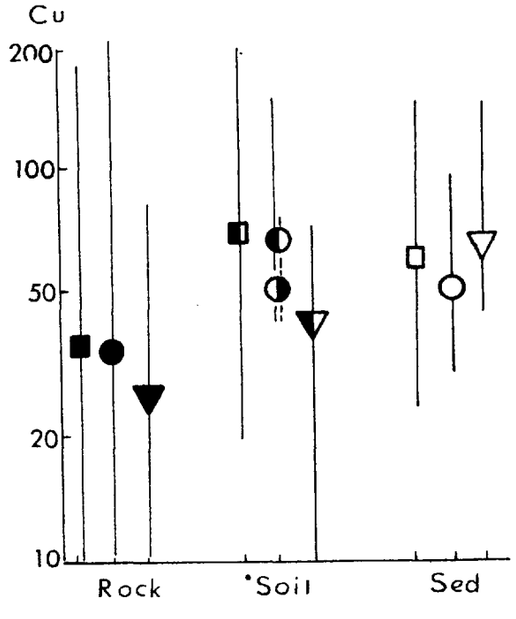



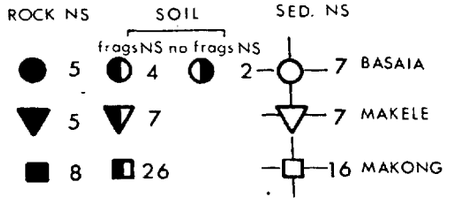




EXPLANATION




**Distribution of minor elements in areas of ultrabasic rocks.**

Element content in ppm

6000 ppm. and 10,000 ppm., compared to an average of >8000 ppm. in the rocks. The vanadium and chromium contents of the soils also show only small variations in concentration compared to the bedrock. The manganese content of 1500 ppm. in the soils of the Makele area is high compared to the average value of 980 ppm. in the rocks. In contrast, the manganese contents of the soils in the Basaia and Bumbuna areas are low, 550 and 600 ppm. respectively, compared to the average content in the rocks of these areas, 1020 and 1500 ppm. respectively.

Cobalt and nickel both occur at much lower concentrations in the soils than in the rocks. For cobalt, the concentration range in the soils is between 6 and 30 ppm., compared to 60 and 65 ppm. in the rocks, while in the case of nickel the range is from 40 to 85 ppm. in the soils compared to 115 to 170 ppm. in the rocks.

Considering the soils as two separate groups, in which soils with rock fragments are compared to those without rock fragments, the group with rock fragments normally contains higher levels of the minor elements, than the group without rock fragments. There are exceptions however. For example, the chromium content of the Basaia soils devoid of rock fragments is high at 240 ppm., compared to the soils with rock fragments at 110 ppm., and the average rock content of 140 ppm.

Copper also shows a variable distribution and occurs at higher levels in the latosols with rock fragments, 160 ppm., than in the average rock of the Basaia and Makele areas, 85 ppm. In contrast, the Bumbuna soils contain a lower content of copper than the associated rocks; the soils without rock fragments containing an average of 40 ppm., compared to 50 ppm. in soils with rock fragments, and 85 ppm. in the average rock.

AREAS OF ULTRABASIC ROCKS

The minor element distribution in soils derived from ultrabasic rocks is slightly different to that in the soils of the basic rocks, and reflects the differing concentrations of the elements between the two major rock types. The most significant difference is the much higher content of chromium and nickel in the soils associated with ultrabasic rocks.

From a comparison of the average minor element content, of the ultrabasic rocks with the associated soils, it is evident that both titanium and copper are relatively accumulated in the soils compared to the rocks in all of the study areas. In contrast, cobalt, and especially nickel, normally occur at lower levels in the soils than in the rocks. Cobalt and nickel, however, are more impoverished in soils without rock fragments than in soils with rock fragments.

The other elements studied display certain regional variations of concentration in the soils which cannot always be correlated

with the presence or absence of rock fragments in the soils. Thus in the Makele area, w ere the latosols frequently contain fragments of weathered rock, the average vanadium, chromium, and manganese contents of the soils are low compared to the rock. In the Makong area, however, the vanadium, chromium and manganese contents of the soils, which are thin and contain rock fragments, are slightly higher than in the rocks. The distribution of these elements in the soils of the Basaia area is unusual, because the chromium and manganese contents of the soils with rock fragments is slightly low compared to the soils without rocks fragments.

It is of special interest to note that in the Makele area, of basic and ultrabasic rocks, manganese is accumulated in the basic soils, but impoverished in the ultrabasic soils.

## Discussion

The observed variations in the distribution of the minor elements in residual and colluvial soils are based on the analyses of the minus 80-mesh dry sieved fraction, which may not be representative of the soil. For instance, the B horizon of latosols frequently contains a large proportion of ferruginous concretions in sizes which range between about 0.5 mm. to 5 mm., and this material would be excluded from the minus 80-mesh fraction. It follows, therefore, that because of this feature only tentative conclusions can be drawn from the present results.

From the distribution of the minor elements in the soils compared to the rocks, it is clear that some elements occur at higher levels in certain types of soils than in others. If the different soil types show contrasting regional distributions, then regional variations in the concentration levels of the stream sediment patterns are to be expected.

## DISTRIBUTION OF MINOR ELEMENTS IN IRON RICH LATOSOLS

### GENERAL

The distribution of the minor elements in the soil profile over amphibolite bedrock near Bumbuna, shows that there is little correlation between the elements Ti, Cu, Mn, Co, and Ni with the visually estimated abundance of iron (as ferruginous concretions), which is largely concentrated in the B horizon. All of the elements studied occur at very low concentrations in the $B_2$ (iron rich) zone of fused and massive ferruginous concretions, but in the $B_3$ zone of pisolitic ferruginous concretions, the vanadium and chromium contents are the same as in the average basic rocks. The titanium content of the $B_3$ zone is low and only increases to a level similar to that in the average basic rock in the $B_4$ zone.

These results are somewhat similar to those obtained by Simpson (1916) who found that the concretions in the laterites of Western Australia contained from nil to 5.3 per cent $Cr_2O_3$, and

between 0.1 and 0.65 per cent vanadium. Oertel and Prescott (1944), from the results of spectrochemical analyses of boiling hydrochloric acid leachates of other ironstone gravels in Western Australia, suggested that the elements Mn, Co, Ni, Cu are not concentrated with iron, whilst Ga, Mo, Pb, V and Zn are concentrated with iron.

The concentration of vanadium and chromium at different levels in the soil profile, notably in the $B_3$ and $C_3$ zones, might be explained by a physical accumulation of insoluble minerals containing these elements, accompanied by an accumulation of the soluble metals in the $C_3$ zone. The accumulation of vanadium and chromium in the B horizon compared to the $C_1$ zone, could be explained by the migration of these elements in a soluble form and their subsequent precipitation with iron in the $B_3$ zone.

The physical accumulation of resistant minerals in lateritic soils was noted by Clarke (1911) and has been used by du Bois and Jeffery (1955) as an aid to mapping a variety of rock types in the Entebbe Peninsular, Uganda. Here, the bedrock is mainly obscured by thick residual latosols.

A presumably chemical accumulation of chromium and vanadium in a latosol has been illustrated by Hawkes and Webb (1962), and is based on the analysis of the minus 80-mesh sample fraction (data from J.S. Tooms, and J.D. Kerbyson of the G.P.R.C.). The elements vanadium, chromium, manganese and copper are strongly concentrated towards the top of the B soil horizon where ferruginous nodules

are most frequent. Cobalt and nickel showed little change in distribution throughout the latosol profile.

The factors which control the essentially chemical weathering of aluminous latosols or bauxites were investigated by Gordon and Murata (1952). They found that in the Arkansas bauxites all of the elements studied, except copper, were concentrated or depleted according to the now classical theory developed by Goldschmidt (1937). Goldschmidt adapted the concept of the 'ionic potential' of the elements (Cartledge 1928, 1930) to geochemistry, and showed that the distribution of the elements in the zone of weathering was largely a function of the charge and ionic radius of an element.

The copper contents of the bauxites were found to occur at much higher concentrations than were expected. Gordon and Marata could not account for this enrichment of copper. As noted previously, in the Sierra Leone area copper is concentrated in the soils associated with basic and ultrabasic rocks, except in the Bumbuna area where the copper content of the soils is less than that of the basic rocks. The mechanism by which copper is concentrated in these soils was not investigated, but from the work of Tooms (1955) this element is known to concentrate with clay minerals.

Interesting features of the distribution of the other minor elements are discussed below:

TITANIUM

The concentration of titanium in the indurated latosol profile over basic rocks at Bumbuna, and particularly in the latosols of ultrabasic rocks, is very probably due to a residual accumulation in the form of insoluble minerals. The strong relative increase in the titanium content from 4000 ppm. in the $B_2$ zone to 10,000 ppm. in the A horizon of the soil profile over basic rocks at Bumbuna is probably indicative of an accumulation of stable titanium rich minerals in the surface soils.

MANGANESE

An anachronism of the minor element distribution, is that manganese generally occurs at reduced levels in the soils on basic rocks, and is slightly concentrated in soils over ultrabasic rocks, compared to the manganese content of the rocks. At Makele however, the distribution of manganese is reversed, and the element is more strongly concentrated in the basic rather than in the ultrabasic soils.

The reason for this unusual distribution of manganese in the soils of the Makele area is tentatively attributed to differing levels of truncation of the residual soils between the areas of basic and of ultrabasic rocks. It is of interest that cobalt is not concentrated with manganese as might be expected from the covariant distribution of these elements in some stream sediments (see below).

A concentration of manganese and other elements in a residual black soil profile has been described by Harden (1962). In black soils overlying the Chinkozia norite in the Nyawa area of Northern Rhodesia, Harden found the trace metal content of the soil to be clearly linked to the carbonate content. In soils with a carbonate content of from 2 to 5 per cent $CaCO_3$, he found numerous small black concretions lying close to the weathered surface of the norite. The concretions contained:

Fe 12% Cu 20 ppm. Co 240 ppm. (bedrock 45 ppm.)

Mn 18% Zn 240 ppm. Ni 3600 ppm.(bedrock 235 ppm.)

Harden ascribed the formation of these concretions to the climatic conditions, in which a heavy wet season is followed by a prolonged period of draught.

The variation in the manganese content of the soils in the Sierra Leone field area at Makele is unlikely to be related to an increase in the carbonate content because the other metals studied, for instance cobalt, nickel and copper, are not concentrated with manganese in the basic soils.

## COBALT AND NICKEL

Cobalt and nickel are strongly depleted in the residual indurated latosol profile at Bumbuna relative to the average basic rock. In the $C_3$ zone, however, the cobalt and nickel contents are equivalent to those of the average basic rock. Between the

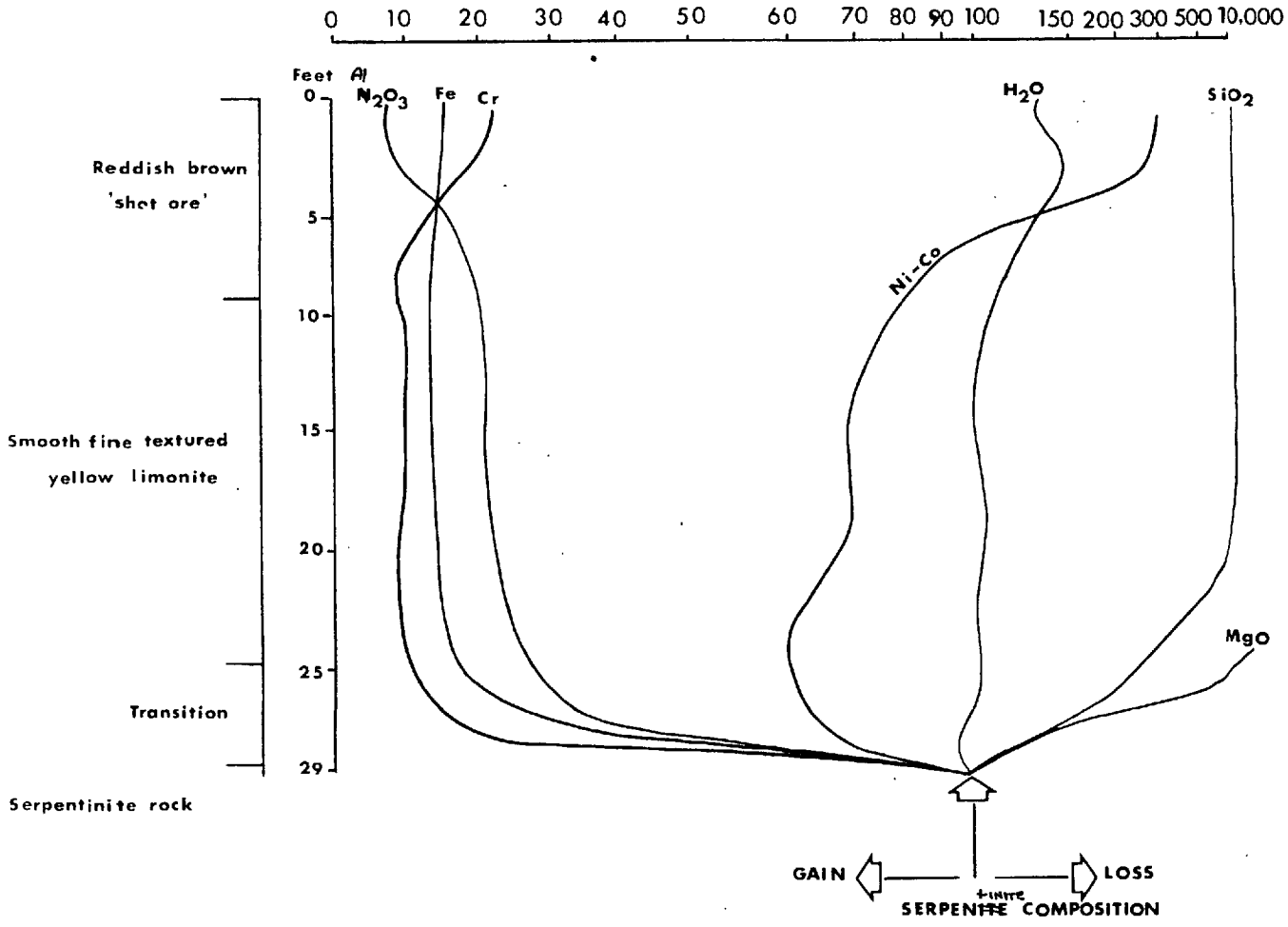
$C_3$ zone and the surface cobalt is undetected, and only small quantities of nickel, less than 30 ppm., are present compared to 150 ppm. in the average rock.

Leith and Mead (1915) reported a somewhat similar distribution of cobalt and nickel in the lateritic iron deposits of North East Cuba. Here, the indurated latosols overlie serpentinite bedrock, and range from a few inches to 80 feet in thickness; they form extensive plateaux at elevations of between 1500-2000 feet. Leith and Mead have compared the analytical results of a vertical series of laterite samples with the chemical composition of the serpentinite bedrock. Their data are presented as a 'straight line diagram' in which the relative loss or gain of the constituents can be compared with the bedrock (fig. 39). The diagram shows that both nickel and cobalt are extensively leached towards the surface, where there is a slight relative concentration. Aluminium, iron and chromium are accumulated, whilst magnesia and silica are strongly leached.

The impoverishment of cobalt and nickel towards the surface in the examples of indurated latosol profiles, is in general, similar in soils developed on basic rocks in Sierra Leone and on ultrabasic rocks in Cuba.

## SUMMARY

From the present work it is evident that there are wide differences of pedology which influence the dispersion of the minor elements, paticularly in areas of basic and ultrabasic rocks.




**Composition of a lateritic soil profile related to the serpentinite bedrock in NE Cuba.**

**From Leith and Mead (1915).**

**FIGURE 39**

Wide variations of minor element distribution in the soil profile were detected, especially in indurated latosols.

There is little difference between the minor element content of granitic bedrocks and the content in the A soil horizons ofrelated iron poor latosols. As a result, any variation in the distribution of the minor elements in iron poor latosols overlying granitic rocks is unlikely to strongly affect the geochemical patterns.

In the iron rich latosols there is a very strong redistribution of the major and minor elements. From a comparison of the minor element content of the average basic and ultrabasic rocks with the average contents of the associated soils, it is evident that in general the minor elements are most reduced in the colluvial latosols devoid of rock fragments. These latosols are taken to be derived from the A, B, or $C_1$ horizons of truncated indurated latosols (fig. 36).

Somewhat higher levels of concentration were detected in latosols containing rock fragments which are taken to be largely derived from the $C_3$ zone overlying the weathered bedrock. The only elements which are not strongly impoverished in indurated latosols are those which are likely to be concentrated in resistant minerals, for example titanium, vanadium and chromium.

From the foregoing description of variations in soil types and minor element contents, it is most probable that the geochemical patterns in stream sediments will be related to local or regional

differences in the soil composition. This feature is accentuated in the field area by marked differences in the depth of truncation of the residual soils. For example, near Basaia, large areas of the basic and ultrabasic rocks are obscured by a mantle of duricrust, whilst at Bumbuna the duricrust area is restricted, and a number of monadnocks rise out of the indurated latosols resulting in a mixed colluvium derived from different depths of truncated soil profiles. The basic and ultrabasic rocks near Makele and the ultrabasic rocks near Makong are largely covered by thin colluvial latosols containing frequent fragments of recognisable rock.

## Erosion and sedimentation

### Introduction

The regional variations in the geochemical patterns observed from the analytical results of stream sediments have been shown to be largely related to the geochemical distribution of the elements in the major rock types. The regional patterns are also strongly influenced by regional differences in soil formation on basic and ultrabasic rocks. Ultimately, the geochemical patterns in stream sediments result from all of the erosional processes, by which the weathered remnants of rock, as well as fresh pebbles, are transported towards the drainage channels, and there sorted as active stream sediments.

The detailed physical and chemical composition of stream sediments was only briefly investigated during the course of the present research programme, and the empirical observations which were made are related to the factors affecting sedimentation. These factors were not investigated, but the known characteristics of rock weathering and sedimentation have been described by Gilbert (1914), Reiche (1945), Twenhofel (1950), and collated with particular reference to problems in applied geochemistry by Hawkes and Webb (1962). The following brief review of physical and chemical factors affecting the distribution of the minor elements is largely taken from these authors.

Of the physical factors which control the composition of the active sediment, the rate of erosion, rate and depth of oxidation, and the mineralogy of the bedrock are possibly the most important. Other factors, such as the grade, ratio of width to depth of the stream bed, velocity, and volume of water, load (suspension and saltation), formation of dunes and antidunes, stratified sediments, distance from source, riffles, waterfalls, alluvial or colluvial banks, river capture, seasonal rainfall and vegetation, can all be expected to influence the composition of the sediments.

The effect of these factors on the composition of the sediment will depend in turn upon the physical and chemical properties of the minerals concerned, for instance grain size, form (angularity-sphericity), specific gravity, elasticity, hardness, and resistance

to chemical decomposition within an aqueous environment. The physical destruction and chemical decomposition of the non-resistant minerals will lead, in some cases, to the formation of stable secondary minerals (clay minerals and iron oxide). The soluble products are likely to remain in solution, provided that the electro-chemical and biological environment is suitable; otherwise the ions are likely to be concentrated by several processes which include precipitation, ionic adsorption and exchange mechanisms, and by macro- and micro-biological agencies. The minor element content of the sample fraction could be reasonably expected to vary according to the relative effects of the factors noted above.

The extent to which erosion and sedimentation have affected variations in the minor element contents amongst associated rocks, soils and stream sediments is illustrated by a study of the areas of basic and ultrabasic rocks (figs. 37, 37a, 38 and 38a). A certain amount of repetition is necessarily introduced where the minor element content of the soils is compared with that of the rocks.

A summary of the differences of concentration is followed by a description of some of the variations in the physical and chemical composition of stream sediments, according to particle size and distance from the stream source. The effects of the variations in the physical and chemical composition according to particle size etc. are afterwards discussed.

## The distribution of minor elements in stream sediments derived from basic and ultrabasic rocks

The outstanding features of the distribution of the minor elements in sediments derived from basic and ultrabasic rocks is that the average results show few major differences in concentration compared to the source rocks. The important differences are the relatively low cobalt and nickel contents of the sediments derived from duricrust areas, compared to both basic and ultrabasic rocks, and also the increased contents of titanium and copper in sediments derived from ultrabasic rocks. Other variations are seen in the generally increased contents of manganese in the sediments of non-duricrusted areas, as in the area of ultrabasic rocks near Makong, and the areas of basic and ultrabasic rocks at Makele. In duricrusted areas of ultrabasic rocks, manganese occurs at lower levels in the sediments than in the rocks.

The distribution of the minor elements in the soils associated with basic and ultrabasic rocks has been described under the heading 'Pedology'. From a comparison of the average minor element contents of the sediments with the soils, it is evident that in general the average values of the soils are intermediate between those of the rocks and the sediments. Notable exceptions are seen in the very low contents of cobalt, nickel and manganese in the soils associated with the basic rocks near Bumbuna, and in the distribution of manganese in the soils near Makele. As noted

previously, manganese is impoverished in the soils on ultrabasic rocks at Makele, but is accumulated in the soils associated with the basic rocks of the same area.

The detailed variations in the distributions of the minor elements amongst the rocks, soils and stream sediments are presented below.

## BASIC ROCKS

### TITANIUM

There is little difference in the titanium contents of the rocks, soils and stream sediments, and the slight difference of titanium content in the rocks of the three areas is reflected by the stream sediments (fig. 37a). A wider variation exists amongst the soils, and whereas in the Bumbuna area, higher titanium contents are found in the soils with rock fragments than in those without rock fragments, in the Basaia area, the reverse is true.

### VANADIUM

The distribution of vanadium is somewhat similar to that of titanium, for there is little difference in the average vanadium content in the rocks, soils and stream sediments. The different average contents of the rocks from the three areas are closely reflected by the sediments, the differences being least in the Makele area, where the range of the average results is from 370 to

400 ppm. The range is also small in the Basaia area, 250 to 300 ppm., and the Bumbuna monadnock area, 260 to 300 ppm., of colluvial latosols. In the Bumbuna area where sediments from duricrust and monadnock catchments can be compared, the difference between the vanadium content of the sediments is so small as to be insignificant.

The higher contents of vanadium in the soils with rock fragments seen in the Bumbuna area is also a feature of the Basaia soils, the differences being slightly greater in the former area than in the latter area.

CHROMIUM

The average chromium contents of the rocks in the three study areas occur at slightly different levels and these differences are reflected in the stream sediments. The levels in the stream sediments are slightly higher than in the rocks, particularly in non-duricrusted areas. In duricrusted areas, as at Bumbuna, the chromium content of the sediment is low, 85 ppm., compared to the average of 360 ppm. in sediments of non-duricrusted areas.

MANGANESE

The average content of manganese in the rocks is closely reflected by the stream sediments in the Bumbuna and Basaia areas, but not in the Makele area. In the Bumbuna and Basaia areas the average manganese contents of the rocks are 1500 ppm. and 980 ppm.

respectively, whilst those of the sediments are 1380 ppm. and 910 ppm. respectively, these differences being regarded as insignificant. In the Makele area, the difference between the rocks and sediments is wide, being 980 ppm. in the rocks and 3750 ppm. in the sediments. An interesting feature of the manganese distribution in the soils is that the average values in the Bumbuna and Basaia areas are less than those of the rocks and sediments, whilst at Makele, the average value of the soils is intermediate between those of the rocks and soils.

COBALT

There are large differences of cobalt content between the rocks and sediments in areas of duricrust, but these differences are only slight in the non-duricrusted areas. The average cobalt contents of the rocks in the three study areas vary between 60 ppm. and 65 ppm., but the average cobalt content in the sediments of the duricrust areas at Bumbuna is 30 ppm. and at Basaia 26 ppm. In the non-duricrust areas the cobalt contents of the sediments are slightly higher than those of the rocks, for example the average content at the monadnock area at Bumbuna is 70 ppm. and at Makele is 90 ppm.

The cobalt contents of the soils are low compared to the rocks and sediments in each of the three study areas, the soils of the Bumbuna area being the most impoverished.

NICKEL

There are wide differences between the average nickel contents of the rocks and of the sediments in the duricrust areas at Bumbuna and Basaia, but not in the non-duricrust area at Makele. The nickel content of the rocks at Bumbuna and Basaia areas is 170 ppm. and 160 ppm. respectively, whilst in the sediments it is 70 ppm. and 26 ppm. respectively. In the non-duricrusted areas, as at Makele, there is no significant difference between the nickel content of the rocks, 115 ppm., and the sediments, 125 ppm. The difference is slightly more in the non-duricrusted monadnock area at Bumbuna where the average nickel content of the rock is 170 ppm. compared to 110 ppm. in the sediments.

The average nickel contents of the rocks in the three areas show different levels of concentration and these levels are reversed in the soils. Thus the nickel contents of the rocks are at the highest, and the nickel contents of the soils at their lowest in the Bumbuna area, the reverse being true in the Makele area.

COPPER

The copper contents of the rocks in the three areas are similar, but this similarity is not reflected in the stream sediments where there are wide differences of concentration. In the non-duricrusted area at Makele, the copper content of the

sediments is higher, 150 ppm., than in the rocks, 85 ppm. There is no appreciable difference in the monadnock areas at Bumbuna between the copper content of the rocks and of the sediments. Sediments derived from areas of duricrust at Bumbuna and Basaia contain much less copper, 60 ppm. and 40 ppm. respectively, than in the bedrock, 85 ppm.

The distribution of copper in the soils is somewhat irregular and occurs at higher levels in the soils of the Makele and Basaia areas than in those of the Bumbuna area.

## ULTRABASIC ROCKS

### TITANIUM

Titanium is concentrated in the stream sediments relative to the soils and to the rocks in each of the three areas. Slightly higher titanium contents were recorded in the rocks at both the Makong and Makele areas, 2150 ppm., than in the Basaia area, 1150 ppm., but these differences are not apparent in the stream sediments, 9000 ppm., 7000 ppm., and 7050 ppm., in the Makong, Makele and Basaia areas respectively. The titanium contents of the soils are intermediate between those of the rocks and sediments.

### VANADIUM

The average vanadium contents of the rocks are closely reflected in the stream sediments in all three of the study areas. The differences between the vanadium contents in the rocks and

sediments is small in the Makong and Makele areas. At Makong the vanadium content of the rocks is 240 ppm. compared to 260 ppm. in the sediments. In the Basaia area the difference between the vanadium content of the rocks, 125 ppm., and of the sediments, 185 ppm., is rather more than in the other areas.

The vanadium distribution in the soils is somewhat similar to that of the rocks and sediments, except in the Basaia area where vanadium occurs at higher concentrations in the soils than in the rocks or sediments.

CHROMIUM

The average chromium contents of the rocks are broadly reflected by the sediments of the Basaia and Makele areas, but not in the Makong area, where chromium occurs at very much higher levels in the sediments than in the rocks. In the Basaia and Makele areas the average chromium content of the rocks is about 1500 ppm. and in the sediments is about 1100 ppm. In the Makong area the rocks contain an average of 1290 ppm. and the sediments 3000 ppm.

The chromium contents of the majority of the soils are intermediate between those of the rocks and sediments. In the Basaia area, however, the chromium content of the soils which do not contain rock fragments is high, 1700 ppm., compared to the rocks, 1400 ppm., and to the stream sediments, 1100 ppm.

MANGANESE

Wide differences of manganese concentration are displayed by the soils and stream sediments when compared to the rocks. In the non-duricrusted areas at Makong and Makele, manganese is concentrated in the sediments, 3780 to 2200 ppm., compared to the rocks, 1350 to 1000 ppm. In the duricrust area near Basaia , manganese is impoverished in the sediments, 750 ppm., compared to the rocks, 1250 ppm.

The distribution of manganese in the soils is more similar to that in the rocks. than in the sediments, except in the Makele area where, as noted previously, manganese is impoverished in the soils.

COBALT

In all of the areas the average content of cobalt is lower in the sediments than in the rocks. This difference is only small in the non-duricrusted areas at Makong and Makele, but is large in the duricrust area at Basaia, where the cobalt content of the rocks is 85 ppm. compared to 45 ppm. in the sediments.

The cobalt content of the associated soils varies widely amongst the areas. At Makele it is similar to the sediments, whilst at Makong it is much less than in the sediments and only half the content of the rock. In the soils at Basaia, the cobalt contents vary according to the composition of the soil. Thus in

latosols containing rock fragments, the cobalt content is similar to that of the rocks, whilst the cobalt content of latosols without fragments is similar to that of the sediments.

NICKEL

The nickel content of the stream sediments is lower than that of the rocks in each of the three areas. This difference is small in the non-duricrusted areas at Makong and Makele, but is wide in the duricrust area at Basaia. For example the nickel content of the rocks in the Makong and Makele areas is 1120 ppm. and 1830 ppm. respectively compared to 970 ppm. and 590 ppm. respectively in the sediments. In the duricrust area at Basaia the nickel content of the rocks is 2150 ppm. but is only 160 ppm. in the sediments.

The nickel content of the soils is variable, for at Makele the level of the soils is similar to that of the sediments, whilst at Makong the content in the soils is much less than in either the rocks or the sediments. The nickel content of the Basaia soils is intermediate between that of the sediments and of the rocks.

COPPER

In each of the three areas, the average copper contents of the stream sediments are higher than in the rocks. The difference in the Makong and Basaia areas is similar, being about 35 ppm. in the rocks and about 50 ppm. in the sediments. In the Makele

area, the copper content of the rocks is 26 ppm. compared to 65 ppm. in the sediments.

The distribution of copper in the soils of the three areas is broadly similar. In the Makele area the copper contents of the soils is intermediate between that of the rocks and of the sediments. In the Makong and Basaia areas, the copper contents of the soils are equivalent to, or slightly more than, the copper contents of the sediments.

## The composition of stream sediment

To investigate the possible variations in the composition of the sample fraction according to the nature of the primary rock and other environmental features, the samples collected from the 'Type Areas' (page 90 and fig. 22) were separated into 5 size fractions and weighed to obtain the percent composition of each fraction and these were subsequently chemically analysed (SECTION 2). Since the size fractions were separated by a dry sieving procedure, it is almost inevitable that some of the fines adhered to the coarse fractions, and that the particles were not entirely separated into their true sizes. Although no complete wet dispersion separations were made, from the results presented below this feature does not appear to have an important effect upon the composition of the samples.

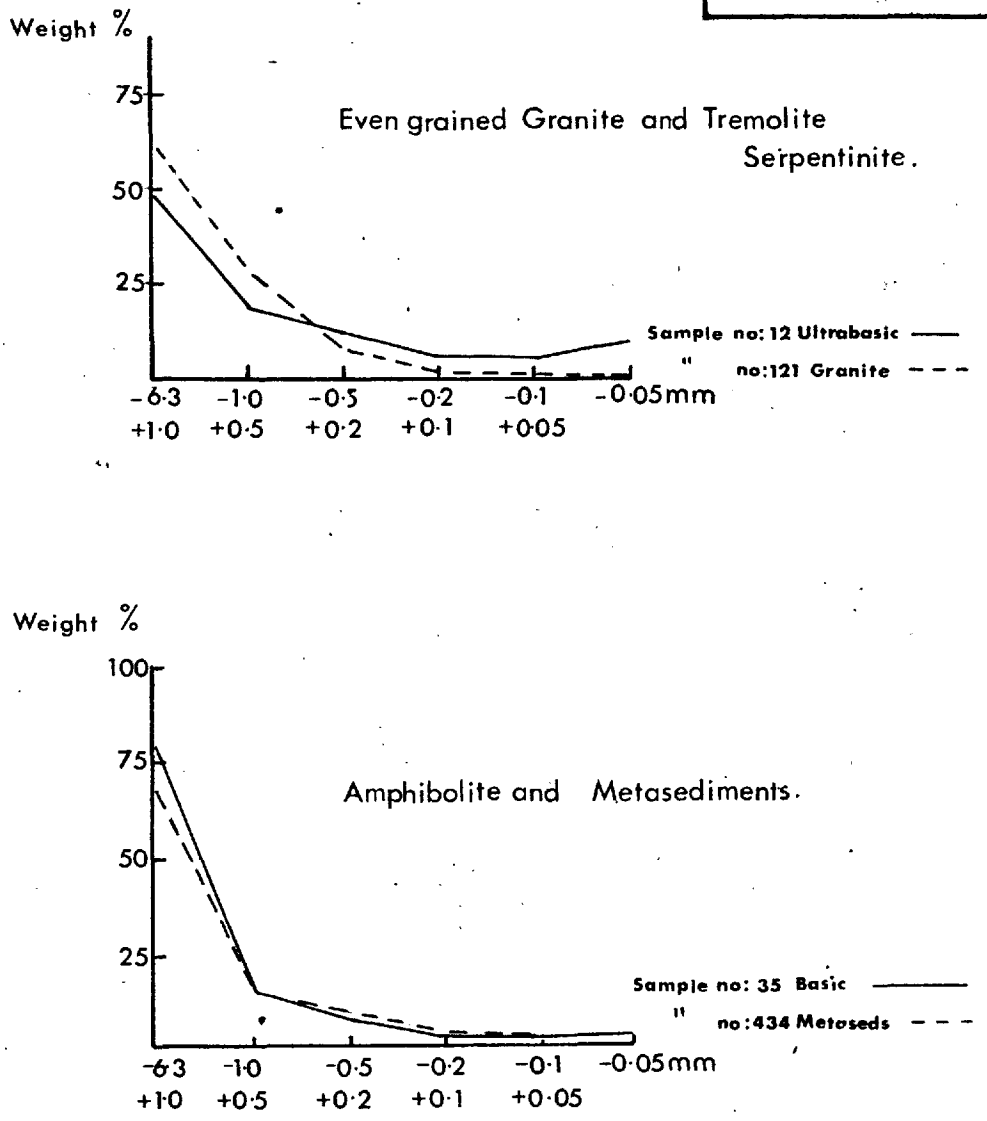
PHYSICAL COMPOSITION

The results of the mechanical analysis are illustrated in fig. 40. Fine gravel (page 28) forms the bulk of all of the samples irrespective of the bedrock mineralogy, although the content is generally somewhat higher in amphibolitic areas, 75 per cent, than where granites or metasediments form the bedrock, 50 to 60 per cent. The coarse sand content of the amphibolites is, however, normally somewhat lower, 15 per cent, than in granitic/metasediment samples, 20 to 30 per cent. Accordingly, the proportion of fines (smaller than 0.2 mm. in diameter) in the samples is relatively constant at 8 per cent (fig. 40).

There is, however, a considerable variation in particle size distribution between sediments derived from amphibolite which is covered by deeply truncated and colluvial latosols and amphibolite which is largely covered by duricrust. Fine gravel forms 50 per cent of the sediment in duricrust areas, compared to 75 per cent in non-duricrusted areas. By contrast, sand forms 20 to 25 per cent of the duricrust sediment, and slightly less than 10 to 15 per cent of the non-duricrust sediment. The fine fractions of both sediments form only a small proportion of the total composition, about 5 per cent (fig. 40).

The samples do not show a trend towards a redistribution of particle size which can be correlated with distance from stream source. Slight variations in the particle size distribution

**FIGURE 40**




**Particle size distribution of stream sediments related to lithology.**

occur, but in general there is very little difference between the physical composition of the samples from different positions in the stream.

In summary, there are small variations in the particle size distribution which can be correlated with the major rock types and areas of duricrust soil, but there is little recognisable redistribution of the particles with increasing distance from the stream source.

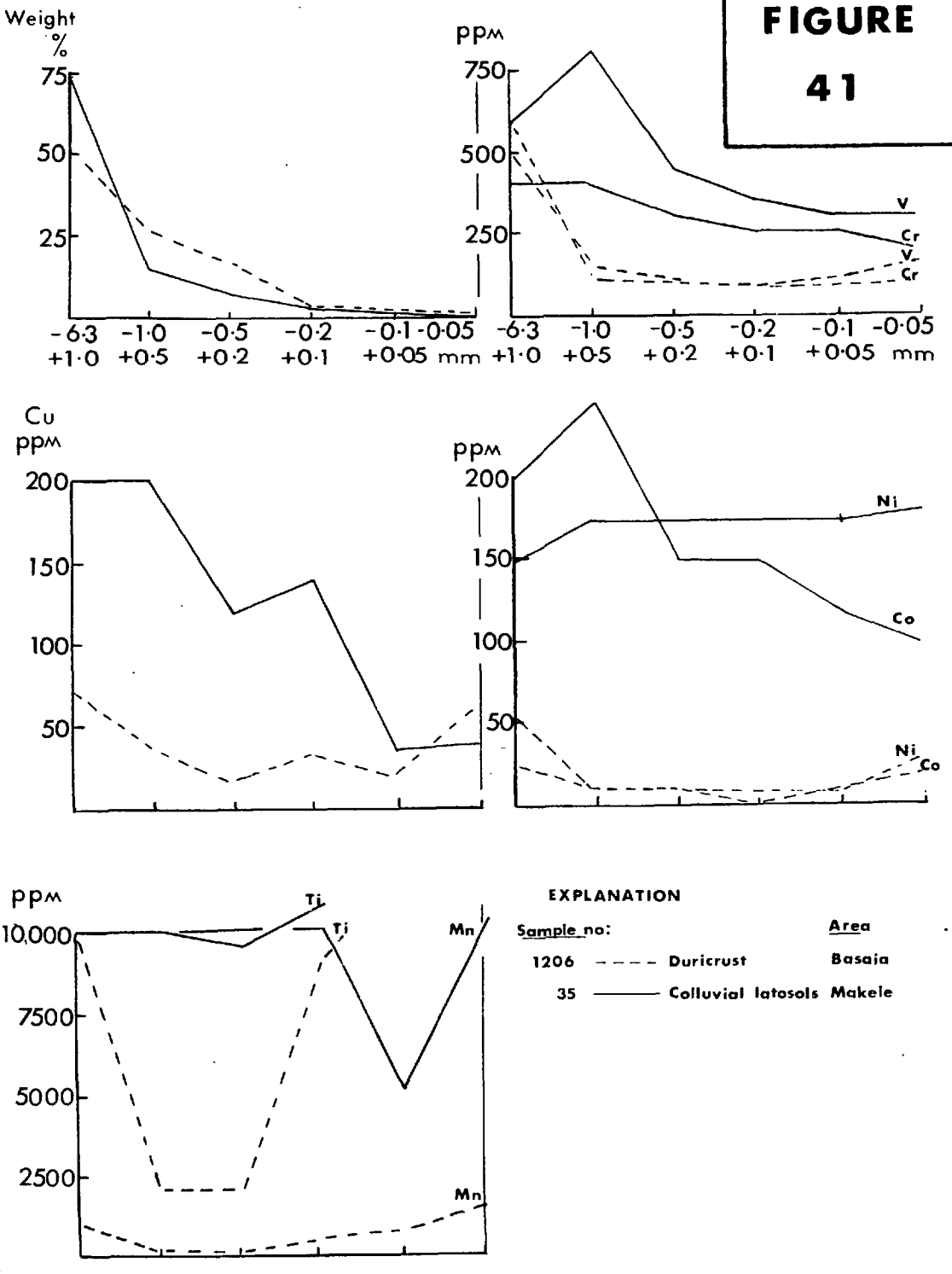
## CHEMICAL COMPOSITION

The dry sieved size fractions were chemically analysed to investigate the minor element distribution within the various size fractions of the samples.

Variations of element concentration according to particle size due to differential concentration in the fine or coarse grained fractions of stream sediments is a well known phenomenon, and the location of the elements is determined by the physical and chemical properties of the environment. For example, copper is frequently found to be concentrated with the clay minerals in the fine fractions of stream sediments (Hawkes and Webb, 1962).

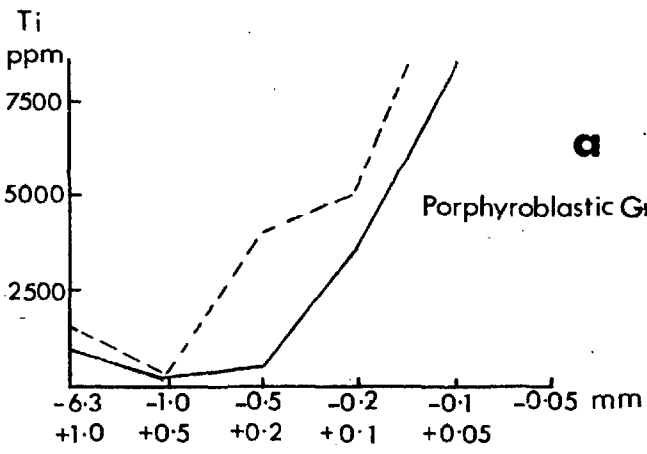
In general, the minor elements are more strongly concentrated in the fine fractions than in the coarse fractions of stream sediments, although the chemical results show a wide variation in the distribution of the minor elements within the different size

**FIGURE 41**




**Minor element distribution in Amphibolitic sediments .**

**FIGURE 42 a,b**




**a**

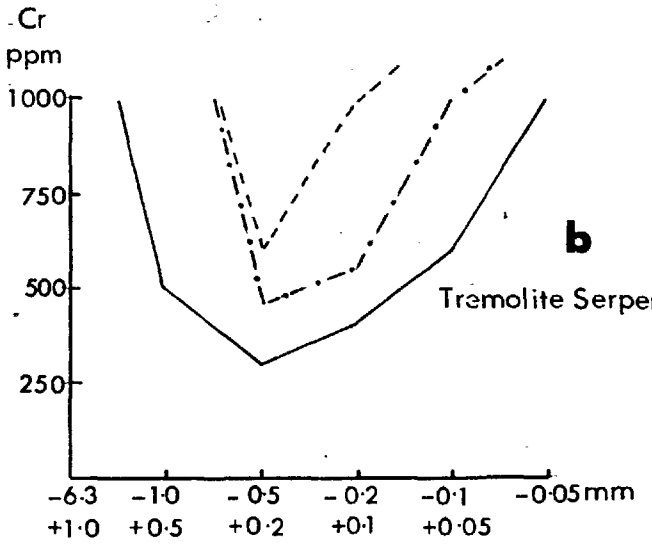
Porphyroblastic Granite and Amphibolite.

**EXPLANATION**

Upstream

Midstream

Downstream




**b**

Tremolite Serpentinite and Granite Migmatite.

**Variation of Ti and Cr content of stream sediments concentrated with distance from stream source.**

fractions. The elements manganese, cobalt, nickel, copper, arsenic, zinc, molybdenum and lead are concentrated in the fine fractions relative to the coarse. Other elements, for instance vanadium and chromium, are frequently found to be more concentrated in the coarse rather than in the fine fractions. Titanium characteristically displays a bi-modal distribution, being concentrated in both the coarse and the fine fractions, relative to the intermediate fractions. This feature is also shown by nickel, vanadium and chromium in sediments derived from mixed granitic and ultrabasic detritus (fig. 42). A weakly bi-modal distribution in the size fractions is also shown in duricrust sediments, by manganese, cobalt, arsenic, and molybdenum (fig. 41).

The analytical results of the same size fractions from the three of four samples derived from any one major rock type extend over a range of concentration, and this range will be referred to as 'the spread of the results'. From the present results, the spread was found to be least in fractions finer than 0.2 mm. in sediments derived from most of the major rock types.

There are important differences between the minor element distribution in sediments derived from duricrust covered amphibolite and those derived from non-duricrusted amphibolite. It is evident from the results (fig. 41) that the titanium, vanadium and chromium contents in the two types are somewhat similar, but in the case of copper, manganese, and particularly cobalt and nickel, the contents

are very low in the duricrust samples compared to the non-duricrust samples.

The geochemical coherence of manganese and cobalt in the zone of weathering is illustrated by the covariant distribution of manganese and cobalt in the stream sediments. In the coarse grained fractions of duricrust sediments the Mn/Co ratio decreases, possibly because these size fractions are normally largely composed of concretionary material containing increased concentrations of cobalt.

Indications were obtained of the concentration of titanium and chromium with increasing distance from the stream source, but this was observed only in sediments derived from mixed and contrasting major rock types. The distribution of the minor elements in vertical profiles in the stream bed was not investigated (see below).

The salient features of the distributions of the individual elements amongst the size fractions are given below.

TITANIUM

The titanium content of the major rock types in the field area varies widely and this variation is reflected in the stream sediments (figs.25, 26a and 26b). On the basis of the analyses of the size fractions there is also a wide variation of titanium content according to particle size. Titanium characteristically

displays a bi-modal distribution, being concentrated in both the coarse and fine fractions relative to the intermediate fractions. The bi-modal distribution is well illustrated in the sediments derived from duricrusted amphibolite, in which the fine gravel and fractions smaller than medium sand contain about 10,000 ppm., compared to 2000 ppm. in the coarse sand and medium sand.

There are some exceptions to the bi-modal distribution, for example in the banded ironstone sediments titanium is evenly distributed between each of the size fractions. The spread of the titanium results is generally least in the fractions finer than the very fine sand.

VANADIUM

Vanadium is frequently found to be more concentrated in the coarse rather than in the fine grained size fractions. Exceptions are displayed by sediments derived from mixed granite and amphibolite detritus in which vanadium shows a bi-modal distribution. In several samples, vanadium is more concentrated in the finest fractions compared to the intermediate, and in the arenaceous facies of the metasediments the concentration increases with decreasing particle size, from 50 ppm. in the fine grained gravel to 150 ppm. in the coarse silt and silt plus clay.

In sediment derived from areas of duricrust covered amphibolite vanadium is concentrated, 500 ppm., in the fine gravel fraction

and displays a broadly similar distribution, 100 to 150 ppm., in the finer size fractions. This distribution is somewhat similar to that in amphibolite sediments from non-duricrusted areas, except that vanadium occurs at higher levels, greater than 300 ppm., in each of the size fractions.

The spread of vanadium is generally the same in each of the size fractions at the different levels of concentration which are characteristic of the major rock types. In sediments derived from tremolite serpentinite, the spread is less in the very fine sand and silt plus clay fractions, 100 to 150 ppm., than in the more coarse grained fractions, 50 to 200 ppm.

CHROMIUM

The distribution and concentration of chromium in the size fraction varies strongly according to rock type, but in general chromium is concentrated in the coarse, rather than in the finer grained fractions. In sediments derived from the argillaceous facies of the metasediments, chromium is more concentrated in the coarse sand and fine gravel, 1000 ppm., than in the smaller fractions, 250 ppm. In granite, quartzite, banded ironstone, and amphibolite sediments there is a slightly bi-modal concentration in which much higher levels of chromium occur in fine gravels, and slightly higher contents occur in the very fine sand and silt plus clay fractions, compared to the intermediate fractions whose

chromium content is approximately similar. The distribution of chromium in some of the tremolite serpentinite sediments is unusual, for the maximum chromium content was detected in the medium sand, rather than in the fine gravel and silt plus clay fractions in which chromium is normally concentrated.

Chromium displays a bi-modal distribution in the size fractions of sediments derived from granite and tremolite serpentinite detritus (fig. 42b). The chromium content of the fine gravel, coarse sand and silt plus clay fractions is about 1000 ppm., and contrasts strongly with the minimum content of 300 ppm. The chromium content of amphibolitic sediments in areas of duricrust is about half that of the sediments in non-duricrust areas. As with vanadium, chromium is concentrated in the fine gravels, 550 ppm., and occurs at lower but similar levels in the finer fractions, 100 ppm.

In general, the maximum spread of chromium is in the fine gravel and gradually decreases through successively smaller size fractions to a minimum in the very fine sand. For example in four samples from quartz biotite schist sediments, the spread in fine gravel is from 150 to 600 ppm., whilst in the very fine sand and silt plus clay it is from 250 to 600 ppm.

MANGANESE

In contrast to the elements titanium, vanadium and chromium, manganese does not appear to be strongly concentrated in the coarse

sand and fine gravel fractions of stream sediments, but frequently displays minimum concentrations in these fractions. The manganese content of fractions finer than the coarse sand is normally similar in each of the fractions, but is sometimes concentrated in the very fine grained fractions. In sediments derived from mixed granite and tremolite serpentinite, manganese is more strongly concentrated in the fractions finer than fine sand, 5000 ppm., than in the coarser fractions where the manganese contents do not exceed 1500 ppm. The distribution of manganese in non-duricrusted amphibolite sediments covers a wide range at high levels of concentration, from 5000 to 10,000 ppm., in the different size fractions. The manganese contents of duricrust sediments are low, 1000 ppm. to 1500 ppm., as compared to those of non-duricrusted areas.

Taking a broad view of the results, the minimum spread and maximum concentration amongst the size fractions occurs in the coarse silt and silt plus clay fractions of the samples.

COBALT

The distribution of cobalt in the size fractions of the stream sediments derived from the major rock types displays a weakly bi-modal distribution in which this element is normally more concentrated in the fine size fractions than in the coarse. An exception to this distribution is seen in the argillaceous

facies of the metasediments where cobalt is more concentrated in the fine gravel than in the silt plus clay fractions. In addition some samples of non-duricrusted amphibolite sediments contain higher levels of cobalt in the coarse fractions, 100 ppm. to 200 ppm., than in the fine fractions, 50 ppm. to 100 ppm. In comparison the cobalt content of amphibolite sediments in areas of duricrust is low and frequently about 50 ppm. in each of the size fractions. In the latter samples, cobalt is slightly concentrated in the coarse and fine fractions, 50 ppm. and 25 ppm. respectively, compared to 10 ppm. in the intermediate fractions.

The spread of the results is at a minimum in the coarse silt and silt plus clay fractions in all of the rock types except the metasediments, where the spread is least in the coarse sand.

NICKEL

Nickel is relatively evenly distributed throughout the size fractions of the stream sediments, but in most areas there is a slight increase of content in the fine grained fractions. In sediments derived from mixed granite and tremolite serpentinite detritus, nickel displays a bi-modal distribution in which the element is more strongly concentrated in the fine fractions than in the coarse and the intermediate fractions: the nickel content of the silt fraction being 800 ppm. compared to 200 ppm. in the medium sand and 350 ppm. in the fine gravel.

In tremolite serpentinite sediments, nickel is frequently more concentrated in the fine gravel than in the silt fraction, whilst in some samples nickel is concentrated in the medium sand fraction.

Except in the duricrust amphibolite sediments, the nickel content, as compared to the other elements studied, is remarkably similar in each of the size fractions.

The distribution of nickel in the duricrust amphibolite sediments is very similar to that of cobalt and varies from between 10 ppm. to 30 ppm. Ni in the size fractions. These nickel contents are low compared to those of amphibolite sediments in non-duricrusted areas (175 ppm.).

The spread of the results is generally similar amongst the size fractions, and there is little variation which can be correlated with the different rock types.

COPPER

Copper shows large variations of concentration amongst the size fractions of the stream sediments derived from the major rock types, but in general, the peak copper contents were detected in the fine grained fractions of the samples. In granitic sediments, the copper content is approximately similar in each size fraction. The same is true, but at much higher levels of concentration, in the non-duricrusted amphibolite sediments. In

the metasediment and tremolite serpentinite sediments, however, there is a distinctly bi-modal distribution in which copper is concentrated in the fine gravel and in the silt, relative to the intermediate fractions.

Copper occurs at higher levels of concentration in stream sediments derived from the non-duricrust covered amphibolite, than in the duricrusted areas. In the duricrust sediments the distribution of copper in the size fractions is somewhat similar to that of cobalt and nickel.

The spread of the copper results is least in the coarse sand fractions, and is generally wide in the fine grained fractions.

ZINC

The separated size fractions of the stream sediment samples were not analysed for zinc, and the writer is not aware of any information regarding the dispersion of this element in the stream sediments of Sierra Leone. The dispersion of zinc in some Sierra Leone soils has been studied by Holman (1956); in New Brunswick by Hawkes and Bloom (1956), and in the stream sediments of the Nyawa Area of Northern Rhodesia by Harden (1962). These authors have shown that zinc is strongly concentrated in the fine grained fractions of stream sediments, compared to the coarse. Harden has shown that the highest concentration of zinc (and also Co, Ni, Cu) is to be found in the silt-sized fraction, and not in the clay.

ARSENIC

Arsenic is frequently concentrated in the coarse sand and fine gravel fractions of the dry sieved stream sediments. The distribution of arsenic in some of the stream sediments of the Yirisen river in the Sula Mountains has been investigated by Elliott (1962). Elliott found that "arsenic resides chiefly in the plus 20-mesh fraction (larger than 1 mm.), with values ranging from 15-50 ppm. As. The intermediate size fractions generally carry only a minor proportion of the total arsenic content of the sediment by virtue of their bulk. Distinct concentrations of the element are found in the silt and clay fractions; particularly in the latter".

Elliott also observed that the 'background' duricrust material carried eighteen times more arsenic than the talc schists.

MOLYBDENUM

Molybdenum was not detected in the analyses of the size fractions of stream sediments derived from the major rock types. Elliott (1962) has also investigated the distribution of this element in stream sediments derived from two molybdenite prospects in the Sula Mountains, situated a few miles to the north of the present field area.

Elliott found that the mechanical composition of the stream sediment was strongly influenced by the presence or absence of

duricrust within the catchment area. In duricrust sediments, molybdenum is concentrated in both the fine gravel and silt fractions, whilst in non-duricrusted areas, molybdenum is only concentrated in the silt fraction.

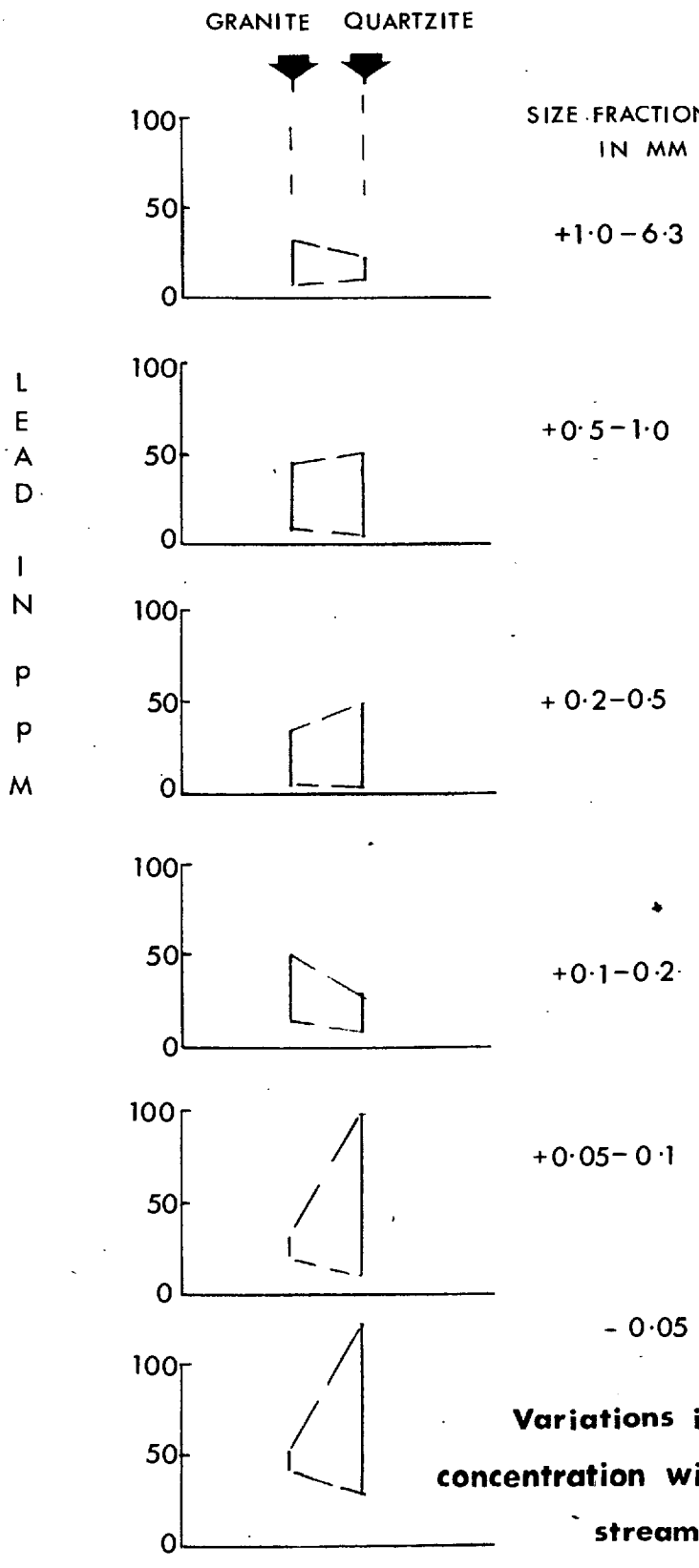
LEAD

Lead is frequently concentrated in fractions finer than the coarse sand, and is most concentrated in the silt fractions. For example in stream sediments derived from quartzites and granite the lead content of the coarse gravel is 5 ppm. and 10 ppm. respectively, whilst in the silt fractions it increases to 40 ppm. and 30 ppm. respectively (fig. 43).

The distribution of lead in the duricrust sediments was not investigated, but Webb (1956) has reported concentrations of lead in fractions larger than 0.2 mm. (i.e. coarse sand and fine gravel). Lead was also found to be concentrated in the silt plus clay fraction of a ferruginous nodular soil (with manganese segregations) lying on a weathered norite in South Africa. Ledward (1960) has observed a tendency for lead to accumulate with iron and/or manganese in subtropical soils.

The spread of the lead results is generally least in the fine grained fractions, but there are exceptions and in the quartzite samples the spread is narrow in the fine gravel, 10 ppm., and wide in the silt sized fractions, 90 ppm. (fig. 43).

# FIGURE 43




**Variations in the range of lead concentration with particle size in stream sediments.**

Based on 3 samples from each rock type.

CO-VARIANT DISTRIBUTIONS

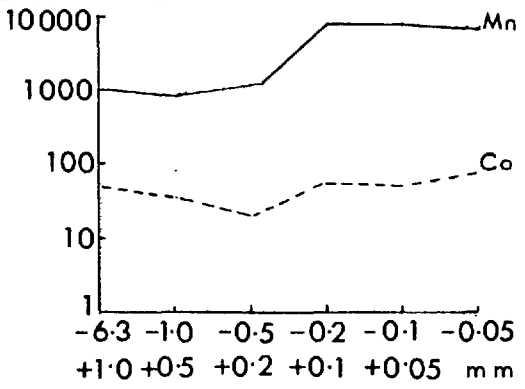
In the samples studied the manganese/cobalt ratio varies between 15 and 100 (figs. 41 and 44). In general the Mn/Co ratios are different for most of the major rock types and also vary according to the soil type. In some stream sediments the ratio is constant in the separate size fractions, whilst in others there is a wide variation of the ratio between the coarse and fine fractions.

In the non-duricrusted amphibolite sediments the ratio is remarkably constant and varies between Mn/Co = 80 to 100. In the coarse sand and fine gravel of duricrust amphibolite sediments the ratio Mn/Co = 20, whilst in the finer fractions the ratio is greater than 75. This variation of the Mn/Co ratio from 20 to greater than 75 possibly results from the increased concentration of cobalt in the ferruginous and/or manganese nodules in the coarse fractions of the duricrusted stream sediments

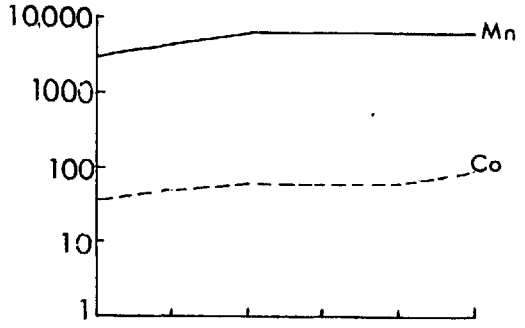
In stream sediments derived from mixed granite and tremolite serpentinite the ratio Mn/Co varies from Mn/Co = 14 in the coarse fractions to Mn/Co = 100 in the fine, and is somewhat similar to the ratios in the duricrusted amphibolitic sediment.

In contrast to the increase of the Mn/Co ratio from the coarse to the fine fractions of the duricrust amphibolite, and mixed granite-tremolite-serpentinite sediments, the ratio Mn/Co in the Farangbaia quartzite sediments shows no regular distribution, and varies between Mn/Co = 40 to 70.

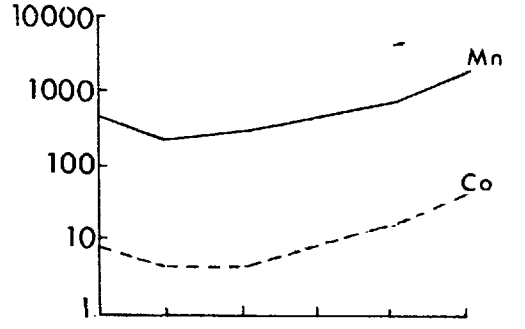
# FIGURE 44




MIXED GRANITE AND TREMOLITE SERPENTINITE




AMPHIBOLITE




QUARTZITE

**The covariant distribution of Cobalt and Manganese**

The distributions of vanadium in the size fractions of stream sediments is somewhat similar to that of chromium, although at different levels of concentration. The Cr/V ratios, however, display wider variations than those of Mn/Co.

## VARIATIONS OF MINOR ELEMENT DISTRIBUTION IN THE DRAINAGE CHANNEL

The distribution of the minor elements in a cross section of the stream bed was not investigated in this research programme, because there was very little evidence of aggradation in the stream beds throughout the field area; nor were layered sediments observed in drainages on the schistose rocks. On the granitic areas, however, where many of the streams are of a swampy nature, and in some swampy drainages on the Farangbaia quartzites, coarse grained bottom sediments were frequently covered by a thin surface layer of fine black silt. These sediments probably result from deposition of flood water deposits towards the end of the rainy season, and during the dry season. Harden (1962), in the Nyawa area of Northern Rhodesia, noted a 'layered sequence' in the stream sediments at the end of the rainy season, which became mixed during the dry season. Harden chiefly attributed this mechanical mixing to the expansion and contraction of the sediment in the wide diurnal variations of temperature in the hot season.

Hawkes, Bloom and Riddell (1957) investigated the error in sampling active stream sediments, at Nash Creek, New Brunswick,

as part of a geochemical reconnaissance survey in Eastern Canada. By collecting multiple samples and comparing the exchangeable metal contents they found the sampling error to be small, and in most cases less than the precision of the analytical method employed. Vertical profiles collected in the stream bed below the active stream sediments showed no significant variation in the content of exchangeable metal (minus 12-mesh fraction).

Since a large proportion of the exchangeable metal is likely to be held in the clay minerals it is probable that in the Nash Creek area the clay minerals are evenly distributed in the vertical profiles. It follows that the resistant minerals could be evenly distributed in the vertical profile.

Variations of element distribution might be expected to occur with increasing distance from the stream source, according to the grade of the stream bed. Although no detailed study was made, the present results do show that there is no significant variation in the minor element content with increasing distance from the stream source. This observation only applies to stream sediments derived from the individual major rock types. If more than rock type is present in the drainage catchment, there appears to be a concentration of titanium and chromium in the downstream samples.

For example, in sediments derived from mixed granite and amphibolitic detritus, the titanium content of the upstream sample is largely concentrated in fractions finer than the medium sand.

In the downstream sample however, titanium is largely concentrated in fractions finer than the coarse sand. In addition, the titanium content in each of the size fractions of the downstream sample is greater than in the equivalent fractions of the upstream sample (fig. 42a).

Another example is afforded by chromium, which in sediments derived from mixed granite and tremolite serpentinite detritus, displays a bi-modal distribution, and is more concentrated in the fine gravel and silt sized fractions than in the intermediate fractions. The chromium contents of the size fractions increase in successive samples, with increasing distance from the stream source (fig. 42b).

### Discussion of erosion and sedimentation as factors affecting the distribution of the geochemical patterns

It has been shown in the discussion of pedology as a factor affecting the geochemical patterns, that regional variations in the depth and rate of erosion strongly influence the secondary dispersion of the minor elements from the bedrock. The analytical data upon which this general conclusion is based were obtained from the minus 80-mesh fraction of soil (and stream sediment) samples, so that this conclusion may not be valid for the sample as a whole. Except in special circumstances where manganese and cobalt are concentrated in the form of concretions, the minus 80-mesh fraction is likely to provide a representative fraction of the soil by virtue of the smaller particle size than fractions larger than 80-mesh.

In stream sediments, the chemical content of a sample will result from the effects of a very large number of factors, some of which will determine the mineralogical composition, and others the possible concentration or leaching of the elements due to chemical dispersion in an aqueous environment. The extent to which the chemical composition of stream sediments will reflect the composition of the bedrock is likely to vary, therefore, according to the interaction of the physical and chemical factors.

In non-duricrusted areas of colluvial latosols the minor element content of the stream sediments is not strongly influenced by the distribution in the soils. For example, in the area of basic rocks at Bumbuna the average cobalt, nickel and copper contents of the soils is lower than in the sediments, whilst at Makele it is only cobalt and nickel which occur at lower levels in the soils. The same is true for cobalt and nickel in the Makong area of ultrabasic rocks. These abnormally low contents of cobalt and nickel in colluvial latosols were not investigated, but could possibly result from a concentration of these elements in fractions larger than 80-mesh. This material would be excluded from the analysed soil sample, but not necessarily from the stream sediments where further diminution of the detritus is likely to occur.

In stream sediments derived mainly from areas of duricrust covered basic or ultrabasic rock, the concentrations of some of the minor elements are frequently at very much lower levels than in the

bedrock and soils, whilst other elements occur at higher levels in the sediments. The concentration of titanium and the distribution of vanadium and chromium in the soils and sediments of duricrust areas of ultrabasic rocks is taken to indicate that these elements occur either in a resistant mineral form or are combined with iron in a concretionary form. In duricrust areas of basic rocks there is a somewhat similar distribution, except that titanium is not concentrated and reflects the content of the bedrock, as also does manganese.

The elements cobalt and nickel occur at lower levels in duricrust sediments than in the areas of both basic and ultrabasic rocks. Nickel is most strongly impoverished in the sediments, and in basic areas is reduced to between one third and one fifth of the bedrock content, whilst in ultrabasic areas it is reduced to one twelfth of the rock content. Cobalt is less strongly impoverished than nickel in sediments from duricrust areas and the level in the sediments is about a half of that in both basic and ultrabasic rocks. In duricrusted areas of basic rocks, the copper content of the sediment is about a half of that in the rocks, whilst in duricrusted areas of ultrabasic rocks, manganese in the sediments is about half of that in the rocks.

The reasons for the impoverishment of particularly cobalt and nickel and also of manganese and copper in the stream sediments in duricrust areas were not investigated. It is evident, however,

that the elements which occur at lower levels in the sediments compared to the rocks differ according to the major rock type, for example, chromium, cobalt, nickel and copper in areas of basic rocks and cobalt, nickel and manganese in areas of ultrabasic rocks. It is probable, therefore, that the different mineralogy of the basic and ultrabasic rocks is an important factor affecting the distribution of the geochemical patterns ,(Mitchell,1955).

The difference between the minor element composition of the stream sediments compared to that of the basic and ultrabasic rocks in duricrust and non-duricrusted areas can be ascribed to a number of factors. Of these the pedology and possibly the mineralogy of the bedrock appear to be the most important, but it is probable that the geochemical patterns are also influenced by variations in the physical and chemical composition of the stream sediment.

From the present investigation it is seen that the physical composition of the minus 80-mesh fraction stream sediment samples is relatively constant, forming about 8 per cent by weight in streams draining the major rock types. The minor elements are frequently concentrated in the sediment fines (particularly copper, zinc, arsenic, molybdenum and lead), and they are normally evenly distributed amongst the fractions smaller than 80-mesh. Further, the spread of the results normally covers a smaller range of concentration in the sediment fines, than in the coarse material.

Other important features of the minor element distribution in stream sediments are that in sediments derived from contrasting rock types, titanium and chromium frequently display a bi-modal distribution in which these elements are concentrated in both the coarse and the fine fractions, compared to the intermediate size fractions. In addition, titanium and chromium are concentrated in successive samples with increasing distance from the stream source. These features were not investigated, but concentrations of this type, if widespread, are likely to effect the distribution of the geochemical patterns. Some of the concentrations of titanium and chromium detected in the stream sediments derived from ultrabasic rocks are taken to result from the accumulation of resistant minerals with a high specific gravity, in which these elements are normally concentrated.

The co-variant distributions of cobalt and manganese in the zone of weathering is likely to influence the geochemical patterns

It is concluded that the environmental factors which influence the physical and chemical composition of the stream sediments will have an important influence on the distribution of the geochemical patterns.

## Biological factors

### Zoological

Although micro and macrobiological factors are bound to influence the development of the regional geochemical patterns no direct

evidence of this effect, as noted by de Grys (1959) and Hawkes and Webb (1962), was observed in the field area. The physical effects of man's activities are more clearly seen and there are two main fields of activity which are likely to affect the patterns. The first, and possibly more important, is the cultivation of large areas of both siliceous and non siliceous rocks (the latter frequently forming steep hill sides) in the cultivation of 'hill rice'. In the past, this has meant the destruction of the primary forest, followed by successive growths of a dense secondary forest in an approximately seven year cycle. The effects of this form of agriculture upon the rate of erosion have not been estimated, but it has undoubtedly resulted in a much more rapid erosion on poorly protected hill slopes during periods of torrential rain storms. It follows that there will be an increased contribution of basic detritus to the stream sediments, compared to the granitic detritus which is derived from generally low lying areas.

The effect of man's alluvial mining activities in the Sula Mountains and Kangari Hills is also difficult to estimate. The stream gravels and alluvial banks of most of the drainages from which the stream sediment samples were collected have been disturbed during the last few years by mining or prospecting activities. The most obvious result is the formation of sand bars and physically separated gravel and boulder dumps. Although placer deposits, particularly of gold, and also of titanium and niobium

minerals have been discovered, it is probable that the disturbed stream sediments would be rapidly resorted in the drainage channels. A more serious aspect of alluvial mining and particularly of underground mining operations, is the contamination of stream sediments. In this respect, zinc (from zinc plated metal) and lead (lead shot) are of possible importance. Insecticides and chemical fertilizers are not generally used by rice farmers in the field area.

## Botanical

The accumulation of trace metals in some forms of vegetation is a well known feature in secondary dispersion (Hawkes and Webb, 1962), but in the present work no significant accumulations of the minor elements were found in surface soils which could be correlated with accumulation by vegetation. Although both primary forest, and secondary growth cover large areas of the ultrabasic rocks in the south part of the field area, no differences were detected in the regional geochemical patterns which could be attributed to the vegetation.

## Sample density

The form of the geochemical patterns in areas of contrasting geochemistry will be largely controlled by the density of the sample locations. Selection of the sample density is primarily

controlled by the dispersion characteristics of the element sought, but the complexity of the bedrock geochemistry is an important additional factor, as also is the density of the drainage network. The over-riding factor is the scale of operation and type of geochemical map required.

Regional geochemical maps are ideally suited to the delimitation of geochemical provinces over comparatively large areas of territory and for this purpose a broad scale reconnaissance sampling network is adequate. In areas of complex and contrasting geology, mineralogy and geochemistry, a close sample network may be necessary in order to detect the geochemical province, particularly where the large scale geological structure consists of an attenuated schist belt surrounded by granite, as in the Sierra Leone field area.

In the present geochemical map the sample density is slightly less than four per square mile. The majority of the geochemical patterns are related to the bedrock geochemistry, a geochemical province of arsenic and micro-province of molybdenum are also clearly defined. It is probable that a wider sample density of two per square mile would reflect the more widespread variations of the geochemical patterns and also define the limits of the geochemical province of arsenic. The simple patterns which result from a sample density of one per square mile are well illustrated by the geochemical map of zinc (fig. 19). The zinc patterns delimit the high contents of the schistose rocks relative to the

granites and also illustrate a few isolated concentrations within the schist belt. Whether these concentrations would form a coherent anomalous pattern if a more dense sampling pattern were employed is not known, but is evident that even on a geochemical reconnaissance map a sample density of one per square mile is inadequate to detect small scale variations in the minor element content of the bedrock.

An important factor affecting the development of the patterns whose interpretation will to a certain extent be controlled by the sample density, is the secondary dispersion characteristics of the elements sought. The behaviour of the minor elements in the zone of weathering is primarily controlled by the resistance to erosion of the mineral forms in which the elements are concentrated. Elements such as titanium and chromium, normally concentrated in heavy resistant minerals, form only short dispersion trains, a feature clearly illustrated by the geochemical maps.

In the Marofo river (map ref. 35) for example, an upstream sample was collected at the contact of the ultrabasic rocks with granite. The detritus at this point is largely of ultrabasic composition. In another sample from one mile downstream the detritus is dominantly granitic. The minor element compositions of the two samples reflect the different geochemistry of the granite and ultrabasic rocks and also illustrate the considerable depletion of chromium, cobalt and nickel (6 to 10 fold) in the downstream sample (table 25).

Table 25. Dilution of ultrabasic sediments by granitic detritus as illustrated by the minor element composition of two samples 1 mile apart

( in ppm. )

| | Ti | V | Cr | Mn | Co | Ni | Cu |
|---|---|---|---|---|---|---|---|
| Upstream sample, on contact of ultrabasic rocks with granite | >10,000 | 150 | 1000 | 900 | 50 | 450 | 20 |
| Downstream sample, on granite | 6000 | 50 | 150 | 550 | 5 | 50 | 5 |
| Background content granitic sediments | 6000 | 10 | 8 | 900 | nd | 5 | 2 |

The rapid depletion of cobalt and nickel, as with chromium, is probably due to short dispersion trains of resistant minerals in which these elements are concentrated. Alternatively, this depletion could be ascribed to a large increase in the proportion of the metal which is chemically dispersed. The titanium content of the upstream sample derived from ultrabasic rocks is also high compared to that of the downstream sample. The content of the latter sample is similar to that of the granite background sediments, 6000 ppm. This distribution is taken to indicate the short dispersion train of titanium.

By comparison, vanadium and copper are less strongly depleted (3 to 4 fold), and indicate a much longer dispersion train.

The manganese content of the upstream sample is similar to that of the background content in the granitic sediments. This similarity is unlikely to be real and is possibly due to a spurious result.

On less clearly contrasting rock types, as for instance the various mineralogical facies of the ultrabasic rocks, there are likely to be only small variations in the minor element content along the stream course.

It is difficult to obtain an overall appreciation of the different dispersions of the minor elements, due to the effects of the regional differences in soil type, but the geochemical patterns on the mixed granite and ultrabasic rocks in the eastern part of the field area allow comparisons to be made (figs. 12 to 20). The elements are listed in order of increasing dispersion; chromium, titanium, manganese, cobalt, nickel, copper, vanadium and possibly zinc. Lead is not normally widely dispersed. Obviously the sample density should be based on the characteristics of the least dispersable of the elements. From the present work, a density of four per square mile is adequate to delimit the complex chromium patterns related to the ultrabasic rocks in the eastern part of the field area, and so, in any other than exceptional circumstances, is likely to be adequate for the other elements studied.

## SUMMARY OF FACTORS AFFECTING THE DEVELOPMENT OF THE GEOCHEMICAL PATTERNS

Of the several factors which are likely to affect the development of the geochemical patterns (i.e. the bedrock geochemistry; pedology, erosion and sedimentation and biology) the bedrock geochemistry is regarded as being the most important. The other

factors are less important and influence the geochemical patterns to varying degrees, depending largely upon the resistance to erosion of the mineral form in which the minor elements are held.

The bedrock geochemistry is shown to vary widely according to the nature of the major rock types. Strong regional variations in the geochemical patterns on areas of basic and ultrabasic rocks could not be explained by the geochemistry of the bedrock, which is shown to be remarkably similar amongst the areas of basic rocks and ultrabasic rocks throughout the field area. Small variations do exist, and the chromium-manganese contents of the basic rocks near Bumbuna are shown to be slightly higher than in the other study areas of basic rocks at Basaia and Makele.

In contrast to the similarity of the minor element composition amongst areas of basic and ultrabasic rocks, certain regional differences of composition, particularly of lead, were found in the granitic rocks. These differences were found to be clearly reflected by the geochemical patterns in the stream sediments. It was also shown that the regional variations in the distribution of lead could be correlated with potassium rich synkinematic granites.

Regional variations in the pedology have a strong influence on the geochemical patterns and it has found that many of the minor elements occur at reduced levels in duricrust and indurated latosols which overlie some areas of basic and ultrabasic rocks. Some elements, for example cobalt, nickel and manganese occur at very low levels in the A and B soil horizons of residual profiles, whilst

others such as titanium, vanadium and chromium show a relative concentration in parts of the B zone and in the A zone. It is considered likely that the geochemical patterns vary according to the degree of truncation of residual soil profiles and that this effect would be an important factor if regional variations in the degree of truncation exist. The widespread areas of thin colluvial latosols in the Pampana river valley and to the south are believed to illustrate the almost complete truncation of residual soils. In these areas, with a few exceptions, the average minor element content of the soils is similar to that of the rocks and associated stream sediments, or has an intermediate composition.

There is little difference between the minor element composition of the iron poor latosols on granitic rocks, compared to the minor element content of the bedrock and the geochemical patterns in stream sediments.

The other environmental factors which are grouped under 'erosion and sedimentation' are also likely to influence the distribution of the geochemical patterns. Although the geochemical patterns are likely to be affected by variations in the composition of the sample fraction selected for analysis, in general the average contents of the stream sediments are somewhat similar to those of the rocks , except in areas of duricrust and indurated latosols.

The physical composition of the minus 80-mesh fraction of the samples was found to be constant, forming approximately 8 per cent by weight of the sample. The chemical composition varied amongst the

size fractions, but in general the maximum contents and minimum spread of the results were found in fractions smaller than 80-mesh. Other variations, for instance the co-variant distributions of manganese and cobalt and the accumulation of titanium and chromium with increasing distance from the stream source in mixed sediments derived from granite and ultrabasic rocks, are likely to have a strong influence on the development of the geochemical patterns.

Biological factors are not believed to influence strongly the development of the geochemical patterns, although there is the possibility of contamination in the drainages from the alluvial gold mining operations.

The sample density, although not a factor affecting the development of the geochemical patterns, does influence their interpretation, and from the present study a density of four samples per square mile was found to be adequate. A wider density, for instance two samples per square mile, is adequate for geochemical mapping on a reconnaissance scale with the object of detecting regional geochemical provinces, but a greater density is necessary to reflect the complex geology of the field area or to locate the source of drainage anomalies related to mineralisation.

The relative dispersion of the elements from ultrabasic rocks is briefly considered and it seems probable that elements normally concentrated in resistant minerals provide short dispersion trains compared to those elements which are normally concentrated in the easily destructable minerals.

The electrochemical environment of the stream sediments, i.e. pH and Eh, was not considered on a regional scale because of the relatively few satisfactory observations obtained.

Owing to the discrepancy between the pH values obtained from indicator papers and those from an electrical meter (a difference of one pH unit) little attempt was made to correlate the observations with the regional geochemical patterns. About 85 per cent of the pH values range between 5.8 and 6.8. It is unlikely, therefore, that the regional geochemical patterns are related to wide scale variations in the relative acidity of alkalinity of the stream waters.

Only a few Eh values were obtained and these results were not used because they were considered to be unreliable.

In conclusion, the most important factor affecting the development of the geochemical patterns is the geochemistry and mineralogy of the bedrock. The patterns are also likely to be affected by the pedology and by the variable composition of the stream sediments.

## SECTION 5

## THE ECONOMIC SIGNIFICANCE OF THE REGIONAL GEOCHEMICAL PATTERNS

### INTRODUCTION

At the beginning of this thesis the economic importance of regional geochemical surveys in defining geochemical provinces enclosing mineral occurrences of a specific type was emphasised. The economic significance of the provinces detected during the present trial survey, and of variations in the metal contents and metal associations within a given province, is considered in this section of the report. Within the Sula Mountains and Kangari Hills schist belt several types of mineral occurrence have been discovered in the past, but they have proved to be of sub-economic grade.

The most important mineral deposits are the widely distributed alluvial gold occurrences. Possible sources of this gold, if it is derived from localised vein deposits as opposed to widespread disseminations in the bedrock, have been recognised only at a few scattered locations and these cannot account adequately for the origin of the alluvial gold.

Molybdenum mineralisation occurs at several localities, either as lodes or as disseminations.

Deposits of lateritic iron ore have been the subject of detailed investigations by mining companies, but have not been developed commercially.

Serpentinites containing anthophyllite asbestos outcrop in the eastern part of the schist belt. Ilmenorutile, columbo-tantalite and monazite also occur within the area as alluvial deposits.

Of the economic minerals known to occur in the area only gold has been worked in the past and it appears unlikely, on the basis of present knowledge, that economic deposits of any other metal, with the possible exception of molybdenum, will be discovered in the foreseeable future. In the following pages particular emphasis has been placed on these types of occurrence. The mineralogical and geochemical characteristics of the known mineral occurrences are discussed in some detail, with particular reference to the possibility of establishing criteria for recognising the different types of bedrock mineralisation. These criteria are then used in the assessment of specific, possibly economically significant, anomalies detected in the geochemical survey.

Finally consideration is given to the validity of the hypothesis that regional geochemical mapping will delimit areas of economic potential, and the conclusions reached on the interpretation of individual anomalies are summarised.

## DESCRIPTION OF KNOWN MINERAL OCCURRENCES

### General

Several types of metal associations occur in the Sula Mountains and Kangari Hills schist belt which are related to gold and

molybdenum mineralisation. The gold deposits associated with concentrations of the minor elements which have warranted investigations by the Geological Survey are situated on the banks of the Yirisen river near Maranda and near Baomahun. Of these only the Baomahun lode (outside the area covered by the present report) has been mined underground.

The gold mineralisation at the Yirisen deposit is accompanied by a heavy impregnation of arsenopyrite, and much smaller quantities of lead, antimony, copper and zinc sulphide minerals. At Baomohun the only minerals which have been reported to accompany the gold (Marmo, 1962b) are arsenopyrite, and lollingite (arsenical pyrite). As at Yirisen, arsenopyrite is heavily impregnated in the wall rocks of the Baomohun lode.

Several other quartz vein gold deposits have been investigated by the Geological Survey, but these are not accompanied by concentrations of the trace metals.

Alluvial gold has been recovered from a large number of the drainage systems on the schistose rocks and no doubt the only streams to have been disregarded during the peak of the gold production are those in which the stream beds are precipitous and little alluvium has accumulated;

Arsenic mineralisation unaccompanied by gold occurs in two areas, one of which is situated two miles on strike to the south-south-west of Yirisen and the other on the Kuntaw stream near

Mabai. In both cases arsenic is concentrated in the argillaceous facies of the metasediments.

The molybdenite deposits may be classified into two types; those which occur associated with quartz veins and those in which the molybdenite is disseminated in the bedrodk.

Of the first, quartz vein type, only the Sende river deposit is accompanied by concentrations of metals other than molybdenum. Here lead, bismuth, copper and zinc sulphides occur with molybdenite in quartz veins. In the other quartz vein deposits, in the Mopoko and Tebenko rivers, the molybdenum concentrations are unaccompanied by concentrations of other metals.

The second type, in which the molybdenum is characteristically disseminated in granitic rocks, is not accompanied by concentrations of other metals. Examples of this type of deposit are situated in the Wankatana and Tebenko rivers, and near Mabeki.

In the following pages these mineral occurrences are examined with the object of determining metal associations which accompany the gold or molybdenum mineralisation. If characteristic metal associations of certain types of mineralisation can be established then these associations can be used as criteria in assessing the type of bedrock mineralisation and economic importance of the anomalous patterns detected in the regional geochemical data.

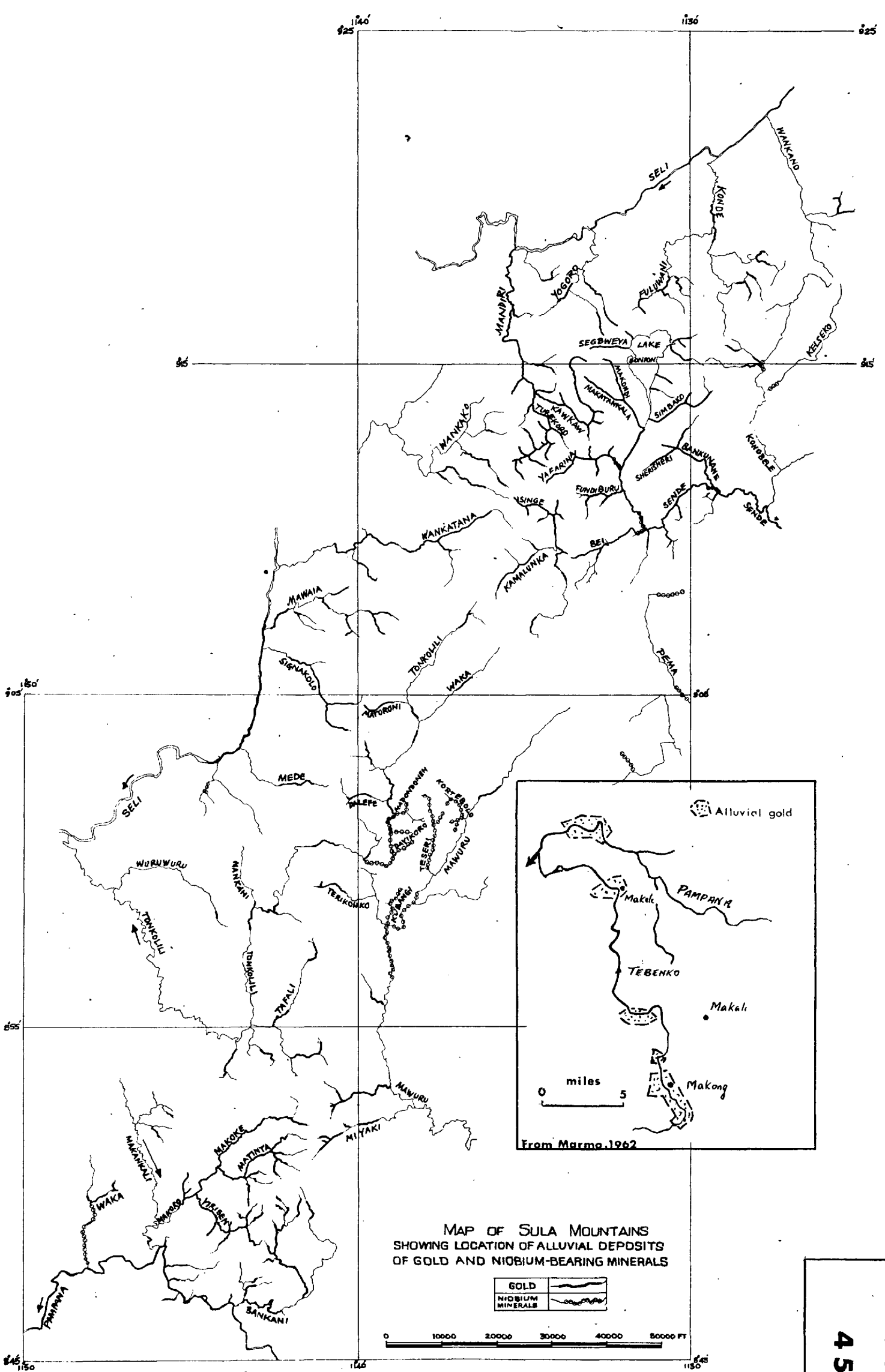
## Alluvial gold deposits

Alluvial gold is probably the most widespread of the valuable minerals discovered in the Sula Mountains and Kangari Hills schist belt. The distribution of the alluvial gold deposits has been reported by Wilson and Marmo (1958), Marmo (1962b), and is shown on a map (fig. 45) compiled by officers of the Sierra Leone Geological Survey. It is evident from the distribution of the alluvial deposits that gold is more widely distributed in the Sula Mountains than in the Kangari Hills.

In the Sula Mountains the deposits of alluvial gold are for the most part situated in drainages on the schistose rocks. Although a few small deposits occur on the dominantly granitic areas on the flanks of the schist belt, these appear to be derived from small lenses of schistose rocks surrounded by areas of granite. For example, on the west flank of the schist belt alluvial deposits in the Waka river are situated downstream of quartzite outcrops surrounded by porphyroblastic granite. The deposits in the Makankali river occur in an area where outcrops of banded ironstone are surrounded by gneissic granite.

Alluvial gold deposits situated on the main schist belt are concentrated in two areas, the larger centred around Lake Sonfon, to the north of the present study area, and the smaller centred on Maranda village (map ref. H16).

From a comparison of the distribution of the alluvial gold deposits with the geological map, between the latitude of Bumbuna




From Wilson and Marmo (1958) and Marmo (1962b).

FIGURE 45

and the Pampana river (map refs. G2 to F21), it is evident that the deposits do not favour any one rock type, but are evenly distributed over the width of the schist belt.

In the Kangari Hills, the widespread occurrence of trenches and boulder dumps on the stream banks indicates former widespread mining or prospecting activity, particularly where the stream beds are gently graded.

The only deposits specially mentioned by Marmo (1962b) which occur in that part of the Kangari Hills covered by the present study are those situated on the Tebenko river at Makele, Waka and Makong (map refs. G24, G31, I37 respectively). The drainage catchments in each of these areas include a large proportion of ultrabasic rocks, but basic and acid igneous rocks are also present. Other occurrences of alluvial gold mentioned by Marmo (1962b) are those which were worked in the Wungi and Mondemabe rivers, to the south east of the present study area.

In summary, alluvial deposits of gold are widespread throughout the Sula Mountains and Kangari Hills schist belt, and do not appear to favour any one rock type. Within the area of the present study the most important deposits were situated near Maranda, Makele, Waka and Makong (map refs. H16, G24, G31 and I37 respectively).

## Quartz vein gold deposits

In only a few cases have the bedrock sources of the alluvial gold been found. Those recorded by Wilson and Marmo (1958) and Marmo (1962b) are summarized in tables 26 and 27.

Table 26. Gold occurrences in the Sula Mountains (after Wilson and Marmo, 1958)

| Place | Lat. N. | Long. W. | Dwt./Ton Gold | Country Rock | Remarks |
|---|---|---|---|---|---|
| 1st mile of Kunantakwi | 09°15' | 11°33'30" | 4.0 | Chlorite Schist(?) | Glassy float quartz. An apparently barren gozzan outcrops at source of Kunantakwi |
| Makondi River | 09°14'20" | 11°32'20" | 0.5 | Amphibolite | Gozzanous quartz float |
| Upper Bankunane River | 09°12'30" | 11°30'20" | 0.8 | Amphibolite(?) | Gozzan float near metasomatic granite |
| East-flowing tributary of Bankunane River | 09°12'00" | 11°30'20" | 4.0 | " " | Composite sample of quartz-tourmaline near metasomatic granite. |
| Fuluwani River | 09°18'00" | 11°29'40" | 0.2 | Biotite-quartz schist | Float white quartz bearing pyrite and molybdenite near late-kinematic granite contact |
| Sende N. of Yafarina | 09°11'50" | 11°32'00" | 1.0 | Weathered banded ironstone(?) | Float from drusy quartz-tourmaline-pyrite vein on W. bank of Sende |
| Sangba, 2400' from mouth | 09°15'00" | 11°30'40" | 1.0 | Amphibolite(?) | Gozzanous walls of 10-ft. wide vertical white quartz vein. |
| Sangba, 5400' from mouth | 09°14'40" | 11°30'20" | 9.6 | " " | Gozzan float near contact with late-kinematic granite |

Table 26 (contd.)

| Place | Lat. N. | Long. W. | Dwt./Ton Gold | Country Rock | Remarks |
|---|---|---|---|---|---|
| Simbili, Numbara | | | 4.0 | Banded ironstones | In quartz stringers prospect adits |
| North Matinta | | | 1½ | " " | Float |
| South Matinta | | | 7.0 | | Quartz float |
| Dalakuru. Sende River | 09°11' | 11°32' | 0.2 | Pillow lava | LKG pegmatite and hybridised peg. with country rock. Pyrite chalcopyrite, galena, molybdenite, aikenite, zincblende, tourmaline |
| Fundiburu River north bank | 09°11' | 11°32'20" | 3.4 | | Quartz veins (max. 79" width) with tourmaline and pyrite |
| Yafarina River south bank | 09°11'50" | 11°20" | 13.4 | | Quartz tourmaline veins 5-600 ft. inferred strike 24" width |
| Tongboten River | 09°12'30" | 11°32' | 1½ | Amphibolite | Quartz tourmaline veins |
| Kawkaw River | 09°13' | 11°33'20" | 5.0 | LKG(?) | Quartz tourmaline veins |
| Kewoli River | 08°48' | 11°45' | 14.0 | | Quartz float. Loaming, no mineralised source discovered |
| Yirisen | 08°49' | 11°43' | 12.0 at surface | Talc chlorite carbonate schist | Tourmaline, arsenopyrite zincblende, galena and lead-antimony minerals |

Table 27. Gold occurrences in the Kangari Hills (after Marmo, 1962b)

| Place | Lat. N. | Long. W. | Dwt./Ton Gold | Country Rock | Remarks |
|---|---|---|---|---|---|
| Makong | | | Nuggets up to 1 oz. in weight (Troy) | Tremolite schist and serpentinite | Sugary quartz veins, visible gold and pyrite |
| Baomahun | 08°29' | 11°34' | Not recorded. Mine exists | Garnet cummingtonite schists and quartzite | Heavy arsenopyrite mineralisation tourmalinised. With gold quartz. A later arsenopyrite mineralisation suspected |

In these occurrences there is no characteristic associate of gold other than the quartz gangue, the only other mineral which commonly, but not invariably, occurs with the gold bearing quartz veins, being tourmaline. Other minerals are associated with some of the gold veins, and of these pyrite is probably the most common. The two best known and largest vein deposits, at Yirisen and Baomahun, are characterised by the presence of arsenopyrite. At Yirisen, as distinct from Baomahun, the gold and arsenopyrite are accompanied by copper, lead, zinc and antimony sulphides. Very small quantities of gold have also been detected in quartz veins which are associated with concentrations of molybdenite, as at Dalakuru and Mopoko, 0.2 and 0.56 dwts. gold respectively, but only at Dalakuru is molybdenite accompanied by other sulphide minerals (Cu, Zn, Pb, Bi sulphides).

It appears possible, therefore, that a proportion of the undiscovered gold deposits, whose presence is indicated by the widespread distribution of alluvial gold deposits, will be associated with concentrations of a number of elements.

As mentioned above, several elements other than arsenic are concentrated in the sulphide minerals at Yirisen and the distributions of these elements are considered in the following pages.

## The Yirisen gold-arsenic prospect

### INTRODUCTION

A limited investigation was made, during the present study, of the minor element distribution in some of the soils and stream

sediments at the Yirisen prospect. The object of this work was to establish which of the elements form anomalous concentrations, with arsenic and gold, in the stream sediments derived from the weathered and mineralised rock, so as to establish geochemical criteria by which mineralisation of Yirisen type can be recognised.

## BRIEF DESCRIPTION OF THE DEPOSIT

The Yirisen gold prospect is situated about 2 miles to the east of Musumbiri village, on the banks of the deeply incised Yirisen river (map ref. H19). The country rocks, talc-carbonate schists, enclose several quartz veins in a strongly sheared zone which is partly impregnated by arsenopyrite, and pyrite. Some of the quartz veins contain copper, zinc, lead and antimony sulphide, whilst in others, pyrite is the only sulphide mineral. Wilson and Marmo (1958), who have described the geology and mineralogy of the occurrence in some detail, have estimated an ore reserve of 485 tons, at 12 dwts. per long ton, per foot of depth (calculated from data obtained at the surface).

## PREVIOUS GEOCHEMICAL WORK

A detailed investigation of the dispersion of arsenic in the soils at the Yirisen prospect was carried out by Mather (1959), following successful preliminary investigations reported by Webb (1955). Mather, although chiefly concerned with the secondary dispersion of

arsenic in the soils, made a limited investigation of the secondary dispersion of arsenic in stream sediments. Elliott (1962) extended Mather's work on the secondary distribution of arsenic in stream sediments and waters. Both Mather and Elliott selected a small tributary, Kalm Col, rising on the strike extension of the mineralisation on the Yirisen river, as the principal site for their investigations on the dispersion of arsenic in the drainage. Unlike the Yirisen river, the Kalm Col stream is not contaminated by prospect workings.

The principal conclusions of Webb, Mather and Elliott are as follows:

SOILS

From the results of chemical analyses on soil samples collected by the Geological Survey of Sierra Leone, along traverses over the mineralised lodes at Yirisen, Webb (1955) showed that anomalous concentrations of arsenic, copper, zinc and lead were detectable in the soils above the mineralisation. Subsequent spectrochemical analyses of the same samples showed that in addition to copper and lead, silver was also present in anomalous concentrations (Mather, 1959).

Mather's principal conclusions have recently been summarised by Elliott (1962) as follows:

"Background Areas

Analyses of minus 82-mesh soil collected from a depth of 18-24 inches at distances greater than 2,000 feet from the mineralisation contain only 1 ppm. As., whilst within 1,000-2,000 feet of the mineralisation, soil overlying talc schist and amphibolite carries between 5 and 10 ppm. As. The arsenic content of synkinematic granite soils is erratic and ranges from 1-20 ppm. As. The patchy distribution of the arsenic in soils derived from this latter rock is attributed to uneven metasomatism of the granite. For the purpose of delineating anomalous zones, Mather established the threshold value of arsenic in soils at 10 ppm. As.

Analysis of the particle size fractions obtained by dry sieving the soil samples revealed an even distribution of arsenic between all the fractions and no concentrations of the element were observed in any particular sub-horizon of the soil profiles examined.

Mineralised Areas

A linear zone of arsenic rich soils 600 feet long and 100-200 feet wide carrying between 100 and 1,100 ppm. As was found by Mather in the vicinity of the Yirisen mineralisation.

A tendency for the arsenic to be associated with the coarse (plus 82-mesh) fractions rather than the fines (minus 82-mesh) was noted, and was more marked in a pit 250 feet from the mineralisation than in those nearer to it. The arsenic was found to be evenly distributed between the sub-horizons of the soil profiles examined, except in the pit at some distance from the mineralisation, referred to above, where higher concentrations of arsenic were found in the upper soils horizons.

This was taken to indicate lateral dispersion of arsenic away from the mineralisation in the upper illuvial (B) horizons of the soil profile.

In the indurated, concretionary latosols on the hill crests the arsenic content of the concretionary horizon was found to correspond closely with that of the underlying weathered rock."

Mather also noted that the position of the peak arsenic values in the weathered rock corresponds closely with the richest part of the lode, although there is no direct relationship between the arsenic content and the amount of gold associated with it.

Elliott, from observations at Kalm Col, found that arsenic is concentrated in the plus 20-mesh fraction of the background bank soils which chiefly consist of ironstone concentrations and fragments of talc schist. There was no significant difference in arsenic distribution in freely drained and waterlogged bank soil in background areas. In the freely drained soils overlying the mineralisation in Kalm Col, arsenic, maximum content 200 ppm., is evenly distributed between the particle size fractions, but in waterlogged soils arsenic was distinctly concentrated in the clay fraction.

STREAM SEDIMENTS

In the minus 80-mesh fraction of stream sediments in Kalm Col, Mather found an anomalous dispersion train half a mile in length and containing between 20 and 200 ppm. As. The strongly anomalous zone was 1000 feet in length and contained from 100-200 ppm. As. The principal source of the stream sediments was believed to be an area of soil, bordering the swampy headwaters of Kalm Col, some 20,000 sq. yards in extent, and containing between about 20 and 750 ppm. As.

Elliott, in a detailed investigation of arsenic dispersion in the Kalm Col drainage found that:

> "sediments consisted of mainly coarse material, arsenic rich latosol concretions, and nearly barren talc schist fragments, with only a small proportion of minus 80-mesh particles."

In the stream sediments of both background and mineralised areas, arsenic was found to be concentrated in the coarse and the fine fractions of the sediment and Elliott suggests that in the coarse fractions arsenic is concentrated in the duricrust and rock fragments whilst in the fine fractions, it is sorbed on the surface of active particles such as clays, and in mineralised areas, is particularly associated with hydrated iron oxides. Arsenic was not found to be associated with manganese or with organic carbon in the stream sediment samples.

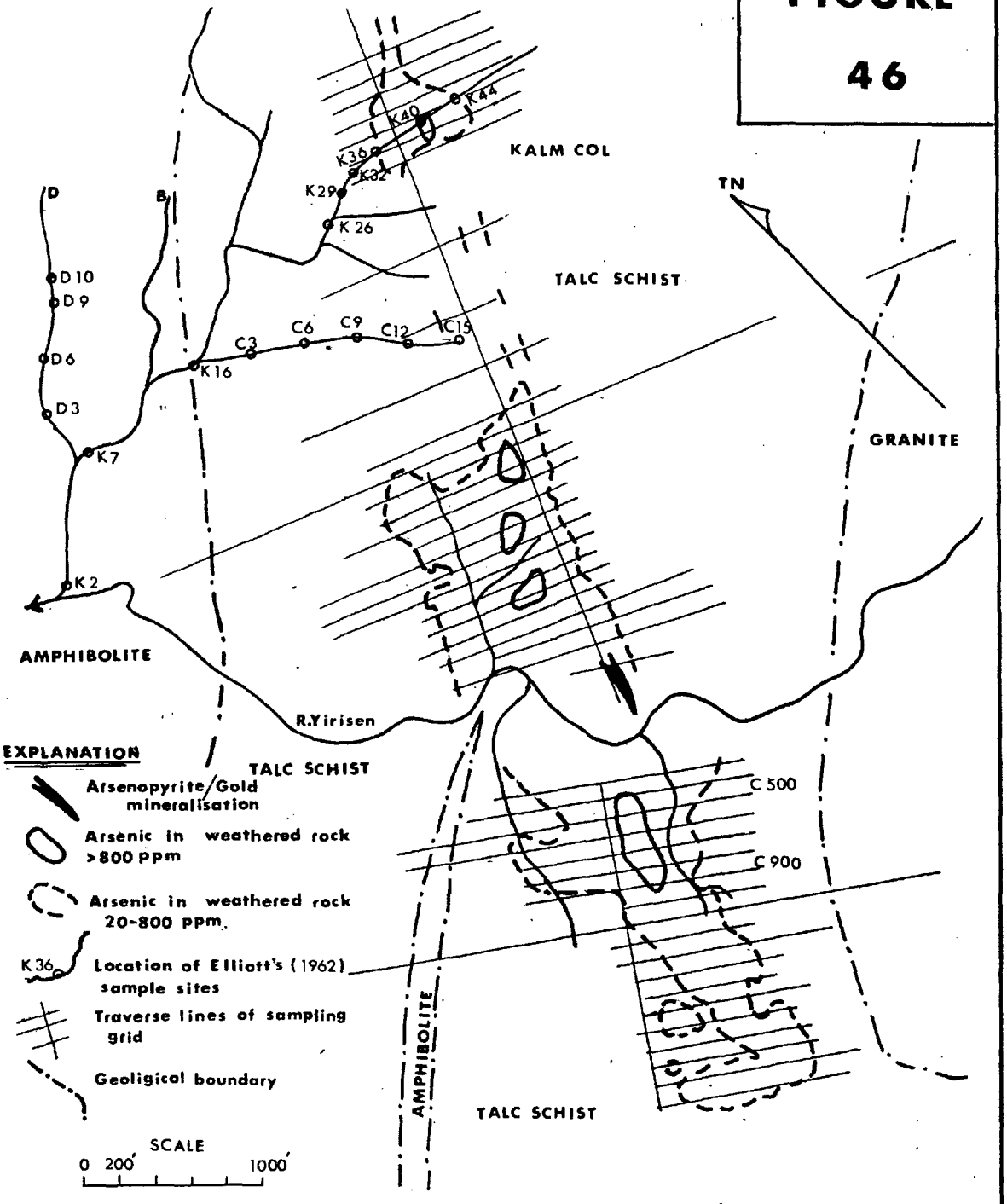
## RESULTS OF PRESENT STUDY

### MATERIAL ANALYSED

The writer, apart from a brief visit to the prospect workings, did no detailed work at Yirisen. The results of the present study are based on soil samples collected by Mather and stream sediments collected by Elliott from the vicinity of the mineralised lodes.

Two traverses of soil samples were selected for investigation, line C 500 crossing the mineralised lode on the south bank of the Yirisen river and the other, line C 900, crossing the strike extension of the mineralised lode 400 feet south of C 500 (fig. 46). Line C 500 is 2000 feet in length and traverses talc-chlorite schists, except for 300 feet at the western extremity where the bedrock is amphibolite. The bedrock on line C 900, some 800 feet in length, is talc-chlorite schist.

# FIGURE 46




**Location of soil and drainage reconnaissance sampling at the Yirisen Prospect.**

AFTER MATHER (1959). Soil sampling depth 1-2 feet.

The sampling interval along the traverse lines is 50 feet over the mineralised lode and its strike extension, but elsewhere is at intervals of 100 feet.

The soil material analysed was the minus 80-mesh fraction of dry sieved loamy soils, which include numerous deeply weathered rock fragments.

The stream sediment samples are from the uncontaminated Kalm Col drainage system (fig. 46). Streams K and C drain the mineralised strike extension of the lode in talc-chlorite schists, whilst stream D is regarded as a background stream draining amphibolite.

The sample material was analysed by spectrochemical and chemical methods, the latter being used to determine arsenic, zinc and antimony. The arsenic values reported are those obtained by Mather (1959) in both soils and stream sediments.

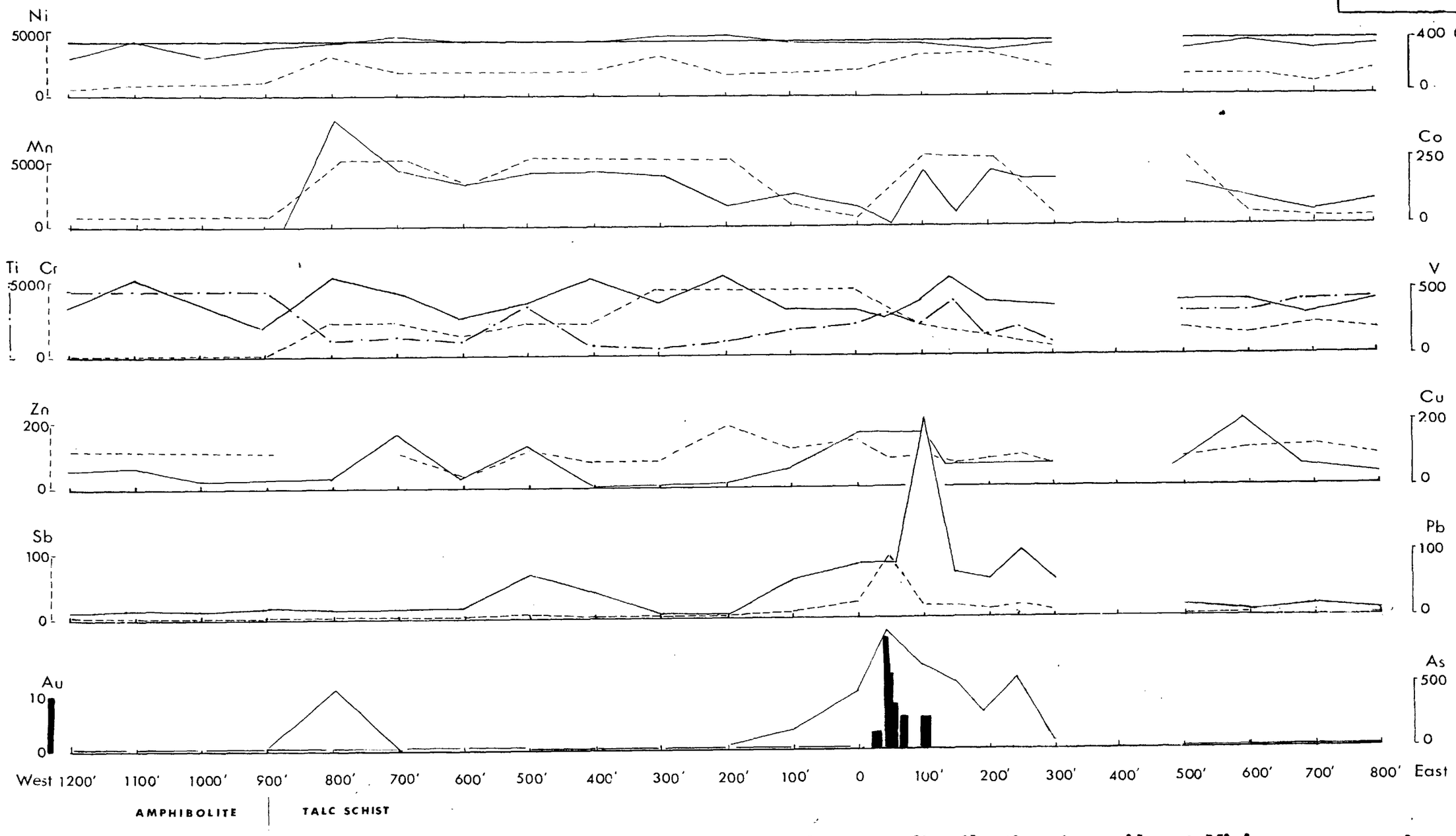
## DISTRIBUTION OF MINOR ELEMENTS IN SOILS

The analytical results of the soil traverses are presented on figures 47 and 48.

The results on the traverse which extends across the mineralised lode, line C 500, shows (fig. 47) that copper, lead and antimony are strongly concentrated in the soils over the mineralised lode and are coincident with concentrations of arsenic and gold detected by Mather (1959).

The elements chromium, manganese, cobalt and zinc show a lower concentration over the mineralised zone than in the areas flanking

**FIGURE 47**

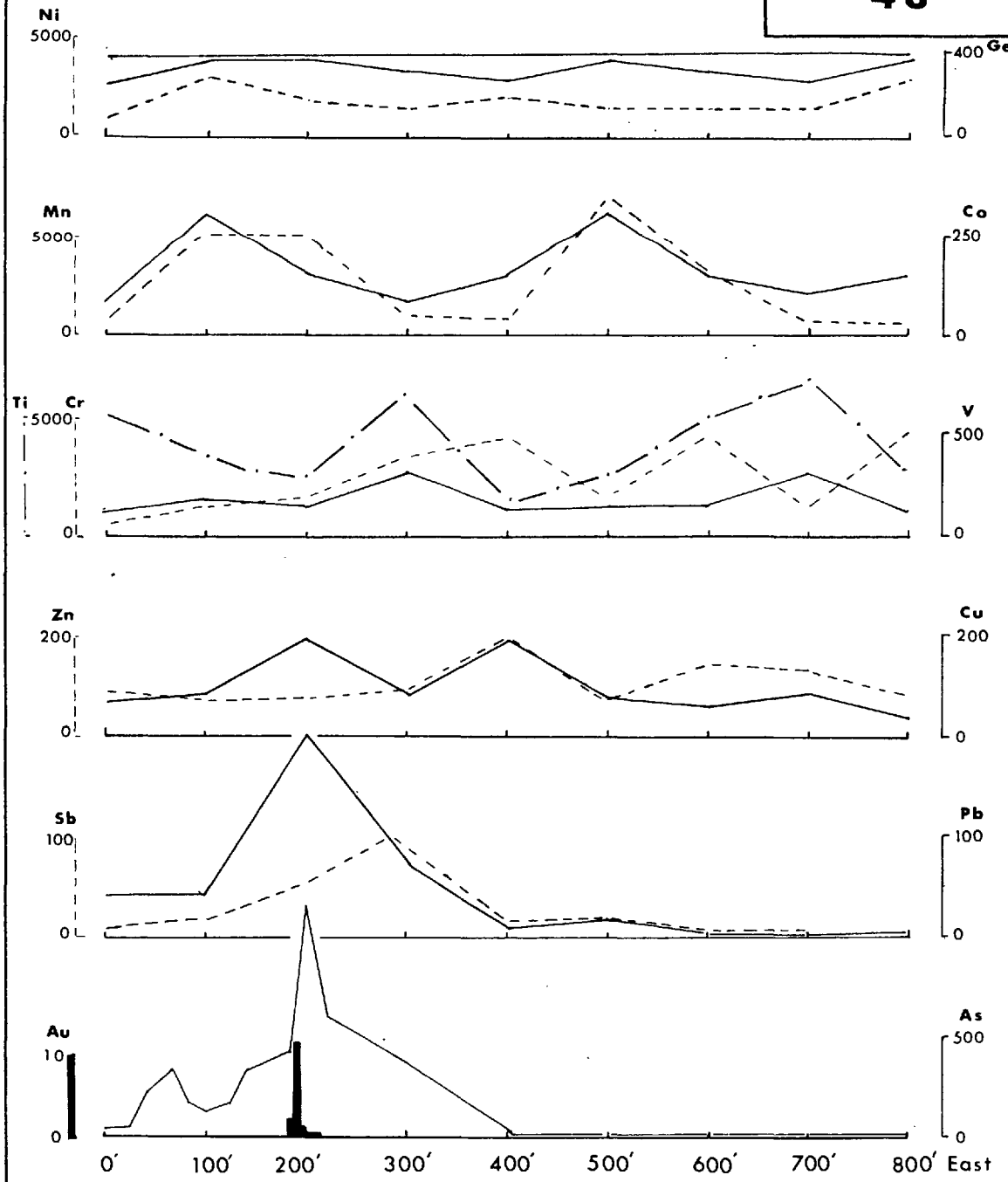



**Minor element distribution in soils at Yirisen prospect**

**Line C 500**

ELEMENT CONTENTS IN PPM Scale 1/2000

# FIGURE 48




**Minor element distribution in soils at Yirisen prospect**

**Line C 900**

Element contents ppm Scale 1/2000

the mineralised zone. There are also distinct differences in the concentration of the elements. titanium, chromium, manganese, cobalt, nickel and copper between soils on amphibolite rocks and soils on talc schists (table 28).

Table 28. Provisional background content of minor elements in soils on Line C 500, Yirisen

| Element | Talc chlorite schist | Amphibolite |
|---|---|---|
| Ti | 5000 ppm. | 10,000 ppm. |
| V | 300 ppm. | 300 ppm. |
| Cr | 5000 ppm. | 200 ppm. |
| Mn | 5000 ppm. | 600 ppm. |
| Co | 50 ppm. | N.D. |
| Ni | 2500 ppm. | 600 ppm. |
| Cu | 10 ppm. | 50 ppm. |
| Zn | 100 ppm. | 110 ppm. |
| Sb | 3 ppm. | 3.5 ppm. |
| Pb | 10 ppm. | 10 ppm. |
| Cr/V = | >1 | <1 |

In addition it is evident that the soils on weathered talc schists have a Cr/V ratio of greater than one, whilst in amphibolitic soils this ratio is less than one.

On the traverse line which crosses the strike extension of the mineralised lode (Line C 900), the results show that only the elements

arsenic, antimony and lead are strongly anomalous in soils over a zone 200 feet wide. Copper is only very weakly anomalous. The elements Ti, V, Cr, Mn, Co, Ni show an irregular distribution which is ascribed to normal background fluctuations of the metal content. Manganese and cobalt show a sympathetic variation at different levels of concentration with a ratio of Mn/Co=20. These elements do not show an anomalous accumulation over the mineralised zone. The zinc distribution, on the basis of a potassium bisulphate fusion sample attack, does not conform to the anomalous patterns shown by arsenic, antimony and lead, but displays a peak content of 190 ppm. at 200 feet to the east of the maximum concentrations of arsenic and lead. The zinc content of the sample containing the peak arsenic and lead contents is low, 70 ppm., compared to the local background of about 120 ppm.

Summary and discussion

From these results it appears that the elements arsenic, antimony, copper and lead all occur in anomalous concentrations in soils over the mineralised zone. Copper and zinc, although present in anomalous concentrations, are more patchy in distribution than the other anomalous elements. On the line which crosses the mineralised strike extension of the lodes (line C 900), the peak of

the zinc concentration is located to the east of the mineralised zone. On line C 500, over the mineralised lode, the maximum zinc contents are displaced to the west relative to the peaks of the other elements. The offset and alternate concentration of zinc relative to the peak contents of arsenic and lead is taken to indicate a patchy distribution of the zinc sulphide in the mineralised zone.

The analytical results of the orientation survey at Yirisen, reported by Webb (1955), show a much stronger contrast of the copper contents in anomalous, compared to background soils. The sample attack which was used in this work was a potassium bisulphate fusion which has been shown by Harden (1962), in the Nyawa area of Northern Rhodesia, to be insufficiently strong to extract all of the silicate bonded metals, particularly cobalt, nickel, copper and zinc, from biotite, amphibolite and pyroxene. This sample attack is, however, more than adequate for the less strongly bonded metals, for instance in sulphide minerals. Harden's observation may account for the high contrast of the copper results obtained from the bisulphate sample attacks on soils from the mineralised zone (Webb, 1955). The low contrast of the present, spectrochemical data in which broadly similar results were obtained from both mineralised and non-mineralised soils is accounted for by the fact that the spectrochemical method will detect the total amount of metal present, irrespective of the mineral form in which it is held.

There are obvious differences in concentration of the elements Ti, Cr, Mn, Co and Ni, in the soils on amphibolites compared to the soils on talc schists. The present results show that freely drained residual soils on amphibolitic rocks can be distinguished from similar soils on ultrabasic rocks on the basis of the Cr/V ratio.

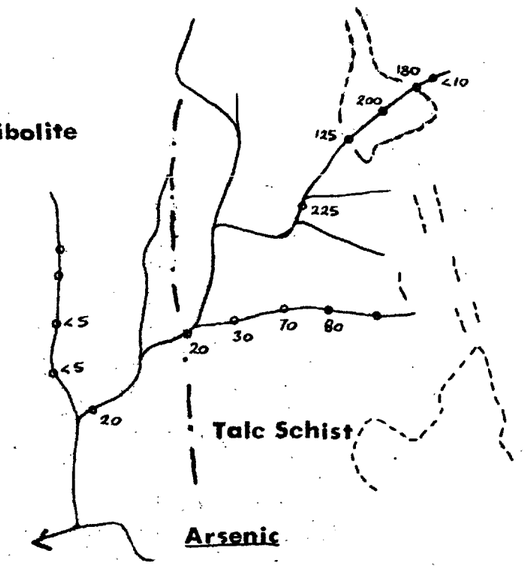
In summary, arsenic, antimony and lead are concentrated in soils overlying the mineralised auriferous zone. Zinc and copper are also concentrated but the contrast of the anomalous to the background concentrations is much less than that of arsenic, antimony and lead. It is very probable that an increased contrast would result from the use of analytical techniques employing a partial sample attack, by which concentrations of elements occurring as sulphide minerals would be detected, whilst elements bonded in the lattices of rock-forming silicate minerals remain undetected.

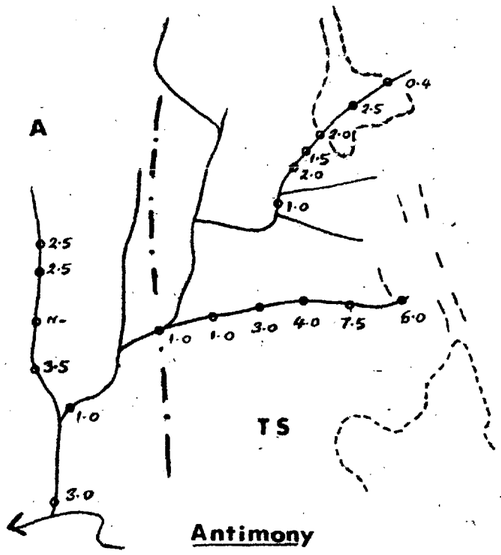
## DISTRIBUTION OF THE MINOR ELEMENTS AND IRON IN STREAM SEDIMENTS

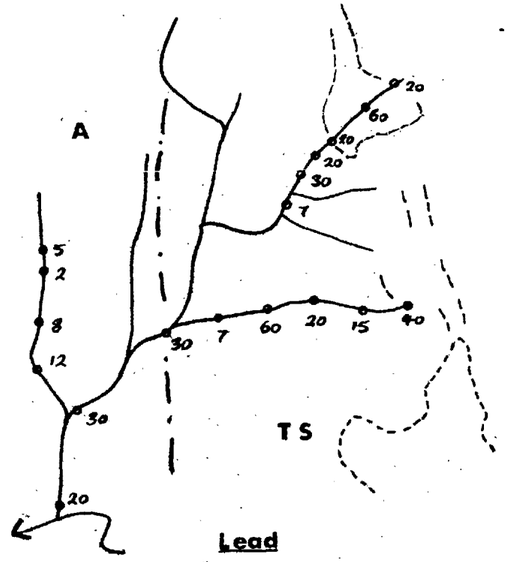
The stream sediments in the Kalm Col drainage system were analysed in order to recognise any anomalous concentrations of metals associated with arsenic. The results show that lead and antimony are so concentrated. Copper and zinc which are erratically concentrated in the soils, do not form anomalous dispersion trains in the sediments.

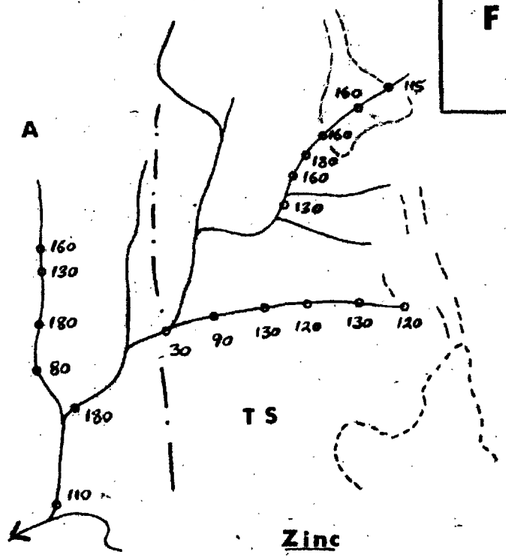
The analytical results are illustrated on figure 49.

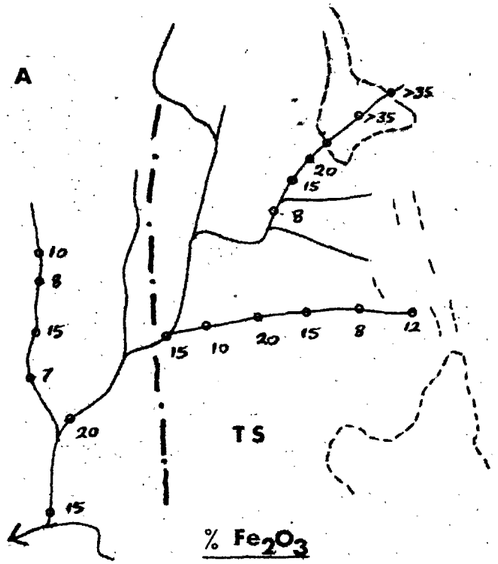
FIGURE 49

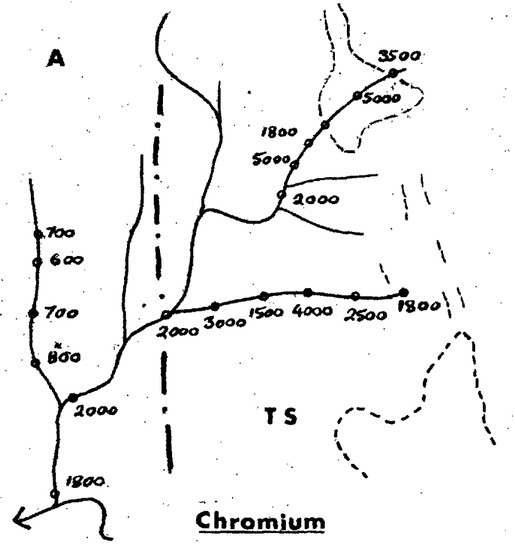


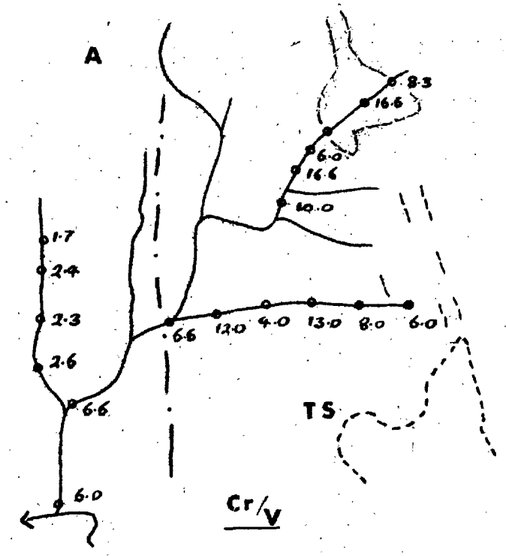



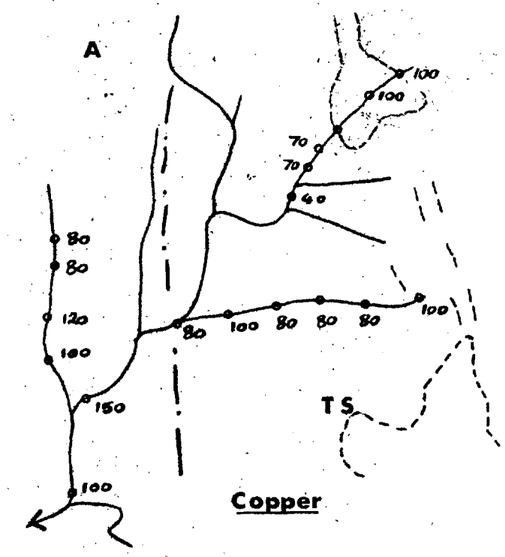




OUTLINE OF DRAINAGE AND ARSENIC FIGURES, AFTER MATHER (1959).
PRESENT DATA FROM SAMPLES COLLECTED BY ELLIOTT (1962).

Scale
1000 feet

EXPLANATION
GEOLOGICAL BOUNDARY
ARSENIC IN WEATHERED ROCK 20-800 ppm

**MINOR ELEMENT DISTRIBUTION IN THE KALM COL DRAINAGE.**

Arsenic

The arsenic results illustrated in figure 49 were obtained by Mather (1959) on minus 80-mesh material, collected from sample sites within a few feet of those used by Elliott (1962). The arsenic contents of the sediments from streams K, 125 to 225 ppm., and C, 20 to 80 ppm., which drain the mineralised zone, reflect the high arsenic content in the soils and show a strong contrast with the results from the background values in stream D of less than 5 ppm.

The erratic arsenic contents of the sediments close to the confluence of Kalm Col with the Yirisen river, have been ascribed to the dilution effects of sediments from barren tributaries which become mixed with the arsenic rich sediments derived from the Col and stream C (Mather, 1959 and Elliott, 1962). Some 3000 feet downstream from the soil anomaly in stream K, the arsenic content of the stream sediments is 20 ppm. This concentration is strongly anomalous compared to the regional background concentration of less than 5 ppm. The threshold concentration of arsenic is about 5 ppm., which is the limit of detection of the analytical method.

Copper

Unfortunately the Kalm Col drainage system does not include a 'background' tributary draining unmineralised ultrabasic rocks. Since the copper contents of sediments derived from basic rocks are frequently greater than those of ultrabasic rocks (fig. 18), it is not possible to determine whether the mineralised ultrabasic

sediments are anomalously high in copper. Compared to the copper content of the soils, however (table 28), the copper contents of the Kalm Col sediments are high. Copper sulphides accompany gold mineralisation and it is most probable that the ratio cxCu:Cu would provide a pattern which would reflect in stream sediments, the anomalous copper contente detected in the soils (Webb, 1955; Coope and Webb, 1963).

Zinc

The zinc contents of the stream sediments in the Kalm Col drainage system, 90-180 ppm., are also of approximately similar range as in the background tributary 'D', 80-180 ppm. The similarity of these results is unexpected, because the analytical method (incorporating a potassium bisulphate sample attack) is only partially effective in breaking down some mineral forms (Harden, 1962). Although the minerals forming the two rock types (amphibolite and talc chlorite schist) are likely to resist the bisulphate attack to different degrees, it is clear from the zinc results that the mineralised stream on ultrabasic rocks cannot be distinguished from the background streams on basic rocks. As seen in the copper results, there is the possibility that the ratio cxZn:Zn will distinguish sediments containing a large proportion of readily extractable zinc, such as those derived from a mineralised source.

Antimony

The peak contents of antimony, 6 to 7.5 ppm., were obtained from the source of stream 'C', and are slightly greater than in

stream K, where the content 1000 feet downstream of the arsenic soils anomaly is 1.0 to 2.5 ppm. Sb. The antimony content of the sediments of the background stream D is between 2.5 and 3.5 ppm. From these results it is possible that either the amphibolite includes antimony mineralisation, or that the background content of this element in amphibolitic sediments, 3.0 ppm., is greater than in talc schist sediments, 0.5 ppm. These possibilities have not been followed up in the field.

Lead

The lead content of stream sediments derived from the Kalm Col arsenic rich weathered rock is anomalous compared to the contents of the background stream. Anomalous lead contents are detected in streams K and C, 15-60 ppm., for about 1000 feet downstream of the mineralised zone, and continue at levels between 20-30 ppm. Pb for 3000 feet, to the confluence with the Yirisen river. The lead contents of the background stream 'D' range from 2-12 ppm. Pb. It is assumed that these lead contents are derived from lead sulphide mineralisation which is known to occur with the gold lodes at Yirisen.

Chromium

Chromium displays characteristically lower levels of concentration in amphibolites compared to talc chlorite schists.

In sediments derived from the amphibolite stream D, the chromium content is between 600 and 800 ppm., compared to 1500 and 5000 ppm. in the talc chlorite schist sediments of streams K and C.

In soils, the ratio Cr/V = less than one. is characteristic of an amphibolitic bedrock. In stream sediments, however, the Cr/V ratio in amphibolitic detritus is less than three, whilst in talc chlorite schist sediments the ratio is greater than three.

Iron

The iron oxide contents of samples from the swampy headwater drainage of Kalm Col are greater than 35 per cent $Fe_2O_3$, within the area covered by the arsenic anomaly (greater than 20 ppm. As). The iron contents decrease to 8 per cent $Fe_2O_3$ at about 1000 feet further downstream, but increase to between 15-20 per cent $Fe_2O_3$ where the stream flows on amphibolitic rocks. The iron contents in sediments from the mineralised tributary 'C' are high, 8-20 per cent $Fe_2O_3$, but not outstandingly high compared to the iron contents of the background stream 'D', 7-15 per cent $Fe_2O_3$ (fig. 49).

Summary and discussion

From the present results it appears that arsenic provides the strongest contrast (30 fold) between the peak and background contents in the Kalm Col drainages whilst the contrasts of lead (6 fold) and particularly of antimony (2 fold) are comparatively weak. For this reason arsenic and lead are the elements which are considered

to be of the greatest value in detecting mineralisation of Yirisen type. Copper and zinc, although shown to be present in anomalous concentrations in the soils over parts of the mineralised zone, appear to be somewhat erratically distributed, and are not concentrated in the Kalm Col drainage system. It is suggested that the ratios cx:Me (readily extractable:total extractable metal) for the elements copper and zinc would probably disclose a contrast between the background and anomalous arsenic drainages.

The ratio Cr/V = less than three in amphibolitic sediments and the ratio Cr/V = less than one as determined from weathered amphibolite is of interest and may be of value in determining the origin of the stream sediments and so indicate the possible background levels of the other minor elements.

## CONCLUSIONS FROM PRESENT WORK

The elements lead and antimony are shown to be concentrated in freely drained residual soils overlying the mineralised zone at Yirisen, and these elements also provide anomalous dispersion trains in the Kalm Col drainage. The contrast between the peak and background content of lead is greater than that of antimony.

The width of the arsenic anomaly in the soils at Yirisen is about the same as that of lead and antimony, but the low concentration of the antimony dispersion train in the Kalm Col drainage is taken to indicate the patchy distribution of the antimony mineralisation, rather than a saline dispersion in the stream sediments.

Copper and zinc show a patchy distribution in the soils which is possibly related to an erratic distribution of the mineralisation. Neither copper nor zinc forms anomalous dispersion trains in the Kalm Col sediments, but it is suggested that the cx:Me ratio might reveal anomalous values for these elements.

It is shown that the Cr/V ratio can be used to distinguish soils associated with basic rocks from those associated with ultrabasic rocks. It follows from the normal distribution of the elements. that soils and stream sediments with a Cr/V ratio of less than one and less than three respectively (basic rocks) will usually be associated with higher contents of copper than soils and stream sediments with a ratio of greater than one and greater than three respectively (ultrabasic rocks).

## Arsenic deposits

From the regional geochemical survey a large number of anomalies were detected in stream sediments which could not be explained as dispersions from the known mineral occurrences. A number of these anomalies were selected for further investigation, on the basis of their different metal associations. In the course of this work two of the arsenic anomalies were traced to their source, one in the Randahuna river near Maruba and the other in the Kuntaw river near Mabai.

The Maruba arsenic prospect

## INTRODUCTION

This arsenic anomaly was considered to be of special interest because of its location at the centre of an arsenic rich area, a content of 80 ppm. being detected in the original survey. In addition, the prospect is situated about two miles to the south west of and on the same strike as the Yirisen gold-arsenic prospect.

## DESCRIPTION OF THE FIELD AREA

The source of the arsenic concentration is mainly situated on the south bank of the Randahuna river, 1500 feet upstream from the confluence of this stream with the Pampana river, at latitude N 8°47'30", longitude W 11°45'30" (fig. 50, in Part 2).

The topography of the area is strongly influenced by the course of the Pampana river, the steep slopes and flat tops of the lower hills being suggestive of old river terraces. The flood plain of the Pampana river forms the banks of the Randahuna river for about 400 feet upstream from the confluence, but above this point for a distance of 1400 feet the banks are incised and particularly on the south side are very steep. The stream bed falls 55 feet in a 1000 feet and there are many small waterfalls.

Upstream from this section, the banks are low and the fall of the stream bed is gentle and there is evidence of alluvial mining or prospecting activity. The headwater drainage channels form a

dendritic pattern amongst steep hill slopes, and include a catchment area of less than one square mile.

The geology of the area is complex, for the metasediments, amphibolite and ultrabasic rocks, possibly repeated by folding, are exposed in the stream bed. For a distance of 900 feet upstream from the Pampana river there are no outcrops, but from here to a position 2000 feet upstream from the confluence, outcrops are numerous. A mainly arenaceous facies of the metasediments is first encountered, the quartzites containing, in some places, heavily disseminated fine grained crystals of pyrite, and smoky blue coloured chert veins, striking across the river. These rocks form bold outcrops in the river bed and support a slight ridge on the north bank. There appears to be rapid change of facies at a position 1200 feet upstream from the Pampana river; above this point the outcrops are less frequent and where exposed, the rocks are schistose and include rare, thin quartz veins or knots of glassy quarts. The geology was not examined further upstream than 2000 feet from the confluence, but from the geological map, narrow strips of amphibolite alternate with ultrabasic rocks.

The soils developed over the different facies of the metasediments are in part residual, colluvial and alluvial, the alluvial soils being confined to the flood plain and stream banks. The soils on the arenaceous horizons are usually thin, less than three inches, whilst on the argillaceous rocks they are often deeper than twelve inches.

The vegetation is all secondary growth and it is probable that the area was last cleared by rice farmers during 1959.

## PREVIOUS WORK

Wilson and Marmo (1958) have reported the discovery of chalcopyrite bearing quartz float, containing 14 dwts. of gold per long ton, in the Kewoli river about half a mile to the north and on the same strike as the present field area. A follow up programme which involved loaming an area of two square miles in extent failed to discover any mineralisation of interest.

Mention has been made of evidence of alluvial gold prospecting in the Randahuna stream and shallow contour trenches were also dug on the steeper south bank. These trenches are now largely obscured by the vegetation and are partly filled by soil, probably resulting from sheetwash and soil creep.

## RESULTS OF PRESENT INVESTIGATION

Following the discovery of the arsenic anomaly in the regional geochemical survey, the stream sediments and the bank soils were sampled at 300 feet intervals. The analyses of these samples indicated a well-defined arsenic anomaly in the stream sediments, the upstream margin of the anomaly being situated in the area of schists, upstream from the pyritic quartzites, at a position 1200 feet from the Pampana river. In the bank samples the highest arsenic contents were detected in the red coloured soils on the south side of the river.

A subsequent soil grid sampling programme disclosed an arsenic anomaly, the peak concentration being 2400 ppm., in the soils on the south bank. A molybdenum anomaly, the peak being 12 ppm., was detected in the soils on the north bank of the river (fig. 50). The arsenic and molybdenum anomalies are apparently unrelated, the molybdenum anomaly being situated over the pyritic quartzites and the arsenic anomaly over the schists. The arsenic mineralisation was not discovered in this preliminary programme.

Although gold was recovered from alluvial deposits in the Randahuna river, only trace quantities of gold were detected in the arsenic and molybdenum rich soils. The arsenic and molybdenum concentrations are presumed to be barren of gold.

ROCKS

Some 30 samples of slightly weathered rock were examined from outcrops exposed in the banks and the bed of the Randahuna river. Upstream, close to the arsenic anomaly, the outcrops were dominantly of schistose argillite containing rare, thin quartz veins. Downstream and in the vicinity of the molybdenum anomaly, the rocks were largely arenaceous and frequently contained abundant and very fine grained (0.5 mm.) crystals of iron pyrites. The quartzites often included thin quartz veins and lenticular masses of grey coloured chert, which also contained pyrite crystals.

No outcrops were seen to contain arsenopyrite or molybdenite, and only small quantities of these elements were detected in the rock samples analysed. One sample of the pyritised chert contained 120 ppm. As (table 29).

Table 29. Trace metal contents of 3 rock samples exposed in the Randahuna river

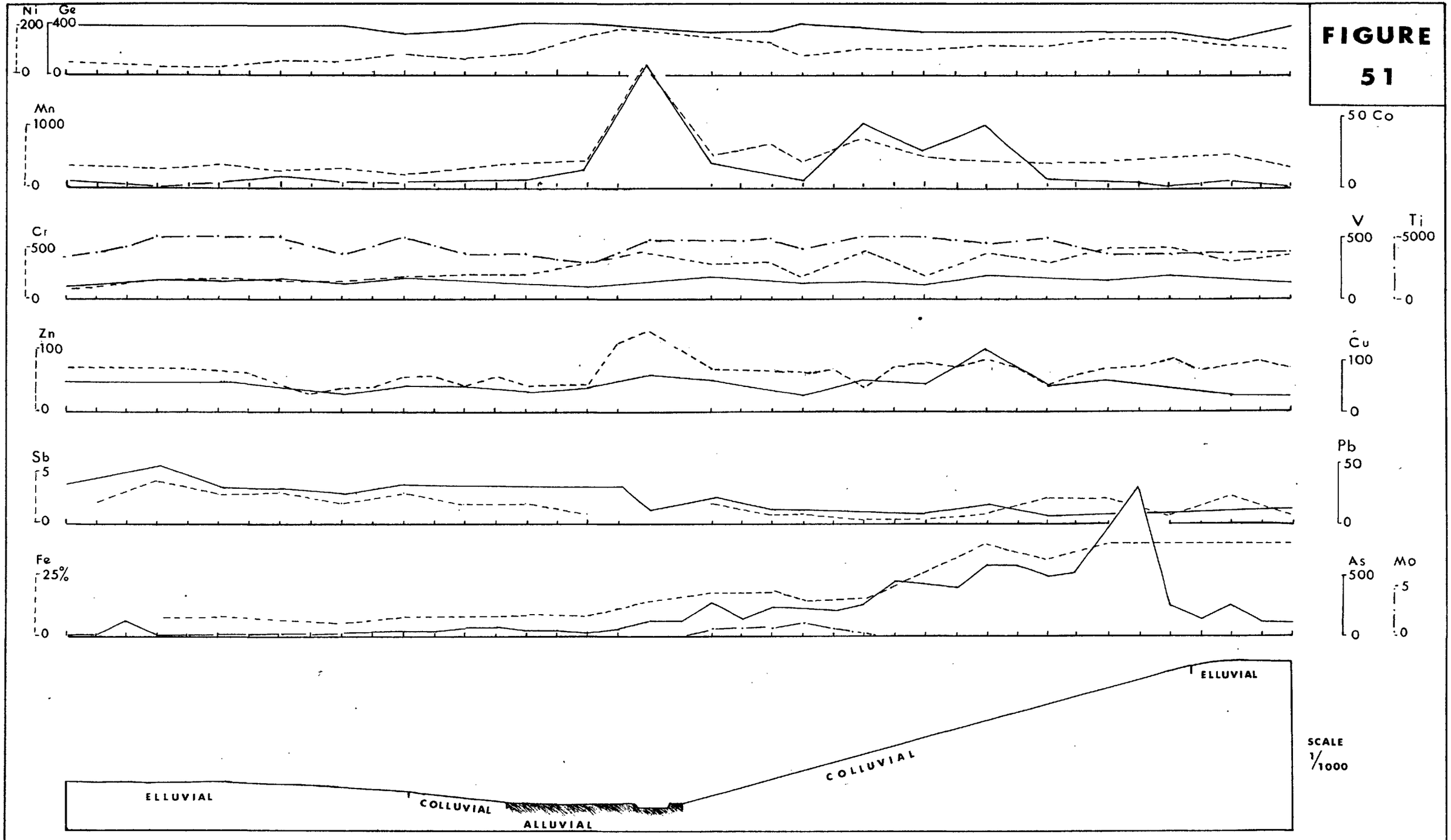
| Sample No. | Rock type | Mineralisation | ppm. | | | |
|---|---|---|---|---|---|---|
| | | | Bi | As | Mo | Au |
| 6630 | quartzite | pyrite | 10 | 20 | 30 | trace |
| 6641 | chert | pyrite | - | 120 | 20 | not detected |
| 6642 | quartzite | pyrite | 10 | 10 | - | not detected |

SOILS

Analytical results of the soil samples were plotted for iron and all of the minor elements recorded, but only the distributions of arsenic and molybdenum are shown on all of the sample lines (fig. 59). The distribution of the elements. Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Pb on line 3 is typical of the distribution of these elements on the other lines (fig. 51).

Only arsenic is strongly concentrated in the soils at the Maruba prospect. Molybdenum is present at very much lower concentrations and is probably unrelated to the arsenic concentration. Metals such as gold, antimony, lead, copper and zinc, typically concentrated in the soils over mineralised lodes at Yirisen, are not concentrated at Maruba.

**FIGURE 51**




**MARUBA ARSENIC PROSPECT. Distribution of minor elements and iron on Line 3**

Element content in ppm.

## Iron

In the west part of line 3 the soils contain 8 per cent $Fe_2O_3$, increasing in the alluvium bordering the Randahuna stream to about 15 per cent $Fe_2O_3$. The iron content of the soils on the steep slopes to the south of the stream is very much greater, and is generally more than 20 per cent $Fe_2O_3$ and more than 35 per cent in the region of the arsenic anomaly. At the eastern extremity of the line, however, it is noticeable that the iron content is greater than 35 per cent $Fe_2O_3$, although the arsenic content is low at about 100 ppm. This distribution is suggestive of an iron rich soil independent of arsenical mineralisation, which could possibly be related to pyrite mineralisation.

The iron contents of the shallow soils developed on the pyritised arenaceous metasediments range from 15 to 20 per cent $Fe_2O_3$. This is much less than in the region of the arsenic anomaly, and in the iron rich soils at the extreme eastern end of the sample line. The non accumulation of iron on arenaceous soils is probably due, amongst other factors, to the more rapid leaching of iron from freely drained siliceous soils than from the thicker loamy soils overlying the argillaceous rocks.

## Arsenic

The threshold content of arsenic in the soils at Maruba is about 40 ppm., and rises to greater than 400 ppm. in a generally

linear zone of reddish soils which strike in a west-south-west direction, on the south bank of the Randahuna stream. Contents of greater than 800 ppm. of arsenic are confined to a peak zone 50 feet in width, which also includes a few samples of greater than 1600 ppm. and a maximum content of 2400 ppm. The strongly anomalous zone of greater than 800 ppm. As extends beyond the limits of the present sample coverage.

The arsenic anomaly is asymmetrical, and the arsenic contents diminish rapidly from greater than 1600 ppm. to less than 50 ppm. in a distance of 100 feet on level ground, on the upstream side of the anomaly peak. On the downstream side, the angle of slope is about $-15^{\circ}$ towards the stream, and anomalous arsenic contents were detected for about 400 feet down this slope.

Although the dominant arsenic anomaly is situated on the south side of the stream, there are several small, frequently single sample concentrations of arsenic to the north of the stream which, although they are apparently discontinuous with the arsenic contents of samples from the adjacent traverse lines, probably strike in the same general direction as the main anomaly.

Molybdenum

Anomalous contents of molybdenum are present in the soils bordering the arsenic anomaly on the banks of the Randahuna river. The background content of molybdenum is lower than the limit of analytical detection, 1 ppm., and the peak concentration is only

12 ppm. Molybdenum contents in soils between 1-12 ppm., form a coherent pattern which strikes in a north-east to south-west direction and extend across the stream and the flanking strip of alluvial soils.

The peak of the molybdenum anomaly is situated in residual soils which rest on an arenaceous horizon of the metasediments, close to the north bank of the stream. The arenaceous rocks are resistant to erosion, and the intermittent outcrops form a narrow ridge. It is possible that the wide area in which the molybdenum concentration ranges from 1-12 ppm. is probably partly due to downslope dispersion of the metal.

Gold

Ten samples of soil whose arsenic contents ranged from 580 to 2400 ppm., and one arsenic poor sample, 105 ppm., were analysed for gold by the fire assay method. No gold was detected in 10 of the samples, but a trace was observed in sample no. 6621, which is situated within the area of the molybdenum anomaly and also contains 1160 ppm. arsenic.

Copper

The background content of copper in the alluvial and colluvial soils is about 50 ppm., and this concentration is only exceeded, on line 3, in one sample, whose copper content is 100 ppm. This sample

is situated about 150 feet downslope from the peak of the arsenic anomaly, and is not substantiated by high copper contents in samples from the adjacent lines. Copper does not appear to be associated with concentrations of arsenic or molybdenum.

Zinc

The results of the zinc analyses are slightly more erratic than those of copper; the background content is about 70 ppm., and no anomalous concentrations appear to be present in the residual and colluvial soils. In the alluvium, however, the zinc content increases to about 150 ppm., showing a somewhat similar distribution to that of manganese and cobalt.

Antimony

The background content of antimony is about 3 ppm. in residual soils in the north side of the stream. On the south side, however, the antimony content is reduced to about 1 ppm., and increases to 2.5 ppm. in the soils which contain the peak arsenic contents. While it is possible that antimony accompanies the arsenic, the very low contrast of the anomaly could result from an enrichment by some feature of the secondary dispersion of this element.

Lead

As with antimony, the lead contents of the soils on the north bank of the stream are somewhat higher, 25 ppm., than on the south

side, 10 ppm., in which the arsenic anomaly is situated. This distribution is the reverse of the concentration of iron in the soils and may possibly be partly due to analytical bias resulting from a matrix effect (see SECTION 2).

Titanium, vanadium and chromium

There is only a slight variation in the contents of titanium, vanadium and chromium in the residual, colluvial and alluvial soils, and this variation is taken as being consistent with normal fluctuations in background concentration.

The background contents are estimated to be 8000 ppm. Ti; 200 ppm. V; and 300 ppm. Cr. There is no apparent accumulation of these elements either in the alluvium, or at the base of the valley slope.

Manganese and cobalt

Manganese and cobalt show a sympathetic variation in the residual, colluvial and alluvial soils, with a Mn/Co ratio of 80. Both elements, but particularly cobalt, show increases from the background contents of 400 ppm. Mn and 5 ppm. Co, to levels of 800 ppm., and 50 ppm. respectively, in the colluvial soils about 150 feet downslope from the peak of the arsenic anomaly. The reason for this fluctuation was not investigated.

Nickel

The background content of nickel varies between 60 ppm. on the north side of the stream, to 100 ppm. on the south side of the stream. Nickel is concentrated in the alluvial soils flanking the river bed, and here the content in the soils is about 150 ppm.

STREAM SEDIMENTS

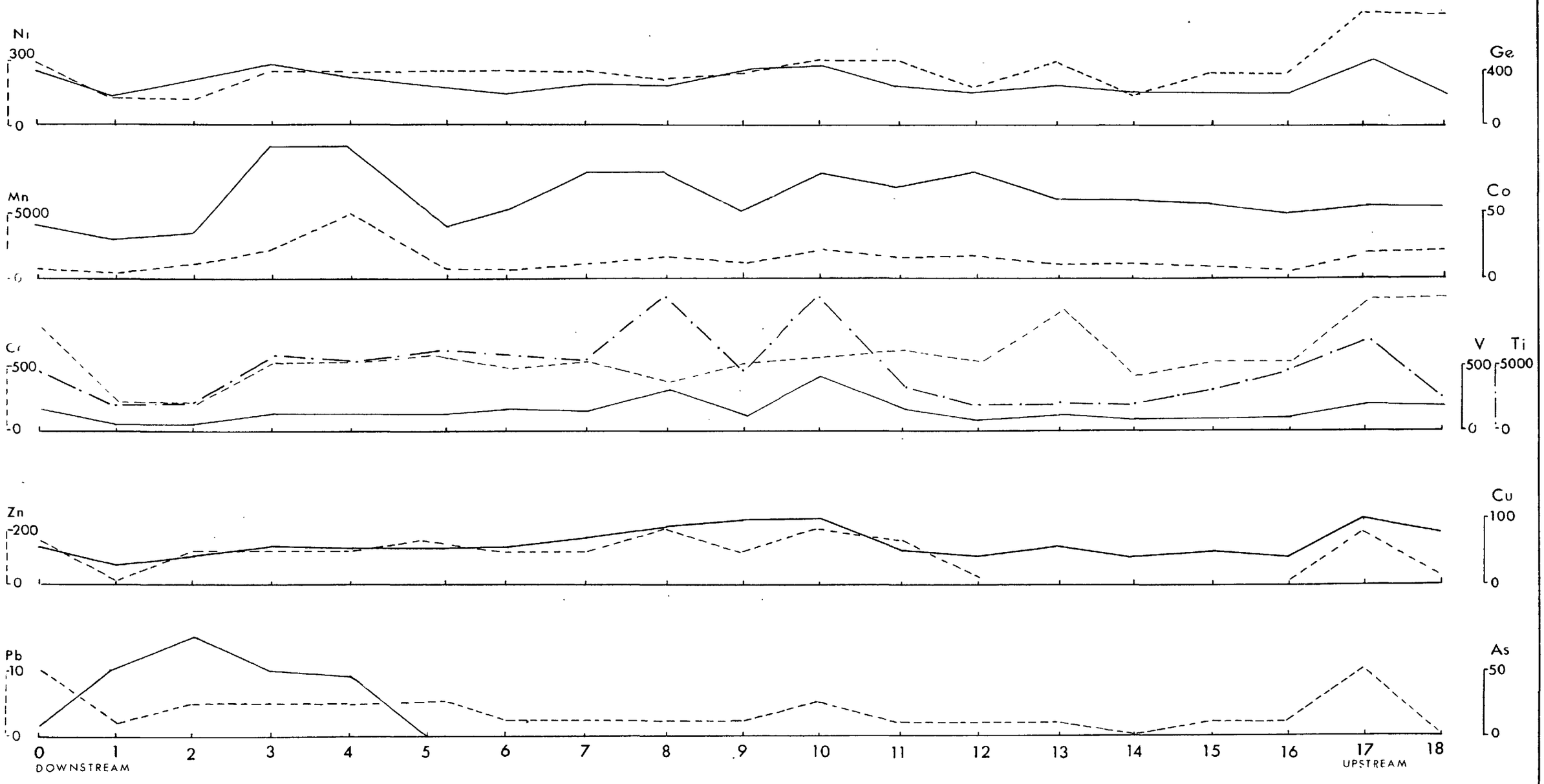
Arsenic is the only element which forms a distinctly anomalous dispersion train in the stream sediments (fig. 52). Slightly higher contents of manganese than usual occur in two of the arsenic rich samples and slightly higher contents of cobalt occur in one of these samples. The variations of concentration shown by the other minor elements are ascribed to normal fluctuations in the background.

The positions of the stream sediment samples were marked by pegs; samples were collec'ed at intervals of 300 feet from peg zero at the confluence of the Pampana river to peg 18 at the source. The peak arsenic contents were detected at peg 2, and the upstream margin of the arsenic anomaly is marked by peg 5.

Arsenic

The peak of the arsenic-soil anomaly would be expected from figure 50 to cross the stream bed at peg 6, but arsenic was not detected in the sediments at this point. Downstream, at peg 5, the sediments contained 5 ppm. arsenic and thereafter the content rapidly

**FIGURE 52**




**Maruba arsenic prospect. Minor element distribution in stream sediments.**

ELEMENT CONTENT IN PPM SCALE IN 1/5000

increases to a maximum of 90 ppm. at peg 2. The dispersion train is truncated by the Pampana river at peg zero, where the arsenic content of the muddy sediments is only 5 ppm.

Molybdenum and antimony

Molybdenum was not detected in the stream sediments and the samples were not analysed for antimony since only background concentrations were detected in the soil samples.

Copper

The background content of copper is about 50 ppm., but increases to 100 ppm. for a distance of 600 feet between pegs 8 and 10. It then falls to 50 ppm. in all but the extreme headwater samples where the content again increases to about 100 ppm.

Zinc

The zinc content of the stream sediment samples ranges from below the limit of detection to 200 ppm., but this variation appears to be due to a fluctuation of the background concentration.

Lead

The stream sediment samples contain from 2 to 5 ppm. lead. In the vicinity of the arsenic anomaly 4 samples contain 5 ppm., in contrast to 2 ppm. detected in the upstream samples. A headwater sample contains 10 ppm.

Titanium, vanadium and chromium

The titanium content of the stream sediments varies between 2000 and 10,000 ppm. The distribution of vanadium follows that of titanium but at levels between 100-400 ppm. Chromium is most concentrated in the headwater samples, 1000 ppm., and shows a gradual depletion in the downstream sediments where the content is about 500 ppm. The ratio Cr/V = greater than 1 is a characteristic of these stream sediment samples.

Manganese and cobalt

The highest manganese content, 500 ppm., corresponds with the arsenic anomaly and also corresponds with high contents of cobalt, 100 ppm., but cobalt is also erratically concentrated in some of the upstream samples. There is the possibility that these elements are associated with the arsenic concentrations, but this is unlikely and was not investigated.

Nickel

Only minor variations in the nickel content of the stream sediment samples occur, and the background level of about 250 ppm. is only exceeded in the headwater samples (450 ppm.).

SUMMARY AND DISCUSSION

From the analytical results of the rock and soil samples it appears that the arsenic anomaly (whose bedrock source was not

discovered) is not associated with detectable quantities of gold. From the location of the arsenic anomaly in the overburden relative to the rock outcrops in the river bed it is probable that the arsenic mineralisation is situated in deeply weathered argillaceous rocks, rather than in siliceous rocks. Gold was not detected in soils, which contain small quantities of molybdenum, overlying quartzites including abundant finely disseminated crystals of iron pyrites. From the map of alluvial deposits (fig.45), gold has been recovered from the stream gravels.

Soils

The elongation of the molybdenum anomaly follows the strike direction of the siliceous rocks, and is broadly parallel to the strike direction of the peak of the arsenic anomaly. It seems likely, therefore, that the arsenic and molybdenum concentrations occur independently of each other. Whilst the molybdenum is probably derived from the underlying pyrite bearing arenaceous rocks, the origin of the arsenic concentration is obscure.

The other minor elements, such as copper, zinc, antimony and lead which in places accompany the arsenic concentration in the soils at Yirisen, are not concentrated with arsenic in the soils at Maruba. Some elements, particularly manganese, cobalt and zinc appear to be concentrated in the alluvial soils bordering the drainage channel.

An interesting feature of the lead and nickel distribution is that to the north of the stream the background content of nickel is less than on the south side of the stream, whilst the background of lead is lower on the south side of the stream. This distribution might be related to analytical bias, but it could also be related to the mineralogy of the bedrock or to the varying nature of the soil, which on the south bank is mainly a soft red loam whilst on the north bank the soil is shallow but contains abundant ferruginous concretions.

Stream sediments

The minor element distribution in the stream sediments shows. with the exception of arsenic and possibly cobalt and manganese, only small variations in concentration which are taken to be normal background fluctuations. The internal standard, germanium, shows a wide variation of apparent concentration and it may be significant, from a consideration of possible analytical bias, that the drift of the germanium results is followed by Ti, V, Mn, Cu and Pb. However, the zinc results (colorimetric analysis) also follow the drift of the germanium results and it is probable that the effects of analytical bias are less than those due to the variations of lithology which have been mapped by the Geological Survey. Thus, the increased contents of titanium, vanadium and copper in the stream sediments at 600 feet and 1200 feet upstream of peg 6 are possibly derived from weathered amphibolite.

Within the area of the arsenic soil anomaly, only arsenic, manganese and cobalt appear to be concentrated in the stream sediments. There seems little doubt that the arsenic in the stream sediments is derived from the arsenic rich soils which predominate on the south side of the river, and a large proportion of the arsenic rich sediments is probably derived from collapse of the river bank material when undercut by the stream. Only a part of the total arsenic content of the stream sediments is likely to be mechanically dispersed, for a sample of brown coloured gelatinous iron hydroxide ($Fe(OH)_3$) collected from a pool within six feet of the main stream. contained 480 ppm. As, and this occurrence is taken to indicate the saline dispersion of arsenic in the ground and stream water (see Elliott, 1962). In comparison, the arsenic content of the minus 80-mesh stream sediment nearby was 50 ppm.

The association of increased contents of manganese and cobalt with the arsenic dispersion train may also be related to concentrations in the soils, for on line number 3 slight increases in the concentration of manganese, cobalt and copper were detected between the molybdenum and arsenic anomalies. The manganese, cobalt and copper concentrations, however, were not detected in the adjacent sample lines and it is probable that these concentrations in the soils are not significant. There is the possibility that the slightly higher contents of manganese and cobalt detected in the arsenic rich sediments, and the concentrations of the elements manganese, cobalt. and zinc ., in some of the samples of alluvium, could be derived from

mineralisation in the stream bed, but this is regarded as being unlikely because the contents of cobalt and manganese obtained are not unusual in stream sediments, particularly when derived from basic and ultrabasic rocks. The concentrations could be due to sorting of the stream sediments by eddying currents resulting from the rock outcrops in the stream bed.

Conclusions

Until proved by trenching, the arsenic occurrence in the soils on the banks of the Randahuna river, near Maruba, is assumed to be unaccompanied by gold mineralisation or by anomalous accumulations of other trace elements such as copper, zinc, antimony and lead. The low concentrations of molybdenum (less than 12 ppm.) detected in soils overlying pyritic quartzites are also unaccompanied by gold, and appear to be unrelated to the arsenic concentration. Although alluvial gold has been recovered from the lower course of the Randahuna river, it seems unlikely that this gold was derived from the soils and weathered rock which contain the peak contents of arsenic.

By comparison with the minor element concentrations accompanying the gold mineralisation at Yirisen, it seems possible that concentrations of arsenic, or molybdenum on their own, as at Maruba, are not pathfinders to gold mineralisation. Gold may occur in the vicinity of arsenic or molybdenum concentrations but it is not necessarily genetically related to these elements.

# The Kuntaw arsenic prospect

## INTRODUCTION

An anomalous concentration of arsenic, 25 ppm., detected in the sediments of the Kuntaw river, during the regional geochemical survey was selected for further work because high contents of cobalt, 200 ppm., and copper, 200 ppm., were detected in the arsenic rich samples. This association of high contents of arsenic, cobalt and copper was investigated as an association likely to be characteristic of a particular type of mineralisation.

## BRIEF DESCRIPTION OF THE AREA

The Kuntaw stream drains the southern slopes of Tebenko river valley and forms a confluence with the Tebenko near the village of Mabai (map ref. C23).

The total length of the Kuntaw stream is about one mile and over much of this length the gradient of the river bed is steep, with numerous waterfalls over rock outcrops. At about 1200 feet upstream from the Tebenko river, the stream flows through steep banks and numerous rocky outcrops. The flat topped form of the east bank, in particular, is suggestive of an ancient river terrace. At this point there are numerous outcrops of quartz mica schists and thin ptygmatic quartz veins . Farther upstream these rocks give way to amphibolites, which are the only other rocks mapped in this drainage.

The soils in the area are dark reddish brown loams on the west bank and dark brown rubbly, probably alluvial soils, on the east bank.

ANALYTICAL RESULTS

The anomalous arsenic contents of the stream sediments were traced to the thin ptygmatic quartz veins in the outcrops of quartz biotite schists and also to an arsenic anomaly in the soils on the steep west bank of the river. The alluvial soils on the east bank did not contain anomalous quantities of arsenic. Some of the soils in the west bank, in addition to their high arsenic contents, also contained slightly higher levels of lead and nickel, compared to the background levels (fig. 53).

Several samples of the quartz mica schists and the thin quartz veins were analysed for arsenic and the results show that this element is at times concentrated in the quartz veins, levels of 125 ppm. being detected. Fire assays of the arsenic rich samples did not detect gold or silver.

In the soils on the steep west bank of the stream, two narrow anomalous zones of high arsenic contents, about 75 feet in width, contain peak arsenic contents of 55 ppm. They appear to strike in a north easterly direction to meet the stream about 600 feet upstream from its confluence with the Tebenko river.

A number of the soil samples were analysed spectrochemically and the results show that lead occurs at slightly higher levels with the

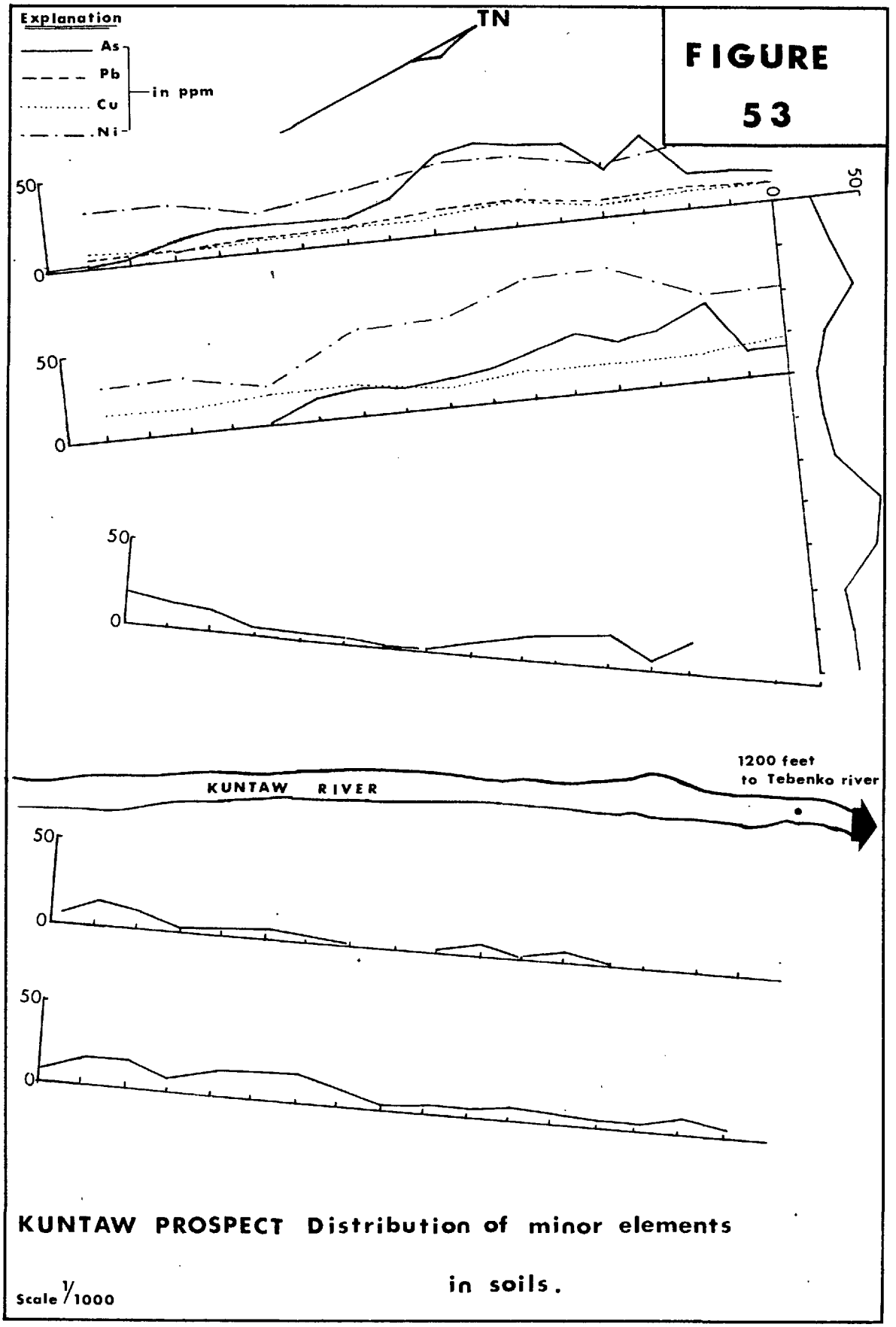



FIGURE 53

KUNTAW PROSPECT Distribution of minor elements in soils.

Scale 1/1000

peak arsenic contents. The maximum lead content is 12 ppm. and the background content is 3 ppm.

The peak contents of nickel do not exceed 70 ppm. and display only a low contrast to the background content of 30 ppm. The copper contents do not exceed 12 ppm. and the cobalt contents, 5 ppm. Silver was not detected and the arsenic rich soils were not assayed for gold.

## CONCLUSIONS

It is concluded from these results that the arsenic concentration in the stream sediments is derived from the arsenic rich ptygmatic quartz veins in the quartz mica schists, and also from the erosion, by sheet wash, of the arsenic rich soils about 150 feet up slope on the west bank of the stream.

The high copper and cobalt contents, 200 ppm. of each element, recorded in the arsenic rich stream sediments are likely to be derived from the amphibolitic rocks upstream. Copper contents of 200 ppm. and cobalt contents in the range 90 to 180 ppm. are commonly found in amphibolite soils in this area. The copper and cobalt contents of the sediments are high, however, compared to the contents of the average rock, 85 and 65 ppm. respectively, so that the possibility of cobalt and copper mineralisation in the amphibolite should not be overlooked.

In summary, the concentration of arsenic detected in the sediments of the Kuntaw river is not related to the high levels of

cobalt and copper detected in the stream sediments. It is believed that the high cobalt and copper contents originate from the amphibolites upstream.

## Molybdenum deposits

The following brief description of the molybdenum deposits in the schist belt is largely taken from the literature.

No detailed study was made by the writer of the molybdenum deposits in the Sula Mountains and Kangari Hills schist belt. The only deposit which was visited is that at Mopoko, situated near to Makele in the centre of the area covered by the geochemical map. Several anomalous concentrations of molybdenum in stream sediments were followed up and some positive results were obtained.

The several molybdenum deposits in the Sula Mountains and Kangari Hills schist belt can be grouped into at least two distinct types. The first is characterised by concentrations of molybdenite in quartz veins and the second by the molybdenite occurring as disseminations in granitic rocks. The deposits in the Sende and Mopoko rivers illustrates the first group and that in the Wankatana river illustrates the second. In addition, the results are presented of a preliminary investigation of the molybdenum anomalies in three small tributaries of the Tebenko river to the south of Makong.

## The Sende river molybdenite

The Sende molybdenite deposit is situated outside the area covered by the present study, in the northern Sula Mountains about 3 miles to the south of Lake Sonfon, near Dalukuru.

According to Elliott (1962) the molybdenite mineralisation occurs in drusy quartz veins, in hybrid rocks, at the contact of an intrusive coloured pink fluorite rich late-kinematic granite with amphibolitised pillow lavas. In order of decreasing abundance, the minerals which occur in the drusy quartz veins are: pyrite, chalcopyrite, galena, molybdenite, sphalerite and aikenite (Cu-Pb-Bi sulphide). The common gangue minerals are: magnetite, quartz, tourmaline, epidote, ankerite, calcite and fluorite.

Mather (1959), has noted that there appear to be two distinct phases of mineralisation in the area, separated by a time interval. The first is a quartz-sphalerite-galena-aikenite gold mineralisation, and the second a quartz-magnetite-pyrite-chalcopyrite-molybdenite mineralisation. This view is slightly different to that of Wilson and Marmo (1958) who consider aikenite to be the latest metallic mineral. The latter authors also report that the molybdenite and galena bearing drusy quartz contains 0.2 cwts. of gold per long ton.

This molybdenite deposit has recently been drilled by the Geological Survey, but the writer is not familiar with the results of this investigation.

Both Mather and Elliott have studied the secondary dispersion of molybdenum from the Sende deposit, which is covered by 20 to 30 feet of residual indurated latosols.

Mather (1959) concluded that anomalous patterns in the stream sediments resulted from the downslope movements of molybdenum rich topsoil during erosion, and from the lateral migration of molybdenum in the B soil horizon as colloidal compounds and soluble molybdates. In background soils there was little variation of molybdenum content in the different soil horizons or amongst the size fractions of these soils. In stream sediments the anomalous dispersion train was essentially derived from the topsoil and its persistence downstream is attributed to the coarseness of the concretionary sediments and the small quantity of diluent sediments.

Elliott (1962) from a more detailed study, emphasised the close association of molybdenum with hydrated iron oxides in the Sende sediments," where the distribution of this element could be largely interpreted in terms of this relationship."

## The Mopoko river molybdenite

The Mapoko deposit is situated in the bed of the Mopoko river, near Makele, on the eastern margin of the schist belt three and a half miles to south of the Lampana river. The deposit has been described by Fowler-Lunn (1933) and Marmo (1962b). Fowler-Lunn observed that the ore-zone was in a biotite schist which she considered, on the

basis of the low silica content, to be of igneous origin. The molybdenite varied in quantity according to the amount of quartz. Analyses by the Imperial Institute detected 0.56 dwts. of gold, 5.17 per cent molybdenum, 0.01 per cent of copper, and 0.07 per cent nickel. Pyrite was observed to antedate the molybdenum mineralisations.

Marmo noted that the biotite occurred with amphibolitic rocks and was most abundant in the zones containing pyrite and molybdenite. The alteration of the amphibolite to biotite is ascribed to potassium metasomatism.

### The Wankatana river molybdenite

The Wankatana deposit has been described in a number of publications, but that by Marmo (1962a) is the most recent. The molybdenite is exposed in the bed of the river Wankatana, on the western scarp of the schist belt some ten miles to the north-east of Bumbuna. The bedrock is a lenticular shaped body of pink coloured, fine grained late-kinematic granite, intrusive into a narrow strip of amphibolitic rocks, bounded by tremolite-serpentinite. The molybdenite mineralisation is disseminated as minute scattered flakes and is also associated with clusters of biotite and rounded, fractured garnets.

The molybdenite is more abundant, half a per cent $MoS_2$, in a narrow and sheared zone, 330 feet wide and 1200 feet long, which is

parallel to the long axis of the granite. Marmo has observed that this granite was a predominately sodic variety, but has been subject to potassium enrichment. Some apilitic rocks associated with this intrusion contained disseminated pyrite, chalcopyrite and pyrrhotite.

Both Mather and Elliott have studied the secondary dispersion of molybdenum from the mineralised late-kinematic granite. Mather (1959) concluded that in red loamy latosols, molybdenum is evenly distributed in the sub-divisions of the B soil horizon; the greater part of the molybdenum being associated with the fine, predominantly kaolinite fraction and only small proportions were associated with the quartzose fraction. In stream sediments there was no anomalous dispersion train, probably because of the high mobility of the fine clay and sesquioxide components with which most of the molybdenum is associated.

Elliott (1962) from a more detailed study found that the molybdenum was concentrated, probably in a mineral form, in the silt sized fraction and that the clay sized fraction carried comparatively little metal.

## The Tebenko river molybdenum anomalies

### INTRODUCTION

Several molybdenum anomalies were detected in tributaries to the Tebenko river in the vicinity of Makong (map ref. H36), but attempts to locate the source of these anomalies were unsuccessful

in several of these streams. This work was rather more successful in a small area between the Batiloma and Tebenko rivers (map refs. J38 to 39 and fig. 54).

In this area molybdenum contents of between 4 and 10 ppm. compared to a background content of 2 ppm., were detected in the sediments of four small streams. One of these locations (sample no. 926) was of special interest because a high copper content, 150 ppm., was detected in a high molybdenum sample.

## BRIEF DESCRIPTION OF THE AREA

The Batiloma river and the Tebenko headwaters have drainage catchments of about three and ten square miles respectively and the main streams are fed by numerous short (about one mile), steep, drainage channels.

The geology exposed in these drainages is complex. Recrystallised granite porphyry and acid volcanic are intensely folded and interleaved with mainly ultrabasic rocks and a few small lenses of amphibolite, probably as a result of large scale faulting movements.

The bedrock is largely obscured by thin colluvial latosols which support a dense forest.

## ANALYTICAL RESULTS

As a result of analysing samples of stream sediment, soil and rock chippings the probable sources of the molybdenum anomalies were detected in three of the four streams investigated.

**FIGURE 54**

EXPLANATION

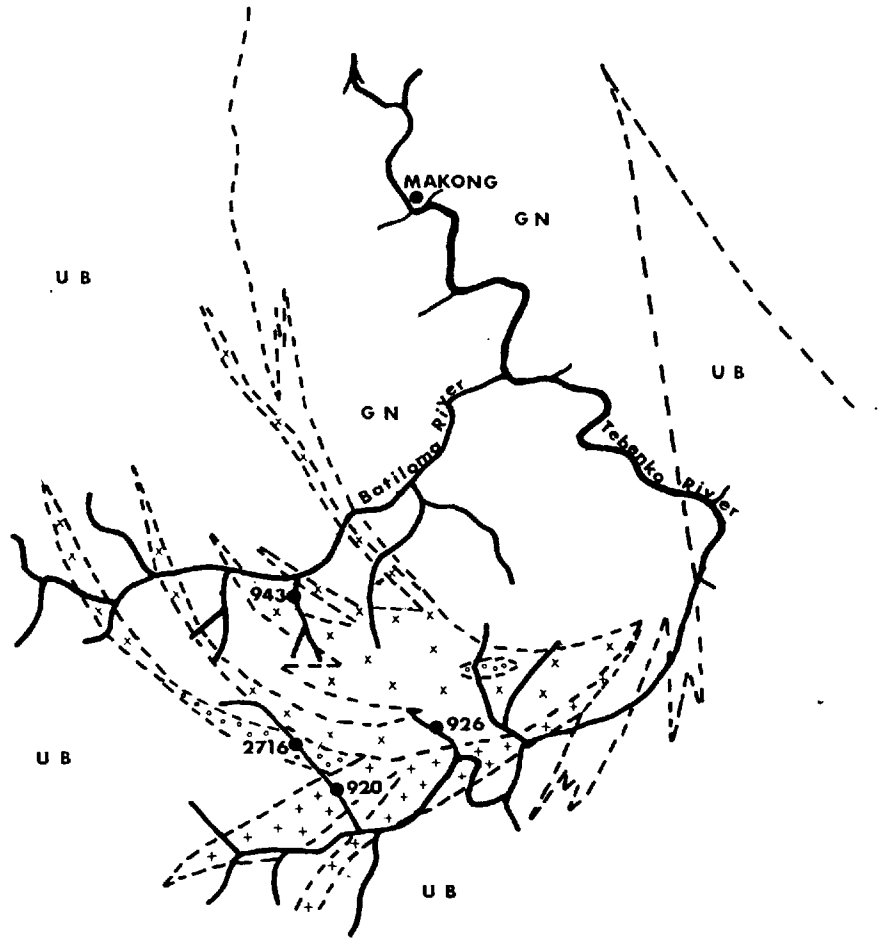
AMPHIBOLITE

RECRYSTALLISED GRANITE PORPHYRY

ACID VOLCANICS

GN GNEISS

UB ULTRABASIC




## TEBENKO MOLYBDENUM ANOMALIES

Locations of stream sediment samples.

SCALE 1/50,000

Geology by the Sierra Leone Geological Survey.

Of the two streams which are tributaries to the Tebenko, the molybdenum in the sediments of that to the east (sample 926) is probably derived from the recrystallised granite porphyry. In the western stream (sample 920) the peak molybdenum contents were detected in pyritised tremolite schists, including thin quartz veins. In a tributary to the Batiloma river, the possible source of the molybdenum anomaly was traced to a quartz vein.

The molybdenum content of the stream sediments at sample location 926 is 15 ppm. (fig. 54), and appears to be mainly derived from anomalous bank soils between 300 and 400 yards upstream from the confluence of this stream with the Tebenko. The content of the colluvial soils on the east bank is 23 ppm. and on the west bank 75 ppm. It is possible that these high contents are related to the recrystallised granite porphyry in which pyrite crystals are evenly disseminated, the molybdenum content being 27 ppm. Molybdenum was not detected in amphibolitic detritus at the source of this stream, but it is possible that the high copper content of the molybdenum rich sediments, 150 ppm., is related to this material.

Half a mile to the west of the stream at location 926 (fig. 54), the molybdenum contents of samples 920 and 2716 were 5 and 8 ppm. respectively. The anomalous contents are probably related to outcrops of strongly pyritised tremolite schists which outcrop 1200 feet upstream from the confluence with the Tebenko river. These rocks are ramified by thin quartz veins, and contain between 15 and

20 ppm. of molybdenum. The recrystallised granite porphyry downstream from the schists contains less than 1 ppm. molybdenum.

In a tributary to the Batiloma river, at location 943, the molybdenum content of the stream sediments is 6 ppm. Similar contents were detected in the bank soils 300 feet upstream from the confluence with the Batiloma river and a slightly higher level of 8 ppm. in a sample of yellow and brown stained quartz float. Chippings from outcrops of recrystallised granite porphyry contained only 2 ppm. molybdenum.

## CONCLUSIONS

From these results it appears that molybdenum is erratically distributed in the recrystallised granite porphyry and also occurs at higher levels than background in vein quartz, in one instance being associated with pyritised tremolite schists.

### Other molybdenum occurrences

Very minor disseminations of molybdenite have been found in pink coloured dykes of late-kinematic granite (Marmo, 1962b), and in aplite veins cutting granodiorite and porphyroblastic granite to the south of the area studied in the present work. Another molybdenite dissemination was found in the contact zone of the synkinematic granite with the western flank of the schist belt, about one mile to the south of the Pampana river, near Mabeki (map ref. B21).

## Other occurrences of sulphide minerals

The wide distribution of pyrite, chalcopyrite and pyrrhotite in very small amounts in the amphibolite has been noted in the Kangari Hills by Marmo (1962b). Arsenopyrite has been observed as minor disseminations in amphibolite and also in a quartz pegmatite. Both of these occurrences are beyond the south margin of the present phase of the geochemical map.

## Summary

From the description of the known mineral occurrences and those investigated during the present work, it is evident that in the Sula mountains and Kangari Hills schist belt there are a wide variety of mineral associations. The quartz gangue is the only mineral which invariably occurs with gold in the known occurrences. Tourmaline is frequently present and so to a slightly less extent, is pyrite. The pyrite at Baomahun has been observed to be arsenical (Marmo 1962b).

Geochemically and economically the most important associations are those which include arsenic. Those which include molybdenum are believed to be of little importance other than as a guide to molybdenum deposits.

Of the arsenic gold associations there are two main types, for example arsenic-gold (Baomahun), arsenic-lead-antimony-copper-zinc (Yirisen). The sulphide mineralisation at Yirisen, other than arsenic, is somewhat erratic and since the levels of copper,

zinc and antimony, in sediments are barely distinguishable from the background level it appears that arsenic-lead-gold is the significant element association at Yirisen.

Arsenic mineralisations barren of gold occur and those in the Randahuna and Kuntow streams, near Maruba and Mabai respectively, provide clear illustrations. Other minor occurrences of barren mineralisation have been found in amphibolites and pegmatites (Marmo, 1962b).

Of the molybdenum associations there are two main types, those in which molybdenum, accompanied or unaccompanied by other elements, is concentrated with quartz veins and those in which molybdenum is disseminated in granitic rocks.

In the former quartz vein type, of which the Sende deposit is an example, the gold contents are from present knowledge insignificant. The molybdenite is, however, accompanied by concentrations of copper, lead, zinc and bismuth in sulphide minerals. At the Mopoko deposit, molybdenum is unaccompanied by concentrations of other metals.

Of the latter disseminated type, examples are provided by the Wankatana deposit in late-kinematic granite, the Mabeki dissemination in synkinematic granite in contact with the schistose rocks, and the high molybdenum content of the recrystallised granite porphyry in the Tebenko valley.

It is concluded that of the elements which can be used as pathfinders to gold mineralisation in the Sula Mountains and Kangari Hills schist belt, only arsenic and lead, and possibly copper, zinc

and antimony are likely to be of value. Concentrations of arsenic are not necessarily accompanied by gold and nor is gold necessarily accompanied by arsenic, or indeed by concentrations of other metals.

## DESCRIPTION OF THE GEOCHEMICAL PATTERNS

### The regional distribution of arsenic

The range of arsenic concentration in the stream sediments in the field area is from less than 5 ppm., the limit of detection, to 150 ppm., the majority of the analysed results being less than 5 ppm. The threshold concentration, above which the arsenic contents are taken to be anomalous, is provisionally selected as 5 ppm.(fig. 21).

In distribution, detectable arsenic is concentrated in a zone, about one and a half miles in width, which follows the axis of the main schist belt, and also in diffuse areas situated in the eastern part of the field area (map ref. U25). Within the axial zone of arsenic concentration there are wide variations of concentration. For example, for approximately ten miles to the north and three miles to the south of the Pampana river (map ref. F20) the arsenic content of the stream sediments is frequently greater than 30 ppm. and in several samples greater than 70 ppm. At greater distances from the Pampana the normal contents are less than 30 ppm. In the extreme south of the field area, however (map ref. J40), the arsenic contents are again in the range of 30 to 70 ppm. The latter area

forms the northern margin of a pronounced arsenic province within the area covered by phase 2 of the regional geochemical survey of the Sula Mountains and Kangari Hills (L.D. James personal comm.).

Although the main zone of arsenic concentration in stream sediments closely follows the axis of the Sula Mountains and Kangari Hills schist belt, it is evident from a comparison of the geochemical map of arsenic (fig. 21) with the geological map (fig. 4) that arsenic concentrations are present in streams draining all the major rock types . . . Many of the strongest arsenic concentrations can be correlated with the outcrop or sub-outcrop of the argillaceous facies of the metamorphosed sedimentary rocks. This rock type occurs over large areas in the axial part of the schist belt, particularly to the north of the Pampana river, and over a large area to the south of the Pampana river where it is the major component of the schist belt (map ref. D29).

Concentrations of arsenic in sedimentary rocks have been reported on a number of occasions (Rankama and Sahama, 1950) and 3,000 ppm. of arsenic has been reported in pyrite of sedimentary origin (Goldschmidt and Peters, 1934). The possibility cannot be ignored therefore, that much of the arsenic in the metasediments is syngenetic. However, arsenic concentrations are present in streams draining all of the major rock types in the field area, and some of the arsenic patterns form distinct concentrations which do not appear to be associated with particular geological horizons.

This distribution strongly suggests that the arsenic patterns cannot be entirely explained as syngenetic concentrations in the metasediments.

In summary, the regional distribution and concentration of arsenic in the stream sediments of the Sula Mountains and Kangari Hills conforms to the definition of a "geochemical province", as outlined in the introduction to this Thesis.

## Anomalous concentrations of arsenic

As noted above, arsenic is widely distributed throughout the schist belt and is concentrated in the axial zone. The threshold concentration is taken as being 5 ppm., the limit of detection of the analytical method. The arsenic contents detected in the stream sediments are (map no. 9 and fig. 21) therefore at anomalously high levels of concentration and are likely to be related to concentrations of arsenic in the weathered rocks.

In the description of the known mineral occurrences in the Sula Mountains and Kangari Hills schist belt, it was shown that a number of different metal associations exist. One type, characterised by the element association at the Yirisen prospect, displays an arsenic-lead-antimony-copper and zinc association. In another type, exemplified by the Maruba prospect situated some two miles on strike to the south-west of Yirisen, arsenic concentrations appear to be devoid of any association with gold or any other metal. The

arsenic rich quartz veins exposed in the Kuntaw river near Mabai are another example. At Baomahun, the only underground gold mine in the area, arsenic is the only metal associated with the gold.

It is apparent therefore, that all of the arsenic anomalies are of direct interest to the prospector as a possible guide to locating gold mineralisation.

The arsenic anomalies are clearly marked on the geochemical maps and those unaccompanied by concentrations of other elements are not described in the text.

The geochemical map illustrates a number of interesting concentrations of other elements with arsenic, as for example, those observed at Yirisen (table 30), but in a regional assessment it is often difficult to distinguish the associations which are likely to be related to mineralisation from those related to normal minor element contents of the bedrock. For simplicity these associations are subdivided and the descriptions are summarized.

## ASSOCIATIONS OF YIRISEN TYPE

As noted previously, the mineralisation accompanying the gold quartz lodes at Yirisen is probably erratic and for this reason the association of arsenic-lead-antimony-copper-zinc may not always be detected, either in soils or stream sediments, associated with mineralisation of Yirisen type. In addition antimony was not analysed in the regional survey. For these reasons the important element associated at Yirisen is that of arsenic and lead.

Table 30. Anomalous concentrations of arsenic with other minor elements

Minor element content in ppm.

| Map Ref. | Sample No. | Alluvial Gold | Co | Ni | Cu | Zn | Pb | As | Mo | Major rock types in drainage catchment |
|---|---|---|---|---|---|---|---|---|---|---|
| K7 | 2953 | x | | | | | | 40 | 5 | Schists |
| K7 | 2954 | x | | | | | 40 | 5 | 2 | Quartz mica schists and banded ironstone |
| K10 | 1087 | | | | | 71 | | 25 | | Quartz mica schists, amphibolite |
| I14 | 261west | | | | | 61 | 50 | 25 | | Quartz mica schists |
| | 258east | | | | | 62 | 5 | 10 | | |
| E16 | 401 | | | | | 79 | | 140 | | Synkinematic granite |
| H16 | 396 | | | | | | 40 | 40 | | Quartz mica schists and quartzites |
| E18 | 333 | | | 400 | 80 | | | 75 | | Quartz mica schists amphibolite granite |
| I19 | 425 | | 200 | | | 415 | 200 | 500 | | Yirisan prospect) Samples collected down- |
| | 426 | | 200 | | | 106 | 100 | 640 | | " " } stream from prospect workings. |
| G20 | 322/5 | x | | | 100 | 113 | 150 | 5 | | Ultrabasic, metasediments, amphibolite |
| C21 | 1061 | | | | | | | 35 | 2 | Amphibolite, mixed rocks |
| D21 | 351 | | | | 30 | | | 15 | | Mixed rocks |
| F21 | 354 | x | | | 100 | | | 5 | | Ultrabasic |
| C23 | 2004/5 | | 200 | | 200 | | | 25 | | Amphibolite, quartz mica schists |
| D30 | 2861 | | | | | | 30 | 40 | | Quartz mica schists, acid volcanics |
| F33 | 833 | | | | 80 | | | 50 | | Ultrabasic |
| I34 | 983 | | 150 | | | 82 | | 25 | | Ultrabasic |
| G39 | 2692 | | | | | | 20 | 35 | 2 | Ultrabasic, amphibolite |
| | 2690 | | | | | | | 15 | 8 | Mixed rocks |

ARSENIC-LEAD-ZINC-COPPER ASSOCIATIONS

The only element association of this type recognised from the geochemical maps is situated at map reference G20, in the sediments of the Big Kewoli river. Significantly, this occurrence is some 2 miles to the south-south-west, and approximately on the same strike as the Yirisen prospect. Wilson and Marmo (1958) have reported that following the discovery of gold bearing quartz float in this drainage, an area of two square miles was prospected by loaming. The source of the gold was traced to a small area in the south bank about 1000 feet above the river, but trenches only revealed a few thin quartz stringers.

It seems probable therefore that the observed geochemical association of minor elements in the Big Kewoli river is likely to be related to gold mineralisation, and it is possible that in this area, geochemical methods might be more successful than the loaming method of prospecting the overburden.

ARSENIC-LEAD-ZINC ASSOCIATIONS

Two metal associations of this type were observed from the geochemical maps at reference I14 near Kendembaia, in the headwater drainages of the Makoke river where it branches to the east and to the west. Alluvial gold has been recovered from both branches and arsenic, lead and zinc concentrations in these branches of the river are anomalously high with respect to the background, the

concentration of these elements being highest in the western branch. This metal association is somewhat similar to that at Yirisen, but is four and half miles to the north of Yirisen and is not on the same strike, being situated on the argillaceous facies of the metasediments. It is probable that these element associations are related to mineralisation in the bedrodk.

ARSENIC-LEAD ASSOCIATIONS

There are four widely separated arsenic-lead concentrations of which two, near Simbili Hill and Lungi, at map references K7, G30 respectively, are accompanied by low contents of molybdenum, 2 ppm., which are below the threshold concentration and are regarded as being insignificant.

Three of the four occurrences are from drainages on the metasediments. Those at map reference K7, near Simbili Hill, and D30, near Sangbari, being on the argillaceous facies, whilst that in the drainage catchment at map reference H16 near Maranda, includes both the arenaceous and the argillaceous facies of the metasediments. The remaining arsenic-lead occurrence is situated at map reference G39 near Lungi. Here, the drainage catchments expose all of the major rock types, including thin strips of both the argillaceous and arenaceous facies of the metasediments.

The arsenic and lead contents in each of these occurrences (table 30) shows a high contrast to the background and it is possible that each are related to mineralisation.

## OTHER ARSENIC ASSOCIATIONS

These include associations of arsenic-zinc; arsenic-copper and arsenic-molybdenum. In some cases abnormally high contents of cobalt or nickel were also detected. These metal associations are of distinct interest as anomalous arsenic concentrations possibly related to mineralisation in the bedrock.

### ARSENIC-COPPER

There are five metal associations of this type situated in the central area of the schist belt, between map reference G18 in the north and F33 in the south. Two of the anomalies, at G18 and C23 are associated with high levels of nickel and cobalt respectively, the latter situated, in the Kuntaw river, having been described previously (see page 221).

The association of arsenic-copper-cobalt in the Kuntaw river near Mabai (map ref. C23) has been shown to be probably fortuitous, the arsenic being derived from thin ptygmatic quartz veins in the quartz biotite schists. Chippings from these veins did not contain detectable gold. The high copper and cobalt contents recorded in these samples are probably derived from the basic rocks which form a large part of the stream catchment, but as previously noted, the cobalt-copper contents are higher in the sediments, 200 ppm., than would be expected from the contents of the rock samples, 65 ppm. and 85 ppm. respectively.

The anomalous association of arsenic-copper-nickel in the Yirisen river at map reference G18, is probably partly due to contamination by the Yirisen prospect workings about two miles upstream; the copper-nickel contents possibly being derived from detritus of basic and ultrabasic rocks which outcrop farther upstream. The possibility of the other occurrences of mineralisation, downstream, being obscured by the contaminated detritus from the Yirisen prospect should not be overlooked.

In the remaining three arsenic-copper occurrences at map references D21 near Malumpo, F21 near Maruba, and F33 near Mabeki, there is the strong possibility that the high copper contents are derived from weathered basic and possibly ultrabasic rocks which occur in the drainage catchments. An alternative explanation for the higher copper content at map reference F33 near Mabeki is that the drainage in this stream is sluggish and the sediment largely consists of clay in which copper is frequently concentrated (Tooms, 1955).

Although explanations are provided for the associations of high contents of copper with arsenic, which could be regarded as fortuitous, it is possible that these associations are in fact related to mineralisation.

ARSENIC-ZINC

Of three arsenic-zinc associations noted in the area, that in the Batpoka river at map reference I34, is associated with cobalt

contents which although anomalously high compared to those further up and downstream, are not unusual in areas of ultrabasic rocks which form the drainage catchment.

The arsenic-zinc anomaly at map reference K10, two miles to the south-west of Sangbaya, is in a drainage whose catchment includes mainly quartz mica schists, intercalated with lenses of amphibolite.

At map reference E16 near Kalifaiya, the country rocks are porphyroblastic and gneissic synkinematic granite enclosing rather infrequent outcrops of coarse grained amphibolites.

In these three arsenic-zinc occurrences it is possible that the high zinc contents are related to basic or ultrabasic rocks in which zinc normally occurs at higher levels (fig. 19) than in the metasediments. It is also possible, however, that the arsenic-zinc associations are related to mineralisation.

ARSENIC-MOLYBDENUM

There is no distinct association of arsenic and molybdenum and these elements do not occur together at high levels of concentration except near Lungi (map ref. G39). This peculiar antipathetic distribution at high levels of concentration in which arsenic and molybdenum occur separately in adjacent tributaries is demonstrated by figure 21 (map refs. J7, E25, V25) in areas of duricrust and non-duricrust soils. At lower levels of concentration,

less than 7 ppm., molybdenum is only rarely associated with concentrations of arsenic, for example at map reference D27 near Makena and I40 about three miles to the south of Makong, where the arsenic content is greater than 30 ppm.

An interesting feature of the rare occurrences of associated detectable arsenic and molybdenum in stream sediments, is their location close to arsenic-lead associations at Lungi (map ref. G39) and in the Terikonko river on the eastern slopes of Simbili Hill (map ref. K7). The significance of this possible association is not understood but from the different regional distributions of arsenic and molybdenum, these associations are probably fortuitous.

## SUMMARY

Minor element associations in which concentrations of arsenic and lead occur with, or without, copper and zinc are regarded as being of Yirisen type and possibly related to gold mineralisation.

Concentrations of arsenic accompanied by copper/zinc and also cobalt or nickel are possibly associated with high contents of these elements in the rock forming silicate minerals and may not be associated with mineralisation. The possibility exists, however, that these associations are related to significant anomalies in the weathered rock.

The arsenic-zinc associations, as with those of arsenic-copper are of doubtful economic significance for in two of

the three anomalies, basic amphibolitic rocks could conceivably be the source of the high zinc contents. In the third instance of an arsenic-zinc anomaly in the Batpoka river, the high content of zinc might be related to the ultrabasic rocks in the drainage catchments.

From the different regional distributions of arsenic and molybdenum it is probable that the associations of these elements at greater than background levels is entirely fortuitous.

## The regional distribution of molybdenum

The molybdenum contents of the stream sediments range from the limit of detection, 1 ppm., to 20 ppm., most of the results being 1 ppm. or not detected. The threshold content is estimated to be 3 ppm.

Low concentrations of this element are very much more widely distributed than is the case with arsenic, but as with arsenic anomalous molybdenum concentrations appear to originate from the schistose rocks, both in the main area of the schist belt and in the mixed rocks of the eastern part of the field area.

There are only two areas in which molybdenum occurs at high levels of concentration, between 8 and 20 ppm. One includes the Miyaki and Tafali river drainages on the east side of the schist belt near Basaia (map ref. K14) and the other, the Batiloma and Tebenko river headwaters in the axial area of the schist belt near

Makong (map ref. H37). The anomalies in the Basaia area are situated in areas of complex geology. In the Tafali river the quartz mica schists alternate with thick horizons of amphibolite, whilst in the Miyaki river, the amphibolite interdigitates with ultrabasic rocks.

The anomalies in the Makong area, as in those near Basaia, are situated in areas of complex geology, and here a variety of ultrabasic rocks are intercalated with recrystallised granite porphyry and small lenses of amphibolite.

There are numerous molybdenum anomalies of low contrast in the range of 3 to 8 ppm., covering areas which are small compared to those near Basaia and Makong. Some of these anomalies traverse the lithological boundaries of the major rock types and from their distribution, are unlikely to be related to varying background concentrations in the different bedrock. It is believed that all of these anomalies are likely to be related to mineralisation.

## Anomalous concentrations of molybdenum

From the description of the known mineral occurrences it is seen that the molybdenum deposits in the Sula Mountains and Kangari Hills can be divided into two groups according to their mode of occurrence. The first group, of which the Sende deposit is an example, is typified by the association of the sulphide mineralisation (Mo, Cu, Pb, Zn, Bi sulphide) with quartz veins.

The second group is characterised by the molybdenum occurring in a disseminated form in granitic rocks, as in the Wankatana deposit.

The molybdenum rich quartz veins of the first group contain small quantities of gold, but the concentrations detected do not approach economic grade. Concentrations of molybdenum related to quartz vein deposits cannot be regarded as pathfinders to gold mineralisation, but are probably related to sulphide mineralisation of various types of which two have been recognised.

The molybdenum anomalies unaccompanied by concentrations of other metals are not further described, but those in which other metals are concentrated with molybdenum are grouped according to the metal association (table 31).

## ASSOCIATIONS OF SENDE TYPE

### MOLYBDENUM-COBALT AND MOLYBDENUM-ZINC

Only one association of each of these types has been recognised (table 31) and they are both situated in the southern headwater branch of the Tafali river (map refs. K-L31) some three miles north-west of Basaia. The drainage catchment of this stream is about three square miles in area and includes alternating strips of amphibolite and quartz mica schists. Contents of between 15 and 20 ppm. molybdenum which occur sporadically in the stream sediments and bank soils over a distance of 2500 yards were not traced to source.

Table 31. Anomalous concentrations of molybdenum with other minor elements

Minor element content in ppm.

| Map Ref. | Sample No. | Alluvial Gold | Ag | Co | Ni | Cu | Zn | Pb | As | Mo | Major rock types in drainage catchment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| K-L13 | 2115 | x | | 30 | | | | | | 15 | Amphibolite and meta sediments |
| | 267 | | | | | | 71 | | | 3 | Amphibolite |
| M15 | 3148 | x | | | | | | | | 20 | " |
| I37 | 2731 | | | | | 100 | | | | 20 | Ultrabasic and acid volcanic |
| J39 | 926 | | | | | 150 | | | | 4 | " " " " |
| J38 | 943 | | | | | 150 | | | | 6 | " " " " |

The molybdenum-cobalt association occurs in sample no. 2115 which contains 15 ppm.Mo and 80 ppm.Co, the latter content being anomalous compared to the background cobalt content of 10 ppm. The molybdenum-zinc association was detected in a sample further upstream from this drainage where molybdenum and zinc contents are 3 ppm. and 71 ppm. respectively.

Although both the cobalt and zinc contents appear to be anomalous these contents are not unusual in sediments derived from amphibolite and it is probable therefore, that these contents are related to the amphibolite which outcrop in the catchment area. The source of the molybdenum anomalies is unknown.

MOLYBDENUM-COPPER

Metal associations of this type have only been recognised in the schist belt to the west and south-west of Makong (table 31) where recrystallised granite porphyry occurs as attenuated outcrops in the ultrabasic rocks.

In this area, some of the molybdenum concentrations in the drainage appear to be derived from granite porphyry and thin quartz veins. It is possible that the high copper contents are associated with the molybdenum concentrations in these rocks.

SUMMARY

From the geochemical maps, anomalous concentrations of molybdenum-cobalt and molybdenum-zinc, an molybdenum-copper occur

in two widely separated areas, the former near Basaia and the latter near Makong. In these occurrences the copper and zinc contents detected, although anomalous with respect to the immediate environment, are not high compared to the levels normally detected in the detritus of basic rocks. It is possible therefore that the high levels of these elements are closely related to the basic or ultrabasic rocks, which in both the Basaia and Makong areas outcrop close to contrasting rock types, such as metasediments or or granite porphyry ,respectively. The bedrock source of the molybdenum concentration in the stream sediments of the Basaia area was not discovered, but in the Makong area is related to both quartz veins and the granite porphyry.

Anomalous concentrations of copper

Copper mineralisation other than that accompanying the gold mineralisation at Yirisen and the molybdenite in the Sende river deposit, has not been recorded in the Sula Mountains and Kangari Hills schist belt.

From the geochemical maps there is a clearly defined 'V' shaped area of high copper contents, greater than 70 ppm., extending over the ultrabasic, basic and metasedimentary rocks centred on map reference H18 (fig. 18 and table 32). Copper contents of greater than 70 ppm. were commonly detected in stream sediments derived from basic rocks, but these levels are believed to be strongly anomalous in areas of metasedimentary rocks.

Table 32. Anomalous concentrations of copper with other minor elements

Minor element content in ppm.

| Map Ref. | Sample No. | Alluvial Gold | Ag | Co | Ni | Cu | Zn | Pb | As | Mo | Major rock types in drainage catchment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| H14 | 2075 | | | | | 95 | | | | | Quartzite |
| " | 2076 | | | | | 95 | | | | | " |
| " | 2077 | | | | | 95 | | | | | " |
| H15 | 215 | | | | | 105 | 102 | 30 | | 2 | " |
| J16 | 308 | | | | | 200 | | | | | Amphibolite, chloritised schist |
| J16 | 320 | | | 150 | | 200 | | | | 3 | Amphibolite |
| E32 | 823 | | | | | 80 | | | | 2 | Ultrabasic |

The western limb of the 'V' shaped pattern extends for seven miles from map reference G14 in the north to map reference F20 in the south and is centred on Kpfaia, map reference F17.

## THE KPFAIA ANOMALY

For convenience, the western limb of the Kpfaia anomaly is divided into three sections, north, central and south.

For most of its length the anomaly covers the arenaceous facies of the metasediments (Farangbaia quartzites), but the eastern part of the central section extends onto the argillaceous facies. In this area a local watershed follows the transition between the arenaceous and argillaceous facies of the metasediments.

Most of the anomalous samples were collected from streams draining to the west, onto the quartzites, but a few samples were collected from the eastward draining streams and of these only two contained anomalous concentrations.

At the northern extremity of the western limb, samples from three small streams (Nos. 2075, 76 and 77) covering a strike length of about one mile, contain 95 ppm. copper, compared to the background content of 45 ppm. Of these samples that to the north is derived from both argillaceous and amphibolitic facies of the metasediments, whilst the two samples to the south are derived from the arenaceous facies only.

The central section of the western limb of the anomaly (map ref. G15) is represented by several samples, those to the north (nos. 212, 215) containing 150 ppm. copper. In addition, the zinc and lead contents of sample 215 are anomalous, 102 and 30 ppm. respectively, compared to the background, 40 ppm. and 5 ppm. respectively. The southern part of the central section is represented by three samples (336, 405 and 407) which contains between 80 and 150 ppm. copper; the centrally situated sample (407) also containing a high content of lead, 55 ppm., compared to the background.

The eastern margin of the central section of the anomaly (near Maranda) which covers the watershed and the argillaceous facies is represented by two samples whose copper content is high, 80 and 100 ppm., compared to the background, 50 ppm. One of these samples, No. 396, contains 40 ppm. arsenic, 100 ppm. copper, and 40 ppm. lead, but only background contents of zinc.

The southern section of the anomaly mainly covers the argillaceous facies of the metasediments, basic and ultrabasic rocks. This section is of less importance than the central and northern sections, because the high copper contents are probably related to the basic and ultrabasic rocks and not to the metasediments.

It was noted in SECTION 3 that high contents of titanium, greater than 7000 ppm., occur in the areas covered by the copper anomaly. The titanium anomaly is overlapped by the more extensive

copper anomaly and it is unlikely, therefore, that the two elements are genetically related, as for instance in sediments derived from basic rocks in which the levels of 150 ppm. Cu and greater than 7000 ppm. Ti are commonplace.

Whether the copper anomaly is related to gold mineralisation is unknown, but alluvial gold has been recovered from drainages at the north and south extremities of the anomaly (samples 2076, 336). Gold has also been recovered from the Makoke river, which drains the eastern slopes of the watershed of the arenaceous and argillaceous facies of the metasediments.

Within the area covered by the Kpfaia copper anomaly, the presence of anomalous contents of zinc, lead and arsenic in some of the stream sediments is taken to indicate the presence of mineralisation which may be related to gold deposits, and the possibility that disseminated copper deposits occur in the metasediments should not be overlooked. The anomaly is worth further investigation.

## OTHER ANOMALIES

Of the other anomalous copper occurrences detected on the geochemical map, those at the headwaters of the Matinta and Kumkenta river (map refs. J16 and E32 respectively) are possibly related to basic or ultrabasic rocks in the drainage catchments.

The samples from the Matinta river display a Cr/V ratio which is characteristic of basic detritus and the copper contents of 200 ppm. and cobalt content of 150 ppm. are high, and possibly abnormally high. These sample sites are situated on the north strike extension of the Yirisen lodes and the high levels of copper and cobalt detected could possibly be related to mineralised fractures.

The sample in the branch of the Kumkenta river (map ref. E32) whose catchment includes dominantly granitic rocks with small outcrops of ultrabasic rocks, contains 80 ppm. copper, which is a high level in probably dominantly granitic detritus.

Another and more interesting copper anomaly is situated in the area of intensely folded basic, ultrabasic and acid extrusive rocks to the south-west of Makong (map ref. J39). Here the copper contents of four samples range between 100 and 150 ppm. and occur in different drainages. The samples which contain the high contents of copper lie on a linear, about one and a half miles in length, which strikes parallel with the main axis of the schist belt, but cuts across the locally intensely folded rocks. It seems probable that this group of anomalous copper contents are related to mineralisation.

## SUMMARY

Anomalous concentrations of copper, likely to be related to mineralisation, occur on the arenaceous and argillaceous facies of

the metasediments near Kpfaia, and in a linear zone to the south-west of Makong. Other anomalous concentrations of copper are possibly related to detritus of basic and ultrabasic composition and these anomalies are probably not significant.

### Anomalous concentrations of zinc

Zinc deposits have not been found in the Sula Mountains and Kangari Hills area in any form other than as minor mineralisations accompanying the quartz vein gold deposits at Yirisen, and the molybdenite mineralisation at Dalakuru. There is no analytical data available on the average zinc contents of the major rock types in the field area and it is therefore difficult to assess the significance of the zinc concentrations in the stream sediments.

The geochemical distribution of zinc is based on samples selected at a density of about one per square mile and shows several areas to contain high concentrations of this element (fig. 19).

Several rather widely scattered zinc anomalies were detected from the regional geochemical survey and some of these display a very high contrast to the background and are likely to be related to mineralisation. Other anomalies display only a low contrast and may be related to the background (table 33). For convenience, the anomalies are divided into two groups: "possibly significant" and "possibly non-significant".

Table 33. Anomalous concentrations of zinc with other elements

Element content in ppm.

| Map Ref. | Sample No. | Alluvial Gold | Ag | Co | Ni | Cu | Zn | Pb | As | Mo | Major rock types in drainage catchment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| J2 | 1146 | x | | | | | 104 | | | | Amphibolite |
| I10 | 1110 | | | | | | 76 | | | 2 | Quartzite |
| I11 | 1103 | | | | | | 330 | | | | " |
| F26 | 734 | | | 150 | | | 112 | | | 2 | Granite and amphibolite |
| F33 | 818 | | | | 1000 | | 80 | | | | |
| | 830 | | | 150 | 1000 | | 107 | | | | Ultrabasic |

POSSIBLY SIGNIFICANT ANOMALIES

There are three zinc anomalies which display a very high contrast to the background content, of about 45 ppm., in the eastern part of the field area. In one, near Kenewa (map ref. 031) the sediments are composed of mixed granitic and ultrabasic detritus, and contain 160 ppm. zinc (sample 1015). In the other two anomalies, situated near Makoni (map ref. 31) the zinc contents are 490 and 370 ppm. (sample nos. 1002, 1001 respectively). These zinc contents are very high compared to the background content of 45 ppm., in sediments derived from the ultrabasic rocks nearby, and are possibly related to mineralisation.

The other concentrations of zinc which are possibly related to mineralisation are situated in the northern part of the field area. One, near Sokoya (map ref. I11), is located on the steep west bank of the Tonkolili river, formed by the Farangbaia quartzite. The zinc content of 330 ppm. has a high contrast compared to contents of 50 and 60 ppm. in drainages situated one quarter of a mile to the north and south of the anomalous sample.

Another high zinc content of 108 ppm., near Kpfaia (map ref. E17), was detected in the upstream sample of a series of four, collected at a quarter of a mile intervals, along a stream draining a steep hill slope on the banded ironstones. The zinc contents are progressively reduced to 26 ppm. in the downstream sample. The background content of zinc on the granites and quartzites is 40 ppm.

These are the only other rocks in the vicinity and are not included by the drainage catchment. The background zinc content of the banded ironstones is not known.

POSSIBLY NON-SIGNIFICANT ANOMALIES

Several zinc anomalies occur in areas of basic or of ultrabasic rocks and these are considered to be non-significant. There is the possibility, however, that they could be related to mineralisation, but no detailed investigations were made.

Near Sunkoni village (map ref. J2) a sample from the Mede river contained 104 ppm. of zinc, in an area of duricrust covered amphibolitic rocks. This value is high compared to another, from a small tributary stream on the south bank, in which the zinc content is 65 ppm. Although the contrast between these results is not high, and could be related to normal background variation, it is of special interest because alluvial gold deposits were discovered in this part of the Mede river.

The high content of zinc in the Kawkaw-yi river sediments (map ref. I10) near Sokoya village, is ascribed to detritus of basic composition within the quartzose facies of the metasediments (see page 56).

Near Makene village, a sample from a steep run-off gully which drains into the Kota river, contains 122 ppm. of zinc. This gully drains granite, amphibolite and ultrabasic rocks and from the titanium content of the sample, 5000 ppm., and the ratio Cr/V = 6, it is probable that the sediment is largely derived from basic detritus. The cobalt content, 150 ppm., and the zinc content are high, however, and could possibly be related to mineralisation.

The high zinc contents in the headwater drainage of the Kumkenta river (map ref. F33) south of Waka, are probably derived from the ultrabasic rocks which form the catchment area. The background content of zinc is about 60 ppm. and the contents of the anomalous samples 80 and 107 ppm. These zinc contents are probably not related to mineralisation.

## SUMMARY

In the absence of analytical data on the zinc contents of the major rock types it is difficult to evaluate the significance of the anomalous patterns of zinc. Several results show very high contents however, and these, by virtue of their great contrast compared to the regional content of zinc in the sediments, are likely to be related to mineralisation. Several other results in which the contrast is low, are found to be associated with high

contents of elements which are normally concentrated in detritus of basic or ultrabasic composition. These anomalies are probably not related to mineralisation.

Anomalous concentrations of lead

The importance of lead as a pathfinder element, with other elements, to gold mineralisation has been demonstrated in the soils and stream sediments at the Yirisen gold prospect. Comparatively high levels of lead in some granitic rocks have also been demonstrated and the use of the ratio Rb/Pb has been suggested to distinguish mineralised, from non-mineralised, occurrences of lead in stream sediments derived from granitic rocks. In the following pages, isolated occurrences of lead, which are likely to be associated with mineralisation are divided into two groups; those which are probably related to lead mineralisation and those which, although anomalous, might be related to concentrations of lead in rock forming silicate minerals (table 34).

POSSIBLY SIGNIFICANT ANOMALIES

Several of the lead anomalies appear to be related to mineralisation, but it is of interest that the highest contents detected are less than 200 ppm. and frequently less than 100 ppm. No large accumulations of lead were detected other than in the contaminated sediments at Yirisen.

Table 34. Anomalous concentrations of lead with other elements

Element content in ppm.

| Map Ref. | Sample No. | Alluvial Gold | Ag | Co | Ni | Cu | Zn | Pb | As | Mo | Major rock types in drainage catchment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| L3 | 3017 | | | | | | | 40 | | 2 | Quartz rich schist, banded ironstone |
| G6 | 2890 | | | | | | | 40 | | 3 | Amphibolite, late kinematic granite. |
| | 2889 | | | | | | | 70 | | | Pegmatite |
| D15 | 376 | | | | | | | 40 | | 20 | Granite |
| J15 | 255 | | | | | | | 30 | | | Quartz mica schists |
| G34 | 2784 | | | | | 70 | | 50 | | | Ultrabasic and acid volcanic |
| G39 | 2687 | | | | | >200 | | 150 | | | Ultrabasic |
| | 901 | | | | | | 89 | | | 2 | |

One of the anomalous lead contents is from the Mabiringini stream (map ref. I3) which drains the south flank of Numbara Hill. Here, a lead content of 40 ppm. was detected 700 yards upstream from another sample which contained 150 ppm. of cobalt. The background content of lead is about 5 ppm.

Another lead anomaly which is possibly related to mineralisation was detected in an area of amphibolite to the south of Mabente (map ref. E32). Here, the sediments of the west branch of a tributary to the Tebenko river contain 25 ppm. lead compared to the background content of 5 ppm. lead. In samples from farther upstream, arsenic and zinc occur at high levels, 45 ppm. and 110 ppm. respectively.

Upstream from the Mopoko molybdenite deposit, near Makele (map ref. E25) the background content of lead is about 5 ppm., but in a few samples (map ref. E25 and fig. 20) the lead content rises to about 20 ppm. The molybdenum content of the same samples is 5 ppm. and a few traces of silver were detected. Since these slightly higher levels of lead occur in the vicinity of the molybdenite mineralisation at Mapoko, they may possibly be associated with other, hitherto undetected mineralisations. Alternatively, outcrops of acid volcanics occur in the vicinity of the anomalous lead contents and the low levels detected could conceivably be derived from these rocks.

POSSIBLY NON-SIGNIFICANT ANOMALIES

Other high lead contents which are possibly related to higher levels in the silicate minerals of acid igneous rocks occur throughout the field area. To the south-east of Bumbuna, on the western scarp of the schist belt, a stream draining amphibolites cuts through the late-kinematic pegmatite at map reference G6. The background lead contents of the amphibolitic sediments is about 5 ppm. and that of the anomalous sediments one half a mile down-stream from the pegmatite outcrops is 70 ppm. and 40 ppm. Such high contents are probably either related to lead rich mineral in the pegmatite or to lead mineralisation.

Near Kalifaiya (map ref. D15), the lead content of the anomalous sample is 40 ppm., compared to the background content of 10 ppm. The drainage catchment includes granitic rocks of both porphyroblastic and gneissic texture, partly obscured by alluvium. From the high contents of lead normally associated with porphyro-blastic granite, it is possible that the present anomalous sample is related to this textural type. Similar levels of lead, about 40 ppm., occur in a few samples in the drainages near Small Magburaka, map reference G21, where they may also be related to porphyroblastic granites or to mineralisation. These occurrences at Kalifaiya and Small Magburaka were not investigated.

An anomalous lead content of 50 ppm. was detected in the southern headwater branch of the Batiloma river, near Mabeki (map

ref. G34). The background content of lead in this area of ultra-basic rocks is about 5 ppm. Evidence that the anomalous lead content is associated with a granite porphyry dyke, which crosses the river, is seen in the abnormally low chromium contents of the anomalous lead sample, 450 ppm., compared to the adjacent samples; 4000 ppm., in the upstream sample and 1200 ppm. Cr in the downstream sample. The anomalous lead sample also contains a high copper content of 70 ppm., compared to the background of 25 to 50 ppm. Since alluvial gold workings are abundant in this area, it is possible that the high lead and copper results are related to mineralisation.

SUMMARY

The anomalous occurrences of lead appear to fall into two groups; those which are probably related to lead mineralisation and those more likely to be related to lead concentrations in silicate minerals. None of these occurrences were investigated but it is suggested that the ratio Rb/Pb of these samples should be determined before planning further field work at these sample sites.

In an earlier section (page 167) it was noted that the ratio Rb/Pb = 5 is constant in unmineralised granite and that this ratio is always greater than one in the associated stream sediments (fig. 33). Ratios of less than one would indicate an abnormal

concentration of lead relative to rubidium, as for example in lead sulphide minerals.

Anomalous concentrations of cobalt.

Cobalt mineralisation has not been observed in the Sula Mountains and Kangari Hills and from the geochemical map there is no marked regional enrichment of this element.

The two highest cobalt contents recorded, of 500 ppm. and 250 ppm. are situated in the area of ultrabasic rocks to the west of Makong (map ref. H 37). The cobalt content of the other stream sediments in the vicinity is 100 ppm. and that of the rock samples in the area is 150 ppm.

The cobalt contents of 500 and 250 ppm. are abnormally high compared to the surrounding results. The nickel and chromium contents, as well as the cobalt contents , are also high compared to the background. It is possible that this anomaly is related to either mineralisation or to an abnormal concentration of these elements in the silicate minerals of the ultrabasic rocks.

Other high cobalt contents detected in stream sediments also occur in drainages whose catchments include ultrabasic rocks. In the south branch of the Matinta river (map ref. H 17) some two

Table 35. Anomalous concentrations of cobalt with other elements

Element content in ppm.

| Map Ref. | Sample No. | Alluvial Gold | Ag | Co | Ni | Cu | Zn | Pb | As | Mo | Major rock type in drainage catchment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| L4 | 3013 | | | 150 | | | | | | 2 | Quartz mica schists and banded ironstone |
| J12 | 2900 | | | 80 | | | | | | | Amphibolite and meta sediments |
| H17 | 302 | x | | 200 | | | 80 | | | 2 | Ultrabasic, amphibolite |
| K25 | 683 | | | 50 | 500 | | | | | | Granite |
| H37 | 2698 | | | 500 | | | | | | | Ultrabasic |
| | 2699 | | | 250 | | | | | | | " |

miles north-east of Yirisen, the bedrock consists of alternating basic and ultrabasic rocks. The stream sediments on the basis of the ratio Cr/V = 20 appear to be largely of ultrabasic composition. The cobalt content of 200 ppm. and zinc content of 80 ppm. is high compared to the contents of those elements in ultrabasic sediments elsewhere, and it is possible that these high values are related to mineralisation.

A high cobalt content of 80 ppm., compared to 20 ppm. of the background, detected in the sediments of a small tributary to the Tafali river (map ref. J12), is unlikely to be related to mineralisation. The catchment area includes mainly quartz-mica schists and thin, intercalated, bands of amphibolite and it is likely that the high result is related to detritus of basic composition.

The high cobalt content detected in the Mabiringini stream (map ref. L4), which drains the south flank of Numbara hill, has been mentioned in connection with a lead anomaly. The cobalt content of 150 ppm. contrasts strongly with the background content of 20 ppm. It is possible this high cobalt content is related to detritus of basic composition, but from the geological map the drainage catchment encloses only a small area of basic rocks.

## SUMMARY

The few anomalously high contents of cobalt which occur on the geochemical map are more likely to be related to detritus of

basic or ultrabasic composition than to mineralisation. The possibility of cobalt mineralisation exists, however, and these anomalies are therefore worth investigation.

## The distribution of silver

Silver was only detected in a very few samples and in most cases only trace quantities were detected (less than 0.1 ppm.). The highest silver content detected was 3.5 ppm. in the contaminated stream sediments about 100 yards downstream from the Yirisen prospect.

Trace quantities of silver in six samples and 0.5 ppm. in a single sample, were detected in sediments from the Terikonko river which drains the east flank of Simbili, (where some of the samples also contain high levels of lead). Other groups of samples in which traces of silver were detected, occur in the northern headwater tributaries of the Mapoko river (map ref. E25), upstream from the molybdenite prospect. These samples contained low levels of lead and arsenic, in addition to the traces of silver. Traces of silver were also detected in the drainages around Makong (map ref. I35) and in the Tonkilile river, north-west of Makali (map ref. K32).

Slightly higher levels of concentration, 0.5 ppm., occur in two samples at map references I21 and G6. A content of 2 ppm. was detected in a small tributary to the Tonkolili at map reference H9. These anomalies were not investigated, but are probably related to mineralisation.

SUMMARY

From these few results it is evident that silver is rarely detectable, even at the present low levels of detection (0.1 ppm.) and although traces were detected in some areas of alluvial gold deposits, silver was not detected in the majority of these areas. The isolated results of 0.5 ppm. and 2 ppm. are probably related to mineralisation.

## SUMMARY AND CONCLUSIONS

Within the area of the present regional geochemical survey, gold is of primary importance. The main area of molybdenum mineralisation is to the north, in part of the area being studied in the second phase of the regional geochemical survey. In the area of the present study only minor occurrences of molybdenum are known. Accordingly the economic success or failure of the present geochemical mapping must be assessed in the first instance on whether the area of bedrock gold mineralisation is outlined by a geochemical province or provinces. From this point of view the survey can be considered to have been marked success in that the only known gold mineralisation which is arsenical is enclosed in a well defined arsenic province extending the whole length of the schist belt.

Other geochemical provinces detected are of doubtful economic interest, although of considerable fundamental significance.

Molybdenum and other rare metals are not present in abnormal concentrations on a provincial scale but do occur as anomalous values of doubtful economic importance. The occurrence of these other metals can be useful, however, in the interpretation of the arsenic anomalies.

Known bedrock gold deposits in the Sula Mountains and Kangari Hills which are of possible economic value, i.e. those at Yirisen and Baomahun, are associated with arsenic anomalies. The highest arsenic values in the areas covered in the present study are in the Yirisen area and values of a similar magnitude have been found associated with the Baomahun deposit to the south (L.D. James, personal comm.). It must be emphasised, however, that all arsenic anomalies are not necessarily associated with gold mineralisation (e.g. Maruba). In addition, certain minor deposits are not associated with arsenic anomalies (e.g. Makong).

The failure to detect other gold mineralisations of the magnitude of Yirisen and Baomahun during the limited number of investigations of arsenic anomalies lends some support to the contention that much of the alluvial gold is derived from low grade deposits disseminated in the rocks.

Association of anomalous concentrations of other elements with arsenic is most marked at Yirisen where lead and antimony, as well as arsenic are anomalous in the drainage. Similar associations of metals elsewhere would no doubt reflect the presence of Yirisen

type mineralisation. There is also reason to believe that the other metal associations (including copper and zinc) reflect this type of mineralisation.

The conclusions reached on the economic aspects of the present geochemical mapping can be briefly summarised as follows:

1. The existence of a widespread arsenic province associated with the location of bedrock gold mineralisation has been established.

2. Of the other elements which are of economic interest, molybdenum is only anomalous in a few samples in widely separated areas, and copper forms an isolated, but extensive linear anomaly of unknown origin.

3. The largest known gold mineralisations in the Kangari Hills and Sula Mountains are associated with arsenic.

4. The highest arsenic values in stream sediments are associated with the known gold deposits of Yirisen and Baomahun. However, arsenic values of similar magnitude to those in the soil at Yirisen have been detected over the non-auriferous arsenic deposit at Maruba. Furthermore, at Yirisen itself Mather has emphasised that the tenor of the gold cannot be accurately correlated with the grade of arsenic in the weathered rock. It is tentatively concluded therefore, on the basis of the limited information available, that major bedrock gold deposits will probably be associated with large amounts of arsenic which will be reflected in the presence of strong anomalies in the drainage, but due to

the apparent great primary mobility of arsenic, the grade of arsenic in the bedrock may not vary significantly between auriferous and barren veins.

5. The failure to detect other drainage anomalies or to locate further gold mineralisation of the Yirisen or Baomahun type in the areas investigated indicates that the alluvial gold elsewhere has probably been derived from low grade deposits disseminated in the rocks.

6. It may be possible to identify the type of gold mineralisation on the basis of metal associations in the drainage. The quartz vein or 'lode' deposit at Yirisen, accompanied by arsenic, lead, antimony, copper and zinc sulphides, is different to the Baomahun deposit, where the gold is erratically distributed in a zone of heavy arsenic mineralisation.

## SECTION 6 .

## SUMMARY OF CONCLUSIONS.

The present study has been concerned with the application of regional geochemical mapping to a mineralised schist belt in Central Sierra Leone. Particular attention has been given to the influence of geology and other environmental factors on broad scale geochemical patterns.

The main conclusions from the various aspects of the investigation are listed below in some detail;

### ANALYTICAL AND PRESENTAION TECHNIQUES.

1. The spectrochemical method employed was adequate for the purpose of the study. However, it must be emphasised that in areas where minor variations of element content are significant the method would need to be modified, (a) to overcome operator bias, (b) to eliminate the marked effects on apparent minor element contents caused by differences in the major element composition of the samples, and (c) to improve the precision of the technique.

2. In general the bias related to sample composition decreases the contrast between the high and low values; the highest trace element contents occur in those samples where suppression due to major element composition is at a maximum. the exceptions to the above are lead, barium and potassium but the enhancement of the

lead, barium and potassium values in granitic areas does not affect any of the conclusions on the development of the geochemical patterns.

3. The presentation of the analytical results in the form of symbols on drainage maps simplified the interpretation of the data. The method used to group the analytical results into a series of classes, each of which is represented by a symbol, takes into consideration the precision of the analytical method. The different ranges of concentration represented by the symbols are therefore regarded as being significant.

## SAMPLE DENSITY AND SAMPLE MATERIAL

4. The sample density obviously affects the interpretation of the data. The present study was based on a density of four samples per square mile and this density was found to be more than adequate for detecting the more significant patterns. Both the geochemical provinces and sub-provinces would have been detected with a density of two samples per square mile.

5. The geochemical maps are based on analyses of the minus 80-mesh fraction of stream sediments. From a limited investigation into the composition of stream sediments, the minus 80-mesh fraction of the samples was found to be a relatively constant proportion of the total sample, forming approximately 8 per cent by weight. The possible effects of environmental factors such as the stream

velocity, gradient and distance from stream source, upon the composition of the sample are, therefore, probably small. There are, however, slight variations in the particle size distribution which can be correlated with the major rock types and with areas of duricrust soil, but there is little variation in the particle size distribution with increasing distance from the stream source.

6. In most of the streams examined, the minor element composition of the particle size fractions showed little tendency to concentrate with increasing distance from the stream source. However, titanium and chromium were found to be concentrated with increasing distance from stream source in two drainages.

7. The minor element content of the stream sediment varied amongst the individual size fractions, but in general the maximum concentrations of the minor elements and the minimum spread of the results were found in the sample fractions smaller than minus 80-mesh.

8. Amongst the particle size fractions, manganese, cobalt, nickel, copper, arsenic, molybdenum and lead are concentrated in the fine fractions relative to the coarse, possibly due to the solubility of these elements and the comminution of the host minerals. Vanadium and chromium are frequently found to be concentrated in the coarse rather than the fine fractions. Titanium characteristically displays a bi-modal distribution being concentrated in the coarse and fine fractions relative to the intermediate fractions. The

concentration of titanium, vanadium and chromium in the coarse size fractions is possibly related to ferruginous concretions. Nickel, vanadium and chromium display a bi-modal distribution in sediments derived from granites and ultrabasic rocks. A weakly bi-modal distribution in the size fractions is displayed by manganese, cobalt, arsenic and molybdenum in the duricrust sediments. In the coarse fractions these elements are probably concentrated with iron as concretions.

9. The often recognised co-variant distribution of manganese and cobalt in the zone of weathering is also a feature of the stream sediments in the field area. It is possible, therefore, that high contents of cobalt in the stream sediments could be more closely related to the manganese contents of the sediments than to the cobalt content of the bedrock.

10. It is unlikely that the regional geochemical patterns are related to wide scale variations in the relative acidity or alkalinity of the stream waters, since the majority of the values of pH range between 5.8 and 6.8.

11. No evidence of contaminants was seen in the many drainages examined, and the effect of contamination are believed to be negligible.

## GEOCHEMICAL PATTERNS RELATED TO THE BEDROCK

12. In general, and as was expected, the minor element composition of the bedrock is closely reflected by the geochemical patterns.

The several important exceptions to this generalisation are detailed under "Patterns unrelated to the bedrock".

The regional geochemical distribution of the elements, with the exception of lead, is broadly similar. The elements titanium, vanadium, chromium, manganese, cobalt, copper and zinc are normally most concentrated over areas of schistose rocks, whilst the granite rocks are characterised by relatively low levels of these elements. Lead is concentrated in certain types of granite.

13. In general, the geochemical patterns of each of the major rock types can be clearly distinguished. Areas of ultrabasic rocks (tremolite serpentinites) are characterised by the highest levels of chromium and nickel, the ratio Cr/V is greater than one and the ratio Ni/Co is between five and ten. In contrast, areas of basic rocks (amphibolites) are characterised by higher levels of copper than on ultrabasic rocks; the ratio Cr/V is less than one, and the ratio Ni/Co is between one and two.

Although titanium occurs in characteristically higher contents in basic rocks than in ultrabasic rocks, this difference is not apparent in the drainage results. This is probably due to the grouping of analytical results and the small difference between the high average titanium content of the stream sediments derived from ultrabasic rocks (greater than 7000 ppm.) and the highest analytical standard (10,000 ppm.).

The minor element composition of the metasediments is likely to vary according to the facies, but in general the contents of most

of the elements are higher than in the granites, but low compared with the basic and ultrabasic rocks. In addition, the ratio Cr/V is approximately one.

14. The geochemical patterns reflect regional variations in the minor element content of individual rock types. The two fold increase of chromium in the basic rocks of the Bumbuna area, dompared to the Basaia and Makele areas, is clearly reflected by the stream sediments . Similar regional variations in the concentrations of manganese and nickel also occur in these rocks, but the variations in these elements are not reflected by the stream sediments; no doubt due to their greater solubility and mobility.

15. Regional variations in the minor element composition of a series of somewhat similar rock types are reflected by the geochemical drainage patterns. Amongst granites, regional variations in the concentrations of lead and titanium in the bedrock are clearly reflected by the stream sediments. In most cases the titanium contents of the bedrock are enhanced in the sediments.

16. Other regional variations in the regional geochemical patterns on granites are less closely related to bedrock composition. In the central granite area, the nickel contents of the rock samples are low compared to those of the sediments. This difference is probably erroneous and due to the poor representivity of the rock samples.

17. Variations detected in the geochemical drainage patterns of synkinematic granites reflect the nature of the original rocks. For example, in the south-west area of lead rich synkinematic granites, a linear zone of discontinuous amphibolite outcrops is reflected by geochemical patterns which are rather more widespread than are the outcrops. In this area relatively high contents of titanium, vanadium, manganese and low contents of lead are present in the stream sediments, suggesting the presence of rocks of basic composition. It is evident that the present mapping technique can confidently be used to assist geological mapping in areas of synkinematic granites, and also to establish the geochemical nature of different zones in the granites.

18. The lead and titanium rich granites are of synkinematic type, and are also enriched in potassium and rubidium. These rocks normally contain abundant feldspar porphyroblasts generally of large grain size.

19. The synkinematic porphyroblastic granites which can be identified by their relatively high lead, potassium and rubidium contents are believed to have been subjected to metasomatic processes during which these elements were introduced. Titanium is also high in these granites reflecting, it is believed, the composition of the pre-existing synkinematic granites.

20. The metasomatised synkinematic granites can be identified from the regional geochemical patterns on the basis of their relatively high lead (and rubidium) contents.

21. The majority of the samples of synkinematic granite display a ratio of K/Rb = 240, which is in the range of the published results . It is improbable, therefore, that these granites are late stage derivatives of granitic magmas.

22. The ratio Rb/Pb = 5 also characterises the synkinematic granites. From the ratios of K/Rb = 240 and Rb/Pb = 5, it is possible, if not probable, that potassium and rubidium and lead are regularly distributed in the bedrock. The higher contents of these elements in the prophyroblastic granites is most probably related to the increased volume of potash felspar.

23. The Rb/Pb ratios of the stream sediments derived from synkinematic granites display a wider scatter than the Rb/Pb ratios of the source rocks. Although this difference is probably not significant, it could possibly be due to slightly different forms of dispersion of these elements in stream sediments. From the present results a ratio of Rb/Pb = less than one, in granitic rocks and stream sediments, would indicate an abnormal concentration of lead relative to rubidium which could conceivably be related to mineralisation. Lead mineralisation is not known in the granitic rocks of the field area, and there was no opportunity to test this hypothesis.

24 Geochemical patterns were detected which are related to a series of rock types, but not necessarily co-incident with their outcrops. Thus, abnormally high concentrations of arsenic and molybdenum are widely distributed and are not confined to any specific rock type. The arsenic forms a geochemical province related to the schist belt. Molybdenum in detectable quantities (greater than 1 ppm) does not form such a sharply defined province in the writer's field area, but the molybdenum high areas might be considered as outliers of the more homogenous pattern detected to the north (L.D. James, personal comm.).

25. The highest arsenic values in stream sediments are associated with the known gold deposits of Yirisen and Baomahun. However, arsenic values of similar magnitude to those in the soil at Yirisen have been detected over the non-auriferous arsenic deposit at Maruba. Furthermore, at Yirisen itself Mather has emphasised that the tenor of the gold cannot be accurately correlated with the grade of arsenic in the weathered rock. It is tentatively concluded, therefore, on the basis of the limited information available, that major bedrock gold deposits will probably be associated with large amounts of arsenic which will be reflected in the presence of strong anomalies in the drainage, but due to the apparent great primary mobility of arsenic, the grade of arsenic in the bedrock may not vary significantly between auriferous and barren veins.

26. The failure to detect other drainage anomalies or to locate further gold mineralisation of the Yirisen or Baomahun type in the areas investigated indicates that the alluvial gold elsewhere has probably been derived from low grade deposits disseminated in the rocks.

27. It may be possible to identify the type of gold mineralisation on the basis of metal associations in the drainage. The quartz or 'lode' deposit at Yirisen, accompanied by arsenic, lead, antimony, copper and zinc sulphides, is different to the Baomahun deposit, where the gold is erratically distributed in a zone of heavy arsenic mineralisation.

## PATTERNS NOT RELATED TO THE BEDROCK

28. Certain variations in the minor element content of the stream sediments are not related to the geochemistry of the bedrock, but to factors operating in the zone of weathering. These geochemical patterns are regarded as spurious in the context of regional geochemical mapping.

The geochemical patterns on similar rock types vary according to the nature of the soil types. These differences could be so large as to give the appearance of geochemical provinces, and for this reason identification of the character of the soil types is of great pertinence.

29. Differences in the mineralogy of the bedrock are likely to affect the distribution of the minor elements in the soils and stream sediments. Thus titanium, in resistant minerals, occurs at high levels in the sediments derived from basic and ultrabasic rocks irrespective of soil type.

Similarly the concentration of chromium (probably occurring as chromite) in the drainages from the ultrabasic rocks, is high in both duricrusted and non-duricrusted areas. However, in areas of basic rocks (where the chromium is probably incorporated with the amphiboles) the chromium content of sediments in duricrust areas is low compared to those in non-duricrust areas. This reflects no doubt, a greater mobility and a possible concentration in the colloidal weathering products of chromium occurring in the lattices of silicates, than that occurring as chromite.

30. No analyses were made of the stream waters or of separated clay size fractions, so that there is no direct evidence of the form in which the metals are dispersed. From the geochemical maps it is evident that the secondary dispersion in areas of thin colluvial latosols is largely mechanical, whereas in areas of duricrust the dispersion of some elements, particularly cobalt and nickel, is saline.

31. The variable distribution of the elements in a vertical profile of indurated latosols is probably largely controlled by the

development of the soil profile . Important additional factors are the weathering characteristics of the minerals in which the minor elements are concentrated, and the solubility of the elements following their release from the mainly silicate crystal structures.

32. The relative concentrations of titanium, vanadium and chromium with iron, in the B horizon of an indurated latosol profile on basic rocks, is taken to indicate the incorporation of the soluble fraction of these elements with iron in the form of concretions.

33. The regional variations of cobalt and nickel shown by the geochemical patterns on basic and ultrabasic rocks are more extreme than those of chromium. This feature is taken to indicate the extensive leaching of cobalt and nickel from the weathered rock. This effect is particularly important in areas of duricrust soils where the geochemical patterns illustrate relatively low contents of both elements. The cobalt contents of the stream sediments in areas of duricrust covered basic and ultrabasic rocks is about one half of the content in the rocks. The nickel content of sediments in duricrust areas of basic rocks is reduced to between one third and one fifth of the bedrock content and in areas of ultrabasic rocks, is reduced to one twelfth of the bedrock content.

34. In most areas of thin colluvial latosols the average contents of the minor elements are intermediate between those of the rocks and the stream sediments. In certain areas, however, the element

content of the soils is relatively low. For example, cobalt and nickel occur at low levels in the soils on the ultrabasic rocks near Makong and manganese is reduced in the soils on the ultrabasic rocks near Makele, but is concentrated in the soils on basic rocks nearby. The reasons for these variations are not known, but they could be related to local variations in the degree of erosion of the residual soils, or to high metal contents of the ground waters being concentrated in the active stream sediments.

35. Erosion, resulting in regional variations in the truncation of residual soil profiles is an important factor affecting the development of the geochemical patterns. The variable distribution of the minor elements in an indurated latosol profile, illustrates the wide range of concentration to be expected according to the depth of truncation. An additional factor is the concentration of some elements in secondary minerals in the soil profile.

On a regional scale, evidence of the varying depths of truncation of residual soils is seen in the almost complete absence of duricrust in the Kangari Hills, whilst relatively large areas remain in the Sula Mountains. On a small scale, the complex geochemical patterns in the Bumbuna area of basic rocks are, no doubt, related to the variations in pedology which exist between the duricrust plateau and the colluvial latosols on the monadnock screes.

36. There is little difference between the minor element composition of the iron poor latosols on granitic rocks and the minor element content of the bedrock.

37. Although the vegetation might be expected to effect the development of the geochemical patterns, no evidence of this feature was detected from the investigation. Similarly, no evidence of animal activity, other than that of man, was recognised as a factor influencing the patterns. It is remotely possible that alluvial gold mining operations have affected the minor element distribution in some of the drainages.

38. The present study has demonstrated that regional geochemical mapping provides data of fundamental and economic importance and is complimentary to regional geological mapping.

## SECTION 7

## RECOMMENDATIONS FOR FUTURE RESEARCH

### GENERAL

During the present study a number of problems have been investigated and solutions found. However, the work has raised many additional problems which, for convenience, are listed below, together with the other major research topics which are closely related to the writer's research.

### MAJOR RESEARCH TOPICS

1. It is suggested that future trial geochemical maps should be made in areas where several inter-related geochemical provinces are likely to exist. These investigations should be extended to other regions with the object of detecting extensive geochemical provinces. Ideally such investigations should include the study of variations of element content in deep drill holes sited at critical localities.

2. A logical extension of the detection of regional geochemical provinces, by sampling drainage components, would be the study of the marine sediments of the continental shelves with the aim of detecting the most favourable catchment areas for more detailed work. Such studies have already been proposed and should, where possible, be associated with studies on the adjacent land masses.

3. The possibility of detecting geochemical provinces on the ocean beds beneath the veneer of recent sediments warrants investigation, although there are, obviously, considerable problems.

4. Research is required in the presentation and interpretation of regional geochemical maps. Although the use of multicolour maps, as distinct from the monocolour maps of the writer, would no doubt assist interpretation, the possibility of using computers for integration of the data should also be considered.

## RESEARCH TOPICS ARISING DIRECTLY OUT OF THE PRESENT STUDIES

5. In the Sierra Leone study area, the most important field for further research in geochemical mapping techniques is in the study of the factors controlling the secondary dispersion of the minor elements from the bedrock. This work is essential to the correct interpretation of the regional geochemical patterns. This topic has been investigated in connection with geochemical prospecting for sulphide ore deposits, but much more work is required on a broad spectra of elements in both mineralised and barren areas. Such investigations should take into account, not only the mineralogical composition of the bedrock and associated soils and sediments, but also the effects of different environments in the zone of weathering.

6. Regional variations in the metamorphic facies of a rock type resulting in different mineral forms would also be expected to influence the geochemical patterns and merits investigation.

7. The many multi-element and single element patterns which are mentioned in thetext, but not investigated, are an obvious choice for more detailed investigations in regional geochemistry.

8. The geochemical dispersion in areas of duricrust, resulting in low levels of cobalt and nickel, is a problem which is particularly important in the Sula Mountains where duricrust obscures large areas of the bedrock. The detection of geochemical provinces and possibly associated mineralisations of cobalt and nickel in such an environment is, from the present results, likely to be difficult. It is suggested, therefore, that the mechanism of the dispersion of the minor elements in indurated laterite or duricrust profiles be fully investigated both on areas of basic and on ultrabasic rocks.

9. There are several problems of the minor element distribution amongst the thin colluvial latosols, for in certain areas the concentration in the soils is markedly low compared to the levels in the rocks and sediments. For example, manganese, cobalt and nickel occur at low levels in the soils on the basic rocks near Bumbuna and cobalt and nickel occur at low levels in the soils on the ultrabasic rocks near Makong. Manganese is concentrated in the soils associated with basic rocks at Makele, but is reduced in the soils associated with ultrabasic rocks nearby.

10. The distribution of the minor elements in stream sediments is an important field for further research in geochemical mapping.

Further research is required into the distribution of the minor elements amongst the particle size fractions according to major rock type or types from which the sediments are derived, and also with increasing distance from the stream source. These features could be investigated by studying the distribution of the minor elements from differing rock types into both separate and common drainage channels.

11. Factors controlling the length of the dispersion trains of the minor elements warrant investigation. Such studies should include an investigation of the mineral forms in which the elements are concentrated with a parallel study on the composition of the ground and stream waters.

12. Amongst the many important problems associated with the economic aspects of the investigation, more work is needed on the metal associations which accompany the gold mineralisation. Research into the origin of the gold deposits is also required.

13. Some further investigation of arsenic anomalies, particularly those detected in streams with large catchment areas, is warranted. Due to the relatively long sample interval, it is probable that certain of the anomalies listed in SECTION 5 might be of considerable magnitude near to the bedrock source.

As a result of this work, apart from the economic aspects, it should also be possible to determine the extent to which the arsenic province is related to syngenetic concentrations in the

argillaceous facies of the metasediments. The recognition of other metal associations, as a result of prospecting operations, would be of value in the further interpretation of the regional geochemical data.

14. As an integral part of the prospecting programme, it is suggested that an investigation be made into the possibility of distinguishing between concentrations of metals related to sulphide mineralisation, and concentrations related to abnormal metal contents in silicate minerals on the basis of their form in the drainage. (In this respect attention is drawn to the work of Harden (1962) on some problems of geochemical mapping in Northern Rhodesia).

15. The possibility of detecting secondary enrichments of cobalt and nickel in the areas of ultrabasic rocks which are obscured by indurated laterite and duricrust is worth investigation. Deposits of these metals might exist on the weathered surface of the ultrabasic rocks beneath the duricrust near Basaia, in the eastern part of the field area, and also in the Sula Mountains area to the north of Bumbuna. This possibility could best be checked by exploratory pitting in the duricrust.

> The considerable economic importance of laterites has been reported by Rumbold (1923), and emphasised by Ingerson (1958), who refers to the accumulation of Cr, Ni, Co, Nb, in addition to the major elements Al and Fe. Lacroix (1934) and de Chatelat (1947) have described the lateritic nickel ores of New Caledonia which are developed in lateritic residual soils overlying peridotite. Both authors have observed

that nickel is released from the peridotite during weathering, and is concentrated as the nickel silicate minerals in the base of the soil profile and particularly in the fissured surface of the weathered peridotite. In addition, cobalt and manganese, also liberated during weathering, are co-precipitated as small black nodules which are concentrated in the lower zone of the laterite. The upper zone of the laterite is characteristically composed of ferruginous nodules which are fused into a scoriaceous mass at surface.

The partition of cobalt and manganese from nickel in the zone of weathering has also been reported from Sao Jose du Tocantins, Goiaz, Brazil (Pecora,1944), where the climate is tropical with a mean annual temperature of 73°F. and a seasonal rainfall of ±70 inches. At Sao Jose, a green clay lies immediately above weathered pyroxenite, and contains from 2 to 5 per cent nickel, compared to 0.1 - 0.2 per cent nickel in the fresh rock. Cobalt and manganese accumulate together, in nodular form and in sufficient quantity to form ore.

From these descriptions, it is evident that under favourable climatic conditions nickel silicates and manganese-cobalt nodules accumulate at the base of lateritic soils which are developed on ultrabasic rocks

Although these relatively low grade multi-element deposits which present metallurgical problems,are of doubtful economic value at the present time, it is possible, if not probable, that they will form an important source of metal in the future. Accordingly, from the long term point of view, it is worth while to delimit areas of maximum concentration of these elements.

16. Of the many interesting features which resulted from a study of the geochemical patterns, the regional variation in the distribution of lead in the bedrock is of special interest. It

is noticeable that the porphyroblastic lead rich granites occupy areas along the flanks of the schist belt where there are flexures and changes of strike. It would be of interest to establish the date of the potassium enrichment of the granites and the date of the intrusion of the late-kinematic granite for comparison with the age determinations on the mineralisation of the schist belt, as a first step in determining the relationship, if any, between the granites and the mineralisation.

17. Since the present work has clearly indicated that some types of gold deposit are associated with the geochemical province of arsenic detected in the regional survey, it is strongly recommended that the survey be extended to other areas of Sierra Leone, particularly those in which mineral deposits are known, or are suspected.

## SECTION 8

## LIST OF REFERENCES


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# A P P E N D I X

The methods described, except where stated, are those currently used at the Geochemical Prospecting Centre at Imperial College.

## SPECTROCHEMICAL ANALYSIS

Dr. I. Nichol has kindly provided the following note on the analytical procedure, which may be divided up into phases as below.

### ASHING

Samples (minus 80-mesh) are ignited for three hours at 400 to 450°C.

### SAMPLE PREPARATION

Samples are hand ground in an agate pestle and mortar to approximately minus 200-mesh and then a 100 mg. aliquot is weighed into a "Wig L. Bug" tube. To this is added 50 mgs. each of lithium carbonate and carbon (Magecol black 888 grade, manufactured by Columbian International Ltd.). The mixture is then shaken by a "Wig L. Bug" shaker for 30 seconds to obtain a homogeneous mixture. Samples analysed for molybdenum only, are not mixed with buffer.

### SPECTROCHEMICAL CONDITIONS

The analysis is carried out on Hilger Large quartz spectrograph with a Hilger & Watts BNF spectrographic source unit FS 131. The spectrograph conditions are as below:

| | |
|---|---|
| Excitation | D.C. Arc |
| Exposure | 20 seconds , molybdenum only; 30 seconds. |
| Gap | 3 mm. |
| Slit | 0.15 mm. |
| Amps | 12.5 amps. |
| Step Sector | 1/16, 1/4, 1 |
| Wavelength Range | 4900-2800 Å |
| Emulsion | Ilford N.30 |
| Collimator | Int. |
| Sample Polarity | Positive |
| Anode | 5 mm. carbon (2.91 mm. diam. crater, 5 mm. deep) |
| Cathode | 5 mm. carbon, flattened |

## PROCESSING

Standard methods of processing are used (Kodak D 19b developer for 5 mins. at 20°C.).

## ESTIMATION

The estimation of the plates is carried out on a Hilger-Jaco Comparator Microphotometer L.90. The concentration of element 'X' is estimated by comparing the line intensity of a suitable line, with the line intensities of the same line at concentration intervals of 1-2-5-10 ppm. etc. up to 10,000 ppm., on a standard plate. (The

composition of the base used for the standard plate approximates to that of an intermediate rock).

## ELEMENT LINES AND PRECISION

Element lines and precision are reported in SECTION 2.

## X-RAY SPECTROGRAPHIC TECHNIQUE

The analysis of Rb, Sr, Y, Zr and Nb was carried out by Mr. A. Smith of the Pure Geochemistry Department. The spectrographic method was similar to that used by P. Bowden (1962) who kindly provided the following note on procedure.

An A.R.L. curved spectrograph was utilised to detect the presence of Rb, Sr, Y, Zr, Nb in pressed sample pellets of equal weights of minus 100-mesh rock powder and cellulose.

The method of analysis after Anderson and Kemp (1958) is to irradiate the pellet with primary X-rays. The secondary or characteristic X-rays ($K_1$, $K_2$) emitted by the elements are diffracted by Li R curved crystals into an X-ray proportional counter and converted into a series of peak heights on a chart recorder.

The signal is integrated for 100 seconds at each wavelength, the peak height then measured and the concentration determined from a working curve constructed from the analysis of samples with a similar matrix.

The critical voltage Kv necessary to excite the characteristic X-rays of each element are given in the table below, together with the wavelength measured at the peak height.

| Element | Critical voltage Kv | Wavelength Å | Reproducibility | Sensitivity ppm. |
|---|---|---|---|---|
| Nb | 16.6 | 0.749 | 20% | 20 |
| Zr | 15.8 | 0.789 | 20% | 50 |
| Y | 14.9 | 0.831 | 20% | 30 |
| Sr | 14.2 | 0.877 | 20% | 20 |
| Rb | 13.4 | 0.928 | 20% | 50 |

The reproducibility is approximately 20% for all the elements but the estimation near the sensitivity limit lead to larger errors.

## SEPARATION OF COBALT, COPPER, LEAD, NICKEL AND ZINC FROM SOILS, SEDIMENTS AND SILICATE ROCKS AFTER DECOMPOSITION WITH HYDROFLUORIC ACID

### ABBREVIATED OPERATING INSTRUCTIONS

#### Procedure

1. Weigh 1 g. of acidic rock, or 0.5 g. of basic rock, or 0.25 g. of soil or sediment into a platinum dish.
2. Add 10 ml. of hydrofluoric acid, 2 ml. of perchloric acid and 1 ml. of nitric acid and allow the solution to evaporate overnight on a water-bath or sand-bath.
3. Heat on a hot-plate to expel perchloric acid.

4. Warm the residue with 5 ml. 1M HCl and filter through a No. 40 Whatman filter paper. Wash the crucible and the filter paper thoroughly with de-ionised water and evaporate the filtrate in a 100 ml. beaker. Transfer to a test tube calibrated at 10 ml. and make up to 10 ml. with de-ionised water.

5. Dry the filter paper and ignite in the platinum crucible and heat until the paper is ashed. Add 1 gm. of sodium carbonate anhydrous, A.R. and fuse, running melt around base of the crucible.

6. Add 20 ml. 1M HCl to each crucible to acidify the fused residue. Add 10 ml. HF and 2 ml. $HClO_4$ to each crucible and evaporate on a hot-plate.

7. Warm the residue with 5 ml. 1M HCl and filter through a No. 40 Whatman filter paper. Wash the crucible and the filter paper thoroughly with de-ionised water and evaporate the filtrate in a 100 ml. beaker. Transfer to a test tube calibrated at 10 ml. and make up to this level with de-ionised water

8. Transfer to a 50 ml. beaker and leave on a water-bath until all the salts have dissolved.

9. Transfer the solution to a 150 ml. separating funnel containing 25 ml. of sodium citrate buffer solution.

10. Extract the reacting metals with successive 5 ml. portions of 0.015% dithizone solution until there is no further reaction, collecting the carbon tetrachloride phases in a second separating funnel. Discard the aqueous phase.

11. Complete the separation of the carbon tetrachloride extracts from any accompanying aqueous phase by transferring the organic layer from the second separating funnel to a 100 ml. beaker.

12. Wash the separating funnel and aqueous layer with carbon tetrachloride and collect the washings in the beaker.

13. Evaporate the combined carbon tetrachloride extracts and washings to dryness on a water-bath.

14. Add 2 ml. of concentrated sulphuric acid and 1 ml. of 60% perchloric acid, and heat the covered beaker on a sand-bath until the solution is colourless; remove the watch-glass and evaporate to dryness.

15. Dissolve the residue by warming gently with 3 ml. of 0.5N-hydrochloric acid, transfer to a test-tube (calibrated at 10 ml.) and dilute to 10 ml. with 0.5N-hydrochloric acid.

16. Take appropriate aliquots of this solution for the determination of cobalt, copper, lead, nickel and zinc, as described in the methods for these elements,(see below).

## Reagents

1. Hydrofluoric acid: 40%, A.R.

2. Perchloric acid: 60%, A.R.

3. Hydrochloric acid: constant-boiling mixture, purified by distillation.

4. 1M-hydrochloric acid: mix 80 ml. of the constant-boiling acid with 420 ml. of water.

5. 0.5M-hydrochloric acid: mix 40 ml. of the constant-boiling acid with 460 ml. of water.

6. Sulphuric acid: sp. gr. 1.84, A.R.

7. Carbon Tetrachloride: A.R.

8. 0.015% dithizone solution: dissolve 60 mg. of dithizone (A.R.) in 400 ml. of carbon tetrachloride.

9. 0.04% thymol blue: dissolve 40 mg. of the sodium salt in 100 ml. of water.

10. Ammonia solution: A.R., sp. gr. 0.880.

11. Chloroform: A.R.

12. Sodium citrate buffer solution: dissolve 200 g. of tri-sodium citrate and 10 g. of hydroxylamine hydrochloride in about 800 ml. of water, add 5 ml. of 0.04% thymol blue solution followed by ammonia solution (sp.gr.0.880) until the colour of the indicator changes from yellow to a distinct blue, and then dilute to 1 litre with water. Extract with successive volumes of 0.015% dithizone until there is no further reaction, and remove the dithizone from the aqueous phase by successive extractions with chloroform.

## Remarks

This method is intended for academic studies, and is not designed for use in geochemical prospecting operations.

The sodium citrate buffer solution (Reagent 12) must have a pH value in the range 10.8-11.0. At Procedure 7, the aqueous phase should have a pH value not less than 8.9.

This procedure is a modification of that described by R.E. Stanton, A.J. McDonald and I. Carmichael, Analyst, 1962, 87, 134-139.

## DETERMINATION OF COBALT IN SOIL AND SEDIMENT SAMPLES

### ABBREVIATED OPERATING INSTRUCTIONS

### Procedure

1. Weigh 0.25 g. of sieved sample into a pyrex test tube (16 x 150 mm.)
2. Mix with 1 g. of potassium bisulphate and fuse.
3. Leach with 5 ml. of 0.5M-hydrochloric acid.
4. Pipette a 2 ml. aliquot into 10 ml. of buffer solution contained in a 16 x 150 mm. test tube previously calibrated at 10 and 12 ml.
5. Add 0.5 ml. of 10% tri-n-butylamine solution.
6. Cork the tube and shake vigorously for 1 min.
7. Compare with standards.
8. If greater than the top standard, repeat the test using an aliquot of 0.1 ml. at stage 4, diluting to 12 ml. with 0.5M-hydrochloric acid.
9. Cobalt in ppm. $= \frac{20 \times (\text{ug. of cobalt in matching standard})}{(\text{ml. of sample aliquot})}$

### Standards

To 22 test tubes, each containing 10 ml. of buffer solution, add respectively 0, 0.25, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 µg. of cobalt using a solution containing 5 µg. of cobalt per ml., and 6.0, 7.0, 8.0, 10.0, 12.0, 14.0, 16.0, 18.0, 20.0 and 25.0 µg. of cobalt using a solution containing 20 µg. per ml. Dilute to the 12 ml. mark with 0.5M-hydrochloric acid, add 0.5 ml. of 10% tri-n-butylamine solution, cork the tubes and shake vigorously for 1 min.

## Reagents

1. Potassium bisulphate: fused powder

2. 6M-hydrochloric acid: mix 240 ml. of acid (sp. gr. 1.18) with 200 ml. of water, or use the constant boiling mixture.

3. 0.5M-hydrochloric acid: mix 20 ml. of acid (sp. gr. 1.18) with 420 ml. of water.

4. Buffer solution: A - dissolve 170 g. of sodium acetate (tri-hydrate), 40 g. of tetra-sodium pyrophosphate (deca-hydrate) and 5 g. of hydroxylamine hydrochloride in water, add 140 ml. of 6M-hydrochloric acid and dilute to 1 litre with water.
   B - dissolve 360 g. of potassium thiocyanate in water and dilute to 1 litre.
   Mix A and B in the ratio 9:1 as required each day.

5. 10% tri-n-butylamine solution: mix together 90 ml. of n- or iso-amyl alcohol and 10 ml. of tri-n-butylamine.

6. Standard cobalt solutions: 100 ug. of cobalt per ml. - dissolve 40.5 mg. of cobaltous chloride (hexa-hydrate) in 0.5M-hydrochloric acid and dilute to 100 ml. with this strength of acid.

   20 µg. of cobalt per ml. - dilute 20 ml. of the 100 µg. per ml. solution to 100 ml. with 0.5M-hydrochloric acid.

   5 µg. of cobalt per ml. - dilute 25 ml. of the 20 µg. per ml. solution to 100 ml. with 0.5M-hydrochloric acid.

## Remarks

The range 1-250 ppm. is covered by an aliquot of 2 ml., and the range 20-500 ppm. by an aliquot of 0.1 ml. Results within ± 20% at the 95% confidence level are commonly obtained in these ranges.

In the presence of 5% or more calcium, results will be low due to coprecipitation of cobalt with calcium pyrophosphate.

The optimum pH range for the final aqueous phase is 4.5 - 5.2.

For further details refer to Stanton, R.E. and McDonald, A.J., Trans. Instn. Min. Metall. (London.), 1961-62, 71, 511-516.

# DETERMINATION OF NICKEL IN SOIL AND SEDIMENT SAMPLES

## ABBREVIATED OPERATING INSTRUCTIONS

### Procedure

1. Weigh 0.2 g. of sieved sample into a 16 x 150 mm. test tube.
2. Mix with 1 g. of potassium bisulphate and fuse.
3. Leach with 5 ml. of 0.5M-hydrochloric acid.
4. Pipette a 2 ml. aliquot into 5 ml. of buffer solution contained in a test-tube (18 x 180 mm.) previously calibrated at 5, 7, 8, 10, 12, etc. to 20, 22 ml.
5. Add 1 ml. of α-furildioxime solution, cork the tube and shake vigorously for 2 min.
6. Compare with standards.
7. If above the top standard dilute with a known volume of benzene until within the range.

   ppm. = 12.5 x (µg. of nickel in matching standard) x (ml. of solvent phase).

### Standards

To each of eleven test tubes, calibrated at 5, 7 and 8 ml., and containing 5 ml. of buffer solution, add respectively 0, 0.25, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 and 5.0 µg. of nickel and dilute to 7 ml. with 0.5M-hydrochloric acid. Add 1 ml. of α-furildioxime solution and shake vigorously for 2 min.

### Reagents

1. Buffer solution: dissolve 20 g. of tri-ammonium citrate in water, add 130 ml. of ammonia (s.g. 0.880) and dilute to 1 litre with water.
2. Potassium bisulphate: fused, powder.

3. 0.5M-hydrochloric acid: 20 ml. of acid + 420 ml. of water.

4. α-furildioxime: 0.3 g. dissolved in 90 ml. of benzene and 10 ml. of ethyl alcohol (absolute).

5. Standard nickel solution: 100 µg. of nickel per ml. - dissolve 50mg. of nickel (metal, powder) in 10 ml. of 25% nitric acid and dilute to 500 ml. with water.

5 µg. of nickel per ml. - dilute 5 ml. of the 100 ug. per ml. solution to 100 ml. with 0.5M-hydrochloric acid.

## Remarks

The method as described will cover the range 1-900 ppm. By using a sample aliquot of 0.1 ml. at Stage 4 of the Procedure, the range can be extended to 18,000 ppm. If this size of aliquot is used dilute to 7 ml. with 0.5M-hydrochloric acid before proceeding to Stage 5.

Results can be obtained with ± 20% at the 95% confidence level over the range 5 - 18,000 ppm.

80 - 100 samples can be analysed per man-day.

Copper will interfere by giving a brown colour when the copper to nickel ratio exceeds 30:1. When maximum tolerance towards this metal is desirable, a solution containing 400 g. of the citrate per litre should be treated with a carbon tetrachloride solution of dithizone until free from copper; use 50 ml. of this solution instead of weighing 20 g. of the solid reagent.

If the zero standard is yellow the buffer solution must be purified with respect to nickel. This may be accomplished by using dithizone as in 4 above, but with the pH 8.9, or by extraction with α-furildioxime, using a solution as in Reagents 4 but containing carbon tetrachloride in place of benzene.

Ferrous ions form a purple complex with α-furildioxime and may occur from inadequate fusion of the sample with potassium.

The buffer solution should have a pH value of 10.3 ± 0.1.

For further information see R.E. Stanton and J. Coope, Trans. Instn. Min. Metall., Lond., 1958-59, 68, 9-14.

# DETERMINATION OF COPPER WITH DITHIZONE IN SOIL, SEDIMENT AND ROCK SAMPLES

## ABBREVIATED OPERATING INSTRUCTIONS

### Procedure

1. Weigh 0.1 g. of sieved sample into a Pyrex test tube (16 x 150 mm.)
2. Mix with 0.5 g. of potassium bisulphate and fuse.
3. Leach with 5 ml. of 1M-hydrochloric acid.
4. Add 5 ml. of water and mix.
5. Pipette a 1 ml. aliquot into 5 ml. of buffer solution contained in a 18 x 180 mm. test tube, previously calibrated at 5 ml.
6. Add 5 ml. of 0.001% dithizone solution.
7. Cork the tubes and shake vigorously for 2 min.
8. Compare with standards.
   Copper in ppm. = 100 x µg of copper in matching standard.

### Standards

To eleven test tubes containing 5 ml. of buffer solution, add respectively 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 µg. of copper. Add 5 ml. of 0.001% dithizone solution, cork the tubes and shake vigorously for 2 min.

### Reagents

1. Potassium bisulphate: fused, powder.
2. 1M-hydrochloric acid: mix 40 ml. of acid (sp. gr. 1.18) with 400 ml. of water.
3. 0.5M-hydrochloric acid: mix 20 ml. of acid (sp. gr. 1.18) with 420 ml. of water.

4. 0.01% dithizone in carbon tetrachloride: dissolve 40 mg. in 400 ml. of carbon tetrachloride and store in a vacuum flask.

5. 0.01% dithizone in benzene: dissolve 40 mg. in 400 ml. of benzene and store in a vacuum flask.

6. 0.001% dithizone in benzene: Mix 40 ml. of the 0.01% solution in benzene with 360 ml. of benzene, and store in a vacuum flask.

7. Buffer solution: dissolve 100 g. of ammonium citrate and 100 g. of hydroxylamine hydrochloride in about 500 ml. of water. Extract with 0.01% dithizone in carbon tetrachloride until free from copper, and then remove the excess of dithizone by extraction with carbon tetrachloride. Dilute the aqueous phase to 1 litre with water.

8. Standard copper solutions: 100 µg. of copper per ml. - dissolve 200 mg. of cupric sulphate crystals in 0.5M-hydrochloric acid and dilute to 500 ml. 5 µg. of copper per ml. - dilute 5 ml. of the 100 µg. per ml. solution to 100 ml. with 0.5M-hydrochloric acid.

## Remarks

The range covered is 10-500 ppm., which may be extended to 5000 ppm. by using a sample aliquot of 0.1 ml.

Results may be obtained within ± 25% at the 95% confidence level over the range 10-5000 ppm.

100 samples can be analysed per man-day of 8 hours.

The buffer solution should have a pH value of 4.5 ± 0.15, and the optimum pH range for the final aqueous phase is 3.0 - 4.65.

100 µg. of zinc in the final aqueous phase give a reaction equivalent to 0.2 µg. of copper at pH 3.0 and to 1 µg. of copper at pH 4.6, but the effective tolerance towards zinc in the sample will be less if this element is not removed from the buffer solution. There is no interference from cobalt, lead and nickel present together at 100 µg. each in the final aqueous phase.

The method is a modification of that described by H. Bloom and H.E. Crowe, U.S. Geol. Surv., Open-file Report, 1953.

## DETERMINATION OF ARSENIC IN SOIL, SEDIMENT AND ROCK SAMPLES

### ABBREVIATED OPERATING INSTRUCTIONS

### Procedure

1. Weigh 0.1 g. of sieved sample into a nickel crucible (15 ml.).
2. Moisten with a few drops of water and add 0.5 g. of potassium hydroxide.
3. Heat gently until dry and then fuse, keeping at red heat for 2 min.
4. Allow the melt to cool and add about 3 ml. of water from a polythene wash-bottle.
5. Loosen the melt by scraping with a nickel spatula and transfer the contents of the crucible to a test tube (16 x 150 mm.) calibrated at 10 ml.
6. Rinse the crucible with 3 ml. of concentrated hydrochloric acid and transfer to the test tube.
7. Adjust the volume in the test tube to 10 ml. with water washings from the crucible.
8. Mix well and allow to settle.
9. Pipette a 2 ml. aliquot into 2 ml. of 2.5% potassium iodide solution contained in a 19 x 150 mm. test tube previously calibrated at 2 and 10 ml.
10. Dilute to 10 ml. with 0.75% stannous chloride solution.
11. Add 2-4 g. of zinc pellets and connect a Gutzeit tube to the test tube without delay, having previously placed a mercuric chloride paper in the head of the Gutzeit tube.
12. Leave for one hour, then remove the mercuric chloride paper and compare with artificial standards.
    Arsenic in ppm. = 50 x $\mu$g. of arsenic in matching standard.

### Standards

Pipette four aliquots each of 0, 0.1, 0.2, 0.4, 0.6 and 1.0 ml. of standard arsenic solution (5 $\mu$g. per ml.) into 2 ml. of 2.5%

potassium iodide solution contained in a 19 x 150 mm. test tube previously calibrated at 2 and 10 ml. Treat as described for the sample in 10 and 11 above. After one hour, remove the mercuric chloride papers and select the average spot for each quantity of arsenic. Prepare artificial standards by matching these spots with painted filter paper.

## Reagents

1. Potassium hydroxide: pellets, A.R.

2. Hydrochloric acid: sp. gr. 1.18, A.R.

3. 2.5% potassium iodide solution: dissolve 10 g. of crystals in 400 ml. of water.

4. 10% stannous chloride solution: dissolve 25 g. of the di-hydrate in 250 ml. of concentrated hydrochloric acid.

5. 0.75% stannous chloride solution: mix 75 ml. of the 10% solution with 375 ml. of concentrated hydrochloric acid and 550 ml. of water. Do not keep this solution for longer than two days.

6. Mercuric chloride solution: dissolve 25 g. in 100 ml. of absolute ethyl alcohol, warming cautiously.

7. Lead acetate solution: dissolve 15 g. of the tri-hydrate in 100 ml. of water containing 1 ml. of glacial acetic acid.

8. Standard arsenic solutions: 100 µg. of arsenic per ml. - dissolve 42 mg. of sodium arsenate ($Na_2 HAsO_4, 7H_2O$) in water, add 0.1 ml. of concentrated hydrochloric acid and dilute to 100 ml. with water.

   5 µg. of arsenic per ml. - dilute 5 ml. of the 100 µg. per ml. solution to 100 ml. with water. Make up this solution only when it is needed to prepare or check standards.

9. Mercuric chloride papers: allow about 15 filter papers (Whatman No. 40, 9 cm.) to soak for 1 hr. in the mercuric chloride solution. Allow to dry, then cut into squares approx. 1 cm. x 1 cm., avoiding the edge of each circle. Prepare freshly each week. If commercial papers are used, check with a standard solution once a day.

10. Lead acetate wool: saturate glass wool with the lead acetate solution and allow to dry. Pack a loose plug of this into each Gutzeit tube, and replenish when it is discoloured along half of its length.

11. Zinc: pellets, activated with copper, A.R.

## Remarks

The range covered is 5-250 ppm. as described above, but this may be extended to 5000 ppm. by using an aliquot of 0.1 ml.

Results within $\pm$ 25% at the 95% confidence level may be obtained over the range 5-5000 ppm.

80 samples can be analysed per man-day of 8 hours.

For further information refer to H. Almond, Anal.Chem., 1953, 25, 1766-1767.

## DETERMINATION OF MOLYBDENUM IN SOIL, SEDIMENT AND ROCK SAMPLES

### ABBREVIATED OPERATING INSTRUCTIONS

### Procedure

1. Weigh 0.25 g. of sieved sample into a nickel crucible (15 ml.) containing 1.25 g. of fusion mixture.

2. Mix the sample and flux, and fuse until frothing has ceased.

3. Allow the melt to cool, add approx. 2 ml. of water and leave overnight.

4. Transfer to a calibrated test tube and adjust to 5 ml. with water washings from the crucible.

5. Bring to the boil and ensure that the melt has completely broken up.

6. Mix thoroughly then allow to cool and settle.

7. Pipette a 2 ml. aliquot of the clear solution into 2 ml. of 2.5% hydroxylamine hydrochloride solution contained in a 16 x 150 mm. test tube previously calibrated at 2 ml.

8. Shake the tube to liberate carbon dioxide and leave to cool below 30°C.

9. Add 0.5 ml. of 1% dithiol solution.

10. Shake gently at frequent intervals over a period of 20 min.

11. Compare with standards.
    Molybdenum in ppm. = 10 x µg. of molybdenum in matching standard.

### Standards

To twelve test tubes containing 2 ml. of 2.5% hydroxylamine hydrochloride, add respectively 0, 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, 3.0, 4.0, 5.0, 7.0 and 10.0 µg of molybdenum. Dilute to 4 ml. with water and add 0.5 ml. of 1% dithiol solution. Shake gently at frequent intervals over a period of 20 min.

## Reagents

1. Fusion mixture: Mix thoroughly 500 g. of anhydrous sodium carbonate (A.R.), 400 g. of sodium chloride (A.R.) and 100 g. of potassium nitrate (A.R.).

2. 2.5% hydroxylamine hydrochloride: dissolve 25 g. of hydroxylamine hydrochloride in 900 ml. of concentrated hydrochloric acid (sp. gr. 1.18) and dilute to 1 litre with water.

3. 1% dithiol solution: weigh 0.5 g. of zinc dithiol into a 50 ml. stoppered cylinder, add 1ml. of hydrochloric acid (sp. gr. 1.18) and shake for 10 sec. Dilute to 50 ml. with amyl acetate and mix well.

4. Standard molybdenum solutions: 100 µg. of molybdenum per ml. - dissolve 125 mg. of sodium molybdate (di-hydrate) in water and dilute to 500 ml.

   10 µg. of molybdenum per ml. - dilute 10 ml. of the 100 µg. per ml. solution to 100 ml. with water.

   1 µg. of molybdenum per ml. - dilute 10 ml. of the 10 µg. per ml. solution to 100 ml. with water.

## Remarks

The range covered is 1-100 ppm. as described above, but this may be extended to 2000 ppm. by using an aliquot of 0.1 ml.

Results may be obtained within ± 40% at the 95% confidence level over the range 1-2000 ppm.

60 samples can be analysed per man-day of 8 hours.

See A.A. North, Analyst, 1956, 81, 660-668 for further information.

# DETERMINATION OF ZINC IN SOIL, SEDIMENT AND ROCK SAMPLES

## ABBREVIATED OPERATING INSTRUDTIONS

### Procedure

1. Weigh 0.1 g. of sieved sample into a Pyrex test tube (16 x 150 mm.)
2. Mix with 0.5g. of potassium bisulphate and fuse.
3. Leach with 5 ml. of 1M-hydrochloric acid.
4. Add 5 ml. of water and mix.
5. Pipette a 1 ml. aliquot into 5 ml. of buffer solution contained in a test tube (18 x 180 mm.), previously calibrated at 5 ml.
6. Add 5 ml. of 0.001% dithizone solution.
7. Cork the tube and shake vigorously for 1 min.
8. Compare with standards.
   Zinc in ppm. = 100 x $\mu$g. of zinc in matching standard.

### Standards

To nine test tubes each containing 5 ml. of buffer solution, add respectively 0, 0.25, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 and 3.5 $\mu$g. of zinc. Add 5 ml. of 0.001% dithizone, cork the tubes and shake vigorously for 1 min.

### Reagents

1. Potassium bisulphate: fused, powder.
2. 1M-hydrochloric acid: mix 40 ml. of acid (sp. gr. 1.18) with 400 ml. of water.
3. 0.5 M-hydrochloric acid: mix 20 ml. of acid (sp. gr. 1.18) with 420 ml. of water.
4. 0.01% dithizone in carbon tetrachloride: dissolve 40 mg. in 400 ml. of carbon tetrachloride and store in a vaccum flask.

5. 0.01% dithizone in benzene: dissolve 40 mg. in 400 ml. of benzene and store in a vacuum flask.

6. 0.001% dithizone in benzene: mix 40 ml. of the 0.01% solution in benzene with 360 ml. of benzene and store in a vacuum flask.

7. Buffer solution: dissolve 500 g. of sodium acetate, 5 g. of sodium fluoride and 125 g. of sodium thiosulphate in about 1500 ml. of water. Add 15 ml. of acetic acid and extract with 0.01% dithizone in carbon tetrachloride until free from zinc. Remove the excess of dithizone by extraction with carbon tetrachloride and dilute the aqueous phase to 2 litres with water.

8. Standard zinc solutions: 100 µg. of zinc per ml. - dissolve 220 mg. of zinc sulphate hepta-hydrate in 0.5M-hydrochloric acid and dilute to 500 ml. with this strength of acid.
5 µg. of zinc per ml. - dilute 5 ml. of the 100 µg. per ml. solution to 100 ml. with 0.5M-hydrochloric acid.

## Remarks

A range of 5-350 ppm. is covered, but it may be extended to 3500 ppm. by using an aliquot of 0.1 ml.

Results can be obtained within ± 25% at the 95% confidence level over the range 5-3500 ppm.

100 samples can be analysed per man-day.

The buffer solution should have a pH value of 6.0 ± 0.15.

For further information see R.E. Stanton, Tech. Comm. No. 19, G.P.R.C., Imperial College, 1962.

# DETERMINATION OF ANTIMONY IN SOIL AND SEDIMENT SAMPLES

## ABBREVIATED OPERATING INSTRUCTIONS

## Procedure

1. Weigh 0.5 g. of sieved sample into a Pyrex test tube (18 x 180 mm.).

2. Mix thoroughly with 1 g. of ammonium chloride.

3. Heat until all the ammonium chloride has sublimed.

4. Allow to cool, add 5 ml. of 6M-hydrochloric acid, and heat until the sublimate has dissolved.

5. Mix well and allow to cool and settle.

6. Pipette a 2 ml. aliquot of the clear solution into a test tube (18 x 180 mm.) previously calibrated at 3, 10, 13, 17 and 21 ml., and dilute to 3 ml. with 6M-hydrochloric acid.

7. Add 0.1 ml. of sodium nitrite and mix.

8. Dilute to 10 ml. with reagent solution.

9. Add 1 ml. of brilliant green in toluene and shake vigorously for 30 sec.

10. Compare with standards.

11. If greater than the top standard, dilute with toluene until within the range.
Antimony in ppm. = 5 x ($\mu$g. of matching standard) x (ml. of solvent phase).

## Standards

To eleven test tubes (18 x 180 mm.) add respectively 0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8 and 2.0 $\mu$g. of antimony. Dilute to 3 ml. with 6M-hydrochloric acid and add 0.1 ml. of sodium nitrite solution. Mix, then dilute to 10 ml. with reagent solution. Add 1 ml. of toluene and shake vigorously for 30 sec.

## Reagents

1. Ammonium chloride: A.R.

2. 6M-hydrochloric acid: mix 240 ml. of the concentrated acid (sp. gr. 1.18) with 200 ml. of water.

3. Sodium nitrite solution: dissolve 25 g. in 500 ml. of water.

4. Reagent solution: dissolve 100 g. of sodium hexametaphosphate in 1 litre of water (solution A). Dissolve 100 mg. of brilliant green in 200 ml. of water (solution B). This solution must be prepared freshly each day. Mix solutions A and B in the ratio 5:1 as required daily.

5. Standard antimony solutions: 100 µg. of antimony per ml. - dissolve 59 mg. of antimony trioxide in 500 ml. of 6M-hydrochloric acid.
2 µg. of antimony per ml. - dilute 2 ml. of the 100 µg. per ml. solution to 100 ml. with 6M-hydrochloric acid.

## Remarks

The range covered is 0.2 - 110 ppm. as described, but it may be extended to 2200 ppm. by using an aliquot 0.1 ml.

Results may be obtained within ± 25% at the 95% confidence level over the range 0.2 - 2200 ppm.

If 1 ppm. is an adequate sensitivity, take 0.2 g. at stage 1 and use a 10 ml. leach at stage 4 of the Procedure.

100 samples can be analysed per man-day of 8 hours.

For further information refer to R.E. Stanton and A.J. McDonald, Trans. Instn. Min. Metall., Lond., 1961-2, 71, 317-522.

# DETERMINATION OF LEAD IN SOIL, SEDIMENT AND ROCK SAMPLES

## ABBREVIATED OPERATING INSTRUCTIONS

## Procedure

1. Weigh 0.1 g. of sieved sample into a Pyrex test tube (16 x 150 mm.). calibrated at 3 and 10 ml.

2. Add 3 ml. of 25% nitric acid and digest for 1 hour on a sand-tray.

3. Dilute to 10 ml. with water, mixing well.

4. Pipette a 2 ml. aliquot into 10 ml. of buffer solution contained in a 19 x 150 mm. Pyrex test tube previously calibrated at 10 ml. and 12 ml.

5. Add 5 ml. of 0.0008% dithizone in benzene.

6. Cork the tube and shake vigorously for 15 sec.

7. Compare with standards.
Lead in ppm. = 50 x (µg. of lead in matching standard).

## Standards

To each of twelve test tubes (19 x 150 mm.) containing 10 ml. of buffer solution and calibrated at 10 and 12 ml., add resepctively 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0 and 7.0 µg. of lead. Dilute to 12 ml. with 7.5% nitric acid and add 5 ml. of 0.0008% dithizone in benzene. Cork the tubes and shake vigorously for 15 sec.

## Reagents

1. 25% nitric acid: mix 125 ml. of acid (sp. gr. 1.42) with 375 ml. of water.

2. 7.5% nitric acid: mix 150 ml. of the 25% solution with 350 ml. of water.

3. 0.01% dithizone in carbon tetrachloride: dissolve 40 mg. in 400 ml. of carbon tetrachloride and store in a vacuum flask.

4. 0.008% dithizone in benzene: dissolve 32 mg. in 400 ml. of benzene and store in a vacuum flask.

5. 0.0008% dithizone in benzene: mix 40 ml. of the 0.008% solution with 360 ml. of benzene.

6. Chloroform.

7. 0.04% thymol blue: dissolve 40 mg. of the sodium salt in 100 ml. of water.

8. Ammonia solution: A.R., sp. gr. 0.880.

9. Buffer solution: dissolve 120 g. of tri-ammonium citrate and 20 g. of hydroxylamine hydrochloride in about 800 ml. of water. Add 5 ml. of 0.04% thymol blue solution followed by ammonia solution (sp. gr. 0.880) until the colour of the indicator changes from yellow to a distinct blue. Add 18 g. of potassium cyanide and dilute to 1 litre with water. Extract with 0.01% dithizone in carbon tetrachloride until free from lead, and remove the excess of dithizone by extraction with chloroform.

10. Standard lead solutions: 100 µg. of lead per ml. - dissolve 80 mg. of lead nitrate in 7.5% nitric acid and dilute to 500 ml. with this strength of acid.

5 µg. of lead per ml. - dilute 5 ml. of the 100 µg. per ml. solution to 100 ml. with 7.5% nitric acid.

## Remarks

The range covered is 10-350 ppm. as described above, but it may be extended to 7000 ppm. by using an aliquot of 0.1 ml.

Results may be obtained within ± 25% at the 95% confidence level over the range 10-7000 ppm.

120 samples can be analysed per man-day of 8 hours.

There is no interference from cobalt, copper, nickel and zinc, jointly present, each at 1000 times the concentration of lead.

High values will result when thallium is present at concentrations greater than twice that of the lead.

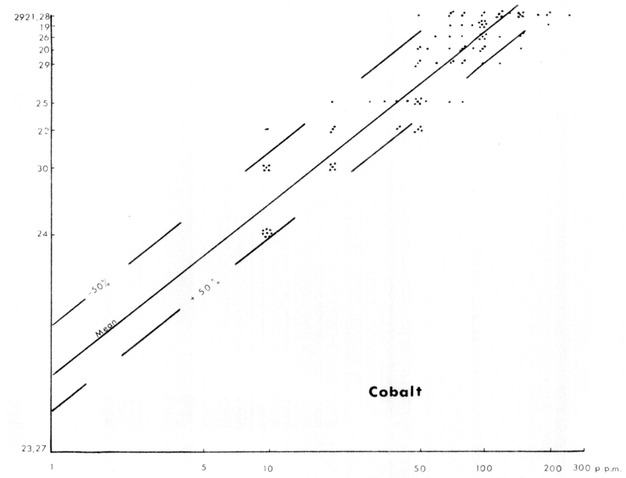
The buffer solution should have a pH value of 9.5-9.8.

When using an aliquot of less than 1 ml. at stage 4 of the Procedure, 7.5% nitric acid solution should be added up to the 12 ml. mark.

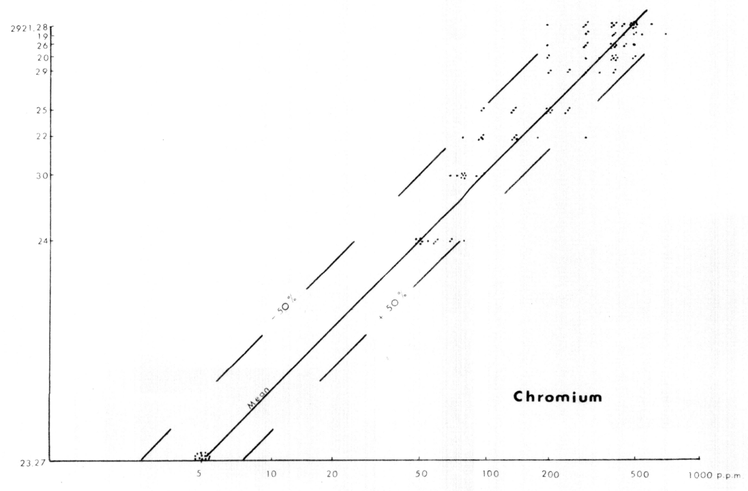
Fusion with potassium bisulphate at stage 1 of the procedure, and leaching with 1M-hydrochloric acid at stage 2, may replace digestion with 25% nitric acid. In this case use 0.5M-hydrochloric acid at all stages requiring 7.5% nitric acid solution.

This method is based on that described by Bureau de Recherches Geologiques, Geophysiques et Minieres, 1957.

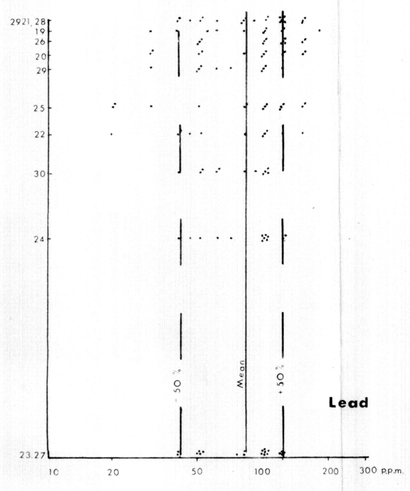
**FIGURE 7**



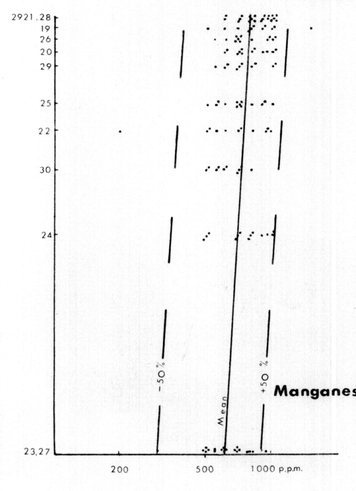

**Cobalt**



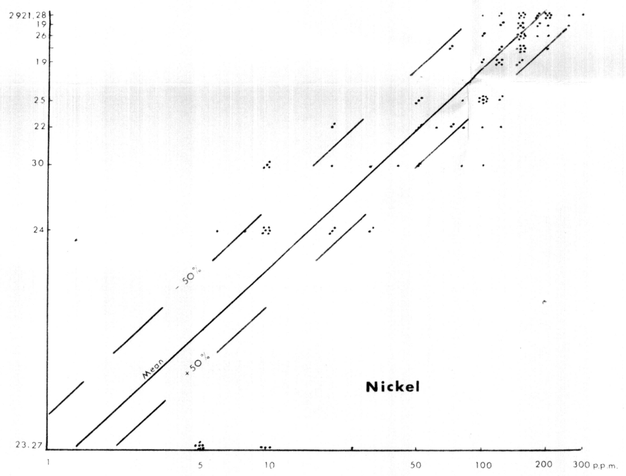

**Chromium**



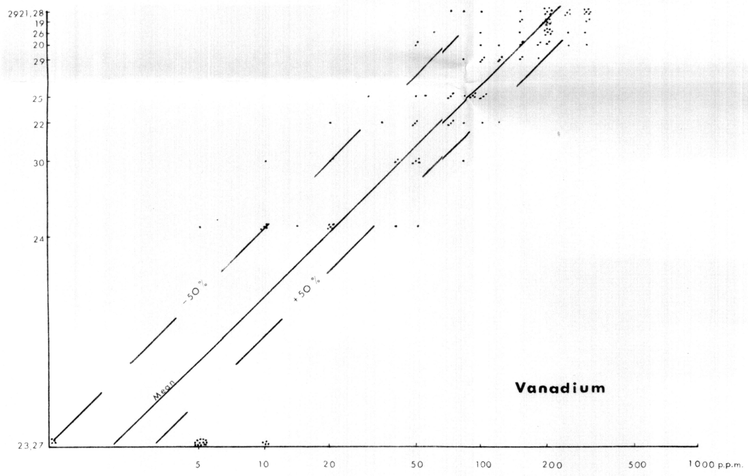

**Lead**



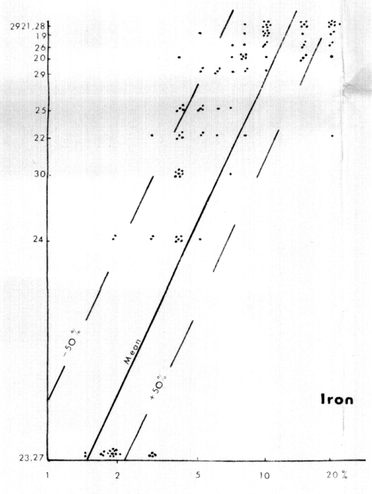

**Manganese**



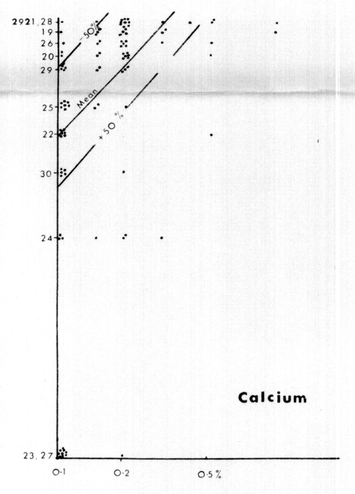

**Nickel**



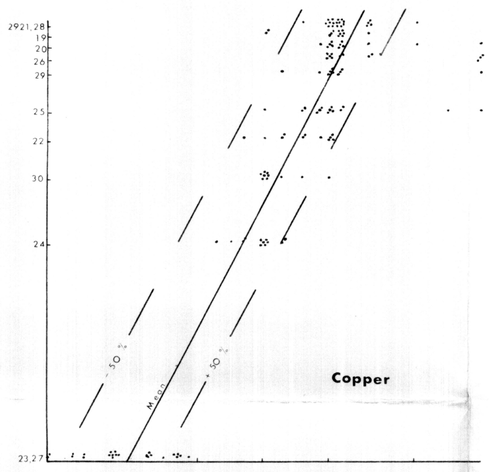

**Vanadium**



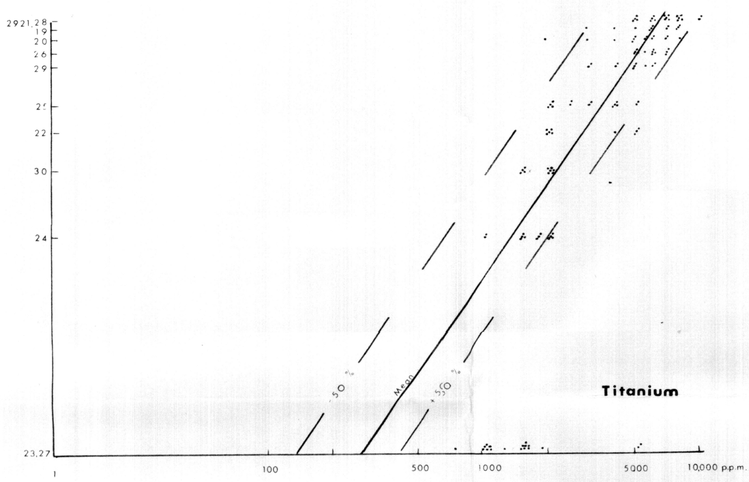

**Iron**



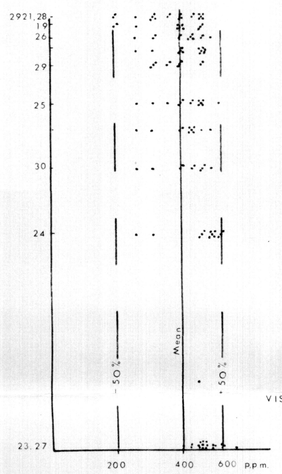

**Calcium**




**Copper**

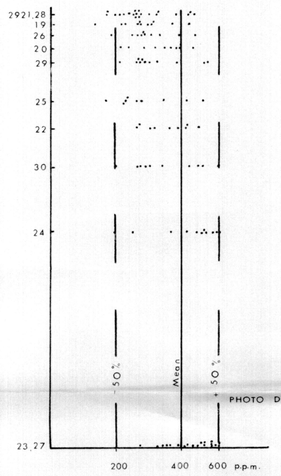



**Titanium**



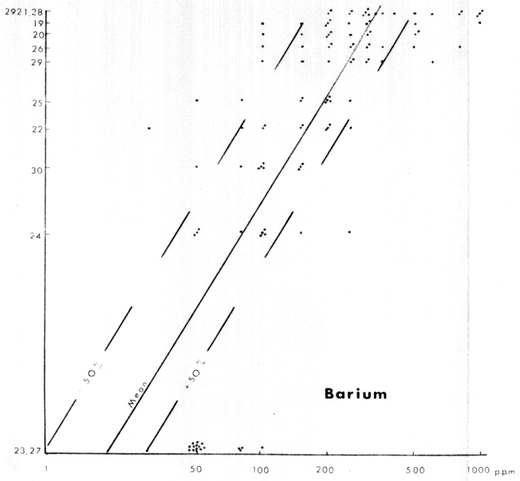

**Germanium**

VISUAL ESTIMATION

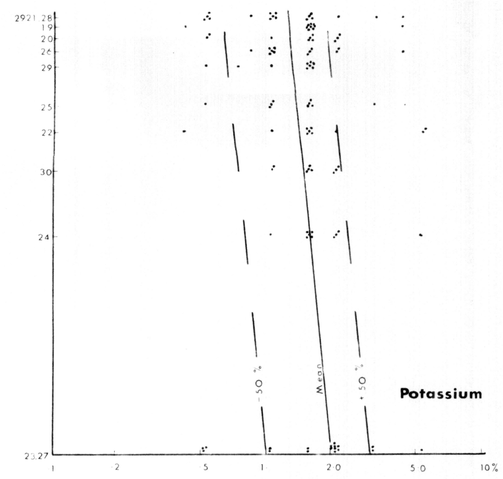



**Germanium**

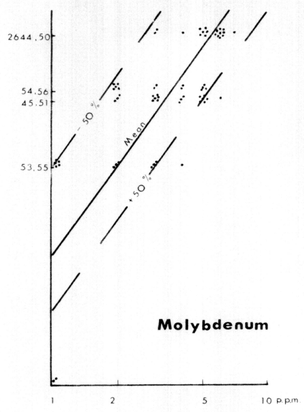
PHOTO DENSITOMETER ESTIMATION




**Barium**




**Potassium**



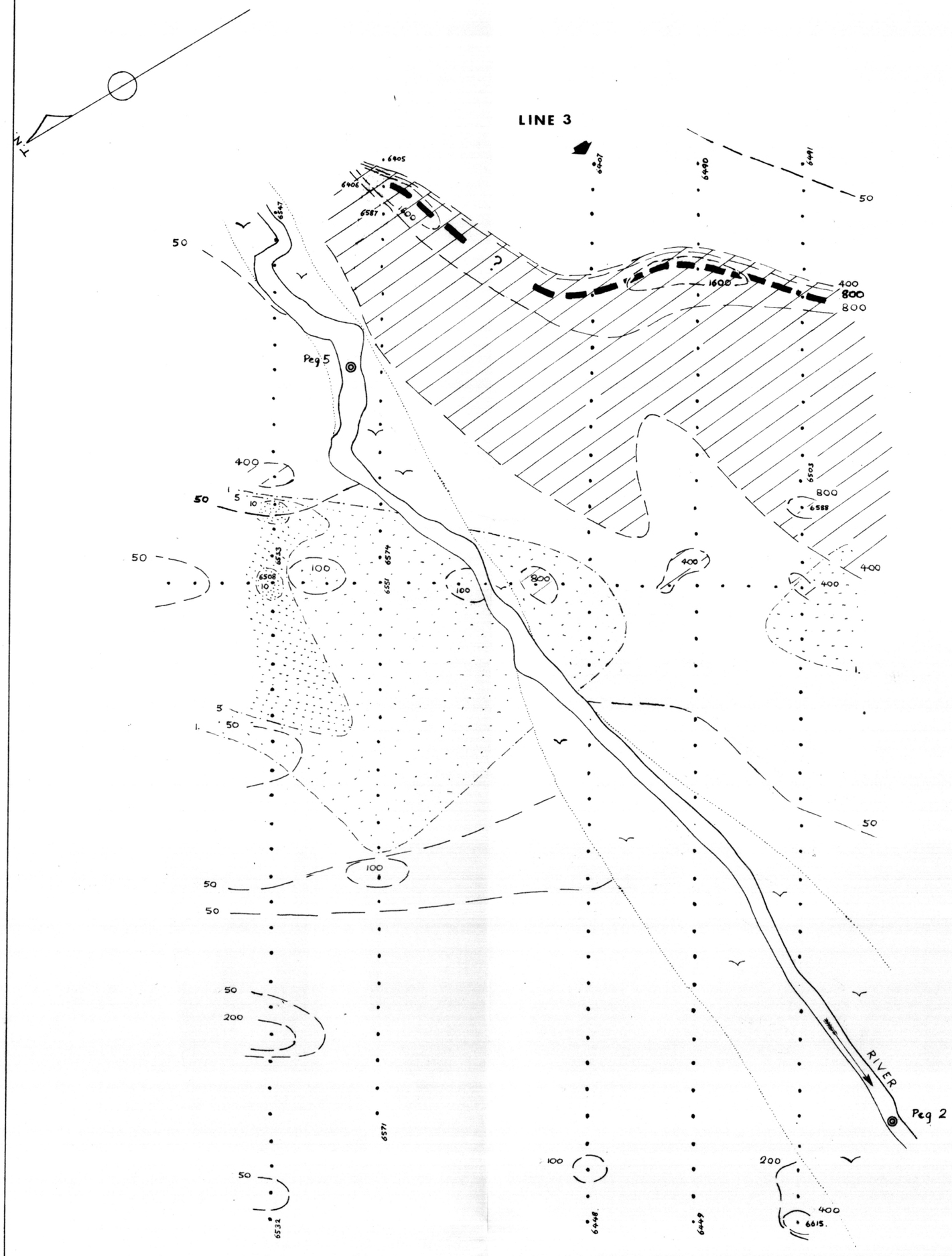

**Molybdenum**

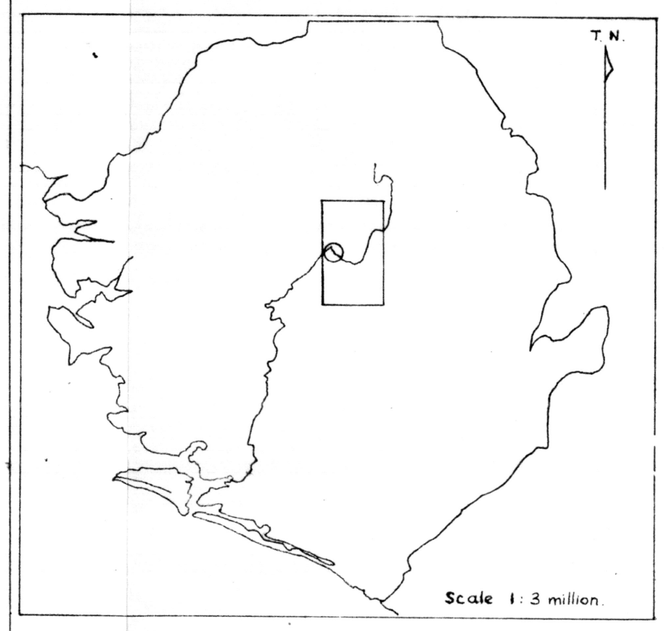
**PRECISION OF SPECTROCHEMICAL ANALYSES**

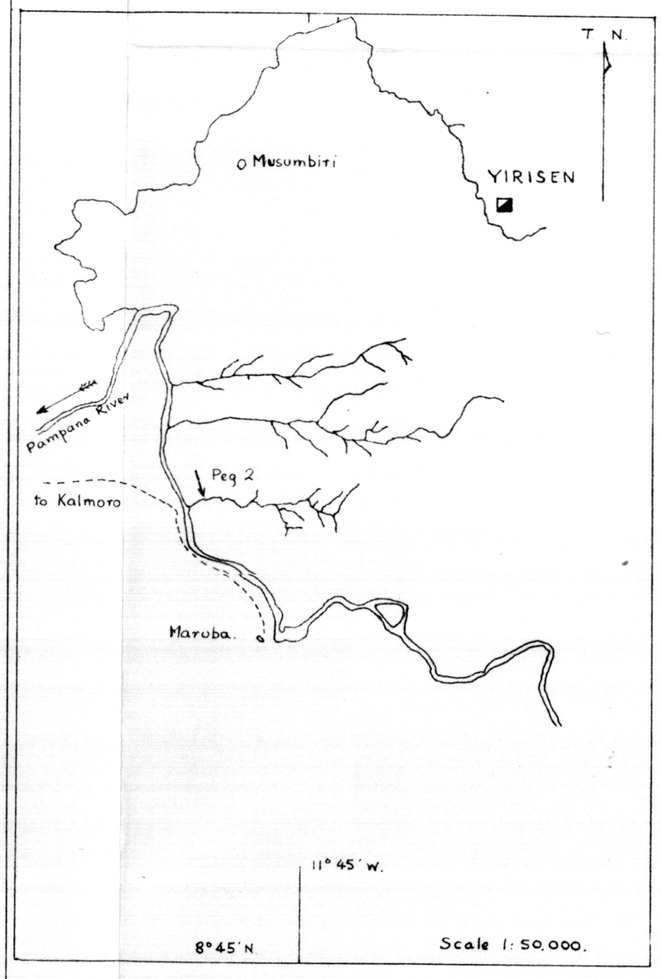
**BY VISUAL ESTIMATION, IN THE STATISTICAL CONTROL SAMPLES.**

To accompany thesis by K.A.Viewing July 1953

**FIGURE 50**




EXPLANATION

Axis of principal anomaly

Arsenic > 400 ppm

Molybdenum > 1 ppm

> 5 ppm

> 10 ppm

• 6508 Soil sample location and number.

alluvium.

..... margin of alluvium.

Note. Analyses of alluvium samples are not represented.

# GEOCHEMICAL PROSPECTING RESEARCH PROJECT 27

## SULA MOUNTAINS - KANGARI HILLS, SIERRA LEONE.

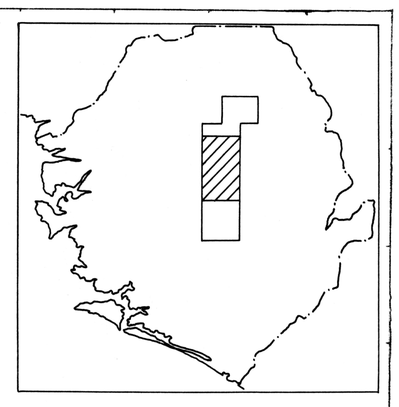
## PLAN

TO SHOW THE LOCATION OF ARSENIC AND MOLYBDENUM ANOMALIES IN SOILS NEAR MARUBA VILLAGE.

SCALE 1 : 1000


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Viewing K. A.
Ph. D. 1963.



T.N.

## EXPLANATION

| SYMBOL | TITANIUM CONTENT IN P.P.M. |
|---|---|
| | < 300 |
| | 300 - 700 |
| | 700 - 1500 |
| | 1500 - 3000 |
| | 3000 - 7000 |
| | > 7000 |

FREQUENCY

0 100 200 300 400 500

# REGIONAL GEOCHEMICAL MAP

## SULA MOUNTAINS AND KANGARI HILLS AREA

## SIERRA LEONE

Reconnaissance stream sediment survey

by K.A.Viewing

## 1 - TITANIUM

SCALE 1:50,000

Miles 1 0 1 2 Miles

Yards 1000 0 1000 2000 3000 Yards

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FEBRUARY 1963

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Ph.D. 1963

T.N.

## EXPLANATION

| SYMBOL | CHROMIUM CONTENT IN P.P.M. |
|---|---|
| + | < 3 |
| × | 3 – 7 |
| ◦ | 7 – 15 |
| ○ | 15 – 30 |
| ○ | 30 – 70 |
| ○ | 70 – 150 |
| ⊙ | 150 – 300 |
| ⊙ | 300 – 700 |
| ● | 700 – 1500 |
| ● | 1500 – 3000 |
| * | 3000 – 7000 |

FREQUENCY
0 100 200 300 400

# REGIONAL GEOCHEMICAL MAP

## SULA MOUNTAINS AND KANGARI HILLS AREA

## SIERRA LEONE

Reconnaissance stream sediment survey

by K.A.Viewing

## 3 - CHROMIUM

SCALE 1:50,000

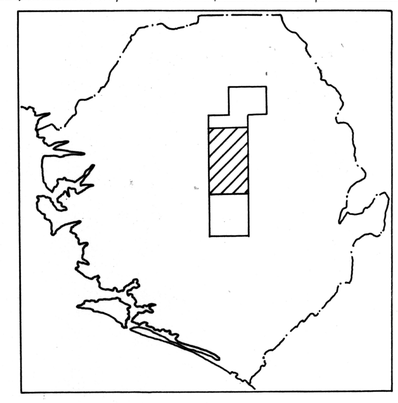
Mile 1 0 1 2 Miles

Yards 1000 0 1000 2000 3000 Yards

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## EXPLANATION

| SYMBOL | MANGANESE CONTENT IN P.P.M. |
|---|---|
| + | < 15 |
| × | 15 — 30 |
| ◦ | 30 — 70 |
| ○ | 70 — 150 |
| ○ | 150 — 300 |
| ○ | 300 — 700 |
| ⊙ | 700 — 1500 |
| ◉ | 1500 — 3000 |
| ● | 3000 — 7000 |
| ● | > 7000 |

FREQUENCY

0 100 200 300 400 500

# REGIONAL GEOCHEMICAL MAP

## SULA MOUNTAINS AND KANGARI HILLS AREA

## SIERRA LEONE

Reconnaissance stream sediment survey

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## 4 - MANGANESE

SCALE 1:50,000

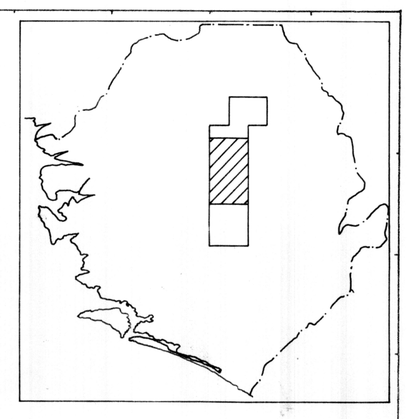
Miles 0 1 2

Yards 1000 0 1000 2000 3000

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## EXPLANATION

| SYMBOL | NICKEL CONTENT IN P.P.M. |
|---|---|
| + | < 3 |
| ◦ | 3 - 7 |
| ○ | 7 - 15 |
| ○ | 15 - 30 |
| ⊙ | 30 - 70 |
| ⊙ | 70 - 150 |
| ◉ | 150 - 300 |
| ● | 300 - 700 |
| ● | 700 - 1500 |
| * | 1500 - 3000 |

FREQUENCY

0 100 200 300 400 500

# REGIONAL GEOCHEMICAL MAP

## SULA MOUNTAINS AND KANGARI HILLS AREA

## SIERRA LEONE

Reconnaissance stream sediment survey

by K.A.Viewing

## 6 - NICKEL

SCALE 1:50,000

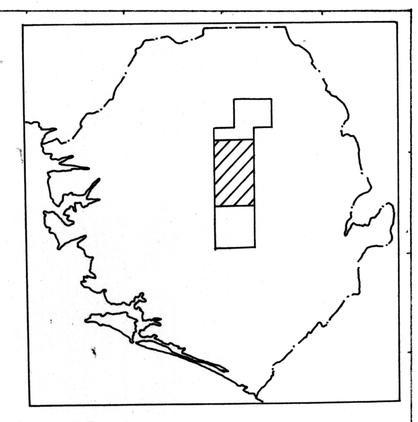
Mile 1 ½ 0 1 2 Miles

Yards 1000 0 1000 2000 3000 Yards

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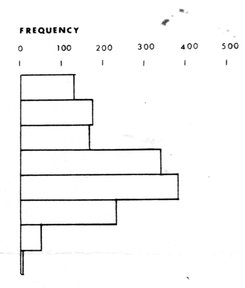
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## EXPLANATION

| SYMBOL | VANADIUM CONTENT IN P.P.M. |
|---|---|
| + | < 7 |
| ◦ | 7 - 15 |
| ○ | 15 - 30 |
| ○ | 30 - 70 |
| ⊙ | 70 - 150 |
| ⊙ | 150 - 300 |
| ◉ | 300 - 700 |
| ● | 700 - 1500 |




# REGIONAL GEOCHEMICAL MAP

## SULA MOUNTAINS AND KANGARI HILLS AREA

## SIERRA LEONE

Reconnaissance stream sediment survey

by K.A.Viewing

## 2 - VANADIUM

SCALE 1:50,000

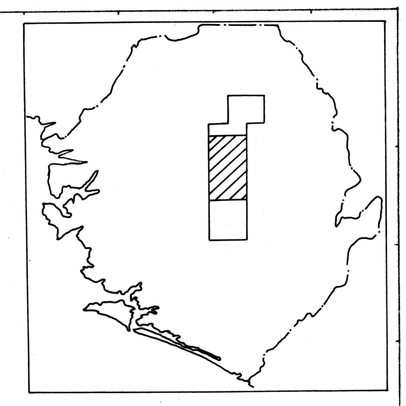
Miles 1 0 1 2 Miles

Yards 1000 0 1000 2000 3000 Yards

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## EXPLANATION

| SYMBOL | COPPER CONTENT IN P.P.M. | |
|---|---|---|
| + | < 1·5 | |
| ◦ | 1·5 | - 3 |
| ○ | 3 | - 7 |
| ○ | 7 | - 15 |
| ⊙ | 15 | - 30 |
| ⊙ | 30 | - 70 |
| ◉ | 70 | - 150 |
| ● | 150 | - 300 |

FREQUENCY

0 100 200 300 400

# REGIONAL GEOCHEMICAL MAP

## SULA MOUNTAINS AND KANGARI HILLS AREA

## SIERRA LEONE

Reconnaissance stream sediment survey

by K.A.Viewing

## 7 - COPPER

SCALE 1:50,000

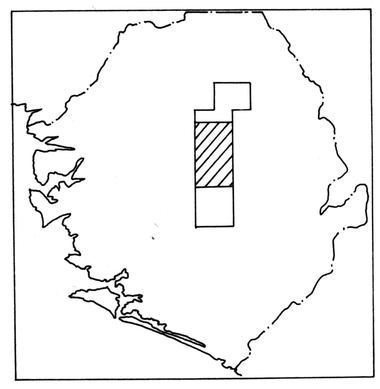
Mile 1 ½ 0 1 2 Miles

Yards 1000 0 1000 2000 3000 Yards

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## EXPLANATION

| SYMBOL | ZINC CONTENT IN P.P.M. |
|---|---|
| ○ | < 7 |
| ○ | 7 – 15 |
| ⊙ | 15 – 30 |
| ⊙ | 30 – 70 |
| ◉ | 70 – 150 |
| ● | 150 – 300 |
| ● | 300 – 700 |

FREQUENCY

0 100 200 300

# REGIONAL GEOCHEMICAL MAP

## SULA MOUNTAINS AND KANGARI HILLS AREA

## SIERRA LEONE

Reconnaissance stream sediment survey

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## 8 - ZINC

SCALE 1:50,000

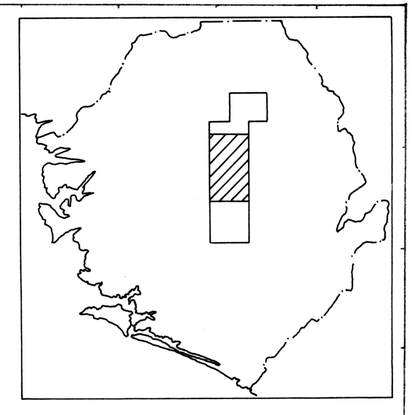
Miles 1 0 1 2 Miles

Yards 1000 0 1000 2000 3000 Yards

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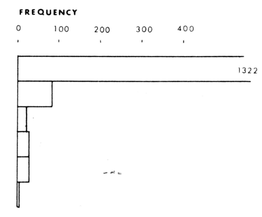


T.N.

## EXPLANATION

| SYMBOL | ARSENIC CONTENT IN P.P.M. |
|---|---|
| ○ | < 3 |
| ⊙ | 3 – 7 |
| ⊙ | 7 – 15 |
| ◉ | 15 – 30 |
| ◉ | 30 – 70 |
| ● | 70 – 150 |

FREQUENCY




# REGIONAL GEOCHEMICAL MAP

## SULA MOUNTAINS AND KANGARI HILLS AREA

## SIERRA LEONE

Reconnaissance stream sediment survey

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## 9 - ARSENIC

SCALE 1:50,000

Mile 1 0 1 2 Miles

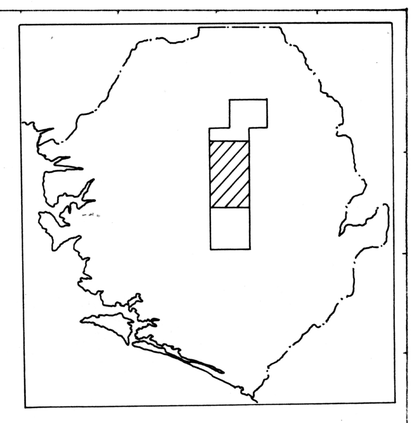
Yards 1000 0 1000 2000 3000 Yards

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FEBRUARY 1963

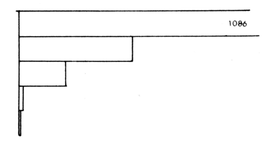
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## EXPLANATION

| SYMBOL | MOLYBDENUM CONTENT IN P.P.M. |
|---|---|
| ○ | < 1·5 |
| ⊙ | 1·5 - 3 |
| ◉ | 3 - 7 |
| ◉ | 7 - 15 |
| ● | 15 - 30 |




# REGIONAL GEOCHEMICAL MAP

## SULA MOUNTAINS AND KANGARI HILLS AREA

## SIERRA LEONE

**Reconnaissance stream sediment survey**

**by K.A.Viewing**

## 10 - MOLYBDENUM

SCALE 1:50,000

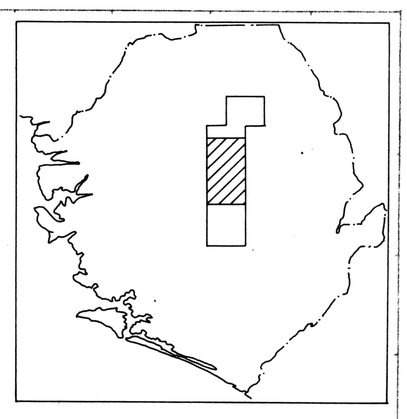
Miles 1 0 1 2

Yards 1000 0 1000 2000 3000 Yards

TOPOGRAPHICAL DETAIL BY THE GEOLOGICAL SURVEY OF SIERRA LEONE

GEOCHEMICAL PROSPECTING RESEARCH CENTRE
IMPERIAL COLLEGE
LONDON
FEBRUARY 1963

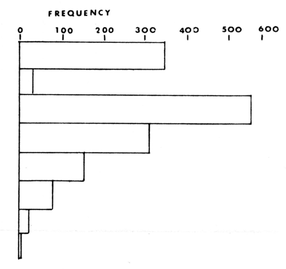
VIEWING. K.A.
Ph.D. 1963



T.N.

## EXPLANATION

| SYMBOL | LEAD CONTENT IN P.P.M. |
|---|---|
| ○ | <1·5 |
| ○ | 1·5 - 3·0 |
| ⊙ | 3·0 - 7·0 |
| ⊙ | 7·0 - 15·0 |
| ⊙ | 15·0 - 30·0 |
| ● | 30·0 - 70·0 |
| ● | 70·0 -150·0 |
| * | >150·0 |




# REGIONAL GEOCHEMICAL MAP

## SULA MOUNTAINS AND KANGARI HILLS AREA

## SIERRA LEONE

Reconnaissance stream sediment survey

by K.A.Viewing

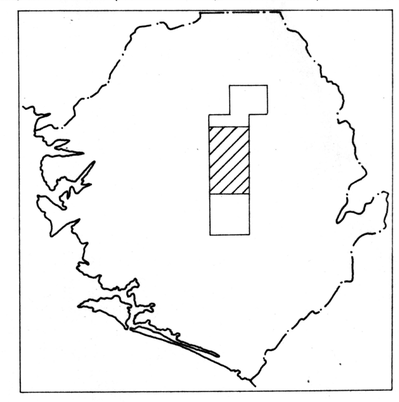
## 11- LEAD

SCALE 1:50,000

TOPOGRAPHICAL DETAIL BY THE GEOLOGICAL SURVEY OF SIERRA LEONE

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T.N.

## EXPLANATION

METAL CONTENT OF -80 MESH FRACTION, STREAM SEDIMENT.

| Arsenic p.p.m. | Molybdenum p.p.m. |
|---|---|
| < 3 | < 1·5 |
| 3 - 7 | 1·5 - 3 |
| 7 - 15 | 3 - 7 |
| 15 - 30 | 7 - 15 |
| 30 - 70 | 15 - 30 |
| 70 - 150 | |

# GEOCHEMICAL MINERAL RECONNAISSANCE

## SULA MOUNTAINS AND KANGARI HILLS AREA

## SIERRA LEONE

12 - Arsenic and Molybdenum Anomalies in Stream Sediments.

by K.A. Viewing.

SCALE 1:50,000

Mile 1 ½ 0 1 2 Miles

Yards 1000 0 1000 2000 3000 Yards

TOPOGRAPHICAL DETAIL BY THE GEOLOGICAL SURVEY OF SIERRA LEONE

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IMPERIAL COLLEGE
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FEBRUARY 1963

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Ph.D. 1963

T.N.

# PROJECT 27

Regional Geochemical Map

## Sula Mountains - Kangari Hills Range

## SIERRA LEONE

14 Location of Stream Sediment Samples

• Sample location 1 per sq. mile.

o Sample location 3 per sq. mile.

SCALE 1/50,000

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# SIERRA LEONE
## Geology of Sula Mountains

Scale 1:50,000

Sheet 2

OUTLINE OF GEOCHEMICAL MAPS

A B C D E F G H I J K L M N O P Q R S T U V W X

SEDIMENTS ETC.
400 Ft. Erosion Surface with Alluvium and Laterite
2000 Ft. Erosion Surface with Duricrust

METAMORPHIC SEDIMENTS
Quartzite
Micaceous Quartzite, Tuffs, Mica Schist and Greywacke with some Amphibolite and Hornblende Schist
Undifferentiated mainly Pelitic Sediments with Tuffs, Amphibolite and Hornblende Schist
Banded Ironstone
Conglomerate

METAMORPHIC BASIC ROCKS
Amphibolite and Hornblende Schist
Uralite Porphyry
Pillow Lava
Serpentinites, Tremolite, Chlorite and Talc Schists
Ultrabasic Rocks (Unaltered)

GRANITIC ROCKS
Undifferentiated Granite & Granodiorite
Synkinematic Granite and Granodiorite — Evengrained; Porphyroblastic Gneissose; Migmatite & Mica Gneiss
Quartz-Diorite and Diorite
Late-Kinematic Granite
Pegmatite
Tourmaline-bearing Rocks

TECTONIC, STRUCTURAL AND MISCELLANEOUS GEOLOGICAL CONVENTIONS
Strike and Vertical Dip
Subvertical Dip
Inclined Dip
Inverted Dip
Probable Fault
Possible Fault
Linear Structural Feature
Thrust
Geological Boundary
Section Lines

TOPOGRAPHICAL CONVENTIONS
Adit
Path
Road
Village
Stream
River
Approximate heights (in Feet) from 1/62,500 Topo Sheets
Spot heights (in Feet)
Centre point of Aerial Photograph

PROSPECTS

| | | | |
|---|---|---|---|
| As | Arsenic | Fe | Iron |
| Asb | Asbestos | Pb | Lead |
| Al | Bauxite | Mo | Molybdenum |
| Bi | Bismuth | Sn | Tin |
| Cu | Copper | Zn | Zinc |

SCALE OF MILES

Geologically surveyed 1950–1954 by J.D. Pollett, N.W. Wilson, V. Marmo, W.N. Woodhead and W.F. Gilman. Topography drawn by Geological Survey Department from R.A.F. Photography 1951. Prepared and photographed by Directorate of Overseas Surveys and printed by D.S.O. 1961.
Bulletin No.1 describes the Geology of this sheet.

SHEET INDEX

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SUPERFICIAL DEPOSITS
400 Ft. Erosion Surface with Alluvium and Laterite
2000 Ft. Erosion Surface with Duricrust
METAMORPHIC SEDIMENTS
METAMORPHIC ACID VOLCANICS
METAMORPHIC BASIC ROCKS
METAMORPHIC ULTRABASIC ROCKS
GRANITIC ROCKS
TECTONIC, STRUCTURAL AND MISCELLANEOUS GEOLOGICAL CONVENTIONS
TOPOGRAPHICAL CONVENTIONS
PROSPECTS
SCALE 1:50,000
SHEET INDEX

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