A

T H E S I S

entitled

GEOCHEMICAL DISPERSION RELATED TO GOLD MINERALIZATION, WESTERN AUSTRALIA.

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ABSTRACT

The primary and secondary dispersion of arsenic and other elements related to gold mineralization has been studied at a number of localities in a belt of auriferous country, 300 miles in length, in central Western Australia.

Arsenic was found to show significant primary anomalies in the wall-rocks adjacent to gold mineralization at Norseman, Kalgoorlie and Agnew. Although there appears to be a close relationship between the distribution of arsenic and gold in each area, the details of the primary dispersion patterns differ according to local geology and the type of mineralization. The important aspect of leakage dispersion was studied in detail at Norseman, where the mineralization consists of lenticular gold-quartz reefs in inclined zones of reverse shearing. In this area, strong leakage halos were found to persist up the shear zones as much as 2000 feet up-dip from blind orebodies and can be detected in soils over the barren sub-outcrops of the ore-bearing structures.

Anomalies related to arsenical gold mineralization are detectable in the various types of residual soils occurring in the area studied, including relict lateritic soils. Arsenic mainly tends to concentrate with secondary iron oxides in the coarse sand and silt fractions of the soils. Appreciable concentrations of arsenic are also associated with the clays, particularly in the alkaline near-surface horizon of the solonized brown soils. The distribution of arsenic in the soil profile appears to be dependent on pH and the abundance of secondary iron oxides. Lateral dispersion processes under the present semi-arid climatic conditions are dominantly mechanical, although appreciable hydromorphic dispersion of arsenic apparently took place during the development of the lateritic soils in the Pliocene.

Preliminary studies have shown that trace element anomalies can be detected in the active sediments of the intermittent streams draining mineralized areas. Dispersion processes in the drainage are believed to consist essentially of the mechanical translocation of soils, contributed to the drainage by sheetwash and bank erosion. During this process, the silt and clay particles travel further in suspension than the coarser soil material and are deposited in salt-lakes, which are the lowest topographic features of the landscape. Extensive fan-like dispersion patterns are developed in the salt-lake sediments at the mouths of anomalous streams, largely as the result of the deposition of metal-rich fines from the drainage channels.

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CHAPTER 1. INTRODUCTION

I. GENERAL

As a result of a decade of considerable activity by research institutions and mining companies throughout the world, the broad principles of geochemical prospecting are now becoming generally understood and widely applied. In each new area of application, however, it is necessary to determine the effects of numerous local factors which may greatly influence the success or failure of a geochemical survey. Thus, research is becoming increasingly concerned with the variations found in dispersion patterns and processes occurring in differing geological, physiographic, climatic and pedological environments.

The research described in this thesis was sponsored jointly by the Geochemical Prospecting Research Centre, London, and Western Mining Corporation Ltd ., a company engaged in gold mining and exploration in Western Australia. Early in 1962 Western Mining became interested in the possibility of using geochemical methods in their exploration programmes. After negotiations with the staff of the Geochemical Prospecting Research Centre, it was agreed that the writer should carry out a programme of research under the general guidance of Professor J.S. Webb of the G.P.R.C. to assess the potential of geochemistry as applied to exploration for gold in Western Australia.

Field work was carried out in two periods -June to August, 1962 and July to December, 1963, during which

suites of rock, soil and sediment samples were collected from selected areas in the Western Australian goldfields. The samples were shipped to London where detailed laboratory studies were carried out.

II. PREVIOUS WORK

Very little is known of the nature of dispersion patterns formed by gold in the vicinity of auriferous deposits. The main reason for this has been the lack of suitable rapid analytical methods, sensitive enough to detect and measure the minute quantities of the element involved.

Sokoloff (1950), in the course of a brief geochemical investigation for Western Mining, developed a rough semi-quantitative test for gold using the colorimetric reagent, dithizone. Using this test he showed the existence of "gold-positive bands" in underground cross-cut and diamond drill traverses in both fresh and oxidised rock in the Kalgoorlie and Yilgarn districts. Continuous halos were not generally observed about known lodes and "gold-positive bands" frequently occurred at distances of hundreds of feet from lodes. Gold anomalies were observed in residual soils overlying, and in the vicinity of, known lodes. Geochemical reconnaissance in one soil-covered area located previously unkown, subeconomic gold mineralization. It was later found that Sokoloff's dithizone test was not specific for gold, due to the interference of other elements. Because of this and the lack of sensitivity, very little further work was

done using these techniques.

Soviet geologists claim success in locating gold deposits by using spectrochemical methods for the determination of gold. (Tsaregradskiy 1962). The method is claimed to give a sensitivity of 0.1 ppm Au but this is not sufficient to show details of the dispersion patterns developed about most gold deposits. Methods of pre-concentration of gold in samples prior to spectrographic analysis have been developed with some success (Sofranov et al, 1960).

Stanton and McDonald (1964) have recently developed a semi-quantitative colorimetric test for gold using the reagent, brilliant green. A sensitivity of 0.05 ppm is claimed and the results agree well with check determination by fire assay. This method has been used for gold determination in the present research.

Much of the published literature on geochemical prospecting for gold concerns the use of "pathfinder" elements such as arsenic, antimony, mercury, tungsten and molybdenum. Arsenic, because of its very common association with gold in ore deposits is the most important. In the Kolar Goldfield, India, Narayanaswami (1956) has found strong arsenic anomalies in soils over the projected outcrops of sulphide-bearing lodes. No anomalies were found over the important Champion gold-quartz lode, which contains negligible sulphides. Tsaregradskiy (1962) reports instances of the successful use of arsenic dispersion halos

in the search for gold in Kazakhstan. Erikson et al (1964) have shown that arsenic, tungsten and mercury anomalies occur in rocks and soils over arsenical gold deposits at the Getchell Mine, Nevada. In this area, the highest metal contents were found in the oxidized iron-rich material along fractures and bedding planes in the barren bedrock, lesser values in caliche coatings on exposed bedrock, and lowest, but still anomalous values in soils.

A number of detailed studies of arsenic dispersion in the vicinity of gold mineralization in Africa have been undertaken as part of the research programme of the Geochemical Prospecting Research Centre, London. C. James (1957) studied the dispersion of arsenic and antimony in rocks, soils and drainage related to gold mineralization in Southern Rhodesia. James' conclusions may be summarized as follows:-

1. Aureoles of anomalous arsenic are detectable in wall-rocks surrounding mineralization in the areas studied. The nature of the anomalies depends largely on the degree of fissuring of the wall-rocks. In un-fissured wall-rocks, anomalies extend up to 25 feet from the vein, the decline of arsenic content following a logarithmic pattern. Where wall-rocks are fissured, anomalies are more erratic in form and persist for more than 100 feet from veins.
2. The width of arsenic anomalies in residual

latosols overlying mineralization appears to be governed by several factors among which bedrock-type, width of primary dispersion pattern and climate are the most important.

3. The fixation of arsenic in soils probably occurs inter alia by the formation of insoluble iron and aluminium compounds and by ionic exchange reactions with clays and other colloids.

4. Iron-rich residual soils show only minor variations in arsenic content with depth. Iron-poor soils occasionally show some variation with depth and there is almost invariably a marked increase in arsenic in the top of the weathered bedrock.

Since 1956, the Geochemical Prospecting Research Centre has been continuously engaged in geochemical investigations in Sierra Leone. Mather (1959) showed the existence of arsenic anomalies in soils, drainage sediments and stream waters in the vicinity of an arsenopyrite-gold mineralization in Precambrian schists. Solution processes are believed to have played an important part in the formation of the broad dispersion patterns observed in soils, particularly in Tertiary times, when laterite was formed under humid climatic conditions on a peneplain. Elliott (1962) extended Mather's work, studying in considerable detail the dispersion of arsenic in the drainage system. It was shown that anomalous dispersion trains, more than 4,000 feet in length exist in

streams draining arsenopyrite-gold mineralization. The magnitude of the drainage anomalies is closely related to the nature of the host rocks, the form of the mineralization and size of the barren catchment area upstream from mineralization.

This work led to a regional geochemical reconnaissance of over 1,000 square miles of potentially mineralized Precambrian Schist belts based on stream sediment sampling (Viewing 1963, L. James 1965, Garrett, personal communication). This work has generally confirmed the correlation of arsenic anomalies with areas of gold mineralization.

III. THE PROBLEM.

The primary purpose of this research was to study trace element dispersion occuring in the vicinity of typical Western Australian gold deposits and, if possible, to develop effective geochemical methods of prospecting for gold under the prevailing conditions. The geological and physiographic environment of Western Australian gold deposits is somewhat different from those studied in other parts of the world. In such a project, therefore, some additional knowledge is obtained on the nature of the processes controlling trace element dispersion in different environments. During the preliminary stages of the investigation it became apparent that problems of more fundamental interest were also involved. The most important of these concerns the relationship between arsenic and gold

in the primary environment.

Any method of exploration involving pathfinder elements must be based on a close fundamental relationship between the pathfinder and the element being sought. Experience in various parts of the world has shown that while many gold deposits are associated with anomalous concentrations of arsenic, not all arsenic anomalies are accompanied by gold mineralization. On the other hand, mineralized structures containing blind auriferous ore-shoots at depth, have been found during this work to give rise to strong arsenic anomalies in surface soils. Such anomalies related to blind orebodies might be neglected unless the full significance of the arsenic anomaly is appreciated. In this thesis, a detailed study has been made of the primary dispersion of arsenic in gold-bearing lodes and the surrounding wall-rocks. Particular emphasis has been placed on the significance of "leakage" anomalies in locating blind orebodies.

Another problem of universal interest is that of prospecting in laterite-covered areas. An attempt has been made to show that gold mineralization overlain by indurated laterite can be detected geochemically by analysing selected fractions of the near-surface laterite soils.

IV. PRESENTATION OF THESIS.

The thesis is divided into eight chapters. Chapter 2 consists of a general description of the geology, physiography, climate, vegetation and pedology of that

part of Western Australia in which studies have been made. The research techniques used are briefly described in Chapter 3, fuller details being set out in the Appendix. Chapters 4 and 5 contain the results of studies of primary and secondary dispersion, respectively. Each of these chapters consists of results from several study areas, and detailed descriptions of local geology, physiography etc. precede the appropriate section on geochemical observations for each area. Both chapters conclude with a discussion of the results obtained in relation to theoretical data and results from other areas. Chapters 6, 7 and 8 consist respectively of a summary of the results and conclusions, suggestions on suitable prospecting procedures, and recommendations for future research.

V. ACKNOWLEDGEMENTS.

The project described in this thesis formed part of the overall programme of research carried out at the Geochemical Prospecting Research Centre, London, under the general direction of Professor J.S.Webb. The writer would particularly like to thank Professor Webb, Dr.J.S.Tooms and Dr.C.H.James for their guidance and encouragement, both in Australia and in London. Special thanks are due to Dr. James for kindly undertaking to read the manuscript of the thesis.

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CHAPTER 2. GENERAL DESCRIPTION OF FIELD AREA.

I. LOCATION OF STUDY AREAS.

Geochemical investigations were carried out at a number of localities in the Eastern and North-Eastern Goldfields of Western Australia, shown in Fig. 1. The most detailed studies of both primary and secondary dispersion were undertaken in the Norseman area, brief studies being made in the other areas mainly for comparative purposes. Agnew and Eulaminna occur in the North-Eastern Goldfields, the other areas lying in the Eastern Goldfields.

II. GEOLOGICAL SETTING.

The following description of the geological setting of the Western Australian gold deposits is drawn from general papers by Prider (1945 and 1955), Forman (1953), Wilson (1958) and others. Detailed descriptions of the geology of various study areas are given where relevant in later sections.

1. Stratigraphy and lithology.

The Western Australian goldfields, without exception, occur on the extensive Precambrian Shield area. The Precambrian Succession in Western Australia is given in Table 1. All of the major gold deposits occur within, or closely related to, inliers of the Kalgoorlie-Yilgarn System in the otherwise dominantly granitic terrain (Fig. 1). Prider (1955) considers that these inliers of older metamorphic rocks are the remnants of a series of "meridional geosynclinal belts". Within each belt, the general sequence of geological events is similar, although it does not

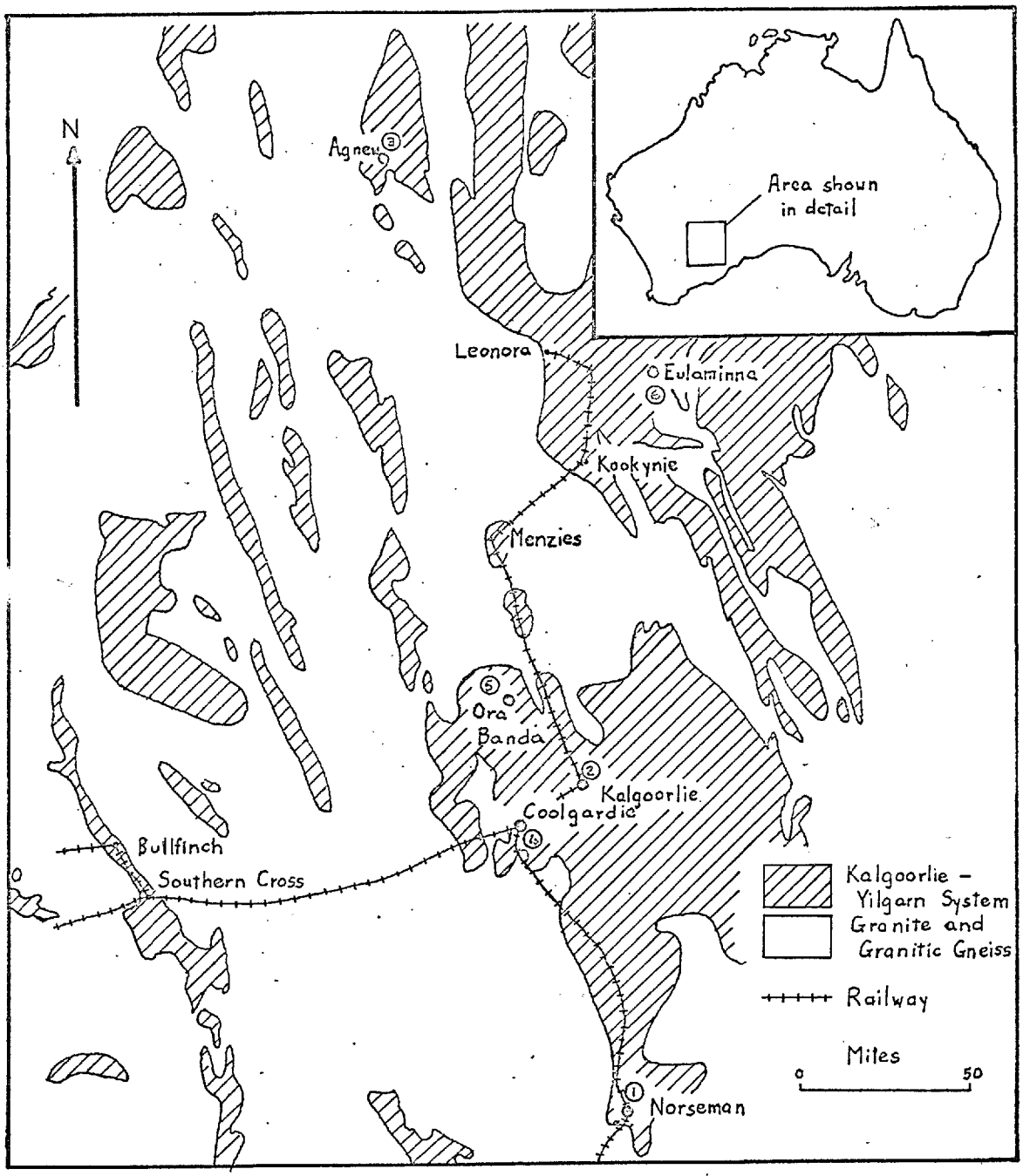


Fig. 1. Locality map, showing study areas (numbered in order of mention), and distribution of rocks of the Kalgoorlie–Yilgarn System.

follow that the rocks in different belts are strictly contemporaneous. Everywhere, the oldest rocks recognised are basaltic volcanics ("Older Greenstones"). These are often spilitic in character and exhibit pillow

TABLE 1.

The Precambrian Succession in Western Australia.

Age	Description.
Late Proterozoic or Lower Cambrian.	Basic dykes (epidiorite, dolerite, norite).
	------ igneous contact ------
Proterozoic	"Nullagine Series"(Unmetamorphosed sediments -not present in areas studied).
	------ unconformity------
Archaeozoic	"Younger Granite" (granite, adamellite, granodiorite intrusives and related pegmatites, aplites etc.
	------ igneous contact ------
	"Older Granite" (gneiss, migmatite and granitized sediments).
	------ igneous or granitization contact--
"Kalgoorlie-Yilgarn System"	"Younger Greenstone" Phase (basic and ultra-basic meta-igneous rocks).
	---- igneous contact ----
	"Whitestone" Phase (metamorphosed clastic sediments, andesitic, rhyolite and dacitic lavas and pyroclastics).
	----(?) unconformity----
	"Older Greenstone" Phase (metamorphosedbasic volcanics with minor sedimentary and pyroclastic beds).

structure as evidence of their submarine extrusive origin. Within the flows there is subordinate development of thin bands of slates, pyroclastics and banded iron formations. The "Older Greenstones" were overlain by varying thicknesses of clastic sediments, acid to intermediate lavas and pyroclastics, ("Whitestones"). A recurrence of basic igneous activity resulted in the invasion of the earlier rocks by dykes and sills of hypabyssal gabbros and dolerites ("Younger Greenstones"). These events were followed by a period of orogenesis, represented by isoclinal folding, granitization and granite intrusion.

The most important host-rocks of gold deposits are the so-called "Greenstones", very few major gold occurrences being known in rocks of the "Whitestone Phase" or granites. Low grade regional metamorphism has resulted in changes in mineralogy, although the original igneous textures and structures are often preserved, in spite of the intense folding. Original pyroxenes of basic rocks have generally reverted to tremolitic amphibole and chlorite, and feldspars have usually been extensively saussuritized and in some cases completely replaced by zoisite aggregates. Locally, however, the effects of shearing and metasomatism are more pronounced, particularly in mineralized areas.

Ultrabasics are generally represented by tremolite-actinolite or serpentine rocks, with local development of talc and anthophyllite schists. The relationship of the ultrabasics to the other "greenstone" rock-types is not

clear. Some occurrences show relict peridotitic textures suggesting an intrusive igneous origin. In many areas ultrabasics occur in a conformable stratigraphic manner and are thought to be altered magnesian limestones (Sofoulis, 1963).

"Greenstone" areas are frequently characterised by dykes and sills of felsite porphyry, which often seem to bear an important relationship to the location of ore. These rocks usually consist of phenocrysts of quartz, microcline or albite (or all three) in a cryptocrystalline quartz-feldspar groundmass. More basic varieties with phenocrysts of hornblende or biotite are known. The development of complex quartz-veining and disseminated sulphides within porphyry bodies is relatively common. Some of these porphyry bodies have been mined as low grade gold deposits. While many porphyries show clear-cut igneous intrusive features, others are believed to result from metasomatic alteration of pre-existing rocks.

2. Geological Structure.

The layered rocks of the Kalgoorlie-Yilgarn System have been intensely folded, the dominant axial trends consistently varying between NW and NNW. This feature is reflected in the NW-NNW alignment of the elongate inliers of these rocks (Fig. 1). Local deviations from the regional trend have been attributed to cross -folding (Ellis 1939, McMath 1953). The significance of "en echelon" folding in some mining centres in Western Australia has

been stressed by Campbell (1958). Faulting is generally of local rather than regional significance. Cross-folds, en echelon folds and faulting have been suggested as important influences in the localization of ore in specific areas.

3. Mineralization.

Gold is the most important and widely distributed economic mineral occurring in the area under consideration. A wide variety of structural and mineralogical types of gold deposits are represented. The types of ore bodies studied in this investigation are listed below. These will be described in greater detail in later sections.

1. Simple gold-quartz reefs (Norseman).
2. Complex of gold-pyrite-telluride replacement lodes in metadolerites and metabasalts (Kalgoorlie).
3. Arsenical replacement lodes in ultrabasic rocks with associated auriferous veinlets (Agnew).
4. Sulphide-bearing replacement lodes in ultrabasic rocks related to felsite porphyries (Surprise Mine, Coolgardie).
5. Sulphide (-telluride) replacement lodes in porphyritic metabasalts (Ora Banda).

A brief comparative investigation was also carried out in the vicinity of a small copper orebody at Eulaminna. This deposit is a pyrite-chalcopyrite siliceous replacement lode in basic and intermediate volcanics. The oxidized and supergene zones are characterized by strong development of cuprite, malachite, azurite and chalcocite with known

associated gold contents of up to 0.5 dwt/ton.

The genesis of the Western Australian gold ores is the subject of considerable debate. The main period of gold mineralization is generally believed to have been associated with the intrusion of the "Younger Granites". While recognising a granitic origin for some ores, Prider (1945) refers some sulphide-bearing replacement lodes, typified by the Kalgoorlie deposits, to the "Younger Greenstone" phase of basic igneous activity.

III. CLIMATE.

Climatically, the whole area under consideration is semi-arid to arid. The average annual rainfall in all the centres studied is 11 inches or less, decreasing from south to north. The wettest period extends from April to August, when the weather pattern is dominated by rain-bearing westerly winds. However, a large proportion of the rainfall in some years is contributed by sporadic downpours in the summer months, as a result of cyclonic activity extending inland from the north-west coast.

The average annual temperature varies from 60-70°F. High temperatures are experienced in summer, resulting in extremely high evaporation rates, which range from 80 to 150 inches per annum.

IV. GEOMORPHOLOGY.

All the areas studied occur on a vast inland plateau which characterizes much of the Precambrian in

south-western Australia. The elevation of the plateau varies from 1,000 to 2,000 feet above sea level. Local relief, however, is very subdued, topographic highs seldom rising more than 100 feet above the broad, shallow valleys. The area is believed to have been a peneplain in Tertiary times, when the formation of lateritic soils is thought to have taken place. Subsequent uplift and erosion under increasingly arid climatic conditions have resulted in the occurrence of two distinctive surfaces of erosion, known as the "old" and the "new" plateaux (Jutson 1934). The "old" plateau, is represented by isolated flat-topped duricrusted hills, which are considered to be the remnants of the dissected Tertiary peneplain. In some areas, particularly in granitic terrain, more continuous remnants of the "old" plateau occur, generally characterized by sandplain soils overlying a gravelly laterite horizon. The "old" plateau is elevated 30 to 100 feet above the level of the "new" plateau, which consists of residual soils developed over the truncated laterite profile and alluvial deposits in the lower regions of the broad shallow valleys. Occasional residuals of more resistant rocks rise above both the "new" and the "old" plateaux but the total range of local variation in elevation seldom exceeds 200 feet. The strong influence of topography on the present-day development of soils in the area is discussed in a later section.

The Eastern and North-Eastern goldfields are characterized by the internal nature of the drainage.

Stream-beds are usually dry all the year round except after heavy rains, when they may flow for a few hours or, at the most, a few days. Sheetwash is an important agent of erosion on the sparsely vegetated hill slopes. Most of the surface run-off accumulates in the so-called salt-lakes which occupy depressions in the surface of the "new" plateau. The water quickly evaporates, leaving a surface crust of white halite and gypsum over silty sediments which may be up to 150 feet or more in depth.

Salt-lakes are the most prominent physiographic features in the area studied, which falls into Jutson's (1934) "Salt-Lake Physiographic Division". Collectively, salt-lakes occupy an appreciable area of the land surface. The largest individual lakes are up to 100 miles in length. They are generally elongated and their chain-line distribution has suggested to some workers (e.g. Gibson, 1909) that they represent remnants of an ancient dismembered river system. During periods of heavy rainfall, it has been known for several lakes to be connected by running water.

At the present time, many salt-lakes are characterized by rocky escarpments on the western margins and extensive deposits of wind-blown material on the eastern shores. This appears to be the combined result of intense rock weathering on the western margins and removal of the weathering products by prevailing westerly winds. The disintegration of rocks on the floors and at the foot of cliffs bordering the lakes is promoted by crystallization of salts originating in the highly saline groundwater.

In the dry season the resulting detritus is removed by wind and is re-deposited in dune formations on the leeward side of the lakes. The base level of wind deflation is limited by the shallow water-table which coincides with, or very nearly with, the lake surface. The continuation of these processes over a long period of time has resulted in considerable westward (upwind) migration of lakes.

The origin of the depressions in which salt-lakes have formed is controversial. There is much evidence to support the theory that lakes originated as remnants of a Tertiary or Pre-Tertiary river system. However, some occurrences suggest that the depressions are of tectonic origin, formed by warping or faulting related to the period of uplift of the plateau.

There are two distinct ground-water provinces in the area studied. In the area to the south of an east-west line approximately 80 miles north of Kalgoorlie and including the Kalgoorlie, Norseman and Ora Banda study areas, the ground-water has a high salt content. Fresh-water supplies are obtained by pipeline from the western coast and minor rock catchments. Throughout the area to the north of this line supplies of potable ground-water are readily obtainable, although saline waters still occur in salt-lakes and depressions.

The widespread distribution of soluble salts in the Eastern Goldfields, as evidenced by the saline ground-waters and salt-lakes, have a strong influence on

soil formation and vegetation in the area. There are two main theories for the origin of the salt. Teakle (1937) and others have shown that wind and rain-borne oceanic salt is currently being deposited in appreciable quantities over the land surface. There is also evidence that a Tertiary marine transgression occurred, at least in the southern part of the area, and it has been postulated that much of the salt has derived from the evaporation of sea-water subsequent to the uplift of the area. Whatever its ultimate origin, it is clear that the present arid climate and internal drainage lead to the retention and accumulation of salt in the area. Recent work (Stephens 1961) has shown that saline material is being recirculated by the action of wind lifting dry residues from salt-lakes and re-depositing them over the adjacent landscape.

V. VEGETATION.

The vegetation of the area is divided into two groups, the distribution of which appears to be related to the difference in ground-water mentioned in the previous section. The southern saline area is characterized by eucalyptus woodlands, the dominant species being the salmon gum, (Eucalyptus salmonophloia). In the North-Eastern Goldfields, mulga scrub, typified by various species of Acacia up to 15 feet in height, predominates. In both areas, natural grass is rare, except after moderate or heavy rain. Apart from sparse development of saltbush,

and associated shrubs, the ground is bare for most of the year.

VI. PEDOLOGY.

1. General.

A distinctive characteristic of Australian geomorphology is the widespread survival of late Tertiary and Pleistocene land sufaces, on which are preserved remnants of ancient soils (Stephens 1961). This is most pronounced in arid plateau areas as found in Western Australia, where the limited uplift and low rainfall have resulted in only partial dissection of such relict soils. Consequently, many soils reflect not only current pedogenic conditions but also characteristics inherited from pre-existing soils. This is an important feature of the soils in the southern part of the area studied in this thesis, where isolated remnants of the "old" plateau of probable Pliocene age are widespread. Where basement rocks have been exposed by erosion, the dominant residual soils are the "solonized brown soils". (The soil nomenclature used in this thesis is that of the Commonwealth Scientific and Industrial Research Organization, Soils Division, as given in recent publications by Stephens, 1961 and 1962). Over duricrust surfaces, modified lateritic soils, termed "calcareous lateritic soils", have developed. Soils intermediate between these two types have formed over the exposed mottled and pallid zones of the truncated laterite profiles. The distribution of

these various soils in relation to the bevelled surface of a typical laterite profile is shown diagrammatically in Fig. 2. In the following sections, the soil types mentioned above are described in some detail, together with the "red and brown hardpan soils" which characterize the northern part of the area (Agnew and Eulaminna).

2. Calcareous Lateritic Soils.

a) Morphology.

A typical profile of this soil-type is shown in Fig. 3a. The thin surface horizon, 0-12 inches deep, of lateritic gravel is usually red-brown to brown in colour and consists of abundant ferruginous laterite fragments in a sandy loam matrix. Lime accumulation commences at a depth of 1-3 inches. Below this depth, lime occurs as a thin coating on the laterite fragments and in a powdery form in the fine fractions of the soil. The lateritic gravel is underlain by an indurated, highly ferruginous, laterite horizon which is vesicular in structure and varies in thickness from 1 to 10 feet. Analyses of the laterite horizon from several occurrences are given in Table 2. Calcareous material occurs in cracks and interstices of the laterite and frequently forms a hard capping up to one inch in thickness at the top of the horizon. There is usually a fairly abrupt change at the base of the laterite to a horizon of mottled texture, consisting of ferruginous nodules in pale kaolinized parent rock. The abundance of the ferruginous nodules decreases

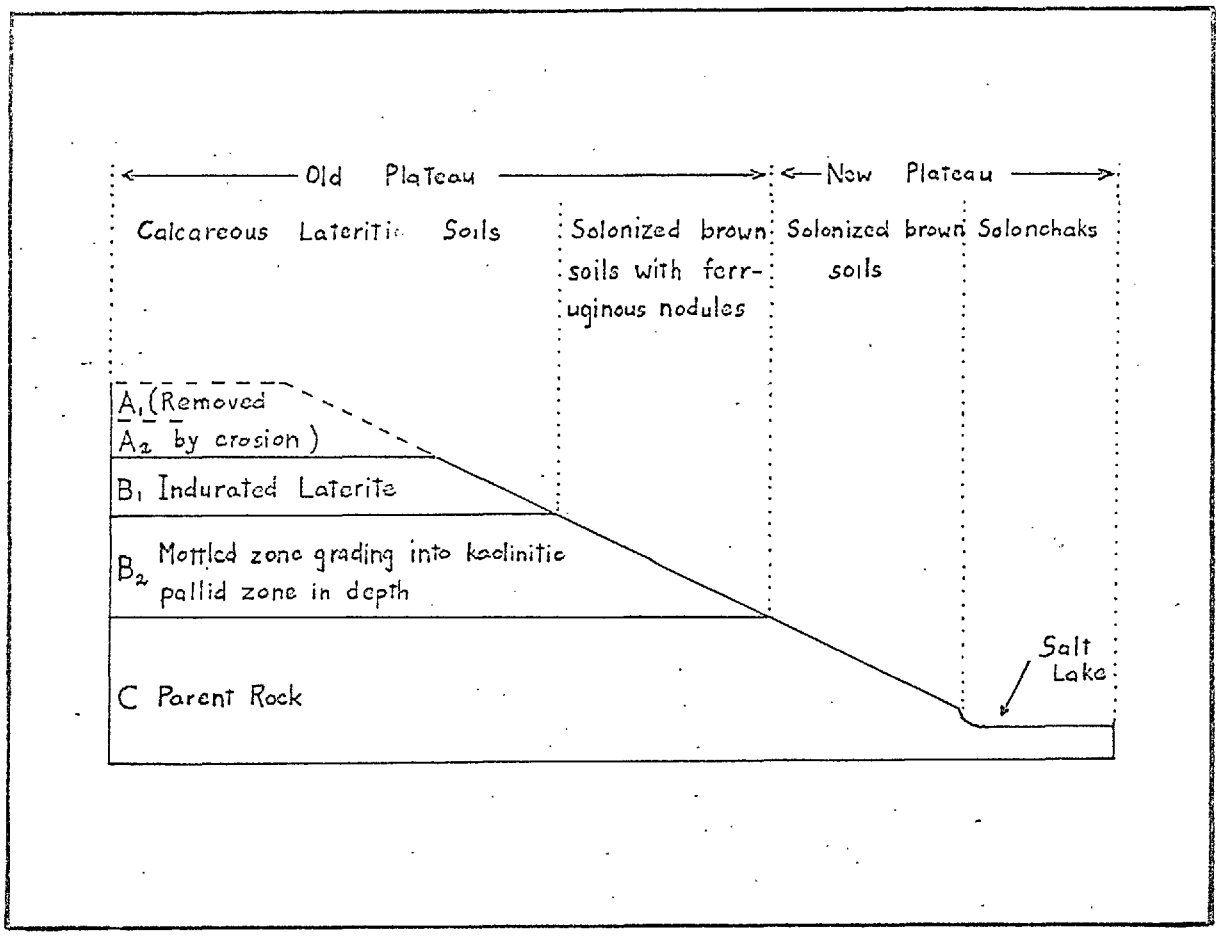


Fig. 2. Diagrammatic representation of soil development on the bevelled surface of a truncated laterite profile.

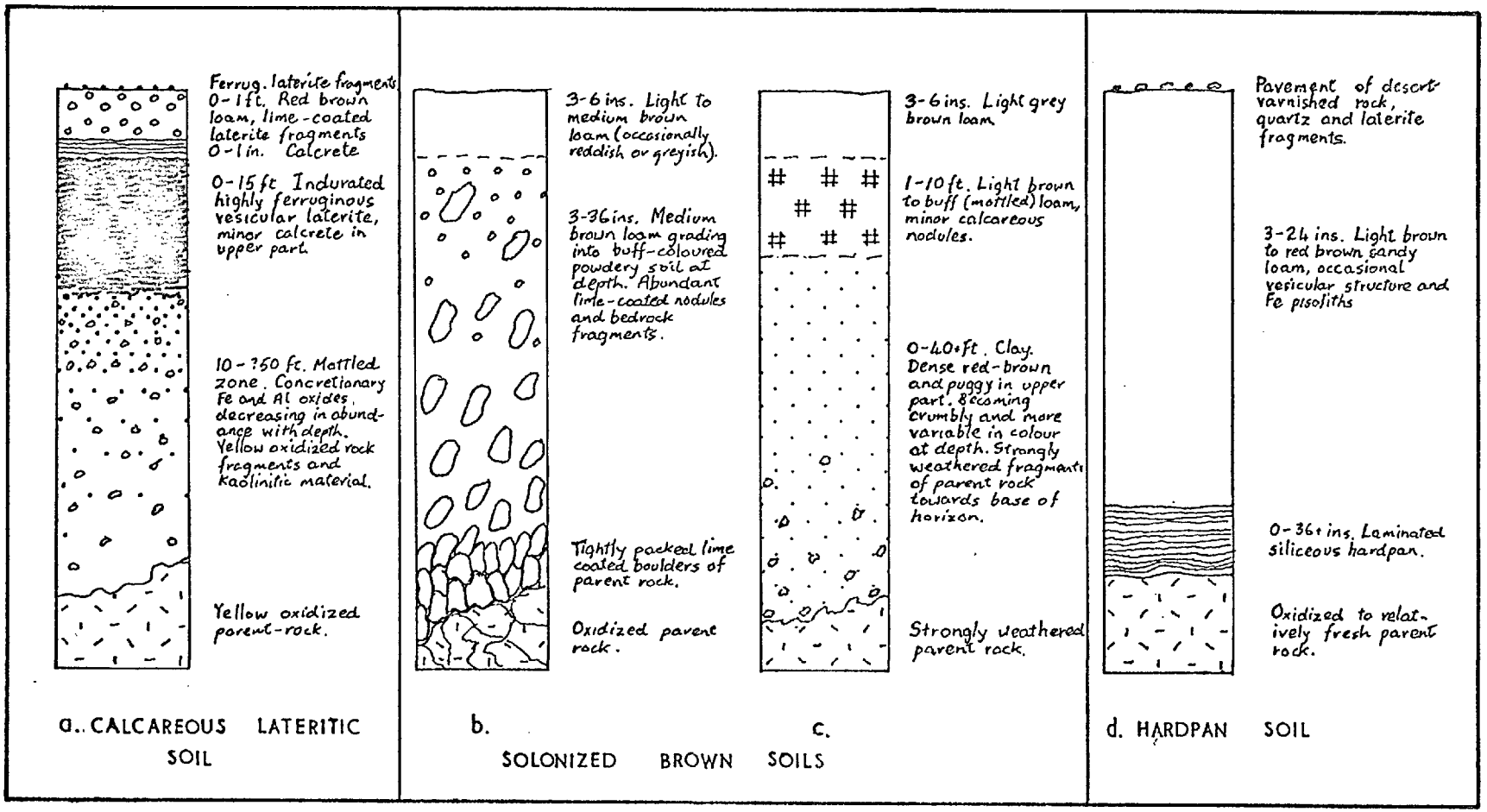


Fig. 3. Diagrammatic representation of soil-types encountered in study areas.

TABLE 2.

Composition of Western Australian laterites, (after Simpson, 1912 and 1916)

	Kalgoorlie*	Coolgardie	Ora Banda
Fe_2O_3	73.97	80.02	60.61
Al_2O_3	10.41	4.32	16.44
Cr_2O_3	0.18	0.08	0.96
V_2O_5	0.41	0.55	0.10
MnO_2	0.23	0.13	0.29
MgO	0.48	Trace	0.28
CaO	Nil	Nil	Nil
TiO_2	3.42	6.06	1.34
SiO_2(qtz)	2.42	0.76	0.33
SiO_2(Combined)		1.77	3.16
P_2O_5	Trace	Trace	0.07
H_2O	8.60	7.06	16.60
	100.12	100.75	100.18

* Mean of 4 determinations.

with depth, giving way to a zone of kaolinized parent rock. The total depth of weathering in laterite profiles at Coolgardie and Kalgoorlie was found by drilling to be at least 20 feet and in some cases over 50 feet.

b) Genesis.

The calcareous lateritic soils are polygenetic, resulting from the calcification of an earlier-formed lateritic soil . Both phases in their formation are briefly discussed below. A comprehensive survey of laterites and lateritic soils has been made by Prescott and Pendleton (1952) and much of the following is derived from their work.

The sesquioxide-rich horizon, which was originally termed "laterite" by Buchanan (1807) is now generally considered to be the exposed illuvial horizon of an ancient soil. Worldwide evidence indicates that these soils were formed on flatter surfaces and under more humid conditions than those in which they now occur. In Australia, laterite formation is believed to have taken place dominantly in the Pliocene. The conditions required for the deposition of iron and aluminium oxides in the form of laterite involve a high degree of leaching and a fluctuating water table. Under these conditions,

alkalis, alkaline earths and much of the combined silica produced in weathering processes would be readily leached out of surface soils. The combined effects of leaching and the thick vegetation which would develop under the climatic conditions envisaged would cause increasing acidity. Kaolinite, iron oxide and resistant minerals would be the stable residual products of weathering under these conditions. Under certain conditions, however, even kaolinite decomposes to release alumina. Iron and aluminium hydroxides would be mobilized and redeposited deeper in the profile where more favourable pH conditions obtain. The most likely locus of concentration would be at or near the surface of the water table.

The increasing abundance of ferruginous nodules towards the top of the mottled zone and considerable thickness of iron-depleted kaolinized bedrock at depth in profiles, suggest leaching and deposition of iron by ascending, as well as descending ground-waters. The ferruginous nodules are usually concretionary in form, implying alternating periods of deposition and leaching in the mottled zone. To explain these features, it has been suggested that the level of the water table was not constant during lateritization, but fluctuated under the influence of alternating wet and dry seasons.

The profile resulting from these processes would consist of a leached sandy 'A' horizon underlain

successively by an illuvial laterite 'B' horizon, mottled zone (B2 horizon) and kaolinized zone (C1 horizon) passing eventually into the unweathered parent rock. The change to a more arid climate has resulted in the induration of the laterite horizon to a hard cuirass, highly resistant to weathering. In most present-day occurrences, the leached 'A' horizon has been completely stripped by erosion, but it is still present in the more extensive lateritic-sand plain areas.

Modifications to the laterite profile under the existing climatic conditions include the development of a superficial lateritic gravel horizon and the extensive calcification of the profile. The lateritic gravel is believed to be the product of partial disintegration of the laterite. This would be aided to a large extent by the crystallization of secondary carbonate minerals in cracks and fissures in the otherwise resistant sesquioxide mass. The origin of the calcareous material is discussed in the next section.

3. Solonized Brown Soils.

a) Morphology.

The solonized brown soils of Southern Australia have many unique features. Morphologically, they are comparable with semi-arid soils of other continents in the marked accumulation of lime in the profile. In addition, however, the highly alkaline soil reaction and high proportion of sodium and magnesium in the cation exchange complex of

solonized brown soils indicate a high degree of solonization. The characteristic structures usually associated with solonetz soils are generally masked by the extensive lime accumulation (Stephens, 1961). The calcium carbonate content of solonized brown soils is commonly greater than 20%.

Considerable variation was observed in the type of solonized brown soil profiles encountered in the areas studied. The lime occurs variously in crusts, nodules and powdery forms. The depth of profile varies from less than one foot to more than 20 feet depending, apparently, on the parent material and topography. Typical profiles of solonized brown soils developed over rocks of basic and ultrabasic composition are shown in Fig. 3 (b and c).

Fig. 3b is typical of the shallow soils encountered on hill slopes where active erosion is taking place. A thin, leached surface horizon is usually present, consisting of light to medium-brown loam with occasional reddish or greyish tinges. The zone of lime accumulation extends from a depth of 0-3 inches to bedrock. In this upper portion, calcareous material occurs dominantly as nodular concretions and lime-coated bedrock fragments. With increasing depth, however, the abundance of nodules decreases and coarse lime-coated rock fragments are found to make up 50% or more of the soil. The fine fraction of the soil becomes lighter brown to buff-coloured due to the presence of powdery calcium carbonate. Bedrock, represented by close-

packed lime coated boulders, is encountered at depths varying from 6 inches to 3 feet.

At the base of hill-slopes and in areas of flatter topography, the thickness of soil is considerably greater. The profile differs from that described above in the general scarcity of rock fragments and the development of a clay horizon below the zone of maximum lime accumulation. There is evidence, in some cases, of transported material in the topsoils but the residual nature of most of these soils is shown by the persistence of some resistant bedrock features, such as quartz veins, to the surface. Fig. 3c shows such a profile. Light grey-brown loam occurs to a depth of 3 inches. This grades into a zone of light brown loam with off-white patches of soft calcareous material, giving the horizon a mottled appearance. Lime nodules are commonly present in this horizon although they are less abundant than in the profile illustrated in Fig. 3b. The clay content of the soil increases with depth and the mottled horizon passes into a horizon of dense red-brown clay which extends to bedrock. The clay content of a Norseman soil profile of the type shown in Fig. 3c was found to be 27% at the surface (leached horizon), 57% at a depth of 6-12 inches (mottled limy horizon), and 70% at a depth of 36-48 inches (red-brown clay horizon). Small fragments of weathered parent rock occur towards the base of the clay horizon.

Solonized brown soils are the most alkaline soils in

Australia, ranging from pH 7.5-9.5 (Prescott, 1931). The pH of the lime-rich horizons of Norseman soils was found to vary from 8.1 to 9.4. The basal clay-rich horizon has a lower pH (7-8.5) and in the vicinity of oxidizing sulphides in the bedrock the pH of the clay horizon drops as low as 4.3, even though the lime-rich horizon remains alkaline (pH up to 9.2). The distribution of pH in the soil profile appears to be closely related to the concentration of carbonate, which varies from less than 1% in the deeper horizons to as much as 16% (CO_3^{--}) in the alkaline near-surface horizons.

Chloride determinations on Norseman soils showed concentrations varying from 0.2 to 0.9%, with a slight tendency towards increasing concentration with depth. Much of this chloride is present as NaCl but it is probable that other salts e.g. Na_2SO_4, Na_2CO_3, $MgSO_4$, $CaSO_4$ and $CaCl_2$ are also present. Small patches of gypsum are commonly observed in soil profiles at Norseman, Coolgardie, Kalgoorlie and Ora Banda. According to Teakle (1937) the solonized brown soils are low in organic matter and extremely low in phosphates.

b) Genesis.

Stephens (1961), in his classification of the Great Soil Group of Australia, considers the unique features of the solonized brown soil to be the result of halomorphic and calcimorphic influences. Solonized brown soils are a special case of saline soils, which are widely dis-

tributed, particularly in arid regions. Joffe (1949, p.528) estimates that 39% of the total dry land area of the earth is covered by saline soils. The presence and probable origin of soluble salts in the soils of Western Australia has been discussed in an earlier section. In freely drained soils, soluble salts would be partially leached down to the lower parts of the profile by the modest rainfall. Teakle (1937) has stressed the significance of the low average rainfall per wet day and high annual evaporation in the area as factors limiting leaching. A state of balance is envisaged where any loss of soluble salts from the soils by leaching would be continually made up by deposition of wind and rain-borne salts from the ocean or the dry salt-lake surfaces.

The Na ions resulting from the hydrolysis of these salts (and to a lesser degree Mg ions) compete strongly for positions in the cation exchange complex of the soils with the result that Na and Mg ions frequently constitute more than 50% of the exchangeable cations present (Stephens 1961). Under conditions of low to moderate leaching, such that the excess soluble salts are washed deeper in the profile, a number of subsidiary reactions take place. Na_2CO_3 is formed by interaction between the Na-saturated complex and the weakly ionized $CaCO_3$ according to the equation:

2Na-sat. complex + $CaCO_3$ = Ca-sat. complex + Na_2CO_3 (Joffe 1949, p. 549). Similarly, in the presence of $Ca(HCO_3)_2$,

$NaHCO_3$ is formed. The presence of Na_2CO_3 and possibly $NaHCO_3$ in the Western Australian solonized brown soils is indicated by the highly alkaline soil reactions observed.

The extensive solonization by sodium ion activity is largely responsible for the type of profile developed. Joffe (1949, p. 552) states:

> "Because of the saturation of the complex with Na and the presence of Na_2CO_3, the solonetz becomes highly dispersed, and the fine particles move to the B horizon to be cemented, forming the typical columnar features".

The "typical columnar features" of the solonetz soils to which Joffe refers are not developed in the Western Australian examples due to secondary modifications in the upper part of the lime horizon. However, the development of clay-rich horizons at depth is clearly the result of solonization, as distinct from podsolization.

Several theories have been advanced by Stephens (1961), to explain the origin of the calcareous material in both solonized brown soils and calcareous laterites. The two most likely to be responsible for the conditions in Western Australia are as follows:

(i) The areas covered by solonized brown soils in southern Australia lie adjacent to calcareous desert soils developed over Tertiary limestones

on the sparsely vegetated Nullarbor Plain. The latter area is susceptible to dust storms which, in periods of greater aridity, transport calcareous loess towards the areas of solonized brown soils. Considering the apparently long duration of the present arid climatic conditions, this source could account for the observed lime accumulation.

(ii) It has been shown that the calcareous material in the soils of the Merredin areas has been derived by westerly winds lifting calcareous and saline material from salt-lakes in the area and spreading it over the adjacent landscape. Salt-lakes are ubiquitous in the areas studied and this explanation could therefore be extended to include the solonized brown soils of the Eastern Goldfields.

There is little comment in the literature on the possible role of atmospheric or biogenic CO_2 in the precipitation of $CaCO_3$. Calcium ions would be readily available in the soils as the result of partial dissociation of cyclic calcium salts ($CaCl_2$ and $CaSO_4$). The disintegration of vegetation under the prevailing highly oxidizing conditions would produce CO_2 in significant amounts, which, in the presence of moisture, could react

with Ca ions to form $Ca(HCO_3)_2$ and $CaCO_3$. The concretionary forms of calcareous material and the presence of a leached 'A' horizon are evidence that solution and redeposition of $CaCO_3$ in the soils does take place. This would be possible only in the presence of CO_2-bearing soil solutions. This explanation seems all the more likely when taking into consideration the world-wide occurrence of calcium carbonate accumulations in desert soils. It is clear that the conditions invoked to explain this phenomenon cannot be unique to any one particular area.

c) Summary.

(i) The solonized brown soils are the result of normal processes of soil formation under arid conditions, modified by the presence of significant amounts of soluble salts and calcareous material in the profile.

(ii) The soluble salts are derived either as wind-borne oceanic salts or as the residues from a Tertiary marine transgression and are retained and recirculated in the area by virtue of the internal nature of the drainage and arid climatic conditions prevailing.

(iii) Extensive solonization of the soil profile due to the presence of soluble Na and Mg salts results in the development of

clay-rich horizons and highly alkaline soil reaction.

(iv) The accumulation of calcium carbonate prevents or obscures the formation of typical solonetz structures in the subsoils.

(v) The calcareous material originates either as calcareous loess from adjacent desert areas or as wind-borne calcareous residues from salt-lakes. Chemical precipitation of $CaCO_3$ *in situ* is also considered a possibility.

4. Solonized Brown Soils Developed over Truncated Laterite Profiles.

In areas where the depth to which the "old" plateau has been eroded is less than the former depth of lateritic weathering, distinctive soils have developed on the exposed mottled zone of the laterite profile. These soils are particularly common at Ora Banda and were also encountered at Kalgoorlie and Coolgardie on the lower slopes of bevelled laterite-capped hills.

a) Morphology.

These soils are similar in most respects to solonized brown soils but contain abundant ferruginous nodules in their profile as well as yellowish brown fragments of oxidized parent rock. Both the nodules and the bedrock fragments are lime-coated below the thin

eluvial surface horizon. Bedrock, where exposed in pits and mine workings, consists of mottled reddish and yellow-brown material, typical of the mottled zone of laterite profiles. Calcium carbonate is evident as coatings and fissure fillings in the bedrock.

b) Genesis.

These soils have obviously developed from the weathering of the mottled zone of lateritic soils under arid conditions. The ferruginous nodules of the original lateritic soils are apparently stable under the prevailing conditions and are therefore retained in the profile.

5. Red and Brown Hardpan Soils.

a) Morphology.

The Agnew and Eulaminna study areas lie in an extensive region characterized by red and brown hardpan soils (Stephens 1961). A generalized profile of these soils is shown in Fig. 3d. There is almost invariably a surface pavement of desert-varnished siliceous stones, rock fragments and ferruginous nodules. Beneath the stony surface, light brown to red-brown sandy loam occurs to a depth varying from 6 inches to 2 feet. There is little or no horizon differentiation in these soils. In some instances a compact vesicular structure is present and small (1-2mm) ferruginous pisoliths have been noted in the deeper portion of the profile. The unconsolidated soil terminates abruptly in depth at an indurated hardpan, which directly overlies the parent rock. The hardpan

consists dominantly of laminated siliceous material but minor amounts of calcium carbonate are occasionally present. Detailed studies (Litchfield and Mabbutt, 1962) have shown that small amounts of clay, feldspar and other mineral grains are included in the siliceous crust. Black manganiferous and reddish ferruginous staining are common. Most of the silica occurs as chalcedony but a small proportion is in readily soluble form, indicating that precipitation is in progress in the upper portion of the hardpan. Litchfield and Mabbutt (1962), have observed hardpan formations more than 50 feet in thickness. However, both soils and hardpan thin out on hill-slopes undergoing active erosion, in which environment they may even be absent altogether.

In the near vicinity of the ore deposits at Agnew and Eulaminna, hardpan is usually less than 3 inches thick or completely absent. The orebodies in both these areas occur on gentle erosional slopes, unfavourable for extensive hardpan formation. At Eulaminna, the soils on the hill-slopes consist of shallow stony red earths, often with compact vesicular structure and small iron pisoliths. In the flatter areas and alluvial valley soils, indurated hardpan was encountered at depths of approximately 12 inches. The soils at Agnew are light brown in colour, and the profile is usually less than 12 inches deep. There is frequently a thin development of hardpan overlying the parent rock. The development of stony surface pavements is

widespread in both areas.

b) Genesis.

Teakle (1950) suggested that the hardpan may represent the remnants of siliceous duricrust from the Tertiary laterite profile. However, the hardpan does not outwardly resemble the silcrete duricrust of the area and hardpan occurs at levels in the landscape well below remnants of the former laterite plateau. Most of the evidence suggests that hardpan is an illuvial horizon which is still forming at the present time. Litchfield and Mabbutt (1962), however, consider it possible that silica from the dissection of silicified lateritic soils, remnants of which occur in the area, may have contributed to the silica in the hardpan. The frequent presence of iron pisoliths in the soils and surface pavement suggests a lateritic origin for at least some of the material in the profile. It has also been postulated that the abundant siliceous stones of the pavement are probably derived from the weathering of former silcrete.

The area, although semi-arid, is occasionally subject to extremely heavy and prolonged rainfall causing flooding and saturation of the soil above the hardpan. Stephens (1962) believes that under such conditions, silica might be leached from the surface horizons and redeposited in the hardpan. However, no explanation has been offered for the fact that in other areas in Australia of comparable aridity and sporadic heavy rainfall similar hardpan soils are not common.

Litchfield and Mabbutt (1962) suggest that the lensing-out of hardpan on hill-slopes may be due to the continual dispersion of silica-bearing leach solutions under the influence of the sloping topography. An alternative explanation follows from the observed tendency for the clays in hill slope soils to be montmorillonitic. The dominant clay minerals occurring in the soils of lower-lying areas are illite and kaolinite. More silica is required in the formation of montmorillonite than in illite and kaolinite. As a result, it is thought that there may have been insufficient excess silica available in hill-slope soils for the formation of hardpan.

CHAPTER 3. TECHNIQUES.

I. COLLECTION AND MARKING OF SAMPLES.

1. General.

During the field studies, some 10,000 samples of rock, soil and sediment were collected in special kraft paper envelopes, sealed by non-contaminating metal tabs. Envelopes were numbered before being taken into the field and details of location and descriptive data were recorded directly on field sheets.

2. Collection of Rock Samples.

For studies of wall-rock dispersion, samples were collected from diamond drill-core and underground cross-cuts along traverses as nearly normal as possible to the plane of lodes or reefs. Two foot sampling intervals were used in most cases, but the interval was varied where necessary to ensure that each sample consisted of only one rock type. Each sample was made up of 500 to 1500 grams weight of chips, so taken as to be approximately representative of the whole sample interval. In some underground traverses, spot samples of equivalent weight were taken from each interval for comparison with the composite chip samples. The results of arsenic analyses showed poor correlation between samples collected by these two methods (Fig. 4). This discrepancy indicates that arsenic is not uniformly distributed in the wall-rocks. In theory, accurate channel sampling would be the most suitable method of sample collection. However, the results indicate

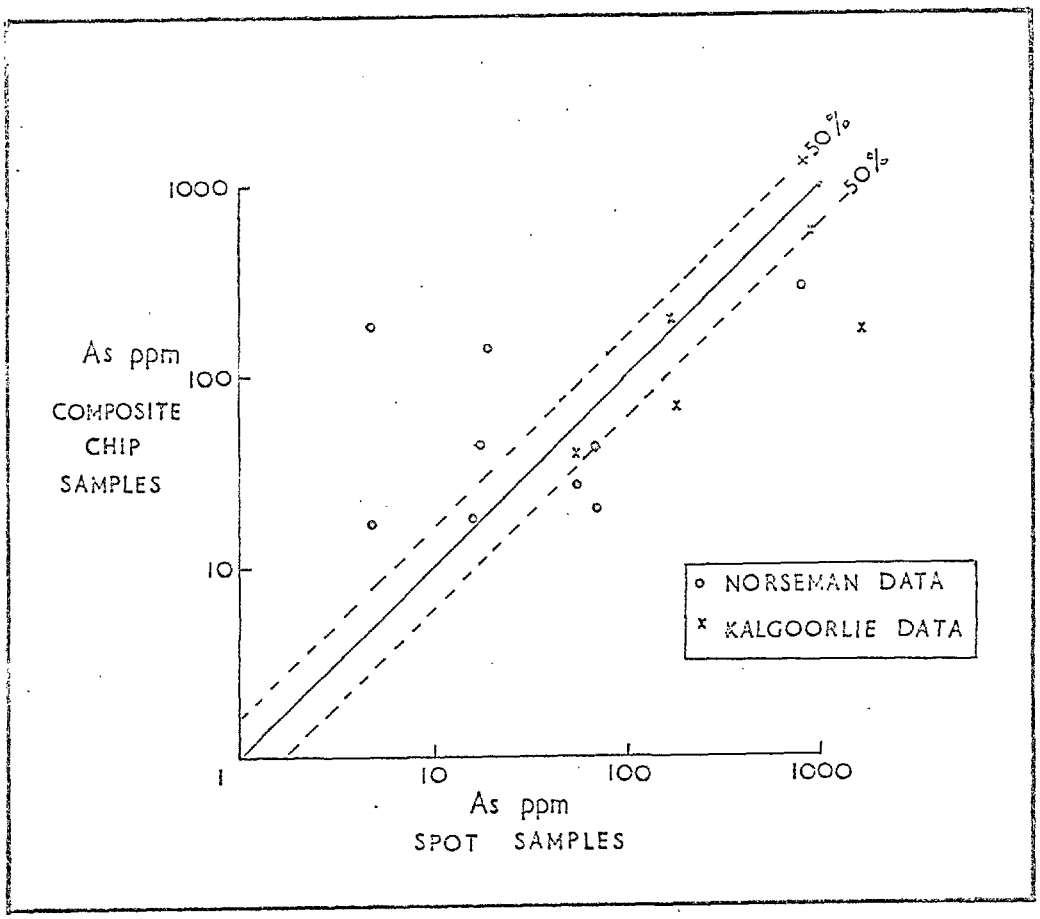


Fig. 4. Comparison of arsenic contents of composite chip and rock samples.

the sampling technique adopted, i.e. taking series of chips over the whole sample interval, is quite satisfactory and more economical, for the purposes of this research.

3. Collection of Soil and Sediment Samples.

Soil samples were normally collected from pits dug to the required depth by spade or hoe. For routine purposes, vertical channel samples were collected from the freshly exposed soil at 6-12 inches depth. To obtain data for complete soil profiles, pits were dug to the weathered bedrock surface and continuous channel samples taken from the side of the pits, starting at the bottom to avoid contamination by falling soil particles. The vertical sample intervals used varied from 3 to 12 inches and fresh samples were started at obvious horizon changes. In some cases it was found that a hand auger could be used advantageously to obtain profile samples at depths of up to 7 feet. However, this method was ineffective in dry, powdery or stony soil profiles. Sampling traverses were laid out by means of prismatic compass and taping or pacing.

A tractor-mounted percussion drill was used at Coolgardie and Kalgoorlie to sample indurated laterite profiles. At Norseman, sampling of deep solonized brown soils to depths of up to 50 feet on one traverse was carried out by means of a motor-driven auger drill.

The representativity of anomalous soil samples was checked by taking a series of samples in a spiral pattern with a maximum radius of 10 feet. The mean

arsenic content (-82 mesh fraction) was 104 ppm with a standard deviation of 19 ppm. Since regional background is of the order of 5 ppm, it was considered that the sampling technique used would be unlikely to lead to errors in locating anomalies.

In sampling the dry stream beds, care was taken to ensure that only unconsolidated active drainage sediments were collected. 50 to 100 gms of this material were scooped up using a garden trowel.

A hand auger was found to be the most efficient implement for sampling the moist silty sediments of the salt-lakes. Samples were normally taken at a depth of 6-12 inches, but at selected localities, continuous profile samples were collected.

II. SAMPLE PREPARATION.

1. Preparation of Rock Samples.

The preparation of rock samples for chemical analysis is one of the most time consuming aspects of studies of primary dispersion. Ideally, a representative portion of the sample should be pulverized completely, care being taken to guard against contamination.

In the present study, samples were reduced initially to -½" mesh by means of a jaw-crusher with cast-steel plates. A small chip from each sample was retained for preparation of thin and polished sections. In the standard procedure used at the G.P.R.C., a representative portion of the -½" mesh material is reduced to -100 mesh by 15

minutes vigorous shaking in ceramic ball mills. By treating 6 samples simultaneously in this way a productivity of 18 samples per hour can be achieved. The ball mills are cleaned between samples by brushing. The risk of contamination using this method is very slight and can be minimized by treating samples, as far as possible, in order of increasing trace element content.

Empirical tests on 12 samples of wall-rocks from Norseman, with arsenic contents ranging from 0-300 ppm showed that a more rapid alternative method could be used, with closely comparable results. Starting with jaw-crushed material, four representative portions were taken from each sample and reduced to powder-form in different ways. Each portion was analysed in triplicate for arsenic and the results were averaged to minimize any differences due to analytical errors. The results are shown in Table 3. Eight of the samples were analysed spectrographically to confirm the results for other elements.

It can be seen from Table 3 that the differences in arsenic content betwen portions prepared by different techniques are insignificant compared with the normal limits of analytical precision ($\pm$25%). Of the methods in which the sample is totally pulverised (A and B), the ceramic ball mills are considerably more rapid than hand crushing and of comparable accuracy. The close agreement of the results for the -82 " fraction of jaw-crushed material (C) with those of methods in which the sample is completely

TABLE. 3.

Comparison of Sample Preparation Techniques.

Arsenic Contents of Norseman Wall-rock Samples.

Sample No.	Arsenic Content ppm.			
	A*	B	C	D
4214	29	26	30	35
4215	33	37	38	37
4217	34	37	35	34
4218	7	7	3	6
4219	72	74	79	74
4292	41	55	44	56
4293	116	130	176	121
4295	27	27	34	33
4297	56	56	77	75
4298	278	288	389	240
4299	32	29	38	27
3607	1	1	1	2

Notes:

* A. Samples hand-crushed between tungsten carbide plates.

B. Samples pulverized in ceramic ball mills.

C. Jaw-crushed material sieved to -82 mesh.

D. +20 mesh fraction of jaw-crushed material pulverized in ceramic ball mills.

pulverized (A and B) suggests a useful ancillary method of sample preparation. Sieving samples to -82# has the advantage of being much more rapid than pulverizing in ball mills. Slight divergence of the results is apparent in the higher concentration ranges, where there is a tendency for the arsenic content to be higher in the -82# fraction. The reverse tendency is observed in the results for the +20# fraction of the jaw crushed material (D). This is presumably due to the differential behaviour of arsenic-bearing minerals in the jaw-crushing stage. (The inaccuracies due to this cause are to some extent compensated by the fact that the -82# material is more representative of the whole sample than the 5 mg portion pulverized in ball mills).

Pulverization in ceramic ball mills was used as the standard technique for preparation of rock samples in the present research. All background samples, key traverses and other important samples were pulverized in this manner. However, preliminary scanning of wall-rock traverses at Norseman was carried out by analysing the -82# fraction of jaw crushed material. Once anomalies were established by this method, critical samples from each traverse were pulverized in ceramic ball mills and check analyses were made. Fig. 5 shows a comparison between the results of analysis of the -82# fraction and check analyses made on completely pulverized samples.

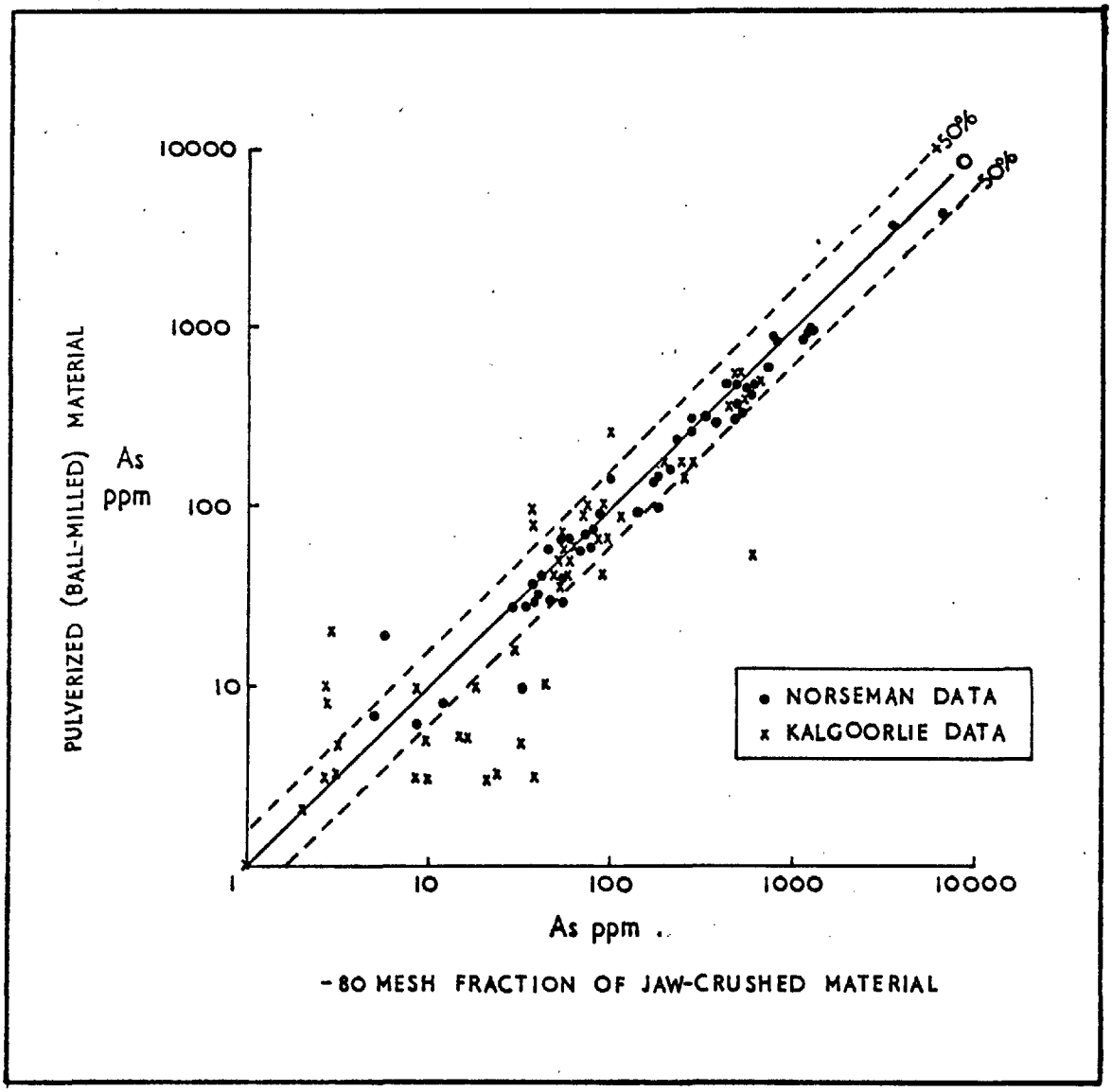


Fig. 5. Comparison of sample preparation techniques. Arsenic contents of pulverized and -80 mesh fraction of jaw-crushed rock samples from Norseman and Kalgoorlie.

The linear distribution of results confirms the reliability of the -82# fraction "scanning" method. Similar tests on Kalgoorlie wall-rock samples showed less favourable correlation in the lower range of arsenic concentration (0-30 ppm As) but good agreement was obtained for more strongly anomalous samples. Although the -82# fraction would clearly give satisfactory results as a scanning method, all Kalgoorlie and Agnew samples were prepared by the ball mill method.

Mineral separations for selected rocks were accomplished by a combination of magnetic and density methods. Very briefly, the procedure was as follows:-

a) Crushing and Sieving.

The rock was hand-crushed between tungsten carbide plates until sufficient material in the -150#+200# range was obtained, usually 20 to 30 gms. (The mesh size collected is determined by the grain size of the rocks. In this study, the rocks were for the most part fine grained).

b) Hand magnet.

After washing and drying the sample, strongly magnetic minerals such as magnetite and pyrrhotite were collected using a hand magnet.

c) Frantz Isodynamic Magnetic Separator.

The slope and tilt of the separator were maintained at 10° and 15° respectively throughout the procedure.

(i) The sample was passed through the separator with the current setting at 0.15 amps to remove mineral grains with inclusions of magnetic pyrrhotite and magnetite and pyrrhotite grains not removed by the hand magnet.

(ii) Weakly magnetic minerals including quartz, feldspars, muscovite, pyrite, arsenopyrite, scheelite and calcite were removed as the non-magnetic fraction at a current setting of 0.95 amps.

(iii) The mafic minerals, biotite, actinolite and chlorite were removed as more or less pure fractions by varying the current between 0.2 and 0.5 amps.

d) Specific Gravity Separations.

Further separations to obtain pure mineral fractions were carried out using heavy liquids, tetra-bromo-ethane (SG=2.96), methylene iodide (S.G. = 3.3) and Clerici's solution (S.G. = 4.3). These solutions were diluted (the former two with acetone and the latter with water) to separate minerals of similar S.G.

2. Preparation of Soil and Sediment Samples.

Soil samples were lightly crushed in a pestle and mortar, to destroy soil crumbs, and sieved through nylon or silk bolting cloth. Initially, selected samples were separated into six size fractions, using a nest of sieves,

to determine the most suitable size fraction for routine analysis. The -82# fraction was generally found to be most satisfactory for non-lateritic soils, but the +20# fraction was also found to be useful in the case of lateritic gravel samples. For more detailed studies, complete separation of selected samples into sand, silt and clay fractions was achieved by wet dispersion. The method used is described in detail in the Appendix. The relationship between the various mesh sizes, sedimentation fractions and particle dimensions is shown in Table 4. All size fractions greater than -38# were ground to pass a -82# sieve before analysis. This was done either in ceramic ball mills or, when the sample was soft enough, in an agate or iron pestle and mortar.

Mineral separations of sand-sized material were carried out using a hand magnet, heavy S.G. liquids and by hand-picking under a low power binocular microscope.

TABLE. 4.

Relationship Between Mesh Sizes,

Sedimentation Fractions and Particle Sizes.

Sieve Material.	Stainless Steel.	Nylon			Silk		Obtained by Sedimentation.	
Mesh size or fraction.	$\frac{1}{4}$"	20	38	82	125	197	Silt	Clay
Aperture or max.particle size mm.	6.5	1.0	0.5	0.2	0.1	0.05	0.02	<0.002
BS sand size	Coarse sand			Fine sand			Silt	Clay.

III. ANALYTICAL TECHNIQUES.

1. Chemical Analysis.

The methods of chemical analysis used in this research are listed in Table 5, together with the reagents used, range covered, precision and published source. Details of the procedure for each of these methods are given in the Appendix. Precision is calculated at the 95% confidence level by the method of Craven (1954). Control samples were included in all sample batches and, from the results obtained for these samples, a constant check could be kept on the reproducibility of routine analysis.

TABLE. 5.

Techniques Used in Chemical Analysis.

Element or Ion	Reagent	Range Covered ppm	Precision %	Published Source
Antimony	Brilliant Green	0.2 - 110	± 25	Stanton & McDonald (1961-2).
Arsenic	Mercuric Chloride	0.5 - 10,000	± 25	Stanton (1964)
Carbonate	(Volumetric-HCl)	500 - 285,000	Not known	Not published
Chloride	Silver nitrate	100 - 12,500	Not known	Not published
Chromium	Dichromate	100 - 3,000	± 25	Wood & Stanton (1956-7).
Copper	2:2 Diquinolyl	5 - 2,000	± 25	Almond (1955)
Gold	Brilliant Green	0.05 - 4.0	Not known	Stanton & McDonald (1964)
Iron	Thioglycollic Acid	100 - 200,000	± 25	Sandell (1959)
Nickel	Furildioxime	1 - 18,000	± 20	Stanton & Coope (1953-9)
Sulphate	Barium Chloride	100 - 10,000	Not known	Scott (1955)
Zinc	Dithizone	5 - 3,500	± 25	Stanton (1962)

A considerable number of arsenic analyses were carried out in a laboratory at Kalgoorlie during field work. The precision of these analyses was within the prescribed limits and the results were useful in guiding the sampling programme. However, repeat analyses carried out in London indicated discrepancies between results obtained in the two laboratories. This was probably due to the use of different makes of chemical reagents in the two laboratories. All important analyses were therefore repeated in the London laboratory. Where the results of Kalgoorlie analyses are used in the following sections to illustrate minor points, mention is made of this fact.

2. Spectrochemical Analysis.

Approximately 600 samples were analysed spectrographically for the elements Pb, Sn, Ga, Bi, V, Mo, Cu, Ti, Ag, Ni, Zr, Co, Mn and Cr. Details of the apparatus used and conditions employed are given in the Appendix. The estimated precision is ± 40% at the 95% confidence level.

As far as possible, comparisons of spectrographic with colorimetric results have been avoided. However, in the case of chromium and nickel, it was necessary to carry out some analyses by spectrograph and some colorimetrically. The relationship between colorimetric and spectrographic determinations for chromium is shown in Fig. 6. There is a tendency for the spectrographic results to be slightly lower than those obtained by colorimetry. This is no doubt due to the differences in

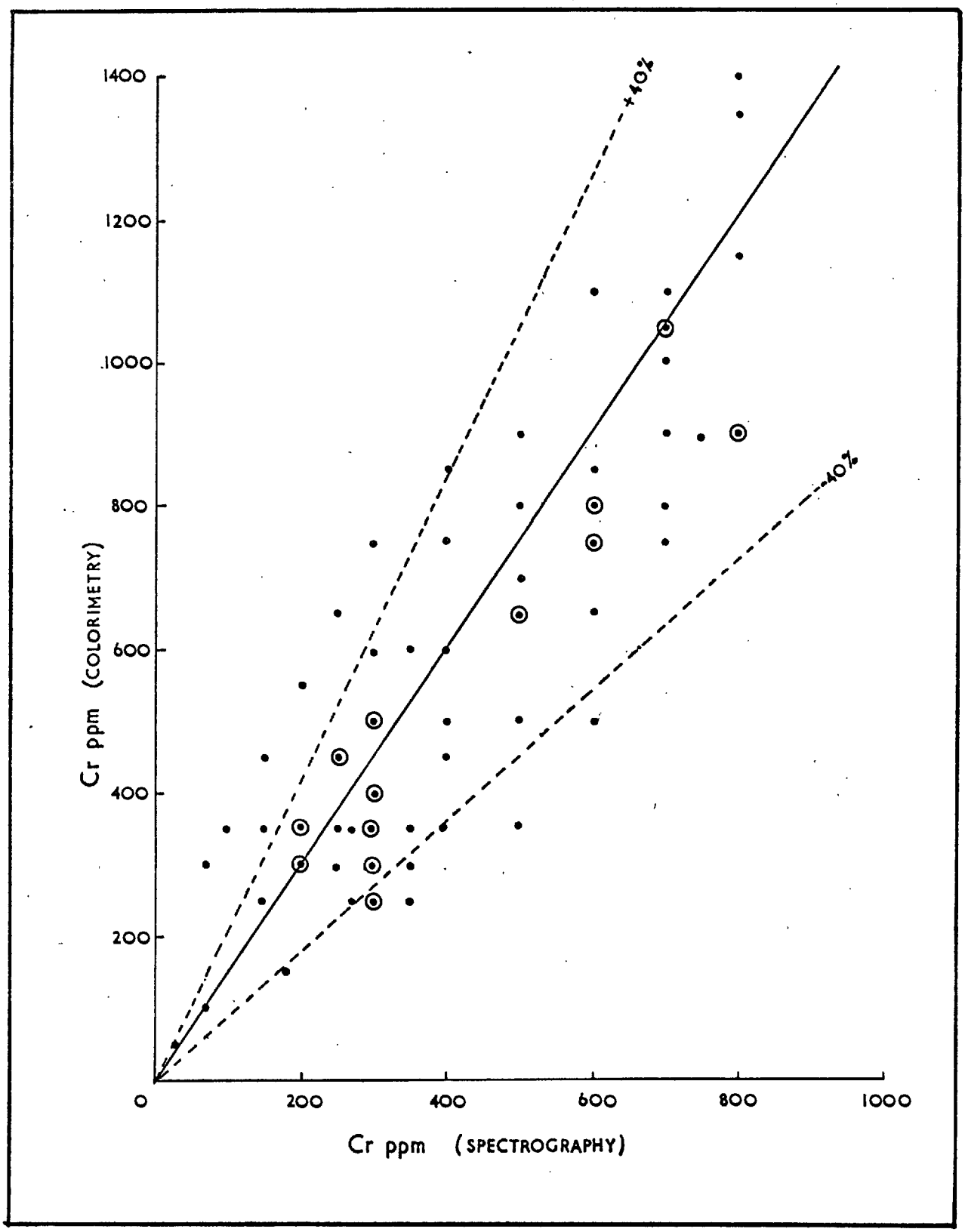


Fig. 6. Comparison of spectrographic and colorimetric methods for the determination of chromium in rock samples from Norseman. (Circled points indicate two or more samples with same values).

attacks to which the sample is subjected in the two methods. A correction factor, based on the distribution pattern shown in Fig. 6, has been applied in the few cases where a comparison of the two sets of data has proved necessary. No detailed study has been made in the case of nickel but results indicate that the spectrographic and colorimetric determinations are comparable.

3. Mercury Analysis.

A limited number of mercury analyses were carried out using a sensitive mercury vapour meter described by James and Webb (1963-4). Basically, the instrument determines the concentration of mercury vapour in air by the absorption of ultra-violet light at specific frequencies. Details of the specifications of the meter and operating technique are given in the Appendix.

IV. MEASUREMENT OF SOIL REACTION.

1 gm portions of selected soil samples (-82# fraction) were vigorously shaken for one hour with 10 mls de-ionized, CO_2-free water in a closed container. The pH of the resulting slurry was measured by means of a portable pH meter, previously callibrated with standard pH solutions.

CHAPTER 4. PRIMARY DISPERSION STUDIES.

I. NORSEMAN

A. GEOLOGY OF THE NORSEMAN DISTRICT.

The following description of the geology of Norseman is derived mainly from recent works by Bekker (1962) and Hall and Bekker (1965).

1. Stratigraphy and Igneous Activity.

Norseman lies at the southern end of an extensive inlier of Archaean greenstones and metasediments, surrounded on three sides by granitic rocks (Fig 1). The main Precambrian rock-types in the area are basaltic lavas and sediments which have been intruded at intervals by sills and dykes of basic, ultrabasic and acid igneous rocks. Small occurrences of Tertiary and younger sediments occur in depressions in the Precambrian surface.

The Precambrian rock succession, as defined by Hall and Bekker (1965) is given in Table 6, starting from the top of the sequence.

TABLE 6.

Precambrian Stratigraphic Succession at Norseman.

Name of Unit	Thickness (in feet)	Lithology
Western granite contact.		
A. Mt. Thirsty Beds	26,000+	Slates, greywackes, quartzites, breccias, metajaspilites, basaltic lavas with large masses of probab-

Name of Unit	Thickness (in feet)	Lithology
		ly conformable ultrabasics.
B. Abbotshall Beds	800 to 4,500	Meta-jaspilites with interbedded basaltic rocks and clastic metasediments.
C. Woolyeenyer Group	28,000 to 32,000	
1. Desirable Pillow Lava	20,000+	Metabasaltic pillow lava with some thin graphitic slate beds, occasionally replaced by quartz (e.g. in Lake Kirk mining area).
2. Crown Basalt	600	Multiple sill of massive aphanitic to strongly ophitic metabasalt with remnant bands of slate.
3. Nulsen Slate	3 to 6	Graphitic slate
4. Royal Amphibolite	370 to 650	Complex sill of meta-quartzgabbro, metadolerite and remnant extrusive metabasalts characterized by a weak schistosity and by the occurrence of small carbonate masses. 250 ft. below the top of the formation occurs the Empress Slate Member (max. thickness 10 ft).
5. Bluebird Gabbro	200 to 350	Sill of massive meta-quartzgabbro; characterized by coarsely porphyritic lower layer.
6. Gee Cee Slate	½ to 6	Graphitic slate.
7. Mararoa Pillow Lava	4200	Metabasaltic pillow lavas.

Name of Unit	Thickness (in feet)	Lithology
8. Venture Slate	3 to 10	Graphitic slate, sometimes partially replaced by quartz, and sometimes dilated by intrusions of doleritic rocks.
9. Kingswood Basalt	1,400	Metabasaltic rocks, including pillow lavas.
D. Noganyer Group.		
1. Holstein Jaspilite	30	Meta-jaspilite.
2. Iron King Formation	150	Meta-conglomerate, sandstone, graphitic slate.
3. Hopetoun Jaspilite	200	Meta-jaspilite.
4. Lady Mary Formation	400	Multiple sill of metagabbro and metadolerite.
5. Lady Miller Jaspilite	100	Meta-jaspilite.
6. Marell Schist	100	Fine-grained grunerite schist.
7. Attlee Jaspilite	200	Meta-jaspilite.
8. Raggedy Formation	400 to 1,000	Meta-conglomerate, biotite andalusite schist, garnet chlorite schist, meta-jaspilite and chert.
9. Bon Accord Jaspilite	350 to 600	Meta-jaspilite.
10. Sawpit Formation	200 to 2,000+	Fine to medium grained mica-schist with prase-rich bands and thin meta-doleritic layers.
E. Penneshaw Beds	10,000±	Meta-basaltic lavas and other basic igneous rocks.
Eastern granite contact.		

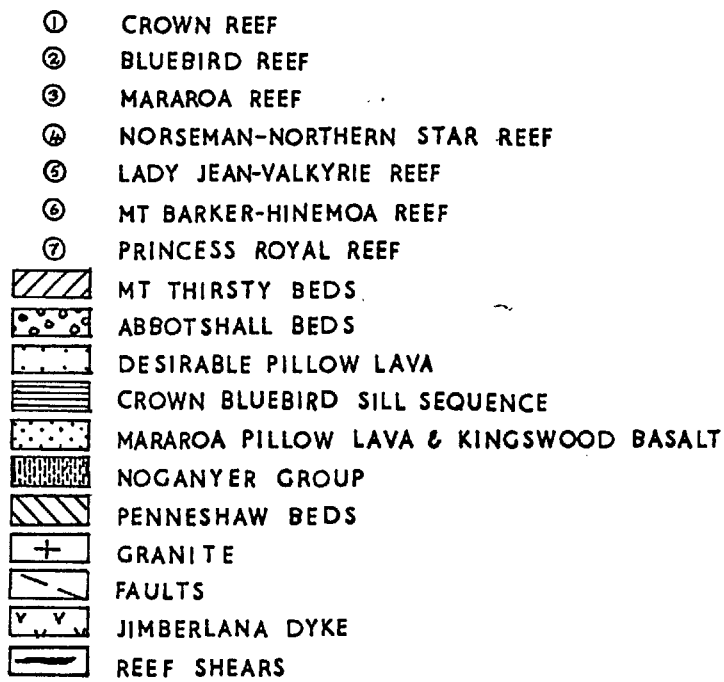
The distribution of the various stratigraphic units and principal gold-quartz veins are shown on the geological map of the area (Fig. 7).

Extensive petrological investigations have recently helped to elucidate the complex history of Precambrian igneous activity that occurred in the area. The oldest igneous rocks are the basaltic lavas ("Older Greenstones"). The widespread development of pillow structure in these rocks suggests that they were deposited as submarine flows, alternating with periods of clastic sediment deposition. The resulting sedimentary-volcanic pile was later intruded by a co-magmatic sequence of sills and dykes of approximately tholeiitic composition ("Younger Greenstones").

The Crown-Bluebird Sill Sequence comprises the most important of the concordant intrusives. The strongly stratigraphic habit of the "Younger Greenstone" sills is well shown by the prominent porphyritic basal zone of the Bluebird Gabbro, which has been traced for 10 miles along the strike. Basaltic, doleritic and gabbroic dykes, striking N.N.W. and dipping 30° to 70°E., intrude the layered rocks. The "Younger Greenstones" are thought to be approximately contemporaneous.

The succeeding phase of igneous activity in the area was the "intrusion" of swarms of albite porphyry dykes which trend approximately N.20°E. and dip west at about 65°. Bekker (1962) considers these rocks to be partly metasomatic in origin and ascribes the origin of the metasomatic emanations to the differentiation of the "Younger Greenstone"

LEGEND FOR FIG. 7.



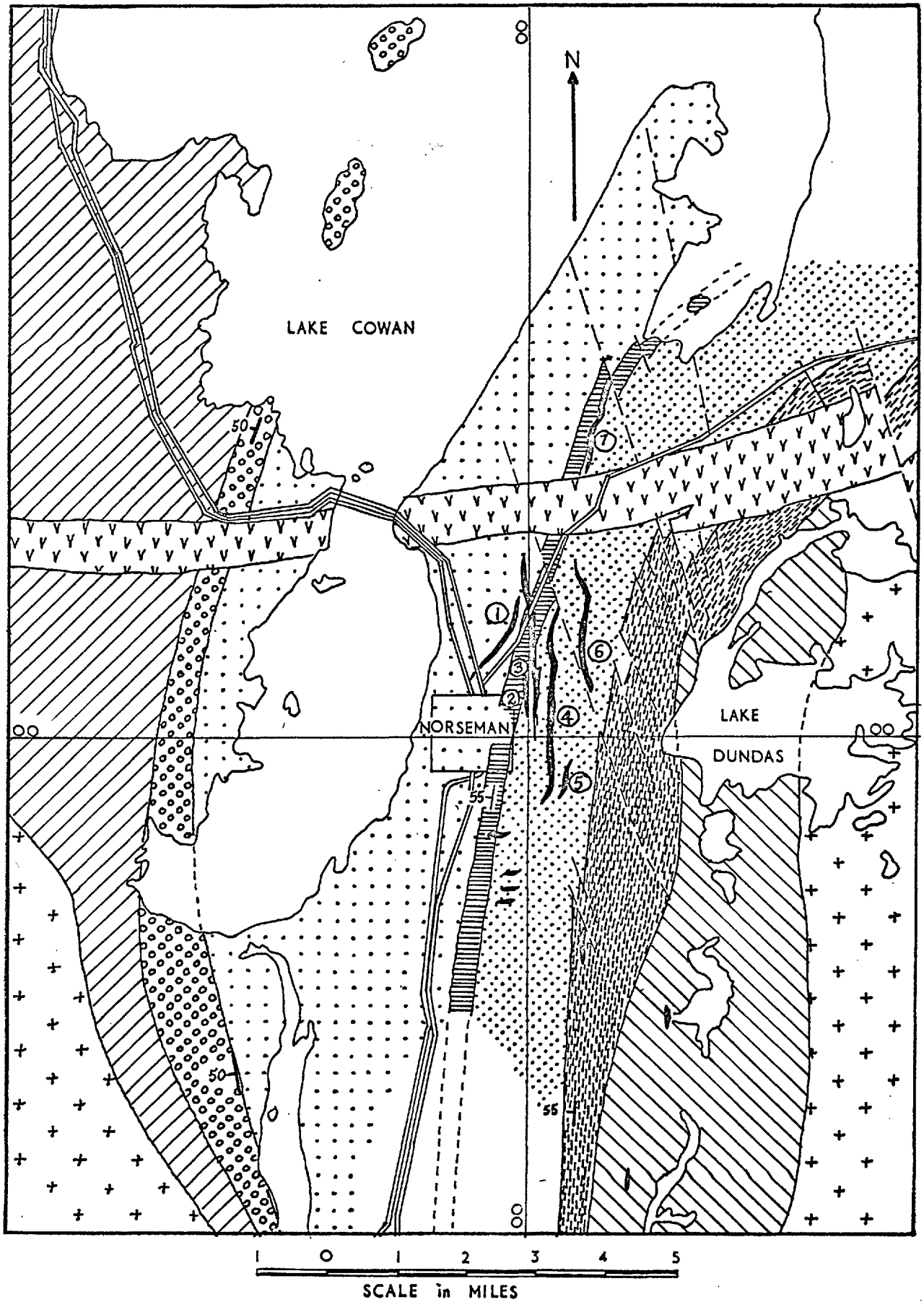


Fig. 7. Geological map of Norseman (after Hall and Bekker 1965).

magma.

Following folding, granite intrusion and the emplacement of gold-quartz veins, dykes of doleritic and noritic composition invaded the country rocks. The most important example of this suite is the Jimberlana Dyke (Fig. 7).

The host-rocks of the major gold-producing reefs of the area are the greenstones of the Crown-Bluebird Sill Sequence and the Mararoa Pillow Lava.

2. Geological Structure.

The Norseman area occurs on the west limb of a major anticline which plunges gently to the north. Within the main mining area, the layered rocks strike 12°E and dip west at about 55°, the trend becoming more north-easterly in the northern part of the area. This change of strike is accentuated by displacements on faults which strike N.20°W. and dip steeply east. Apparent horizontal displacements of up to one mile in an east-block-south direction have been observed.

The major gold-quartz reefs in the area occur in zones of reverse faulting which strike north and dip approximately 45° east. Normal faults, striking parallel to the bedding and dipping 60-75° east have also been encountered in the productive section of the field.

3. Rock Alteration.

The rocks throughout the area have undergone mineralogical changes as the result of regional

metamorphism and, more locally, metasomatic, contact, and dislocative metamorphism. The usual mineral assemblages of the basic meta-igneous rocks, tremolite-actinolite, chlorite and saussuritized calcic plagioclase indicate the upper greenschist facies of regional metamorphism (Fyfe, Turner and Verhoogen, 1959). However, Bekker (1962, p.137) emphasizes that deuteric alteration could have produced similar mineral assemblages, which would have remained stable under greenschist facies metamorphic conditions. He cites the characteristic alteration of the margins of quartz gabbro dykes to an incompetent tremolite-chlorite-carbonate rock as possibly due to deuteric alteration. Where unaffected by subsequent locallized metamorphism, the regionally metamorphosed rocks retain their original igneous textures and structures. Thus, pillow structure, amygdales, ophitic texture etc. are commonly observed.

Narrow aureoles of contact metamorphism have been noted in the vicinity of post-gold norite-dolerite dykes. While pyroxene hornfelses occur up to 700 feet from the margins of the Jimberlana Dyke, the zone of alteration is usually two feet or less in width in the vicinity of smaller intrusives. There is no surviving evidence of contact metamorphism associated with the pre-gold intrusives.

Strongly schistose chloritic rocks with minor quartz, albite, carbonate, mica and epidote have developed in major NNW-trending fault zones. This type of alteration is present but less marked in the east-dipping zones of

reverse faulting which became the loci for quartz reef formation. The rocks in these zones are comprised of sub-parallel elongated tremolite-actinolite grains with chlorite, carbonates and patches of biotite.

Extensive biotitization has taken place as a result of potash metasomatism associated with porphyry intrusion. These effects are found most commonly in the altered walls of quartz gabbro dykes and zones of reverse faulting which later became the channels for quartz reef emplacement.

4. Mineralization.

Two types of gold mineralization occur - minor bedded quartz-sulphide lodes in the jaspilites, and gold-quartz-reefs in the meta-igneous greenstones. The former type are relatively unimportant and will not be considered further.

The most productive quartz reefs strike N-S and dip about 45° east. A parallel sequence of such reefs is developed immediately east of Norseman townsite and is shown in cross section in Fig. 8. In addition, minor quartz reefs, striking E-W and dipping steeply south occur throughout the area. In the present research, work has been concentrated on the major N-S reefs.

The productions of the various major reefs up to the end of 1963, are given in Table 7.

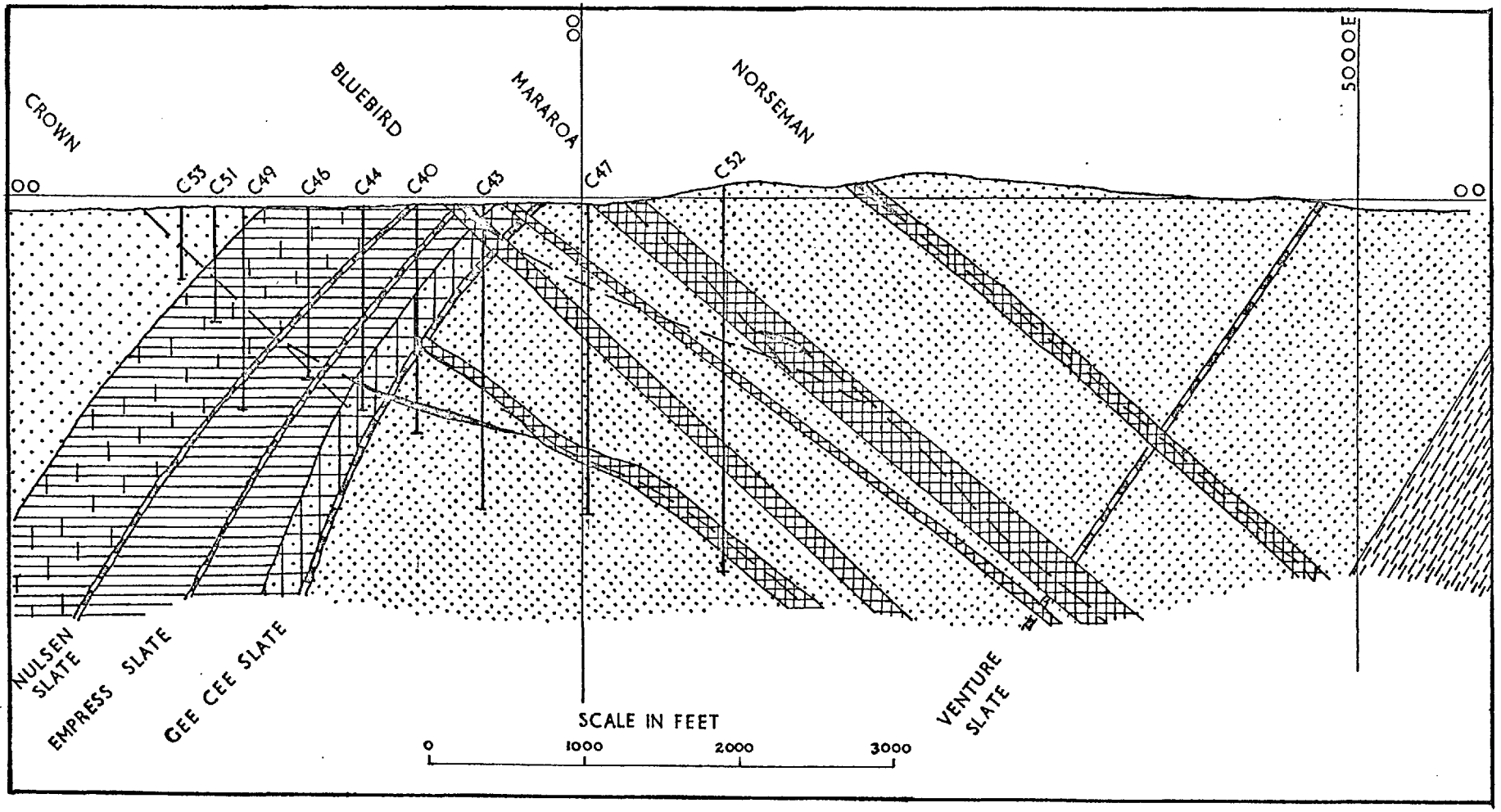


Fig. 8. Geological cross section at 4400N, Norseman, showing drill-holes sampled. (After Hall and Bekker, 1965).

- DESIRABLE PILLOW LAVA
- CROWN BASALT
- ROYAL AMPHIBOLITE
- BLUEBIRD GABBRO
- MARAROA P.L. & KINGSWOOD BASALT
- NOGANYER GROUP
- GABBRO DYKE
- SHEAR
- REEF

TABLE. 7.

Production of Major N-S Gold-Quartz Reefs, Norseman.

Reef	Tons of Ore	Gold Recovered (Oz.)	Grade dwt/ton
Mararoa	3,104,000	1,078,000	6,9
Princess Royal	1,000,000	747,000	14.5
Crown	440,000	260,000	11.7
Total	4,544,000	2,085,000	9.2

These orebodies have been developed over strike lengths of up to two miles and as much as 4,500 feet down the dip. The Norseman, Northern Star, Lady Jean-Valkyrie, Mt. Barker, Hinemoa and other reefs in the area were worked out in the earlier days of the field.

The N-S reefs occur as tabular bodies along the planes of reverse faults. The disposition of orebodies within the reef-shears is largely controlled by reverse faulting movements, which, in places where the dip of the shear is relatively flat, have created tensional openings favourable to quartz deposition. The quartz lenses out along the steeper sections of the shear such that areas of quartz alternate with sections of barren shear. Consequently, many orebodies do not outcrop at the surface; e.g. the major orebodies on Crown Reef are blind and were only

located by deep-drilling from the surface. The average width of quartz in stopes is 6 feet, but locally, the reef may swell out and quartz up to 20 feet thick has been encountered. Individual ore-shoots pitch gently southwards within the plane of the reef but the ore zone as a whole usually pitches gently to the north.

Both massive and laminated forms of quartz occur, frequently side by side in the same reef. Gold is distributed uniformly in association with micro-fracturing throughout the massive variety. In the laminated quartz, the gold is concentrated together with small amounts of sulphides and green hydromica in or near the laminae. Buck quartz, showing no internal fracturing, is always found to be barren.

Gangue minerals, apart from quartz, are only present in small quantities, usually totalling less than 1% of the reef. The gangue minerals observed most commonly are; sericite, green hydromica, ankerite or dolomite, pyrite, chalcopyrite, pyrrhotite, arsenopyrite, galena, sphalerite, scheelite and tourmaline. The tellurides sylvanite, hessite, petzite, altaite and calaverite have also been reported. Reef minerals most closely associated with gold, and regarded as favourable indications of ore are tourmaline, green hydromica, sericite, carbonates, galena and arsenopyrite.

The reef shears, whether barren or quartz-filled, generally occur within an envelope of strongly altered greenstone locally known as the "reef channel", which

varies in thickness up to 100 feet. The altered zone consists of biotite schist or schistose chlorite-tremolite-actinolite-carbonate rock. The tremolite-actinolite occurring in the altered "reef channels" tends to be more acicular in habit than the variety which pseudomorphously replaces pyroxene in the regionally metamorphosed greenstones. Within two feet of the reef the wall-rocks are often highly silicified. The schistosity is generally parallel to the reef, but locally the reef may cut across the foliation. It is thought that the alteration is the result of shear stresses and metasomatic activity that affected zones of weakness and shearing throughout the area and preceded the deposition of quartz. Hence, the development of biotite and tremolite-actinolite-chlorite-carbonate schists is not in itself indicative of reef channels. The only metasomatic activity directly related to ore deposition was minor carbonate and sulphide impregnation of the adjacent wall-rocks.

5. Ore Controls.

As mentioned earlier, ore shoots and sections of barren quartz were developed in flatter sections of the reef shears, where reverse faulting had created tensional openings. This relationship between reef attitude and ore occurrence was convincingly demonstrated by Connolly (1936). The irregularities in the dip of the reef shears are probably due to refraction of the shear zone as it passes through rocks of differing competence. King (1950)

postulated a stratigraphic control for the ore occurrences. It was shown that the flat northerly pitch of the ore zones coincided with the pitch of the intersections of the stratigraphy on the reef shears. This theory is apparently supported by the occurrence of ore on Princess Royal, Bluebird and Crown Reefs, adjacent to the base of the Bluebird Gabbro. Although exploration based on the "Favourable Bed Hypothesis" has resulted in the discovery of several new ore-shoots, it does not appear to be valid in all cases. Petrological work has shown that there is no distinctive stratigraphic control for Mararoa Reef and what seems to be a favourable zone on one reef is not always productive on adjacent reefs.

Hall and Bekker (1965) have pointed out that all the ore-shoots developed in the last 5 years occur in the deuterically altered zones in gabbroic dykes (Fig. 8). The quartz reefs are slightly transgressive to the dykes, the intersections pitching flatly south. The individual ore-shoots also pitch gently south and so it is probable that the presence of dykes has influenced the development of the south-pitching fracture system occupied by the ore-shoots.

The intersections of the NNW-trending faults with the reef channels also pitch flatly south and have influenced ore-shoot development to some degree. Hall and Bekker (1965) also consider the faults which delimit the ore zones on Crown and Princess Royal Reefs to be significant. The

productive areas on both reefs are terminated on their northern ends by NNW-trending faults, and up-dip, by normal faults which strike NNE and dip at right-angles to the reef.

It is clear from the above that many factors are involved in the control of ore deposition at Norseman. The detailed study of these factors is still in progress.

B. PRIMARY TRACE ELEMENT DISTRIBUTION IN THE WALL-ROCKS IN THE VICINITY OF GOLD-QUARTZ REEFS AT NORSEMAN.

1. Preliminary Investigation.

In the early stages of the investigation, samples from two diamond drill-holes, both intersecting the Crown Reef, were analysed for 18 elements in order to determine:

(i) those elements which show anomalous concentration in the wall-rocks adjacent to the quartz reef,

(ii) the width and general form of wall-rock anomalies.

Ag, Bi, Co, Cr, Cu, Ga, Mn, Mo, Ni, Pb, Sn, Ti, V, and Zr were determined spectrographically whilst As, Zn, Au, and Sb were determined by the chemical methods indicated in Chapter 3. Fig. 10 (a and b) shows the results for C12, a diamond drill-hole intersecting low grade quartz on the margin of a major ore-shoot. The abbreviations and symbols used in figures relating to primary dispersion studies are shown in Fig. 9. The nature of the distribution patterns for the various elements are summarized in Table 8.

ROCKS

MB	METABASALT	SCH	SCHIST
MD	METADOLERITE	P	PORPHYRY
MG	METAGABBRO	GN	GNEISS
AMP	AMPHIBOLITE	SL	SLATE

MINERALS

ac	ACTINOLITE	asp	ARSENOPYRITE
ch	CHLORITE	py	PYRITE
bi	BIOTITE	po	PYRRHOTITE
ca	CARBONATE	tn	TENNANTITE
qtz	QUARTZ STRINGERS	si	SILICIFICATION

GRAIN SIZE

Fg	FINE GRAINED (<1mm)
Mg	MEDIUM GRAINED (1-5mm)
Cg	COARSE GRAINED (>5mm)

SHEARING



WEAK



MODERATE



STRONG

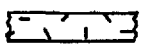
OTHER FEATURES



BLEACHING (MOD. TO STRONG)



QUARTZ VEIN



FRACTURING

Fig. 9. Abbreviations and symbols used in figures relating to primary dispersion studies.

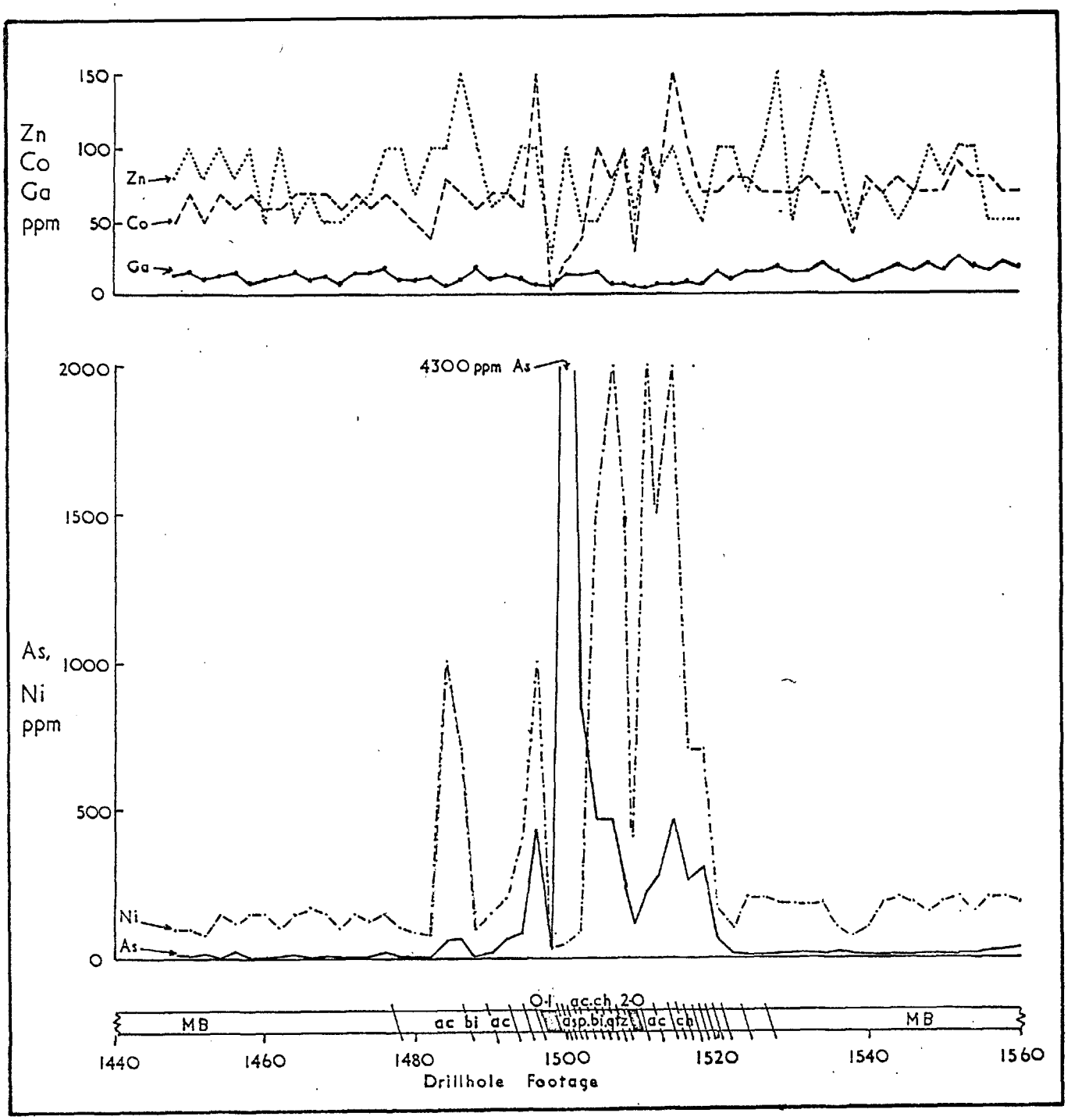


Fig. 10a. Distribution of As, Ni, Ga, Co & Zn in D.D.H. C12, Crown Reef, Norseman.

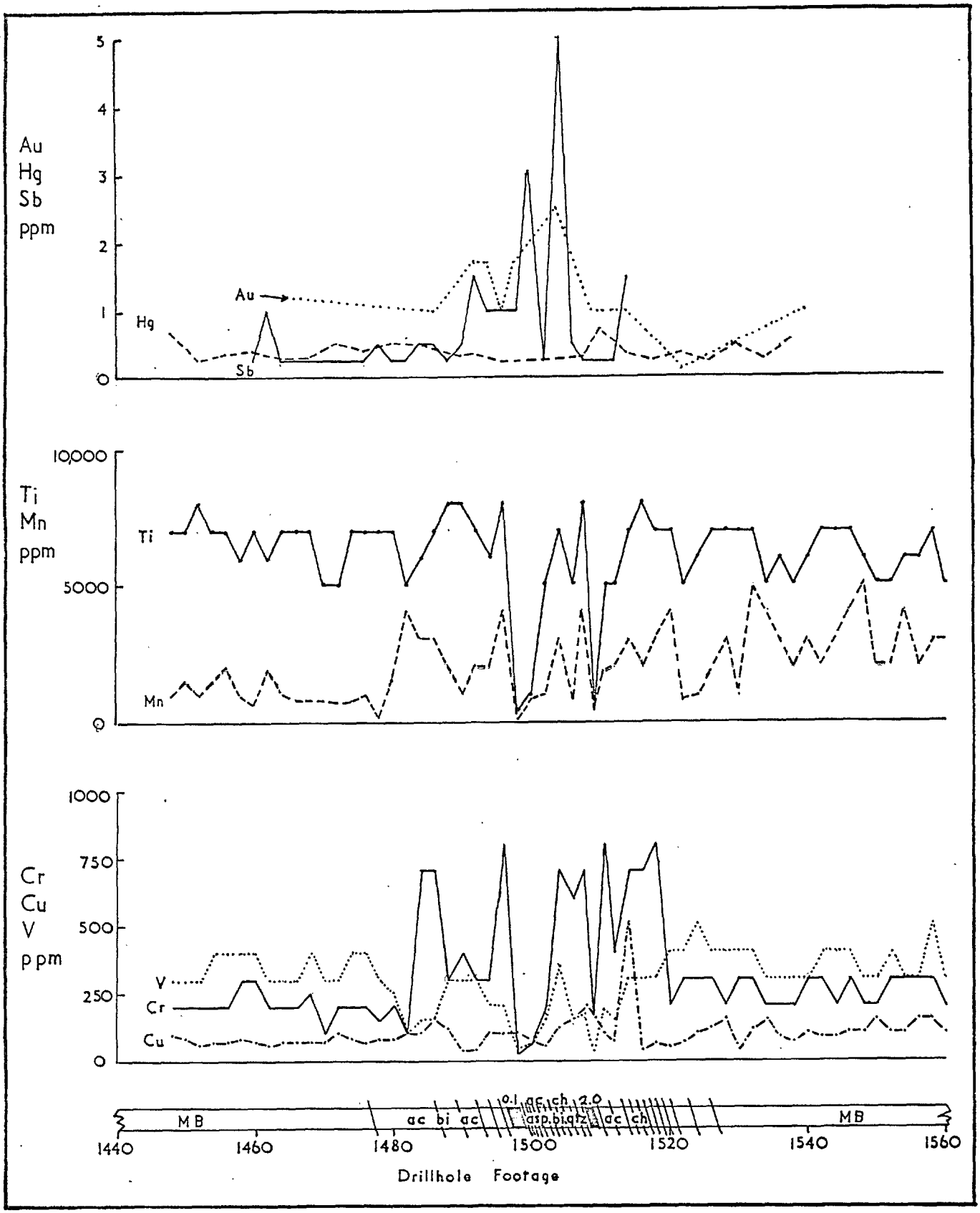


Fig. 10b. Distribution of Au, Hg, Sb, Ti, Mn, V, Cr & Cu in D.D.H. C12, Crown Reef, Norseman.

TABLE.8.

Nature of Distribution of Trace Elements in DDH C12, Norseman

Elements	Remarks.
As, Ni	Strong wall-rock anomaly approx. 40 feet wide surrounding quartz intersections.
Cr	Moderately strong but erratic anomaly, approx. 40 feet wide surrounding quartz intersections.
Co, Cu, Mn, Zn, Sb, Au,	Weak erratic anomalies consisting of one or more high samples in general vicinity of quartz reef. Mn anomaly persists more than 50 feet in footwall.
Ga, Ti, Mg,	No significant variation in vicinity of quartz apart from low Ti content of quartz itself.
V	Negative anomaly or "trough" in a position corresponding to the positive As, Ni and Cr anomalies.
Ag, Bi, Mo, Sn, Zr,	Less than limits of detection (see Appendix) throughout traverse.

Fig.. 11 (a and b) shows the trace element distribution found in CU 15, an underground diamond drill-hole intersecting Crown Reef at a point where the quartz

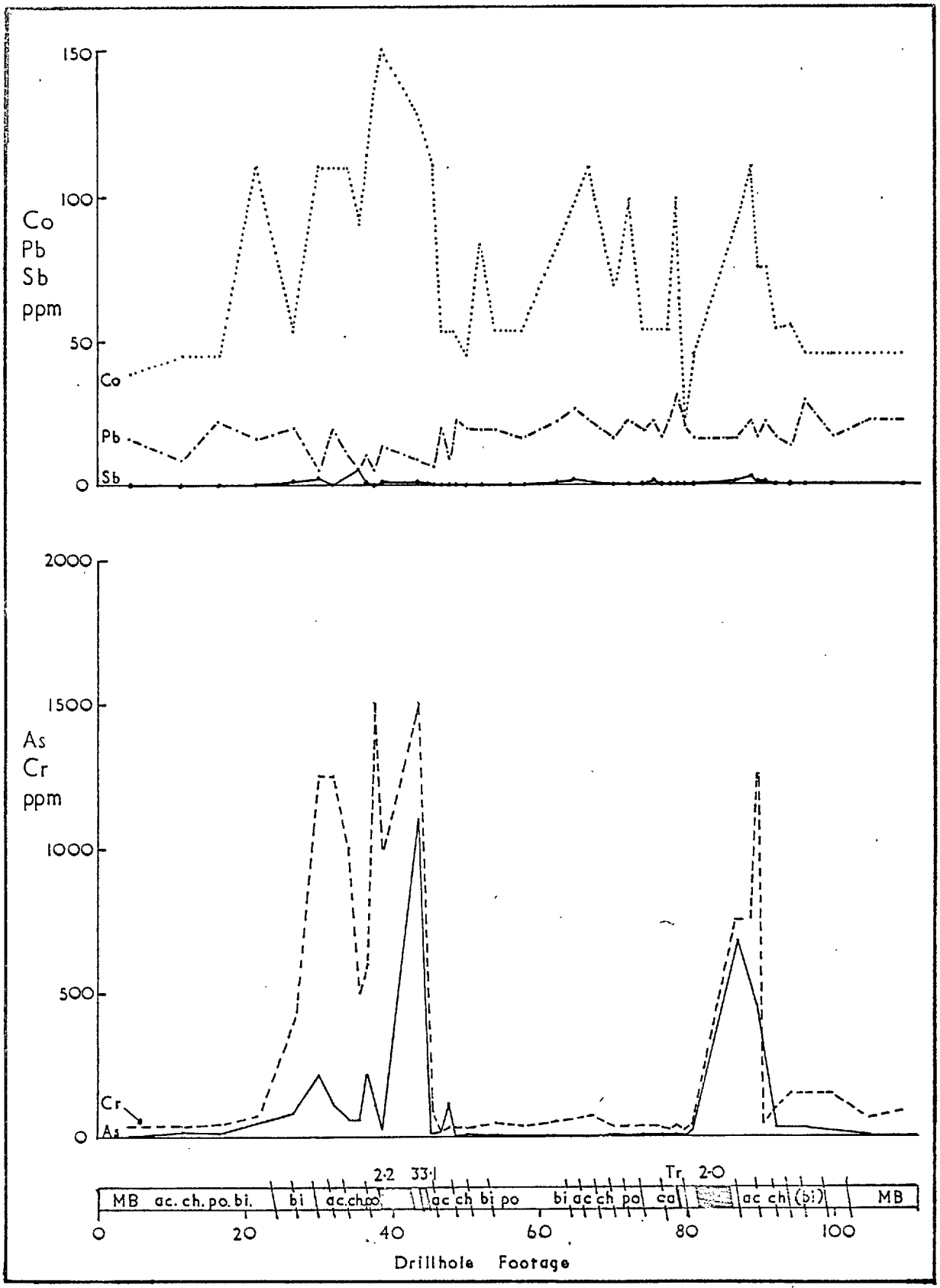


Fig. IIa. Distribution of As, Cr, Sb, Pb & Co in D.D.H. CU15, Crown Reef, Norseman.

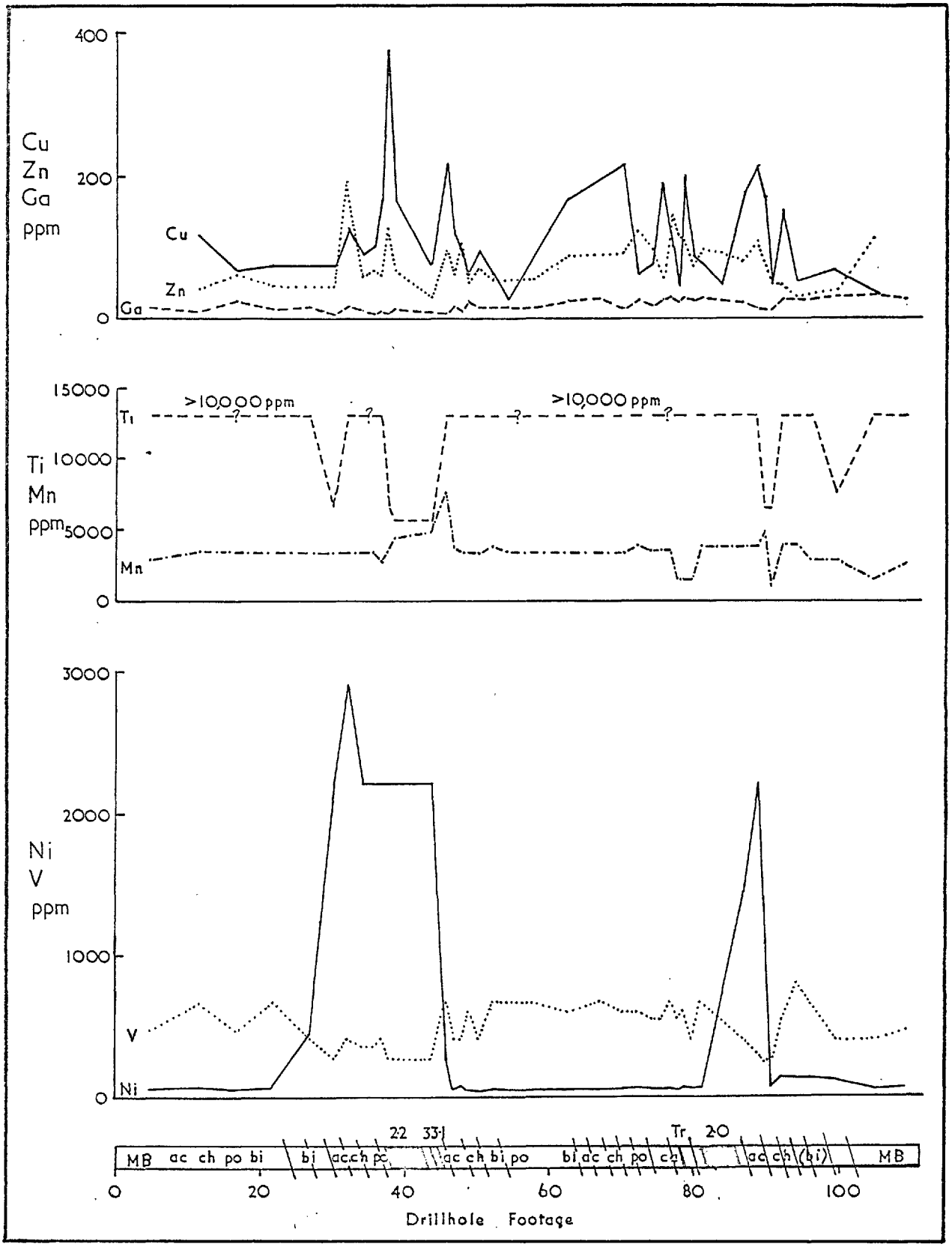


Fig. IIb. Distribution of Ni, V, Mn, Ti, Ga, Zn & Cu in D.D.H. CU15, Crown Reef, Norseman.

has locally split into a hanging-wall and a footwall reef. The salient features of the distribution are given in Table 9.

TABLE. 9

Nature of Distribution of Trace Elements in DDH CU 15, Norseman.

Elements	Remarks.
As, Ni, Cr.	Strong anomalies totalling nearly 40 feet in width about the two quartz intersections.
Cu, Zn, Co.	Moderate to strong, erratic anomalies with one or more high samples in the vicinity of quartz intersections.
Mn, Sb.	Weak anomalies in the vicinity of quartz intersections. Levels of concentration very low in the case of Sb.
Ga, Pb.	No significant variation in vicinity of quartz.
V ± Ti.	Weak negative anomalies in vicinity of quartz intersections.
Ag, Bi, Mo, Sn, Zr.	Less than limits of detection throughout traverse.

The results of this preliminary investigation indicated that wall-rock anomalies are best shown by analysing samples for As, Ni and Cr. In subsequent studies of wall-rock dispersion, emphasis has been placed on the distribution of these elements. It is of interest to note that the concentrations of many elements (As, Ni, Cr, Zn, Co, Ti, Mn, V) are significantly lower in quartz samples than in the wall-rocks.

2. Background Data for Norseman Rocks.

a) Distribution of trace elements in unmineralized Norseman rocks.

Knowledge of the trace element contents of background rocks, unaffected by mineralization, is essential for the interpretation of primary geochemical anomalies. For this purpose, 90 samples of the vaious rock-types occurring in the area were collected and analysed.

Owing to the poor outcrop and weathering of rock exposures, the samples were necessarily obtained from drill-core. Care was taken to ensure that only unaltered rocks were sampled, avoiding as far as possible the zones affected by primary dispersion, which appear to be restricted to within 100 feet of mineralized reef-shears.

The range of concentrations and arithmetic means for 11 elements in the main rock-types occurring in the productive belt are given in Table 10. Apart from As and Zn, for which chemical techniques were used, spectrography was used for all determinations. Ag, Bi, Mo, Sn, and Zr, were found to be below the limits of detection of the

TABLE. 10

Trace Element Contents of Unmineralized Norseman Rock-Types.

Rock-Type	As ppm	Pb ppm	Cu ppm	Zn ppm	Ga ppm	Ni ppm	Co ppm	Mn ppm	Cr ppm	V ppm	Ti ppm
Metabasalts (34 samples)	<0.5 (7) 27	<2 (4) 7	10 (115) 500	50 (95) 250	7 (15) 30	40 (131) 350	25 (71) 150	800 (1670) 7000	70 (286) 500	80 (307) 700	1500 (7600) >10,000
Metadolerites (19 samples)	<0.5 (5) 33	2 (4) 15	70 (147) 700	<50 (111) 250	10 (18) 30	30 (111) 200	50 (69) 100	800 (1820) 5000	30 (235) 400	250 (445) 700	5000 8100 >10,000
Metagabbros (22 samples)	0.5 (7) 24	1 (10) 150	40 (180) 500	50 (139) 200	7 (17) 30	30 (119) 250	30 (78) 200	700 (1880) 5000	15 (158) 300	120 (435) 700	190 (8900) >10,000
Porphyries (10 samples)	1 (169) 1200	4 (23) 40	7 (48) 170	<50 (72) 150	8 (23) 35	<5 (14) 80	<5 (9) 60	100 (278) 1000	5 (31) 200	<5 (28) 200	350 (1355) 4000
Slaty Sediments (5 samples)	<1 (16) 64	4 (7) 12	70 (410) 800	100 (200) 400	10 (16) 30	40 (126) 300	50 (96) 180	300 1500 4000	50 (90) 150	80 (316) 800	3000 (6000) >10,000

Key: 0.5 - Minimum value
(7) - Arithmetic mean
27 - Maximum value.

spectrographic method employed in all but a few samples.

Although the main object of this study was the determination of threshold for geochemical prospecting purposes, the results also provide some interesting information regarding the geochemical characteristics of the different rock-types present. This aspect is dealt with more fully in the discussion at the end of this chapter, but some features require mention in the present section.

The trace element variations occurring between the various basic igneous rock-types are relatively minor with regard to geochemical prospecting but have nevertheless been taken into account in calculating threshold values. Slates, although somewhat higher in the chalcophile elements As, Cu, and Zn, and lower in Cr, are generally similar in their trace element contents to the basic igneous rocks. On the other hand, porphyries, which are relatively common in the productive belt, show a number of outstanding differences in trace element content, which may affect the interpretation of geochemical data, especially in soil surveys in areas of poor outcrop, where the bedrock geology is not known. Apart from the fact that Ni and Cr are generally much lower in porphyries than in the other rock-types, some porphyry samples, seemingly unrelated to reef-shears, were found to contain abnormally high concentrations of arsenic. Of the ten porphyry samples analysed, seven

had arsenic contents of 30ppm or less. The remaining three contained 130, 280 and 1200ppm respectively. Evidence presented in a later section suggests that the arsenic occurring in these supposedly background samples was present at the time of porphyry emplacement and was not introduced by the later hydrothermal emanations that accompanied ore-formation. It should be mentioned, however, that although the arsenical porphyry samples all occurred some distance from reef-shears, there is believed to be a genetic relationship between the porphyries and gold-quartz mineralization (Bekker, 1962).

b) Threshold for As, Ni, and Cr in basic igneous rocks.

It was established earlier that the most important elements with regard to wall-rock anomalies related to gold mineralization at Norseman are As, Ni and Cr. It has become a common convention to specify threshold, or upper limit of background fluctuations, as the mean plus two standard deviations of the distribution obtained by analysing background samples. However, it is only possible to apply this criterion in the case of normal or lognormal distributions. Frequency histograms for As, Ni and Cr in background rocks from Norseman are plotted in Figs. 12, 13 and 14. In most cases, the distribution patterns are seen to be neither normal nor lognormal. The results for the different elements are considered in greater detail below.

(i) Arsenic.

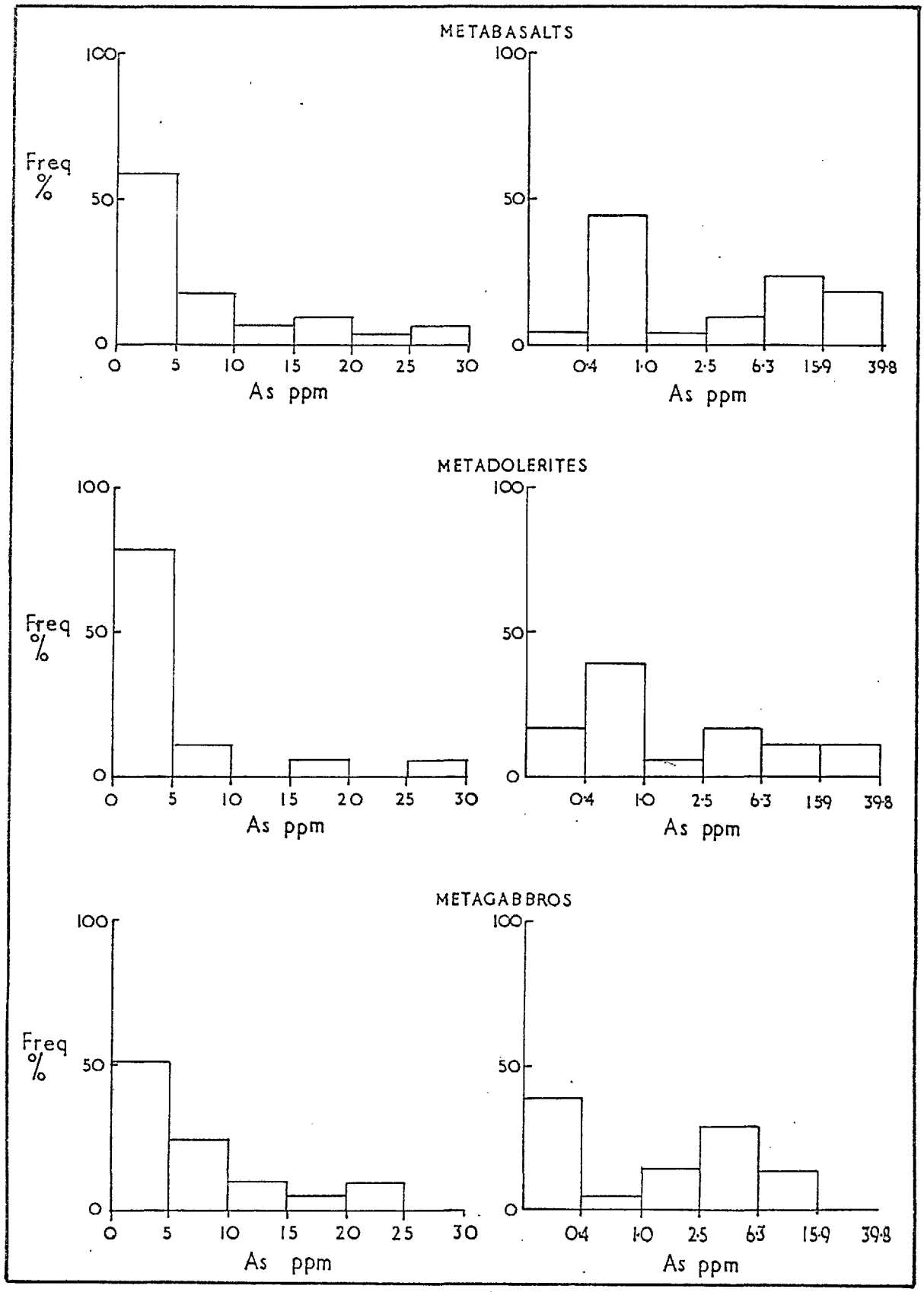


Fig. 12. Frequency distribution of arsenic in basic meta-igneous rocks, Norseman.

The histograms for arsenic plotted on an arithmetic scale exhibit a pronounced positive skew. This feature is attributable to two causes:- the inadequacy of the analytical method to give accurate results below 1 ppm, and the possible accidental inclusion of some anomalous samples with the background material. The first cause is self-explanatory in view of the high proportion of samples with As contents of less than 1 ppm. The bimodal distributions obtained when the data is plotted on a logarithmic scale support the conclusion that some anomalous material has unwittingly been sampled. The histogram peaks in the lower range of arsenic contents (0-1 ppm) probably represent regional background whilst the peaks corresponding to arsenic contents in the range 2.5 -16 ppm are believed to represent a local background appropriate to the broad mineralized environment.

It is worth noting that Onishi and Sandell (1955) obtained similar skewed frequency distributions for arsenic in unmineralized igneous rocks. These authors attribute the occasional arsenic-rich samples to the high mobility of arsenic which therefore tends to be localllized in the upper levels of the crust in concentrations not typical of the crust as a whole. Such local concentrations are even more probable at Norseman, since it is known to be a centre of arsenical hydrothermal activity.

Calculations of standard deviation are meaningless

when applied to such distributions. Smirnov (1963) has suggested the approximation below for establishing a threshold value:

Threshold = (2 to 3) x mode.

The modes for the arsenic distribution in metabasalts, metadolerites and metagabbros have been calculated at 1.6, 0.5 and 2.5 ppm respectively. Hence, by Smirnov's method, threshold would be 4.0, 1.3 and 6.3 ppm. respectively for these rock-types.

(ii) Nickel.

The frequency histograms of background nickel contents are similar to those of arsenic, showing strongly skewed distributions when plotted on an arithmetic scale and bimodal distributions on a logarithmic scale. An exception is noted in the case of the metabasalts, where the semi-logarithmic histogram shows a more nearly normal distribution than that of the arithmetic plot. In this case, threshold can be calculated on the basis of the right hand limb of the distribution curve, giving a result of 185 ppm Ni for metabasalts. Using the method of Smirnov op. cit., the threshold values for various greenstones would be in the ranges:

metabasalts	170 - 225 ppm Ni.	Mean 200 ppm Ni.
metadolerites	130 - 200 ppm Ni.	Mean 165 ppm Ni.
metagabbros	160 - 240 ppm Ni.	Mean 200 ppm Ni.

(iii) Chromium.

The distribution of chromium in metabasalts is

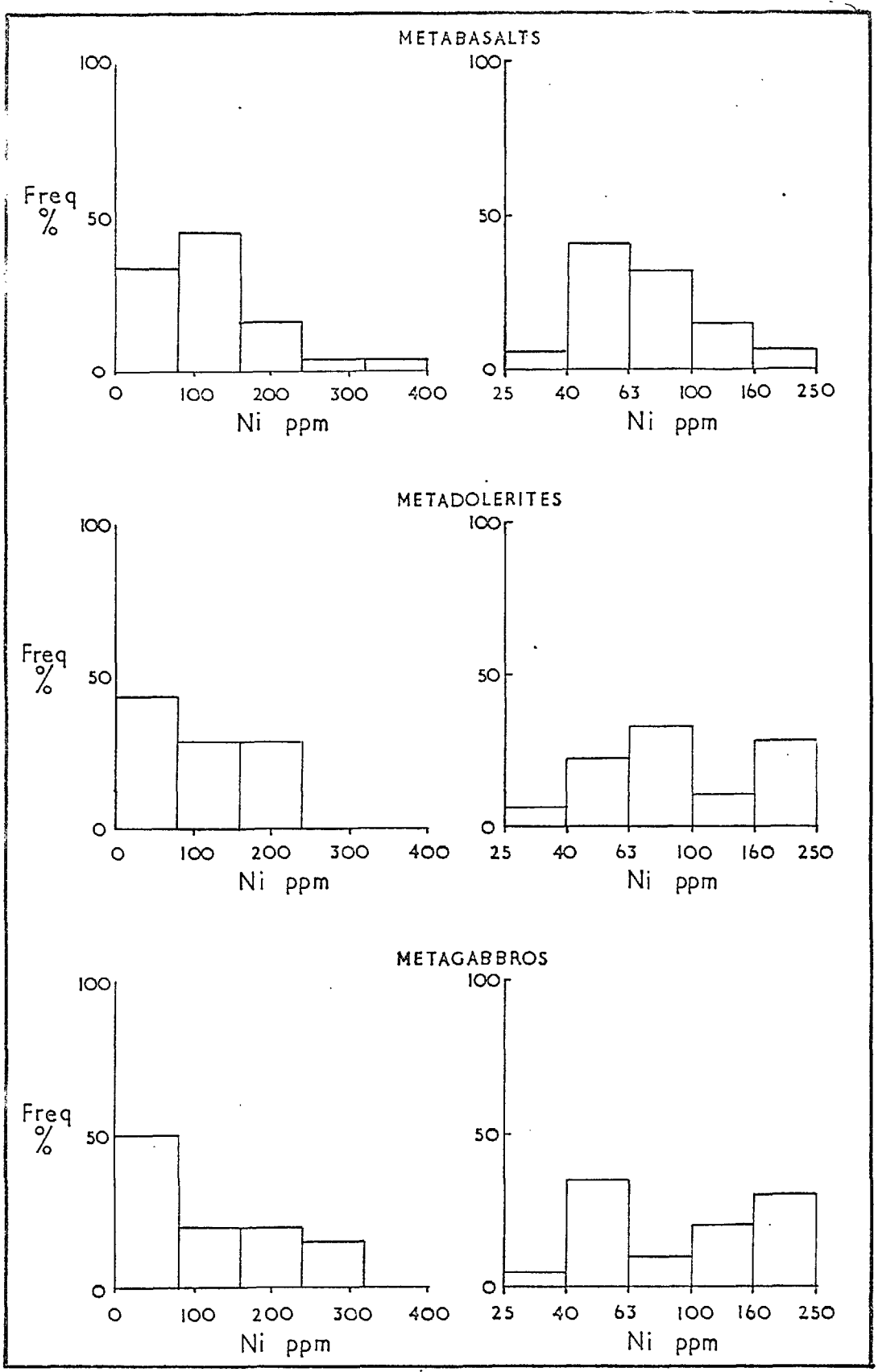


Fig.13. Frequency distribution of nickel in basic meta-igneous rocks, Norseman.

approximately normal and threshold calculated on this basis is 480 ppm. The distributions in the case of metagabbro and metadolerite are bimodal and no attempt has been made to calculate threshold. Visual inspection of Fig. 14 suggests a value of 350 ppm would be appropriate for both rock-types.

(iv) Local threshold.

The foregoing has shown that the frequency distribution patterns of arsenic, nickel and chromium in background samples are, in general, not mathematical in form, making the calculation of threshold difficult. Examination of geochemical profiles of wall-rock traverses, to be described later, shows that it is possible to select arbitrary "local" threshold values which provide a more suitable basis for the estimation of anomaly contrast. The arsenic anomalies associated with Norseman reef-shears are generally quite distinct (e.g. Fig. 10), the arsenic content of the wall-rocks in the immediate vicinity of the reef-shear intersection ranging from 20 to several thousand ppm. Beyond this anomalous zone, the arsenic content of the rocks fluctuates between 1 and 15 ppm, with occasional values of up to 20 ppm. 15 ppm would therefore appear to be a suitable local threshold level, expressing the normal upper limit of background fluctuation in the vicinity of reef-shears. This figure corresponds approximately with the value suggested on the basis of the bimodal frequency distribution. Similarly, local threshold values for nickel and chromium have been obtained. The local threshold

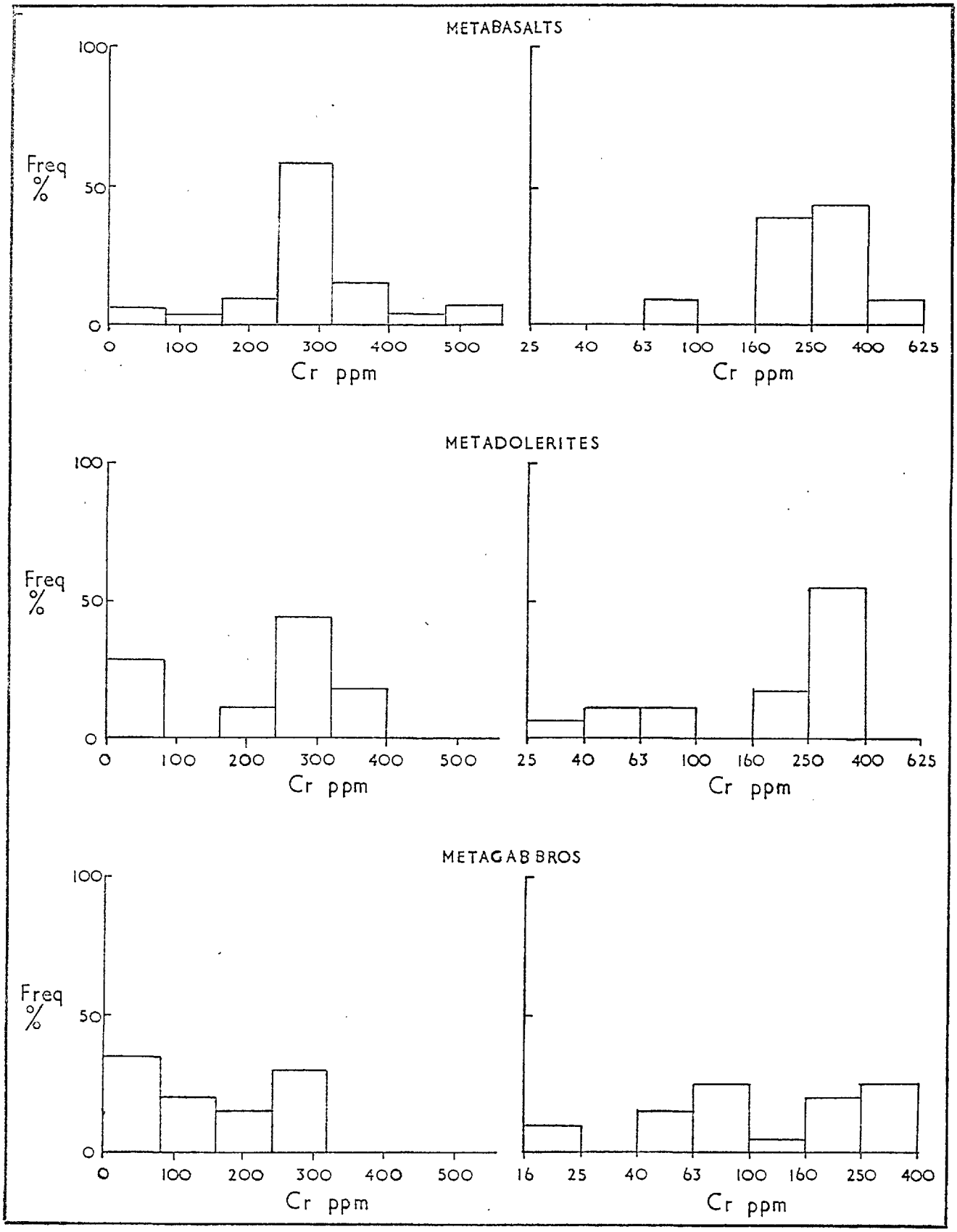


Fig. 14. Frequency distribution of chromium in basic meta-igneous rocks, Norseman.

values for arsenic, nickel and chromium, obtained by inspection, are compared in Table 11 with the threshold values calculated on the basis of studies of background samples. The local threshold values have been used in the ensuing sections for the calculation of contrast.

TABLE.11.

Regional and Local Threshold Values for Arsenic, Nickel and Chromium in Norseman Greenstones.

Rock-Type	Element	A. Regional Threshold	B.Local Threshold
Metabasalts	As	4.0	15
	Ni	185	250
	Cr	480	300
Metadolerites	As	1.3	15
	Ni	165	250
	Cr	(350)	300
Metagabbros	As	6.3	15
	Ni	200	250
	Cr	(350)	300

3. Wall-rock Anomalies Associated with Crown Reef-Shear.

a) General.

Crown Reef is the most recently discovered of the reefs in the area. It differs from the other N-S reefs in its more north-easterly strike and somewhat flatter dip (20°E). Several very small, low-grade ore-shoots outcrop at the northern end but these were worked out in the

early days of the field. The major blind orebodies were located by diamond drilling from the surface. Since then, a number of large ore-shoots have been outlined by underground development. It can be seen from Fig. 15, that the intersection of the Bluebird Gabbro on the reef-shear appears to have had an important controlling effect on the location of ore-shoots. This reef was considered to be ideally suited to a detailed primary geochemical investigation for two main reasons.

(i) The geology of the Crown Reef is the least complicated of the N-S reefs being worked at present.

(ii) Drill-core was available for sampling from numerous drill-holes, well-situated for use in such a study.

The locations of drill-holes sampled are shown in relation to known ore-shoots on a composite plan of Crown Reef in Fig. 15, which also shows the major geological features. Two east-west surface drilling traverses, one intersecting ore in several holes (4400N traverse) and one which intersected no ore (2000N traverse), were sampled in some detail to study the variation in wall-rock dispersion patterns down the dip of the reef-shear. Additional drill-holes were sampled so that the variation in dispersion patterns could be studied over a total strike length of more than 12,000 feet. A number of drill-holes in close proximity to one specific ore-shoot (A on Fig. 15) were sampled to establish the nature of wall-rock patterns adjacent to ore grade quartz,

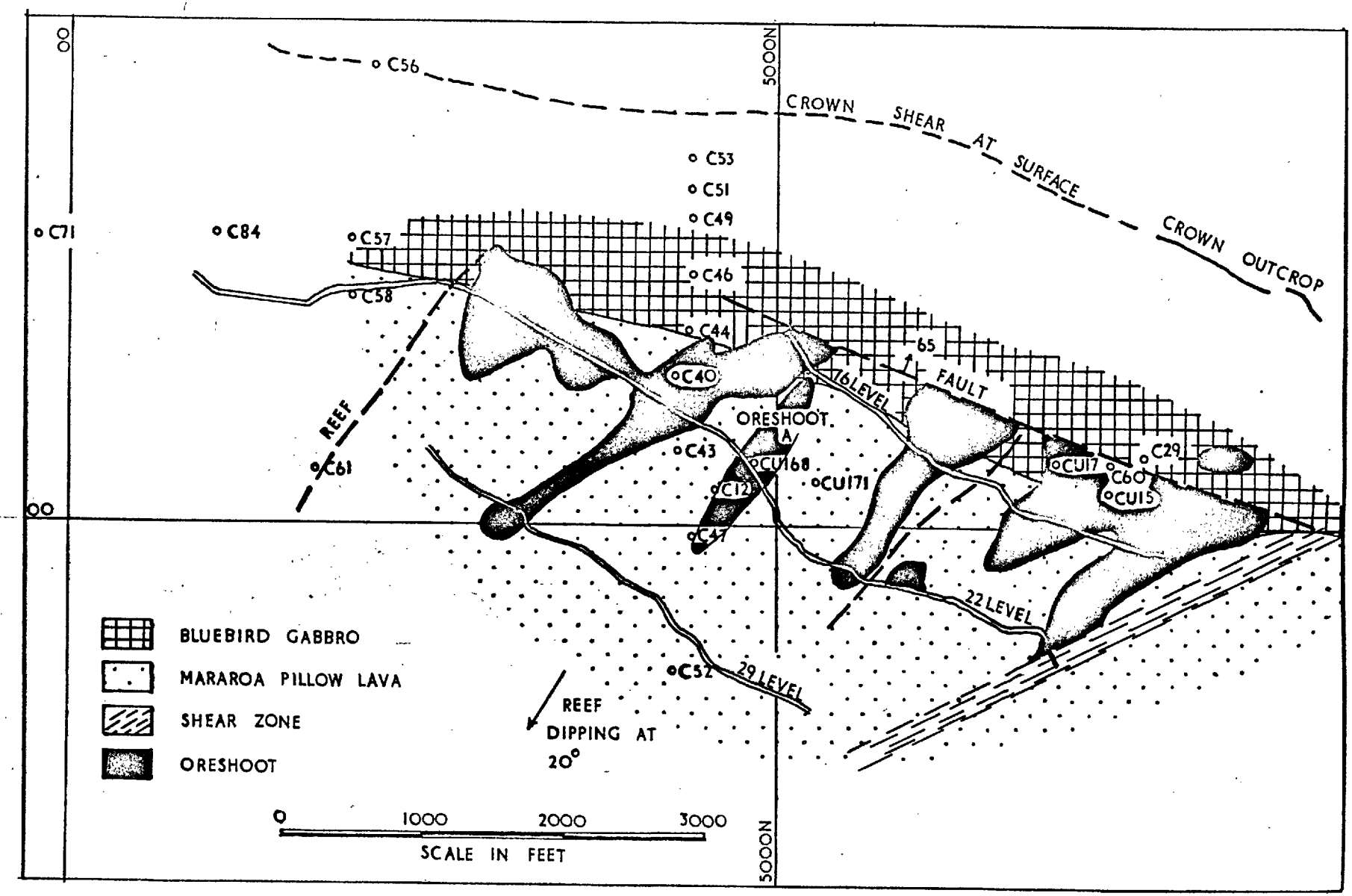


Fig. 15. Composite plan of Crown Reef, Norseman, showing major geological features and D.D.Hs. sampled (after Hall and Bekker, 1965).

subeconomic quartz and barren shear in a restricted environment. This study was linked with an investigation of the distribution of trace elements within the plane of the quartz reef about the same ore-shoot.

b) Wall-rock anomalies on Crown Section at 4400N.

The location of the diamond drill-holes sampled, and the geology of the 4400N section are shown in Fig. 8. The known ore zone on this section occurs between the intersections of C47 and C44. However, C40 is the only drill-hole which actually intersected an ore-shoot, C47, C43 and C44 intersecting low grade quartz near to the margins of ore-shoots (Fig. 15). Some minor pockets of ore have been outlined by underground development in the general vicinity of C52. The remaining holes, C46, C49, C51 and C53, encountered only low grade quartz or barren shear.

The distribution of arsenic in the wall-rocks adjacent to Crown Reef-Shear in the drill-holes sampled, is shown in Figs. 16, 17 and 18. Distinct arsenic anomalies were obtained in each case, peak values ranging from 290 to 2125 ppm As. The highest arsenic contents ($>$ 600 ppm) were found to occur in drill-holes intersecting, or in close proximity to, ore-shoots and up to 1600 feet up-dip from the ore zone (C47, C40, C44, C46, C49 and C51). C52, 1000 feet down-dip from the known lower limit of the ore zone, and C43, intersecting low-grade quartz within the ore zone, have peak arsenic contents of 357 ppm and 290 ppm As

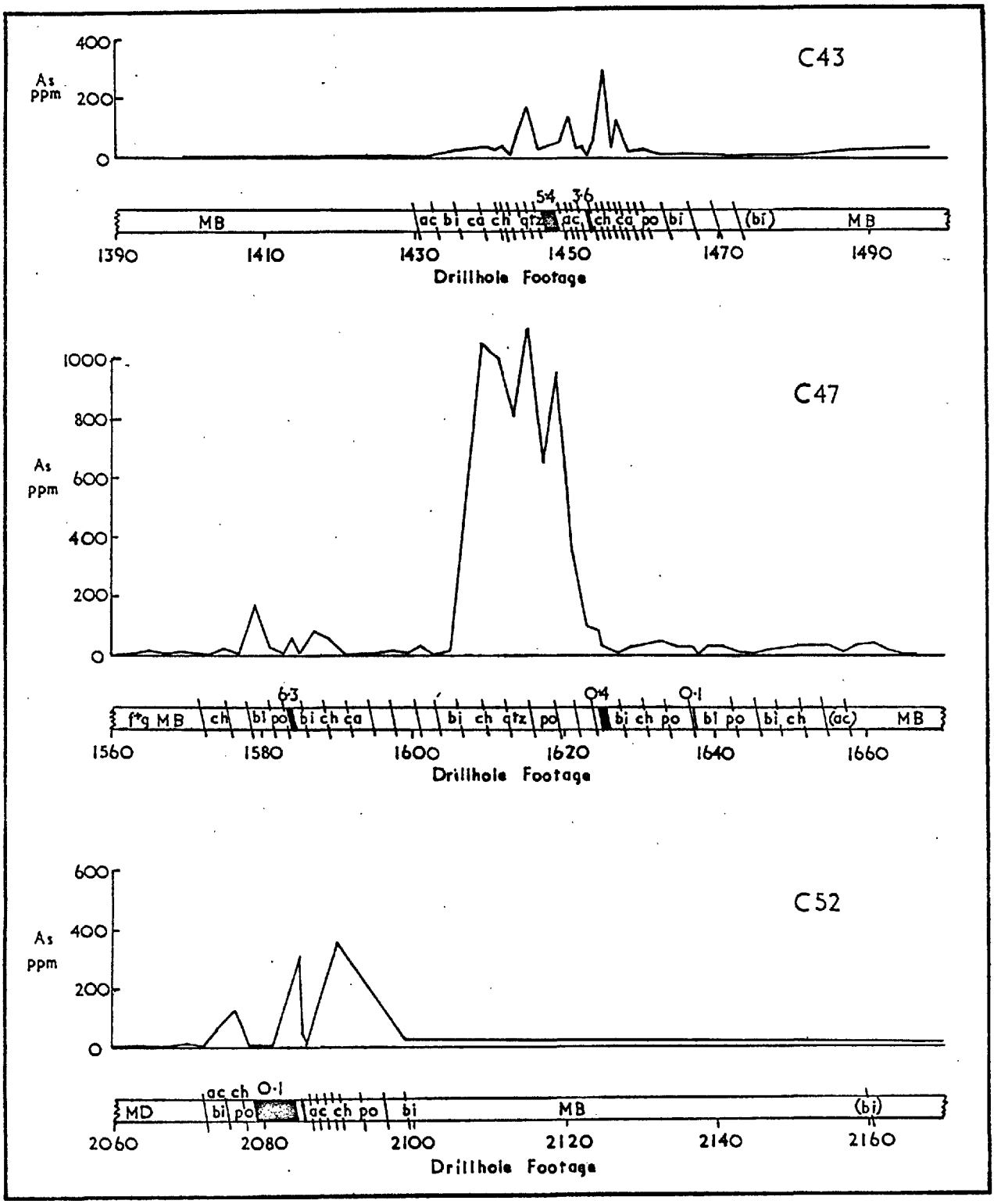


Fig. 16. Distribution of arsenic in D.D.Hs. C52, C47 & C43, Crown Reef-Shear, Norseman.

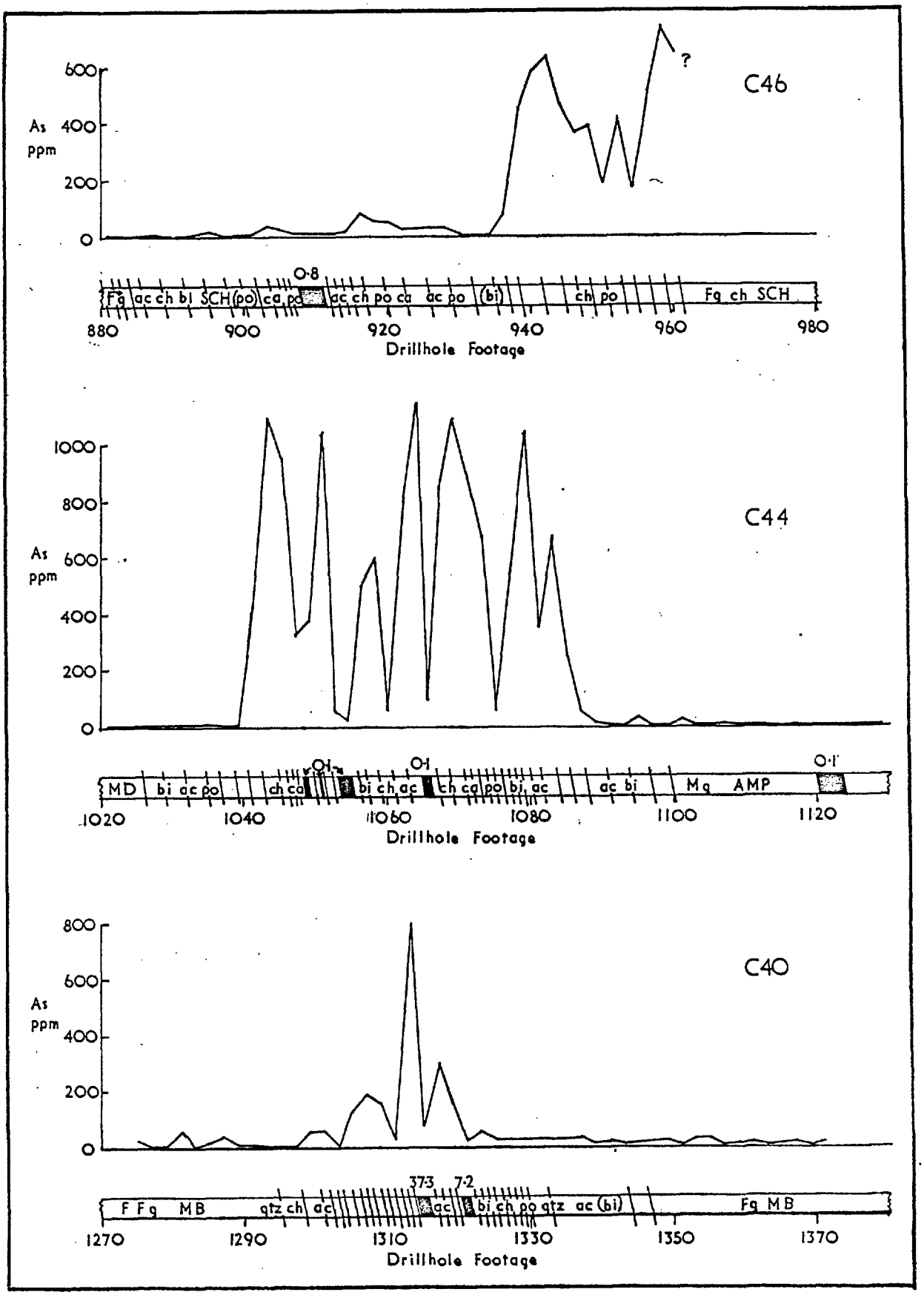


Fig. 17. Distribution of arsenic in D.D.Hs. C40, C44 & C46, Crown Reef-Shear, Norseman.

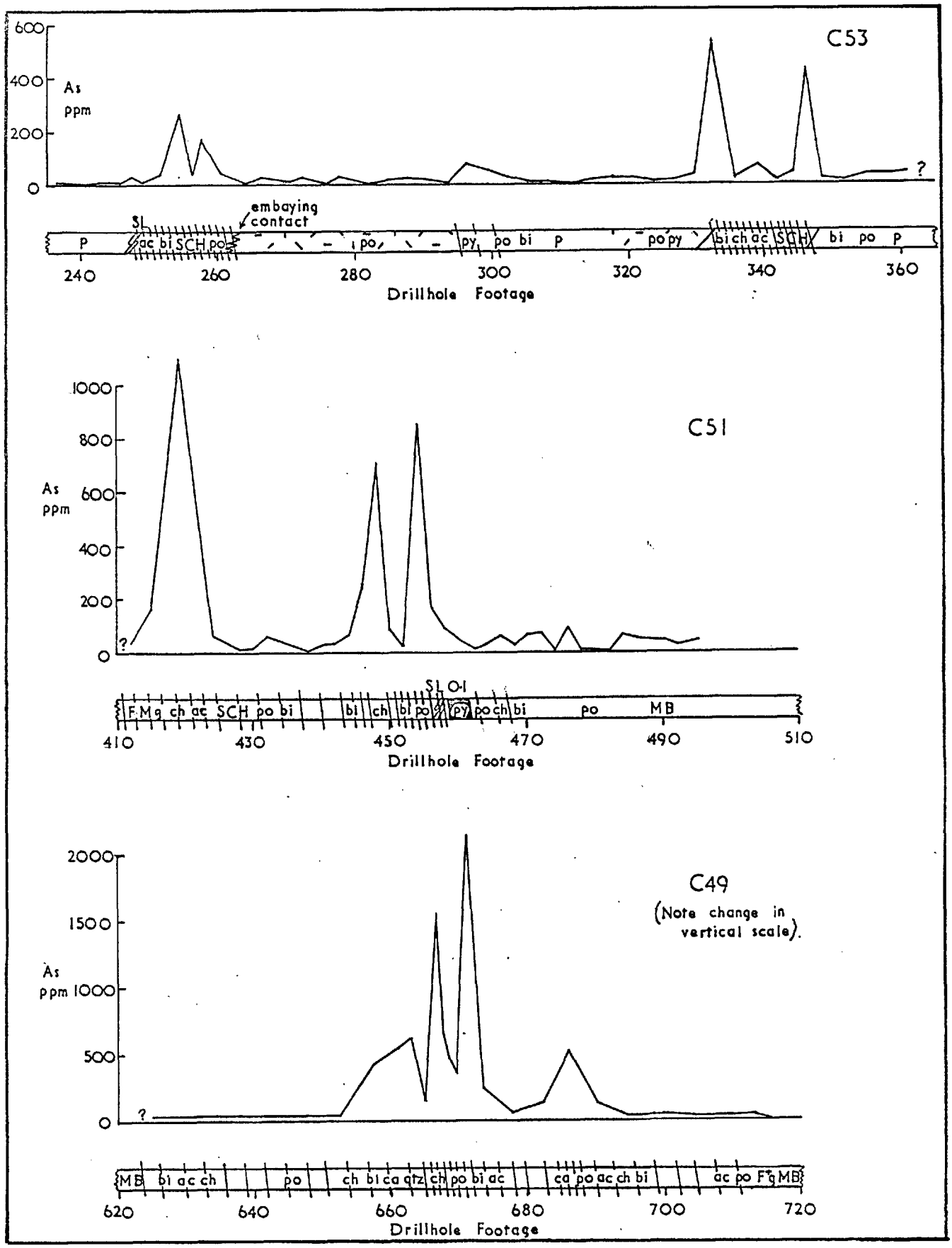


Fig. 18. Distribution of arsenic in D.D.Hs. C49, C51 & C53, Crown Shear, Norseman.

respectively. Two strongly anomalous zones, were found to occur in C53, coinciding with greenstone remnants within the felsite porphyry, which is the dominant rock-type occurring in this hole.

The widths of the anomalies in the drill-core are, for the most part, between 50 and 100 feet. However, the anomaly in the case of C43 is only 24 feet wide, whilst in C53, erratic anomalous values were obtained over a total width of more than 118 feet. The general pattern obtained is one of a broad zone, or "plateau" of values between 15 and 70 ppm As, from which arise one or more peaks of higher arsenic content. The full extent of the anomalies in some drill-holes (e.g. C53, C51, C49, C46 and possibly C43) was not established due to the fact that sampling was not extended sufficiently far into the wall-rocks.

The results obtained for C40 were confirmed by analyses of samples from two underground diamond drill-holes (CU335 and CU336), which were drilled from a rise at a point very close to the intersection of C40 on Crown Reef. The results for these two holes disclosed an anomaly greater than 50 feet in width with a peak value of 800 ppm As.

A limited study of the distribution of nickel and chromium was undertaken by analysing 122 samples selected in the vicinity of the peaks of the arsenic anomalies in each traverse. The results are summarized in Table 12. In

TABLE. 12

Data Relating to Trace Element Anomalies

Associated with Crown Reef-Shear. 4400N Section, Norseman.

D.D.H.	Element	Peak Value ppm	Contrast	Width. ft.	Sample Description
C52	As	357	24	64	F-M.g. actinolite-chlorite schist
	Ni	2500	10		Schistose M.g. actinolitic greenstone
	Cr	1100	3.7		ditto
C47	As	1100	73	90	Schistose, silicified chloritic greenstone
	Ni	1100	4.4		ditto
	Cr	1470	4.9		Schistose F.+g. chloritic greenstone
C43	As	290	19	24	F-M.g. actinolite-chlorite schist, carbonate bands
	Ni	3000	12		C.g. actinolite-chlorite schist.
	Cr	5000	17		M.g. actinolite-chlorite schist.
C40	As	800	53	58	F+g actinolite-chlorite schist
	Ni	1500	6.0		ditto
	Cr	800	2.7		ditto
C44	As	1150	77	62	Actinolite-chlorite schist
	Ni	900	3.6		ditto
	Cr	1170	3.9		ditto
C46	As	750	50	58+	Schistose F.+g. chloritic greestone
	Ni	860	3.4		ditto
	Cr	1100	3.7		ditto (streaky pyrrhotite)
C49	As	2125	140	82+	Chlorite-biotite, schist, quartz stringers
	Ni	1800	7.2		F.g.chlorite schist, quartz stringers
	Cr	870	2.9		F.g.chlorite schist (pyrrhotite).
C51	As	1100	73	88+	F-M.g.chlorite-actinolite-carbonate schist
	Ni	3000	12		Schistose F.-M.g.chloritic greenstone
	Cr	700	2.3		ditto
C53	As	526	35	118+	F+g biotite-carbonate schist (pyrrhotite)
	Ni	360	1.4		Porphyritized biotite-actinolite schist
	Cr	830	2.8		ditto

Calculated as the ratio:- Peak Value: Local Threshold.

(Local Thresholds as given on p. 72).

general, the peak Ni and Cr contents occur in the ranges 830 - 3000 ppm Ni and 700-5000 ppm Cr. The maximum value of 360 ppm Ni encountered in C53 is exceptionally low compared with other drill-holes on the 4400N section. A notable feature is the fact that, in most drill-holes, the highest As, Ni and Cr contents do not coincide but occur at different points in the traverse. The results for nickel and chromium must be considered to some extent provisional because of the selective nature of the study.

The characteristics and relationships to geological features of the anomalies described in the above and following sections, will be discussed in more detail in a later part of this thesis.

c) Wall-rock anomalies in the vicinity of ore-shoot A.

A number of drill-holes were sampled to obtain information concerning trace element distribution in the wall-rocks adjacent to, and in the vicinity of, ore-shoot A (Fig. 15). The dispersion pattern adjacent to ore-grade quartz was obtained from samples from CU168 and CU169, two inclined holes collared at a point near the centre of the ore-shoot. An arsenic anomaly approximately 40 feet in width, with a peak value of 510 ppm As, was found to be present (Fig. 19). Diamond drill-holes C12 and C47 both intersect low grade quartz on the margins of the ore-shoot. Strong arsenic anomalies are associated with both of these holes (Figs. 10 and 16 respectively), with peak arsenic contents in excess of 1000 ppm and widths of

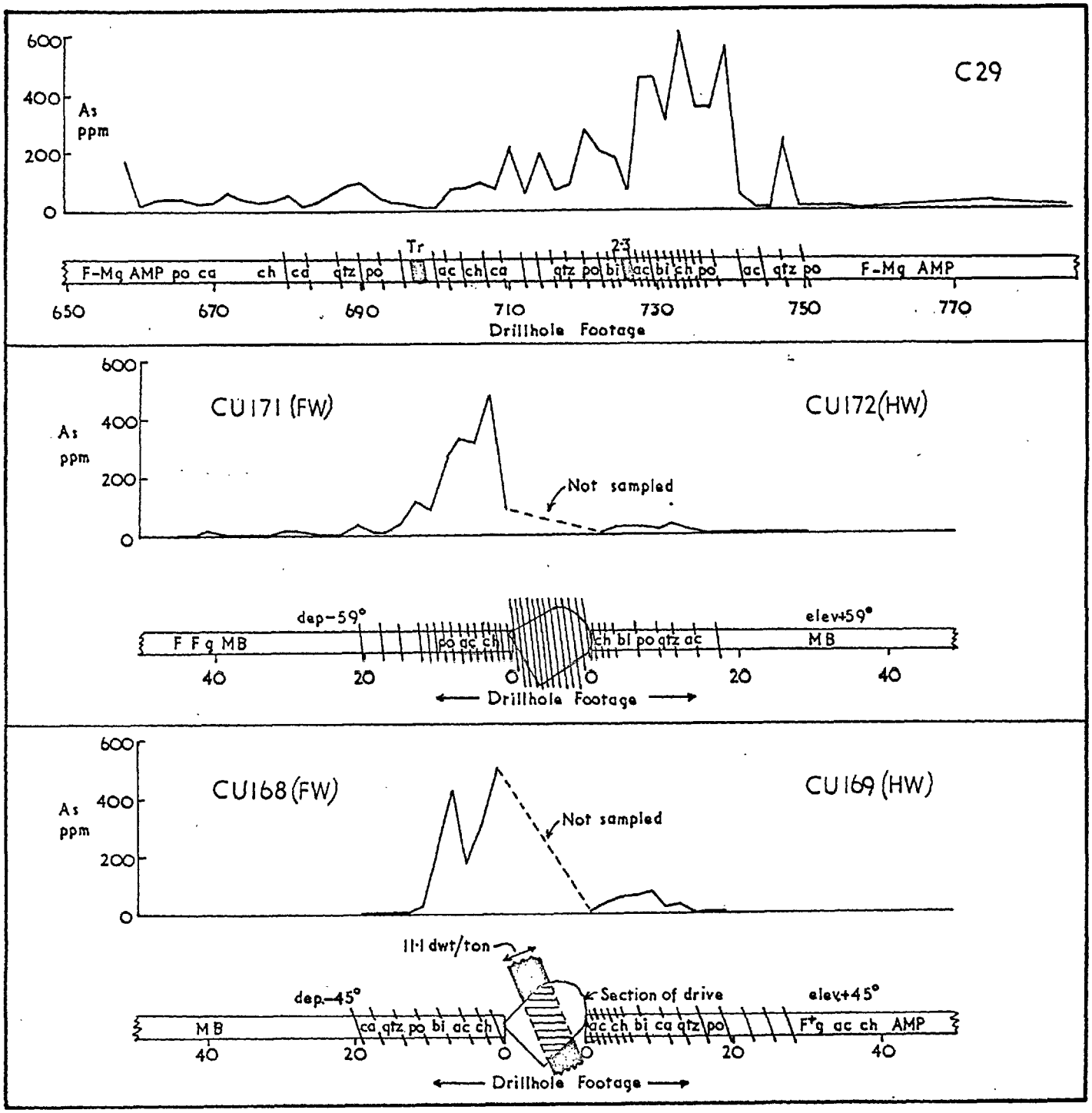


Fig. 19. Distribution of arsenic in D.D.Hs. CU168/169, CU171/172 & C29, Crown Reef-Shear, Norseman.

40 feet in the case of C12, and 88 feet in the case of C47. An anomaly 48 feet wide and with maximum arsenic content of 470 ppm was disclosed in diamond drill-holes CU171 and CU172, which were drilled from a winze at a point where the Crown Structure is represented by barren shear only (Fig. 19).

The results of nickel and chromium analyses on selected samples are summarized in Table 13, with the exception of those for C47, which have been given in Table 12. The maximum values for these elements range from 780-2000 ppm Ni and 800-1470 ppm Cr.

d) Wall-rock anomalies Associated with Crown Reef-Shear to the North of 4400N.

Diamond drill-holes CU15, C29 and CU17 were sampled to investigate variation in wall-rock anomalies in the northern portion of the Crown ore structure. Studies were also made of trace element distribution in CU60, an inclined hole intersecting the fault which bounds the orebody to the west, to establish the geochemical patterns associated with this fault. This will be described in a later section.

The trace element distribution in CU15 is shown in Fig. 11. At this point, Crown Reef is comprised of two parallel mineralized quartz reefs, separated by 35 feet of weakly sheared, slightly altered greenstone. CU15 intersects an ore-shoot on the hanging-wall vein and subeconomic quartz on the footwall vein. As described earlier, analysis of samples from CU15 disclosed strong arsenic,

TABLE. 13.

Data Relating to Trace Element Anomalies Associated with Crown Reef-Shear in the Vicinity of Ore-Shoot A and to the North of the 4400N Section, Norseman.

	D.D.H.	Element	Peak Value ppm	Contrast	Width ft.	Sample Description
Drill-holes in the vicinity of ore-shoot A.	CU168-CU169	As	510	34	40	Actinolite-chlorite schist
		Ni	780	3.1		ditto
		Cr	1170	3.9		ditto
	C12	As	4300	286	40	F.+g. biotitic greenstone (arsenopyrite)
		Ni	2000	8.0		F.g. actinolite-chlorite schist
		Cr	800	2.7		F+g. actinolite schist
	C47	As	1100	73	88	Schistose, silicified chloritic greenstone
		Ni	1100	4.4		ditto
		Cr	1470	4.9		Schistose F.+g. chloritic greenstone
	CU171-CU172	As	470	31	48	F+g. actinolite-chlorite schist.
		Ni	860	3.4		ditto
		Cr	830	2.8		ditto
Drill-holes to the north of the 4400N Section.	CU15	As	1100	73	40	Schistose actinolitic, chloritic greenstone
		Ni	2900	12		ditto (biotitic patches)
		Cr	1500	5.0		F-M.g. actinolite-chlorite (-biotite) schist
	C29	As	600	40	90+	F-M.g. chlorite (-actinolite) schist.
		Ni	530	2.1		Schistose F+g chloritic greenstone
		Cr	1850	6.2		F+g silicified chlorite schist.
	CU17	As	575	38	?	F+g. actinolite-chlorite schist, quartz blebs
		Ni	730	2.9		ditto
		Cr	750	2.5		ditto

nickel and chromium anomalies, approximately 40 feet in total width with peak values of 1100 ppm As, 2900 ppm Ni, and 1500 ppm Cr.

The results of arsenic analyses carried out on samples from C29 are of interest in that they demonstrate the continuation of the arsenical Crown Shear on the up-dip side of the major fault which limits the orebody to the west. The full lateral extent of the anomaly has not been determined, due to insufficient sampling, but it is at least 90 feet in width with maximum arsenic content of 600 ppm (Fig. 19).

CU17 was drilled horizontally to intersect ore on Crown Reef. The results of analysis indicated a weak, erratic anomaly in the hanging-wall and a strong anomaly (up to 575 ppm As) in the immediate footwall. The diamond drill-hole was not extended sufficiently far into the footwall to enable complete sampling of the anomaly. As a result of the good gold values encountered at this point (60 inches at 21.6 dwts/ton) the drill-hole was followed up by a cross-cut. This cross-cut was also sampled and the results obtained confirmed the drill-core anomaly.

The peak values for As, Ni and Cr obtained in the above traverses are given in Table 13.

e) Wall-rock Anomalies on Crown Section at 2000N.

Drilling on the 2000N section encountered a shear zone showing characteristic "reef channel" alteration, dipping 35°-40° to the east, which was presumed to be Crown Shear. Only two of the nine holes drilled on this traverse

intersected quartz, which in both cases was less than 20 inches thick and assayed only 0.1 dwt/ton. Recent underground development on 22 level has indicated a marked change to a more southerly strike and it is suspected that, in the vicinity of 2000N, Crown Shear has been displaced by an oblique fault, which may or may not be part of the pre-ore fracture system.

Four drill-holes from this traverse were sampled and studied geochemically (C61, C58, C57 and C56). Compared with the 4400N section, the arsenic anomalies associated with the Crown Shear on the 2000N traverse are relatively weak, peak values ranging from 55 to 120 ppm As (Fig. 20). The anomalies are greater than 50 feet wide in the cases of C56, C57 and C58. In C61, as in C53, the anomaly is confined to sections of sheared greenstone, which alternate with intrusive porphyry of generally low arsenic content.

Some 50 selected samples from the arsenic anomalies in the above drill-holes were analysed for nickel and chromium (Table 14). Except in the case of C56, in which a peak value of nearly 800 ppm Ni occurs, nickel contents are exceptionally low (< 100 ppm). Chromium is high in C56 and C58 whilst only background values were obtained in C57 and C61.

f) Wall-rock Anomalies associated with Crown Reef-Shear to the south of 2000N.

In recent years, a programme of exploratory drilling has been carried out to test the possible extension of the

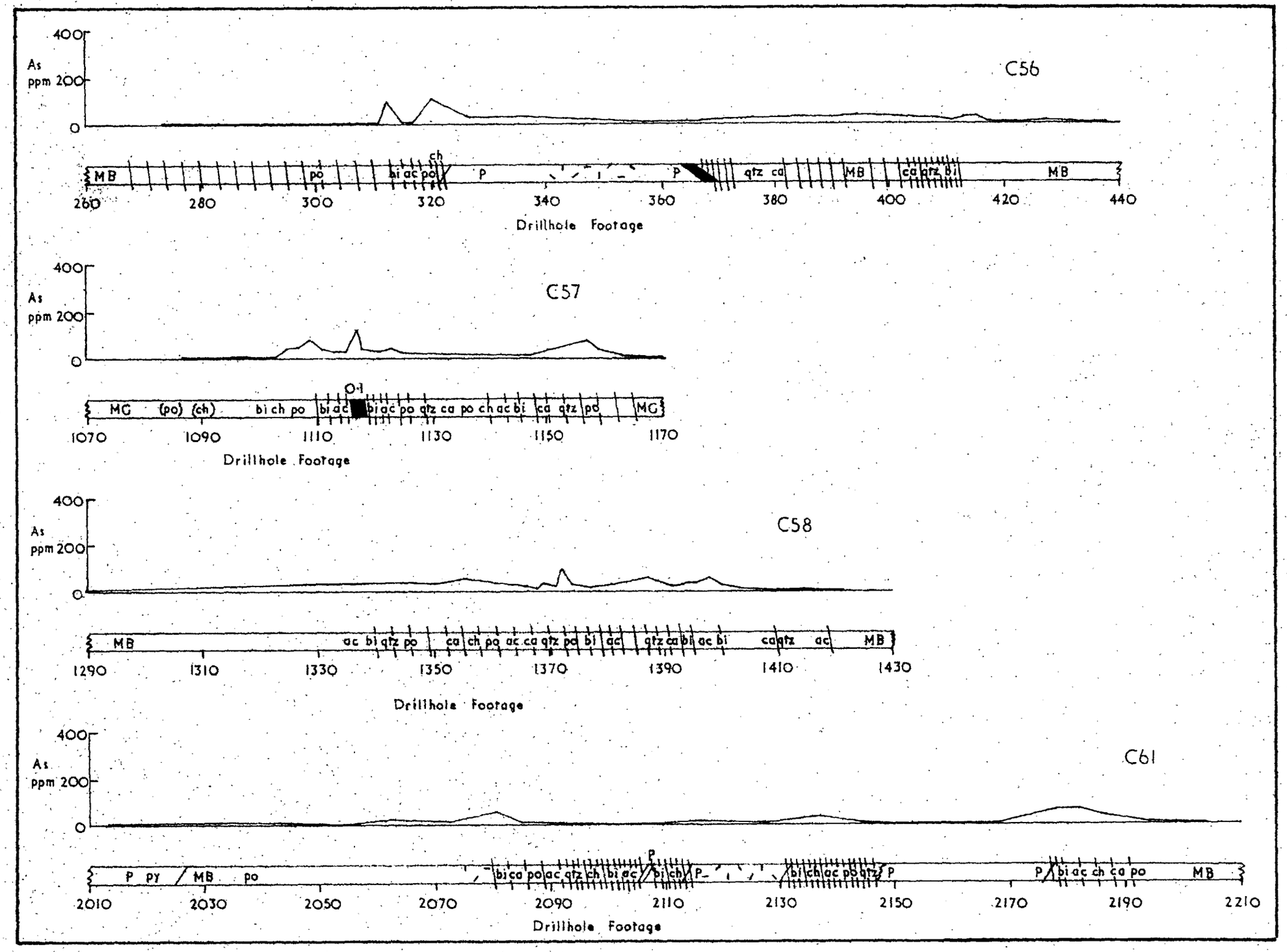


Fig. 20. Distribution of arsenic in diamond drill-holes C61, C58, C57 and C56, Crown Shear, Norseman.

TABLE. 14

Data Relating to Trace Element Anomalies Associated with Crown Reef-Shear on, and to the South of the Section at 2000N, Norseman.

	D.D.H.	Element	Peak Value	Contrast	Width	Sample Description
Drill-holes on Section at 2000N	C56	As	109	7.3	104	Chlorite schist
		Ni	790	3.2		F-M.g. carbonated actinolite-biotite schist
		Cr	1430	4.8		ditto
	C57	As	120	8.0	56	Mineralized quartz with greenstone inclusions
		Ni	64	<1.0		Silicified biotite schist (pyrrhotite)
		Cr	300	1.0		ditto
	C58	As	94	6.3	79	F.g. silicified biotite-actinolite schist
		Ni	96	<1.0		F.g. schistose biotitic actinolitic greenstone
		Cr	1030	3.4		ditto
	C61	As	56	3.7	30	Schistose actinolite chlorite greenstone
		Ni	150	<1.0		F-M.g. metadolerite
		Cr	300	1.0		F.g. silicified biotite-chlorite-actinolite schist
Drill-holes to the South of Section at 2000N	C84	As	825	55	72+	Silicified, carbonated, biotite schist (pyrrhotite)
		Ni	1400	5.5		F+g. schistose chloritic greenstone
		Cr	830	2.8		ditto (patches biotite)
	C71A	As	1100	73	50	F.g. biotite-chlorite-carbonate schist
		Ni	135	<1		F.g. schistose biotitic greenstone (pyrrhotite)
		Cr	430	1.4		F.g. biotite-chlorite-carbonate schist
	C71B	As	140	9.3	30	Highly silicified biotitic greenstone
		Ni	155	<1		F.g. silicified biotite schist (pyrrhotite)
		Cr	170	<1		F.g. biotite-chlorite schist.
	C82	As	525	35	95+	M.g. schistose (biotitic) greenstone
		Ni	640	2.6		Silicified, chlorite-biotite-actinolite schist
		Cr	830	2.8		Dark grey quartz with chloritic greenstone inclusions.

Crown ore structure in the area to the south of the known orebodies. Numerous zones of "reef-channel"-type alteration and low grade quartz intersections have been encountered, some of which are thought to represent the extension of Crown Reef-Shear. Samples have been taken in the wall-rocks adjacent to four such intersections in the drill-holes C84, C71, and C82. The distribution of arsenic in these drill-holes is shown in Fig. 21. The maximum arsenic, nickel and chromium contents of samples from these drill-holes are given in Table 14.

Samples from C84 showed the existence of a strong arsenic anomaly ($\geq$ 72 feet in width with a peak arsenic content of 825 ppm) in the wall-rocks adjacent to a quartz intersection assaying 4.6 dwt/ton over 36 inches. This anomaly was similar in all respects to those obtained in the vicinity of the Crown ore zone to the north, and subsequent underground development has confirmed that this intersection represents Crown Reef.

A moderately strong arsenic anomaly approximately 50 feet in width with one high sample (1100 ppm As) was found to be associated with a thin, low-grade quartz intersection in C71. A second, weaker anomaly, approximately 30 feet wide and with a maximum arsenic content of 140 ppm was found in the vicinity of a quartz intersection of 13 inches width carrying 0.1 dwt/ton gold at 1792 feet vertical depth (not plotted). Background nickel and chromium contents were found to be associated

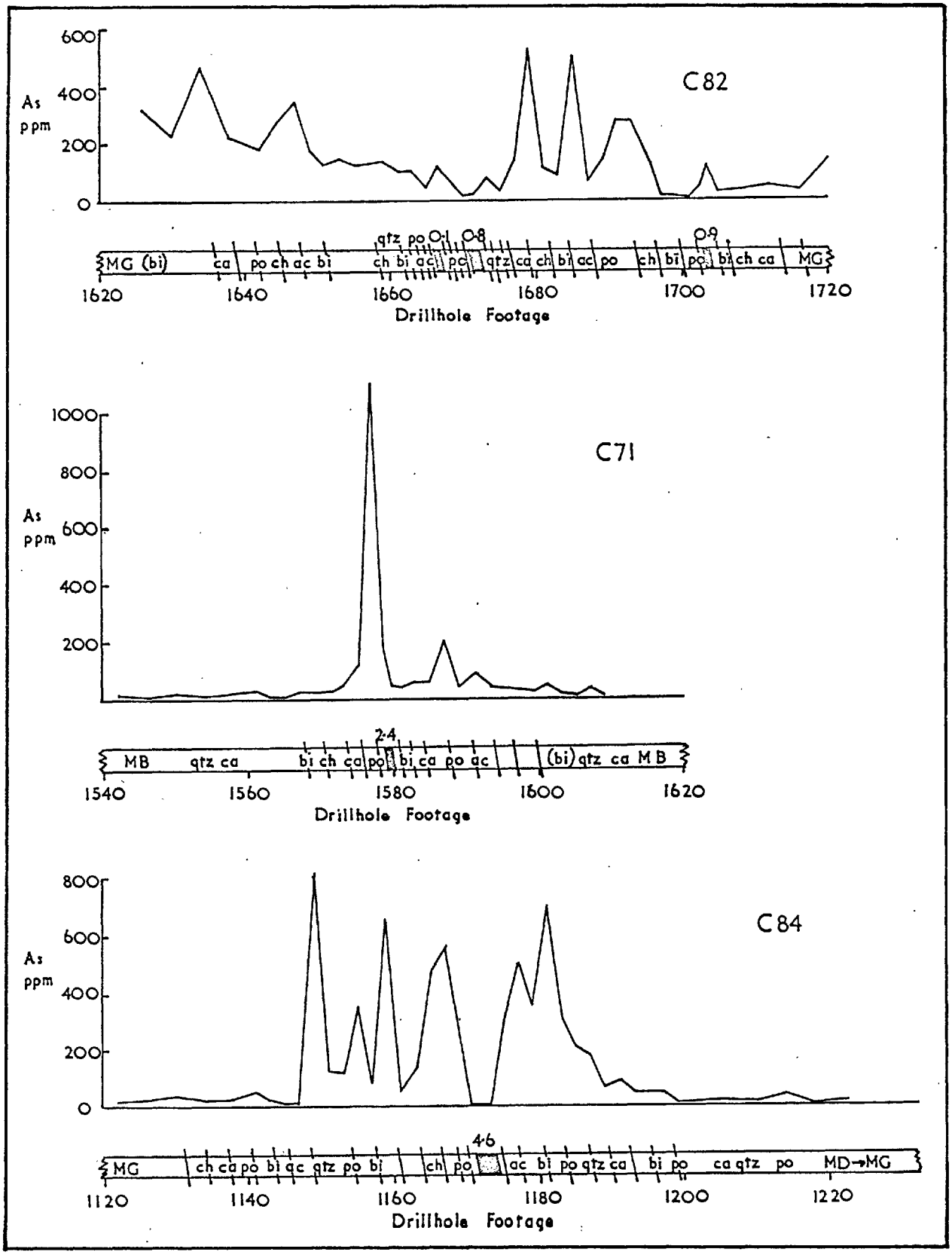


Fig. 21. Distribution of arsenic in D.D.Hs. C84, C71 & C82, Crown Reef-Shear (?), Norseman.

with this arsenic anomaly.

C82 was drilled at a point well to the south of the area shown in Fig. 15, having co-ordinates 4200S, 500W. A broad (>95 feet wide), strong arsenic anomaly was found to occur in the vicinity of a number of close-spaced low grade quartz intersections, considered to represent Crown Reef Shear at this point.

4. Wall-rock Anomalies Associated with other Reef-Shear Structures at Norseman.

a) Princess Royal Reef-Shear.

Princess Royal Reef, the richest of the orebodies worked in recent years, is shown in composite plan on Fig. 22. The outcrop of the reef is very insignificant in size, compared with the major blind ore-shoots (those in the vicinity of the North Royal Shaft), which were located by diamond drilling based on the "Favourable Bed Hypothesis". The ore zone appears to coincide with the intersection, on the reef, of the base of the Bluebird Gabbro, although the main orebodies occur in an east-dipping metagabbro dyke. The geological environment is complicated by extensive faulting and the variable attitude, and occasional bifurcation, of the quartz reef. Appreciable quantities of arsenopyrite, associated with good gold values, occur in the northern exposures of the reef. Arsenopyrite is seldom present in sufficient concentrations to be noticeable in other Norseman orebodies.

Geochemical studies of the Princess Royal Reef-Shear

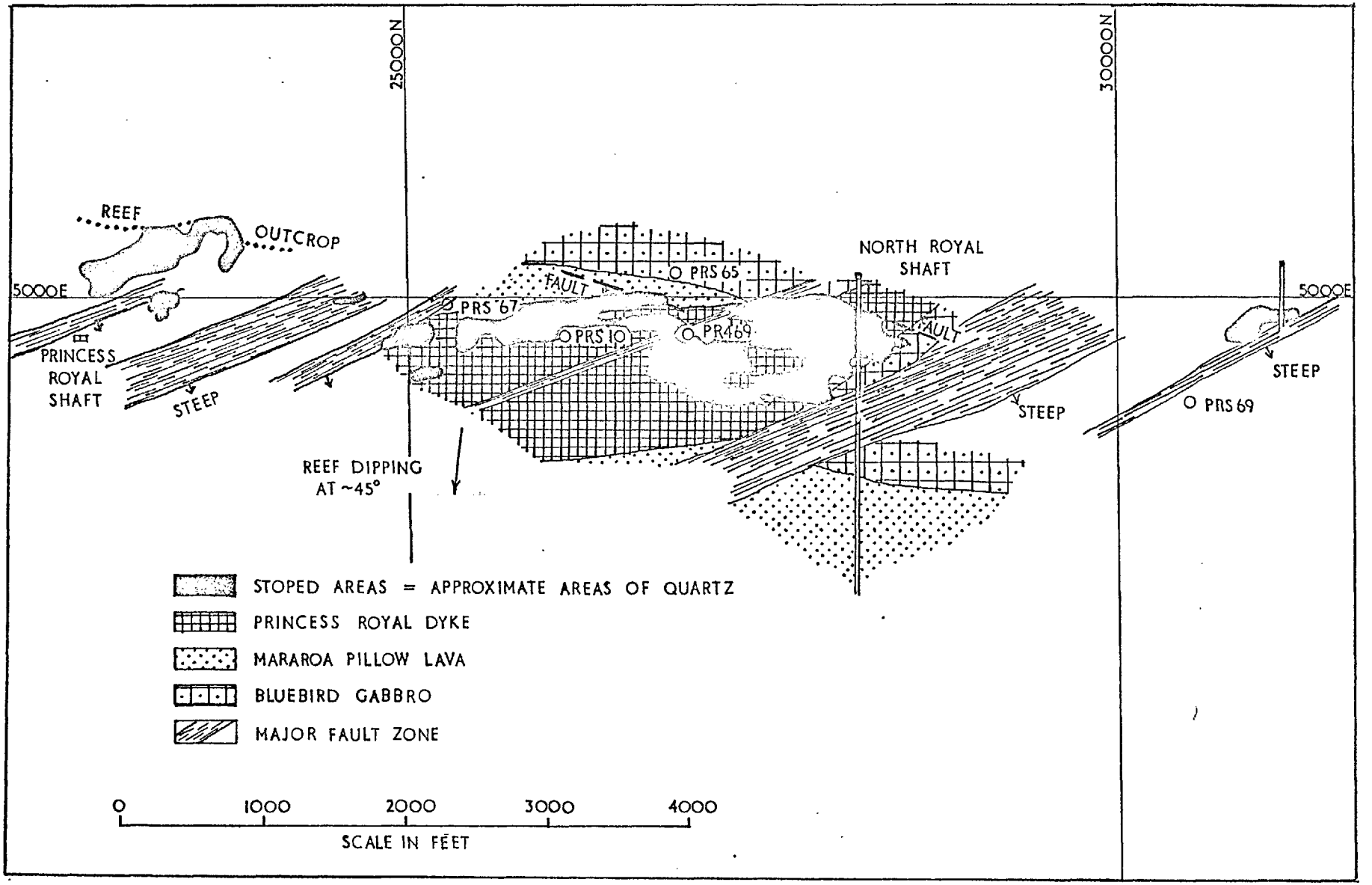


Fig. 22. Composite plan of Princess Royal Reef, Norseman, showing major geological features and D.D.Hs. sampled (after Hall and Bekker, 1965).

were limited to the sampling and analysis of five holes, selected in order to establish the trace element distribution patterns associated with this reef in the following geological situations:

(i) Dispersion pattern in greenstone wall-rocks adjacent to a rich ore-shoot (PRS10).

(ii) Dispersionpattern in porphyry wall-rocks adjacent to a rich ore-shoot (PR469).

(iii) Wall-rock anomaly associated with high grade quartz in greenstones near the northern-most known orebody (PRS69).

(iv) Dispersion pattern associated with Princess Royal Shear directly up-dip from a major gold-quartz orebody (PRS65).

(v) Trace element distribution associated with a north-easterly shear zone. (To be discussed in a later section).

The distribution of arsenic in the three drill-holes which intersected ore grade quartz is shown in Figs. 23 and 24. The arsenic anomaly associated with PRS10 is greater than 100 feet in width with a peak value in excess of 1000 ppm As. A very strong arsenic anomaly, over 70 feet in width, was disclosed in the vertical underground diamond drill-hole PR469. In this hole, the anomaly is strongest in the porphyry footwall rocks, where a number of erratic high samples occur, with a

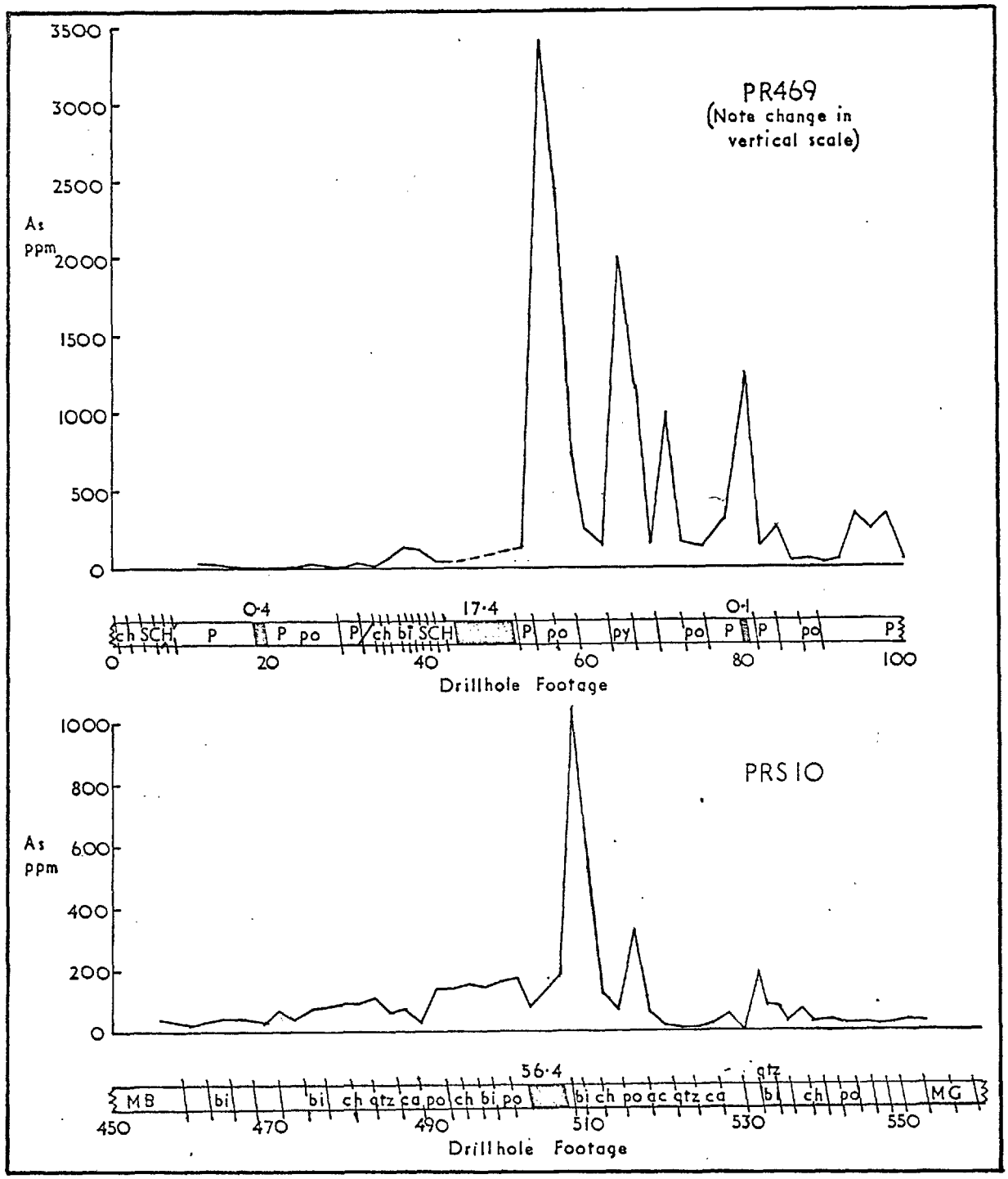


Fig. 23. Distribution of arsenic in D.D.Hs. PRS10 & PR469, Princess Royal Reef, Norseman.

maximum arsenic content of 3400 ppm. Although the arsenic anomaly is strongest in the footwall, the highest nickel and chromium values were obtained in the greenstone hanging-wall, very low values for chromium being obtained in porphyry samples (Cr $\leq$35 ppm, Ni not determined). Analysis of samples from PRS69 showed the existence of an arsenic anomaly greater than 50 feet in width, the peak of which (500 ppm As) occurs in the hanging-wall rocks, some 45 feet from the quartz intersection.

The highest arsenic values obtained in wall-rock studies at Norseman were found to occur in PRS65, which intersects the Princess Royal Shear some 400 feet up-dip from the major ore-shoot intersected by PR469. The arsenic anomaly in PRS65 is at least 90 feet in width and has a maximum arsenic content of 9000 ppm (Fig. 24). Sulphides are abundant in the vicinity of the anomaly peak and mineragraphic studies showed that approximately 2% of arsenopyrite is present.

The results for PRS67 are discussed in section 5 of the present sub-chapter.

The peak arsenic values and maximum nickel and chromium contents determined from 64 samples selected from the vicinity of the arsenic anomaly peaks in the above traverse are tabulated below (Table 15.) In all the drill-holes studied, the nickel contents are generally below or only slightly above the local threshold values, while, with the exception of those in PRS65, chromium

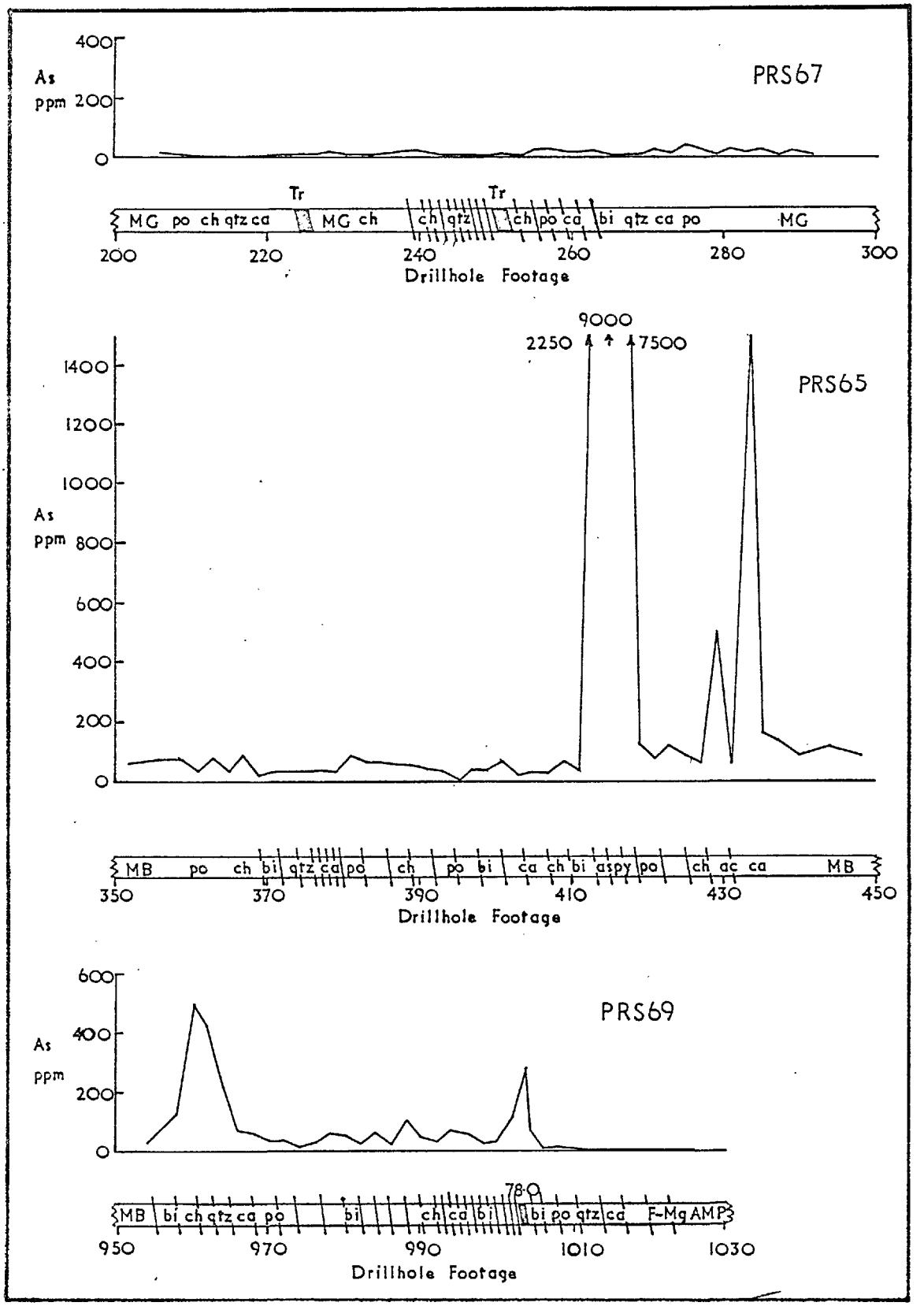


Fig. 24. Distribution of arsenic in D.D.Hs. PRS69, PRS67 & PRS65, Princess Royal area, Norseman.

TABLE 15.

Data Relating to Trace Element Anomalies Associated with Princess Royal, Mararoa, Bluebird, Norseman-Northern Star Reefs and E-W Vein, Norseman.

Reef-Shear	D.D.H.	Element	Peak value ppm	Contrast	Width ft.	Sample Description
Princess Royal	PRS10	As	1050	70		F.g. silicified biotite schist (sulphides)
		Ni	300	1.2	100+	F.g. chlorite (-biotite) schist (sulphides)
		Cr	700	2.3		ditto
	PR469	As	3400	226		Schistose Fg. sericitized porphyry.
		Ni	290	1.2	70+	Silicified biotite (-chlorite) schist.
		Cr	830	2.8		Silicified chlorite (-biotite) schist.
	PRS69	As	500	33		Schistose chloritic, biotitic greenstone
		Ni	92	<1.0	50+	Schistose F.g. biotitic greenstone
		Cr	730	2.4		ditto
	PRS65	As	9000	600		(Silicified) biotite schist (sulphides)
		Ni	68	<1.0	90+	Schistose F.g. carbonated greenstone
		Cr	278	<1.0		ditto
Mararoa	C52	As	160	11		M.g. actinolite-biotite schist.
		Ni	320	1.3	96+	Schistose F-Mg. actinolitic chloritic greenstone.
		Cr	1500	5.0		ditto
Bluebird	C47	As	65	4.3		F-M.g. schistose actinolitic (biotitic) greenstone.
		Ni	76	<1.0	33	Massive F-Mg. actinolitic greenstone
		Cr	300	1.0		ditto
Norseman	S28	As	85	5.7		Silicified (30%) biotite schist
		Ni	156	<1.0	32+	F.g. biotite schist.
		Cr	370	1.2		ditto
Norseman ?	S35	As	10	<1.0		Metabasalt
		Ni	148	<1.0	-	Schistose biotite-chlorite-actinolite greenstone
		Cr	900	3.0		ditto
E-W Vein	C82	As	525	35		Quartz (Pyrite, pyrrhotite)
		Ni	260	1.0	60+	Silicified biotitic greenstone
		Cr	300	1.0		ditto

contents are more or less similar to those obtained in the vicinity of Crown Reef-Shear, ranging from 700 to 830 ppm.

b) Mararoa Reef-Shear.

Only one drill-hole intersection (C52) on the now worked-out Mararoa Reef was sampled in the present study. This drill-hole intersected low grade quartz on the up-dip margin of a major orebody. The results of analyses for arsenic indicated an aureole at least 96 feet in width with arsenic contents between 15 and 160 ppm (Fig.25). Maximum values of 320 ppm Ni and 1500 ppm chromium were obtained by analysing 13 samples in the vicinity of the highest arsenic values (Table 15).

c) Bluebird Reef-Shear.

Wall-rock samples about a single drill-hole intersection on Bluebird Reef-Shear (C47) revealed a weak arsenic anomaly with maximum value of 65 ppm As. The intersection occurs some 600 feet down-dip from the known orebodies, which were worked at shallow depths. The erratic anomaly occurs over a zone 33 feet wide surrounding two close-spaced, low grade quartz intersections (Fig.25). Maximum nickel and chromium contents of 76 and 300 ppm respectively were found to occur in the anomalous zone.

d) Norseman Reef-Shear.

The Norseman Reef is the more southerly of two major quartz reefs occurring on one reef-shear structure,

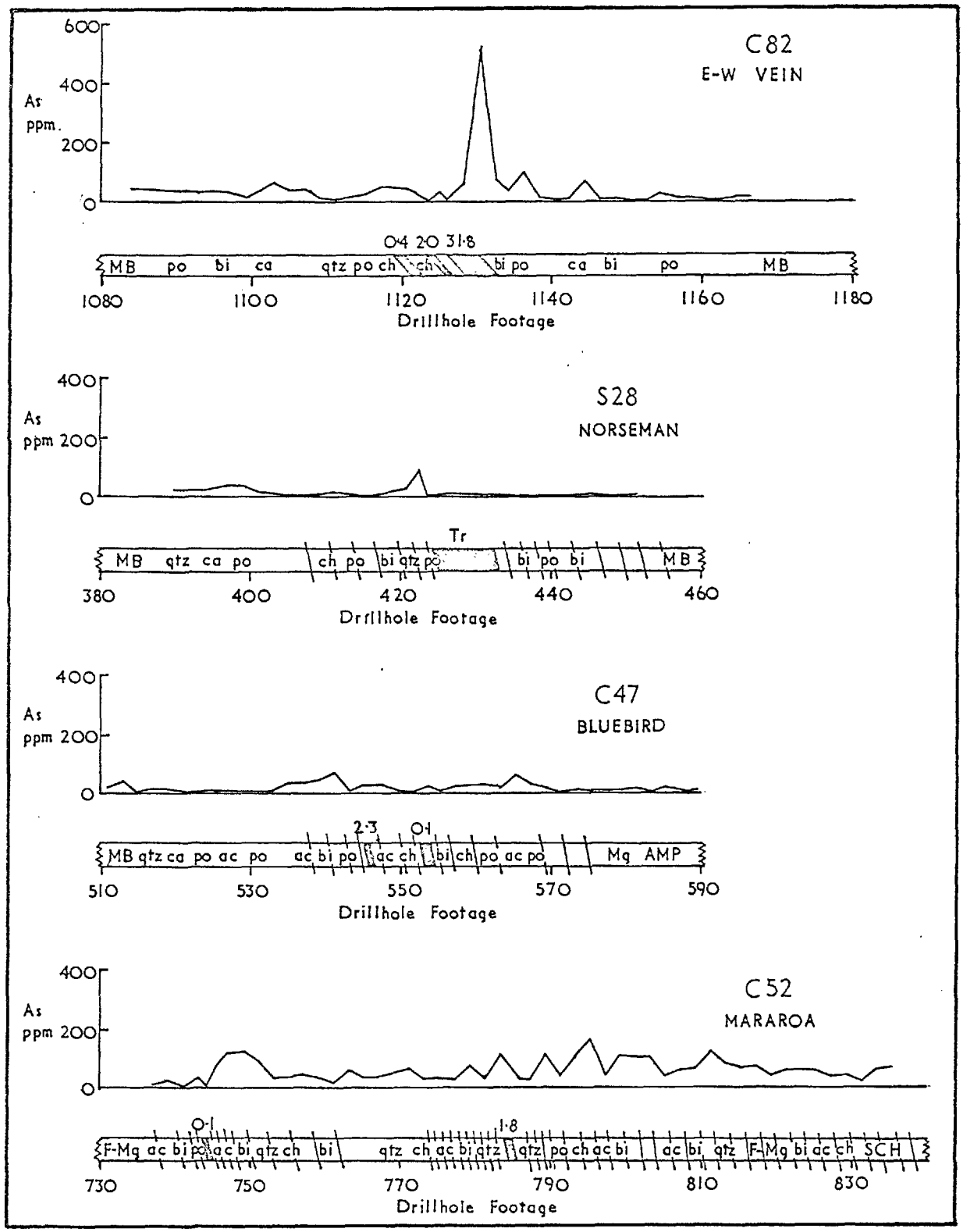


Fig. 25. Distribution of arsenic in wall-rocks in the vicinity of Mararoa, Bluebird and Norseman Reef-Shears and an east-west vein.

3 miles in strike length, known as the Norseman-Northern Star Reef-Shear. The Norseman Reef was one of the biggest gold-producing N-S reefs in the early days of the field and to the end of 1904 had produced 55,529 oz. of gold at an average grade of 0.65 oz. Au/ton. However, with few exceptions, the ore-shoots exposed at the surface did not persist in depth.

Two drill-hole intersections were studied to determine the nature of trace element dispersion patterns in the adjacent wall-rocks.

Diamond drill-hole S28 was originally put down to test the extension of an ore-shoot on the southern end of the reef in depth. The drill-hole intersected a quartz reef, 8 feet in thickness, which was found to contain only a trace of gold. Arsenic analysis disclosed a weak anomaly with peak value 85 ppm As in the hanging-wall of this reef. The anomaly is erratic but appears to extend at least 32 feet from the quartz in the hanging-wall. Only background arsenic contents were found to occur in the footwall rocks. The maximum associated nickel and chromium contents are 156 ppm Ni and 370 ppm Cr.

A quartz intersection of 10 inches carrying 0.8 dwt Au/ton, thought to represent the Norseman-Northern Star Reef-Shear, was encountered in S35, which was collared between the more northerly Northern Star workings and those on the Norseman Reef. Background arsenic contents were obtained in samples of the wall-rocks adjacent to

this intersection. The nickel values obtained were similarly low although relatively high chromium contents were obtained (Table 15).

A distinct antimony anomaly was established in soil samples collected in a traverse over the sub-outcrop of Norseman Reef-Shear (Fig.55). Both S28 and S35 were therefore tested for antimony but no primary anomaly for this element was found to be present.

e) East-West Vein.

A high grade quartz intersection encountered in the South Crown exploratory drill-hole C82, was considered to belong to the E-W striking vein system on account of the abnormally steep dip of the quartz and absence of associated "reef channel" - type alteration. The arsenic anomaly surrounding this intersection is at least 60 feet in width with a maximum arsenic content of 525 ppm (Fig. 26). It should be noted, that this maximum arsenic value occurs in the quartz itself and the highest arsenic value obtained in the wall-rock is 100 ppm. Novertheless, the lateral extent of the anomalous zone is remarkable in view of the lack of shearing in the basaltic wall-rocks. Peak values of 260 ppm Ni and 300 ppm Cr were found to be associated with the arsenic anomaly in this drill-hole.

5. Wall-rock Anomalies Associated with Faults, Non-Auriferous Shear Zones and Quartz Intersections.

Two diamond drill-holes were sampled to establish

the nature of trace element distribution patterns associated with post-ore dislocative faults.

The arsenic distribution within the zone of normal faulting which bounds the Crown ore zone on the west (Fig. 15) was determined by analysing samples from CU60, a drill-hole which passes through this fault at 7350N. The geological section and geochemical profile associated with CU60 in the zone of shearing is shown in Fig. 26. Anomalous arsenic values ranging from 35 to 4300 ppm were found to occur throughout the shear zone. The highest arsenic contents occur in rocks immediately adjacent to a number of quartz intersections which appear to represent fractured portions of Crown Reef that have been dragged into the fault zone. It is therefore probable that the highly arsenical wall-rocks within the fault zone are also of "drag" origin. Owing to the lack of other drill-holes through the fault it was not possible to test this hypothesis by sampling the fault zone at greater distance from Crown Reef.

The geochemical characteristics of one of the major north-easterly trending shear zones were established by analysing samples from PRS67 (Fig. 22). The arsenic distribution in the vicinity of the shearing in this drill-hole is plotted in Fig. 24. A zone of weakly anomalous values (15-40 ppm As) approximately 40 feet in width was found to be present. Low nickel contents (up to 250 ppm) and relatively high chromium contents (up to 1370 ppm) were

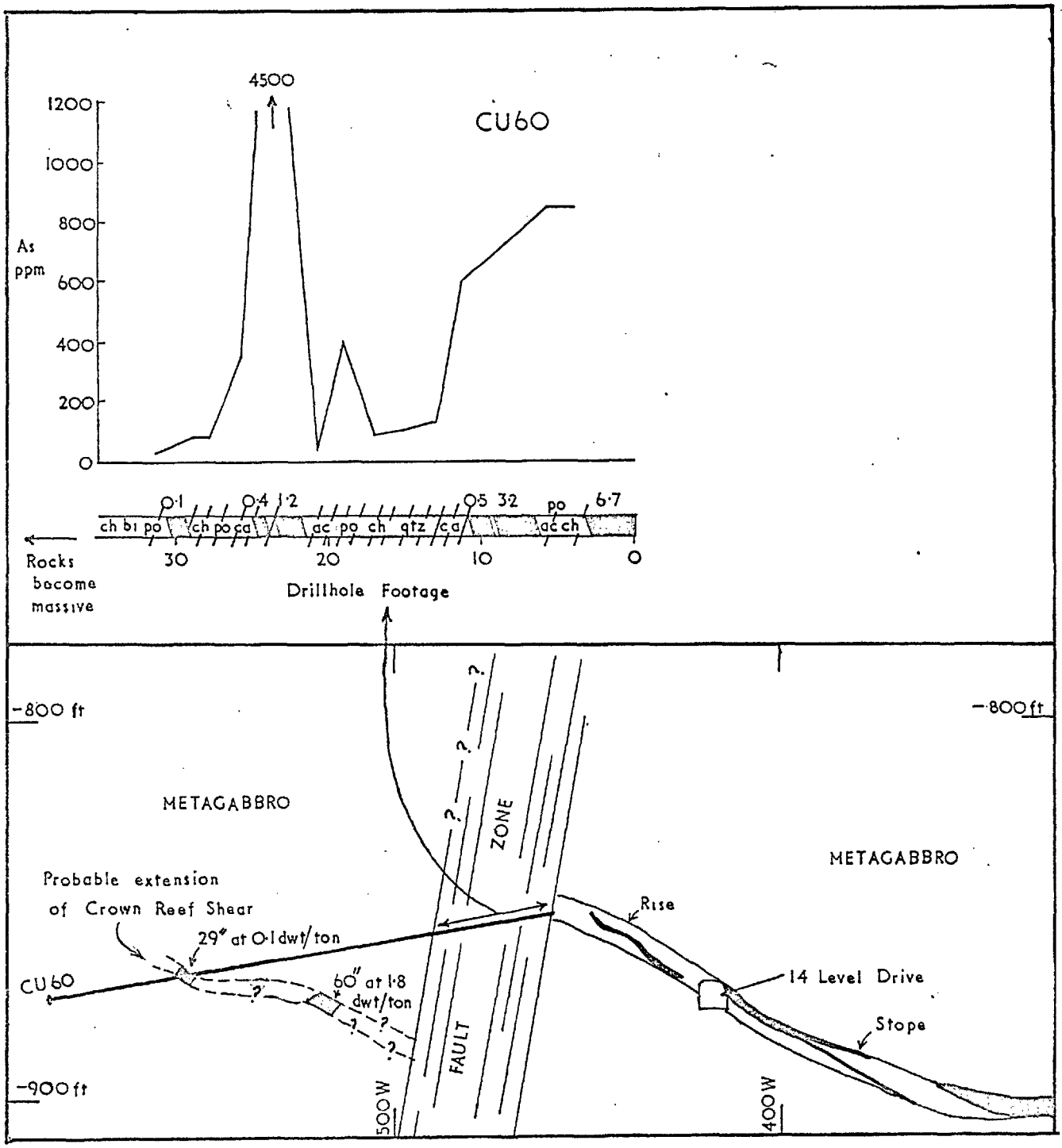


Fig. 26. Geological Section of Crown Reef at 7350N, showing arsenic distribution within zone of faulting in D.D.H. CU60.

found to be associated with the arsenic anomaly.

Diamond drill-holes at Norseman frequently encounter low-grade quartz intersections and shear zones which appear to be similar to those in the vicinity of known mineralized quartz reefs. The interpretation of these intersections is difficult for two reasons.

(i) On many occasions, deceptive, low-grade quartz intersections have been obtained in drill-holes which have actually penetrated ore zones in close proximity to economic grade quartz (e.g. C12 and C47).

(ii) Schistose chloritic, biotitic and actinolitic rocks, which are typical of the wall-rocks adjacent to reef-shears, are also found to occur in shear zones unrelated to ore, particularly in zones of weakness on the margins of intrusive dykes.

A number of such intersections, known to be unrelated to auriferous quartz reefs, were sampled to determine if the associated trace element dispersion patterns differ significantly from those in the vicinity of reef-shears.

Details of the sampling and analysis of a zone of schistose, altered metagabbro adjacent to a low-grade quartz intersection some 200 feet vertically below Crown Reef are given in Table 16.

TABLE 16.

Trace Element Distribution Associated with Non-Auriferous Quartz Intersection in DDH C52, Norseman.

Drill-hole Footage	Description	As	Ni	Cr.
2213' to 2223'	Massive M.G.Metagabbro	1	180	180
2238' to 2243'	F-MG amphibolite.	1	180	200
2248' to 2253'	M.G. massive metagabbro (pyrite)	18	60	18
2255' to 2257'	Schistose M.G.actinolitic-biotitic greenstone (sulphides).	1	75	40
2261' to 2262'	M.G. actinolite-biotite schist, quartz carbonate veinlets	1	60	30
2263'3"to 2264'1"	Quartz with actinolite-chlorite schist inclusions	1	30	12

It can be seen from this table that background trace element contents occur up to 50 feet from the quartz intersection, with the exception of the one sample containing 18 ppm As, which is only slightly above threshold.

Similar results were obtained for all the non-auriferous shear and quartz intersections tested. Schistose, actinolitic and biotitic greenstones adjacent to a narrow, low-grade quartz vein intersected in C56, showed a maximum arsenic content of 38 ppm. In a shear zone, over 60 feet in width, about a number of close-spaced quartz intersections in a hole drilled to the south of the Princess Royal orebodies (PRS 124), arsenic contents were

found to range from 2 to 5 ppm, with one sample containing 35 ppm As. The maximum associated nickel value in the vicinity of this intersection, which was deceptively like that of a major reef-shear, was found to be 370 ppm. The highest arsenic value in the unsheared, sulphide-impregnated wall-rocks surrounding 52 inches of quartz intersected at a depth of 376 feet in C40 was found to be 25 ppm. In addition to the above, a considerable number of spot samples were collected over shear zones and quartz intersections encountered in the drill-holes studied. The results in all cases supported the conclusion that shear zones and quartz veins unrelated to known reef-shears, in general, show background or only slightly higher than background trace element contents.

6. General Characteristics of Wall-rock Anomalies at Norseman.

a) Width of Anomalies.

Wall-rock anomalies associated with N-S reef-shears at Norseman were found to vary in width from 24 feet to more than 118 feet. However, in most cases, the anomalies are between 40 and 100 feet in width.

b) Anomaly Contrast.

The anomaly contrast for arsenic with respect to local background, ranges from 19 to 600 in the vicinity of, and up-dip from, ore zones on Crown and Princess Royal Reefs. Excluding the very high values obtained in C12,

PRS 65 and PR 469, the average contrast is 49. Somewhat lower contrast values (average 6.3) were obtained in drill-holes on the Crown 2000N section, but the anomalies are still distinct. Insufficient work was done on wall-rock dispersion patterns associated with the Mararoa, Blue-bird and Norseman Reef-Shears to permit critical comparison.

An alternative method of expressing the magnitude of anomalies is to calculate the average trace element content over the whole of the anomalous zone. Average trace element contents may actually be better than contrast as a means of representing anomalies, since the effect of erratic high samples is minimised. The average arsenic contents of wall-rock anomalies studied in this project are compared with peak values in Table 17. It can be seen from this table that there is no consistent relationship between the average and peak values.

Nickel anomalies related to Crown Shear (except at 2000N) vary in contrast from 1.4 to 12.0, the average contrast being 6.1. With one exception (C56), background nickel contents were encounted in the vicinity of Crown Shear at 2000N. Significant nickel anomalies were not found to occur in the wall-rocks adjacent to any of the other reefs tested.

Contrast for chromium varies from 2.3 to 16.7 (average 4.5) in the wall-rocks about ore zones, and up-dip from ore zones, on Crown Reef. Two of the drill-holes sampled on the 2000N traverse showed chromium

TABLE 17.

Average and Peak Arsenic Contents of Wall-Rock Anomalies at Norseman.

Reef-Shear	DDH.	Aver-age As ppm	Peak	Reef Shear	DDH	Average As ppm	Peak
Crown (In vicinity of and up-dip from ore zone)	C12	475	4300	Crown (2000N Section)	C58	37	94
	C29	134	600	" " "	C61	46	56
	C40	86	800	Crown (Exploratory Holes)	C71	70	1100
"	C43	55	290	" " "	C82	157	525
"	C44	454	1150	" " "	C84	188	825
"	C46	223	750	Princess Royal	PRS 10	96	1050
"	C47	171	1100	" "	PRS 65	467	9000
"	C49	210	2125	" "	PRS 69	98	500
"	C51	142	1100	" "	PR 469	489	3400
"	C52	60	357	Mararoa	C52	61	160
"	C53	58	526	Bluebird	C47	25	65
"	CU15	151	1100	Norseman	S28	17	85
"	CU168/9	152	510	"	S35	<10	10
"	CU171/2	108	470	E-W Vein	C82	37	525
Crown (2000 N	C56	31	109	Non-Auriferous Veins	PRS 67	15	40
Section)	C57	41	120	and shears	PRS124	<10	35

anomalies with greater than threefold contrast, while the other two contained only background chromium contents throughout. Three of the four wall-rock anomalies tested on Princess Royal Reef-Shear had associated chromium anomalies with contrast greater than 2. Background chromium values were obtained in PRS65.

The low arsenic and nickel contrasts associated with non-auriferous shear and quartz intersections distinguish them from similar structures related to ore. However, the relatively high chromium content associated with a weakly arsenical north-easterly fault zone in PRS 67 suggests that high chromium may not be exclusively diagnostic of reef-shears at Norseman.

c) Form and Homogeneity of Anomalies.

The anomalies obtained in greenstone wall-rocks adjacent to reef-shears generally consists of a broad plateau of weakly anomalous values between 20 and 100 ppm As, within which occur one or more narrower peaks. The anomalies are therefore essentially heterogeneous, with highly anomalous sections alternating with weakly anomalous and occasional background samples (e.g. C44).

A number of authors studying wall-rock dispersion patterns about orebodies, have reported a logarithmic decrease in trace element concentration with increasing distance from the lode or vein (see later). Geochemical profiles for all the Norseman wall-rock traverses were

plotted on a logarithmic scale but no indication of log-linear concentration gradients was observed.

The distribution of anomalies about actual quartz reefs is seldom symmetrical. In some cases, the anomaly is stronger in the footwall (C52, C46 and CU168, C29, PR469) and in others in the hanging-wall (C47, C51, C71). In some instances, the anomaly peaks are associated with zones of shearing a considerable distance from quartz intersections (C46, C51, and PRS69).

In most cases, it is evident that the trace element contents of the actual quartz reefs are much lower than those of the adjoining wall-rocks. In numerous instances (e.g. CU15, C52 Crown and Mararoa, C47 Crown and Bluebird, C43, C46, C44, C51, C84, C71, C82, PRS10, PRS67, PR469, S28) the arsenic content of wall-rocks immediately adjacent to the quartz intersections are also considerably lower than those found at distances of 5 feet or more, i.e. there is a decline in the arsenic content of the wall-rocks in close proximity to the reefs.

d) Relationship between Anomalies and Nature of the Host-rocks.

The geochemical profiles (Figs. 16-21 and 23-25) do not show any obvious differences in the widths and contrasts of wall-rock anomalies that could be related to the nature of the greenstone rock-types. However, when average arsenic contents are plotted on the Crown

Section at 4400N, it becomes apparent that stronger anomalies are present in the Crown-Bluebird Sill Sequence than in the metabasalts (Fig 28). There are three possible explanations for this phenomenon:

(i) the chemical composition of the intrusive rocks may be more favourable to the precipitation of arsenic than that of the metabasalts.

(ii) the coarse grained rocks of the sill sequence are presumably more porous than the basalts, so that greater volumes of the arsenic-rich hydrothermal fluids may be accomodated.

(iii) as a result of reverse faulting, the steeper section of Crown Shear in the sill sequence would be compressive, impeding the upwards flow of hydrothermal solutions and possibly leading to precipitation.

The presence of porphyry intrusives in the vicinity of reef-shears also seems to have influenced the distribution of anomalous arsenic, nickel and chromium. Sporadic, weakly anomalous arsenic values were encountered in porphyry dykes in the vicinity of Crown Shear in drill-holes C53, C56 and C61. However, considerably higher arsenic contents occur in the schistose greenstones adjacent to the porphyry in these drill-holes. In contrast, the arsenic anomaly occurring in the porphyry footwall of the Princess Royal Reef in PR469 is much stronger than that in the greenstone hanging-wall. The essential

difference between this hole and those intersecting Crown Shear is that the porphyry in PR469 is somewhat sheared and sericitized. The porphyries sampled in C53, C56 and C61 showed virtually no shearing but occasional fracturing. Nickel and chromium values are invariably very low in porphyries and anomalies for these elements are confined to greenstone wall-rocks in the vicinity of reef-shears.

The above leads to a consideration of the significance of shearing and micro-fissuring in the localization of trace element anomalies in wall-rocks.

e) Relationship Between Anomalies, and Shearing and Fracturing in the Wall-Rocks.

The distribution of trace elements in the wall-rocks adjacent to reef-shears appears to bear some relationship to the degree and extent of shearing and fracturing in the rocks. This is based on the somewhat arbitrary assessment of the degree of shearing, as observed in hand-specimen, into the categories: massive, weakly sheared, moderately sheared and strongly sheared. Inspection of Figs. 16 to 21 and 23 to 25 shows that, in general, the zone of anomalous arsenic contents coincides approximately with the zone of shearing. In some drill-holes, however, the arsenic anomalies were found to extend into the massive rocks beyond the zone of shearing. In most of these cases, only weakly anomalous values were obtained in the massive rocks but arsenic contents up to 170, 325 and 330 ppm

were found in C29, C82 and PR 469 respectively, outside the visible shear zone. The anomaly related to an E.W. reef in C82 is significant in this connection, since the zone of weakly arsenical wall-rocks in this hole extends over 60 feet in unsheared greenstones.

The dependence of trace element anomalies on shearing is evident in drill-holes in which porphyry occurs in close proximity to reef-shears, as in C53, C56, C61 and PR469, (discussed in the previous section). Continuous arsenic anomalies appear to be developed only in porphyry wall-rocks in which shearing has taken place (PR469). Occasional anomalous samples encountered in unsheared porphyry can usually be related to local fracturing within the rock.

f) Relationship Between Trace Element Anomalies and Mineralogical Wall-Rock Alteration.

In many drill-holes, there appears to be a close association between the lateral extent of trace element anomalies and the zone of mineralogical wall-rock alteration. However, mineralogical alteration of the type encountered in reef-shears is commonly found in other zones of weakness and shearing throughout the area, including the margins of gabbro and porphyry dykes and non-auriferous faults. Arsenic and nickel occur in near-background concentrations in these non-auriferous altered zones, (although anomalous chromium values were sometimes encountered). Since arsenic and nickel anomalies appear

to be exclusively restricted to those altered zones associated with known reef-shears, it must be presumed that these elements were not closely related to the agencies which caused the more widespread wall-rock alteration. Further evidence is presented in a later section to show that the arsenic and nickel anomalies were, in fact, genetically related to the gold mineralization, which, according to Bekker (1962), occurred later than the wall-rock alteration stage.

It is considered possible that, although the distribution of arsenic and nickel was not directly related to wall-rock alteration processes, both features were dependent to a large degree on the extent of shearing in the wall-rocks, thus explaining the apparent association. On the other hand, the available evidence suggests that the chromium anomalies were developed during the wall-rock alteration stage. This is supported by the studies of separated mineral fractions, described in the following section.

g) Mineralogical Distribution of Trace Elements.

A number of representative samples from the diamond drill-holes C12 and CU15 were separated into their constituent minerals, in order to determine the mode of occurrence of arsenic, nickel and chromium in the wall-rocks. Mineral identification was based on microscopic studies of thin sections and grain mounts.

The arsenic and nickel contents of the various mineral fractions were determined from the same leach solutions, after fusion with potassium bisulphate. Chromium was determined spectrographically on a separate sample. In the case of some of the least abundant minerals, there was insufficient sample material to produce reliable data for chromium. Where this was the case, provisional chromium values were obtained on a smaller sample weight than normal, using the dichromate method. In Table 18, which sets out the results of mineral separation studies, these suspect chromium values are given in brackets.

It was found from these studies that arsenic occurs dominantly as arsenopyrite, both in discrete grains and in intergrowths with pyrrhotite. The most marked arsenic concentrations were found to occur in a nonmagnetic ore mineral fraction, which usually consisted of grains of arsenopyrite, with pyrite and occasionally scheelite and chalcopyrite. Only very small quantities of these minerals (usually 0.3% or less) are present in the rocks, so that it was not practicable to separate the individual minerals further. In highly arsenical samples, the non-magnetic ore mineral fraction was found to be comprised almost entirely of arsenopyrite, as in 4658, where the arsenic content obtained corresponds, within the limits of analytical precision, to that of pure arsenopyrite. Arsenopyrite had not previously been recognised as widespread in the

TABLE 18.

Mineralogical Distribution of Trace Elements in Norseman Greenstones.

D.D.H.	SAMPLE No.	ROCK TYPE	DISTANCE FROM VEIN (FT)		PYRRHOTITE MAGNETITE	ARSENOPYRITE PYRITE	ACTINOLITE	BIOTITE	CHLORITE	QUARTZ-FELDSPAR-CARBONATE	WHOLE ROCK
CU15	3908	Metadolerite with biotitic streaks	24	Rock Comp.	3%		45%		6%	46%	
				As	3	3420	1			18	5
				Ni	60	21	60			5	60
				Cr	570	(3600)	40			5	40
CU15	3913	Schistose F+g actinolite-chlorite greenstone	8	Rock Comp	3%		72%		20%	5%	
				As	2290	12500	26		<1	18	60
				Ni	19650	4420	130		325	20	3,000
				Cr	(3900)	(2900)	400		800	(1400)	600
C 12	4658	F.g. chlorite-biotite-actinolite schist, quartz veinlets	3	Rock comp	2%		40%	30%	10%	18%	
				As	2730	492000	45	10	36	5	1,128
				Ni	3960	575	35	135	165	<3	120
				Cr	(5500)	(140)	400	400	400	45	200
	4631	F.g. to F+g metabasalt	50	Rock comp.	2%		50			48	
				As	100	63300	2			10	9
				Ni	4250	7000	55			8	10
	4694	M.g. feldspathic metadolerite	260	Rock Comp	2%		50%			48%	
				As	<8	>4550	3			1	10
				Ni	3800	7260	45			3	200
	4696	Mass F.g. metabasalt	550	Rock comp.	2%		50%			48%	
				As	125	>6000	19			3	10
				Ni	1250	300	10			5	80
	4698	M.g. metagabbro (pyrrhotitic)	760	Rock Comp.	3%		52%			45%	
				As	2	>4580	3			1	3
				Ni	780	125	13			3	40

wall-rocks at Norseman and is only rarely present in the actual quartz reefs.

Minute amounts of arsenopyrite were found to occur in rocks as much as 760 feet vertically from Crown Reef, as indicated by the high arsenic contents of the non-magnetic ore mineral fraction of samples 4631, 94, 96 and 98. At distances greater than 50 feet from ore, the amount of arsenopyrite present is too small to be effectively concentrated. The figures given in Table 18 for samples 4694, 96 and 98 refer to an impure fraction containing 1-20% sulphide, the remainder consisting mainly of quartz and feldspar. Had a pure fraction been obtainable, the arsenic results would no doubt have been higher. It should be noted that scheelite comprises approximately 50% of the non-magnetic ore mineral fraction of sample 3913, but in all the samples from C12, arsenopyrite is the dominant ore mineral in this fraction. The wall-rocks adjacent to Crown Reef in C12 were tested for tungsten but no anomaly was found to be present, the concentration of this element in all samples being less than the limits of detection (<200 ppm) of the spectographic method employed. The presence of scheelite in the wall-rocks in CU15 is therefore probably of local significance only.

As mentioned earlier, appreciable concentrations of arsenic also occur in the pyrrhotite-rich, strongly magnetic fractions of the anomalous samples 3913 and

4658. In concentrating pyrrhotite by magnetic means, it was impossible to avoid the inclusion of small quantities of magnetite and composite grains with silicate impurities. It was therefore necessary to find a reagent which would selectively attack pyrrhotite in the presence of other minerals. Experiments were carried out using varying strengths of different acids on test samples of pyrrhotite and magnetite. 2M HCl was found to be the most effective, achieving a virtually total attack on pyrrhotite (the residue was found to contain no pyrrhotite) whilst at the same time attacking less than 10% of the magnetite (Table 19).

TABLE 19.

Leaching Experiments on (-100 mesh) Samples of Pyrrhotite and Magnetite : 20 minutes digestion at 100°C.

Reagent	Wt. % Pyrrhotite Leached	Wt. % Magnetite Leached.
1M HCl	60.4	11.0
2M HCl	90.9	7.7
4M HCl	89.8	36.4
1M HNO_3	2.8	6.4
2M HNO_3	4.9	7.7
4M HNO_3	6.0	15.0
2M H_2SO_4	90.2	22.4
4M H_2SO_4	90.0	33.8

The results obtained on residues after leaching by 2M HCl were compared with the total As results obtained by bisulphate fusion. It was found that in the case of sample 3913, 80% of the arsenic present in the pyrrhotite-magnetite fraction was leached by 2M HCl, whilst only 10% was leached in the case of 4658. These apparently conflicting results are believed to be due to differences in grain size. In cases such as 4658, the arsenic presumably occurs as discrete grains of arsenopyrite in intergrowths with pyrrhotite. The size of the arsenopyrite grains is apparently sufficient to resist attack by dilute HCl. The more extensive leaching of arsenic from the pyrrhotite-magnetite fraction in 3913 suggest a more pervasive distribution of the arsenic within the pyrrhotite, either as minute exsolution grains or incorporated within the pyrrhotite lattice.

Polished section studies, for which the writer is grateful to Mr. G. Hopkins of Western Mining Corporation, give some support to the results of the above studies, with regard to pyrrhotite-arsenopyrite intergrowths. A sample of highly arsenical biotitic greenstone from PRS 65 was found to contain approximately 2% arsenopyrite as euhedral grains 0.1 to 0.5 mm. in diameter in quartz-carbonate-filled microfractures and smaller grains, 30-40 microns in diameter disseminated throughout the rock fabric. Pyrrhotite was introduced through a later set of microfractures invading and enclosing arsenopyrite grains

in the vicinity of the fractures. The pyrrhotite has subsequently reverted to a granular intergrowth of pyrite and marcasite but some remnant pyrrhotite is retained as small inclusions in arsenopyrite. Minor amounts of exsolved chalcopyrite, in the form of laths and rims, are also present, apparently having been introduced with the pyrrhotite. Secondary ilmenite, the development of which preceded that of the sulphides, is a minor constituent. Unfortunately, no information as to the size of the arsenic inclusions was obtainable on the samples for which mineral separations were made.

The silicate minerals of the greenstone wall-rocks are relatively low in arsenic compared with the sulphides. The highest values occur in anomalous samples and it is thought that, in these cases the arsenic occurs as arsenopyrite inclusions or metasomatic replacement rims on the margins of the silicate grains. Rankama and Sahama (1950, p.739) note that arsenic does occur in silicates and phosphates, particularly apatite, a few grains of which were observed in the quartz-feldspar-carbonate fraction of the rocks studied. However, the low concentrations of arsenic in the silicate fractions of background rocks (samples 4631, 4694, 96 and 98) suggest that the element was introduced as arsenopyrite, after the rocks were formed, and was not an important constituent of the original magmatic rocks.

In contrast with the above results, the silicate fract-

ions from an arsenical porphyry, which occurred some 500 feet from Crown Reef-Shear, have high arsenic contents (150 to 500 ppm As: Table 20). The highest concentrations of arsenic in this sample, as in greenstone, are associated with sulphide minerals and it is again considered probable that the high arsenic contents in silicates are due to minute inclusions of arsenopyrite. These results suggest that much of the arsenic in porphyries may have been present at the time when the silicates crystallized whereas, in greenstones, the evidence points to the introduction of arsenic subsequent to the crystallization of silicate minerals.

TABLE 20.

Mineralogical Distribution of Trace Elements in an Arsenical Porphyry Sample (3609) from DDH. C61, Norseman.

Mineral Fraction	As ppm	Ni ppm	Cr ppm
Pyrrhotite	49,950	125	(1000)
Pyrrhotite + 20% limonitized magnetite	1,640	115	(2300)
Pyrite - arsenopyrite	254,450	19	(1550)
Biotite + chlorite (impure)	360	≤3	(2300)
Muscovite	550	≤3	700
Quartz-feldspar-sericite	150	<3	<2
Whole rock	1,200	5	5

With the exception of one background sample from

CU15 (3908), nickel is concentrated in the pyrrhotite fraction. The association of nickel with pyrrhotite is very common and Dana (1957, p.428) states that the nickel usually occurs as grains of pentlandite enclosed in the pyrrhotite. Leaching experiments carried out with 2M HCl showed that only 33% of the nickel associated with pyrrhotite in 3913 was attacked by this reagent whereas nearly 90% of the nickel was leached from the pyrrhotite in 4658. This is attributed to differences in the modes of occurrences of the pentlandite in the two cases, particularly with regard to grain size. Pentlandite itself is only slightly soluble in HCl. This is supported by the relatively higher proportion of nickel occurring in the non-magnetic ore mineral fraction in 3913, where it presumably occurs as discrete grains of pentlandite.

Pyrrhotite is a common and widely distributed accessary mineral in the greenstones at Norseman, occurring in appreciable quantities in rocks even hundreds of feet from reef-shears. The nickel contents of the analysed pyrrhotite samples from C12 tend to increase on approaching Crown Reef (Fig. 27). This suggests that very broad nickel anomalies, related to ore, may be obtained by analysing the pyrrhotite fraction of samples well beyond the limits of wall-rock alteration and the trace element anomalies established in earlier parts of this thesis. This approach could be very useful, and warrants futher investigation.

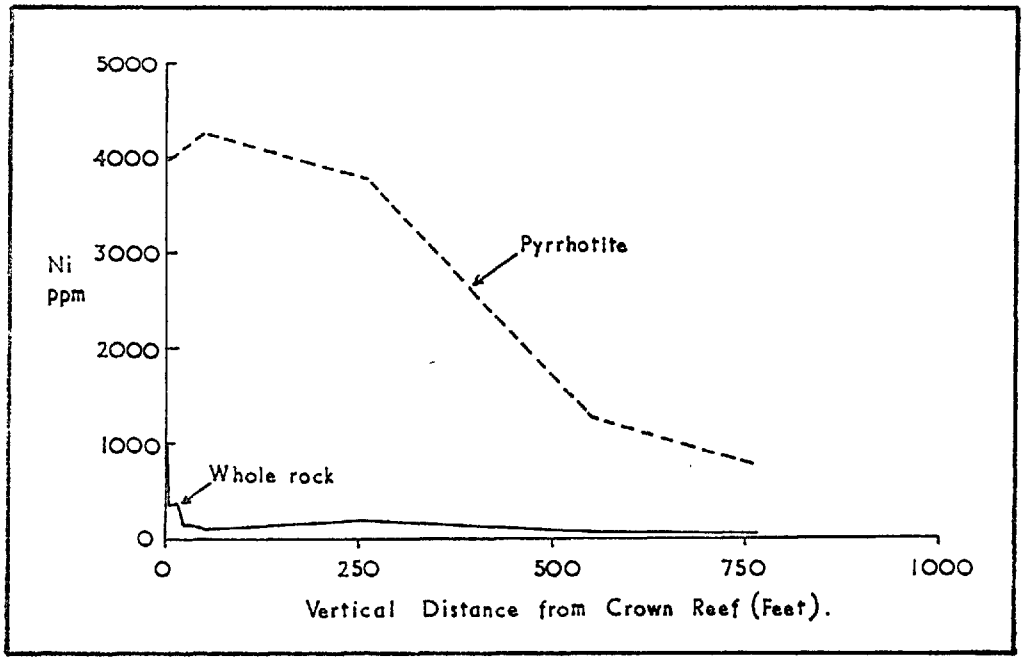


Fig. 27. Comparison of nickel contents of pyrrhotite and whole rock samples at varying distances from the Crown Reef, Norseman. Samples from D.D.H. C12.

The nickel contents of silicates are apparently insignificant compared to those of the sulphide fractions. However, it should be noted that the bisulphate attack is inefficient for some silicate minerals (Harden, 1962) and only part of any nickel held within silicate lattices would have been detected by the method used. Nevertheless, the amount of lattice-held nickel is unlikely to be comparable with the amount associated with pyrrhotite in anomalous samples. Since sulphides appear to be the most significant nickel-bearing minerals with regard to geochemical prospecting, this partial attack for silicate-bound nickel is unlikely to lead to serious errors of interpretation.

The distribution of chromium differs markedly from that of arsenic and nickel in that appreciable amounts of chromium occur in the silicate minerals. There was insufficient sample material to obtain reliable chromium figures for the less abundant ore minerals. Some concentration of chromium in sulphides is evident (Table 18), but the chromium present in silicates would largely account for the observed anomalies in wall-rocks. It seems likely that the distribution of chromium was related to the early wall-rock alteration stage of the hydrothermal activity at Norseman and its relationship to the localization of gold is more indirect.

Nickel and chromium are both very low in porphyry

samples, although minor concentrations of these elements occur in the sulphide fractions, which together make up less than 2% of the total rock. The high chromium contents for the mica and chlorite fractions, shown in Table 20 are probably suspect owing to the limited sample material available for analysis. Furthermore, these minerals together constitute less than 3% of the rock.

h) Relationship Between Wall-Rock Anomalies and Grade and Location of Orebodies.

The following considerations are based mainly on the results of geochemical investigations in the vicinity of Crown Reef. The conclusions are compared with the results obtained from the limited studies of other reef-shears and comment is made as to the extent to which they may be applicable to the area in general.

It is almost certain from the results of the foregoing studies that arsenic and nickel wall-rock anomalies are closely related to the hydrothermal emanations responsible for ore formation. Evidence for this is as follows:

(i) Arsenic and nickel occur almost exclusively in the sulphide minerals of the wall-rocks. The introduction of sulphides into the wall-rocks is believed to have been closely related to the emplacement of the mineralized quartz reefs (Hall and Bekker, 1965).

(ii) It has been shown that arsenic-nickel anomalies are restricted to the wall-rocks surrounding known reef-shears. Outwardly similar shear zones and quartz intersections, not known to be related to ore, invariably have low associated arsenic and nickel contents.

A consideration of the arsenic anomalies obtained in the vicinity of intersections on Crown Reef shows that there is no direct relationship between the magnitude of the anomalies and the grade of ore intersected. For example, the anomaly obtained in C40, which intersected high grade ore, is less prominent than that in C12, which intersected very low grade quartz. Moreover, the anomalies obtained in many holes which intersected no quartz at all are of comparable or greater magnitude to those which did intersect quartz (e.g. C49 and CU171-172).

The persistence of arsenic and nickel anomalies along the Crown Reef-Shear as much as 1600 feet up-dip from the known ore zone clearly constitutes an example of leakage dispersion. Leakage halos are formed as the result of ore-stage material leaking upwards from the blind orebody via a series of connected openings in the rock. In this case, the channel-way for the arsenical fluids was provided by the zone of reverse faulting in which the orebodies were developed. It is presumed that the mineralizing hydrothermal emanations moved upwards along

the reverse fault zone, depositing ore where conditions of temperature, pressure, lithology and structure were favourable. The arsenic and nickel-rich zone above the known ore zone marks the path followed by the hydrothermal fluids, either before or after the emplacement of the Crown orebodies or both. It is not known whether the ore-forming components were exhausted or were still in sufficient concentration to form further ore deposits higher up the shear, which have subsequently been eroded away.

The leakage anomaly associated with Crown Reef is best illustrated by reference to the Crown Sections at 4400N and 2000N (Figs 28 and 29). Strong arsenic anomalies (average > 50 ppm As) were found to occur in the wall-rocks adjacent to the reef-shear structure throughout the 4400N section (Fig. 28). The strongest anomalies, in terms of average arsenic content, are associated with the barren or low grade shear, immediately up-dip from the orebody. The reason for this is not obvious, although the influence of stratigraphy may have been significant. It can be seen from Fig. 28 that the weakest anomalies (average As <100 ppm) all occur in basaltic pillow lavas. The stronger anomalies (average As>100 ppm) were found in drill-holes where Crown Shear occurs in the coarser-grained rocks of the Crown-Bluebird Sill sequence, or in the case of C47, an east-dipping metagabbro dyke (Fig 8). The strongest anomaly, that in C44, occurs in the Bluebird Gabbro. The

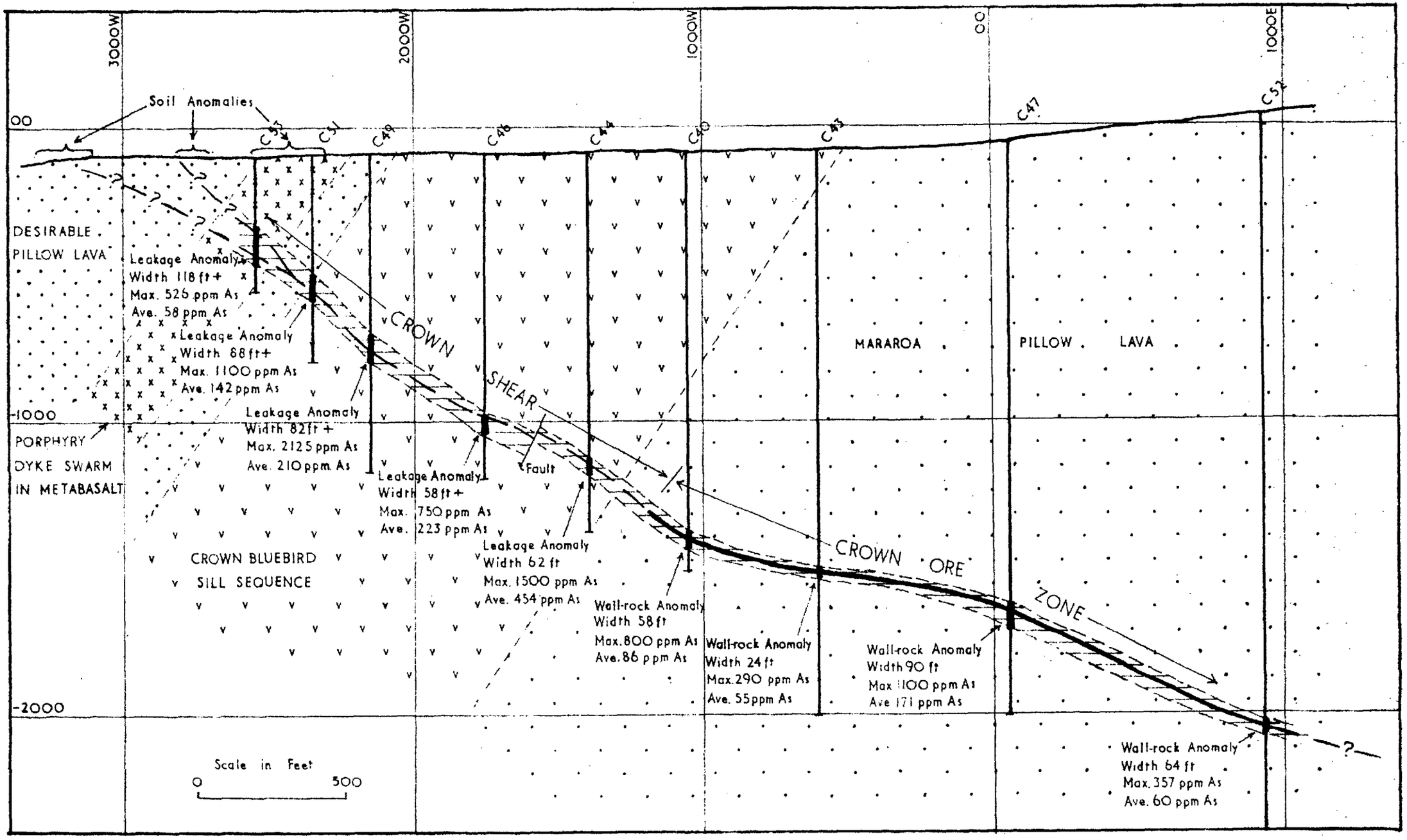


Fig. 28. Geological section at 4400N showing wall-rock and leakage anomalies in relation to ore occurrence on Crown Reef-Snear.

strength of the anomaly decreases slightly towards the surface, and in C53, the reef-shear appears to split into two separate channels. The extrapolated sub-outcrop of these two branches of Crown Shear coincide in position with arsenic anomalies found in soil samples collected at the surface (see Fig.52). A third soil anomaly occurring in the vicinity of the collars of C53 and C51, can be related to an outcropping porphyry dyke. It is conceivable that this anomaly is due to part of the arsenical mineralizing fluids' being diverted by the porphyry encountered in C53 and moving upwards along zones of shearing and fracturing within and adjacent to the porphyry. That porphyries have had some influence on the movement of hydrothermalfluids is suggested by Campbell's (1906, p.37) observation that "the intersection with felsite and quartz porphyry dykes is favourable to the deposition of gold in the reefs..., probably due to the arresting of the ore solutions". On the other hand, the anomaly could be due to a chance local concentration of arsenic within the porphyry, such as those found to occur in "background" porphyries (p.67).

In contrast with the section at 4400N, the arsenic anomalies associated with Crown Shear at 2000N are relatively weak (Fig. 29). Nevertheless, they are still sufficiently strong to delineate the reef-shear in drill-holes. No anomaly was found to occur in soils over the projected sub-outcrop of the shear at 2000N.

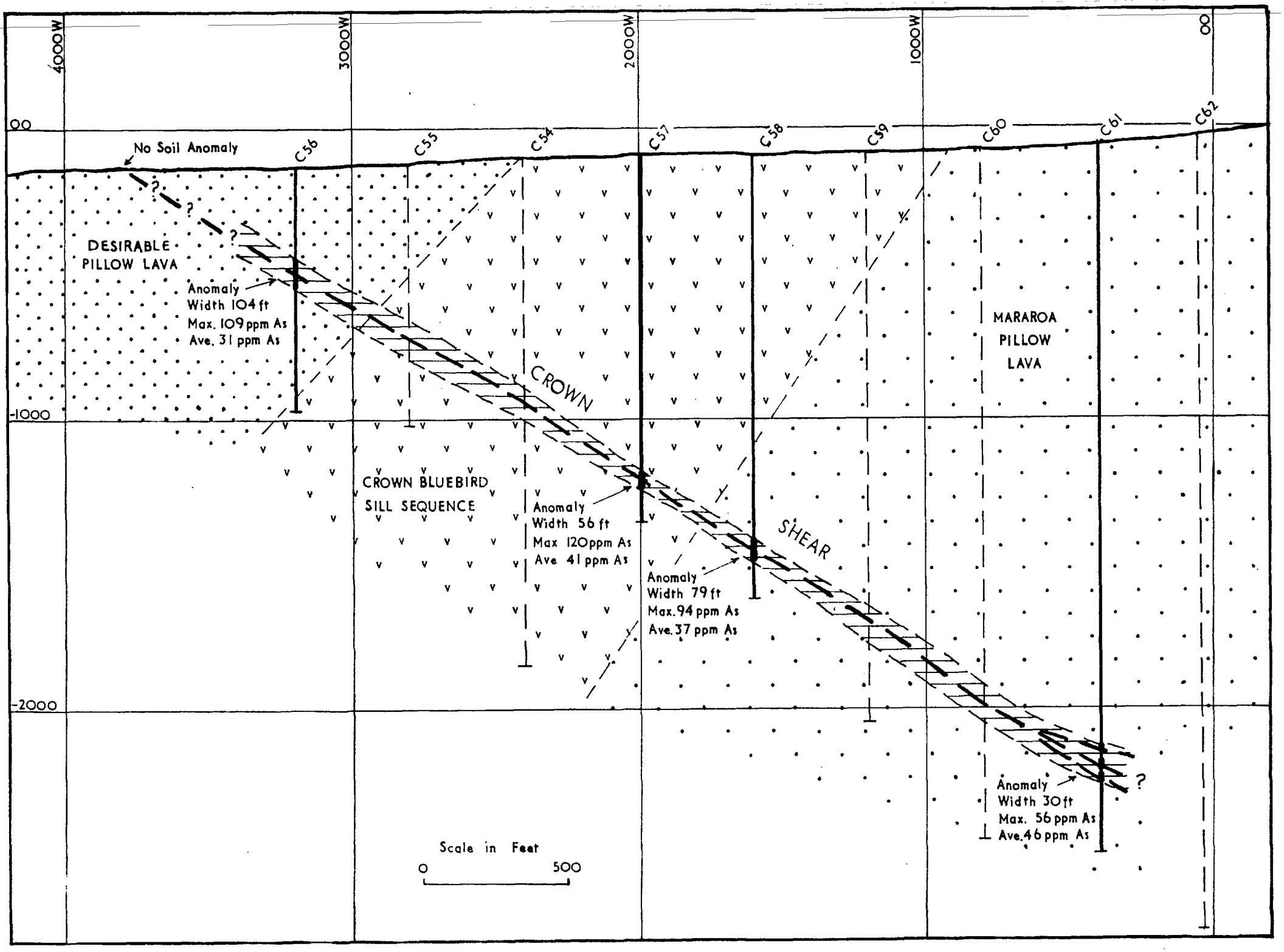


Fig. 29. Geological section at 2000N, showing arsenic anomalies associated with Crown Reef-Shear. Diamond drill-holes C55, C54, C59, C60 and C62 not sampled.

It would appear from this, that strong leakage anomalies occur only in an up-dip direction from orebodies. Anomalies associated with reef-shears to one side of orebodies tend to be much weaker, although still sufficiently strong to enable recognition of the ore structure.

It should be borne in mind, however, that the interpretation of the shear at 2000N as Crown Reef-Shear may be incorrect. Recent evidence has suggested the existence of a fault at 2000N, which displaces the Crown Shear. There are therefore two possible explanations for the arsenical shear structure encountered on this section.

(i) If the shear is pre-ore, the trace element anomalies are of similar origin to those encountered on the 4400N section and are due to the permeation of hydrothermal emanations along the shear zone.

(ii) If the fault is post-ore, the anomalies could be due to the "dragging" of anomalous wall-rock material into the zone of shearing during fault movements.

Many factors seem to indicate that the former is the more likely explanation.

(i) The nature of the wall-rock alteration is similar to that associated with the known Crown Reef-Shear in other parts of the area.

(ii) The widths of the wall-rock anomalies at 2000N are comparable with those encountered in other drill-holes intersecting Crown Shear.

(iii) If the trace element anomalies were of "drag" origin, erratic high values, such as those obtained in CU60 (Fig. 26) might be expected to occur.

(iv) The change of strike of the shear at 2000N is no more marked than the many other changes in attitude, both in dip and strike, observed in other parts of the Crown Reef-Shear.

(v) The dip of the shear at 2000N is uniform and comparable with that of the barren shear to the west of the Crown ore zone at 4400N. The absence of ore is explained by the lack of "flat" sections on the shear which would have created favourable loci for quartz deposition during reverse faulting movements (Connolly, 1936).

It is therefore considered that the arsenical shear at 2000N was part of the pre-ore Crown fracture pattern and that the weak arsenic anomalies associated with this shear were formed at the time of gold deposition. The possibility of additional post-ore faulting cannot be ruled out, but this would not affect the above conclusions regarding leakage dispersion.

The only other Norseman reef studied in any detail, the Princess Royal Reef, was found to have consistently high arsenic contents in the wall-rocks in the vicinity of, and up-dip from, ore. No evidence of associated nickel anomalies was found in the drill-holes studied,

but a weak nickel anomaly was obtained in soils in the vicinity of the outcrop of the reef (Fig. 53). Nickel anomalies in general, do not seem to be as characteristic a feature of reef-shears as arsenic, since the nickel anomalies associated with Crown Reef-Shear are also insignificant in some holes where strong arsenic anomalies were obtained (e.g. C53, C29 and C71). In addition, a strong nickel anomaly was found in C57 on the 2000N Crown section, where it is accompanied by only weakly anomalous arsenic values. Chromium contents are likewise somewhat erratic in the vicinity of Princess Royal Reef, being relatively high in PRS10, PRS69 and PR469, but low in PRS65. It has already been suggested that chromium is probably only indirectly related to mineralization at Norseman.

Weak arsenic anomalies were found to occur in drill-holes intersecting the Mararoa and Bluebird Reefs, an E-W vein and in one hole drilled to intersect the Norseman Reef. This implies that these reefs have similar geochemical characteristics to the Crown and Princess Royal reefs. However, in view of the results obtained on Crown Reef, it is obvious that more detailed work needs to be done to establish the relationship, if any, between the nature of the anomalies and grade and location of ore-bodies on the reefs. The intersections on the Bluebird and Norseman (S28) Reefs were both down-dip from the known orebodies. Since, in the absence of suitable drill-core, no detailed information could be obtained on Crown

Shear below the ore zone, it cannot be stated whether the Bluebird and Norseman Reef anomalies are abnormally low for this environment. It is not certain that the reef intersected in S35 was actually the Norseman-Northern Star Reef, and the background arsenic and nickel contents obtained seem to suggest that the intersection is not related to any major reef-shear.

The relatively weak arsenic anomaly associated with the Mararoa Reef-Shear, is somewhat surprising in view of the fact that the intersection occurs immediately up-dip from an orebody. Soil samples (p.177) demonstrate that leakage halos do occur on the Mararoa Reef-Shear and hence, a stronger primary arsenic anomaly might have been expected in this hole.

The arsenic anomaly in the wall-rocks adjacent to the E.W. vein is considerably weaker than those related to high grade ore in the Crown and Princess Royal Reefs. However, high arsenic values were obtained in the reef quartz itself and it is suggested that the arsenical mineralizing fluids were largely confined to the quartz due to lack of shearing in the adjacent wall-rocks.

Chromium anomalies were found to occur in the vicinity of the Mararoa and (?) Norseman-Northern Star Reef-Shear (S35), but with these exceptions, nickel and chromium anomalies were not generally found to be present in other reefs.

To summarize:

(i) Primary arsenic wall-rock anomalies were found to be characteristic of all the reef-shears tested. There appears to be a definite relationship between the magnitude of the arsenic anomalies and ore occurrence on the Crown, and possibly Princess Royal Reef-Shears, but the significance of the anomalies related to other reef-shears has yet to be established.

(ii) Nickel anomalies are fairly consistently associated with the Crown Reef-Shear but were not encountered in drill-core samples from intersections on other reefs. High nickel in wall-rocks may be a useful indication of proximity to orebodies on Crown Reef-Shear when used in conjunction with arsenic. Determinations of the nickel contents of pyrrhotite appear to give very broad anomalies related to mineralization on Crown Reef-Shear and hence may be of considerable use in prospecting by deep drilling.

(iii) Chromium anomalies are usually, but not always, associated with all reef-shears, as well as many zones of rock alteration unrelated to ore and are therefore only of minor importance with regard to the search for ore occurrences.

C. TRACE ELEMENT DISTRIBUTION IN GOLD QUARTZ REEFS AT NORSEMAN.

Composite chip samples of the quartz reef were

collected at 20 foot intervals from underground workings, to determine the nature of trace element distribution in the vicinity of ore-shoot A (Fig. 15) on Crown Reef. The ore-shoot outline and trace element distribution in quartz samples are shown in Figs. 30 to 40. The range and average concentrations of the elements determined are given in Table 21. With the exception of As and Zn, which were analysed colorimetrically, spectrography was used for all the determinations.

TABLE 21.

Concentration of Trace Elements in Quartz Reef in the Vicinity of Ore-Shoot A, Crown Reef, Norseman.

Element	Minimum ppm	Arithmetic Mean ppm	Maximum ppm	Element	Minimum ppm	Arithmetic Mean ppm	Maximum ppm
Ag	<0.2	26	>1000	Mo	<2	2	15
As	<2	43	800	Ni	5	211	1500
Bi	<5	4	60	Pb	<2	116	3000
Co	<5	19	100	Sn	<5	6	150
Cr	15	125	800	Ti	40	923	>10,000
Cu	4	58	200	V	<5	36	400
Ga	<2	5	15	Zn	<3	50	1200
Mn	15	442	1800	Zr	<200	<200	<200

It will be noticed from Table 21 that the average levels of concentration of Co, Cr, Cu, Ga, Mn, Ti, V and

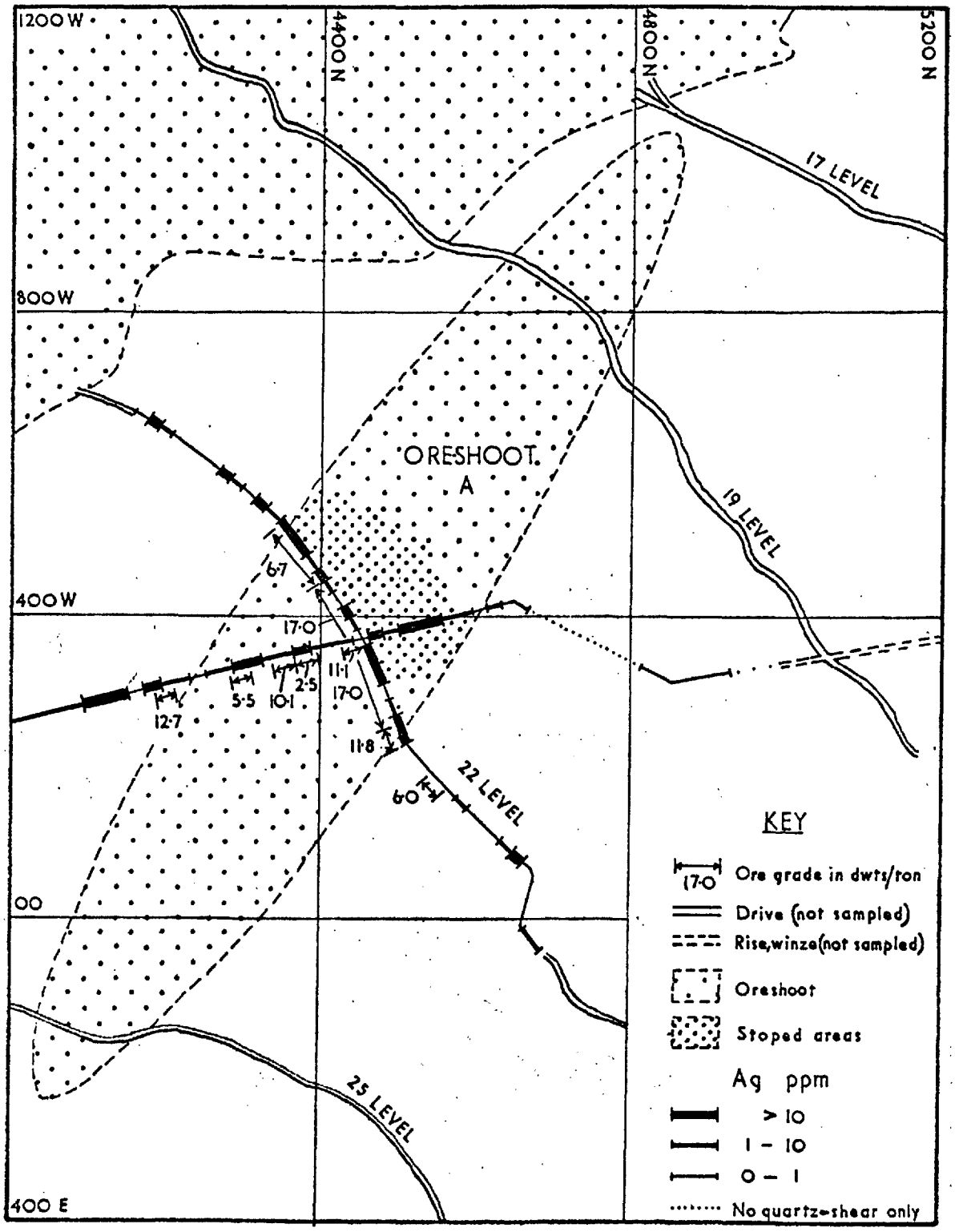


Fig. 30. Composite plan of part of Crown Reef, Norseman, showing distribution of Ag in quartz in the vicinity of ore-shoot A.

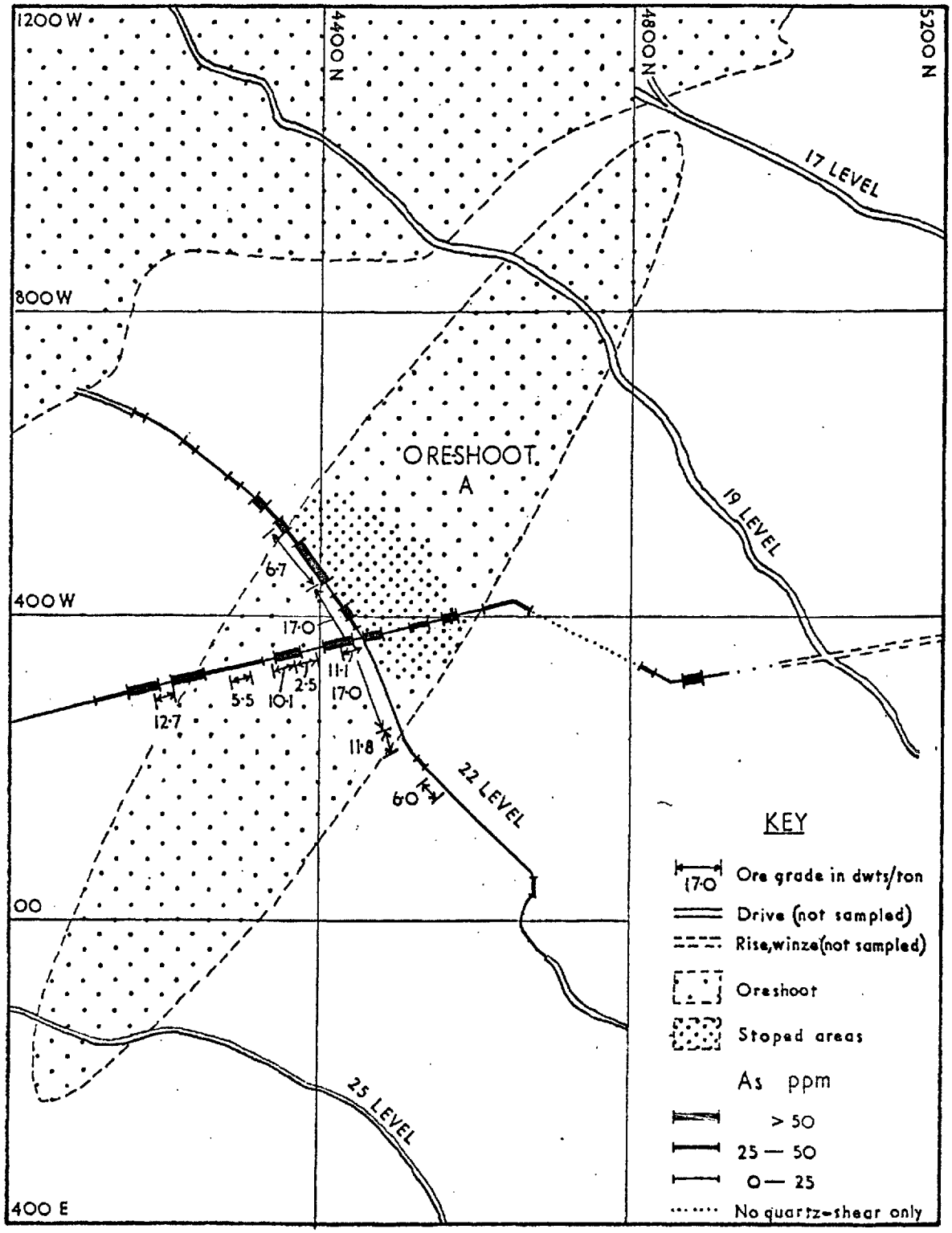


Fig. 31. Composite plan of part of Crown Reef, Norseman, showing distribution of As in quartz in the vicinity of ore-shoot A.

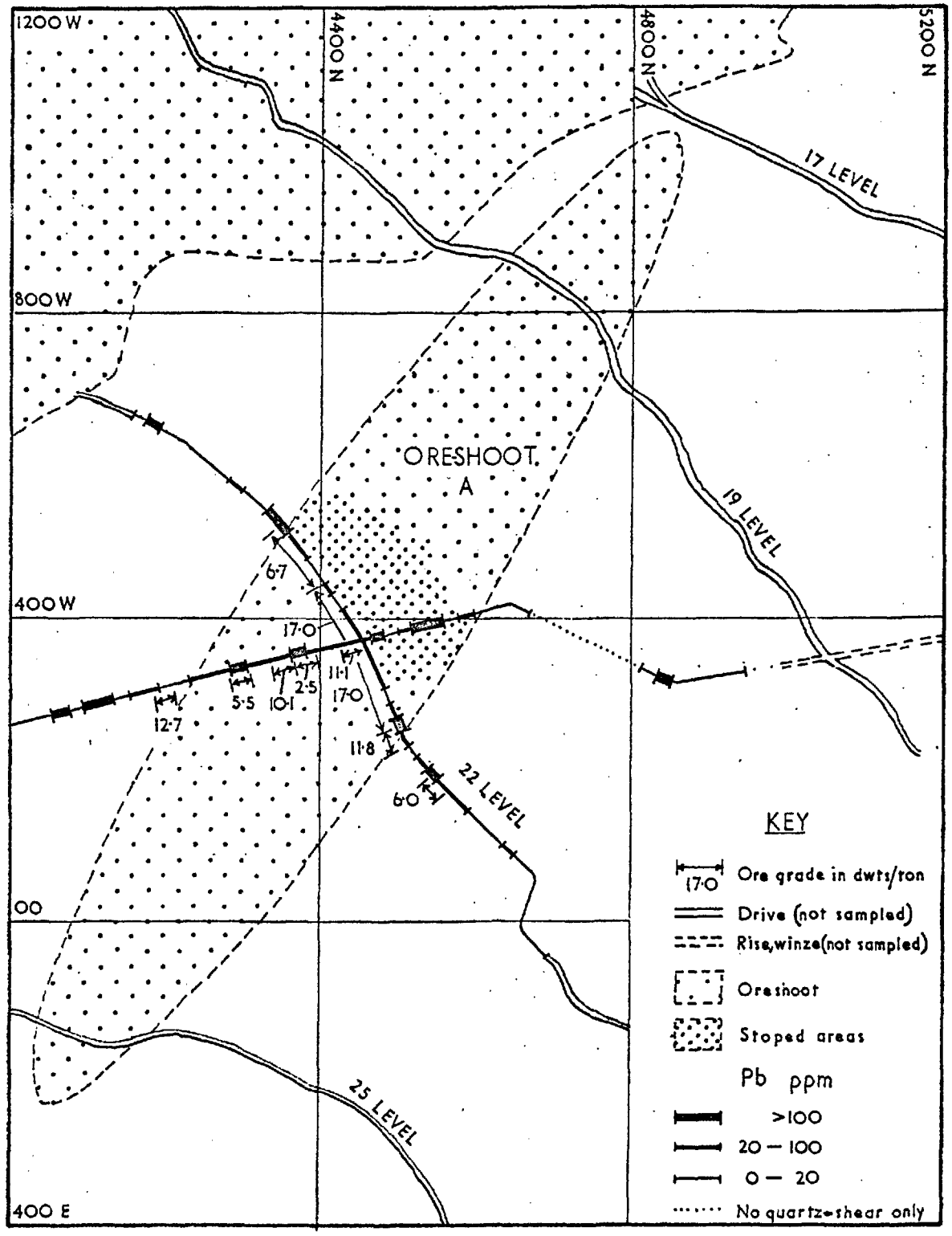


Fig. 32. Composite plan of part of Crown Reef, Norseman, showing distribution of Pb in quartz in the vicinity of ore-shoot A.

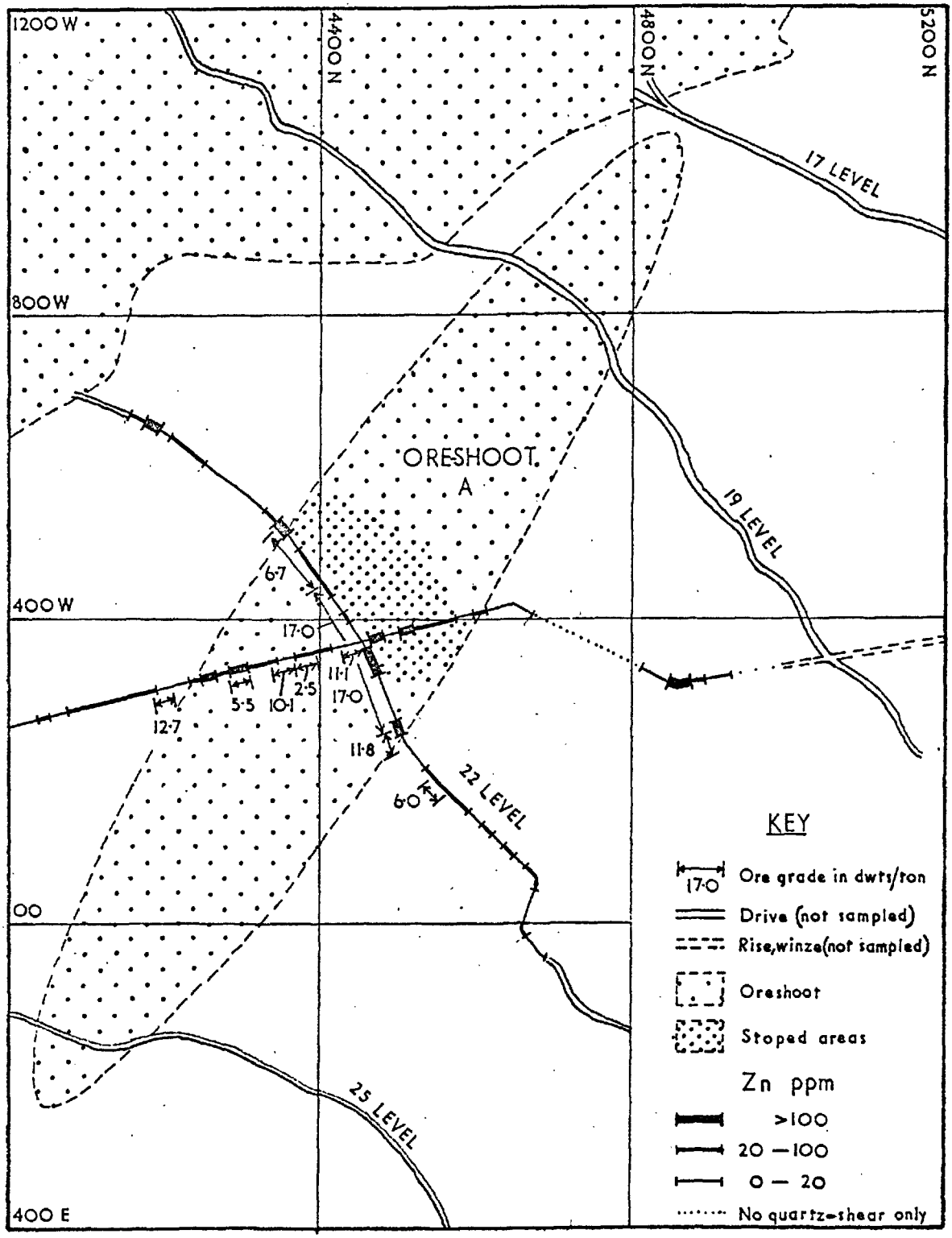


Fig. 33. Composite plan of part of Crown Reef, Norseman, showing distribution of Zn in quartz in the vicinity of ore-shoot A.

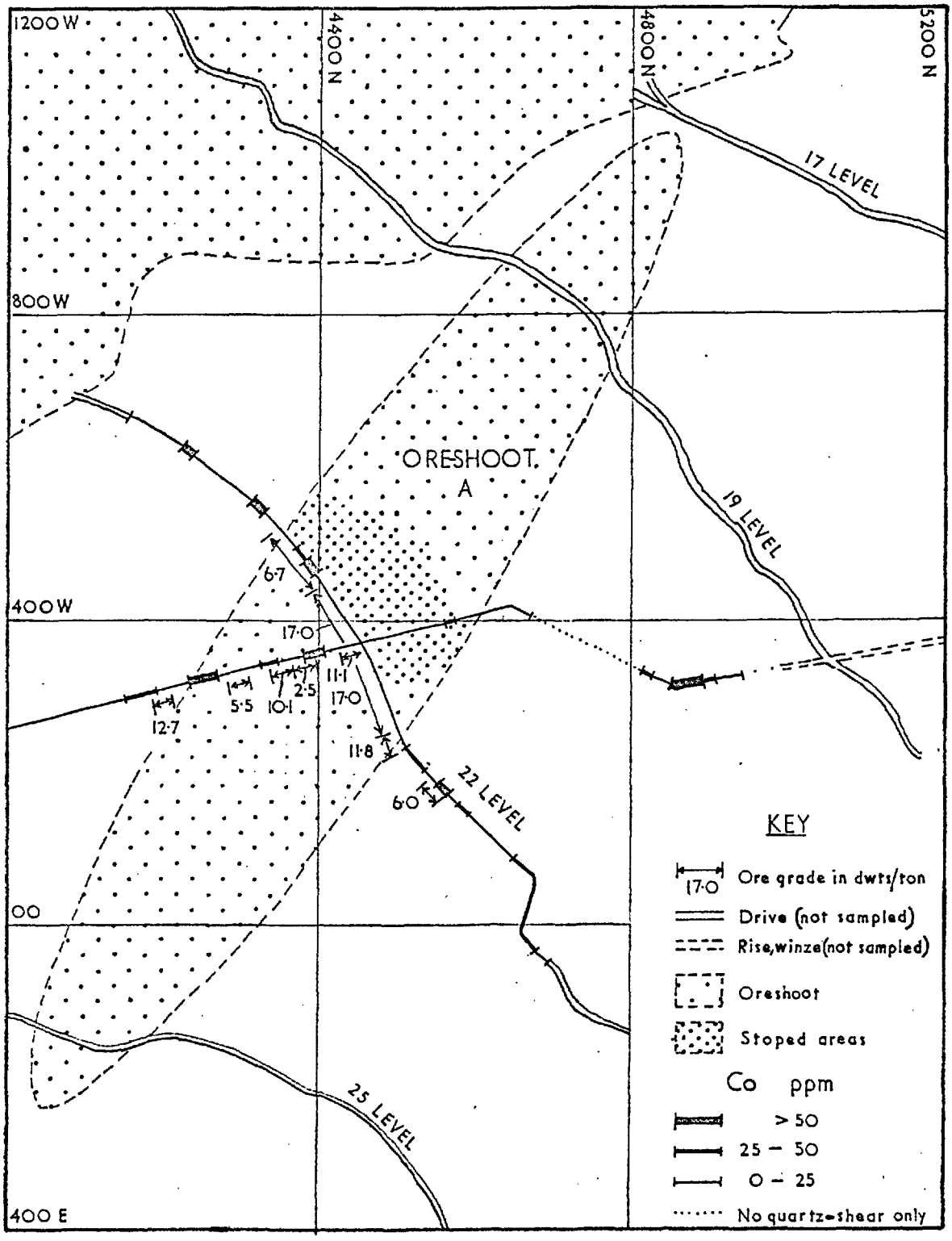


Fig. 34. Composite plan of part of Crown Reef, Norseman, showing distribution of Co in quartz in the vicinity of ore-shoot A.

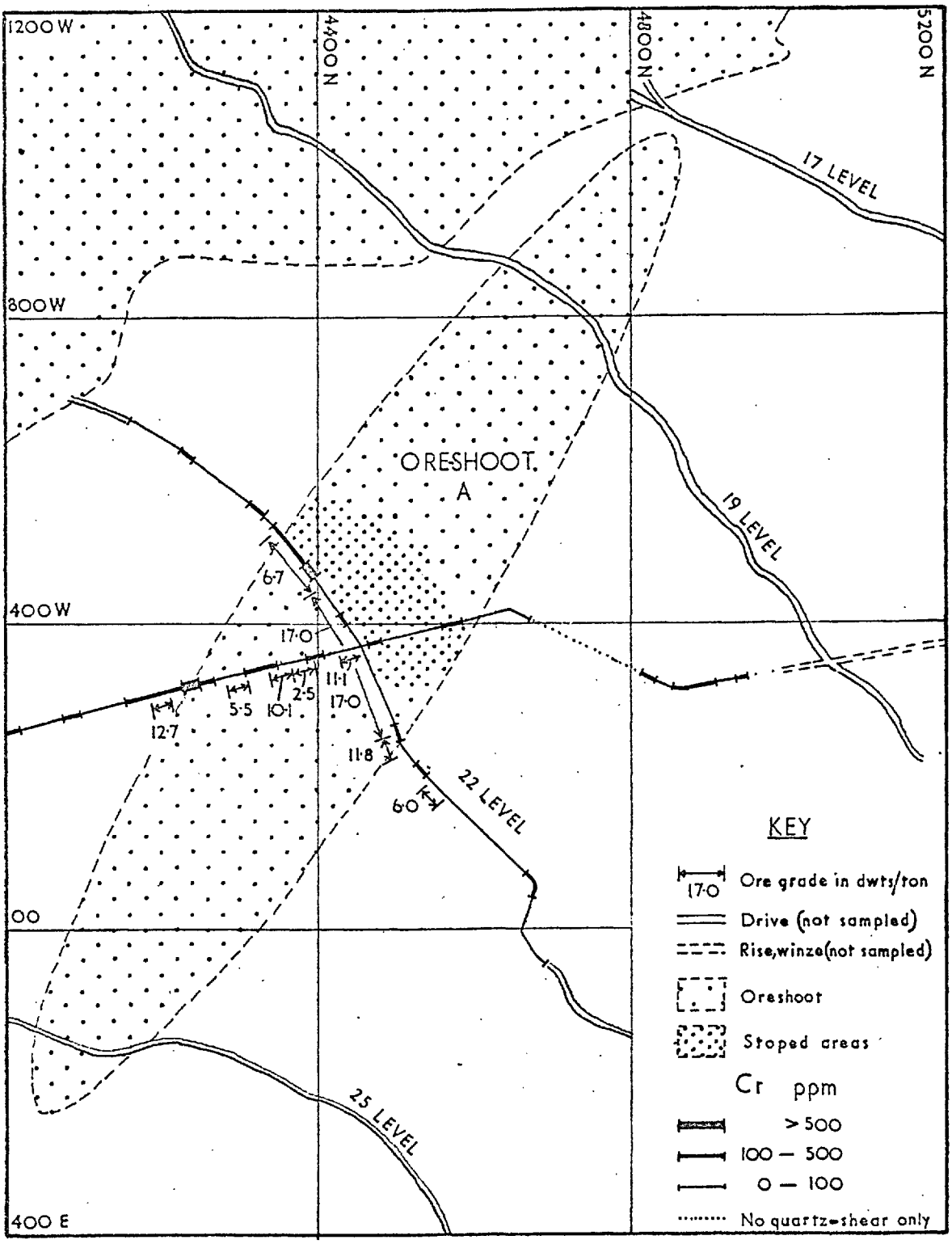


Fig. 35. Composite plan of part of Crown Reef, Norseman, showing distribution of Cr in quartz in the vicinity of ore-shoot A.

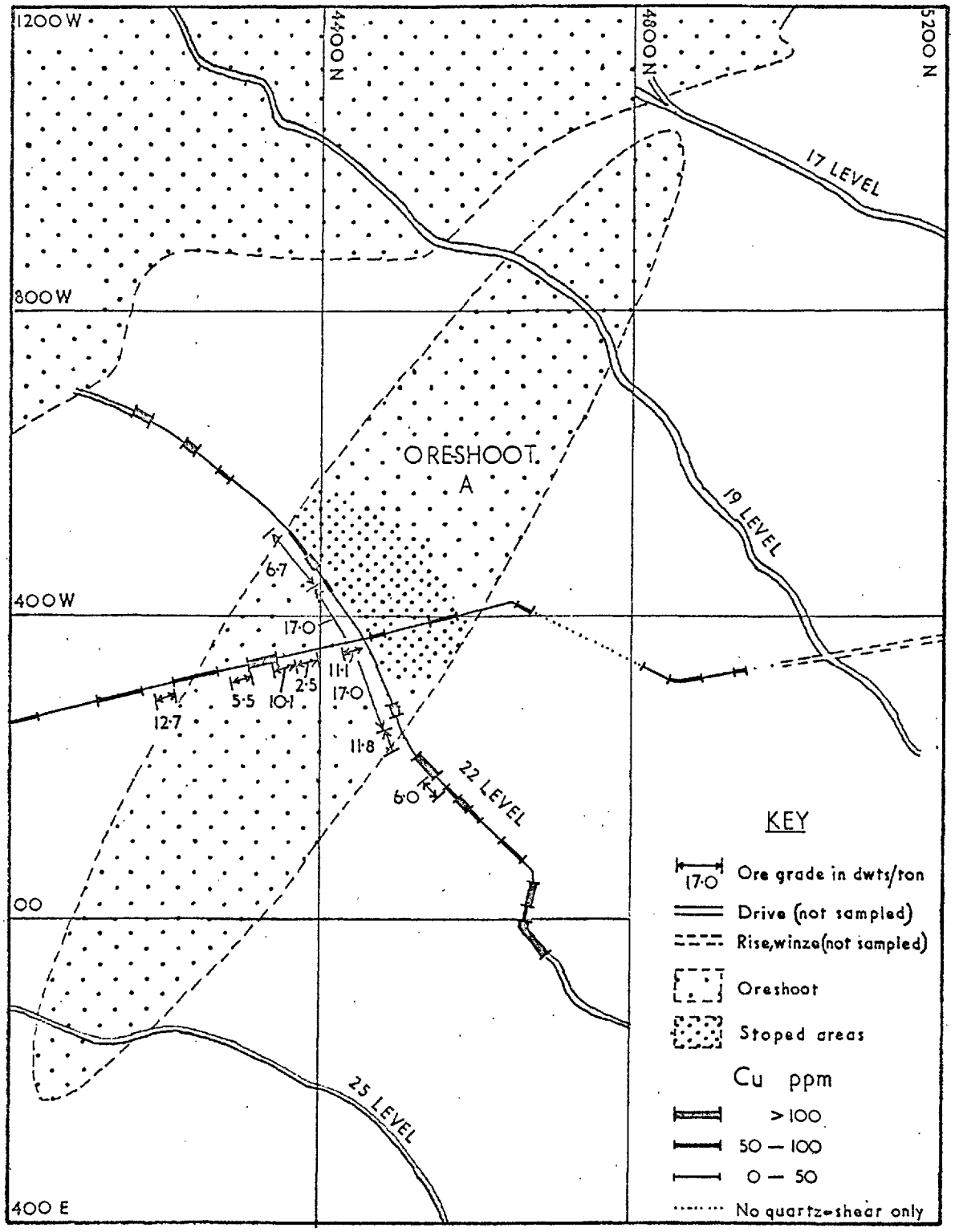


Fig. 36. Composite plan of part of Crown Reef, Norseman, showing distribution of Cu in quartz in the vicinity of ore-shoot A.

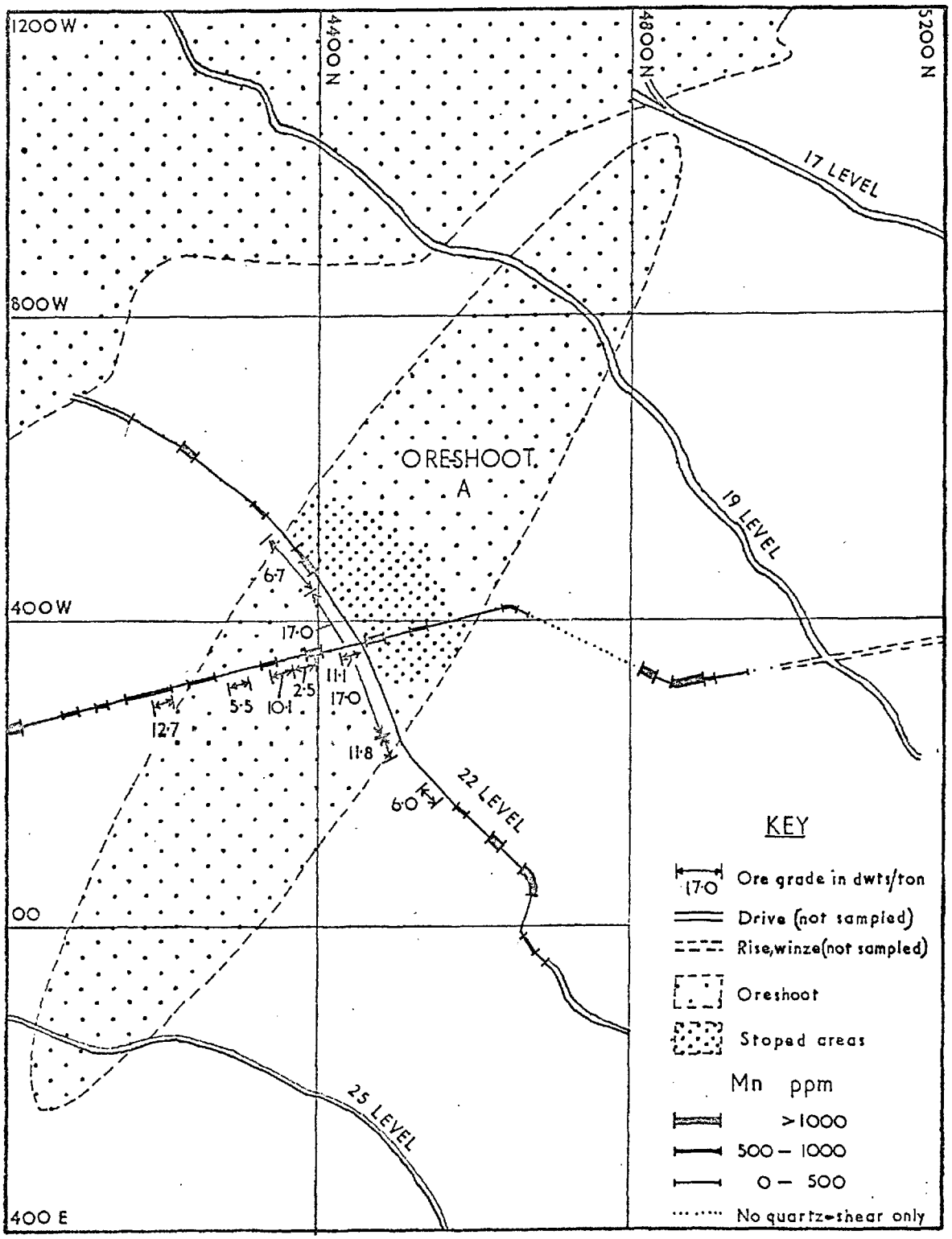


Fig.37. Composite plan of part of Crown Reef, Norseman, showing distribution of Mn in quartz in the vicinity of ore-shoot A.

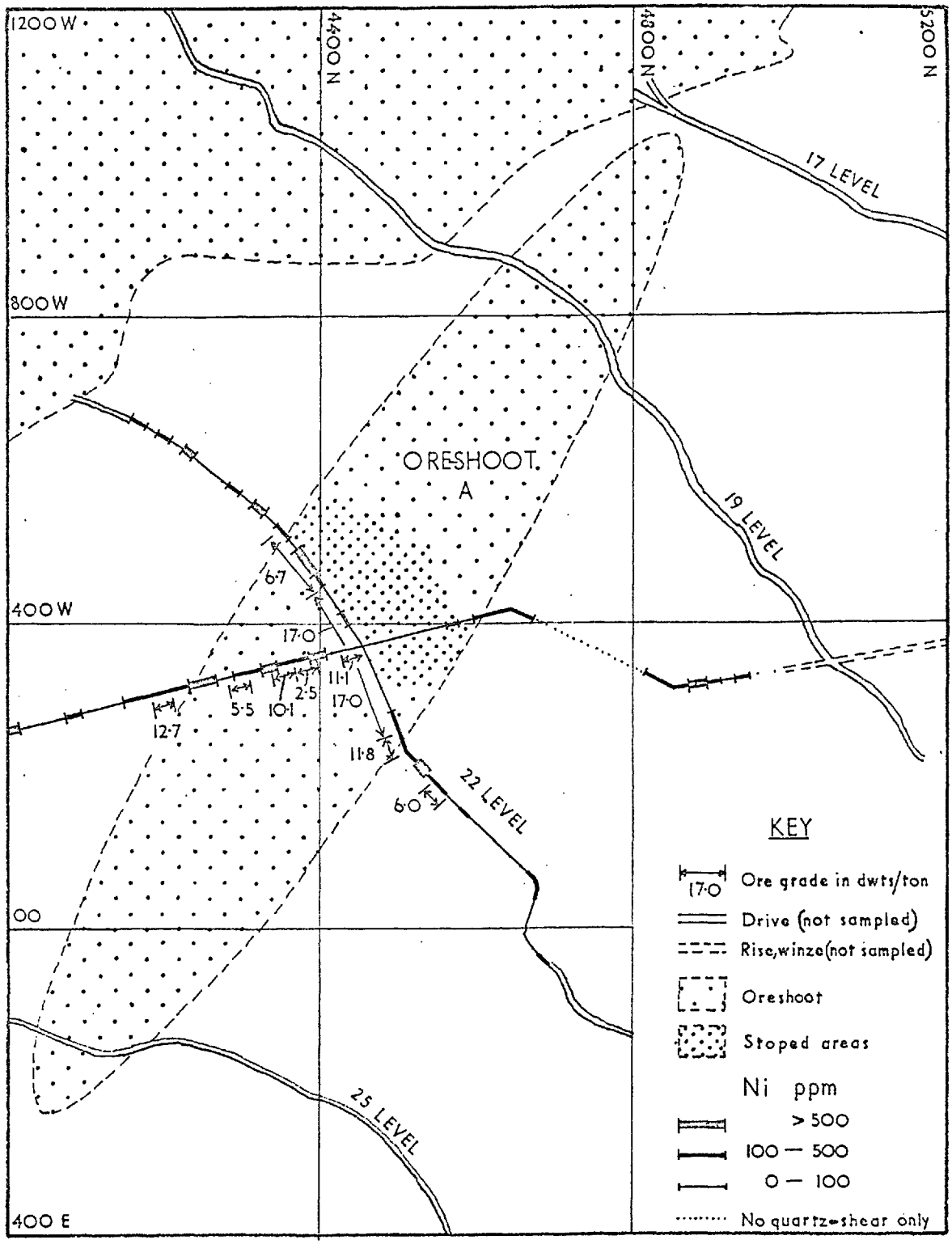


Fig.38 Composite plan of part of Crown Reef, Norseman, showing distribution of Ni in quartz in the vicinity of ore-shoot A.

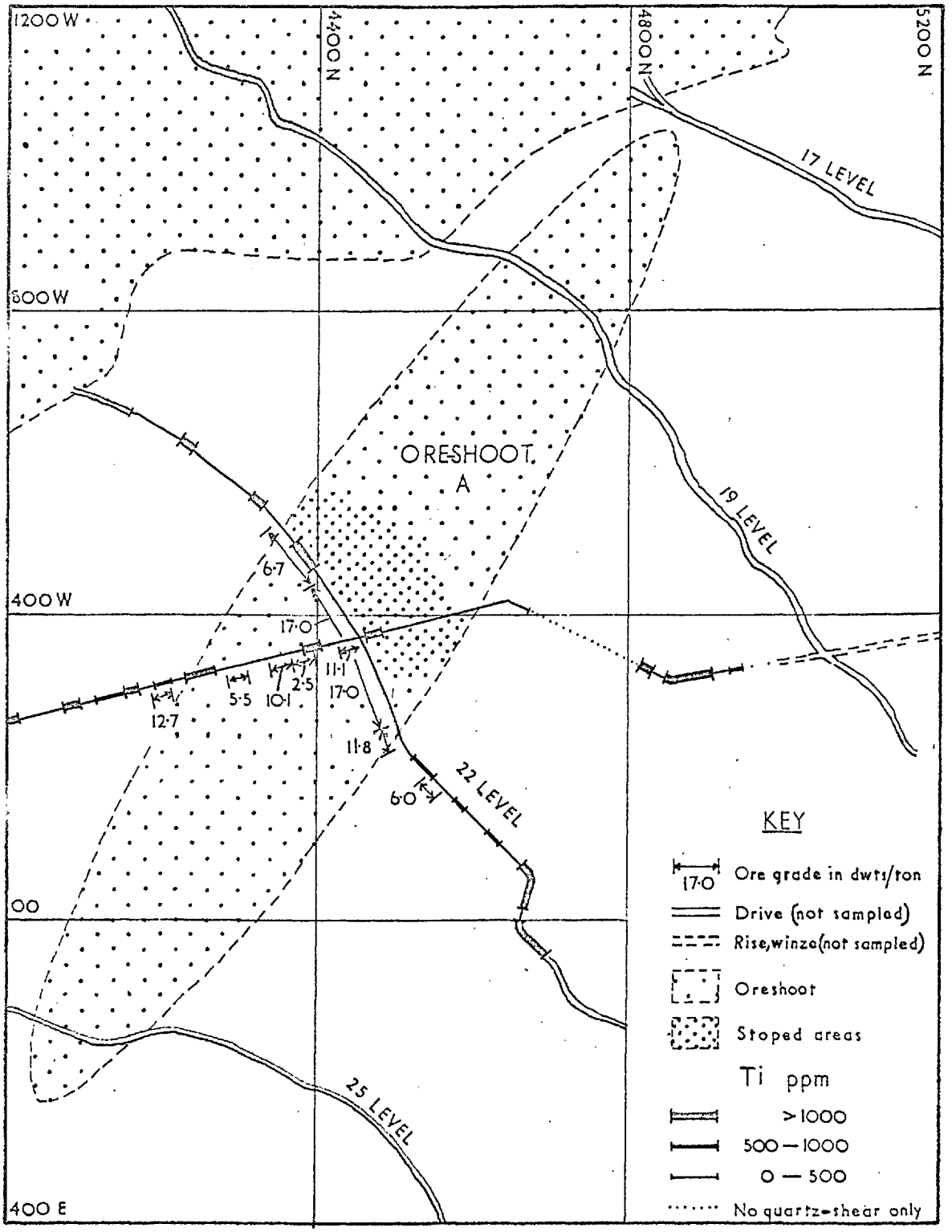


Fig. 39. Composite plan of part of Crown Reef, Norseman, showing distribution of Ti in quartz in the vicinity of ore-shoot A.

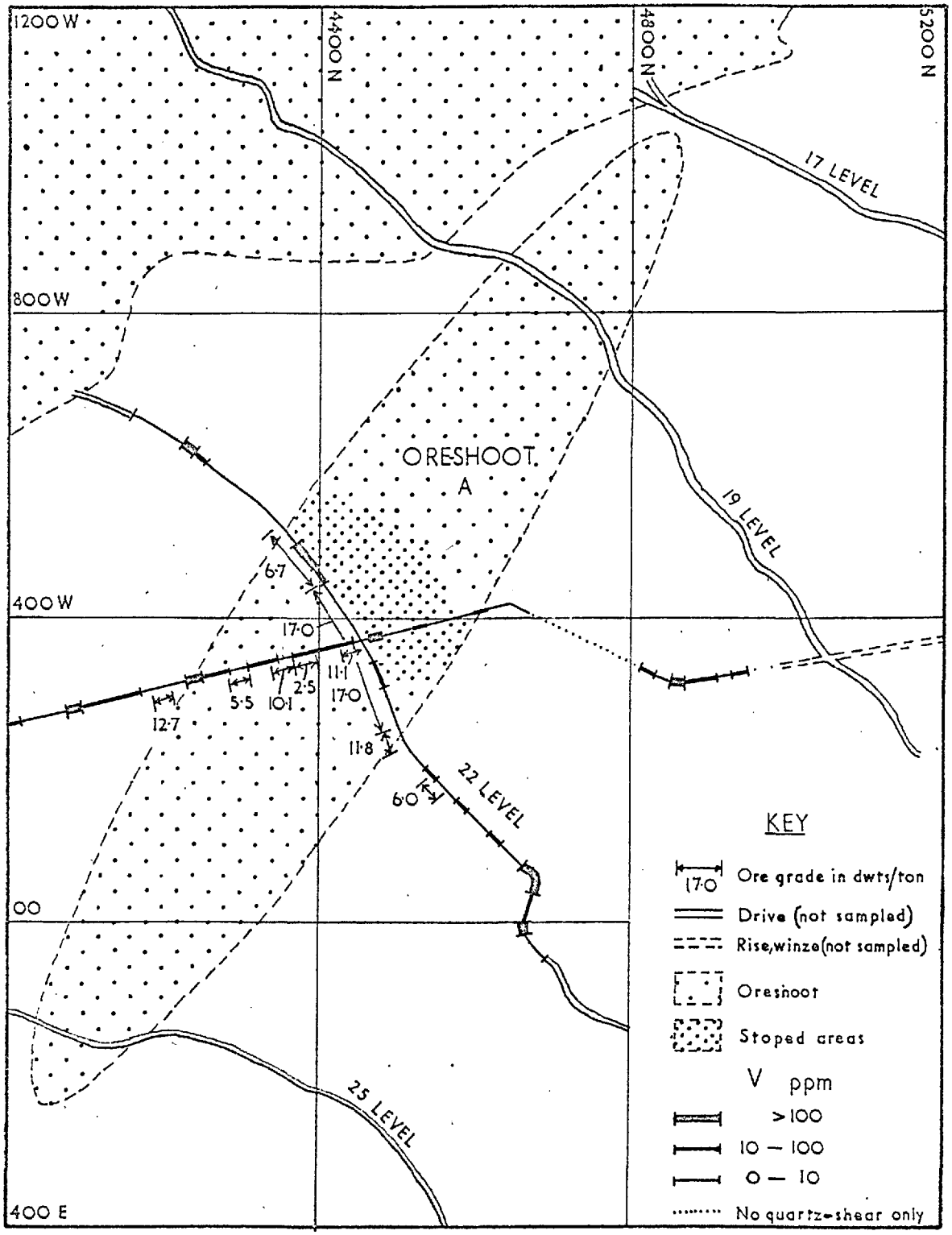


Fig.40. Composite plan of part of Crown Reef, Norseman, showing distribution of V in quartz in the vicinity of ore-shoot A.

Zn in the quartz reef are appreciably lower than those in background greenstone. As, Ag, Ni and Pb appear to have been concentrated in the quartz, relative to background greenstones, although the As and Ni contents are appreciably lower in the quartz than in the anomalous wall-rocks adjacent to the ore-shoot (c.f. diamond drill-holes C12, C47 and CU169). The concentrations of Bi, Mo, Sn and Zr are, with few exceptions, less than the limits of detection of the analytical method in both quartz and greenstone.

The distribution patterns shown by most elements, (Ag, As, Pb and Zn excluded) are erratic and bear little relation to the distribution of gold values.

The distribution of Ag, As, Pb and to a lesser extent, Zn, is more regular and appears to follow that of gold, in that the highest concentrations for these elements are generally found within the estimated outline of the ore-shoot (Figs. 30, 31, 32 and 33), although sporadic high values also occur outside the ore zone. The actual relationship between these elements and gold is obscure. When data for As, Ag, Pb and Zn from ore-shoot A and a large number of drill-hole intersections are plotted against the corresponding gold values a random distribution is obtained (Fig.41a). Nevertheless, the geochemical evidence generally supports Hall and Bekker's (1965) observation that the presence of galena and arsenopyrite in the quartz reef is an indication of gold values.

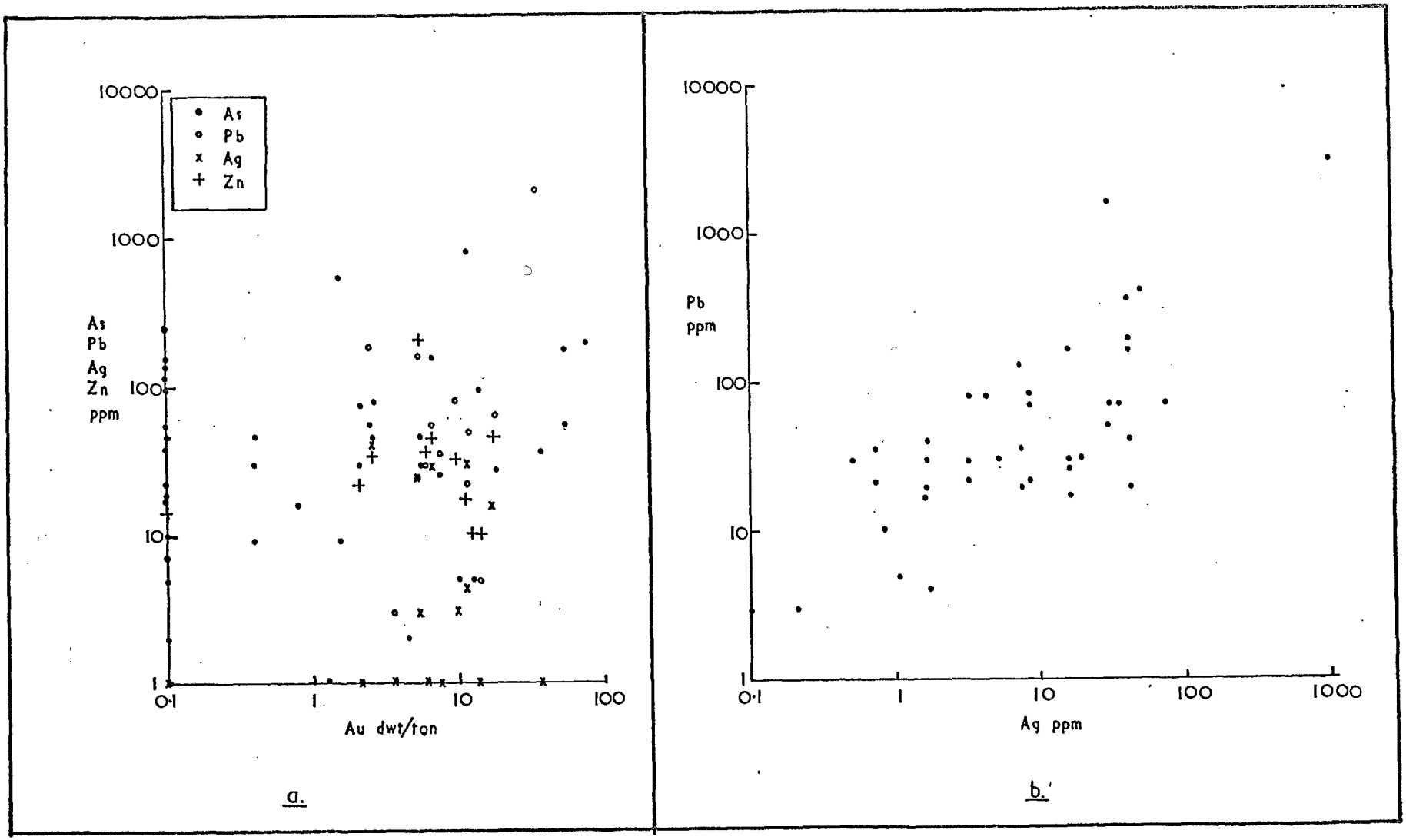


Fig. 41 a. Relationship between As, Pb, Ag, Zn & Au in auriferous quartz reefs, Norseman.

b. Relationship between Pb & Ag in quartz within oreshoot A, Crown Reef, Norseman.

Campbell (1906) reported that the galena in Norseman quartz reefs is silver-bearing, which would explain the similarity in the distribution patterns for these two elements. A vaguely linear relationship between silver and lead has been found to exist in samples from oreshoot A (Fig.41b).

The distribution patterns for arsenic and zinc are somewhat different from those of silver and lead, bearing out the essentially independent mode of occurrence of the minerals, arsenopyrite, sphalerite and galena. Some of the high arsenic values occurring outside the ore-shoot can be attributed to inclusions of highly arsenical greenstone wall-rocks in the quartz.

The highest concentrations of the elements Co, Cr, Mn, Ni, Ti, and V almost invariably occur in samples with included greenstone remnants. These elements all occur in appreciably higher concentrations in the wall-rocks than in the actual reef. There is no evidence of a relationship between the chromium and vanadium values and the occurrence of the green hydromica, mentioned by Hall and Bekker as an indicator of gold values. This micaceous mineral is apparently neither fuchsite nor roscoelite.

Copper values appear to be erratic and unrelated to other geological features. The concentration of gallium within the quartz reef does not show significant variation, whilst the nature and significance of the distribution patterns for B, Mo, Sn, and Zr remains unknown due to the

low concentrations present and poor sensitivity of the spectrographic method for these elements.

II.KALGOORLIE.

A. GEOLOGY OF THE KALGOORLIE DISTRICT.

1. General.

Kalgoorlie is currently the foremost gold-mining centre in Australia, the total production since the discovery of the field in 1893 to the end of 1962, amounting to 33,853,215 oz. gold from 80,556,572 tons of ore, an average grade of 8.4 dwts/ton. The present annual production is approximately 500,000 oz. gold at an average grade of 5 dwt/ton.

2. Stratigraphy and Lithology.

The rocks at Kalgoorlie consist of a sequence of Precambrian sediments, ultrabasics, lavas and pyroclastics that have been intruded by sills of doleritic composition and small dykes of acid and intermediate porphyritic rocks. The rocks have suffered greenschist facies regional metamorphism and extensive propylitization has taken place in the vicinity of mineralization.

The rock succession at Kalgoorlie is given in Table 22.

TABLE 22.

Stratigraphic Succession at Kalgoorlie

(After Woodall,1965)

Rock Unit	Thickness	Lithology
Black Flag Beds	10,000 ft (approx)	Tuffs, acid to intermediate lavas and agglomerate, sandstone, shale, slate and quartzite.
Golden Mile Dolerite	1000-2500 ft.	Sill of meta-quartz-dolerite and meta-quartz-gabbro with minor, more basic sections.
Paringa Basalts	1000-3000 ft.	Metabasaltic lavas, in part pillow lavas, with minor interbedded slates.
Williamstown Dolerite	500-1000 ft.	Sill of metadolerite and metagabbro, transitional to meta-quartz-dolerite near top and hornblendite near base.
Kapai Slate	10 ft.	Graphitic slate.
Devon Consols Basalt	200-300 ft.	Metabasaltic lavas, typically pillow lavas.
Hannan's Lake Serpentinite	1000-3000 ft.	Massive fine-grained serpentinite.

The doleritic rocks are broadly stratigraphic but evidence of relict igneous textures, locally transgressive contacts and possible magmatic differentiation imply that they are intrusive sills. These rocks are equivalent to the

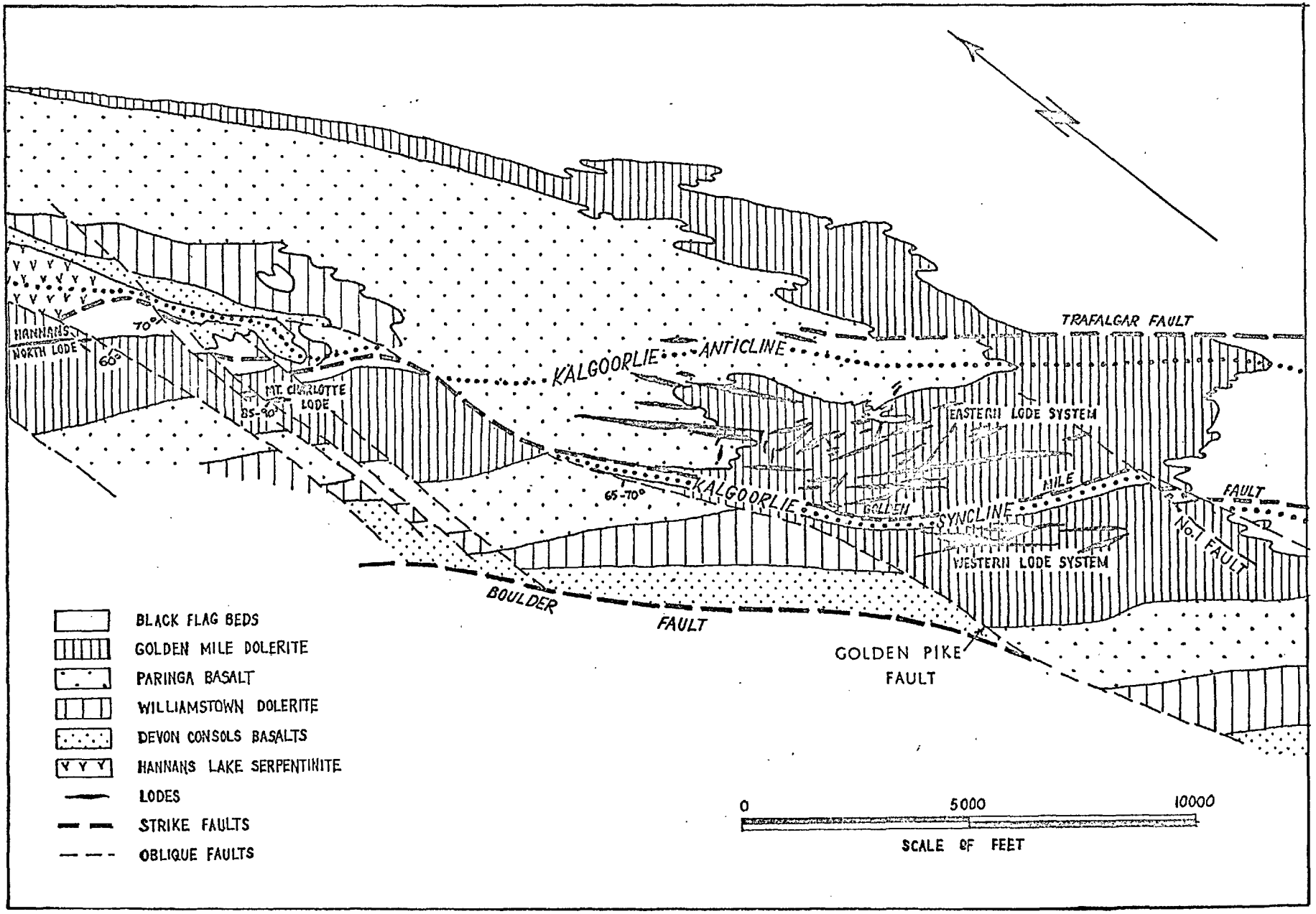


Fig. 42. Geological map of Kalgoorlie (after Woodall, 1965).

"Younger Greenstones" and the basaltic rocks to the "Older Greenstones" of Western Australia (p.11).

The most important host-rocks of gold deposits are those of the Golden Mile Dolerite but important mineralization also occurs in the Paringa Basalt.

3. Geological Structure.

The area has been folded into a series of steeply dipping isoclinal folds, trending north-north-west, with which are associated several major strike faults. Oblique faults with more northerly trend have segmented some sections of the fold structure.

The main ore deposits are concentrated about a tight infold of the Black Flag Beds, known as the Kalgoorlie syncline. This fold, which has been extensively invaded by albite porphyry, divides the main mineralized area into the Eastern and Western Lode Systems (Fig. 42). The Kalgoorlie anticline-syncline system has a consistent plunge of 20° to the south throughout the mineralized area.

4. Mineralization.

Two types of gold mineralization occur at Kalgoorlie. The most important group, from which 98% of the total gold production has come, are locally known as "lode formations". These are essentially pyritic replacements along steeply dipping shears and fractures. They exhibit

varying degrees of silicification, carbonation and sericitization and carry both free gold and gold tellurides. The occurrence of gold telluride mineralization is restricted to the southern three miles of the auriferous belt, known as the Golden Mile. Apart from auriferous pyrite and tellurides of gold, silver and mercury, Simpson and Gibson (1912) note the frequent occurrence of small amounts of tourmaline, arsenopyrite, chalcopyrite, sphalerite and minerals of the tetrohedrite-tennantite series in the lodes.

The second type of deposit occurs sporadically over a total strike length of ten miles, but has been exploited mainly in the northern part of the area. Tellurides are absent and quartz is more abundant in this type, which occurs both as replacement lodes and as stockworks of quartz veins. The Mt. Charlotte and Hannan's North Lodes are examples of this type.

Both types of mineralization occur only in chloritized host-rocks. The present research has only been concerned with the former type of deposit.

Finucane and Jensen (1953) recognise four different types of lodes in the Golden Mile, on the basis of structure:

(i) Main Lode Series, which strike 315° to 330° and dip either vertically or steeply to east or west.

(ii) No. 2 Lode Series, which strike 300° to 305° and dip 65° to 75°W.

(iii) Caunter Lodes, which strike 270° to 290° and dip south at 55° to 70°, the mean dip being in the

vicinity of 65°.

(iv) Cross Lodes, which strike 40° to 70° and dip steeply to the north or south.

Woodall (1965) has shown that the three main structural lode-types, the Main, Caunter and Cross Lodes, were developed in response to stresses resulting from movement along the major oblique faults, the Golden Pike and No. 1 Faults, which form the northern and southern boundaries of the Golden Mile mineralization.

Fig. 42 shows only the major gold-telluride lodes and gives no indications of the intensity of mineralization. Near the centre of the field, lodes and minor mineralized structures frequently occur at intervals of less than 100 ft. across the strike.

5. Wall-rock Alteration.

All the known mineralization at Kalgoorlie occurs in broad areas where the tremolite-actinolite and plagioclase of the barren greenstones have been converted into chlorite and carbonate. This regional alteration is believed to have preceded the gold mineralization (Bartram, 1964). Zones of more intense alteration, varying in thickness, occur in the wall-rocks immediately adjacent to the lodes. Bartram has studied this aspect in detail and shows that the main process involved the introduction of potassium to form sericite, at the expense of chlorite, and the

removal of calcium and some sodium and magnesium. Sericitic alteration is usually associated with visible bleaching of the wall-rocks. The altered wall-rocks commonly grade imperceptibly into the lodes and, as Stillwell (1929) points out, the only criterion as to whether a given rock is altered wall-rock or ore is the test by assay.

B. PRIMARY TRACE ELEMENT DISPERSION PATTERNS RELATED TO GOLD MINERALIZATION, KALGOORLIE.

1. General.

A detailed investigation of primary trace element dispersion at Kalgoorlie was not possible in the time available, owing to the complexity of the mineralization. The object of the present brief study was to establish the general nature of trace element dispersion patterns in the vicinity of representative Kalgoorlie lodes, for comparison with the Norseman data and to provide a basis for further studies. Accordingly, twelve sampling traverses were carried out to test the wall-rocks in the vicinity of lodes of the various types and of varying grade, both in the Golden Mile Dolerite and the Paringa Basalt.

The results of early work, in which samples from a drill-hole which intersected a lode assaying 18.8 dwt/ton over 14 inches (P295) were analysed for As, Sb, Pb, Sn, Ga, Bi, Mo, V, Cu, Ti, Ag, Ni, Zn, Co, Mn, and Cr, indicated

arsenic to be the most useful pathfinder element. In subsequent work, emphasis was therefore placed on the determination of arsenic in wall-rock samples.

2. Background data for Arsenic.

Insufficient background samples were collected in the Kalgoorlie area to permit rigorous definition of theshold values. The arsenic and mercury contents of six samples of propylitic metadolerites and metabasalts from exploratory drill-holes located more than one mile to the south of the Golden Mile, are given in Table 23.

TABLE 23.

Arsenic and Mercury Contents of Background Greenstones, Kalgoorlie.

Sample No.	Description	Hg ppb.	As ppm.
2979	Propylitic metadolerite	960	1
80	Propylitic, leucoxenitic metadolerite	810	4
81	Propylitic metabasalt	570	2
82	Slightly propylitized metabasalt	860	1
83	Propylitic albite-leucoxene meta-dolerite	600	1
86	Semi-bleached, propylitic, ilmenitic metadolerite	550	19

These results, together with results from wall-rock traverses on the outskirts of the mineralized area (see Kelly and Main Lode traverses Fig. 44), suggest that regional threshold is in the vicinity of 5 ppm.

3. Wall-rock Anomalies Associated with the Main Lode Series.

The results of arsenic analyses on samples collected in the vicinity of orebodies of the Main Lode Series are shown in Figs. 43 and 44. Anomalies were found to occur in all traverses, the maximum arsenic contents varying from 60 to 550 ppm.

The few lode samples analysed were found to be higher in arsenic than the surrounding wall-rocks. However, it was not possible to obtain lode samples in all cases owing to the general practice at Kalgoorlie of assaying all the drill-core from lode intersections.

The wall-rocks adjacent to the important Lake View Lode were sampled at three localities where the ore grade was respectively high (BP83), moderate (10 Level cross-cut), and low (BP 57), in order to test the possibility of a relationship between the grade of ore and the nature of the wall-rock dispersion patterns. The distribution of arsenic was found to be similar in all three traverses, (Fig. 43), consisting of a broad zone of weakly anomalous arsenic values between 40 and 100 ppm with occasional higher values. The full lateral extent of the anomalies was

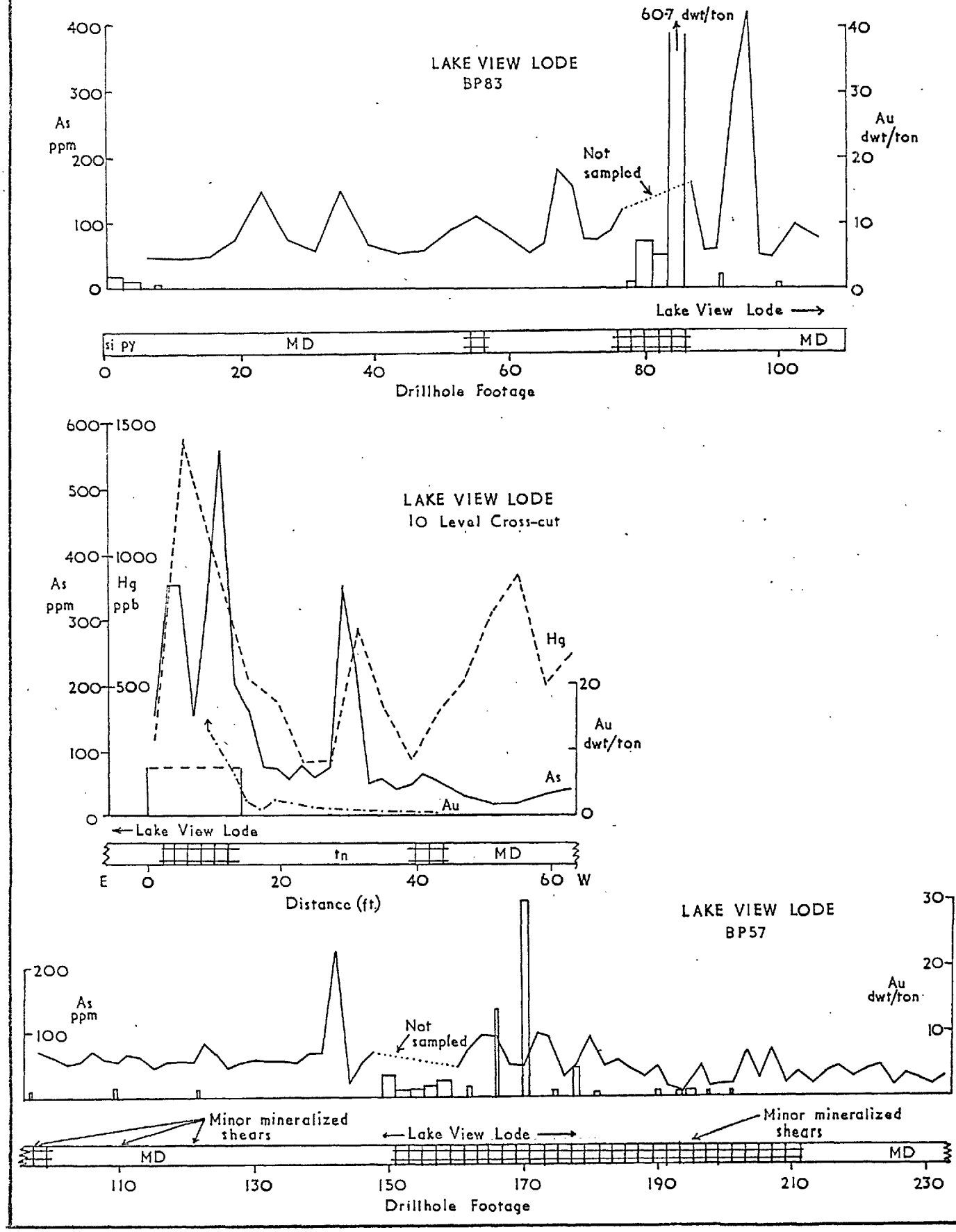


Fig. 43. Distribution of As, Hg & Au in the vicinity of the Lake View Lode, Kalgoorlie.

not determined due to inadequate sampling but anomalous values appear to persist more than 50 feet from the lode in each case.

The arsenic distribution appears to be unrelated to the visible wall-rock alteration which, in the examples studied by Bartram (1964) seldom extends more than 20 feet from the Lake View Lode. The zone of bleaching intersected in BP 57 is somewhat wider than normal, a fact accounted for by extensive distribution of mineralized stringers, which are themselves bleached.

Mercury determinations on selected samples from the 10 Level Cross-cut showed an erratic distribution, with values ranging from 210 to 1430 ppb Hg. Background samples (Table 23) had mercury contents ranging from 550 to 960 ppb and so only one sample, within the lode, can be regarded as anomalous on the 10 Level Cross-cut traverse.

It is significant to note that the mercury results for the samples in the vicinity of the Lake View Lode are in close agreement with the results of a brief study carried out on Kalgoorlie lodes and wall-rocks by the Cordero Mining Co. for Western Mining Corporation. However, the Cordero instrument recorded values between 23 and 124 ppb Hg for samples of Kalgoorlie rock-types from areas several miles from mineralization. These background figures are consistent with published estimates of the abundance of mercury in basic igneous

rocks (80 to 100 ppb, according to Rankama and Sahama, 1950, p. 716). It is therefore probable that the background values given in Table 23 are too high. This may be due to the fact that the "background" samples for the present study were taken from drill-holes which were put down to test the possible extension of the Kalgoorlie ore structure. Although the actual samples were not associated with mineralization, the high mercury contents may reflect proximity to a broadly mineralized zone.

Seven selected samples from the 10 Level Cross-cut traverse were also analysed for gold by the method of Stanton & McDonald (1964). Values of 6.4 and 13.0 dwt/ton were found to occur within the lode itself. Low, but detectable, concentrations of gold were found to occur in the wall-rock as much as 12 feet from the margin of the lode, but in a sample taken 29 feet from the lode, the gold content was less than the limits of detection of the analytical method used. The presence of small amounts of gold in the wall-rocks is not unexpected, since the lode boundaries are essentially gradational and are defined only on the arbitrary basis of assay values. The lateral extent of gold dispersion appears to be considerably less than that of either arsenic or mercury.

The No. 3 Lode (Fig. 44) is typical of the Main Lode Series, as developed in the Western Lode System. The wall-rock anomaly was found to be essentially similar

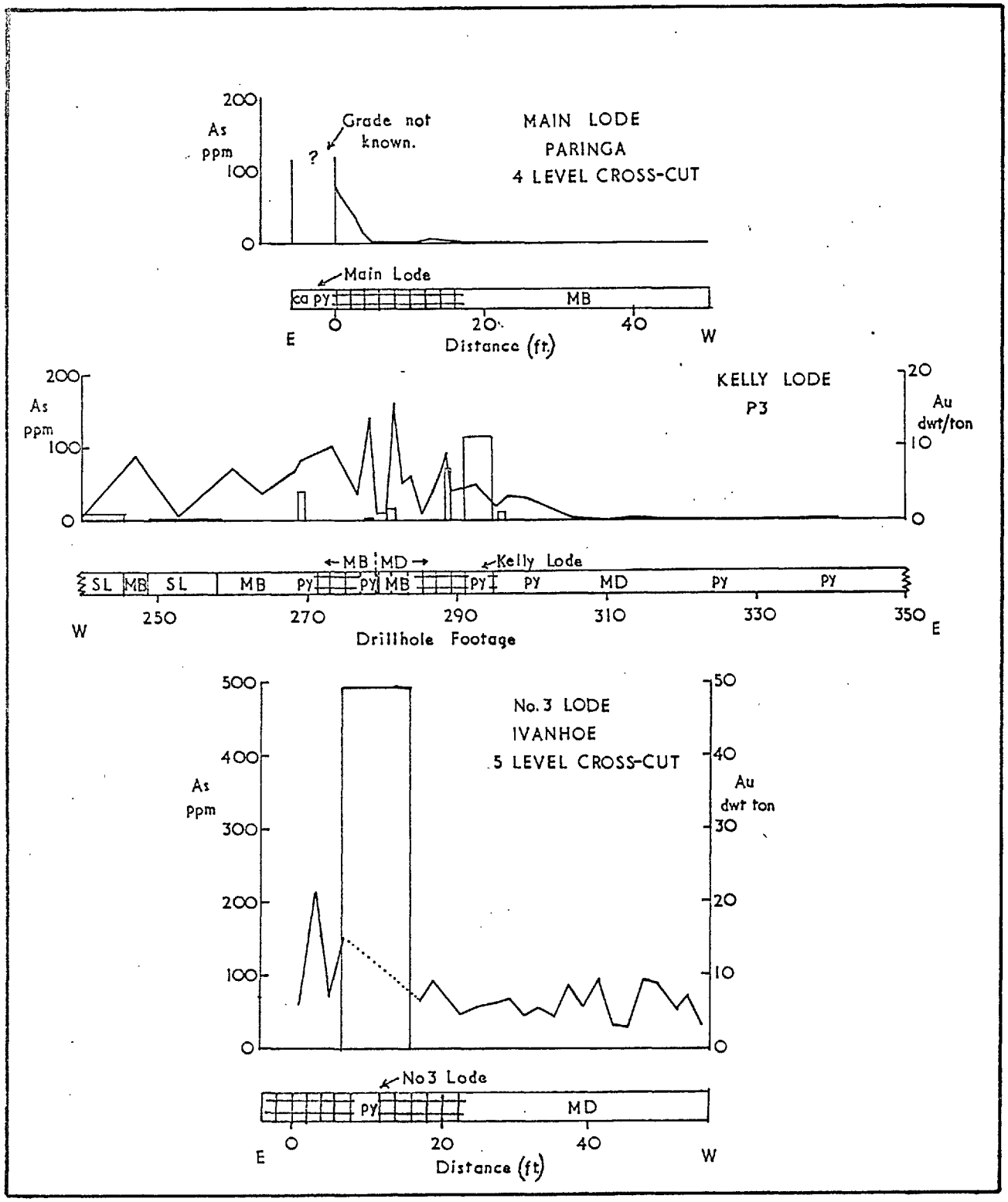


Fig. 44. Distribution of arsenic in the vicinity of the No.3, Kelly and Main Lodes, Kalgoorlie.

to those obtained in the vicinity of Lake View Lode, anomalous values between 30 and 100 ppm As extending at least 40 feet from the lode zone and the peak value of 210 ppm in highly bleached mineralized metadolerite, a short distance to the east of the lode.

Samples were collected about a moderate to high grade intersection on Kelly Lode (P3), mainly for comparison with studies of secondary dispersion in soils in the vicinity of the sub-outcrop of this lode. A weak arsenic anomaly, approximately 10 feet wide, with maximum arsenic content of 50 ppm, was found to occur on the eastern side of this orebody. The anomaly is much more extensive on the western side of Kelly Lode, with arsenic contents generally between 40 and 100 ppm and higher values associated with numerous mineralized stringers.

A cross-cut to the west off Main Lode (Fig. 44) was sampled in order to study the dispersion of arsenic adjacent to an orebody of the Main Lode Series in meta-basalts. The grade of ore is not known precisely, but the cross-cut was started on the southern margin of a high-grade ore-shoot. The rocks are moderately bleached for a distance of 15 feet from the lode. A weak anomaly, only 5 feet in width, was found to be present. The maximum arsenic content of 80 ppm was found in a sample of the actual lode.

4. Wall-rock Anomalies Associated with the Caunter Lode Series.

The dispersion of arsenic in metadolerites in the vicinity of a moderate to high grade intersection of Perseverance Lode (BP78), an important representative of the Caunter Lode Series, is shown in Fig. 45. The arsenic content of the wall-rocks increases gradually from approximately 15 ppm, 50 feet from the lode, to 98 ppm in the middle of the mineralized zone. The anomaly persists at least 26 feet beyond the lode, with arsenic contents in the vicinity of 50 ppm and a peak value of 130 ppm associated with a minor mineralized stringer.

It was not possible to sample the actual lode in BP78 but 22 samples of Perseverance Lode, collected by Mr. G.M. Hopkins, were found to contain between 50 and 900 ppm As (arithmetic mean 270 ppm). Hopkins (1965) has found that the arsenic content is related to the abundance of tennantite in the ore, in which mineral the arsenic presumably occurs. According to Hopkins, there is a linear relationship between arsenic and gold in Perseverance Lode samples containing up to 8 dwt gold/ton. The relationship breaks down in samples containing more than 8 dwt/ton due to the presence of free gold.

The dispersion of arsenic in metabasalts associated with a Caunter Lode was studied in samples from SK345, a drill-hole which intersects ore of moderate grade on the No. 6 Caunter Lode. A weak erratic arsenic anomaly extends over a zone more than 70 feet in width (Fig. 45).

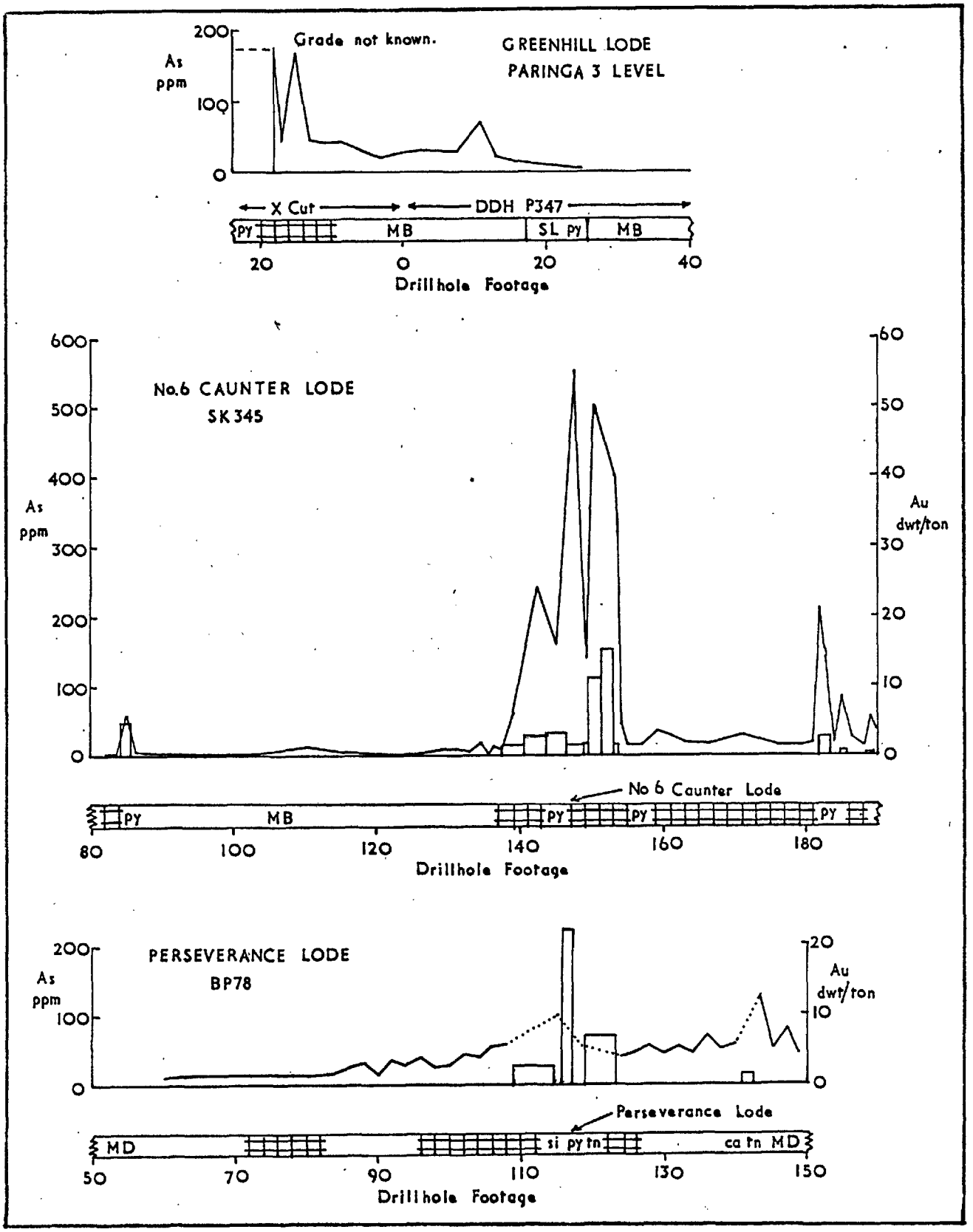


Fig. 45. Distribution of arsenic in the vicinity of the Perseverance, No. 6 Caunter and Greenhill Lodes, Kalgoorlie.

The highest arsenic contents were found to occur in the lode itself, but minor geochemical peaks also occur over a number of narrow intersections of low grade mineralization.

5. Wall-rock Anomalies Associated with the Cross Lode Series.

The dispersion of arsenic in metabasalts adjacent to the Greenhill Cross Lode is shown in Fig. 45. The samples were collected partly from underground workings and partly from a drill-hole (P347), collared approximately 20 feet from the margin of the lode. An anomaly extends approximately 40 feet from the lode, the maximum values occurring in the altered mineralized rocks on the immediate margin of the orebody. The lateral extent of this anomaly is comparable with those obtained in the vicinity of lodes of the Main and Caunter type in metadolerite.

The only example of a Cross Lode in metadolerite was studied in samples from P295, a hole drilled from an opening on sub-economic mineralization of the Cross-Lode type. The samples from this traverse were analysed for 16 elements, including arsenic, but no significant distribution patterns were found in the vicinity of the Cross-Lode.

6. Wall-rock Dispersion Associated with Unclassified Drill-Hole Intersections.

As mentioned above, P295, which was drilled from a

sub-economic Cross Lode, intersected a narrow zone of mineralized metadolerite which assayed 18.8 dwt/ton over 14 inches. Background arsenic contents predominate throughout this hole, except for a zone approximately 30 feet in width about the intersection, where erratic, weakly anomalous values between 15 and 25 ppm As were obtained. None of the other elements determined showed significant distribution patterns.

P347, which has been mentioned in connection with Cross Lode dispersion patterns, also intersected two mineralized bands in metabasalt, which together assayed 9.9 dwt./ton over 26 inches. Arsenic concentration shows no significant variation in the vicinity of this intersection. A subsequent drill-hole failed to confirm the existence of a lode at this point and it was concluded that the mineralization encountered in P347 was a small isolated patch of little consequence.

7. Summary of Results.

a) Distinct anomalies were found to occur in the wall-rocks in the vicinity of all the lodes which were examined.

b) In the traverses where full sampling was possible (i.e. Lake View Lode 10 Level Cross-cut, P3, Main Lode 4 Level Cross-cut, and SK345), the highest arsenic contents were found to occur within the actual lode, with lower but still anomalous values

in the adjacent wall-rocks. Minor mineralized stringers were also frequently accompanied by high arsenic contents.

c) Wall-rock anomalies vary considerably in width. Anomalies more than 100 feet wide were found to exist in the vicinity of major lodes in the most intensely mineralized part of the Golden Mile, but background arsenic contents were obtained within 5 to 15 feet of strong lodes on the margins of the area.

d) The variations in the widths of anomalies were found to be similar in both metadolerites and metabasalts.

e) There appear to be no significant differences in the nature of the wall-rock anomalies associated with the different lode-types.

f) In some cases, e.g. the Perseverance, Kelly, Main and Greenhill Lode traverses, the arsenic concentration in the wall-rocks increases steadily, with only minor fluctuations, on approaching lodes. In other cases, a broad zone of more or less constant arsenic content surrounds the lodes, with minor peaks which are generally related to sub-economic mineralized stringers.

g) The Lake View Lode traverses indicate that the magnitude of the wall-rock anomalies does not vary

significantly with the grade of ore.

h) Hopkins' (1965) work shows that the bulk of the arsenic associated with the Perseverance Lode occurs as tennantite. This is the most commonly occurring arsenical mineral at Kalgoorlie and probably accounts for the anomalous arsenic associated with most of the other lodes studied. Small amounts of arsenopyrite have been reported as being present in some Kalgoorlie lodes but according to Simpson and Gibson (1912), this mineral is more commonly associated with secondary non-auriferous shears than with the main gold lodes.

i) The limited work done to date suggests that mercury could prove a useful pathfinder element for gold. Most of the mercury probably occurs as coloradoite, which is one of the most abundant tellurides in the Kalgoorlie lodes (Stillwell, 1929).

j) Apart from arsenic and mercury, none of the other trace elements determined showed significant concentration variations in the wall-rocks adjacent to lodes. However, the only intersection tested for general elements (P295) was probably not typical of the Kalgoorlie lodes, and further work might indicate additional path-finder elements.

k) The dispersion of gold about the Lake View Lode

appears to be of limited lateral extent compared with that of arsenic and mercury.

III. AGNEW

A very limited study of primary dispersion was carried out in the vicinity of the Emu Lode at Agnew, mainly to supplement the secondary dispersion studies, which are described in the next chapter. Although only one rock-sampling traverse was undertaken, the results are given here for comparison with the results for Norseman and Kalgoorlie.

A. GEOLOGY AND MINERALIZATION AT AGNEW

The geology of the Agnew area is shown in Fig. 46. The major Emu Lode Line closely follows the contact between ultrabasics (talc-chlorite rocks) on the east, and meta sediments (dominantly quartz-biotite-actinolite gneiss) on the west. Gold mineralization is known over a total strike length of 10,000 feet to the south of the Kim Shaft. The main workings occur in the vicinity of the Emu Shaft, which produced 411,000 oz. from 1,297,000 tons of ore. In this area, two parallel lodes are developed on the margins of a band of coarse-grained chlorite-actinolite schist, varying in thickness from 25 to 100 feet, which occurs on the ultrabasic-metasediment contact. Both hanging-wall and footwall lodes have dips

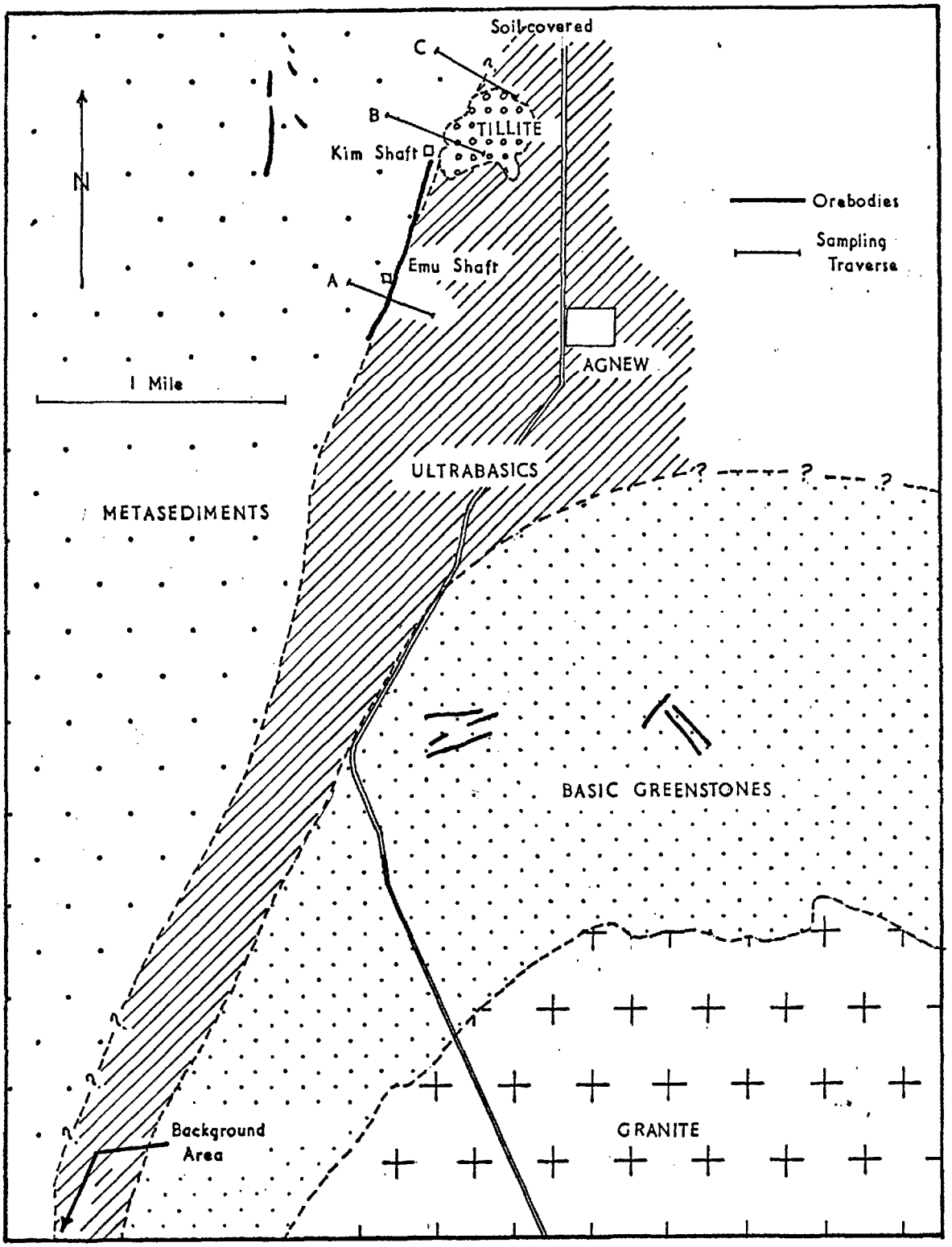


Fig. 46. Geological map of Agnew showing sampling traverses (based on Western Mining Corporation Mapping).

parallel to that of the contact, which averages 60° to the west.

The actual lodes are not clearly defined and consist merely of a concentration of thin mineralized quartz veins and lenses in the chlorite-actinolite schist. Arsenopyrite chalcopyrite, pyrite and free gold are present, both in the quartz veins and in the adjacent schist. Although gold enrichment occurs predominantly on the hanging-wall and footwallcontacts, gold values are frequently associated with mineralized quartz veins throughout the chlorite-actinolite schist band. Recent development to the north of the Kim Shaft has shown the presence of a further parallel series of transverse gold-bearing quartz veins in a north-trending zone to the west of the contact, and within the gneissic sediments. This is known as the Kim Shaft hanging-wall lode. Although the individual quartz veins are highly auriferous, they are so thin and widely spaced that the overall grade of the lode is low. Coarse crystals of arsenopyrite occur in the gneiss associated with these veins.

B. PRIMARY DISPERSION OF ARSENIC IN THE VICINITY OF MINERALIZATION

The distribution of arsenic in rocks about the Emu Lode is shown by analyses of samples from the diamond drill-hole A3 (Fig. 47). This hole was drilled at an

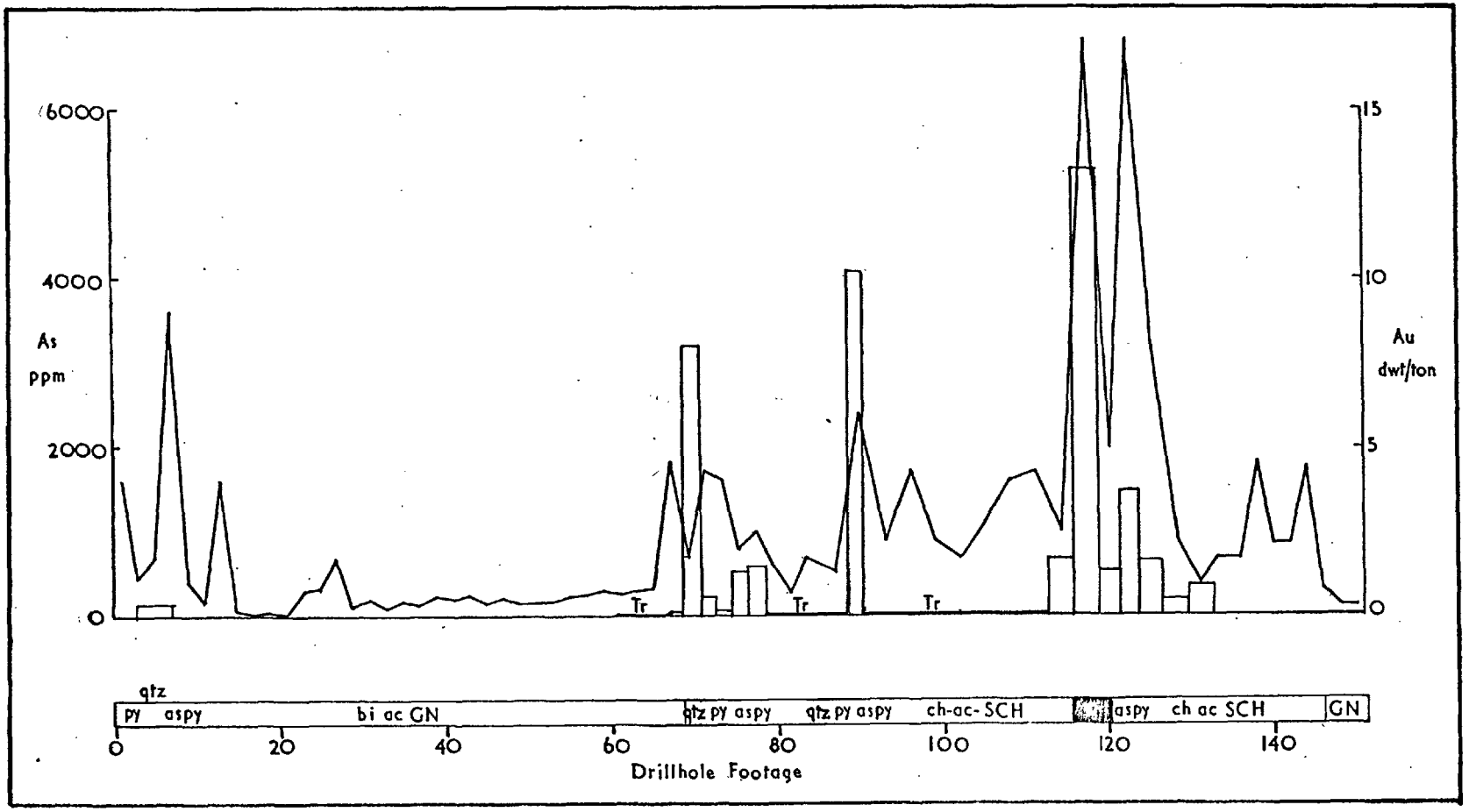


Fig. 47. Distribution of arsenic and gold in D.D.H. A3, Agnew.

inclination of 70° from the Kim Shaft hanging-wall lode in the gneiss to intersect the chlorite-actinolite schist horizon.

The levels of concentration of arsenic are seen to be considerably higher than those normally encountered at Norseman and Kalgoorlie, reaching a maximum of more than 6000 ppm. This was not unexpected in view of the abundant visible arsenopyrite in the rocks.

It was not possible to collect fresh background rock samples for comparison with the results for A3. However, two slightly weathered samples of metasedimentary gneiss and talc-chlorite rock from the background soils area were found to contain 2ppm and <2ppm respectively. The A3 traverse would therefore appear to be strongly anomalous throughout, very few samples containing less than 200 ppm As.

Arsenic concentrations are generally higher throughout the chlorite-actinolite schist horizon than in the gneiss, with the exception of the first 25 feet of the hole where values up to 3600ppm are associated with the hanging-wall lode. Within the chlorite-actinolite schist, a close relationship between arsenic and gold is apparent, the highest arsenic values (up to 6800ppm) being closely associated with high gold contents.

IV. DISCUSSION : PRIMARY DISPERSION.

A. THEORETICAL CONSIDERATIONS.

The primary geochemical anomalies described in this thesis are believed to be epigenetic, in that they are related to hydrothermal mineralization and were formed later than the rocks in which they are enclosed, as distinct from syngenetic anomalies, which are formed concurrently with the enclosing rocks (Hawkes and Webb, 1962).

Safronov (1964) in a review of primary epigenetic trace element halos, proposes two mechanisms by which primary dispersion may take place - infiltration and diffusion, which may occur separately or in combination.

Infiltration may be regarded, from the geological view-point, as the process of seepage, or flow, of a solution through a system of connected pore-spaces or fractures in the rocks. The velocity of the solute in infiltration is generally less than that of the solvent, the velocity difference depending on such factors as the diameter of the solute particles relative to the dimensions of the openings in the rock, the viscosity of the solvent, the chemical mobilities of the solute particles, reactions with the wall-rocks etc. As a result of these differences in velocity, the solute "lags" behind the

solvent by an increasing increment such that a logarithmic concentration gradient is set up within the moving system. Precipitation may occur when the concentration exceeds the saturation level under the conditions obtaining or by reactions forming insoluble compounds. This precipitated material ultimately constitutes the primary halo.

Diffusion involves the movement of the solute through a stationary solid, liquid or gaseous medium. Because the medium is stationary, the rate of diffusion is controlled essentially by chemical factors. Safronov explains the process in terms of the general concept of "chemical potential" which is a function temperature, pressure and the concentrations of the various components in the system. Matter is diffused from rock with high chemical potentials, in most cases the locus of mineralization, to rock with low chemical potentials.

As a result of the concentration gradients set up during infiltration and diffusion, the variation in concentration of any one component with distance from the vein would be expected to follow a logarithmic decay pattern. The existence of log-linear concentration gradients has, in fact, been established in a number of studies of wall-rock dispersion (Morris, 1952; James, 1957; Walker, 1964; Nicolls, 1964).

Although the factors governing the dispersion of trace elements are similar in both processes, infiltration differs from diffusion in that the system as a whole moves, so that in a similar time, the distance travelled by each component is likely to be greater than if dispersion took place entirely by diffusion. Safronov considers that infiltration velocities should be at least ten times greater than diffusion velocities, so that the extent of anomalies where the former mechanism is dominant, should be greater by a similar factor.

In hydrothermal systems, the solute invariably consists of numerous components, each with differing physical and chemical properties. The concentration gradients resulting from infiltration and/or diffusion would therefore differ for each component, resulting in the development of zoned halos. The most widely dispersed elements would be those with the greatest mobilities under the existing conditions.

Very little data has been published regarding the zoning of trace elements across the strike of ore deposits. James (1957) found that antimony formed a broader dispersion pattern than arsenic in the wall-rocks adjacent to gold mineralization in the Bell-Riverlea Mine in Rhodesia. Morris (1952), however, found only slight differences in the distances travelled by lead and zinc in the wall-rocks

of mineralization at Tintic, Utah. The widths of wall-rock anomalies for Pb, Zn, Ag, Cu, and Mn at Broken Hill, New South Wales, are all similar, despite the widely differing properties of these metals (Walker 1964). Walker, however, believes that the trace element distribution in this area reflects the original distribution in the sediments and is not the result of epigenetic dispersion.

Safronov believes that the conditions governing the vertical zoning of elements in hydrothermal deposits should be similar to those controlling the zoning of elements in wall-rock anomalies. He presents the following generalized sequence of metals in order of decreasing depth of occurrence (or increasing mobility) based on observations in numerous mineralized areas: Sn (5.4), W (5.9), Mo (5.9), As (4.3), Bi (2.5), Cu (1.05), Zn (2.4), Ca (?1.05), Pb (1.5), Ba (1.4), Ag (0.9), Au (0.7), Sb (3.3), As (4.3), Hg (1.8) and Te (0.7). In general, the inferred mobilities of these elements follows the order of decreasing ionic potential (given in brackets). This is believed to be due to the tendency for elements with high ionic potentials to be hydrated in aqueous systems, with a resulting decrease in mobility. However, numerous exceptions occur, these being generally attributable to the formation of highly mobile combinations with other ions present. In particular, arsenic, the occurrence of which often suggests high mobility, is known to form

volatile halides and may be dispersed in the gaseous form (Onishi and Sandell, 1955). Mercury vapourises at relatively low temperatures and is probably transported in gaseous elemental form.

Mention should also be made, at this point, of the lateral secretion theory of ore genesis, as advocated by Boyle (1961 and 1963) to explain the development of the gold deposits of the Yellowknife District, Canada, (which in many respects closely resemble those of Western Australia). According to Boyle, the elements in veins and similar epigenetic deposits come from the enclosing country rocks and are concentrated by diffusion processes under the influences of free energy gradients. The trace element dispersion patterns believed to form as a result of this process may, under certain circumstances, be similar to those formed by outward dispersion from hydrothermal veins and both interpretations are often applicable.

B. PRIMARY DISPERSION AT NORSEMAN

1. Geochemical Characteristics of Norseman Rock-Types.

A full geochemical study of the rocks occurring at Norseman is beyond the scope of the present study. Nevertheless, the results of determinations on background rocks show some features which are relevant in the discussion of

trace element dispersions related to mineralization which follows the present section. The validity of any observations drawn from this work may be limited for three reasons:

(i) The methods of trace analysis used in this research were only semi-quantitative and may not be sufficiently sensitive to detect subtle differences in concentration.

(ii) The rocks of the area have suffered low grade regional metamorphism, during which the trace element contents of the original rocks may have been modified.

(iii) The trace element concentrations in the rocks may have been further affected by the hydrothermal activity associated with gold mineralization.

Bearing these limitations in mind, the average trace element concentration in Norseman rocks are compared with the published clarkes for similar rock-types (Table 24).

a) Basic Igneous Rocks.

On the whole, the differences between the trace element contents of the meta-igneous greenstones at Norseman and clarke values are relatively small. However, in the case of arsenic, the abnormally high values are probably related to the hydrothermal mineralization in the Norseman area. This is supported by the bimodal

TABLE 24.

Comparison of Trace Element Contents of Background Norseman Rock-Types with Clarke Values.

Element.	Norseman Rocks			Clarke for Basic Igneous Rocks ⌘	Norse. Slates (5 samples)	Abundance in black shales ⌘	Norseman Porphyries (10 samples)	Clarke for Felsic Igneous Rocks ⌘
	Metabasalts (34 samples	Metadolerites (19 samples)	Metagabbros (22 samples)					
As	7	5	7	2	16	4-225	? 169	1.5
Pb	4	4	10	±12	7	20-400	23	48
Cu	115	147	180	140	410	20-300	48	30
Zn	95	111	139	130	200	100-1000	72	60
Ga	15	18	17	7-22	16	?7-50	23	15-74
Ni	131	111	119	160	126	20-300	14	8
Co	71	69	78	45	96	5-50	9	5
Mn	1670	1820	1880	2200	1500	890	278	600
Cr	286	235	158	300	90	10-500	31	25
V	307	445	435	200	316	50-2000	28	40
Ti	7600	8100	8900	9000	6000	4400	1355	2300

⌘ Data from Hawkes and Webb (1962) and Rankama and Sahama (1950).

frequency distribution for arsenic (Fig. 12). The modal values for all three rock-types (2.5 or less) are comparable with the clarke and probably reflect the arsenic contents of the original igneous rocks. The higher average values are caused by a small population of relatively arsenic-rich samples, containing from 6 to 40 ppm arsenic. These local concentrations of arsenic are believed to have formed during the hydrothermal phase during which gold mineralization took place.

It can be seen from Table 24, that the concentrations of some elements appear to show distinct trends with increasing grain size in the Norseman greenstones. Pb, Cu, Zn, Mn, V and Ti all tend to increase in concentration in the coarser grained intrusive rocks. Cr shows the reverse tendency, whilst As, Ga, Ni and Co show no definite trend either way.

Three possible hypotheses can be advanced to explain these features:

(i) The similar bulk compositions and close field association of the pillow lavas ("Older Greenstones") and intrusives ("Younger Greenstones") suggest that they were co-magmatic, although the field and petrographic evidence offers no definite proof of this. If this was the case, the observed trends may be the result of gradual differentiation

within the magma chamber, causing variations in the concentrations of some elements in the bodies of magma ejected at different times. Alternatively, the trends may be due to heterogeneity within the common parent magma.

(ii) The differences may be due to the conditions of emplacement which actually caused the grain size variations. However, if this were the case, elements such as Pb, Zn and Mn could be expected to be more abundant in the metabasalts than in the metagabbros, since, in the crystallization of a basic magma at depth, these elements are usually concentrated in the residual fluids and either removed from the system or retained in pegmatitic schlieren within the rock mass. In suites of co-magmatic extrusive and intrusive rocks, such elements are usually trapped in greater concentrations in the lavas due to the rapid cooling and crystallization of the extrusive rocks.

(iii) Selective mobilization and concentration of elements in certain rock-types could conceivably have taken place during post-magmatic metamorphism and metasomatism. However, there is no apparent reason why such differential concentration should favour coarse grained rocks for some elements and fine grained rocks of similar bulk composition for

others. In particular, this could not account for the opposing trends shown by the geochemically similar elements Cr and V.

It is concluded that the observed trends are due largely to differences in the concentrations of trace elements in the magmas which formed the different rock-types. These differences are probably the result of sub-crustal differentiation.

b) Slates

According to Bekker (1962) the slates interbedded with basaltic lavas at Norseman are of sedimentary and partly pyroclastic origin. The abundance of graphite and bedded sulphides (mainly pyrrhotite) show that they were originally of the black shale variety. The concentrations of trace elements in black shales are typically highly variable and average values are of little significance except in areas of limited extent.

Not unexpectedly, the Norseman slates show abnormally high concentrations in a number of chalcophile elements, with respect to the basic igneous rocks in which they occur. As, Cu, and Zn are significantly higher, whilst a local concentration of 8 ppm Ag and 5 ppm Mo was found in one slate specimen, these latter elements being below the limits of detection (<0.2 ppm Ag and <2 ppm Mo) in all

other background samples analysed. Pb, Ga, Ni, Co, Mn, V and Ti are present in concentrations similar to those in the greenstones and published ranges of abundance for black shales. The concentration of chromium is considerably lower in the slates than in the basic igneous greenstones.

c) Felsite Porphyries.

Bekker (1962), on the basis of field relations, petrography and major element chemistry, has postulated that the felsite porphyries were formed by metasomatic replacement of pre-existing rocks by the residual fluids resulting from the differentiation of the "Younger Greenstone" magma. He further proposes that the formation of porphyries is part of a genetic series:
"Younger Greenstones" - porphyries - gold-quartz reefs.

If these rocks are in fact of hybrid metasomatic origin, it is clear that the comparison of the trace element data with the clarke for felsic igneous rocks may be irrelevant. Nevertheless, a broad similarity is shown by most elements in Table 24. It should be pointed out that the major discrepancy in the case of arsenic in the Norseman rocks is due to abnormally high concentrations (130 to 1200 ppm) in only three of the ten porphyry samples analysed.

Bekker's proposed relationship between the porphyries

and gold mineralization is supported by the occasional occurrences of high arsenic concentrations and small amounts of gold in the porphyries. In particular, the high arsenic contents in the silicate minerals of arsenical porphyries (Table 20) suggest that arsenic was present in the metasomatic solutions involved in the development of the porphyries, and was not introduced during the later hydrothermal phase associated with gold mineralization.

With regard to the possible relationship between the porphyries and the "Younger Greenstone" magma, it may be noted that the porphyries are enriched in As, Pb, and Ga relative to the meta-igneous greenstones, and depleted in V, Ni, Cr, Co, Ti, Cu, Zn, and Mn. The concentration of As, Pb and Ga in porphyries is in accord with the known geochemistry of these elements, which tend to be enriched in the siliceous residual differentiates of basic magmas (Rankama and Sahama, 1950). Pb and Ga are commonly concentrated in feldspars, substituting for K^{+} and Al^{3+} respectively. As is capable of substituting for Al^{3+}, Si^{4+}, Fe^{3+} and Ti^{4+} but the greatest concentrations in the arsenic-rich Norseman porphyries occur in the sulphide fractions. Of the elements which are relatively deficient in porphyries V, Ni, Cr, Co, and Ti usually tend to be more abundant in basic igneous rocks, in which they concentrate in the early crystallates. Mn and Zn, however, frequently tend to be concentrated with

iron in the later-formed minerals of igneous rocks or enriched in the residual fluids. Even so, only Mn is significantly lower in the porphyries than the clarke for felsic igneous rocks. Thus, apart from Mn, the trace element data are generally consistent with Bekker's thesis that the porphyries are at least partly derived from the late differentiates of the "Younger Greenstone" magma.

2. Development of Wall-Rock and Leakage Anomalies at Norseman.

The list of features which suggest a genetic relationship between the arsenic and nickel wall-rock anomalies and the gold-quartz mineralization at Norseman, given on page 112, may now be expanded as follows:

(i) Occurrence of arsenic and nickel in the wall-rocks predominantly as sulphide minerals, which Hall and Bekker (1965) believe were introduced during the mineralization stage.

(ii) The exclusive association of arsenic and nickel anomalies with known reef-shears and absence of anomalies for these elements in outwardly similar zones of non-auriferous schistose, altered rocks.

(iii) The general association on a broad scale, of strong arsenic anomalies with ore zones, as distinct from non-auriferous parts of the reef-shears,

which are characterized by weak anomalies.

iv) The apparent concentration of arsenic with gold in the quartz reefs.

v) The fact that the average concentrations of arsenic and nickel are higher in the quartz reefs than in background greenstones.

Before proceeding to a discussion of the various mechanisms by which the anomalies may have been formed, a brief review of the currently accepted theory of the genesis of the gold-quartz reefs is appropriate.

Bekker (1962) sees the emplacement of the gold-quartz reefs as the culmination of a more or less continuous series of igneous-metasomatic events, which were broadly contemporaneous with mechanical deformation in the area. According to Bekker, the concurrence of magmatic differentiation with tectonic activity was a strong influence in bringing about the conditions favourable for ore deposition at Norseman. The sequence of events at Norseman included the following phases, in approximately chronological order (after Bekker, 1962) :

(i) Deposition of basaltic pillow lavas.

(Time interval)

(ii) Intrusion of "Younger Greenstone" sills and dykes, probably during late folding and penecontemporaneous with late regional metamorphism.

(?) Development of reverse fault zones.

iii) Metasomatism by siliceous alkaline differentiates of the "Younger Greenstone" magma, resulting in biotite schists in reverse fault zones (and other zones of weakness) and porphyry dykes.

iv) Quartz reef emplacement and gold deposition in reverse fault zones by hydrothermal solutions derived as a result of further differentiation ($\pm$ assimilation) of the solutions responsible for biotitization and porphyritization.

Safronov's (1964) theoretical consideration of the features to be expected in primary wall-rock anomalies was based on the assumption that the trace elements were dispersed laterally from the focus of mineralization (i.e. the vein or lode). However, the observed distribution of trace elements in wall-rocks at Norseman is not consistent with an origin involving lateral dispersion as the major process. If lateral dispersion had taken place the resulting anomalies would be expected to be symmetrical and show a log-linear decay with distance from the reef. Instead, the anomalies are markedly erratic and often assymetrical with respect to ore, peak values frequently occurring some considerable distance from the reef. The apparent lack of lateral zoning for elements of differing mobility also conflicts with the theory of lateral dispersion. It is

apparent from Figs. 10 and 11 that the wall-rock anomalies for arsenic, nickel and chromium are of almost equal widths.

The form of the wall-rock anomalies is also contrary to what one would expect if lateral secretion was the mechanism controlling trace element distribution. Ideally, in lateral secretion, the geochemical profile for any element should show a zone of impoverishment in the wall-rocks with a very marked increase in the actual reef (or in the near vicinity of the reef). Although continuous sampling was not extended sufficiently far into the wall-rocks to definitely prove or disprove the existence of zones of impoverishment, the results suggest that there is no such zone, at least in the case of arsenic. The concentration of arsenic shows a general, though erratic, increase from the regional threshold (<5 ppm) to local threshold (approximately 15 ppm) reaching a maximum between 500 and 2000 ppm within 50 feet or so of the reef. In the actual quartz reef, the values drop to much lower levels. This does not preclude the possibility that lateral secretion was an important factor in controlling the distribution of some of the other elements. For example, the ultrabasic composition of the altered tholeiitic rocks in the shear zones suggest that the SiO_2 in the quartz reefs may have been derived from the wall-rocks.

The geochemical results at Norseman suggest that the trace element anomalies were developed largely as the result of the movement of hydrothermal fluids in an up-dip direction along the shears in which the quartz reefs were emplaced. This is strongly implied by the presence of leakage halos in the shears, up-dip from blind orebodies. However, this theory would also account for a number of other features of the trace element data, which cannot be explained in terms of outward lateral dispersion from the quartz reefs or lateral secretion from the country rocks.

It was pointed out in an earlier section that the zone of anomalous arsenic contents, in general, coincides with the zone of shearing, as observed in drill-core. Since the foliation of the schistosity is parallel to the plane of the reef-shear, permeability in this zone would presumably be at a maximum for solutions moving up the structure. It is therefore reasonable to assume that the widths of anomalies were governed by the lateral extent of the permeable zone, through which percolation was possible, and that this permeable zone was defined essentially by the extent of shearing. If this was the case at Norseman, the effective width of the permeable zone would have been the same for every component of the hydrothermal system moving up the shear and no lateral zoning of elements could be expected.

The marked variations in concentration and frequent assymetry observed in geochemical profiles are probably related to local variations in permeability within the shear zone. This is supported to some extent by the fact that the highest arsenic contents are associated with the most intense shearing in many drill-holes in which the degree of shearing is variable. However, considering that it was only possible to make qualitative estimates of the degree of shearing, it is not surprising that some exceptions occur (e.g. C46, C82, CU169, PR469, PRS69 and PRS65). There are other possible reasons for these apparent discrepancies, such as post-mineralization shearing and locally varying concentrations of chemical precipitants of trace elements in the host-rocks.

It follows from the above that log-linear concentration gradients would not be in evidence in geochemical profiles if up-shear dispersion was the dominant process.

The fact that wall-rock /and/ leakage anomalies are stronger adjacent to and up-dip from blind-orebodies than in other parts of the shear has already been cited as evidence for the upward movement of hydrothermal fluids. The strong development of such anomalies was no doubt influenced by the fact that orebodies were formed in zones of relative tension on the shears. It is probable that the reef-shears in such tensional zones (e.g. the section at 4400N) were

more permeable, favouring greater penetration of hydrothermal fluids, than sections in which the shear was compressive (e.g. the section at 2000N).

The appreciable distances travelled by trace elements along the shear in forming leakage halos are consistent with the theory of infiltration. Diffusion is thought to have been of relatively minor importance, but could account for the occasional penetration of anomalous arsenic into apparently massive rocks on the margins of the shear zone. Diffusion was probably responsible for the very broad dispersion shown by nickel in pyrrhotite and the wide distribution of traces of arsenopyrite in the wall-rocks. However, in both these instances, the amount of material dispersed was so small that the anomalies could not be detected by analysing whole rock samples.

There is some evidence to suggest that the development of wall-rock anomalies preceded the emplacement of the quartz reefs. The features leading to this conclusion are as follows:

(i) Although arsenic was shown to be concentrated with gold in the oreshoot studied, the levels of concentration in the quartz reef are considerably lower than in the anomalous wall-rocks. Furthermore, the magnitude of the arsenic wall-rock anomalies bears no relationship to

the grade of ore or arsenic concentration in the quartz, to which they are adjacent. This is interpreted as the result of changing composition of the hydrothermal solutions during mineralization. It is considered probable that the emanations were highly arsenical in the early stages of mineralizing activity but became somewhat depleted in this element and enriched in others, especially gold, prior to quartz reef emplacement.

The disparity between the trace element concentrations in the quartz reefs and wall-rocks may alternatively be explained in terms of a lack of precipitants for arsenic and nickel in the quartz. However, this explanation is considered unlikely in view of the fact that sulphides (mainly pyrrhotite and pyrite, but also some galena, sphalerite, chalcopyrite and arsenopyrite) are equally, if not more abundant, in the quartz reefs as in the wall-rocks. Furthermore, arsenopyrite-rich quartz veins are by no means a geological rarity (Dana, 1932).

(ii) Further evidence for the early development of the wall-rock anomalies is the fact that arsenic and nickel concentrations were frequently found to be very much lower in the wall-rocks immediately adjacent to the quartz reefs than elsewhere in the anomalous zone. This suggests that later, arsenic-depleted fluids, probably those responsible

for quartz deposition, have leached some of the earlier, fixed arsenic in the wall-rocks and re-deposited it elsewhere (possibly within the actual quartz reefs).

(iii) Silver and lead, which were concentrated with gold in the quartz reefs, do not show anomalous dispersion patterns in the wall-rocks. Silver, theoretically, has a very high mobility and lead also has been found to be capable of forming wall-rock anomalies comparable in extent to those of zinc (Morris 1952). Therefore, if silver and lead had been introduced at the same time as the bulk of the arsenic and nickel, wall-rock anomalies for these elements could also be expected, whereas in fact, no significant concentration variations were found for silver or lead near ore.

It must be emphasized that the above hypothesis does not imply that the development of trace element anomalies and quartz reef emplacement were independent processes. The features enumerated on page 155 strongly suggest that the two phases were closely inter-related, but do not necessarily imply that they were contemporaneous.

The visuallized sequence of events leading to the development of orebodies and associated trace element anomalies is shown diagrammatically in Fig. 48. Following

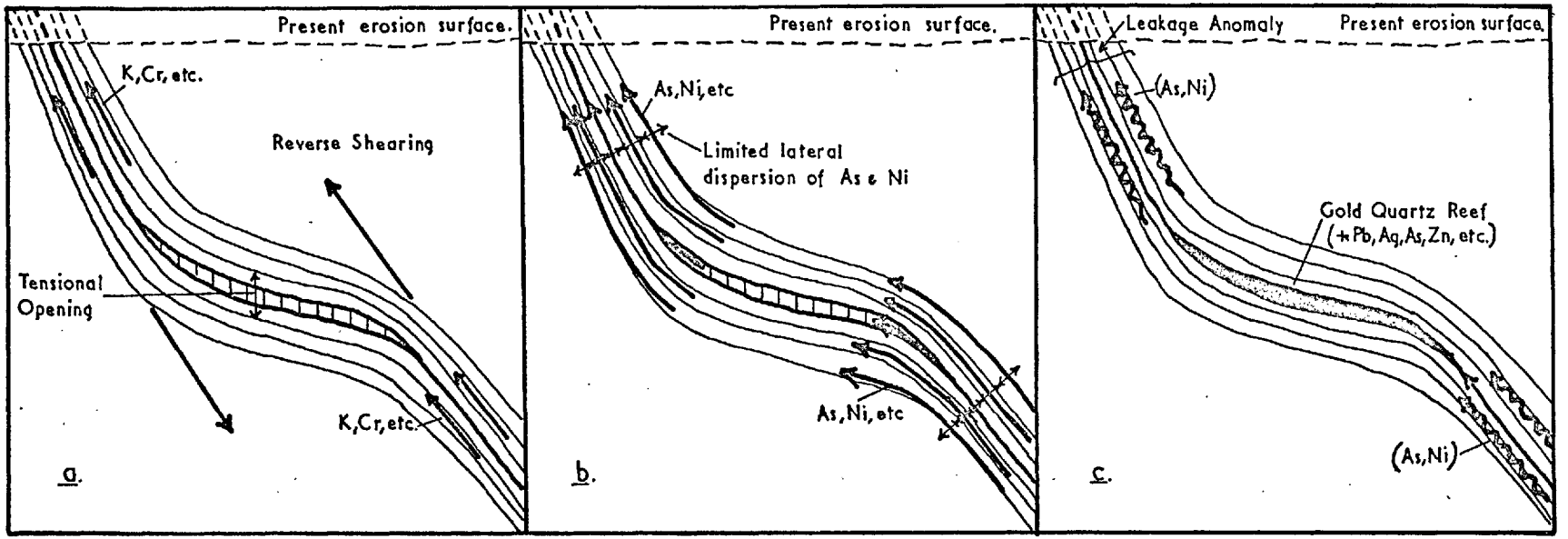


Fig. 48. Diagrammatic representation of probable sequence of events leading to development of gold-quartz reefs and arsenic-nickel wall-rock anomalies at Norseman.

a. Reverse faulting. Development of shear zone and tensional openings on flat sections. Potash (+Cr?) metasomatism.

b. Introduction of As and Ni-rich fluids in an up-shear direction.

c. Waning of As and Ni-rich fluids and emplacement of gold quartz reefs with associated gangue minerals in tensional openings.

Bekker's proposal, it is considered that the different phases were part of one more or less continuous process of deformation and metasomatism, and the stages illustrated probably overlapped each other to some extent.

The earliest phase involved reverse faulting, with associated metasomatism, to form the schistose zones of altered rocks, and tensional openings on the flatter sections of the inclined shears, in which the gold-quartz orebodies were subsequently emplaced. Chromium was probably introduced during this pre-mineralization metasomatic stage, and was incorporated in the secondary silicate minerals (± sulphides and oxides) formed. The stage at which the other anomalous elements (Co, Cu, Zn and Mn) were introduced is not known. However, the fact that these elements, like chromium, are less abundant in the quartz reefs than in background greenstones, possibly indicates they accompanied chromium. It should be noted, however, that the presence of small amounts of chalcopyrite and sphalerite in the quartz reefs shows that the later mineralizing fluids were to some extent cupriferous and zinciferous (unless the copper and zinc were derived from the adjacent wall-rocks).

In the succeeding phases of hydrothermal activity, arsenic and nickel-rich solutions were introduced, forming wall-rock and leakage anomalies, followed by the

emplacement of the gold-quartz reefs with no appreciable lapse of time.

Insufficient data was obtained to permit any conclusions on the possibility of vertical zoning along the reef-shears. The variability of nickel with respect to arsenic might possibly be due to zoning. On the 4400N section, the nickel content drops considerably in the shallowest intersection on the Crown Reef (C53). The absence of nickel anomalies adjacent to the other reef-shears studied, could be due to the greater distances of these orebodies from the hypothetical deep-seated source of the hydrothermal emanations. With the possible exception of the Mararoa Reef, all the orebodies on other reef-shear structures were mined at considerably shallower depths than the Crown orebodies.

C. PRIMARY DISPERSION AT KALGOORLIE AND AGNEW

The limited studies carried out at Kalgoorlie and Agnew do not permit a full discussion of primary dispersion in these areas. In this section, it is only intended to briefly mention some of the more important features of the results in relation to the Norseman data.

One of the most significant findings of the investigation of primary dispersion is the fact that arsenic was found to be a pathfinder for gold in all three areas

studied. Furthermore, at Norseman and Kalgoorlie, there appears to be some quantitative relationship between arsenic and gold in the orebodies. This relationship is somewhat vague in the quartz reefs at Norseman, being indicated only by the relatively higher number of arsenic-rich samples within the outlines of the ore-shoot studied, than in the sub-economic quartz. However, it should be noted that the geochemical sampling was not as through or close-spaced as the routine mine sampling and arsenic determinations on the actual samples assayed for gold might reveal a closer relationship between the two elements.

At Kalgoorlie, a linear relationship between arsenic and gold in ore samples assaying up to 8 dwt/ton has been established for at least one lode (Hopkins, 1965). Below this grade, the gold occurs in very fine granular intergrowths with tetrahedrite-tennantite, in which form most of the arsenic detected apparently occurred. Hopkins' mineragraphic studies showed that the ore minerals were deposited simultaneously, suggesting crystallization from a eutectic solution. In ore samples with grades in excess of 8 dwt/ton, larger particles of free gold were generally observed and the relationship breaks down. No definite relationship between arsenic and gold in the minor mineralized shears at Kalgoorlie has been observed. Arsenopyrite is probably the dominant arsenic mineral in these structures and it is considered possible that this type of mineralization was not contemporaneous with the development of the

major lodes.

It is obvious from Fig. 47 that there is a close relationship between arsenic and gold at Agnew. Within the mineralized chlorite-actinolite schist band, the peak arsenic values coincide with, or occur adjacent to high gold values, the highest arsenic contents being associated with the highest gold assays. However, insufficient lode samples were collected to fully establish the nature of the relationship.

These considerations indicate that there is a close genetic relationship between arsenic and gold over a broad area of auriferous country in Western Australia, despite the varying levels of concentration of arsenic in each area studied.

Despite the close association between arsenic and gold in ore samples, the results from both Kalgoorlie and Norseman show that the magnitude of wall-rock anomalies in drill-core and cross-cuts bears little or no relation to the grade of ore intersected. The Norseman data have been interpreted in terms of two separate, but related, phases of hydrothermal activity, the earlier resulting in the development of wall-rock and leakage anomalies, and the later in the emplacement of gold-quartz reefs. However, a number of features of the geology and trace element distribution patterns at Kalgoorlie, suggest that

the origin of the anomalies in this area is somewhat different to that postulated for the Norseman mineralization.

The wall-rock anomalies at Kalgoorlie are more variable in width than at Norseman, where the widths of anomalies were seen to be generally related to macro-shearing. Shearing is only of local significance at Kalgoorlie, being restricted essentially to the actual lodes and faults. However, the rocks throughout the area are closely fractured and this could account for the appreciable penetration of hydrothermal fluids into the wall-rocks. The limited work done suggests that the variation in the widths of the wall-rock anomalies at Kalgoorlie were related to local differences in the intensity of mineralization. The broadest anomalies in the Eastern Lode System were generally found to be associated with lodes in the vicinity of the Perseverance Lease, where the concentration of lode-shears, and hence, intensity of mineralization, was at a maximum. The narrowest anomalies (Kelly and Main Lode traverses) were encountered on the margins of the mineralized area.

The mechanism by which the Kalgoorlie wall-rock anomalies were developed cannot be ascertained on the basis of the present results. The gradual increase in concentration of arsenic approaching mineralization in some traverses is consistent with outward lateral dispersion

from the lode shears. This is supported by the greater lateral extent of arsenic wall-rock anomalies compared with those shown by gold. This is believed to reflect the different mobilities of gold and arsenic during primary dispersion. On the other hand, the broad, weakly anomalous zones, in which arsenic concentration vary consistently between 30 and 100 ppm, are more suggestive of a pervasive saturation of the rocks about lodes with arsenic-rich fluids, presumably ascending from a deep-seated source (e.g. Lake View and No.3 Lode traverses). It is probable that both mechanisms were involved to a greater or lesser extent in producing the observed anomalies.

CHAPTER 5. SECONDARY DISPERSION STUDIES.

I. INTRODUCTION.

Secondary dispersion studies have been concentrated in the Norseman area, in order to complement the detailed investigation of primary dispersion carried out in this area. Additional brief studies were also made in a number of other areas for comparison with the Norseman results and in order to extend the applicability of the conclusions reached over as wide an area as possible. Emphasis has been placed on the dispersion of arsenic, which was found to be a pathfinder element for gold in all the areas studied.

Contamination due to past or present mining activity constituted a serious problem in orientation studies in most areas. In order to avoid the effects of contamination, it was often necessary to conduct soil-sampling traverses over the sub-economic extensions of orebodies rather than over the orebodies themselves. It was reasoned that if an anomaly could be proved to occur over the strike extension of an orebody, an anomaly of comparable or greater magnitude could be expected to occur over an economic orebody. Where sampling was carried out close to dumps of mine waste, special samples were collected in order to assess the extent of contamination.

For convenience, the secondary dispersion studies are considered in three sections, corresponding to the dominant soil-types occurring in the areas examined. These categories reflect the slightly differing

physiographic, climatic and pedological environments and hence, indirectly, the factors controlling secondary dispersion in the different study areas.

II. AREAS OF SOLONIZED BROWN SOILS.

A. NORSEMAN.

1. Description of the Area.

The geology and mineralization of the Norseman area have been described in detail in the previous chapter.

The topography of the area is much more varied than in the more northerly study areas. The productive section occupies a north-south trending belt of hilly country between two large salt-lakes, Lake Cowan on the west and Lake Dundas on the east. The maximum elevation of the hills above the silt floors of the salt-lakes is of the order of 400 to 500 feet. On the higher ground, the soil cover is very thin (generally less than 1 foot) with frequent rock exposures. Considerable thicknesses of soil (up to 50 feet or more) occur on the more gentle, lower slopes of the hills. The soils are essentially residual solonized brown soils, as described in Chapter 2.

The typical vegetation of the area is of the Eucalyptus woodland type, with saltbush scrub forming a sparse covering at ground level. Samphire vegetation is common on the drier portions of the salt-lakes and dune formations on the eastern lake shores.

2. Trace element Dispersion in Residual Soils, Norseman.

a) Background Data.

To obtain an indication of the range of

concentration of arsenic in background soils, a sampling traverse was carried out over the Crown-Bluebird stratigraphy in an unmineralized area some 5 miles south of Norseman. Most samples were collected at a depth of 6-12 inches, but several full soil profiles were sampled to determine if significant concentration variations occurred in depth.

The arsenic concentration in the -82 mesh fraction of 18 samples from depths of 6-12 inches range from <1 to 8 ppm with an arithmetic mean of 2 ppm. Since more than 70% of the samples analysed had arsenic contents <1 ppm, the frequency distribution of the results is non-mathematical in form and no attempt has been made to calculate standard deviation. The value of 5 ppm has been selected as a safe approximation of local threshold, although regional background is probably of the order of 2 ppm.

The variation in arsenic content for two soil profiles is given in Table 25. There is no apparent fluctuation in the values over greenstone bedrock and even the value of 5 ppm in the topsoil of the profile over porphyry is probably not significant when the overall levels of concentration are so low.

TABLE 25. Variation in Arsenic Content with Depth in Background Soil Profiles, Norseman

Depth Ins.	Description	As ppm	Depth Ins.	Description	As ppm.
0 - 3	Light to medium brown loam + lime-coated rock fragments.	< 1	0 - 3	Medium-red brown organic-rich top-soil.	5
3 - 6	Light grey brown loam + lime coated rock fragments.	<1	3 - 6	Medium to red-brown loam	1
6 -12	Ditto	<1		Ditto	<1
12-18	Powdery buff loam + lime coated rock fragments	<1	9+	Kaolinized porphyry	1
18-25	Ditto	<1			
25+	Weathered F-Mg actinolitic greenstone	1			

Antimony contents of background soils at 6-12 inches show an approximately normal distribution. Values range between <0.2 and 4.5 ppm, and threshold has been calculated at 4 ppm.

b) Trace Element Anomalies in Soils in the Vicinity of Sub-Outcropping Gold-Quartz Mineralization at Norseman.

(i) Particle size distribution of arsenic in profile samples.

A brief study of the distribution of arsenic in Norseman soils was made in order to determine the optimum sampling depths and size fractions for routine analysis. Samples taken at various depths in an anomalous profile, near the outcrop of Crown Reef, and a background profile were separated, by dry sieving, into six size fractions. The results of arsenic determinations on these samples are given in Table 26. Although a thorough separation of the silt and clay particles from the coarser fragments of the soil was not achieved, as shown by more detailed studies (p 193), dry sieving is an adequate means of size separation for routine prospecting purposes.

It can be seen from Table 26, that there is a marked tendency for the maximum arsenic concentrations to be associated with the coarser fractions in both anomalous and background samples. A secondary concentration of arsenic is often present in the -197 mesh fraction.

The concentration of arsenic in all fractions of the two deeper samples of the anomalous profile is appreciably greater than that in the surface soils. No significant variation in arsenic content with depth is

TABLE 26. Comparison of Arsenic Distribution in Size fractions of Anomalous and Background Profile Samples, Crown Reef Traverse, Norseman.

Sample Depth, Ins.	Size Fraction	Anomalous Soil		Background Soil		Contrast
		Wt.%	As ppm	Wt.%	As ppm	
0-3	+20	19	10	25	5	2.0
	-20 +38	13	20	14	3	6.7
	-38 +82	29	13	21	2	6.5
	-82 +125	23	15	22	1	15.0
	-125 +197	11	15	15	1	15.0
	-197	5	25	3	1	25.0
	-82	39	16	40	1	16.0
6-12	+20	35	53	44	5	10.6
	-20 +38	27	33	19	8	4.1
	-38 +82	21	30	18	5	6.0
	-82 +125	9	33	9	<2	16.5
	-125 +197	6	33	7	2	16.5
	-197	2	35	3	2	17.5
	-82	17	33	19	1.5	22.0
Over bed-rock (depth 36-60 inches)	+20	72	30	40	10	3.0
	-20 +38	13	55	14	3	18.3
	-38 +82	7	30	19	1	30.0
	-82 +125	3	30	12	<1	30.0
	-125 +197	3	28	11	1	28.0
	-197	2	33	4	3	11.0
	-82	8	31	27	1	31.0
Bed-rock	(Pulverized)	-	20	-	2	10

evident in the background profile.

Contrast is seen to be at a maximum in the finer size fractions of the soil at all three depths. The calculated values for the -82 mesh fraction indicate that this is the most suitable size range, giving consistently good contrast, combined with adequate sample material and good representativity.

On the basis of contrast alone, the best sampling depth would appear to be immediately over the weathered bedrock. However, the requirements of economy and speed make sampling at this depth (which may be up to 50 feet at Norseman) impracticable except in very detailed surveys. There would appear to be little to choose between the samples at 0-3 inches and 6-12 inches, both showing adequate contrast in this traverse. The depth of 6-12 inches is usually preferable to surface samples, since the latter may be affected by locally transported overburden and/or contamination.

As a result of these studies, samples were provisionally collected at a depth of 6-12 inches and sieved to -82 mesh in all soil sampling at Norseman. In some traverses, the initial results indicated the need for more detailed sampling of the soil profile, as will be seen in subsequent sections.

(ii) Lateral dispersion in soils in the vicinity of the Crown Reef outcrop.

The lateral dispersion of arsenic and other elements in soils in the vicinity of outcropping

gold-quartz mineralization is illustrated by a traverse in the vicinity of Crown Reef. The datum of this traverse is situated over a stope on the small ore-shoot outcropping at coordinates 8250N, 1660W (Fig.15). The terrain over which the traverse was collected is relatively flat, as indicated in the sketch section in Fig.49. The thickness of soil averages 1 to 2 feet but thicknesses up to 7 feet were encountered in the immediate vicinity of the reef, where the ultrabasic composition of the altered rocks and presence of oxidizing sulphides have presumably promoted more intense weathering.

A very strong arsenic anomaly, approximately 200 feet in width and with a peak value of 210 ppm As. occurs in soils over and adjacent to the Crown Reef. A second moderately strong anomaly occurs at the eastern end of the traverse. This anomaly coincides in position with the projected sub-outcrop of the Mararoa Reef-Shear and is associated with outcrops of schistose rocks. Apart from these two anomalies, the arsenic content of the soils varies from 1 to 5 ppm throughout the traverse.

Strong anomalies are also shown by cold-extractable arsenic in the vicinity of Crown Reef and Mararoa Reef-Shear. Local background for cold-extractable arsenic, based on the results for several traverses in the area, is approximately 0.5 ppm, and so the peak values of 23.0 and 27.0 ppm cxAs indicate slightly better contrast than for total arsenic. The plateau of weakly

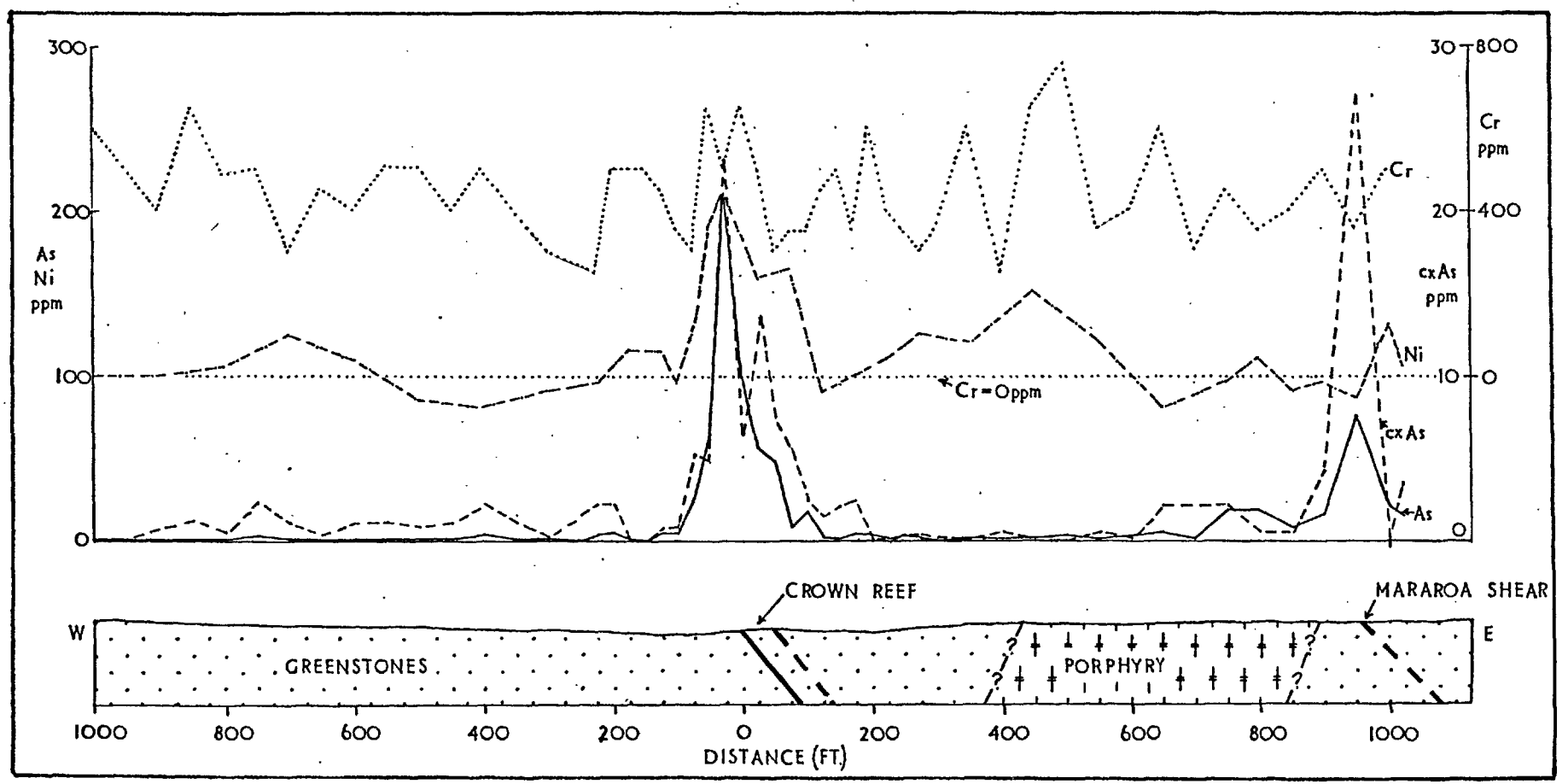


Fig. 49. Lateral dispersion of As, cxAs, Ni & Cr in soils (-82#; 6-12" depth) in the vicinity of Crown Reef, Norseman.

anomalous cxAs values (0.5 to 2.0 ppm) between 200W and 900W, associated with background total arsenic contents, indicates a marked departure from the normal cxAs/total As ratio of approximately 10-20%. This may be related to higher than normal organic contents in the soils, the significance of which is discussed in a later section.

Nickel exhibits a distinct but weak anomaly, of similar width to that of the arsenic anomaly, in the vicinity of the Crown Reef outcrop. Background for nickel in Norseman soils is not accurately known but it would appear from Fig. 49, that the anomaly contrast is somewhat less than 2. Chromium contents vary randomly between 250 and 750 ppm throughout the traverse and no significant anomaly is apparent in the vicinity of Crown Reef.

Selected size fractions of seven samples from the Crown Reef traverse were analysed for gold to see if significant anomalies could be obtained. The results (Table 27) showed no consistent concentration of gold in any particular fraction.

Although measurable quantities of gold occur in the soils over and in the vicinity of Crown Reef, relatively high values also occur in all fractions at considerable distances from the reef, such that the anomaly associated with the reef is indistinct. The relatively high gold contents at 700E could hardly be due to dispersion from Crown Reef, since this location is topographically higher than the outcrop of the reef.

However, it has been noted previously (p.154) that porphyry dykes frequently contain low grade gold mineralization. Hence, the gold could have been derived from the underlying porphyry bedrock.

TABLE 27. Gold Content of Selected Size Fractions of Soils, Crown Reef Traverse, Norseman.

Location on Traverse (ft)	Au ppm		
	+20 mesh fraction	-20 +82 mesh fraction	-82 mesh fraction
725W	0.05	0.20	0.35
75W	1.20	0.05	0.05
25W	0.05	0.07	0.05
10W	0.05	0.05	0.90
0	0.80	0.05	0.05
25E	0.10	0.30	0.30
75E	0.05	0.50	2.00
700E	0.50	0.45	1.00

Possible reasons for the erratic distribution of the results, both laterally and in the different size fractions, are :- inadequacy of the analytical method; fundamental variations in the mode of occurrence of gold in soils; non-representativity of the samples due to the small weight (1 gm) taken for analysis.

The possibility of contamination from a small mine dump, situated 20 feet north of the datum of the Crown Reef traverse, was tested by a series of traverses radiating from the edges of the dump. Profile samples were collected at varying distances from the dump and the -82 mesh fraction was analysed for arsenic. The interpretation of the results (Table 28) is somewhat complicated by the fact that the soils, on which the dump stands, could be expected to be anomalous in any case, being in close proximity to the Crown Reef outcrop. However, the results become intelligible if it is assumed that contamination would be at a maximum in the surface soils in close proximity to the dump. It can be seen that, in all four traverses, the highest arsenic contents in the profile samples within 10 feet of the dump occur in the uppermost 3 to 6 inches of the soils. In the profiles sampled at distances of 25 feet or more from the dump, the arsenic content of the topsoil is generally similar to, or less than, the arsenic values obtained at greater depths. It has been seen (Table 26) that in uncontaminated profiles, arsenic tends to be concentrated in the deeper horizons. Hence, the high arsenic values obtained in the surface soils of profiles nearest the dump may be regarded as being due to

contamination from the dump. It is concluded that contamination is restricted to within a radius of less than 25 feet from the dump and that only the upper 6 inches of the soil profile is affected to any extent.

TABLE 28. Contamination Study: Arsenic Contents of Profile Samples Collected in the Vicinity of a Mine Dump*

Location(Feet from margin of Dump)		0	10	25	50	75	100
Bearing of Traverse	Depth (Ins)	As ppm	As ppm	As ppm	As ppm	As ppm	As ppm
360°	0 - 3	38	13	3	5	n.d.	3
	3 - 6	5	n.d.	5	3	3	n.d.
	6 -12	5	5	10	8	20	3
	12-18	5					
	18-24	3					
90°	0 - 3	125	10	3	3	n.d.	8
	3 - 6	125	8	n.d.	5	20	3
	6 -12	45	5	10	3	10	n.d.
	12-18	38					
163°	0 - 3	45	15	8	n.d.	5	3
	3 - 6	8	3	10	10	3	n.d.
	6 -12	20	15	13	3	8	n.d.
	12-18	18					
270°	0 - 3	45	8	20	18	5	
	3 - 6	23	15	30	20	15	
	6 -12	18	13	55	20	15	
	12-16	30					

* Analytical data from Kalgoorlie Laboratory.

c) Trace Element Anomalies in the Vicinity of Sub-Outcropping Reef-Shears at Norseman.

The Crown Reef traverse demonstrates that sub-outcropping gold-quartz reefs can be readily located by analysing the near surface soils for traces

of arsenic. However, the application of this in prospecting is likely to be limited, since quartz veins are usually obvious in the field and their potential readily assessed by conventional methods. Nevertheless, geochemical testing of soils could help to distinguish between mineralized quartz and non-auriferous buck quartz. A much more important prospecting problem at Norseman, however, is the location of unsilicified reef-shears, which might possibly contain blind orebodies at depth. It has already been shown that strong primary arsenic anomalies are associated with the Crown and Princess Royal Shears and that the anomalies persist considerable distances up-dip from orebodies. Hence, secondary anomalies should occur in residual soils over the sub-outcrops of shears of this type, even though these structures rarely have any visible surface expressions. The present section deals with an investigation of the soil anomalies associated with known reef-shears.

(i) Crown Shear.

A soil-sampling traverse was carried out over the presumed sub-outcrop of the Crown Shear at 4550N, approximately 150 feet to the north of the 4400N drilling traverse, which was sampled in detail in the studies of primary dispersion. The terrain slopes gently to the west over most of this traverse, which is characterized by marked variation in the thickness of the soil profile. At the eastern end of the traverse, the

soil cover is generally 1 to 2 feet in thickness but drilling in the central and western parts of the traverse has shown thicknesses up to 60 feet of unconsolidated overburden to be present.

The results for the -82 mesh fraction of soils taken at a depth of 6 - 12 inches depth are shown in Fig.50. The location of the sub-outcrops of the (?) two branches of Crown Shear (see Fig.28) can only be inferred approximately by projecting the structure up-dip from the shallowest drill-hole intersection. The soil traverse was set out in such a way that anomalies could be expected to occur in the vicinity of the datum and 200 to 400 feet west of the datum. In fact, only high background values occur at these points with a maximum of 7 ppm at the datum. Somewhat greater contrast was obtained in these positions by analysing for cxAs. Considerably stronger As and cxAs anomalies (up to 34 ppm As) were found to occur in the eastern part of the traverse, associated with outcrops of porphyry and with a silicified slate horizon, which itself is closely associated with porphyry. It was suggested in an earlier section (p115) that the anomalies associated with this porphyry may have been formed as a result of the diversion of some of the hydrothermal emanations by the porphyry dykes, which intersect the Crown Reef-Shear at shallow depth.

The lack of any appreciable anomaly in the vicinity of, and to the west of, the traverse datum could

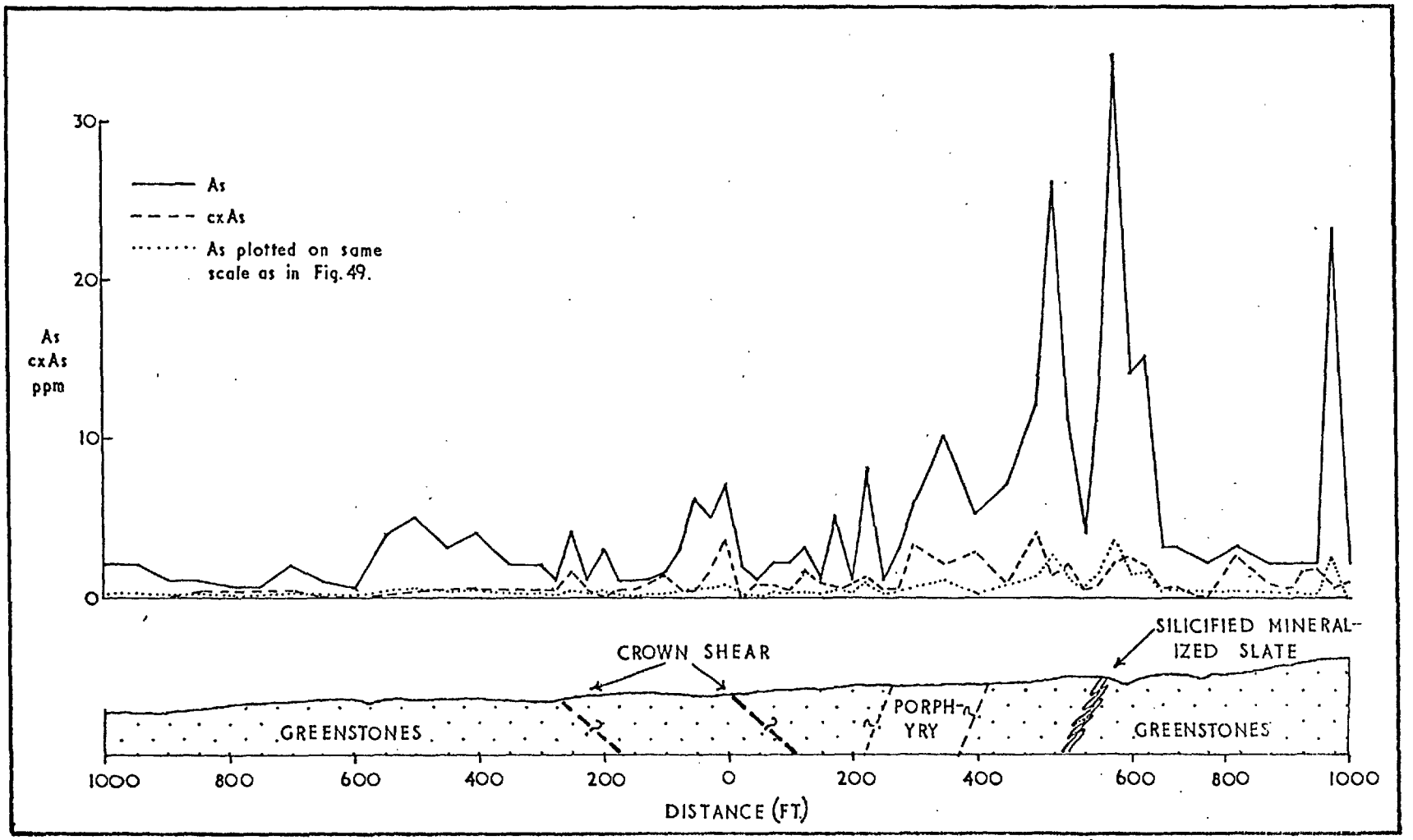


Fig. 50. Lateral dispersion of As & cxAs in soils (-82#; 6-12" depth) in the vicinity of the inferred suboutcrop of Crown Shear, Norseman.

be due to the possibility that Crown Shear dies out completely to the west of C53 and does not sub-outcrop. Alternatively, if the shear does sub-outcrop it is possible that the expected anomaly is suppressed by some factor related to the abnormal thickness of soil which occurs in the area of interest. In order to test these hypotheses, profile samples were obtained by means of a motor-driven auger drill over the central 800 feet of the traverse. The sampling intervals were varied with depth as follows:

Depth	Sample Interval.
0 - 4ft	1 ft.
4 -10ft	2 ft.
10 -30ft	5 ft.
30ft+	10 ft.

The distribution of arsenic in the -82 mesh fraction of the resulting samples is shown in Fig.51.

It can be seen from Fig.51 that although the uppermost foot of the profile almost invariably contains only background arsenic values, there is an increase in arsenic content with depth in the majority of holes. Anomalous subsoils occur more or less over the whole width of the drilling traverse, although several background profiles occur within this broad anomalous zone. A striking concentration of arsenic occurs at a depth of 1 to 2 ft. in profiles between 2600W and 2700W.

Examination of rock fragments obtained in

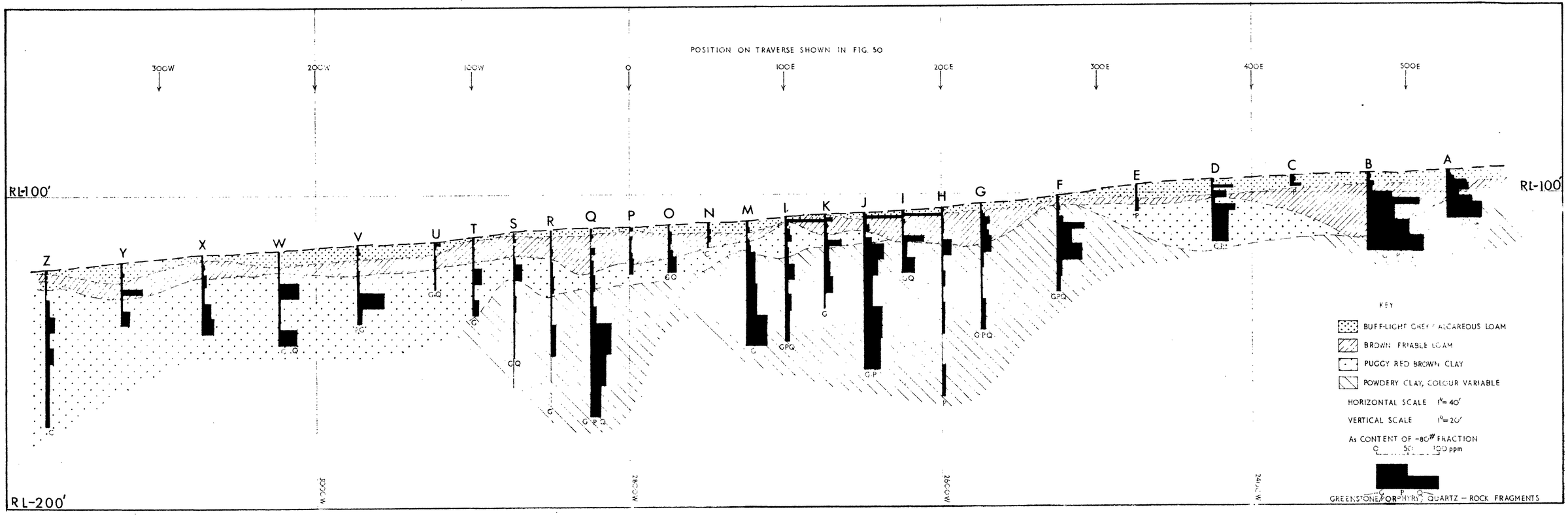


Fig. 51. Distribution of arsenic in deep soil profiles in the vicinity of the inferred suboutcrop of Crown Shear, Norseman

drilling indicates that porphyry dykes occur at intervals in the greenstone between 2200W and 3000W, although the only outcrops of porphyry were seen to occur to the east of 2500W. It is also apparent that anomalous arsenic values are not exclusively restricted to those profiles in which porphyry fragments occur. Hence, the anomalous subsoils are probably not entirely due to the presence of arsenical porphyry dykes.

Quartz fragments were recovered from many of the holes. In a number of these, (e.g. W, Q, L, I, G, F, B, A) the quartz is associated with high arsenic contents, possibly indicating the presence of reef-shears.

Four main soil horizons were recognised on the basis of the colour and texture of the samples recovered. These are listed below in order of increasing depth of occurrence.

(i) Buff to light grey-coloured loam with calcrete fragments (A & B_1)

(ii) Brown friable loam (B_2).

(iii) Puggy red clay (B_3)

(iv) Powdery clay - colour variable: white, yellow-brown or pinkish (?C).

All four horizons are not necessarily represented in any one profile. It was intended to drill through to weathered bedrock in all cases. However, in some profiles, the drill was unable to penetrate the puggy red clay. Horizon (iv) probably represents, at least in part, the highly weathered, crumbly bedrock. The soils are

apparently residual although the thickening of the solum at the western end of the traverse suggests that some downslope colluvial movement has taken place.

In an attempt to obtain a clearer interpretation of the results, the arsenic results for each soil horizon were averaged and replotted in Fig.52. The maximum values obtained in each horizon are also plotted. The results indicate three more or less distinct anomalies occurring between 400W and 100W, 50W and 200E, and 350E and 500+E. The easternmost anomaly corresponds to the anomaly established in surface soils (Fig.50) which was seen to be associated with porphyry outcrops. The other two anomalies coincide approximately with the inferred position of the sub-outcrops of Crown Shear. However, the anomalous subsoils at the western end of the drilling traverse could also be explained as the result of seepage of arsenic-rich material from the topographically higher anomaly near the datum (see p.261). It is therefore concluded that Crown Shear does extend to the surface of the weathered bedrock and gives rise to arsenic anomalies in the overlying soils.

An interesting feature of the drilling results is that although all three anomalies persist in depth, the westernmost anomaly is not evident in the upper calcareous soil horizon whilst the central anomaly has its strongest development in the base of this horizon. These variations in the distribution of arsenic in the soil profile are of considerable importance since it is

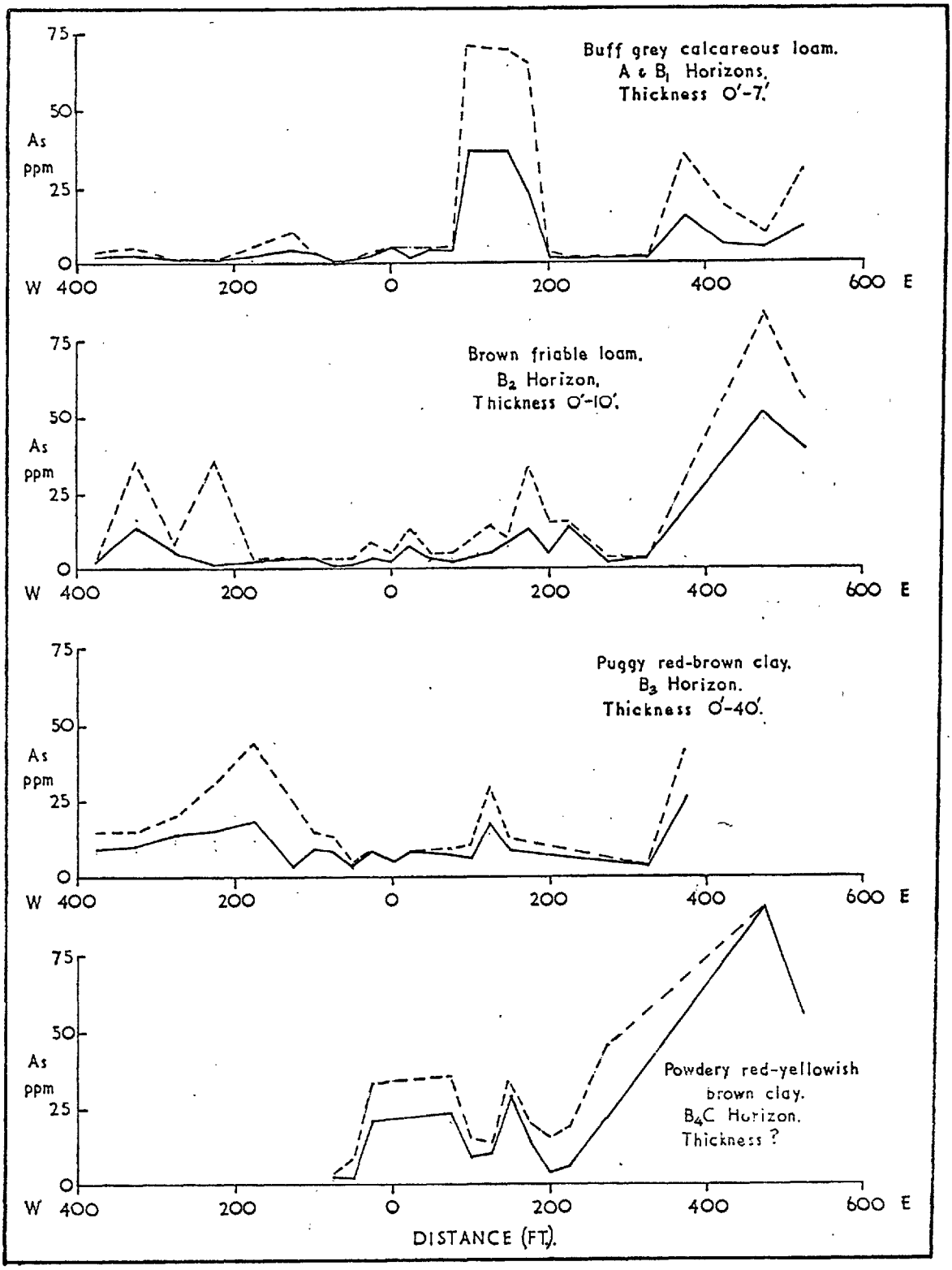


Fig. 52. Lateral dispersion of arsenic in the different soil horizons (-82#) in the vicinity of the inferred suboutcrop of Crown Shear, Norseman.

clear that the anomaly associated with Crown Shear sub-outcrop might have been missed in prospecting if the poor results obtained for near-surface soils had not been followed up by deeper sampling. A more detailed discussion of the distribution of arsenic in the soil profile is given in a later section.

(ii) Princess Royal Shear.

A relatively weak arsenic anomaly, approximately 125 feet in width occurs in soils in the vicinity of the Princess Royal Reef-Shear (Fig.53). The datum of this traverse is situated over a number of thin quartz stringers in sheared metagabbro, exposed by trenching, approximately 50 feet south of the southernmost known orebody. Although the peak value of 30 ppm As is considerably lower than the values encountered in the Crown Reef traverse, the anomaly is still distinct when compared with the threshold value of 5 ppm.

Cold-extractable arsenic shows an anomaly of greater width and contrast than total arsenic. Since local background for cold-extractable arsenic is 0.5 ppm, the peak value of 4 ppm represents a contrast of at least 8. The cxAs anomaly is assymetrical, with a secondary peak occurring some 200 feet to the west, and downslope, from the traverse datum.

This assymetry is confirmed by total arsenic analyses on profile samples collected in the central

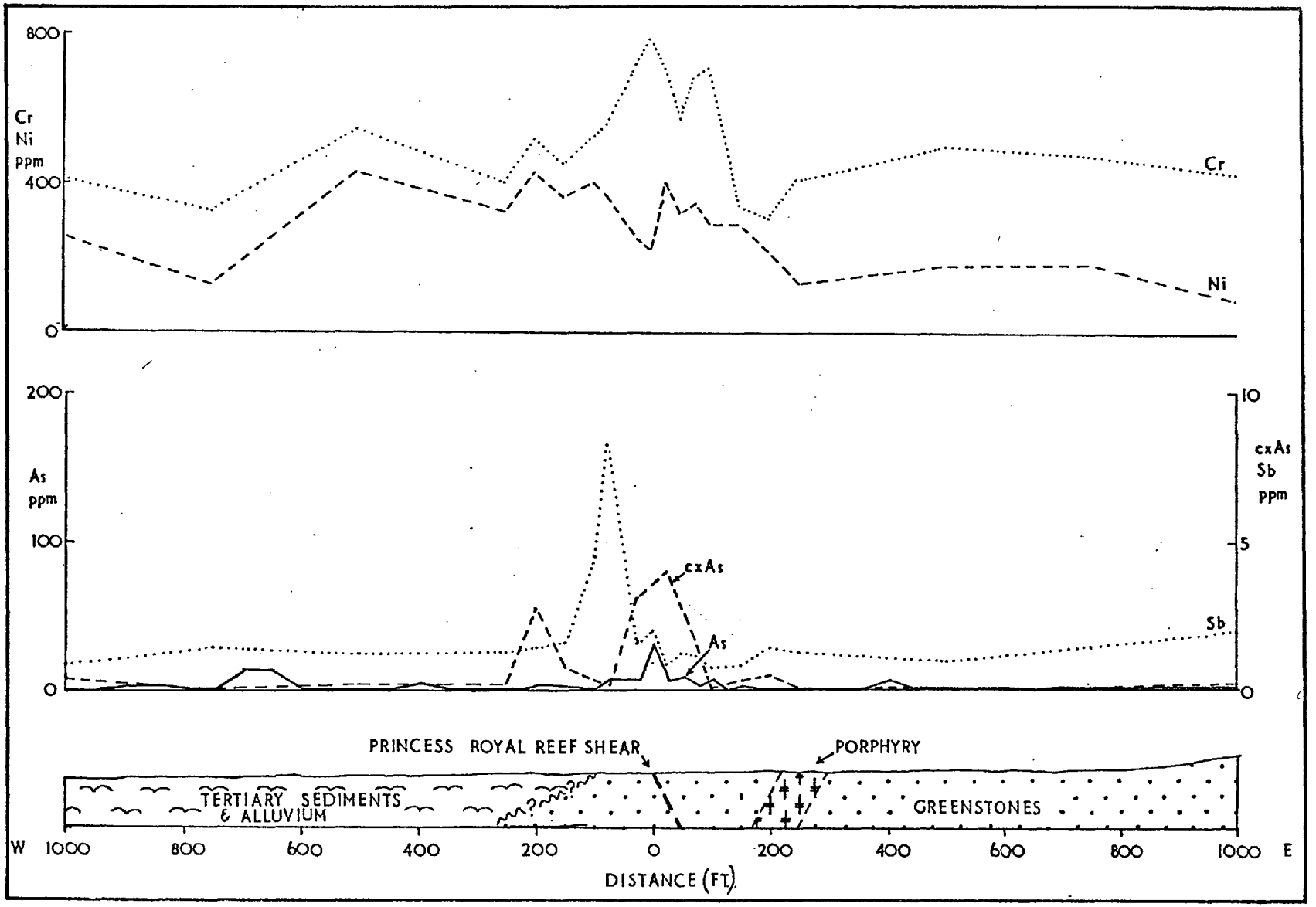


Fig. 53. Lateral dispersion of As, cxAs, Sb, Ni & Cr in soils (-82#; 6-12" depth) in the vicinity of Princess Royal Reef-Shear, Norseman.

portion of the traverse (Fig.54). As in Table 26, it can be seen from Fig.54, that the arsenic content of the topsoils is appreciably lower than in the deeper soil horizons. Maximum contrast was obtained at 6 - 12 inches although the general level of values is similar at both 6 - 12 inches and immediately over bedrock. The anomaly width is slightly greater at the latter depth. The highest arsenic contents occur in the weathered bedrock.

The low arsenic contents obtained in the solum in this traverse, which are very much below the concentration levels found in primary dispersion patterns about Princess Royal Reef-Shear, may be partly due to the blanket of Tertiary and Recent sediments which at one time unconformably overlaid the Precambrian orebody. It can be seen from Fig.53 that the present erosion surface lies only a short vertical distance below the inferred former position of the unconformity. Hence, only limited erosion of the arsenic-rich Precambrian rocks about the reef-shear has taken place in the development of the present soil profile - probably insufficient for the accumulation of appreciable concentrations of arsenic in the solum.

The assymetry of the arsenic and cold-extractable arsenic anomalies could be due to recent sheetwash erosion. There is very little vegetation present in the area and considerable evidence to suggest that recent downslope movement of the topsoils has taken place. It is also

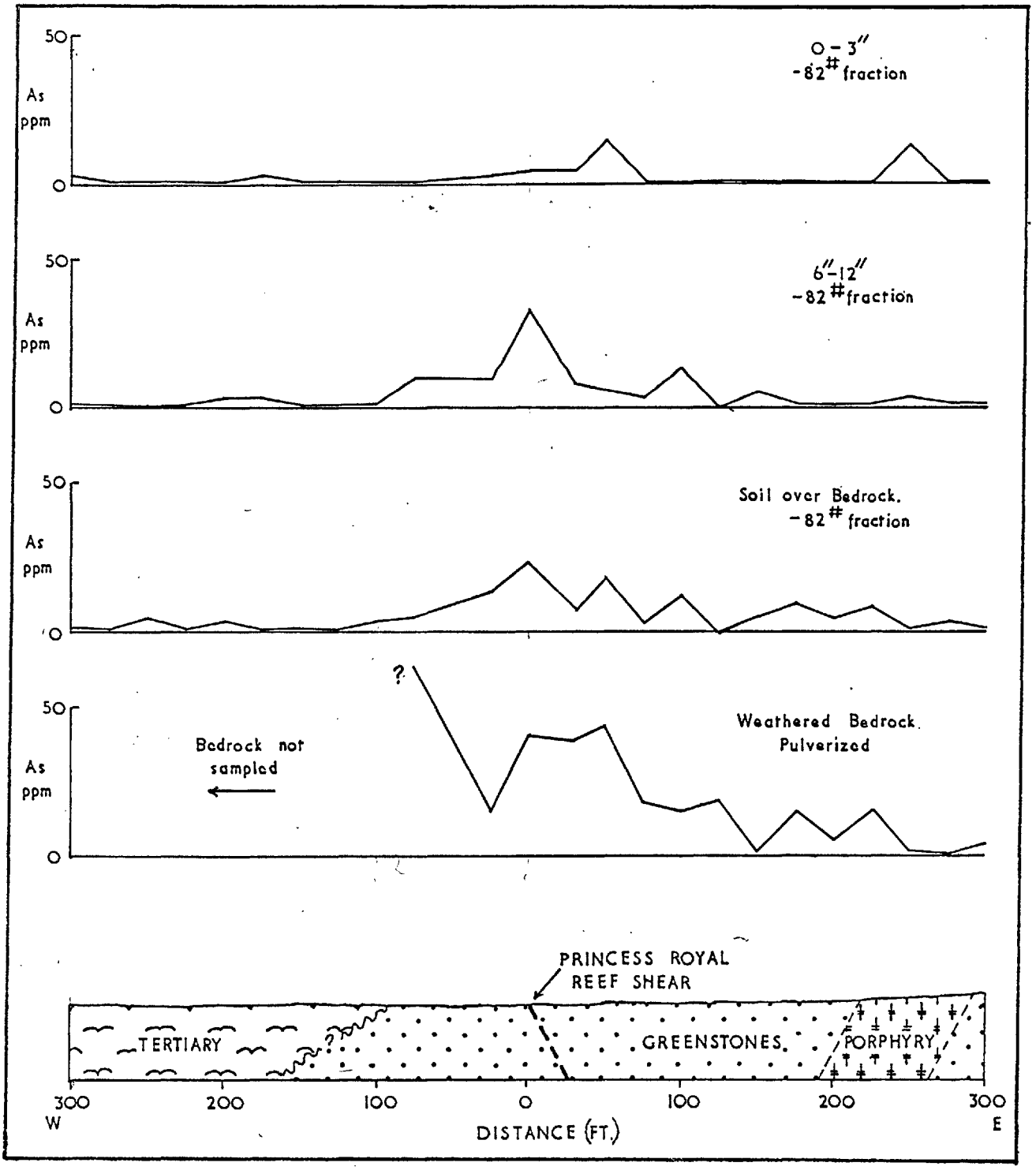


Fig. 54. Lateral dispersion of arsenic at selected depths in soils in the vicinity of Princess Royal Reef-Shear, Norseman.

possible, however, that the displacement could be of more ancient origin, since deep lead (buried placer) deposits of gold, presumably derived from the weathering of the Princess Royal outcrop, have been worked in an area approximately 500 feet west of the datum. The deep leads were overlain by some tens of feet of transported overburden, indicating a considerable period of erosion and deposition in the topographic lows to the west of the reef-shear.

Chromium and nickel both show relatively weak anomalies with contrast *2 (Fig.53). The chromium anomaly has a fairly sharply defined peak, coinciding approximately in position with the arsenic anomaly. It is of interest to note that the distribution of chromium in the soil profile is similar to that shown by arsenic, the maximum concentrations occurring in the weathered bedrock (Table 29). The anomaly in the case of nickel is more vague and further analysis would be required to delineate the anomaly more accurately. The presence of a nickel anomaly in soils is somewhat surprising in view of the fact that no nickel anomalies were encountered in the brief study of primary dispersion about Princess Royal Reef-Shear.

A sharply defined antimony anomaly of twofold contrast occurs in soils immediately to the west of the reef-shear sub-outcrop. Mercury determinations on soils from the Princess Royal traverse ranged from 100 to

300 ppb, with no significant variation in the vicinity of the shear.

TABLE 29. Distribution of Chromium with Depth in Soils (-82 mesh fraction) in the vicinity of the Princess Royal Reef-Shear, Norseman*

Position on Traverse(ft)	500E	100E	60E	10E	0	10W
Depth (ins)	Cr ppm	Cr ppm	Cr ppm	Cr ppm	Cr ppm	Cr ppm
0 - 3	350	850	600	700	850	650
3 - 6	300	600	600	600	600	650
6 -12	280	600	660	470	720	600
12-18	350					
18-24	300					
Weathered Bedrock	350	4200	2100	3000	2200	2400
Depth of Bedrock	24ins.	12ins.	12ins.	12ins.	12ins.	10ins.

* Colorimetric determinations.

(iii) Norseman Shear

The distribution of arsenic and antimony in soils in the vicinity of the Norseman Reef-Shear is shown in Fig.55. The datum of this traverse is over a short unsilicified section of the shear between old workings on gold-quartz ore-shoots. The terrain over which the traverse passes is hilly with relatively shallow soils of the type shown in Fig. 3b.

Background arsenic values predominate in the central and western parts of the traverse with a maximum value of 8 ppm at the datum point. Somewhat higher

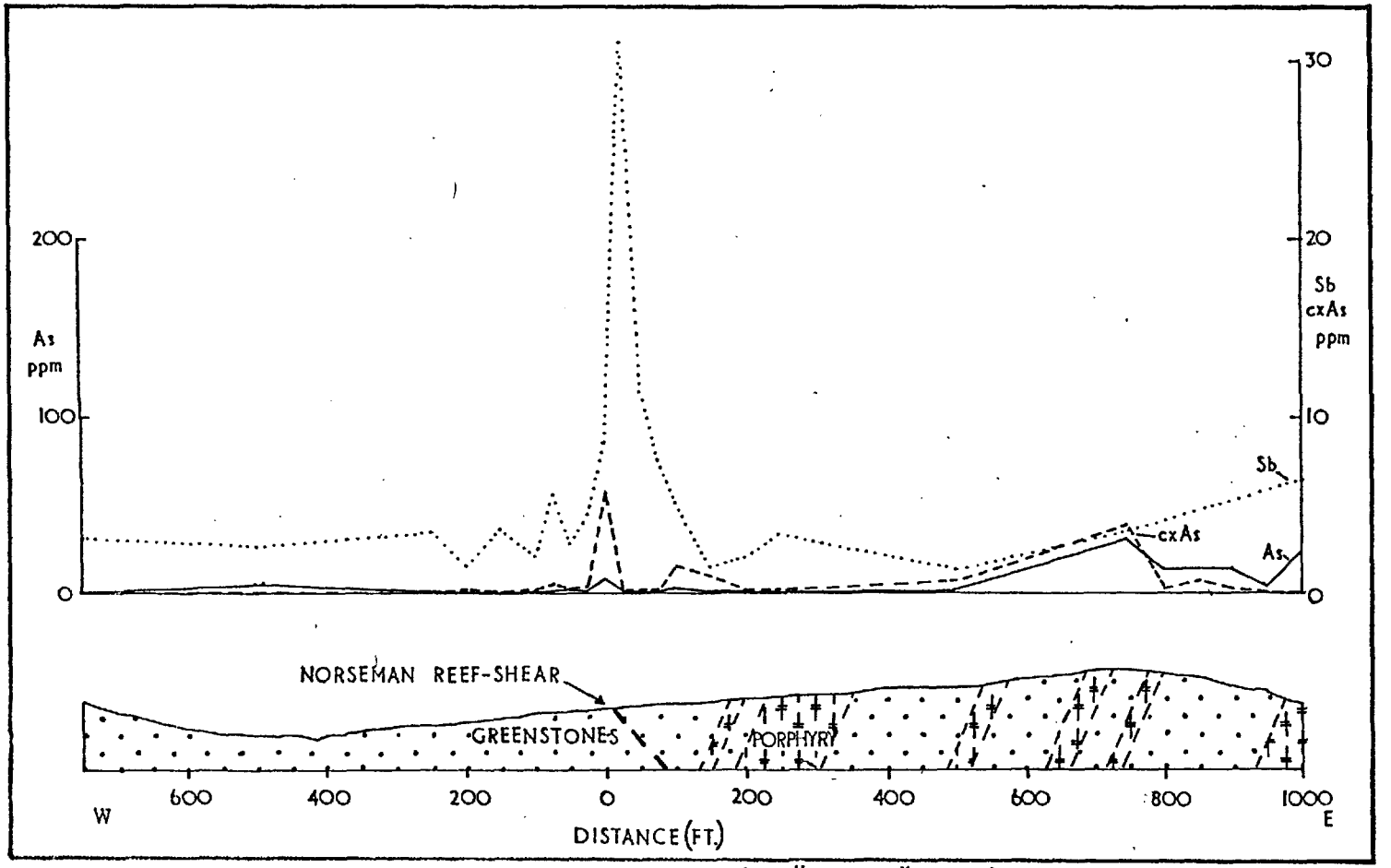


Fig. 55. Lateral dispersion of As cxAs & Sb in soils (-82#; 6-12" depth) in the vicinity of Norseman Reef-Shear.

values (up to 30 ppm As) were obtained towards the eastern end of the traverse, where they are associated with outcrops of silicified, mineralized porphyry dykes. There is no known reef-shear at the eastern end of the traverse and it is considered that the anomaly is due to an accumulation of arsenic within the porphyry. A value of 280 ppm As was obtained for a "background" porphyry sample from this same porphyry swarm in a drill-hole intersecting the Norseman Reef some 2,300 feet to the south of the present traverse. In view of the westerly dip of the porphyries, it is almost certain that the porphyry intersects the Norseman Reef at depth. The anomaly may therefore be indirectly related to the reef-shear structure in the manner suggested in the discussion of the leakage anomaly associated with the Crown Reef-Shear on page 115 .

Cold-extractable arsenic shows greater contrast in the immediate vicinity of the reef-shear sub-outcrop than total arsenic and is also high at the eastern end of the traverse.

The weak arsenic anomaly in soils in the vicinity of the Norseman Reef-Shear is in accord with the relatively weak primary anomalies found to be associated with this ore structure. It might be concluded that the Norseman Reef is of a different geochemical type to the other reefs in the area. However, the insignificant nature of the arsenic

dispersion patterns associated with this reef-shear may also be explainable in terms of vertical geochemical zoning mentioned on page 165.

A strong antimony anomaly with a width of 200 feet and a peak value of 31 ppm occurs adjacent to the sub-outcrop of the reef-shear. In view of the fact that no primary antimony anomaly was encountered in the two drill-hole intersections on Norseman Reef studied, antimony cannot be regarded as a significant pathfinder element. It is considered likely that a chance local accumulation of antimony was associated with the reef at this point but the association probably does not persist along the strike.

Samples from the Norseman Reef traverse were also analysed for Ag, Bi, Co, Cr, Cu, Ga, Mn, Mo, Ni, Pb, Sn, Ti, V and Zn. No significant variations in these elements were found to occur in the vicinity of the reef-shear.

d) Mode of occurrence of arsenic in Norseman Soils.

A complete size separation of the three anomalous samples referred to on page 174 was carried out using the wet dispersion method described in detail in the Appendix. The tenor of arsenic in the various size fractions is shown in relation to the mechanical composition in Fig. 56. While high arsenic contents occur in the coarse fractions, particularly those of the

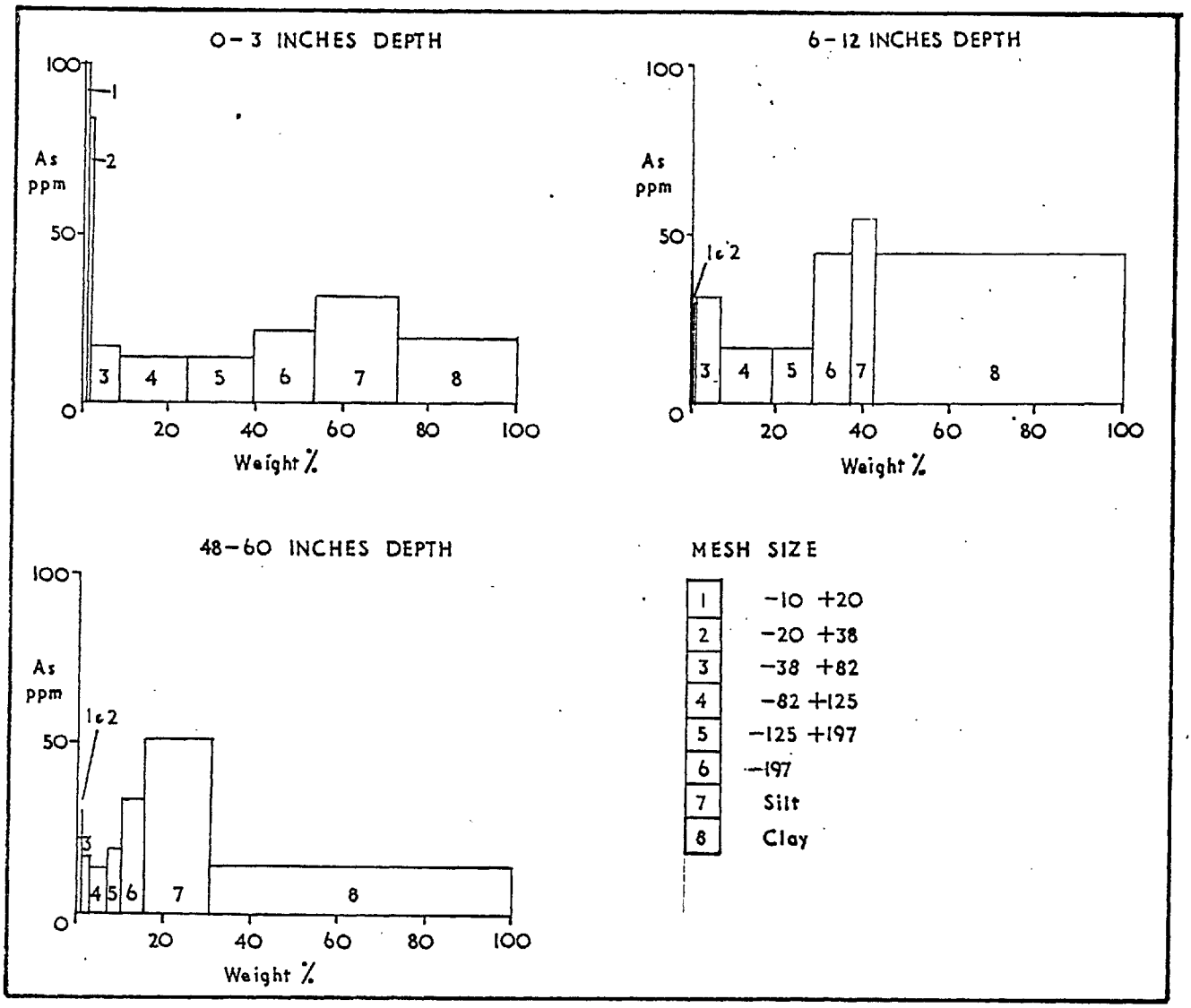


Fig. 56. Distribution of arsenic according to particle size at different depths in an anomalous soil profile, Norseman.

topsoils, it can be seen that the bulk of the arsenic occurs in the -197 mesh, silt and clay fractions. The silt fraction shows the highest arsenic tenor of these three size ranges.

An interesting feature of Fig.56 is that more than 60% by weight of all three samples consists of particles in the -197 mesh size. Thus, wet dispersion demonstrates that the soils are considerably finer in texture than was indicated by the results of dry-sieving (Table 26), this being due to the difficulty in separating the clay and silt from the coarser particles prior to dry-sieving. From Fig. 56 it can be seen that the clay content varies from 27% to 70%, showing a marked increase with depth. The amount of material in the -10 mesh to +82 mesh size range shows a corresponding decrease with depth, from 8.7% at the surface to 2.7% in the deepest sample.

Analyses of minerals separated from the coarse sand fractions of the 6 - 12 inches sample clearly show that arsenic is concentrated with the iron oxide grains, rather than the carbonates or quartz which together make up the bulk of the coarse fractions (Table 30).

In order to test the extent of this association between arsenic and iron oxides, all size fractions were analysed for total iron (Fig 57). It can be seen

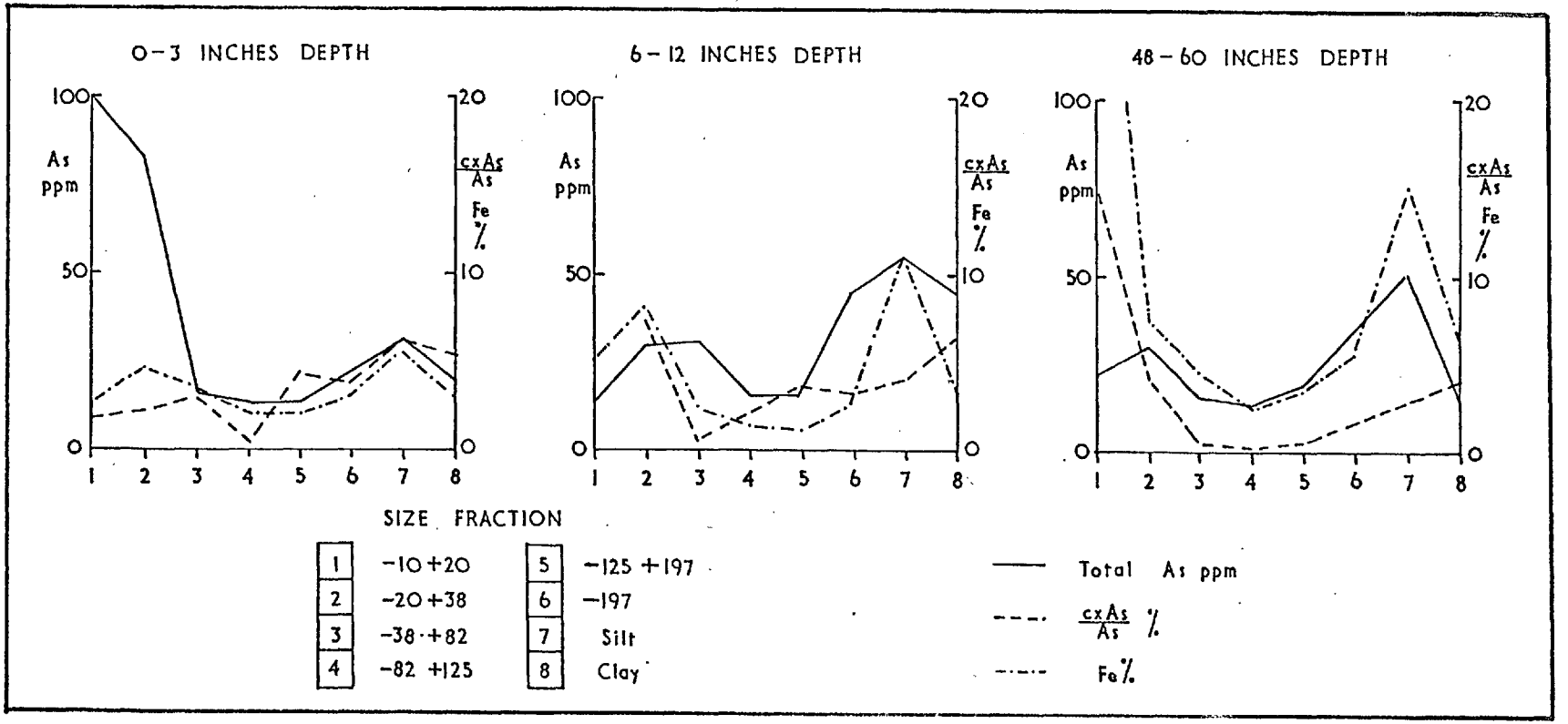


Fig. 57. Distribution of As cxAs/As & Fe according to particle size at different depths in an anomalous soil profile, Norseman.

that there is a close similarity in the distributions of these two elements, suggesting that arsenic is closely associated with iron in all size fractions. This is most marked in the silt fractions of the two deeper soil samples where both arsenic and iron show maxima.

TABLE 30 Arsenic Content of Mineral Fractions Separated from an Anomalous Soil Sample, Norseman.

Size Fraction	Iron oxides As ppm	Carbonates As ppm	Quartz As ppm.
-10 +20	393	10	1
-20 +38	270	26	0.5
-38 +82	165	24	5

The cxAs/total As ratio, in general, increases with diminishing particle size, reaching a maximum of 20% to 35% in the clay fraction. This gives some indication of the proportion of the arsenic that is weakly attached to soil particles in exchange positions. The main hosts of exchangeable arsenic in the Norseman soils are presumably colloidal iron oxides and clay minerals in the silt and clay fractions. The high cxAs/total As ratios in certain of the coarse sand fractions is explained by the fact that the cxAs attack is virtually complete for the relatively minor amounts of arsenic associated with carbonate minerals. Some

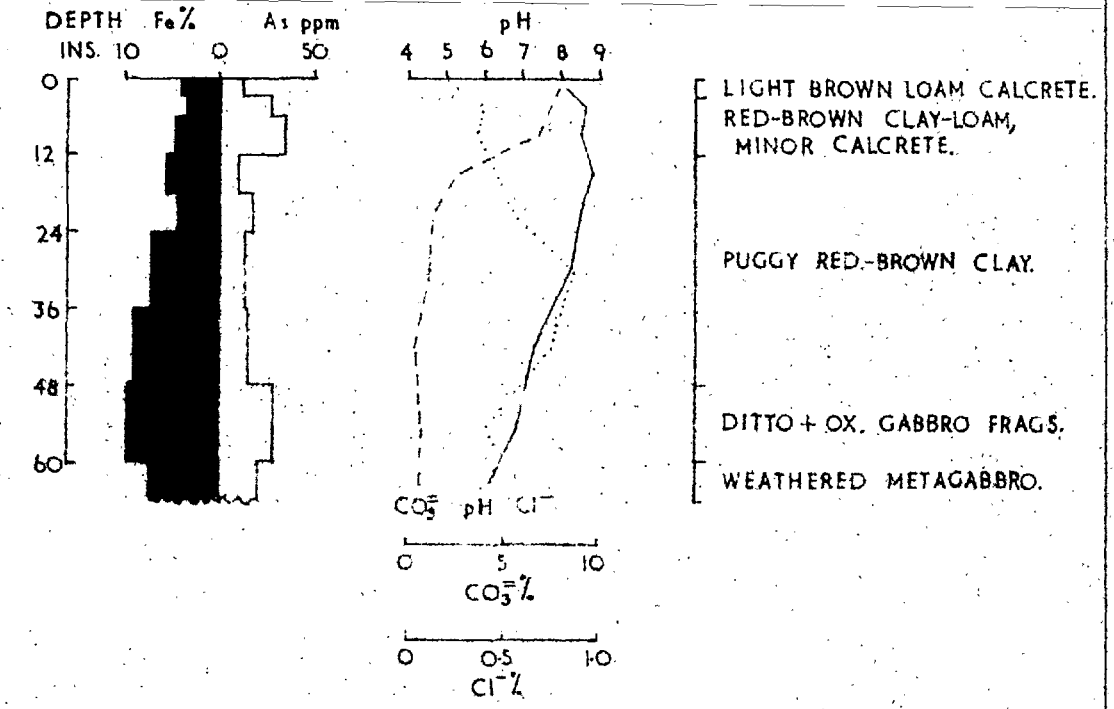
workers believe that the arsenic fixed by carbonates is in adsorbed form (see in discussion). Moreover, the carbonate granules separated from the Norseman soils were found to consist of loose, cellular aggregates and the vigorous effervescence shown when the highly acid stannous chloride solution was added to samples suggests that a complete break-down of the carbonates occurs.

It was concluded from this work that the bulk of the arsenic in the soils is associated with the secondary iron minerals, partly by chemical combination and partly by weaker adsorption bands. A lesser proportion occurs as exchangeable arsenic associated with clay minerals and possibly with carbonates. These results are largely consistent with the known geochemical characteristics of arsenic, which will be discussed in a later section.

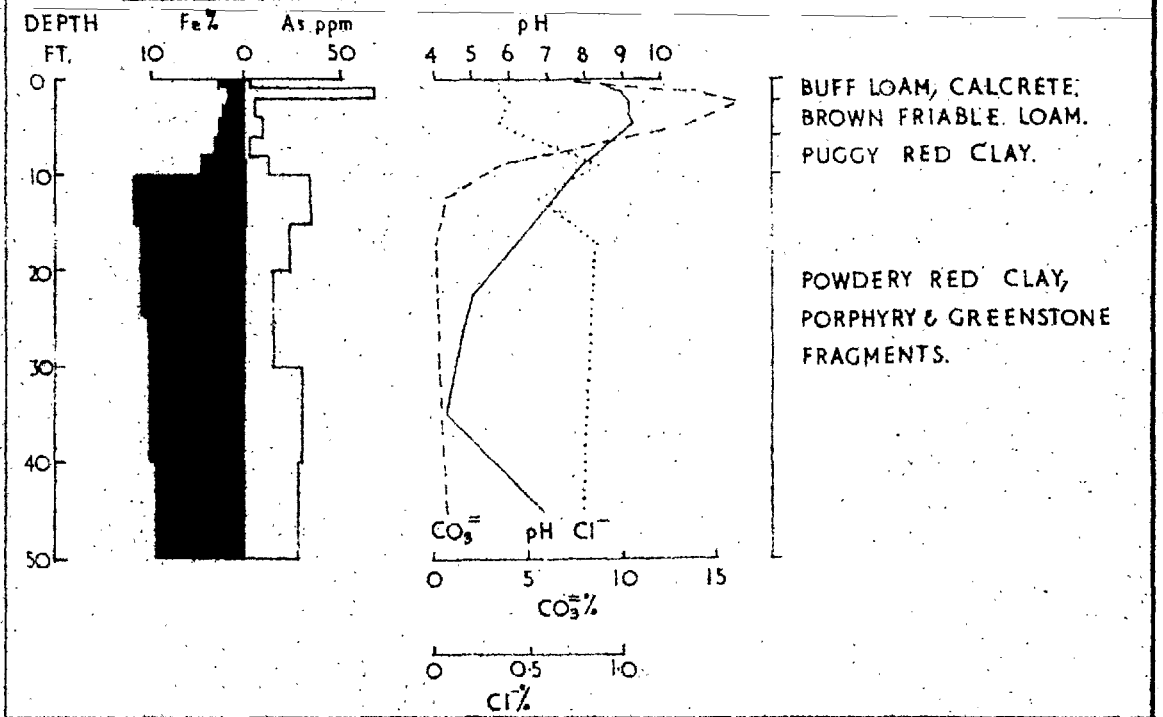
e.) Relationship Between Arsenic, Iron and Other Factors in the Soil Profile.

The close association of arsenic with secondary iron oxides in the soils suggests that the observed variability of arsenic concentration in the soil profile might be related to the vertical distribution of iron. This is evident to some degree in four anomalous profiles studied in some detail (Fig 58). In all cases, there is a concentration of arsenic in the deeper ferruginous clay horizons of the profile. The distributions of arsenic and iron are broadly similar in these horizons

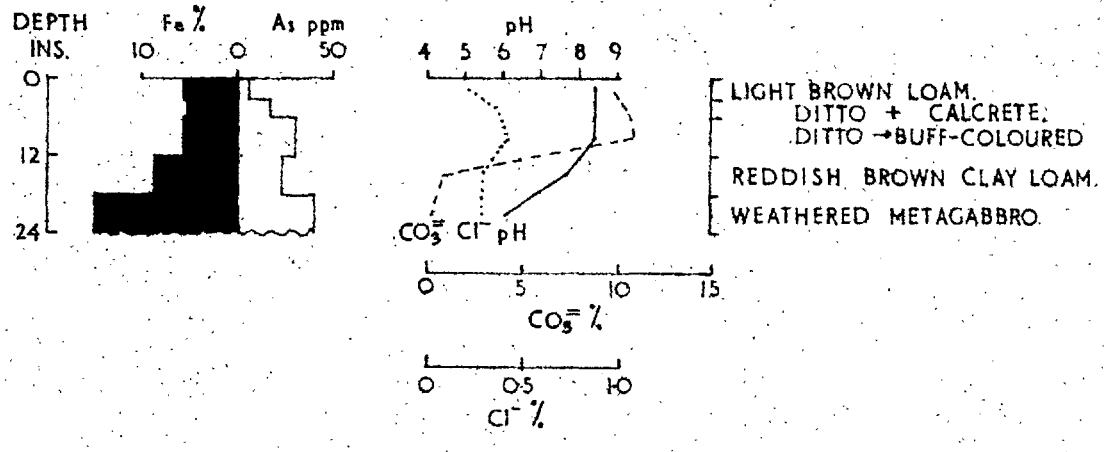
a) Soil Profile 10ft E. of Datum (Fig. 49).



c) Soil Profile J (Fig. 51).



b) Soil Profile at Datum (Fig. 53).



d) Soil Profile Q (Fig. 51).

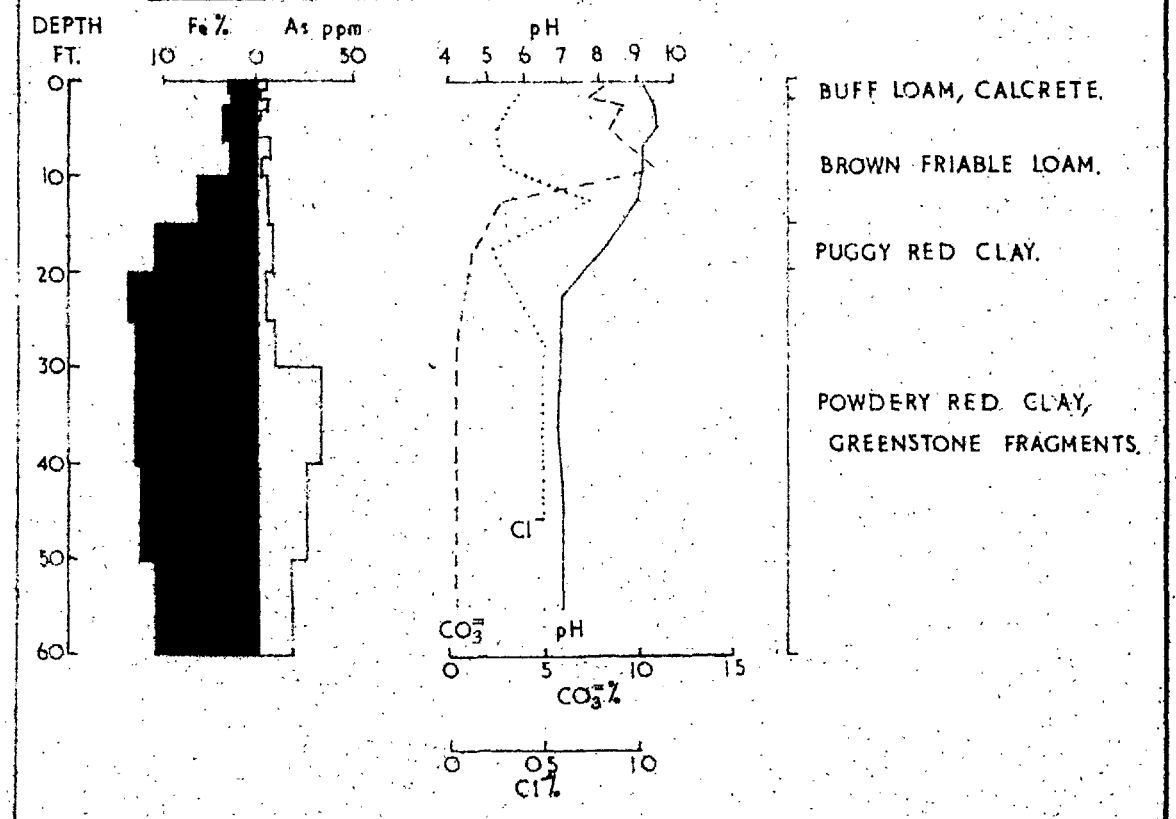


Fig. 58. Distribution of arsenic with depth in anomalous soil profiles, in relation to iron, carbonate, chloride, and pH, Norseman.

in three of the profiles studied, the maximum arsenic concentration coinciding with that of iron. In the profile shown in Fig. 58d, however, the highest arsenic content occurs somewhat deeper than the maximum concentration of iron.

In three of the profiles studied, there is also /a/ concentration of arsenic in the relatively iron-poor soils between the depths of 3 inches and 2 feet. This generally coincides approximately with the zone of maximum lime accumulation which is reflected in the high pH values near the top of the profile. It is significant to note that the only profile not showing such a concentration of arsenic in the calcareous topsoils is that in which there is a poor correlation between arsenic and iron at depth (Fig.58d). These results suggest that some additional factors are involved in the control of arsenic dispersion.

The roles of the various factors influencing the distribution of arsenic in the soil profiles are discussed in some detail in a later section of the thesis.

3. Arsenic Dispersion in Drainage Sediments, Norseman.

a) Introduction.

A brief study was carried out to determine if the presence of arsenical gold mineralization could be detected by analysing samples of the active stream sediments and the salt-lake muds in the vicinity of the

stream delta. All of the drainage channels in the vicinity of known mineralization are prone to contamination so that some difficulty was experienced in finding a suitable study area. Although anomalous stream sediment samples were found to occur in a drainage channel in the vicinity of the Crown Reef outcrop, there would have been some doubt as to whether or not the anomaly was enhanced by material shed from the ubiquitous mine dumps.

The anomalous area studied in detail was selected on the results of a drainage reconnaissance survey carried out some 7 miles south of Norseman, where very little mining had been carried out. The anomaly is associated with a complex of arsenical quartz veins which, at the surface, carry only traces of gold. However, it is quite possible, in view of the results of primary dispersion studies, that ore might be present at depth. The soils in the area are not typical of Norseman in that remnants of lateritic soils are present in the vicinity of the quartz veins. Background stream and salt-lake sediment samples were collected from an unmineralized area nine miles north of Norseman.

Active stream sediments were collected at 100 foot intervals along drainage channels. Salt-lake sediments were sampled at a depth of 6-12 inches at 100 foot intervals on a square grid pattern centred about the debouchement of the streams.

b) Background Data.

The range of concentration, arithmetic mean and threshold for arsenic in the -82 mesh fraction of stream and salt-lake sediments from the background area are given in Table 31. The frequency distribution of arsenic values is approximately normal for both types of sample and threshold has been calculated as the mean plus twice the standard deviation.

TABLE 31. Background Arsenic Data for -82 mesh Fraction of Stream and Salt-Lake Sediments, Norseman

Sample type	No. of Samples	As ppm			
		Min.	Arith. Mean.	Max.	Thres-hold.
Stream sediments	13	1	4	8	8
Salt-lake sediments	21	1	4	8	7

c) Particle Size Distribution of Arsenic in Drainage Sediments.

Four representative samples were dry-sieved to determine the particle size distribution of arsenic in anomalous and background stream and salt-lake sediments (Table 32).

In the anomalous stream sediment sample, there is a marked concentration of arsenic in the abundant coarse fractions, the arsenic tenor decreasing with

diminishing grain size. No significant variation in arsenic concentration occurs in the background stream sediment sample so that contrast appears to be at a maximum in the coarse fractions. The difference in the nature of the partition of arsenic in these two samples is undoubtedly related to the different soil-types occurring in the anomalous and background areas. The anomalous sample was collected in an area of truncated lateritic soils and coarse ferruginous laterite fragments constitute the greater part of the stream sediments. It will be seen in a later section that, in weathered lateritic soils, arsenic tends to concentrate in the coarse sesquioxide fragments rather than the fine earth fraction. The background sample was collected from an area of typical solonized brown soils and ferruginous material is present only in small amounts in the coarse fractions. The two samples are therefore not strictly comparable and the contrast values given in Table 32 may, in the light of further work, prove to be misleading. Unfortunately, no background stream sediment samples were collected from areas of lateritic soils for comparison with the anomalous sample. For convenience, the -82 mesh fraction was used in the present investigation, clearly giving adequate contrast for purposes of prospecting.

There is no apparent variation in the distribution of arsenic according to particle size in the salt-lake sediments. Any significant variations

TABLE 32. Particle Size Distribution of Arsenic in Drainage Sediments, Norseman.

Sample Type	Size Fraction	Anomalous Sample		Background Sample		Contrast
		Wt%	As ppm	Wt%	As ppm	
Stream Sediments	+20	42.4	65	25.0	<1	>65
	-20 +38	26.7	68	17.0	1	68
	-38 +82	20.4	28	28.0	1	28
	-82 +125	5.8	28	15.0	<1	>28
	-125 +197	2.8	8	9.0	1	8
	-197	2.0	5	6.0	1	5
	-82	10.6	18	30.0	1	18
Salt-lake Sediments	+20	14.8	45	4.2	3	15
	-20 +38	15.4	38	16.8	1	38
	-38 +82	21.0	33	11.6	<1	>33
	-82 +125	35.8	30	26.3	<1	>30
	-125 +197	10.8	35	33.7	1	35
	-197	2.3	50	7.4	1	30
	-82	48.9	31	67.4	1	31

present would, however, probably be masked by the very poor separation of silt and clay particles achieved by dry sieving. The results are nevertheless adequate for prospecting purposes. Good contrast is evident in all fractions. The -82 mesh fraction was selected for use in the present study.

d) Dispersion of Arsenic in Drainage Near Mineralization.

The distribution of arsenic in stream and salt-lake sediments and bank soils in the vicinity of the

quartz reef complex is shown in Fig.59.

A stream sediment anomaly of better than twofold contrast occurs in the short northern tributary of the main east-flowing drainage system. Bank soils collected on the eastern side of this tributary are generally higher in arsenic than on the western side, indicating that the anomalous material was derived from the quartz reef area. The arsenic content of the stream sediments decreases slightly on merging with the main drainage channel, which is characterized by background arsenic contents throughout. The anomaly again increases in contrast for a very short distance immediately before the drainage channel reaches the salt-lake.

Contouring of the arsenic values obtained in the salt-lake sampling indicated a very broad area of weakly anomalous sediments (up to 20 ppm) off-shore from the quartz reef area. Arsenic contents greater than 21 ppm (contrast ≥ 3) occur in comparatively small areas in the immediate vicinity of stream 'deltas' and following the shore of the lake adjacent to the quartz.

The anomalous arsenic in the lake sediments is no doubt partly due to residual arsenic-rich soil left behind during the westward migration of the lake shore (p.18) and partly due to the discharge of arsenical sediments by the streams during periods of heavy rainfall.

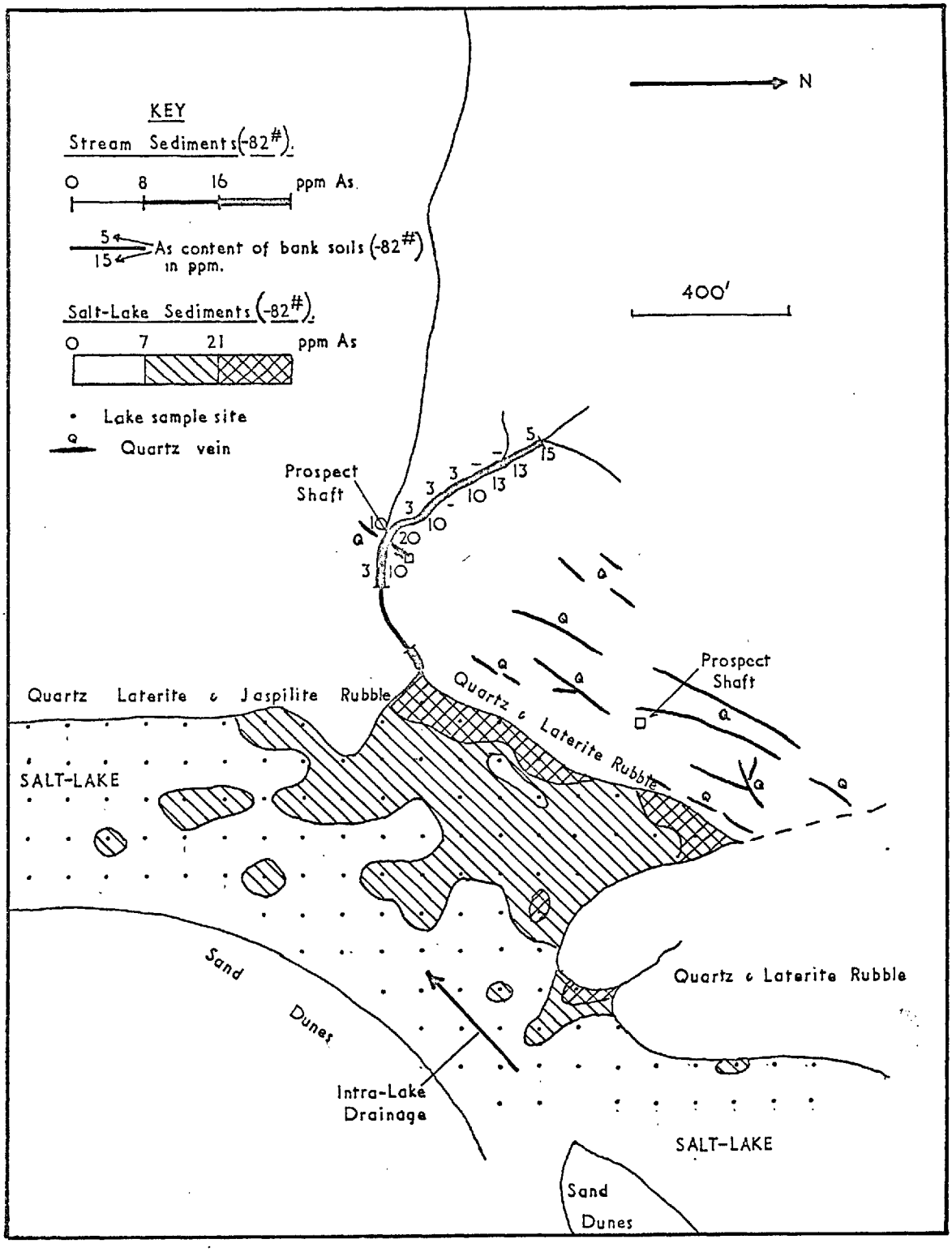


Fig. 59. Distribution of arsenic in drainage sediments near mineralization, Norseman.

The limited effect of lake migration is probably seen in the high arsenic values occurring along the shore-line near the quartz outcrop. Stream discharge would appear to be the more effective dispersion process of the two. The scattered occurrences of weakly anomalous sediments as much as 900 feet south-east of the stream mouth must be almost entirely due to this source, perhaps aided to some extent by the sluggish southerly flowing intra-lake drainage.

B. KALGOORLIE

1. Description of Area

The high density of old mine shafts and surface workings at Kalgoorlie makes it virtually impossible to carry out critical geochemical studies to assess the nature of secondary dispersion in soils near mineralization. Because of this, only one sampling traverse was carried out, in an area where contamination was thought to be at a minimum. This traverse crosses the sub-outcrop of the Kelly Lode (see page 134) at rightangles.

The geology and mineralization at Kalgoorlie has been described in some detail in the previous chapter. Topography in the area is subdued, the Golden Mile mineralization occurring on a low ridge with occasional laterite-capped hillocks. Apart from these small areas

of laterite, the soils of the area are solonized brown soils, containing relict lateritic fragments on the higher ground.

2. Distribution of Arsenic in Residual Soils at Kalgoorlie

The distribution of arsenic in the -82 mesh fraction of soils in the vicinity of the Kelly Lode is shown in Fig. 60. The soils were sampled at three depths - 0 to 1 inches, soil over bedrock (or 9 - 12 inches where the soil was occasionally more than one foot in thickness) and the weathered bedrock itself. Distinct anomalies were obtained in the vicinity of the Kelly Lode and other known mineralized zones, the anomalies in the weathered bedrock being reflected in the overlying solum. The arsenic contents of the soils immediately over bedrock are lower than those of both the topsoils and the weathered bedrock itself. Background samples collected at similar depths over unmineralized greenstones some miles north of Kalgoorlie were found to have arsenic contents of 1 ppm. or less. The Kelly Lode traverse may therefore be considered anomalous throughout its length. The form of the geochemical profile for soils over bedrock suggests a local threshold of approximately 20 ppm for the area, the presence of lodes being indicated by locally higher values.

The bedrock values are largely consistent with the results of primary dispersion studies at Kalgoorlie, although the anomaly is somewhat broader than the primary

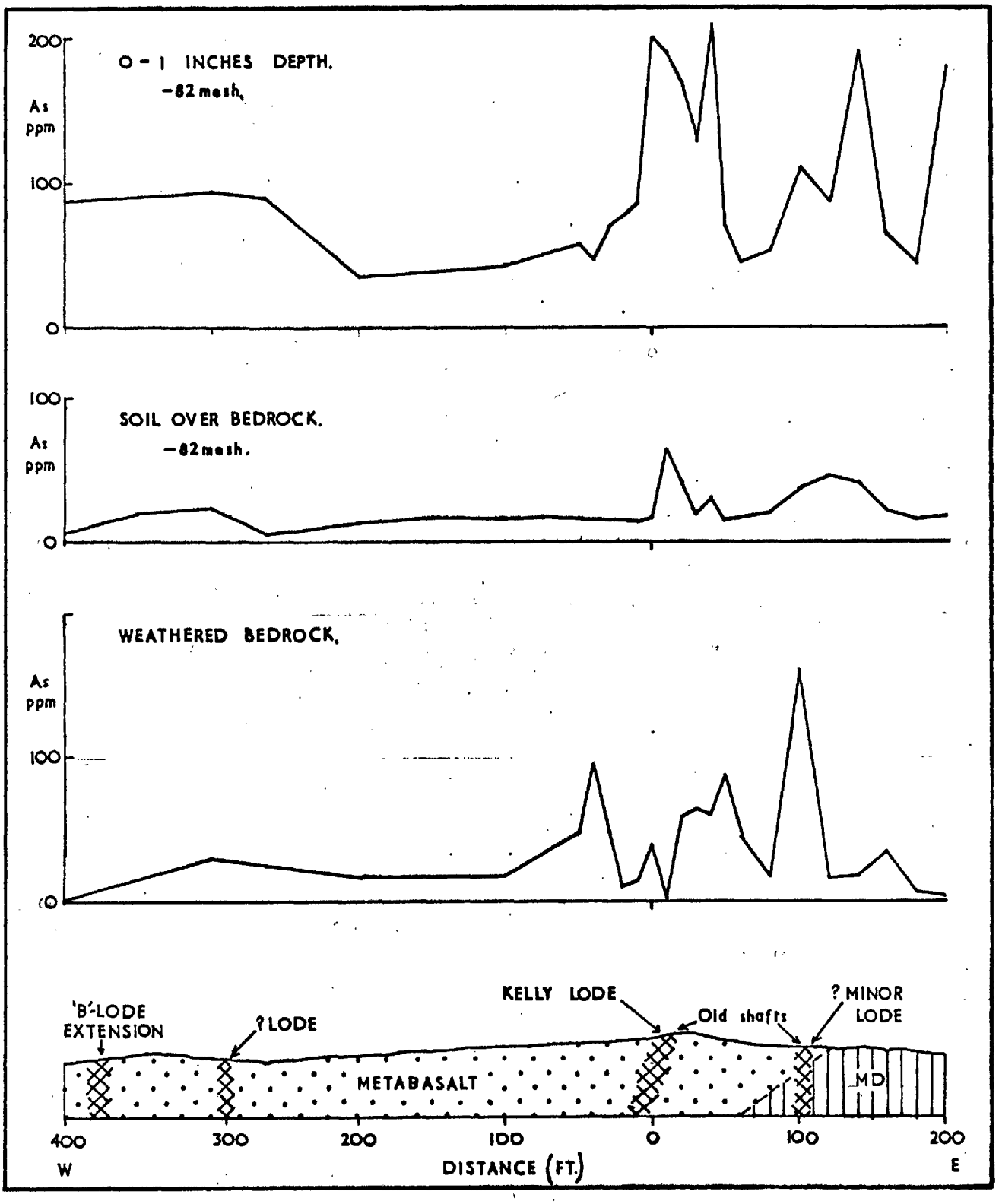


Fig.60. Lateral dispersion of arsenic at selected depths in soils near mineralization, Kalgoorlie.

halo on the eastern side of the Kelly Lode (Fig.44). This is probably due both to secondary surface enrichment and the development of another parallel lode 100 feet east of the Kelly Lode between the No.3 Level and the surface. The apparent enrichment in arsenic shown by the bedrock with respect to the soils immediately overlying bedrock is similar to the results obtained for the Princess Royal traverse at Norseman (Fig.54). Samples of the lime-rich material accreted onto bedrock fragments at Kalgoorlie were found to be low in arsenic, suggesting that the arsenic in the bedrock is largely concentrated in the ferruginous weathered rock.

The high arsenic contents of the Kalgoorlie topsoils are not in agreement with the results obtained for similar soils at Norseman, where the arsenic contents of the topsoils are almost invariably less than or equal to those of the subsoils. It is considered that the highly arsenical topsoils are due to contamination from one or both of two probable sources - arsenical smelter fumes and anomalous material derived by erosion from dumps of mine spoil. In view of the fact that mine dumps are concentrated in the immediate vicinity of lodes, one would expect contamination from this source to be at a maximum near the lodes. This may partly account for the very high values in the vicinity of the Kelly Lode outcrop. The results, however, also suggest

that there has been a more or less uniform addition of arsenical material over the whole traverse. This indicates that smelter fumes are probably the most important source of contamination. There are at present three ore-roasting plants in the area immediately to the south of the present traverse but in the past, many more were operating in the area. No attempt was made to assess the contamination from this source but James (1957, p.72) found that smelter fumes caused significant contamination of topsoils at distances up to one mile from a plant treating arsenical gold ore in Rhodesia. It is possible that some smelter-derived arsenic has been leached down from the topsoils to contribute to the arsenic content of the sub-soils. However, the extent to which this has taken place cannot be judged on the basis of the present results.

III. AREAS OF CALCAREOUS LATERITIC SOILS

A. INTRODUCTION

The exploration geologist has always been confronted with special problems when prospecting in areas of lateritic soil-cover. In such areas, the bedrock is often completely obscured by a considerable thickness of material of great hardness. The absence of surface indications of mineralization severely limits the chances of success of conventional exploration techniques and the cost of pitting and

trenching through the indurated laterite to expose bedrock would clearly be prohibitive. A brief investigation was made as part of the present research to ascertain whether or not arsenical gold mineralization underlying indurated laterite, could be located geochemically by analysing samples of the near surface lateritic soils for arsenic.

Occurrences of laterite in the vicinity of known Western Australian gold deposits are generally of limited lateral extent, as a result of which the areas available for orientation studies were not completely suitable. However, there are considerable expanses of potentially auriferous country in Western Australia which are covered by laterite, where the results of this research might be usefully applied. During this investigation, field studies were undertaken at three localities in the Western Australian Goldfields. The first lies close to the Surprise Mine, near Coolgardie, where the inferred extension of a small gold-bearing orebody passes under a laterite-capped hillock. A comparative study was carried out near an abandoned prospect which lies about three miles north of Kalgoorlie. The third study area was at Ora Banda, where solonized brown soils over gold mineralization have developed on the exposed mottled zone of the truncated laterite profile.

B. SURPRISE AREA, COOLGARDIE

1. Description of the Area.

The Surprise Mine, situated 6 miles east of Coolgardie occurs in an area of folded ultrabasic rocks with associated sill-like lenses of felsite porphyry (Fig.61). Two types of orebodies occur, both of which are arsenical (ore specimens from the oxidized zone were found to contain 85 to 1500 ppm As). Most of the gold produced has come from mineralized actinolitic shear zones in the ultrabasics, adjacent to porphyry bodies. Small, rich orebodies are also found in silicified fracture zones within the porphyries. Mineralization is widespread throughout the area and apart from two major mines, whose joint production was 139,000 oz. gold from 271,000 tons of ore, numerous small prospects on minor shear zones have been exploited. In the area of principal interest, a porphyry sill, in which several small orebodies are known to occur, passes under a small laterite-capped hillock, 1000 feet south of the Yellow Lode (Fig. 61).

2. Background data for Soils at Coolgardie

The results of arsenic analyses on lateritic and non-lateritic soils collected at 6-12 inches depth over unmineralized ultrabasics is summarized in Table 33.

The frequency distribution of arsenic in non-lateritic soils is approximately normal and threshold has been calculated as the mean plus twice the standard

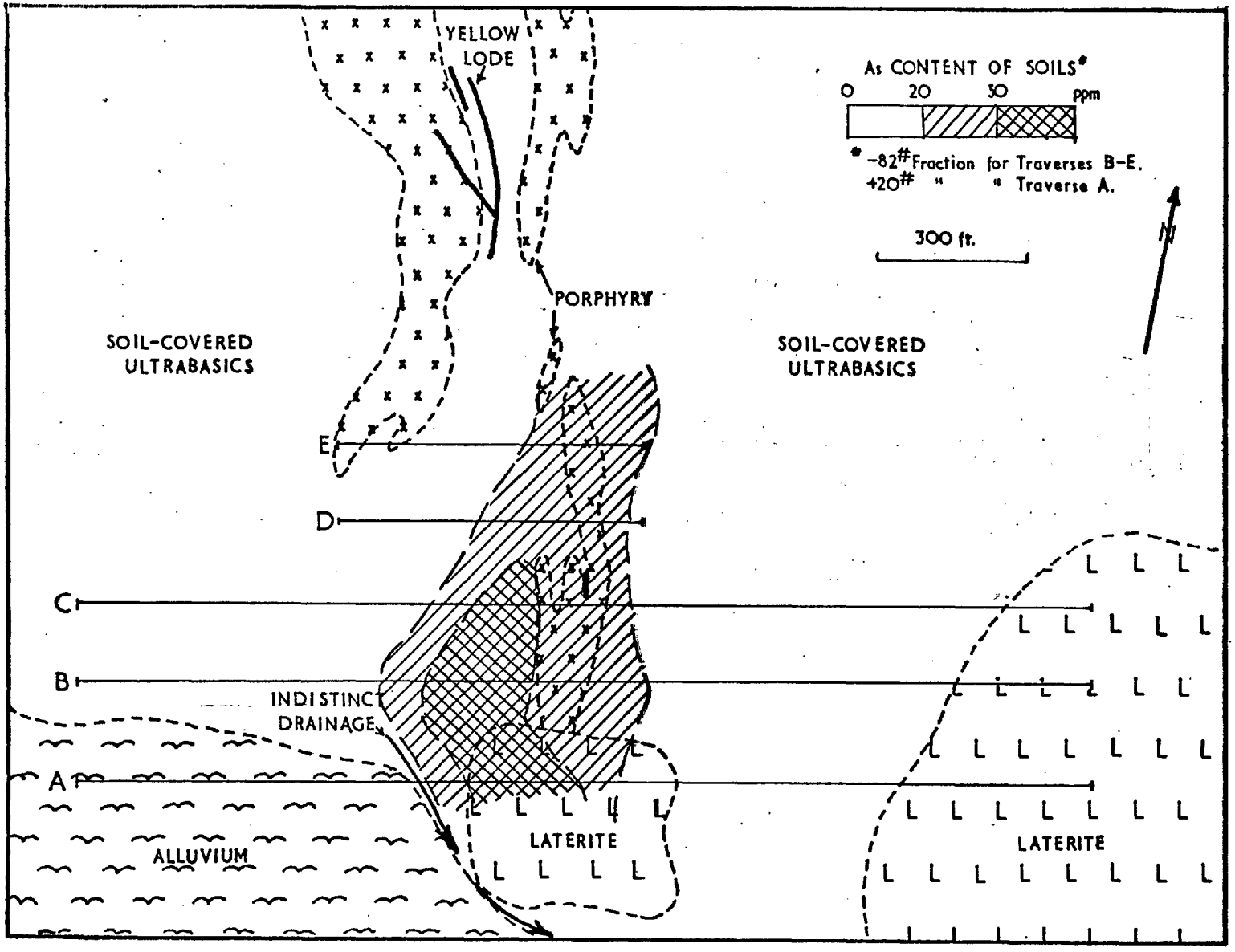


Fig. 61. Geological map of the Surprise Area, Coolgardie, showing sampling traverses and area of anomalous soils.

TABLE 33 Background Arsenic Data for Lateritic and Non-Lateritic Soils, Coolgardie.

Sample Type	No. of Samples	As ppm			
		Min.	Arith. Mean.	Max.	Threshold
Solonized brown soils -82 fraction	15	8	11.5	18	18
Lateritic soils -82 fraction	5	8	10.4	13	?13
Lateritic soils +20 fraction	5	35	50.8		?58

deviation. Insufficient samples of background lateritic soils were collected to enable similar calculations of threshold. The tentative values given in Table 33 may be slightly too high in the case of the +20 mesh fraction and too low for the -82 mesh fraction in the light of results obtained in traverses in the Surprise Area.

3. Arsenic Dispersion in Non-Lateritic Soils near Mineralization.

Arsenic analyses on the -82 mesh fraction of solonized brown soils collected at 50 foot intervals along a series of traverses in the area between Yellow Lode and the lateritic area disclosed a broad

anomaly associated with the porphyry body (Fig.61). Within this anomaly, the peak values were found to rise to between 50 and 80 ppm, which correspond closely with the results for samples collected from open cuts over the Yellow Lode. This represents a contrast of approximately 4.5 compared with background soils.

A more detailed investigation was made in an attempt to establish the source of the arsenic anomaly in solonized brown soils. Sampling of the full soil profile at 5 foot intervals along the anomalous portion of traverse C indicated an arsenic-rich zone in the ultrabasic bedrock (Fig.62). A short trench was dug to obtain channel samples of the bedrock over this zone. Arsenical lode-type material was encountered in the rock under the peak of the soil anomaly, although only traces of gold were found to be present. ($\leqslant$ 0.1 dwt/ton). Despite the absence of significant gold values at this point, it is clear that the arsenic anomaly in the soils is associated with mineralized shearing in the ultrabasics.

4. Arsenic Dispersion in Lateritic Soils Near Mineralization.

a) Particle Size Distribution of Arsenic in Near-Surface Lateritic Gravel Samples.

Preliminary studies of arsenic distribution in the various size fractions (obtained by dry-sieving)

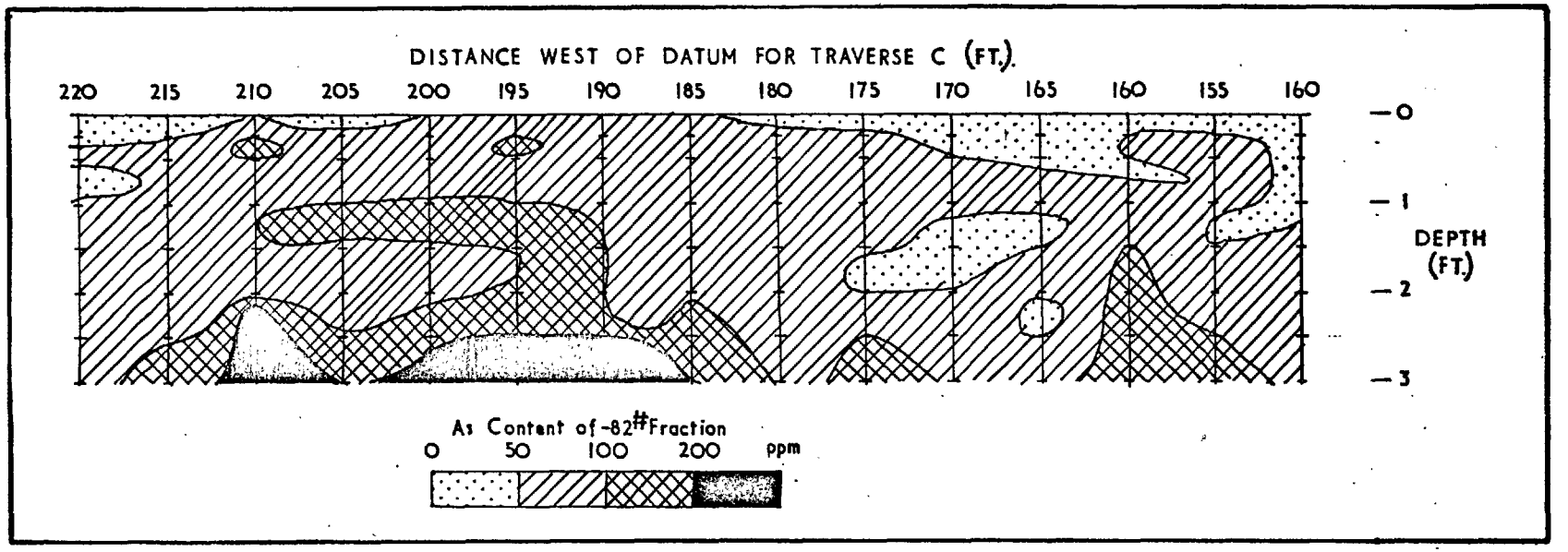


Fig. 62. Distribution of arsenic in soil profile over anomalous section of traverse C, Surprise Area, Coolgardie.

of lateritic gravels indicated a very marked concentration in the coarser particles (Table 34). Comparison with background samples showed that maximum contrast occurs in the finer fractions, but, in view of the much higher arsenic contents of the coarser material, both the +20 mesh and -82 mesh fractions were analysed in subsequent work.

TABLE 34 Comparison of Arsenic Distribution in Anomalous and Background Lateritic Gravel Samples, Coolgardie

Size Fraction		Anomalous Sample		Background Sample		
		Wt%	As ppm	Wt%	As ppm	Contrast
	+10	56.5	240	74.0	53	4.5
-10	+20	12.8	230	2.1	35	6.6
-20	+38	10.8	230	5.5	55	4.2
-38	+82	11.6	115	6.7	23	5.0
-82	+125	4.4	130	5.7	15	8.6
-125	+197	3.0	160	4.4	28	10.7
-125		0.9	160	1.6	28	5.7
	+20	69.3	238	76.1	52	4.6
-82		8.3	144	11.7	17	8.5

b) Lateral Dispersion of Arsenic in Lateritic Soils Near Mineralization.

Initially only the surface lateritic gravel horizon was sampled to a maximum depth of 12 inches

along traverse A. Comparison of the anomalies obtained by analysing the +20 mesh and -82 mesh fractions (Fig.63) confirms the marked concentration of arsenic in the coarser particles, which are comprised predominantly of lime-coated sesquioxide fragments. The ferruginous sesquioxides and calcareous coating from the coarse fraction of one anomalous sample were analysed separately and were found to contain 220 ppm and 40 ppm As respectively, showing that the arsenic is largely associated with the former.

It can be seen from the local threshold values plotted in Fig.63 that, in contrast to the results indicated in Table 34, slightly better anomaly contrast and definition is obtained by analysing the +20 mesh fraction in preference to the -82 mesh material. The anomaly for the +20 mesh fraction would appear to be more than 500 feet in width.

The arsenic anomaly is also clearly indicated by analysing laterite fragments collected on the daylight surface. Arsenic values are found to be generally higher in this material than in the +20 mesh fraction at 6 to 12 inches depth, presumably due to the absence of arsenic-poor coatings on the surface fragments. However, the form of the geochemical profile in Fig.63 suggests that considerable mechanical translocation of the surface fragments has

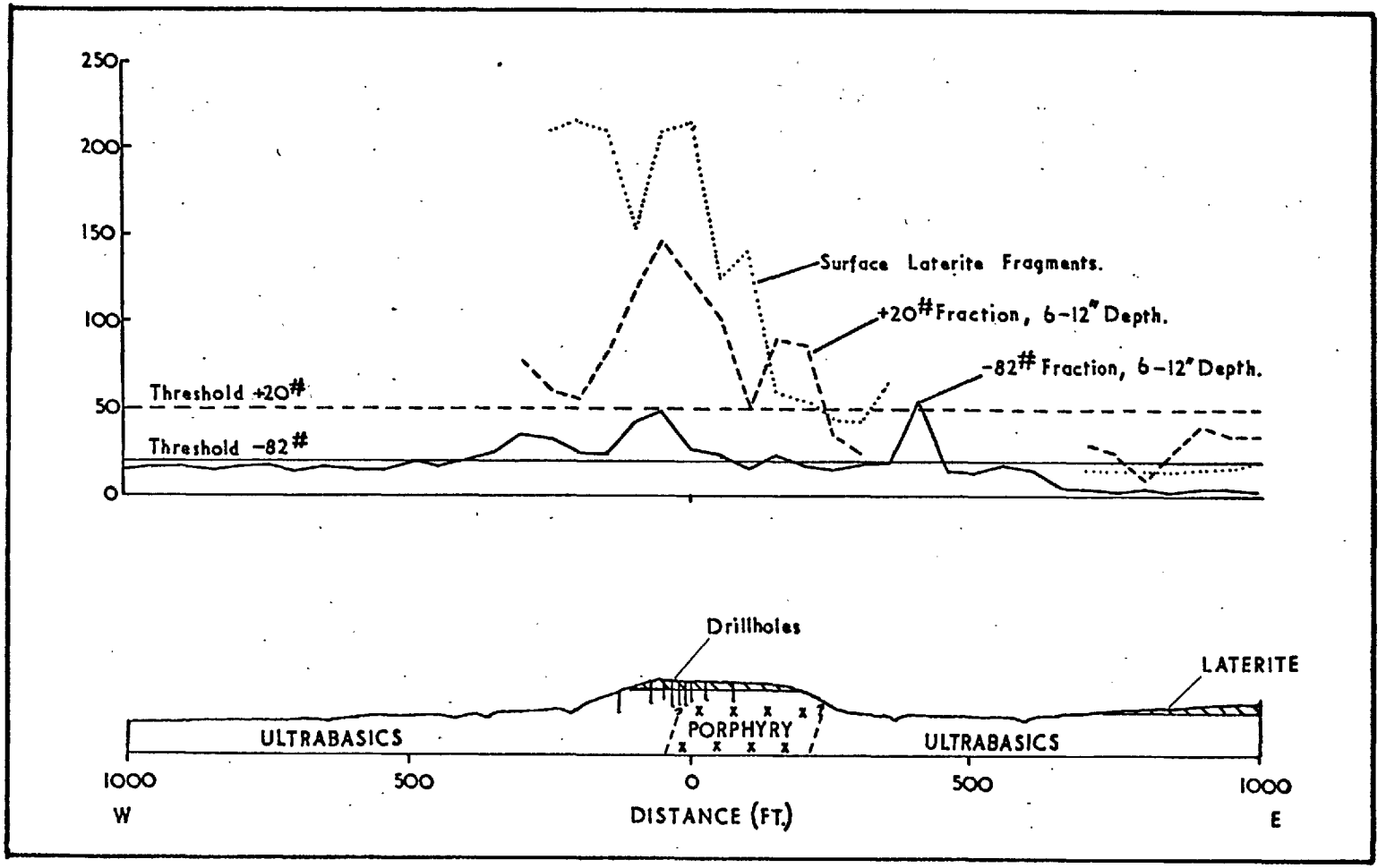


Fig. 63. Lateral dispersion of arsenic in +20# and -82# fractions of lateritic gravel samples, Traverse A, Surprise Area, Coolgardie.

occurred and under these circumstances, the anomaly peaks may not be spacially related to bedrock sources.

c) Vertical Dispersion of Arsenic in Lateritic Profiles.

The distribution of arsenic in percussion drilling samples from a typical anomalous laterite profile is shown in Fig.64. The maximum concentration of arsenic occurs in the massive laterite horizon, corresponding with the maximum iron concentration. As mentioned earlier, this horizon is thought to represent a zone of illuviation in the original lateritic soil profile. A further high arsenic value occurs at a depth of 10 to 12 feet. This is probably related to primary dispersion about the auriferous zone intersected between 16 and 20 feet. The actual gold intersection is accompanied by an increase in iron content, although the arsenic content does not increase above 100 ppm. pH varies only slightly between 7.3 and 8.0 throughout the profile.

d) Mode of Occurrence of Arsenic in Lateritic Soils.

A detailed size separation of an anomalous lateritic gravel sample was carried out in an attempt to obtain more information on the mode of occurrence of arsenic in this material. The distribution of arsenic

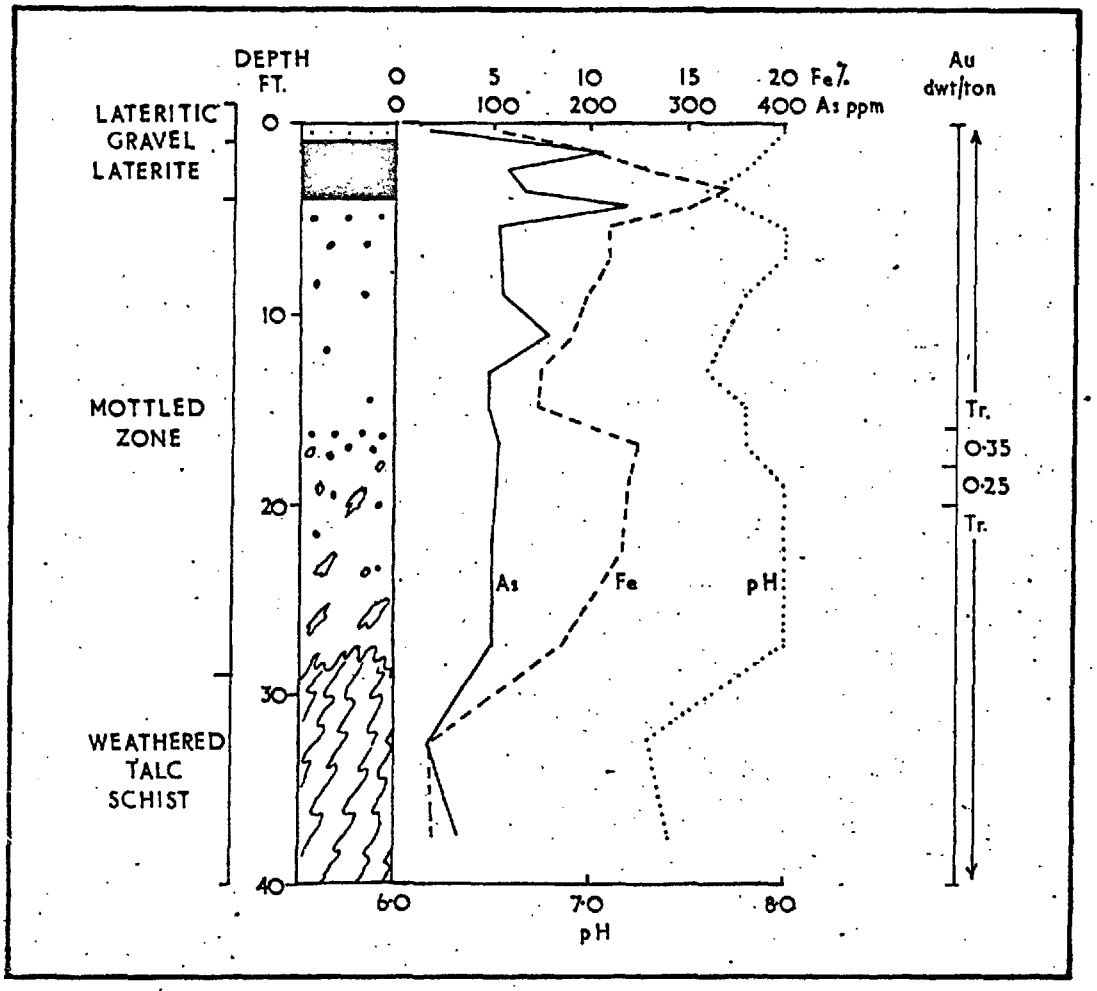


Fig. 64. Distribution of As, Fe & pH with depth in anomalous laterite profile, Surprise Area, Coolgardie.

(Fig.65) shows a marked concentration in the coarse fractions, which consist predominantly of secondary iron oxides, and a lesser concentration in the silt fraction. The distribution of iron varies sympathetically with that of arsenic. Although this does not prove a definite association between iron and arsenic, taken with the results for separated minerals (p 211) and profile studies, these results strongly suggest that the arsenic in laterite is largely held by the secondary iron oxides. As in solonized brown soils, the cxAs/total As ratio reaches a maximum in the silt and clay fractions, reflecting the increased amounts of arsenic held by weak adsorption bonds to the finer colloidal particles.

5. Relationship between Arsenic Anomalies and Gold Mineralization.

A brief percussion-drilling programme was carried out to test the arsenic anomaly in laterite for underlying gold mineralization. The location of drill-holes is shown in Fig.63. Low grade gold intersections were obtained in most of the holes, suggesting the existence of a zone of low grade mineralization, approximately 100 feet in width, under the anomalous zone detected at the surface. The best intersection (0.4 dwt/ton) was obtained in a hole drilled on the peak of the arsenic anomaly.

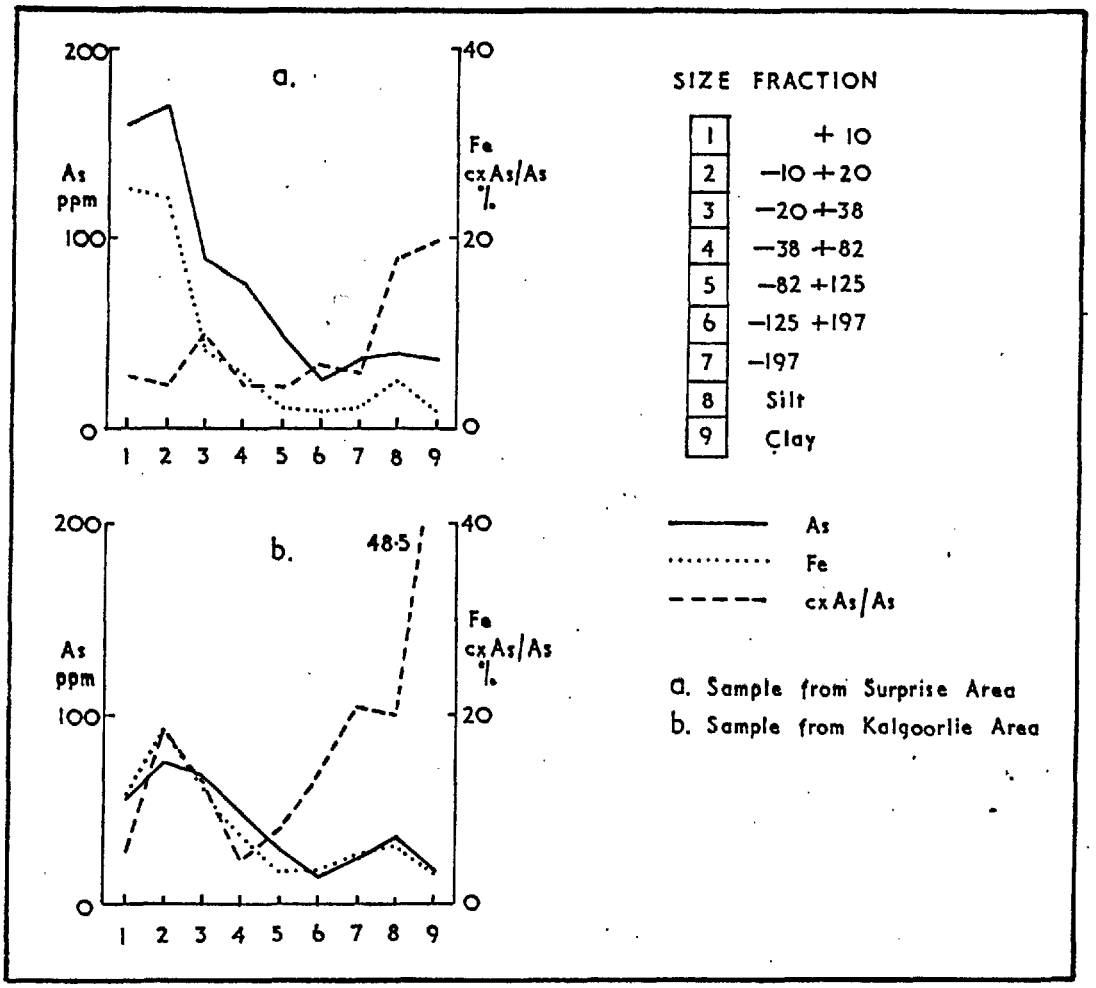


Fig. 65. Distribution of As, cxAs/As e Fe according to particle size in anomalous lateritic gravel samples.

Despite the low gold values obtained, these results confirm the close relationship between the arsenic anomaly in the near-surface lateritic gravel horizon and underlying gold mineralization.

C. KALGOORLIE STUDY AREA

1. Description of the Area.

The results obtained in lateritic soils at Coolgardie were corroborated by studies carried out in an area 3 miles north of Kalgoorlie. In this area an arsenic anomaly was found to occur in soils in the vicinity of a series of old prospect workings along a major geological contact between metabasalts and metadolerte (Fig.66). The contact is accompanied by considerable shearing and a series of thin jaspilite bands. The rocks in this area are stratigraphically contiguous with those of the Golden Mile, some 6 miles to the south, where metabasalts and metadolerites are the principal host-rocks for gold-telluride mineralization. In the Kalgoorlie mining area, it has been shown that many so-called jaspilites are merely the silicified surface expressions of slate bands, which frequently carry sulphide mineralization and occasionally some gold (Feldtmann, 1916).

The jaspilite-shear zone passes under a laterite-capped ridge to the east of the prospecting

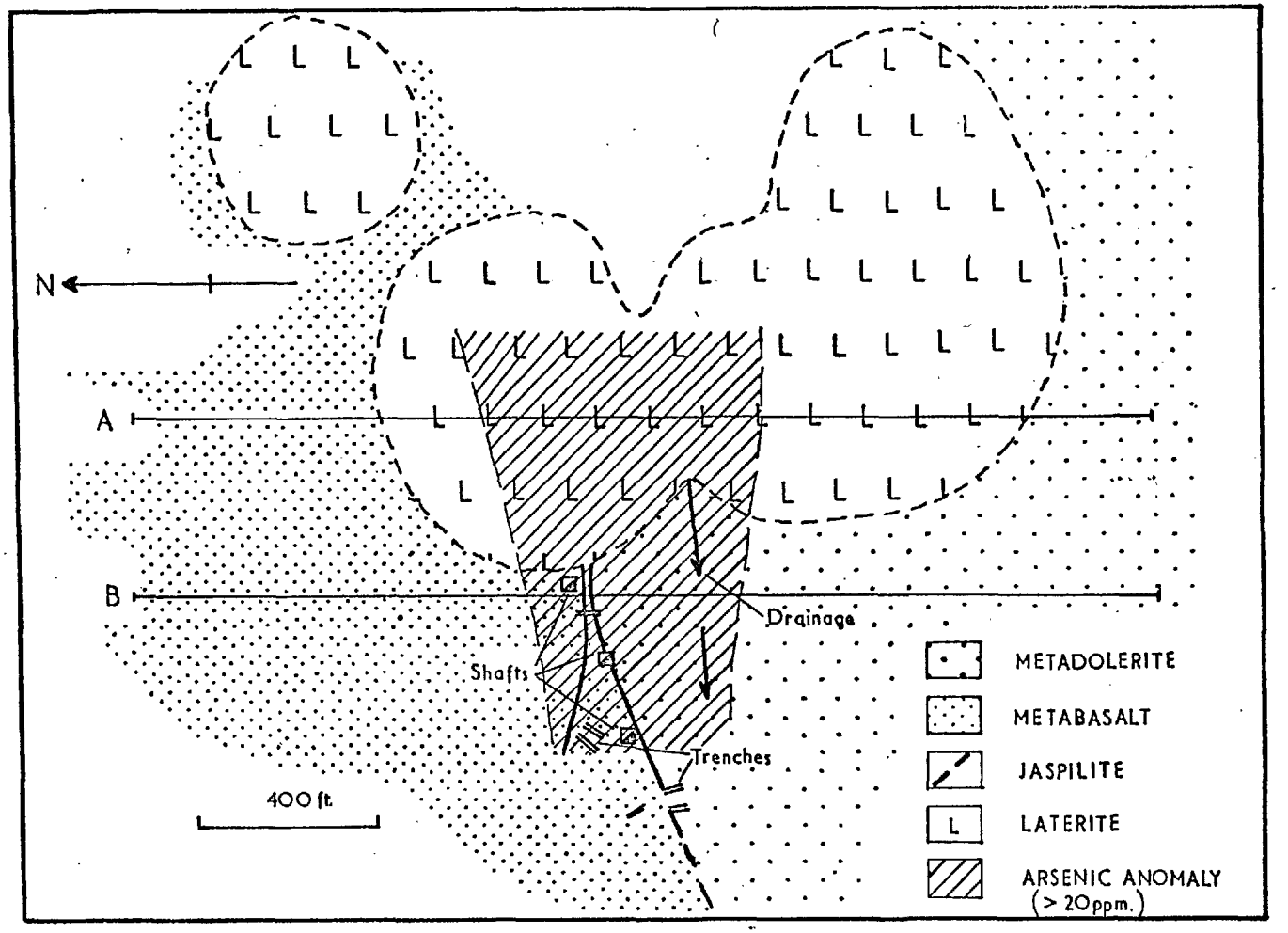


Fig. 66. Geological map of Kalgoorlie Laterite Study Area, showing sampling traverses and area of anomalous soils.

shafts. The dispersion pattern related to this arsenical structure has been studied in samples of lateritic gravel collected along traverse A on this ridge. Solonized brown soils of the type shown in Fig 3b predominate over the rest of the area.

There is no record of any past gold production from this area and subsequent work has so far failed to locate any ore. It is considered that the arsenic anomalies to be described are related to arsenical sulphide mineralization which is non-auriferous, at least at the surface. Nevertheless, the results of geochemical studies in this area are of interest for the useful information they contribute regarding the dispersion of arsenic in laterite over an arsenical bedrock source.

2. Background Data

Background samples of solonized brown soils over greenstones in the Kalgoorlie area were found to contain 1 ppm As or less. The results of arsenic analyses on the +20 mesh and -82 mesh fractions of lateritic gravel samples collected over the metabasalt-metadolerite contact in an unmineralized area 1 mile east of the study area are given in Table 35. A significant feature of the results is the relatively low arsenic content of the coarse laterite fragments over greenstones of basic composition at Kalgoorlie

compared with those over ultrabasics at Coolgardie.

TABLE 35 Arsenic Data for Background Lateritic Gravel Samples, Kalgoorlie

Size Fraction	No. of Samples	As ppm.			
		Min.	Arith.Mean.	Max.	Threshold
+ 20	17	1	3.1	8	7.0
-82	16	1	2.4	5	5.0

3. Arsenic Dispersion in Non-Lateritic Soils near (?) Mineralization

The distribution of arsenic in the -82 mesh fraction of solonized brown soils sampled at a depth of 6 - 12 inches (or over bedrock where the soils are less than one foot thick) is shown in Fig.67a. A broad anomaly is present, extending assymetrically to the north in the direction of a minor drainage channel. Profile samples collected at 10 foot intervals up to 50 feet each side of the traverse datum indicated a zone of highly arsenical bedrock between 10 feet and 25 feet north of the datum. Channel samples of the bedrock over this section of the traverse showed that the arsenic anomaly was associated with oxidized schistose rocks containing abundant ferruginous and siliceous stringers. It is thought that the ferruginous material probably represents the remnants of sulphides. In support of this,

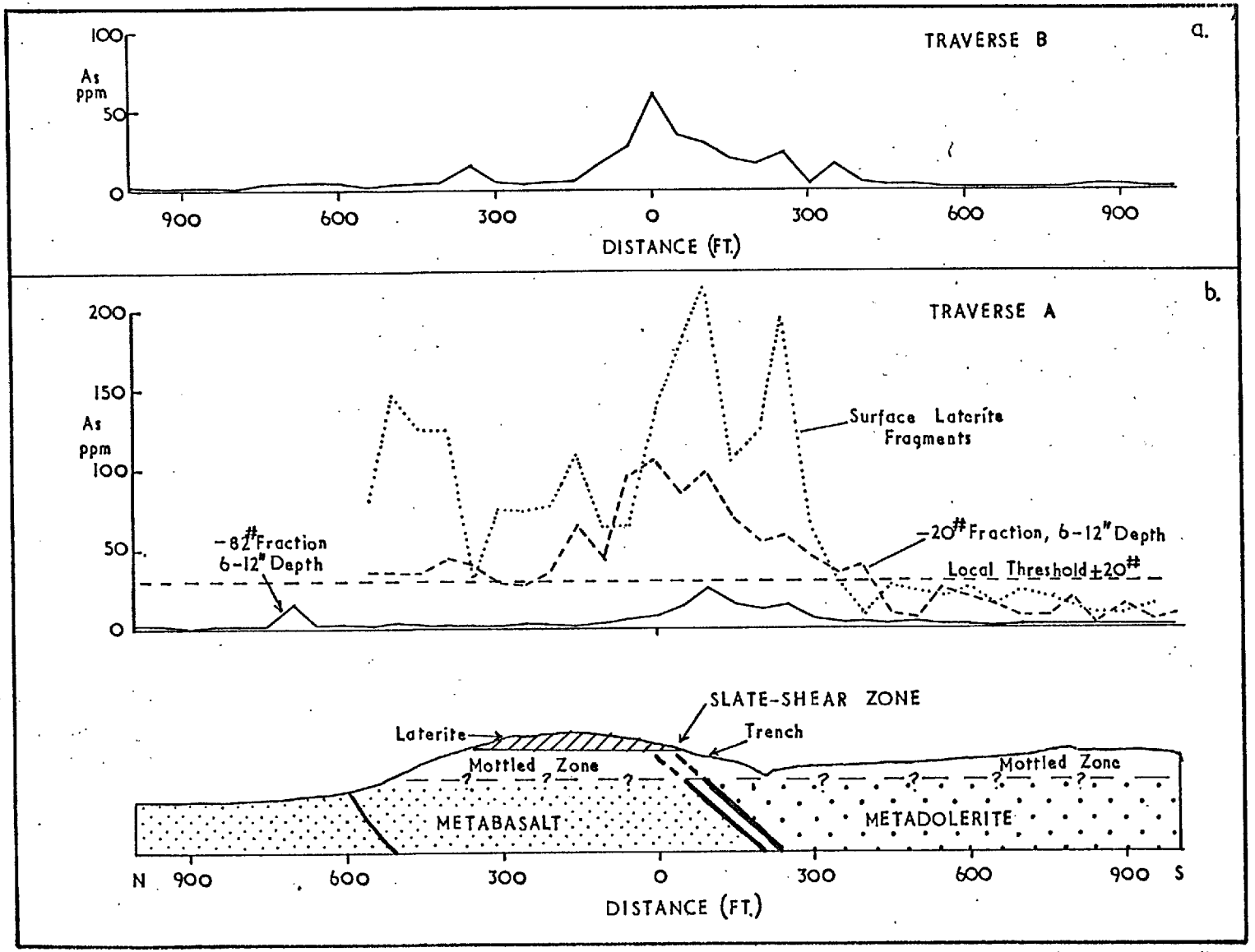


Fig. 67. Lateral dispersion of arsenic in solonized brown soils (a), and in +20# and -82# fractions of lateritic gravel samples (b), Kalgoorlie Laterite Study Area.

anomalous soils were found to contain up to 1600 ppm $SO_4^{=}$ compared with values of 200 ppm obtained in background sections of the traverse. Although arsenic contents of more than 250 ppm were obtained for all these samples, only traces of gold were found to be present.

4. Arsenic Dispersion in Lateritic Soils near Mineralization

The results obtained for lateritic gravel samples collected at depths of 6-12 inches show a strong anomaly, at least 600 feet in breadth, associated with the inferred strike projection of the arsenical jaspilite-shear zone (Fig.76b). A marked concentration of arsenic is again apparent in the sesquioxide-rich +20 mesh fraction compared with the -82 mesh fraction. In this traverse, superior contrast was evident in the results for the coarse fractions of the lateritic gravel.

As in the Surprise area, the arsenic content of surface laterite fragments, which are free from calcrete, is somewhat higher than the +20 mesh fraction of deeper lateritic gravel samples. The anomaly obtained in the case of these surface laterite fragments is wider and more erratic than that obtained for samples from greater depth. Secondary peaks occur at the base

of the laterite-covered slopes, suggesting that some downslope movement has taken place during the breakdown of the laterite profile. Such movement would obviously be at a maximum near to the surface.

The distribution of arsenic and iron according to particle size in an anomalous lateritic gravel sample was found to be similar to the results obtained in the Coolgardie study (Fig.65b). However, the concentration of arsenic in the coarse fractions is less marked than in the sample from Coolgardie. This is attributed to the fact that the Kalgoorlie sample was taken at the margin of the laterite-covered area and probably includes some material weathered out of the mottled zone. It will be seen that the concentration of arsenic in coarse ferruginous material from the mottled zone is not so marked as that in material weathered from the laterite horizon. The higher cxAs/total As ratio obtained for the Kalgoorlie sample is presumed to be due to the different exchange capacities of the materials making up the -197 mesh fractions, there being similar quantities of fine sand, silt and clay (50 to 60% by weight) in both samples.

Percussion drilling in the vicinity of the peak of the anomaly in the lateritic gravel horizon intersected by arsenic-rich structure in the C horizon,

as shown by geochemical contours of the arsenic content of the drill-hole samples (Fig.68). Samples of arsenic-rich material from this structure were found to contain only traces of gold. However, it is clear that prospecting on the basis of arsenic determinations on samples of the surface lateritic gravel would have located arsenical gold mineralization if any were present.

D. ORA BANDA STUDY AREA

1. Description of the Area

A brief study of arsenic dispersion was carried out at Ora Banda in order to determine the nature of arsenic anomalies in soils developed on the mottled zone of truncated laterite profiles. The samples for this study were collected by the writer and laboratory work was carried out by Western Mining Corporation at Kalgoorlie.

The gold mineralization at Ora Banda consists of an east-west striking series of steeply-dipping sulphide replacement lodes in porphyritic metabasalts. Ore samples were found to contain between 100 and 10,000 ppm arsenic, indicating the suitability of arsenic as a pathfinder element in the area.

The area is one of gentle relief and inspection of open-cuts shows that soils are largely developed on the mottled zone of former laterite

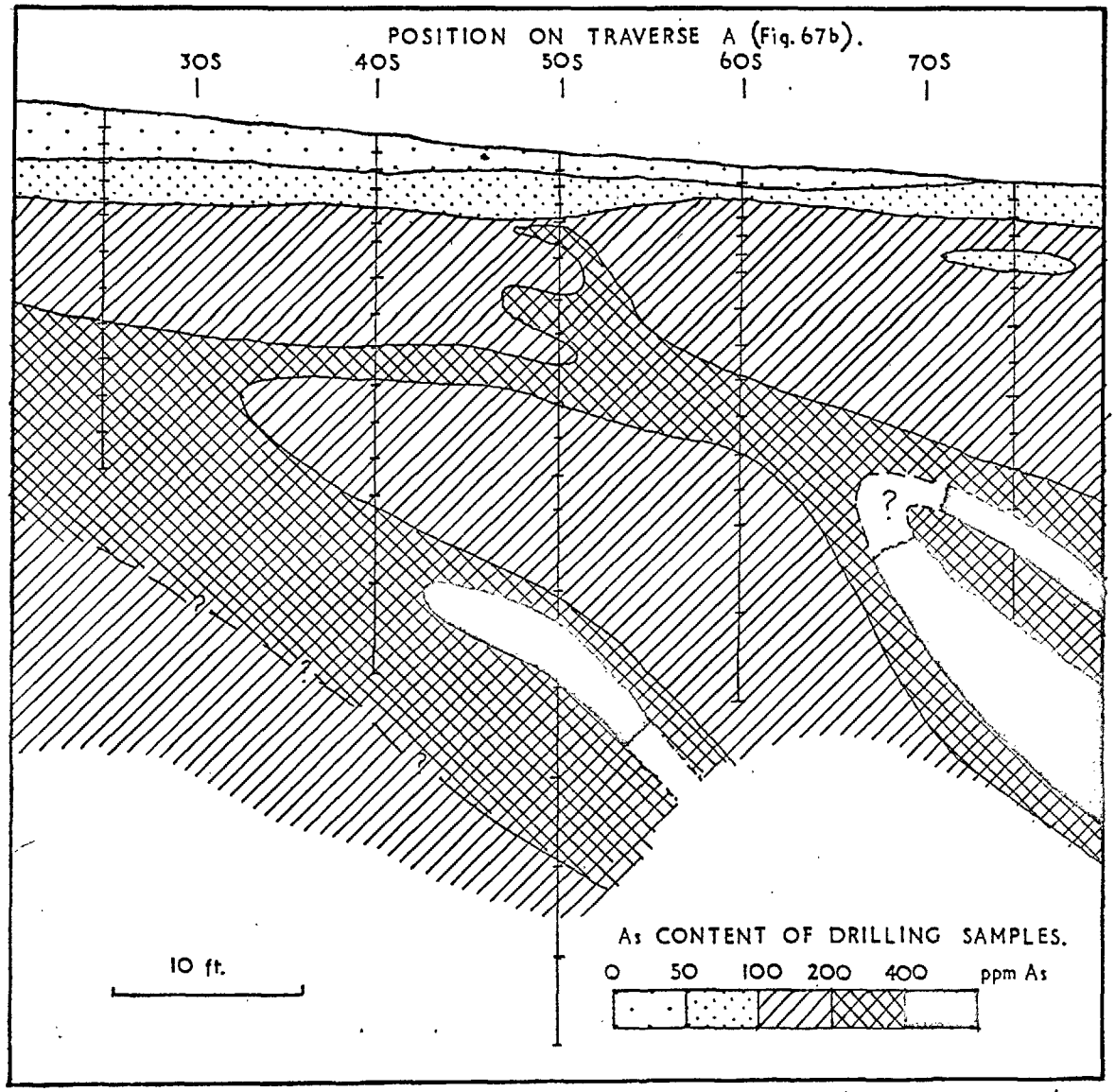


Fig. 68. Distribution of arsenic in laterite profile over anomalous section of Traverse A, Kalgoorlie Laterite Study Area.

profiles. These soils are of the type described on page 33, being essentially similar to solonized brown soils but containing a high proportion of ferruginous pisolites of lateritic origin. Patches of calcareous lateritic soils, of limited extent, occur on the higher ground throughout the area.

2. Results of Brief Geochemical Studies at Ora Banda

The results of arsenic determinations on samples collected at a depth of 6 to 12 inches along a traverse over the Golden Gimlet Lode are shown in Fig.69. A strong anomaly nearly 800 feet in width is evident in the -82 mesh fraction with peak values of up to 125 ppm As in the immediate vicinity of the workings on the two parallel Golden Gimlet veins. The arsenic content of background soil samples collected over similar lithology, several miles from the Ora Banda mineralization, was found to vary between <1 to 3 ppm. It would therefore seem, from the comparatively high arsenic values which appear to persist as far as 700 feet from the Golden Gimlet Lode, that there is a local threshold of approximately 20 ppm in the area.

The levels of concentration of arsenic near ore are similar both in the -82 mesh and +20 mesh fractions, the latter consisting largely of lime-coated ferruginous concretions. Only one arsenic

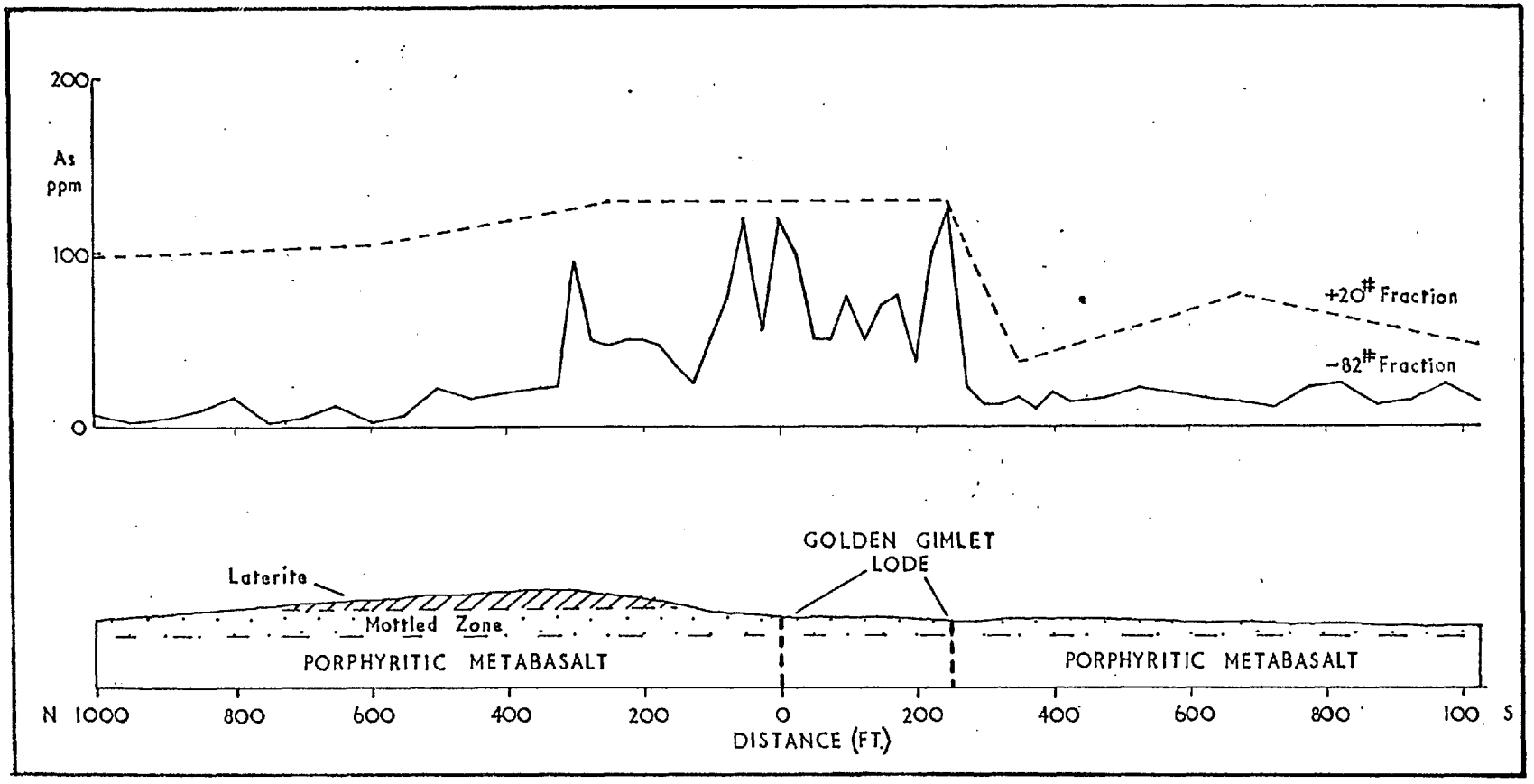


Fig. 69. Lateral dispersion of arsenic in soils (-82#; 6-12" depth) in the vicinity of the Golden Gimlet Lode, Ora Banda.

determination was made on the +20 mesh fraction of a background sample, giving a value of 5 ppm. If this sample is representative, it would appear that the anomaly obtained for the +20 mesh fraction is broader than that in the case of the -82 mesh fraction, even though contrast is somewhat lower. This result is more or less consistent with those obtained in lateritic soils at Coolgardie and Kalgoorlie. "Colours" of gold have been detected by a prospector between 200 and 400N on this traverse and the minor peak in the geochemical profile at 300 N should be further investigated.

IV. AREAS OF HARDPAN SOILS

A. AGNEW

1. Description of the Agnew Area.

A description of the Precambrian geology and mineralization at Agnew has been given in the previous chapter.

One of the major prospecting problems in the area stems from the fact that the metasediment-ultrabasic contact is obscured by superficial deposits for approximately three miles to the north of the Kim Shaft before further outcrops of Precambrian rocks enable its position to be established (Fig.46). Small scattered exposures of tillite of probable Permian age occur in the intervening area but the extent to which

the Precambrian is overlain by these glacial deposits is uncertain because of the poor exposure.

In the area studied in detail, the terrain is very flat with a thin cover of hardpan soils, as described on page 35. However, occasional remnants of the lateritic "old" plateau, bounded by steep escarpments, are also present throughout the area shown in Fig.46.

The main object of the present brief study was to investigate the nature of the arsenic dispersion patterns in the hardpan soils of the Agnew district. A secondary aim was to determine if the northern extension of the mineralization associated with the metasediment-ultrabasic contact zone could be followed in the soil-covered area by geochemical methods.

2. Background Data for Agnew Soils

The results of arsenic determinations on the -82 mesh fraction of soil samples collected over the metasediment-ultrabasic contact approximately 4 miles south of the Emu Shaft (just off Fig.46) indicates that the regional threshold is in the vicinity of 2 ppm. All but one of the samples collected were found to contain 2 ppm As or less. Full soil profiles sampled over gneiss and ultrabasics showed no significant variation in arsenic content with depth.

3. Arsenic Dispersion in Soils near Known Mineralization

The lateral dispersion of arsenic in soils in

the vicinity of mineralization is illustrated by traverse A, the results for which are shown in Fig.70. The datum of this traverse is on the southern lip of a large open-cut, where the chlorite-actinolite schist horizon is at its narrowest and has been mined as one lode. The terrain slopes very gently to the west, towards a prominent drainage channel approximately 900 feet from the lode. The soil cover is generally less than 6 inches thick and samples were collected over a three inch vertical channel immediately above the weathered bedrock/hardpan surface.

It can be seen from Fig.70 that the soils throughout traverse A are anomalous with respect to regional threshold. A value of 165 ppm As occurs at the traverse datum and erratic high values up to 400 ppm are present in the western half of the traverse, which on the whole, is higher in arsenic than the eastern half. These high values are thought to be largely due to downslope dispersion from the arsenical lode. In such shallow soils, sheetwash would probably be an important factor influencing trace element dispersion. However, the possibility of local arsenic highs in the bedrock cannot be overlooked.

The values obtained between the datum and 500E suggest that a local threshold of approximately 30 ppm may be typical for the area. This could be due

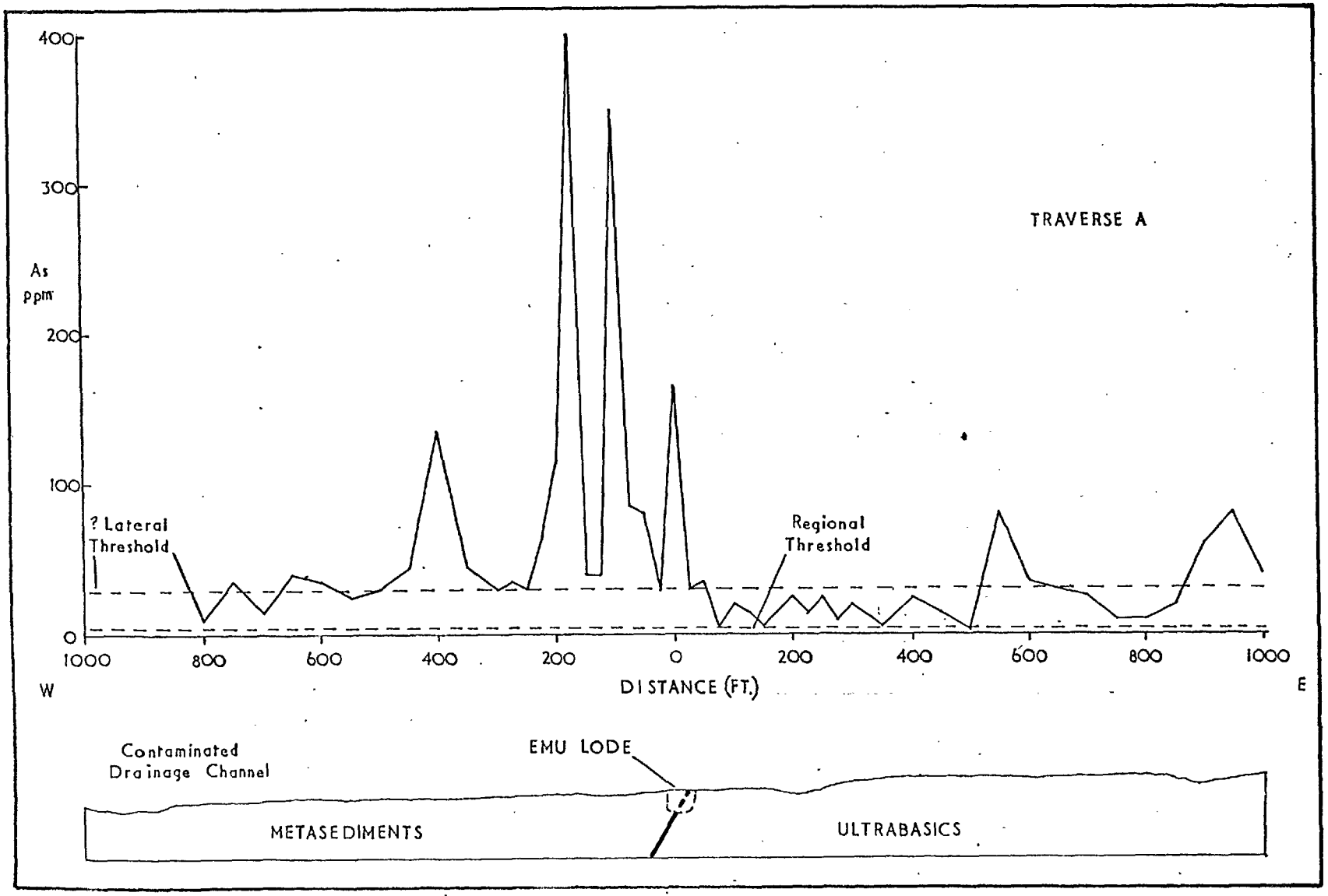


Fig. 70. Lateral dispersion of arsenic in soils (-82#) over bedrock in the vicinity of the Emu Lode, Traverse A, Agnew.

to a wide aureole of feebly mineralized rock surrounding the contact zone. The limited study of primary dispersion carried out gives no information as to this possibility. The anomaly in diamond drill-hole A3 corresponds to a horizontal width of 40 feet. However, the total width of the anomaly related to both the hanging-wall and footwall mineralization was not established in this hole and would probably have been considerably more than 40 feet. Assuming a local threshold value of 30 ppm, the anomaly due to the Emu Lode would still be in excess of 800 feet wide and shows a marked assymetry in the downslope direction. The two additional highs of 80 ppm As at 550E and 950E cannot be due to secondary dispersion related to the Emu Lode and warrant further investigation.

4. Vertical Dispersion of Arsenic near Mineralization

The distribution of arsenic in profile samples collected over the footwall lode near the Emu Shaft is given in Table 36. Although the arsenic content of the bedrock is somewhat greater than that of the solum, good contrast was obtained in all three samples.

5. Dispersion of Arsenic in Soils over the Inferred Northern Extension of the Emu Lode Line

Geochemical profiles for traverses B and C are shown in Fig.71. In Traverse B, which is only

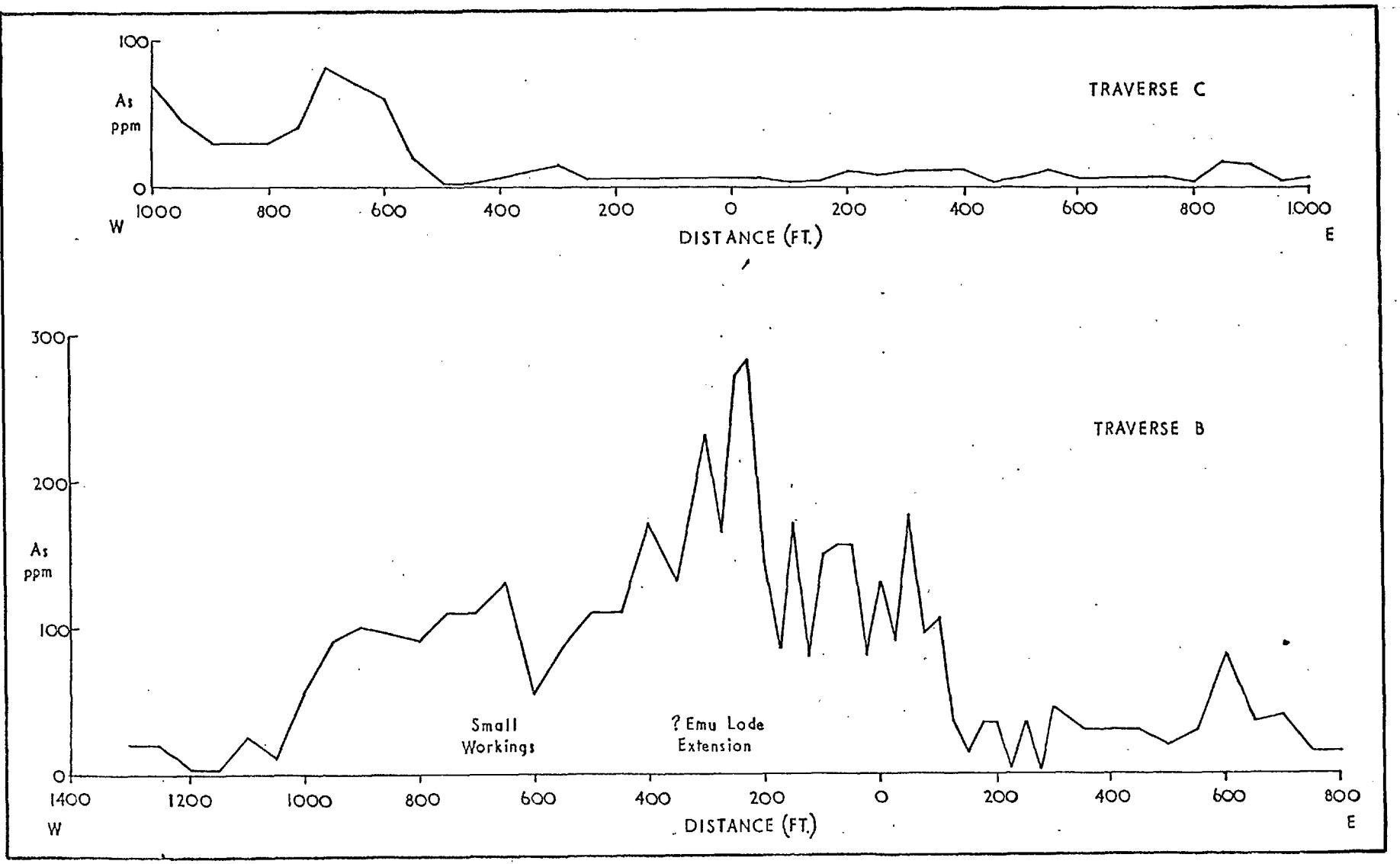


Fig. 71. Lateral dispersion of arsenic in soils (-82#; 6-12" depth) over the inferred northern extension of the Emu Lode, Agnew.

TABLE 36. Distribution of Arsenic with Depth in Soils (-82mesh fraction) over Known Mineralization, Agnew.

Sample depth inches	Description	As ppm
0 - 3	Light brown loam, abundant quartz, rock fragments and ferruginous concretions.	220
3 - 6	Light brown loam, fragments of weathered bedrock	165
6+	White oxidized talc schist, limonite pseudomorphs after coarse actinolite	450

300 feet north of known mineralization, a very strong anomaly was obtained with peak arsenic values up to 300 ppm occurring between 225W and 300W. Profile samples collected in this area confirmed that the soil anomaly is related to an arsenic-rich source in the bedrock, almost certainly the extension of the Emu Lode line. A second, weaker anomaly is associated with a parallel line of lode, workings on which occur between 700W and 1,000W. Samples from dumps of mine spoil on this weaker lode were found to contain more than 1,000 ppm As.

Traverse C, carried out nearly 2,000 feet north of the Kim Shaft, disclosed the existence of an anomaly to the west of 600W. The full extent of this anomaly was not established due to inadequate sampling.

Soils on the western half of the traverse directly overlie Precambrian rocks, whereas the eastern part of the traverse was largely over Permian sediments. It cannot be judged from these results whether the anomaly in traverse C is related to the Emu Lode or to the minor lode line detected in Traverse B. If the Emu Lode line does, in fact, intersect the western end of traverse C, it must be presumed that it has diverged some distance to the west of the metasediment-ultrabasic contact, which can be placed with some certainty at, or to the east of, the traverse datum. This is not improbable since the hanging-wall lode in the Kim Shaft appears to have a more westerly strike than the contact and this divergence is even more pronounced in traverse B. However, it is also possible that the Emu Lode line

(i) peters out between traverses B and C.

(ii) occurs under a cover of Permian sediments to the east of the traverse datum and does not give rise to an anomaly in the overlying soils.

These problems cannot be resolved on the basis of the present results but the fact that an anomaly was obtained at all in traverse C shows that there is considerable scope for more detailed geochemical testing of the northern continuation of the Emu Lode line in this potentially auriferous area.

B. EULAMINNA

1. Description of the Area.

A brief study was carried out at Eulaminna in order to investigate the trace element dispersion patterns associated with an auriferous base metal deposit, the Anaconda Lode.

The general geology of the area consists of a typical "Greenstone" sequence - weakly metamorphosed lavas and intrusives of basic to intermediate composition, ultrabasics and sediments which locally strike north-north-east and dip steeply to the east (Fig.72). The Anaconda Lode, which strikes parallel to the stratigraphy and dips 70° to the east, is a siliceous pyrite-chalcopyrite replacement body in basaltic and andesitic lavas. Four main ore-shoots have been developed over a strike length of more than 1,000 feet.

In the most extensive workings, on the southern end of the lode, the grade is reported to have been 15-25% Cu to a vertical depth of 192 feet. The ore from this zone of secondary enrichment consisted of native copper, cuprite, malachite, azurite and chalcocite. Between the 192 feet and 250 feet levels, the grade varied from 1 to 10% and below this level, the orebody was worked for pyrite. In addition to their copper content, ore samples collected from surface workings and mine dumps were found to contain up to

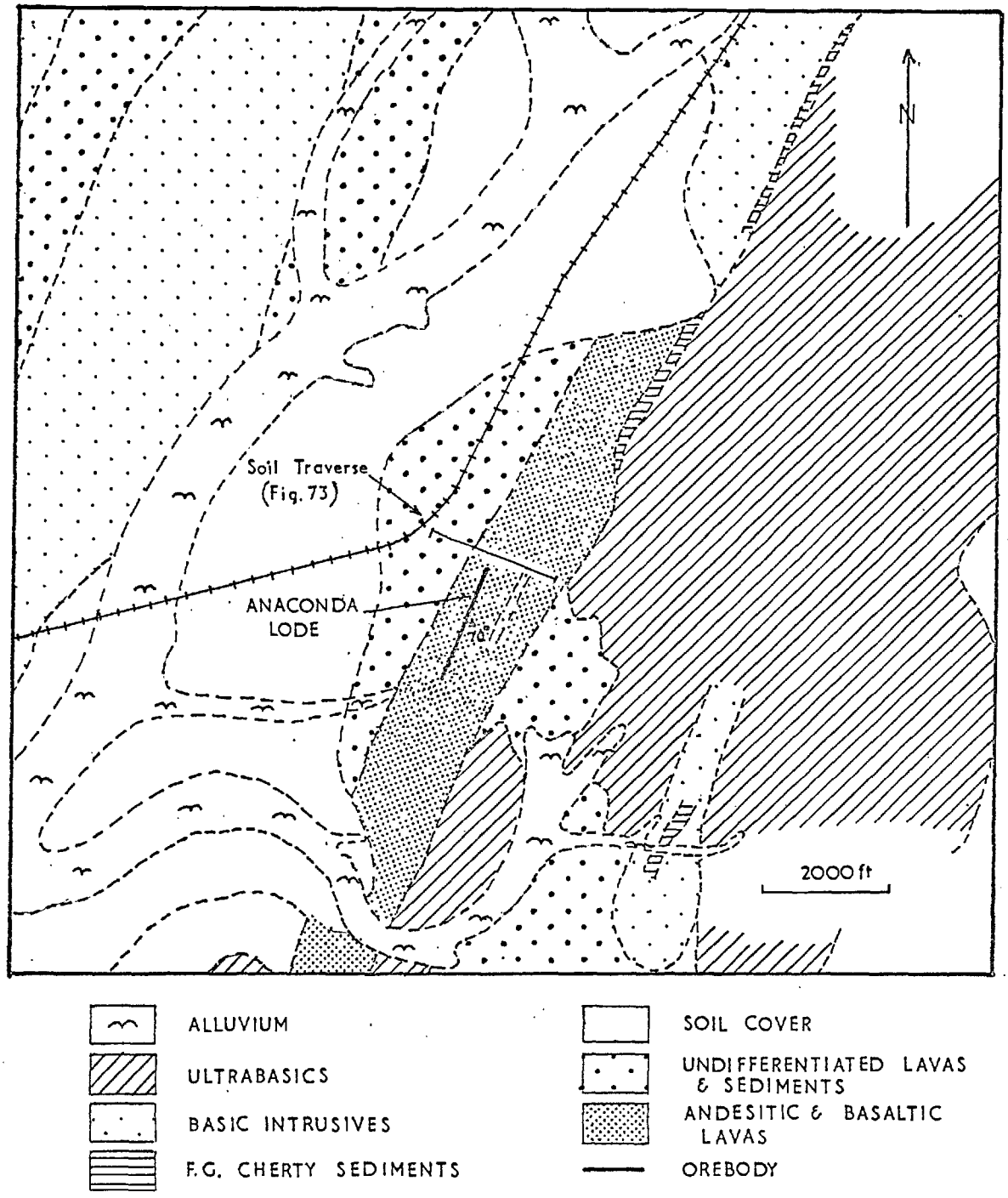


Fig. 72. Geological map of Eulaminna (after Hobson and Miles, 1951).

2,500 ppm Pb and 7000 ppm Zn. There is no record of any gold production from the cupriferous ore but samples of subeconomic ore from the oxidized zone, taken during the present investigation, were found to contain up to 0.5 dwt/ton.

The terrain slopes gently to the west from a low ridge of ultrabasic rocks occurring to the east of the lode. As a result of active erosion, the soils in the area (described on page 35) are immature and generally less than one foot in thickness. It is of interest to note that surface indications of the three northern ore-shoots were negligible, despite the thin soil cover and marked secondary enrichment in the oxidized zone. Although weakly anomalous arsenic values were obtained for ore samples and soils near mineralization, it became obvious at an early stage that the dispersion patterns of copper and zinc were more significant and work was concentrated on these elements.

2. Trace Element Dispersion in Soils at Eulaminna.

a) Background Data.

The regional threshold values for copper and zinc were calculated on the basis of determinations on the -82 mesh fraction of 12 samples from a geochemically similar, but unmineralized area, five miles north of Eulaminna (Table 37).

The distribution of copper and zinc with depth and

TABLE 37. Copper and Zinc Data for Background Soil Samples, Eulaminna Area

	Cu ppm	Zn ppm
Low value	15	40
Arithmetic mean	38	60
High value	55	90
Regional threshold (mean +2σ)	58	95

particle size for background soils are shown in Tables 38 and 39.

b) Distribution of Copper and Zinc with Depth in Soil Profiles at Eulaminna

The distribution of copper and zinc with depth in a number of anomalous and background profiles is shown in Table 38.

TABLE 38. Distribution of Copper and Zinc in Soil Profiles, Eulaminna(-82 mesh fraction for Solum Samples).

Sample Depth	Cu ppm				Zn ppm			
	Profile 1	Profile 2	Profile 3	Profile 4	Profile 1	Profile 2	Profile 3	Profile 4
0 - 3	1400	180	290	70	3250	90	305	50
3 - 6	1200	250	140	65	2150	75	75	45
6 -12				65				45
12-18				45				45
Weathered bedrock	2000	700	100	55	5500	55	70	55
Depth of bedrock	6"	6"	6"	18"	6"	6"	6"	18"

Notes:

Profile 1: Anomalous soils over subeconomic ore, Anaconda Lode.

Profile 2: Anomalous soils on projected Anaconda Line (Datum of traverse shown in Fig.73).

Profile 3: Anomalous soils, 100 feet east of Anaconda Lode.

Profile 4: Background soils, 5 miles north of Eulaminna.

Copper and zinc do not appear to vary significantly with depth in the background profile samples. Anomalous profiles 1 and 2 show considerable enrichment in the bedrock with respect to the solum. There does not appear to be any significant variation within the soils over the weathered bedrock. In profile 3 however, copper and zinc show a marked concentration in the uppermost horizon with respect to both the subsoils and bedrock. This is thought to be the result of contamination. It is unlikely to be due to natural dispersion processes since the profile site is upslope from the lode.

c) Particle Size Distribution of Copper and Zinc in Soils, Eulaminna.

Table 39 compares the distribution of copper and zinc in the various size fractions of anomalous and

background samples, separated by dry-sieving. Both samples were from depths of 6 to 12 inches, sample A from anomalous soils in the vicinity of the Anaconda workings, and sample B from the background area. No significant variation in copper content is apparent in the background sample although zinc shows a distinct tendency to concentrate in the coarser fractions.

TABLE 39. Particle Size Distribution of Copper and Zinc in Soils at 6-12 inches Depth, Eulaminna.

Size Fraction		Wt%		Cu ppm			Zn ppm		
		A	B	A	B	Contrast	A	B	Contrast
	+20	11.0	56.7	345	75	4.6	1600	130	12.3
-20	+38	19.3	7.9	290	110	2.6	800	140	5.7
-38	+82	24.8	7.9	245	130	1.9	700	100	7.0
-82	+125	22.1	10.2	200	95	2.1	600	80	7.5
-125	+197	11.7	7.9	240	110	2.2	700	70	10.0
-197		11.0	9.4	410	135	3.0	1200	60	20.0
-82		44.8	27.5	260	115	2.3	770	70	11.0

In the anomalous sample, both metals tend to concentrate in two definite size ranges:

(i) The +20 mesh fraction - in this fraction copper and zinc probably occur in partly weathered rock and mineral fragments and associated with sesquioxides, which occur as nodules and coatings on other soil and rock particles.

(ii) The -197 mesh fraction - a large proportion of the copper and zinc in this fraction probably occurs as ions adsorbed onto clay minerals and other colloids, particularly hydrated iron oxides which are abundant in the fine fractions.

d) Lateral Dispersion of Copper and Zinc in Soils Near Mineralization.

Copper and zinc show very strong anomalies in the -82 mesh fraction of soils over bedrock along a traverse 200 feet north of the northern workings on the Anaconda Lode (Fig.73). The zinc anomaly is the more pronounced, being more than 500 feet in width and with contrast better than 10. One copper sample shows similar contrast with respect to regional threshold but the erratic distribution of copper throughout the traverse suggests a local threshold greater than 60 ppm, which decreases the apparent width and contrast of the anomaly. Arsenic determinations showed low values throughout the traverse except for one sample, in the vicinity of the copper and zinc anomalies, which was found to contain 20 ppm As.

The anomaly peaks for copper and zinc are displaced about 250 feet west of the projected Anaconda Line. This is consistent with the observation that at the northern end of the Lode line, successive ore-shoots

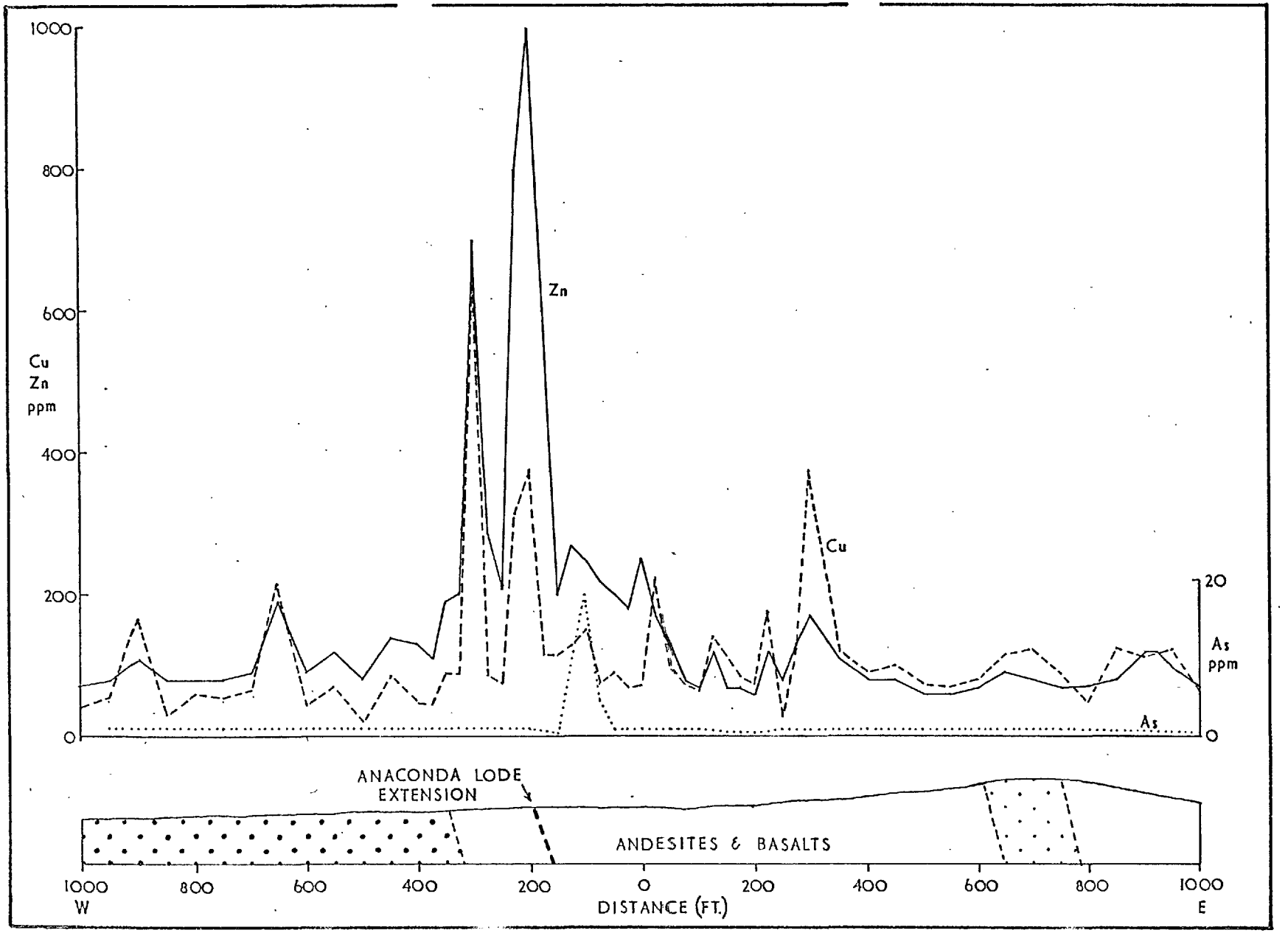


Fig. 73. Lateral dispersion of As, Cu & Zn in soils (-82#) over bedrock in the vicinity of the inferred extension of the Anaconda Lode, Eulaminna.

are offset to the west going north. However, it is also possible that the soil anomaly is assymetrically extended downslope from the copper and zinc-rich bedrock source, which might therefore lie between 250W and the traverse datum. In this connection, it is possibly significant that the maximum for arsenic, which is probably the least mobile of the three elements studied in the iron-rich soils of the area, occurs to the east of both the zinc and copper anomaly peaks. Bedrock sampling over the anomalous zone should be carried out to resolve this.

Selected samples from a traverse crossing the Anaconda lode in the midst of workings showed very high copper and zinc contents. Although the whole traverse was not analysed, because it was thought that the anomaly would be enhanced by contamination from mine spoil, the work done suggests that the anomaly would be of similar or greater magnitude to that shown in Fig.73. Two other soil traverses, 600 feet north and 1000 feet south of the Anaconda workings showed very weak anomalies with less than twofold contrast.

3. Dispersion of Copper and Zinc in Drainage Sediments.

a) Background Data.

Frequency histograms have been drawn to show the distribution of copper and zinc values in the -82 mesh fraction of stream sediments collected from

drainage channels, both in the background area and in the general vicinity of the Anaconda Lode (Fig.74). Data for samples from the major drainage channel (B in Fig.75), immediately south of the Anaconda workings, were not included because of probable contamination.

Plotted arithmetically, the distributions show a pronounced positive skew, no doubt due to the inclusion of a small proportion of anomalous samples. The distributions approximate more nearly to the normal type when plotted on a logarithmic scale and a lognormal distribution has been assumed in calculations of threshold, which gave the following values:

Copper threshold = 70 ppm

Zinc threshold = 95 ppm

b) Particle Size Distribution of Copper and Zinc in Stream Sediments.

The distribution of copper and zinc according to particle size in stream sediments (Table 40) follows much the same pattern as that in soils, with maxima in both the coarse and fine fractions of the anomalous sample. The reasons advanced to explain the bimodal distribution in soils are equally applicable to the stream sediment data.

c) Dispersion of Copper and Zinc in Stream Sediments Near Mineralization.

Samples of active stream sediments were

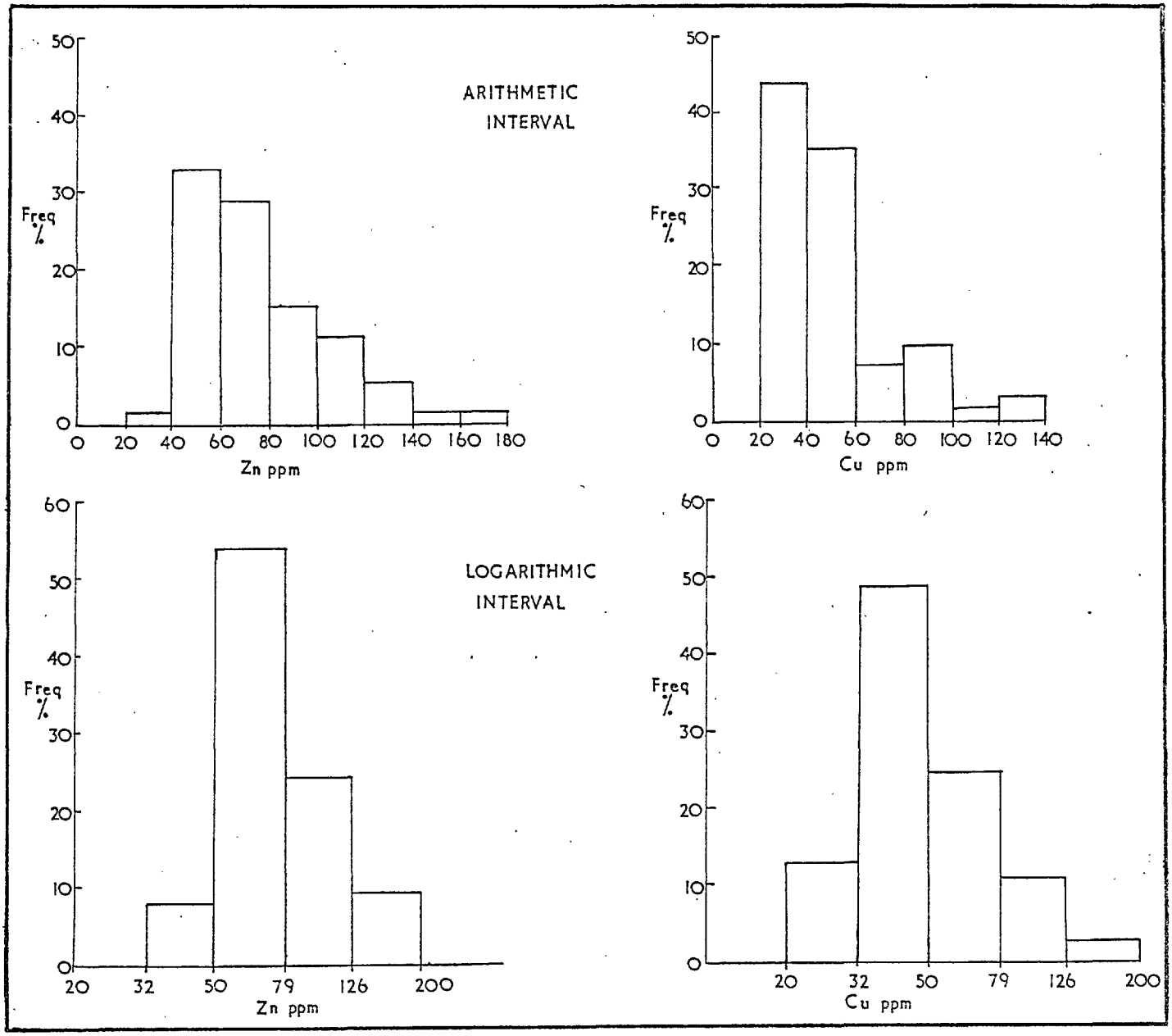


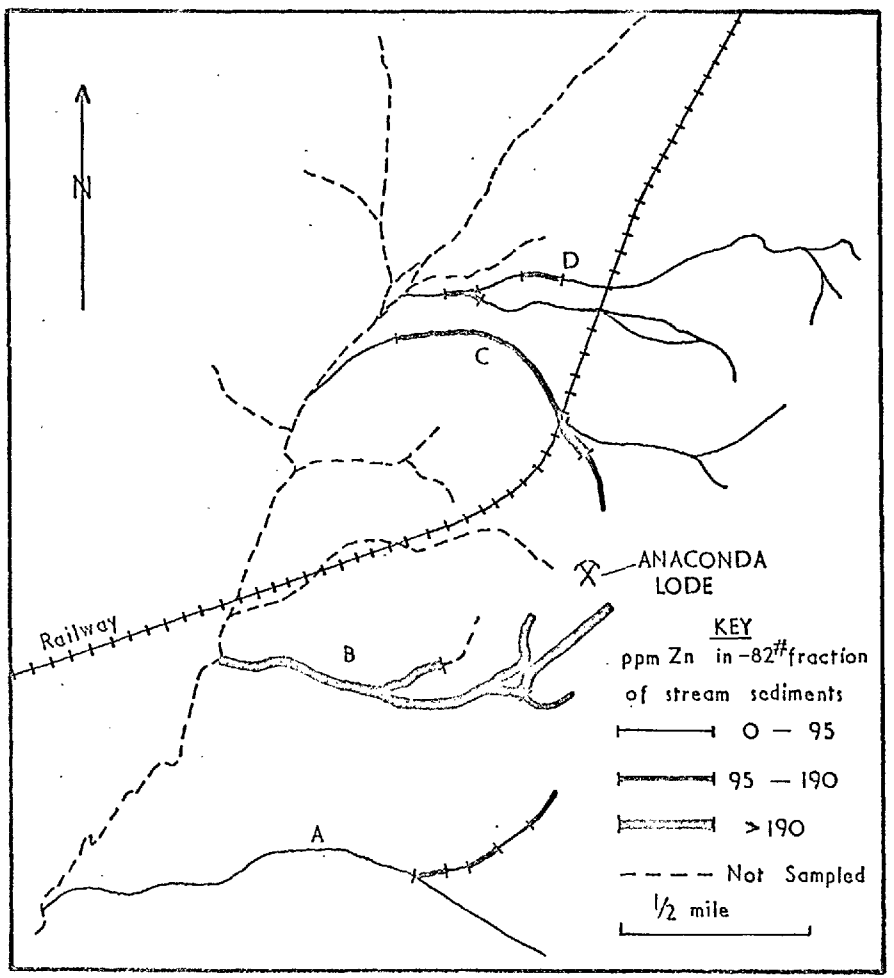
Fig. 74. Frequency distribution of Cu & Zn in the -82# fraction of active stream sediments, Eulaminna.

TABLE 40. Particle Size Distribution of Copper and Zinc in Active Stream Sediments, Eulaminna.

Size Fraction		Wt%		Cu ppm			Zn ppm		
		A	B	A	B	Con-trast	A	B	Contrast
	+20	5.1	9.9	230	45	5.1	600	90	6.7
-20	+38	12.5	10.7	165	35	4.7	500	80	6.3
-38	+82	60.4	32.8	125	35	3.6	360	90	4.0
-82	+125	18.5	40.5	125	30	4.2	280	45	6.2
-125	+197	2.5	4.6	140	35	4.0	440	70	6.3
-107		1.0	1.5	240	35	6.9	640	110	5.8
-82		22.0	46.6	130	30	4.3	315	50	6.3

collected from drainage channels crossing the Anaconda Lode line over a total strike length of approximately 2 miles. The results of analyses on the -82 mesh fraction of these samples are shown in Fig.75.

The very strong anomaly in stream B was to be expected since most of the Anaconda workings are situated in the catchment. Profile samples of the culluvial banks were collected in conjunction with the stream sediment sampling. In the vicinity of the Anaconda Lode, where the stream presumably receives



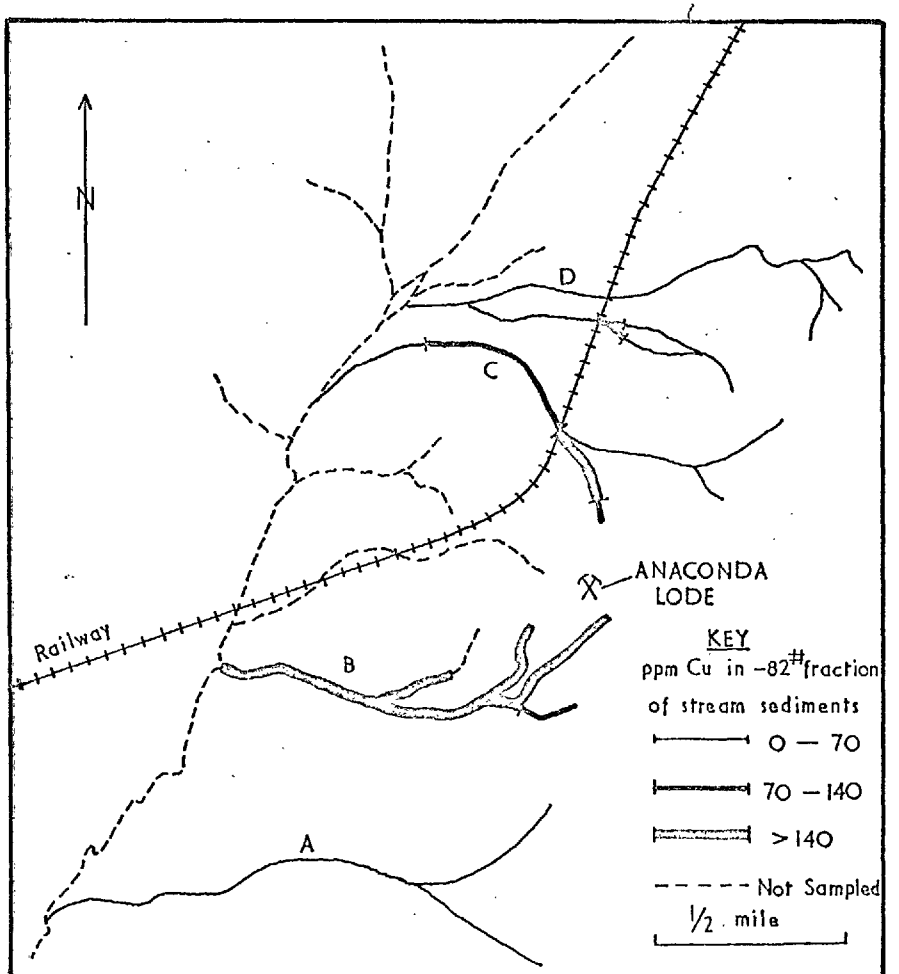


Fig. 75. Drainage dispersion patterns for Cu & Zn in the Eulaminna area.

anomalous material from the mine area, the uppermost horizons of the colluvium on the north bank are considerably enriched in copper and zinc, as shown in Table 41. It can be seen from this table that the topsoils on the bank nearest the mine are strongly enriched in both copper and zinc with respect to the subsoils and soils on the opposite bank. This suggests that some form of mechanical dispersion, probably sheetwash, is the dominant means by which anomalous copper and zinc are contributed to the drainage. It seems likely that this contribution would have been increased as a result of the mining operations carried out in the area but it is not possible at present to assess the extent to which this has taken place.

TABLE 41. Zinc and Copper Content of the -82 mesh Fraction of Bank Colluvium Near the Anaconda Mine, Stream B, Eulaninna.

Element	Sample Depth	No. of Sample sites	North Bank	South Bank
Average Zn ppm	0-3	2	750	190
" " "	6-12	4	180	170
Average Cu ppm	0-3	2	1200	145
" " "	6-12	4	120	130

The stream sediment anomaly in the south fork of stream C is of considerable interest with regard to

prospecting. This stream does not drain any of the mine workings and, as far as is known, is uncontaminated. Peak values of 800 ppm Zn and 390 ppm Cu were found in follow-up work and there is a sharp cut-off, approximately 500 feet east of the railway line where the zinc content drops from 700 ppm to 190 ppm. As in soils at Eulaminna, copper shows a more erratic distribution and samples showing better than threefold contrast alternate with samples of lower but still anomalous copper content as much as 800 feet east of the railway line. Samples of colluvium from both banks in the vicinity of the stream sediment anomaly cut-off points contain over 1000 ppm Zn and 650 ppm Cu. These values quickly drop to background to the east of the stream sediment cut-off points.

V. DISCUSSION: SECONDARY DISPERSION OF ARSENIC

A. GENERAL

The development of secondary dispersion patterns may be regarded as the net result of three mutually related processes - the mobilization, transportation and fixation of the elements concerned. In the case of arsenic, the effectiveness of these processes is governed by the mobility of arsenic under the varying environmental conditions occurring in the zone of weathering and soil formation. In the subsequent

pages, a general discussion of the various mechanical, chemical and biological factors which may affect the mobility of arsenic is undertaken. This is followed by an assessment of the extent to which these factors affect dispersion processes in the environments of the areas studied. Before this can be done, however, it is necessary to consider the forms in which arsenic may occur in the zone of weathering.

B. MODE OF OCCURRENCE OF ARSENIC IN THE ZONE OF WEATHERING.

Arsenical sulphides are readily oxidized in the zone of weathering. Blanchard (1942) showed that arsenopyrite is oxidized to limonite and scorodite ($FeAsO4.2H_2O$). The latter slowly decomposes further forming limonite and releasing arsenic to the soil. Arsenic may be present in soils in both the trivalent and pentavalent states. However, the trivalent form is unstable, except in the most strongly reducing environments as found in poorly-drained swampy conditions. Under most soil-forming conditions As^{3+} is quickly oxidized to the pentavalent state. The relatively small ionic radius of the As^{5+} ion ($0.46A^{o}$) and high positive charge favours the formation of the arsenate radicle (AsO_4^{3-}). It is probable that all the arsenic present in the soils of the area under consideration is in the form of arsenates.

For the purposes of the following discussion, the mode of occurrence of arsenates in the zone of weathering may be generally classified as follows:

(i) Arsenates in free soil solution

(ii) Adsorbed arsenates associated with colloids.

(iii) Fixed arsenates present in the form of difficultly soluble compounds of iron, aluminium etc.

C. FACTORS AFFECTING THE MOBILITY OF ARSENIC IN THE SECONDARY ENVIRONMENT.

1. Mechanical Factors

a) Soil Creep.

Under the influence of gravity, the solid particles of the overburden tend to move downslope, normally causing the anomaly to extend assymetrically in the downslope direction. The very subdued relief and dry conditions encountered in semi-arid Western Australia, suggest that dispersion due to soil creep would be imperceptibly slow. Nevertheless, over a long period of weathering, even under the present conditions, soil creep could be a significant factor.

The weathering of an inclined arsenic-rich bedrock feature may result in dispersion patterns apparently similar to those due to soil creep. In this case, other factors being equal, the dispersion

pattern would be more extensive on the footwall side of the source of arsenic than on the hanging-wall side.

b) Sheetwash.

There is considerable evidence in all the areas studied to indicate that sheetwash is an important agent of erosion affecting the surface soils. During the occasional torrential downpours to which the area is subject, the clay-rich subsoils, and shallow impervious laterite and hardpan formations, prevent the rapid absorption of the water, and the scanty cover of vegetation is insufficient to prevent erosion by running water, even on gentle slopes.

c) Groundwater movement.

Ground-water movement is a major factor in the dispersion of readily soluble or dispersed soil components in humid climates. In semi-arid Western Australia, however, the permanent water-table generally lies some tens of feet below the solum-bedrock boundary and lateral movement is at a minimum, owing to the low rainfall, high evaporation and subdued topography. Nevertheless, the movement of soil moisture and dissolved substances could have an important bearing on secondary dispersion.

During periods of heavy rainfall, downward percolation of meteoric water may be resisted by the

impervious clay-rich basal horizons of the solonized brown soils or the indurated horizons of lateritic and hardpan soils. This would lead to the development of a "perched" water-table, within which limited lateral migration of soluble and colloidal material could take place for short periods.

In dry seasons, the movement of ground-water solutions is predominantly upward, to replace soil moisture lost by evaporation near the surface. This may occur in part by capillary action, which is effective up to a maximum vertical distance of 30 feet above the water-table. It has also been shown, however, that upward movement of ground-water is possible for considerable distances above the capillary fringe (Hawkes and Webb, 1962, p.132). The mechanism is believed to involve the migration of water along the surfaces of mineral grains. This type of movement is likely to lead to increased dispersion, both vertically and laterally. The present-day deposition of concretionary calcium carbonate (part of which is believed to be derived from ground-water) in the upper horizons of solonized brown and calcareous lateritic soils, is evidence for the presence of soil-moisture well above the water-table.

2. Chemical Factors

a) Temperature and Water.

Apart from their effect on the physical

conditions of the secondary environment, temperature and water together have an important bearing on the chemical reactions taking place in soils and drainage. According to Jenny (1941), chemical reaction rates increase exponentially with temperature. It has been estimated that for every 10°C rise in temperature, the rate of a chemical reaction increases by a factor of two or three. Thus, under Western Australian conditions, soil reactions might be expected to proceed at considerably faster rates than in cooler temperate regions.

Water affects chemical reactions in soils in three capacities - as a reacting component in many soil reactions, as a catalyst, and as the medium in which the reacting components circulate. In the absence of water, chemical weathering proceeds very slowly, to the extent that, in low-latitude desert areas, physical weathering processes are dominant, despite the high temperatures (Jenny 1941, p.183). Thus it is clear that the effects of temperature and water must be considered together. It has been pointed out above that, despite the low rainfall, significant amounts of soil moisture are present in the Western Australian goldfields and there is considerable evidence suggesting that chemical processes play an important part in secondary dispersion in the area, as will be seen later.

The influences of temperature and moisture are also important in the control they exert on the abundance of active organic substances in the soils. The organic content of soils in high-temperature semi-arid areas is generally very low for two reasons. Firstly, the low rainfall limits the growth of vegetation which is the main source of organic matter in soils. Furthermore, the dead vegetation is quickly oxidized and decomposed as a result of the high summer temperatures and is largely "burnt up" so that very little organic matter is imparted to the soils (Joffe, 1949, P.242).

In general, climatic factors, of which temperature and water are important parameters, profoundly influence the chemical composition of soils and thus are indirectly related to most of the chemical factors influencing arsenic dispersion, which are to be discussed. The effects of climatic factors in relation to soil genesis in the areas studied have been mentioned in Chapter 2.

b) Oxidation Potential and pH

The oxidation potential (Eh) and hydrogen ion potential (pH) are important factors, in that they determine, to a large extent, the nature of chemical reactions which will occur in any environment. The natural environment is characterized by Eh values between 4.0 and 0.8 volts and pH values between 4.0 and 9.0 (Krauskopf, 1955). This field is

shown in Fig.76 together with the stability fields of the ionic species of interest.

pH values were found to vary widely in Western Australian solonized brown soils (between 4.3 and 9.3) but were more constant in laterites (7.3 to 8.0). Teakle (1937) reports pH values varying from 5.6 to 8.7 in hardpan soils from an area in the vicinity of Eulaminna. The higher pH's in this area were associated with calcareous soils which, however, are not common at Agnew and Eulaminna.

Eh is known to vary with pH, temperature and the partial pressure of oxygen. Although no determinations of Eh were made on Western Australian soils, highly oxidizing soil conditions are probable in the areas studied in view of the high summer temperatures, freely drained character of the soils and relatively high pH values, especially in the lime-rich horizons of the solonized brown soils. Even where pH values are very low, as in the basal clays of these soils, the abundance of ferric iron, as reflected by the strong reddish coloration of the soils in this horizon indicates Eh values in excess of 0.4 volts (Fig.76). From this it may be inferred that local conditions favour arsenates as the stable form of arsenic in soils.

c) Chemical effect of major soil components

(i) Iron and Aluminium Oxides.

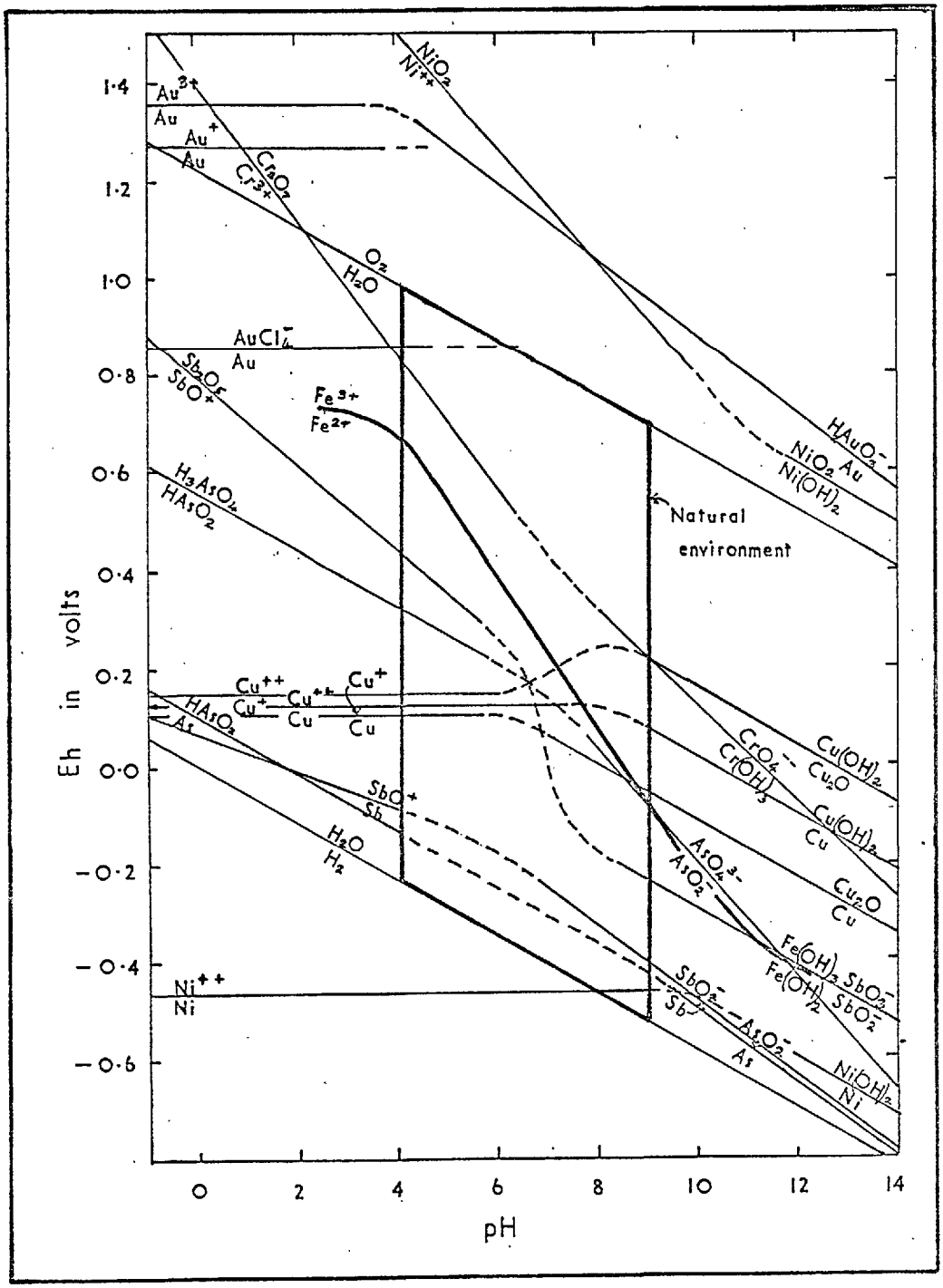


Fig. 76. Stability of ionic species in relation to Eh and pH at 25°C and 1 atmos. pressure (after Krauskopf, 1955 and Elliott, 1962).

Arsenates and arsenites exhibit a strong affinity for iron and aluminium oxides, to which they may be bound by adsorption and the formation of insoluble compounds such as scorodite (Krauskopf, 1955).

A number of workers have called attention to the importance of iron oxides in fixing arsenic in soils. Keaton and Kardos (1940) found that arsenic poisoning of soils by spray residues could be reduced by the addition of iron, which effectively fixes the arsenic. The addition of aluminium oxide, on the other hand, only slightly increased the fixation of arsenic.

Wiklander and Frederikson (1946) consider that the wide variation in arsenic sorption shown by different soil-types is due, among other things, to differences in the amounts of iron and aluminium oxides present. Laboratory experiments by these authors showed that hydrated iron oxides achieved virtually 100 percent sorption of arsenate in synthetic solutions containing up to 1600 mg As per 100 g. iron oxide. Aluminium oxide was also found to be capable of sorbing arsenate, though to a lesser extent than iron oxide.

James (1957) found only minor variations in arsenic content with depth in iron-rich soils in Rhodesia, the arsenic content in soils corresponding closely to that in the bedrock. Iron-poor soils, on the other hand, occasionally showed some variation in depth,

there being in most cases a marked concentration in the top of the weathered bedrock. James attributes the variation in iron-poor soils to leaching, the effects of which were restricted to iron-rich soils, due to arsenic fixation.

The strong adsorption of the arsenate anion by iron and aluminium oxides has been explained by the fact that these oxides form positively charged colloids in most geologic environments (Krauskopf 1955). There is probably some interchange between arsenate ions held by adsorption bonds and arsenic in the form of combined iron and aluminium arsenates. However, there is evidence to suggest that drying of soils tends to make the change from adsorbed to combined arsenates irreversible (James 1957, Elliott, 1962).

Wiklander and Alvelid (1950) have investigated the solubility of ferric and aluminium arsenates. Both compounds show similar variation in solubility with pH, having minima at pH 2.3 and 4.1 respectively (Fig.77a). The rise in solubility on the alkaline side of the minima is attributed to replacement of arsenate ions by hydroxide ions. Below the pH of minimum solubility, the rise in the solubility of arsenic is believed to be due to the formation of undissociated arsenic acid, which is comparatively weak. From this data, it would appear that iron and aluminium arsenates should be appreciably

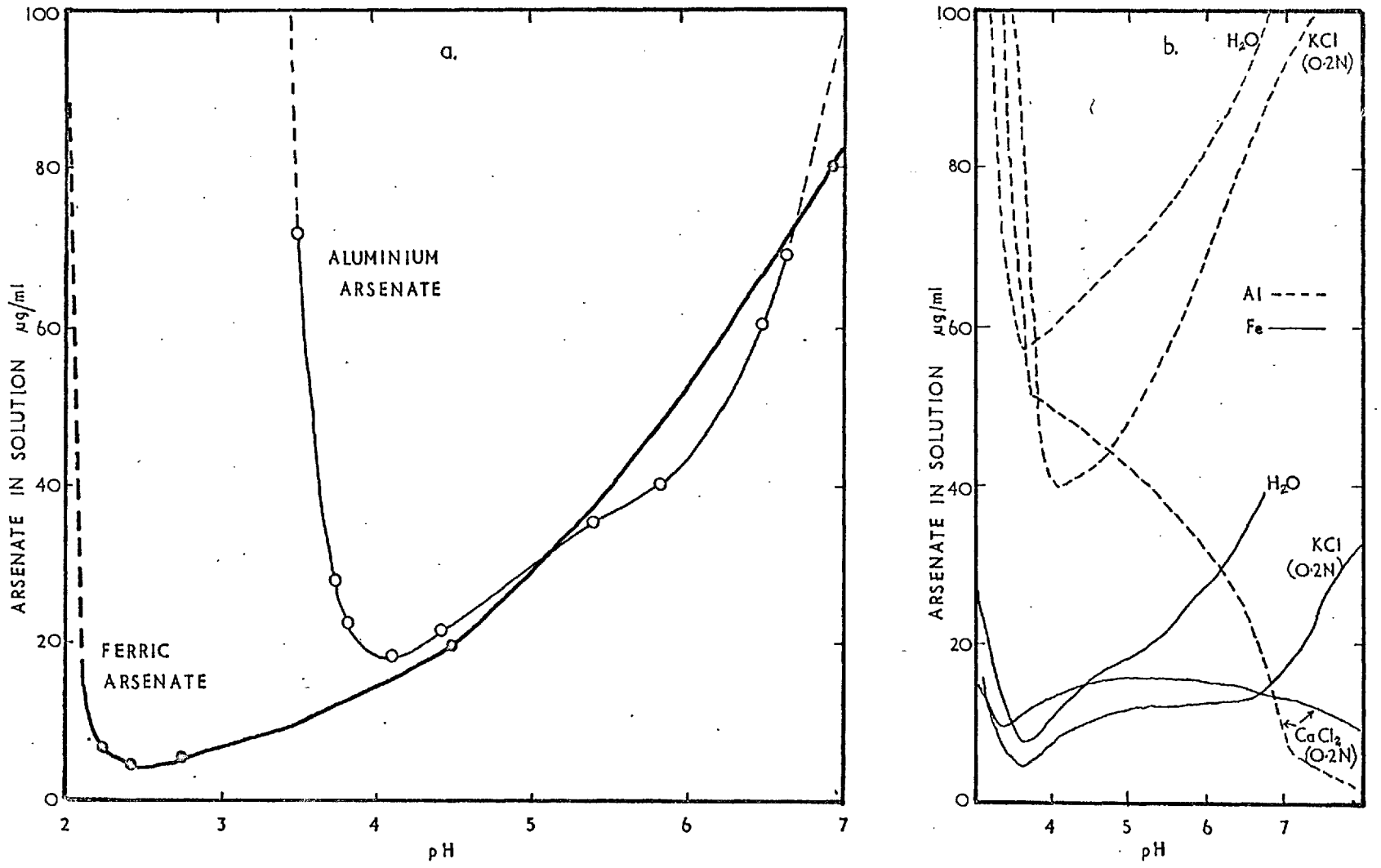


Fig. 77. a) Solubility of arsenates precipitated with $AlCl_3$ and $FeCl_3$.
b) Effect of neutral salts and pH on the solubility of aluminium and iron arsenates in the presence of phosphates.
(After Wiklander and Alvelid, 1950).

soluble under the comparatively high pH conditions encountered in Western Australian soils.

Wiklander and Alvelid also studied the effects of other ions on the solubility of ferric and aluminium arsenates (Fig.77b). The presence of KCl and $CaCl_2$ tends to decrease the solubility of arsenates in both the iron and aluminium systems. $CaCl_2$, in particular, causes a marked decrease in solubility in the higher pH range, due to the formation of insoluble calcium arsenate.

The presence of phospate was found to increase the solubility of arsenic. This is explained by the similarity between the phosphate and arsenate radicles, which are therefore in competition with each other and the equilibrium status is determined by their relative replacing powers and the concentration ratios.

Experiments on soils, instead of synthetic hydroxides, showed that the solubility of arsenates was decreased by the addition of KNO_3, K_2SO_4, KCl, NaCl and $CaCl_2$ but increased by the addition of phosphates.

Very low concentrations of phosphate are present in Western Australian solonized brown soils (Teakle, 1937) and laterites (Table 2). However, the abundance of soluble salts in the semi-arid soils of Western Australia could influence the solubility of iron and aluminium arsenates appreciably.

(ii) Manganese oxide.

The work of Sugawara et al (1956) suggested that hydrated manganese oxides are capable of scavenging arsenic from natural solutions. However, Elliott's(1962) studies of drainage sediments in Sierra Leone showed that there was no direct correlation between manganese and arsenic. Although no detailed studies were made of the distribution of manganese in the particle size fractions of Western Australian soils, analyses on the -82 mesh fraction of soil samples from traverses at Norseman and Kalgoorlie showed no obvious correlation between manganese and arsenic. It is therefore thought that manganese does not affect the dispersion of arsenic in Western Australian soils to any great extent.

(iii) Calcium

The precipitation of insoluble calcium arsenate has already been mentioned in connection with Wiklander and Alvelids' (1950) studies of the solubility of ferric and aluminium arsenates. Margulis and Bourniquel (1949) found that calcareous soils fixed large amounts of arsenic. Boischot and Hebert (1948) state that the fixation of arsenate by calcareous soils is by adsorption and not by combination.

Mattson et al (1950) have shown that the presence of neutral salts promotes the solubility of calcium phosphate. It is therefore probable that the solubility of calcium arsenate would also be increased

by the presence of neutral salts.

Erikson et al (1964), studying the dispersion of arsenic near the Getchell Mine, Nevada, found appreciable concentrations of arsenic in the caliche accreted to the weathered bedrock, with respect to the overlying soils, although both the caliche and the soils were lower in arsenic than the oxidized iron-rich material associated with bedrock fractures and bedding planes.

From this data, it would therefore appear that calcium may be an important factor in the fixation of arsenic.

(iv) Clays.

Arsenate may be fixed in soils by adsorption onto colloidal clay minerals. According to James (1957) the most probable mechanism for anion adsorption by clay minerals involves the replacement of accessible $-OH^-$ ions. A consideration of the structures of clay minerals leads to the conclusion that single-layer clays of the kaolinite type, which exhibit one face of hydroxyl ions in each unit, should be more capable of anion exchange than the double-layer clays (e.g. montmorillonite), in which hydroxyl ions are only exposed at the broken lattice edge.

In the case of clays like kaolinite, where cation exchange is due to broken bonds, the anionic

and cationic exchange capacities should be approximately equal. In montmorillonite, on the other hand, where cation exchange also involves lattice substitutions, the anion exchange capacity would be only a fraction of the cation capacity. However, since the cation exchange capacity of montmorillonite is approximately 12 times that of kaolinite (Grim 1962), limited anionic exchange probably takes place in both clay types.

Experimental studies carried out by Sieling (1946) on the role of kaolin in anion sorption suggest that the anion exchange capacity of kaolinite is very low. Sieling found that natural kaolinite did not sorb arsenate even under optimum conditions at pH 3. However, appreciable sorption occurred when the kaolinite was ball-milled or treated with hot NaOH. Sieling believes that the increased sorption shown by this "activated" kaolinite is due to the breakdown of the kaolinite structure and the development of a partially hydrated alumina, similar to γ-AlOOH. Arsenates adsorbed on clays were found to be readily displaced by phosphates and it was considered that the presence of anions such as citrate, oxalate, tartrate and silicate in the soil would have a similar effect.

The results obtained in the present research showed that significant amounts of arsenic are present in the clay-sized material, especially in the calcareous near-surface horizons of the solonized brown soils.

The tenor of arsenic in the clay fractions is, however, invariably lower than in the iron-rich silt-fractions (Figs. 56 and 65). It is probable that part of the arsenic in the clay fraction is associated with iron oxides but some clay adsorption is suspected.

The clay types occurring in the areas studied in this project have not been determined. Litchfield and Mabbutt (1962) have found that montmorillonite is the dominant clay mineral occurring in hardpan soils on hill-slopes. Since the orebodies at Agnew and Eulaminna both occur on hill-slopes this is probably true of the soils studied in the present project. Theoretically, the alkaline, near-surface soils and limited leaching of bases from the solonized brown soils, also favour the development of montmorillonite (or illitic) clays (Hawkes and Webb, 1962, p. 86). Jenny (1941, p.138) shows that the SiO_2: Al_2O_3 ratio of colloids from arid soils lies between 2.9 and 4.7 The same ratio for montmorillonite is theoretically 4:1 as against 2:1 for kaolinite so it seems likely that the clays in present-day soils in semi-arid Western Australia would be largely montmorillonitic in character. However, the strongly leaching conditions believed to have been prevalent during the period of laterite-formation would have favoured the development of kaolinite as the most stable clay mineral.

3. Biological Factors.

a) Vegetation.

Although arsenic is not essential to plant growth, some plants growing on arsenic-rich soils have been found to incorporate appreciable quantities of the element in the living tissues. Goldschmidt and Peters found up to 500 ppm As in the ash of beech humus and reported high arsenic contents, generally 500 to 2000 ppm, and sometimes much higher, in the ash of many coals (Onishi and Sandell, 1955). Warren and et al (1964) have shown appreciable accumulation of arsenic in Douglas Fir needles. Biogeochemical prospecting based on arsenic determinations on present year tips is claimed by these authors to give better anomaly contrast in the vicinity of arsenical gold and base-metal mineralization in Canada than soil sampling. On the other hand, Mather (1959) found only 0.2 to 5.0 ppm and 0.1 to 2.0 ppm As in the leaves and twigs respectively of the plant Ricinodendron africanus, growing in soil with arsenic contents of 9 - 1140 ppm As in Sierra Leone.

No determinations of the arsenic content of vegetation growing in the vicinity of gold mineralization have been made in the present study. However, vegetation must be regarded as a possible means of redistribution of arsenic in soils. Theoretically arsenic may be taken up from anomalous soils by means of the roots and

incorporated in the aerial parts. On dying, the leaves and branches disintegrate, releasing arsenic back into the surface soils. Over a long period, appreciable lateral translocation of arsenic may occur by this means.

b) Microorganisms

Certain soil bacteria have the ability to oxidize arsenite to arsenate (Quastel and Scholefield, 1953). However, probably the main influence of micro-organisms on the mobility of arsenic is in the production of chelating agents from organic matter, which are capable of releasing arsenic from sesquioxides.

c) Organic Matter in Soils.

As mentioned above, chelating substances derived from organic matter may be important influences in the mobilization of sesquioxide-held arsenates. The mechanism involves the combination of these organic anions with iron and aluminium to form soluble compounds, simultaneously releasing arsenates. This mechanism is also held to be an important factor in accounting for the movement of iron from the surface to the subsoils (Marshad, 1955). Mather (1959) considers the substitution of organic ions for arsenates to be the dominant factor in accounting for the observed leaching of arsenic from the surface horizons of vlei profiles contaminated by arsenical material.

The extent to which chelating agents affect soils in the areas studied is probably limited, since the semi-arid climate militates against the formation of large quantities of active organic substances.

Arsenic is known to concentrate in some organic-rich materials. In black shales, arsenic is enriched to between 15 and 45 times its crustal abundance. In coal ash the enrichment factor is commonly between 20 and 100, and in asphalt and petroleum ash, approximately 300 (Krauskopf 1955). Vinogradov (1948), on the other hand, found that highly organic soils have abnormally low arsenic content, and Elliott (1962) found no apparent relationship between the organic carbon and arsenic contents of Sierra Leone drainage sediments. These data probably reflect the highly selective nature of arsenic absorption by living organisms.

No direct determinations of organic carbon in soils were made by the writer. It is possibly significant that in most of the study areas, the arsenic concentrations in topsoils, in which organic matter appears to be most abundant, are generally lower than those in the subsoils, suggesting that organic matter either does not accumulate or retain arsenic to any extent.

D. DISPERSION PROCESSES IN SOLONIZED BROWN SOILS

1. Dispersion in the Soil Profile

The levels of concentration of arsenic

encountered in the soils and the upper part of the weathered bedrock at Norseman are generally much lower than those found in the primary dispersion halos about reef-shears. Since the soil thickness at any point probably represents the residue of the weathering of considerably greater thicknesses of rock, it is clear that considerable overall leaching of arsenic has taken place during soil-formation.

The variation in arsenic concentration with depth in solonized brown soil profiles in Western Australia is problematical, both from a theoretical point of view and also from the aspect of developing a satisfactory prospecting method. Detailed studies of typical soil profiles at Norseman show two distinct loci of arsenic concentration - the iron-rich basal clay horizons (and/or the ferruginous weathered bedrock) and the near-surface calcareous horizons (Fig.58). This suggests that there are at least two separate mechanisms governing the distribution of arsenic in the soil profile. These will be discussed in turn.

a) Concentration of Arsenic in Iron-Rich Horizons.

The apparently close association of arsenic and iron in Norseman soils, suggested by particle size distribution, mineral separations and profile studies (Figs. 57,58 and Table 30) is in accord with theoretical

considerations and experimental results from numerous other areas. Due to the high degree of solonization, the Norseman soils are in a highly dispersed condition and colloids such as iron hydroxides and clays are readily leached from the surface, leading to the development of the iron-rich clay horizon at depth. During this process, arsenic bound to these colloids by combination and adsorption would also be removed from the surface and redeposited in the deeper horizons. Some additional arsenic may well be mobilized near the surface and fixed in the deeper horizons by iron oxides and, to a lesser extent, clay. It has already been pointed out that ferric arsenate should be appreciably soluble under the high pH conditions prevailing in the near-surface soils. The mobilizing effect of phosphates and organic substances may also contribute to the solubility of arsenates, but the effects of these agencies would, however, be minimised by the deficiency of phosphates and organic matter and the abundance of salts in the soils.

In the Princess Royal Traverse, the shallowness of the soil profile militates against the accumulation of appreciable amounts of ferruginous silt and clay at depth and the maximum arsenic concentration occurs in the iron-rich weathered bedrock (Figs 54 and 58b). This feature is less noticeable in profiles where the basal

clay horizon is present. The mechanism envisaged is essentially similar to that described above, i.e. the fixation by iron oxides in the bedrock, of arsenic leached from the surface soils. It should also be remembered, however, that at least part of the arsenic in the weathered bedrock no doubt results from the weathering of arsenopyrite in situ and has not been transported from the upper horizons.

b) Concentration of Arsenic in Calcareous Horizon .

From the discussion on page 248, it might have been expected that fixation by calcium was responsible for the concentration of arsenic in the calcareous horizon of solonized brown soils. However, sand-sized calcium carbonate grains separated from a sample containing 33 ppm As in the -82 mesh fraction at 6-12 inches depth were found to contain only small amounts of arsenic ($<$10 to 26 ppm) compared with values of 165 to 393 ppm As for iron oxides from the same sample. The calcrete coating on bedrock at Kalgoorlie contained only 2 ppm As as against 45 ppm in the soils over bedrock. Similar results were obtained for calcrete in a lateritic gravel sample from Coolgardie (p 211). Hence, it is apparent that calcium has no significant effect on the fixation of arsenic in calcareous soils in the areas studied.

The concentration of arsenic in the calcareous horizon can be explained by one or both of two possible mechanisms:

(i) It can be seen from Fig.56 that the arsenic concentration in the clay fraction of the sample at 6-12 inches depth is more than twice that in the clay fractions of the samples at 0-3 inches and 48-60 inches. Furthermore, in view of the abundance of clay in the sample, the clay-held arsenic would clearly account for a considerable proportion of the total arsenic present and could explain the observed concentration in the -82 mesh fraction of samples from the calcareous horizon. The apparent increase in anion exchange capacity shown by the clays in this horizon is presumably due to the abnormally high soil pH, which may "activate" the clay minerals, as in the experiments of Sieling(see page 250).

(ii) It is evident that the calcareous horizon is the locus of maximum deposition of carbonate, part of which is believed to be precipitated as the result of evaporation of ascending ground-water in the dry season. It is possible that some water-soluble arsenate, brought up from the deeper horizons, would also be deposited in this zone in a similar manner. During the long dry periods, this arsenic would revert to difficultly soluble iron (or aluminium) arsenate and would not be readily available for re-leaching. For the same reason, its presence would not necessarily be indicated by a high

higher than normal exAs/total As ratio. The proportion of water-soluble arsenic in soils is usually very low, so the rate at which such enrichment by evaporation could occur would be very slow. However, the cumulative effect over a long period could be quite appreciable.

Anomalous profiles, such as that in Fig.58d, in which there is no concentration in the near-surface calcareous horizons, may be explained in one of two ways:

(i) The anomalies in the deeper clay horizons are due to lateral (probably hydromorphic) dispersion (see page 261)

(ii) Much of the adsorbed arsenic has been mobilized and leached from the near-surface soils by the action of local concentrations of phosphates or chelating substances.

2. Lateral Dispersion in Soils

The widths of anomalous dispersion patterns in near-surface solonized brown soils are not usually much larger than the observed underlying primary dispersion patterns. At Norseman, for example, primary anomalies, 40 to 100 feet in width, give rise to anomalies 125 to 200 feet in width in near-surface soils. This suggests that lateral dispersion is limited. On the other hand, there is some evidence to suggest that anomalies in the deeper iron-rich horizons are considerably broader and stronger than those in the near-surface

soils (Figs. 51 and 54). The various factors thought to influence lateral dispersion in solonized brown soils are discussed below with special emphasis on their effects in the different soil horizons.

a) Inclination of Orebodies.

The weathering of the east-dipping reef-shear structures at Norseman could be expected to lead to assymetrical anomalies, broader on the western, or up-dip, side of the sub-outcrop. However, there is very little evidence to suggest that this is an important factor contributing to the width of the anomalies in near-surface soils. In the case of the Princess Royal traverse, the cxAs anomaly shows some assymetry but the westward prolongation might alternatively be related to the Tertiary period of deep lead formation. This interpretation however cannot be applied to the results for the Crown Reef traverse and the anomaly in this case shows no signs of assymetry. It is considered that the strong leaching of arsenic from the surface soils counteracts any tendency for accumulation of arsenic due to this cause.

b) Sheetwash.

There is considerable evidence to indicate that sheetwash is an active agent of erosion in the areas studied. However, since the effects of sheetwash are, for the most part, confined to the uppermost three

inches of the soil profile, which are usually depleted in arsenic by strong leaching, this can only have limited effect in creating a wider distribution of anomalous arsenic. The measurable effects of sheetwash would be further reduced by dilution with arsenic-poor soils and by subsequent leaching of any arsenical material transported by this means.

c) Movement of Ground-Water

It has been indicated previously that under the prevailing arid climatic conditions, ground-water movement is dominantly in a vertical direction. However, at times of heavy rainfall, it is possible that the basal clay-rich horizons may act as an impermeable barrier to the downwards percolation of water and limited lateral movement of water might take place for short periods. This is suggested by the fact that, the upper part of the clay horizons was almost invariably found to be moist and puggy when sampled, even in the dry season. If such lateral movement does take place, soluble and colloid-bound arsenate might be mobilized and transported some distance before being re-deposited. Such arsenic might be derived both from the surface, by leaching, and also from the deeper arsenic-rich clay horizon. Hydromorphic dispersion of this type could account for the very broad anomaly in the subsoils at the western end of the Crown Shear

traverse at 4550N (Fig.52).

d) Vegetation.

Although no experimental data were obtained, vegetation must be regarded as a possible means of redistribution of arsenic in soils. In view of the strong leaching of arsenic from the near-surface solonized brown soils, deep-rooted vegetation is likely to be most effective.

e) Chemical Migration of Arsenic.

It is theoretically possible that free arsenic ions could migrate laterally in the direction of decreasing concentration. However, the extent to which this process occurs, if at all, cannot be judged on the basis of the present results. In any case, it is believed that chemical migration would be subordinate to dispersion resulting from the other mechanisms suggested above.

3. Summary

The dispersion of arsenic in solonized brown soils appears to be dominated by the marked leaching of the surface horizons, which tends to limit and disguise the effects of lateral dispersion. Arsenic is believed to be transported principally as colloid-bound asenates. A minor amount of arsenic is probably mobilized as free arsenate ions in the surface soils, mainly as a result of the high pH levels. The

solubilizing effects of chelating agents and phosphates are presumably at a minimum due to the supposedly low concentrations of these substances in the soils. The abundance of neutral salts in these soils also reduces the solubility of arsenic.

The fixation of arsenic is accomplished by adsorption and chemical combination with iron oxides and by adsorption onto clay minerals. This is believed to be responsible for the two zones of maximum arsenic concentration observed in the soil profile. The main factor in the fixation of arsenic in the deeper horizons is undoubtedly the abundance of iron oxides, most of which is in very fine-grained form, favouring maximum adsorption. Clay adsorption appears to be the main cause of arsenic concentration in the near-surface calcareous soils. The increased anion exchange capacity of the clays in this horizon is considered to be due to the high pH levels but it is also possible that the precipitation of arsenates from ascending groundwater, as the result of evaporation, contributes to the concentration in this horizon.

Mechanical processes causing lateral dispersion in near-surface soils, such as soil-creep and sheetwash, appear to have had little effect, as witnessed by the limited breadth of the anomalies detected in samples from shallow depths. However, it

is possible that the arsenic which has been laterally translocated by these agents has been subsequently leached from the surface and has contributed to the apparently broader dispersion patterns in the deeper horizons. Lateral seepage dispersion during wet periods is also believed to play some part in the development of the broader anomalies in the clay-rich subsoils.

E. DISPERSION PROCESSES IN CALCAREOUS LATERITIC SOILS.

In assessing the effects of dispersion processes in calcareous lateritic soils, both the present semi-arid environment and the more humid environment which prevailed at the time of lateritization, must be taken into consideration.

1. Dispersion During Laterite-Formation

The high rainfall and low relief, believed to have characterized much of Western Australia during the period of laterite-formation, would have fostered conditions in which chemical dispersion processes were more prominent than mechanical processes. The main chemical factors affecting the mobility of arsenic during lateritization were presumably pH, active organic substances, and the presence of abundant iron and aluminium oxides and clay minerals.

The observed pH values in Western Australian

laterites (7.5 to 8.0) are consistent with the approximately neutral pH levels encountered in non-indurated lateritic soils found at the present time in sub-tropical and tropical Africa (James 1957, Mather,1959). Since these values are on the alkaline side of the solubility minima for iron and aluminium arsenates, a significant proportion of free arsenate ions would be expected.

In view of the high rainfall, the role of chelating agents in surface soils would have been considerably more important than in the present-day semi-arid conditions. This would tend to increase the mobility of arsenic. On the other hand, the effects of neutral salts and phosphates would have been at a minimum due to the extreme leaching.

The mobility of arsenates would have been limited by fixation by hydrated iron and aluminium oxides and clays, which were the main residual products of lateritic weathering.

In the profile, the distribution of arsenic was evidently dominated by the marked concentration of the element in the sesquioxide-rich laterite horizon (Fig.64). It is considered likely that this arsenic was derived both from the A horizon by leaching and from the C horizon by ascending ground-water during the dry season. Much of the arsenic may have been transported with the sesquioxide colloids but some was

no doubt in the form of free arsenate ions. The latter would have been readily adsorbed by the abundant sesquioxides on entering the B horizon. It is considered probable that much of the adsorbed arsenate was irreversibly fixed by chemical combination with the sesquioxides during the intermittent dry periods and subsequent period of aridity.

The concentration of arsenic in the mottled zone of the laterite profile is somewhat lower than in the sesquioxide horizon. It is probable that arsenic was fixed both in the ferruginous nodules and clay minerals present in this horizon. The results from Kalgoorlie and Ora Banda (Figs. 65 and 69) suggest that the tendency for arsenic to concentrate in the iron oxides rather than the clay minerals was less marked in the mottled zone than in the lateritic gravel. However, this may be due to the friable nature of the iron-rich nodules in the mottled zone, which on weathering, appear to readily disintegrate, releasing arsenical iron oxide particles in both the coarse and fine size ranges.

There is some evidence to suggest that considerable lateral dispersion of arsenic occurred during the period of lateritization. Mather(1959) found indications of lateral migration of the order of 500 feet in indurated laterite in Sierra Leone.

However, no definite conclusions could be drawn because of lack of knowledge as to the primary distribution of arsenic about the mineralized source. Although some idea of the extent of primary dispersion in the study areas described in this thesis was obtained by drilling, the full extent of the secondary dispersion pattern could not be assessed because of the lack of continuous laterite cover. At Coolgardie, the arsenic anomaly in laterite is greater than 500 feet in width, compared with a primary dispersion pattern approximately 100 feet in width. A primary anomaly approximately 150 feet wide has given rise to a secondary anomaly in laterite at least 600 feet in width in the Kalgoorlie study area. Despite the paucity of data, it is apparent that lateral dispersion of arsenic was more extensive during lateritization than it is in the present-day solonized brown soils. (The broad anomalies in solonized brown soils in the Surprise and Kalgoorlie laterite study areas are exceptional in that they result partly from the weathering of the broad anomalies in laterite which formerly covered the whole area).

Owing to the supposedly subdued topography, on which the laterites were formed, and the dense vegetation, sheetwash and soil creep presumably played only a small part in the lateral translocation of

arsenic. The most probable mechanism of lateral dispersion is believed to have involved the transportation of dissolved and dispersed arsenic by sluggish groundwater movement.

2. Dispersion Consequent on Weathering of Laterite Under Semi-Arid Conditions.

The indurated laterite resultant on the change to more arid conditions is highly resistant to weathering. This is evidenced by the characteristic occurrence of laterite as a protective capping on the elevated remnants of the "old plateau". Nevertheless, weathering and erosion under the present conditions appears to have caused partial disintegration of the upper part of the laterite horizon to form a shallow lateritic gravel horizon in place of the original sandy leached horizon, which in the areas studied, has been completely removed by erosion.

The breakdown of the tough laterite horizon is considered to have been achieved by mainly mechanical processes, the foremost of which was related to the extensive calcification of the upper part of the profile. The limited nature of the chemical breakdown of laterite is indicated by the marked concentration of arsenic in the coarse sesquioxide fragments in the lateritic gravel, with respect to the fine fractions and calcrete in this horizon.

Appreciable lateral dispersion of sesquioxide-bound arsenic appears to have taken place under the prevailing arid conditions. Sheetwash and soil creep are considered to be the most important factors involved. During the gradual erosion of the lateritic plateau, arsenic-rich sesquioxide fragments would migrate slowly in a downslope direction and accumulate around the base of the low laterite-capped hillocks. During the occasional downpours which occur, it is also probable that surface laterite fragments would be transported in a downslope direction by sheetwash. The effects of these processes can be inferred from the erratic distribution of arsenic in sesquioxide fragments collected from the surface at both Coolgardie and Kalgoorlie. In both areas, high values occur at the base-of-slope, in addition to the peaks over the anomalies established by deeper sampling. The anomalies obtained at depths of 6-12 inches were found to be more homogeneous and closely related arsenic-rich sources in the C horizon, as outlined by drilling.

F. DISPERSION PROCESSES IN RED AND BROWN HARDPAN SOILS.

A detailed discussion of the dispersion of arsenic in hardpan soils is not possible in view of the limited work carried out. However, the following comments may be made.

Although the pH levels in hardpan soils are probably slightly lower than those in solonized brown soils, in the absence of large concentrations of neutral salts, the chemical mobility of arsenic at Agnew should be at least comparable to that in other areas. This is supported by the fact that arsenic concentrations in the soils near mineralization are considerably lower than the concentrations encountered in primary dispersion studies ($\leqslant$400 ppm in soils, as against more than 6000 ppm in rocks). This indicates that, as at Norseman, the soils are generally depleted in arsenic with respect to the rocks from which they were developed, suggesting an overall leaching of arsenic during soil-formation.

It is reasonable to assume that as in the other areas studied, arsenic is fixed by both (a) adsorption and combination with iron(and aluminium) oxides and (b) adsorption by clay minerals.

From the work done, there appears to be no significant variation in the distribution of arsenic in the solum. The same may be said of copper and zinc in hardpan soils at Eulaminna, although in both areas there is an appreciable impoverishment of trace elements in the solum with respect to the bedrock. The lack of variation in the trace element content of the solum is believed to be due to the immature character of the soils in the areas studied, there being no visible

indications of horizon differentiation. There is therefore no tendency for the preferential concentrations of trace elements at any specific depth.

The work at Agnew suggests that very broad anomalies are developed in hardpan soils in the vicinity of mineralization, even though the chemical mobility of arsenic is unlikely to be appreciably greater than in solonized brown soils. A number of reasons can be advanced to explain this.

(i) The widths of the anomalies in residual soils may closely reflect very broad primary dispersion patterns in the underlying rocks. It was not possible to determine the full extent of primary dispersion at Agnew owing to the lack of suitable drill-core or cross-cuts but it was considered likely to be considerably in excess of the 40 feet established in diamond drill-hole A3 (Fig.47). This is suggested by the wide distribution of weakly anomalous values in soils, even upslope from the sub-outcrop (Fig.70). However, the broad local threshold could be explained in at least two other ways. (See (ii) and (iii) below).

(ii) The scattered remnants of the lateritic "old plateau" in the topographically subdued Agnew area and abundant ferruginous pisoliths in the soils suggest that the Emu Lode was formerly overlain by laterite and that the present land surface is only some

tens of feet, at the most, below the now-eroded laterite surface. It has been shown that broad anomalies were developed in lateritic soils at Coolgardie and Kalgoorlie and the anomalies in present-day soils after erosion of the overlying laterite are of similar widths. Thus, the broad anomalies at Agnew could be inherited from the weathering of broad anomalies in pre-existing lateritic soils.

(iii) The importance of flooding and saturation of the soils above the hardpan during the occasional periods of prolonged heavy rainfall has already been mentioned in connection with the genesis of these soils. It would seem quite possible that dissolved and dispersed arsenic might be transported laterally within the "perched" water-table that would exist during these periods.

(iv) Sheetwash has also been suggested as an important agent causing secondary dispersion. This process could be expected to be particularly effective in the areas studied in view of the shallow soils and apparent absence of surface leaching. The prominent stony pavement at the surface of hardpan soils attests to the action of sheetwash in selectively transporting the fine fraction of the surface soils. Sheetwash is considered to have been the dominant mechanism involved in the development of the erratic, assymetrical anomaly downslope from the Emu Lode (Fig.70).

G. DISPERSION IN DRAINAGE

Preliminary studies have shown that trace element anomalies can be detected in the active sediments of streams draining areas of anomalous soils.

The active stream sediments theoretically approximate to a composite sample of the soils occurring in the catchment area. This should be particularly true for the intermittent streams of semi-arid Western Australia. In view of the very few occasions when running water is present in the drainage channels and the short duration of these active periods, reactions between the water and the solid particles are unlikely to occur to any significant extent. Hence, the transportation of arsenic in the drainage channels of the area is believed to be effected almost entirely by the mechanical translocation of arsenic-rich soil particles.

Differences in the tenor and distribution of arsenic between stream sediments and soils are thought to be the result of selective transportation, leading to the sorting of drainage sediments. Stream sediments were generally found to be coarser in texture than soils, owing to the removal of the fine fractions in suspension, these being carried further and deposited in salt lakes. This tends to reduce the anomaly contrast shown in the -82 mesh fraction, by virtue of the relative increase of metal-poor quartz in this fraction.

Owing to the depth of the water-table, it must be concluded that sheetwash and bank erosion are the dominant mechanisms by which anomalous material is introduced into the drainage channels. The efficiency of sheetwash in contributing anomalous copper and zinc to the drainage has been demonstrated at Eulaminna and, although profile studies were not carried out at Norseman, it was shown that the bank soils nearest to the source of anomalous arsenic are higher in the element than the soils on the opposite bank.

The present studies were carried out on streams with very limited catchment areas. The size and relative proportions of anomalous and background soils in the catchment areas can have an important bearing on the nature of the anomalous drainage trains developed and further investigations should be carried out to fully assess the potential and limitations of drainage dispersion anomalies in the search for mineralized areas.

The anomalous dispersion pattern found in salt-lake sediments at Norseman may be explained in terms of two dominant mechanisms.

Firstly, during periods of prolonged heavy rainfall, the streams draining the area of anomalous soils, discharge their load of transported soil particles in a broad fan pattern over the surface of the lake. Coarse rock debris and sand are deposited first, generally within 100 feet of the debouchement, but

arsenic-rich silt and clay particles are dispersed over a wider area, thus accounting for the extensive anomaly shown by the -82 mesh fraction of the lake sediments (Fig.59).

Since the example studied lies near the western margin of the lake, the westward migration of the lake may also increase the areal extent of the anomaly, both as a result of increasing the east-west extent of the fan-out pattern and by actively eroding anomalous soils on the western shore. The latter process is believed to be the cause of the high values occurring within 100 feet of the edge of the lake nearest to the quartz vein complex (Fig.59). It should be noted,however, that the ground-water table comes to within inches of the surface in the salt-lakes and hydromorphic dispersion could account for this marginal concentration of arsenic. It has been pointed out that much of the arsenic released during the weathering of orebodies has been leached out of the soils and is probably dispersed in the ground-water.

Lake migration would, in theory, also increase the areal extent of anomalous fan-out patterns on the eastern sides of salt-lakes but the resulting anomalies may be largely buried by accumulations of wind-borne material.

Further hydromorphic dispersion of arsenic may take place after deposition in the salt lakes, as a

result of the high water-table. However, as the chemical environment within the salt lake has not been studied, no further comment can be made at this stage.

H. SECONDARY DISPERSION OF OTHER ANOMALOUS ELEMENTS

Although this study of secondary dispersion has been primarily concerned with arsenic, it is intended here to give a very brief review of the dispersion of the other elements showing anomalous distributions in the areas studied. Table 42 summarizes data relevant to the secondary dispersion of the elements As, Cr, Sb, Au, Ni, Cu and Zn, drawn from various sources (Rankama and Sahama, 1950; Hawkes and Webb, 1962; Dana, 1932; Zviagintzev, 1941; James, 1957).

1. Chromium and Antimony

Chromium and antimony show certain broad geochemical similarities to arsenic in that all three elements possess two possible oxidation states and relatively high ionic potentials (particularly in the higher states of oxidation). They therefore tend to occur as anions in environments of high Eh and pH.

It can be seen from Fig 76, that the chromate ion (CrO_4^{--}) could be present in the near-surface horizons of soils at Norseman, where pH is in excess of 8 and Eh is probably greater than +0.4 volts. Hawkes and Webb (1962) state that, in this form, chromium possesses considerable mobility. In the lower pH levels encountered in the deeper horizons Cr^{6+} would probably

TABLE 42. COMPARISON OF GEOCHEMICAL DATA FOR TRACE ELEMENTS ASSOCIATED WITH MINERALIZATION IN THE AREAS STUDIED.

PROPERTY	ARSENIC	CHROMIUM	ANTIMONY	GOLD	NICKEL	COPPER	ZINC
Atomic Number	33	24	51	79	28	29	30
Atomic Weight	74.9	52.0	121.8	179.8	58.7	63.5	65.4
Periodic Group	V	VI	V	I	VIII	I	II
Oxidation States	As^{3+} As^{5+}	Cr^{3+} Cr^{6+}	Sb^{3+} Sb^{5+}	Au^{+} Au^{3+}	Ni^{2+}	Cu^{+} Cu^{+}	Zn^{2+}
Ionic Radius (A^{o})	0.69 0.47	0.64 0.35	0.90 (0.62)	1.37 (?)	0.78	(0.96) 0.83	0.83
Ionic Potential	4.3 10.6	4.7 17.2	3.3 8.1	0.7 (?)	2.6	1.0 2.4	2.4
Primary Minerals	Arsenopyrite, FeAsS; Tennantite, $3Cu_2S.\ As_2S_3$	(?) substituted in silicate & oxide lattices	(?) Stibnite, Sb_2S_3; Tetrahedrite, $3Cu_2S.\ Sb_2S_3$.	Native Au and tellurides e.g. Calaverite, $Au\ Te_2$	Pentlandite, $(Fe\ Ni)_9S_8$, Associated with pyrrhotite	Chalcopyrite $CuFeS_2$	(?) Sphalerite ZnS
Secondary Minerals	Scorodite, $FeAsO_4.2H_2O$	(?)	(?)	Native Au	(?)	Native Cu, Cuprite, Cu_2O, Chalcocite, CuS, Malachite $CuCO_3.Cu(OH)_2$ Azurite $CuCO_3.Cu(OH)_2$	(?) Smithsonite $ZnCO_3$
Aqueous Phase (near-surface)	(AsO_2^-), AsO_4^{3-}	$CrO4^{2-}$	(?)	Complex ions, eg. $AuCl_4^-$, stable colloids, soluble organic complexes	(?) Ni^{2+}	Cu^{+}, Cu^{2+}, and soluble organic complexes	Zn^{++} and soluble organic comples.
Soil Phase	Limonite, clays	Limonite	(?) Limonite	Native gold (?) organic matter	Probably, limonite clays	Limonite, clays MnO_2 and organic matter.	Limonite, clays

revert to Cr^{3+} which has an ionic potential in the intermediate range (Krauskopf, 1955). Ions of intermediate ionic potential tend to be precipitated as insoluble hydroxides and chromium would therefore tend to concentrate with the secondary iron oxides in the deeper horizons. This is supported by experimental evidence from the Princess Royal traverse (Table 29), which shows that chromium has been leached from the surface horizons and re-deposited in the iron-rich bedrock.

Very little is known of the behaviour of antimony in the secondary environment. Goldschmidt (1954) states that trivalent antimony is more common in nature than the pentavalent form, despite the computed stability relations (Fig 76), which suggest that SbO_3^- should occur alongside AsO_4^{3-}. According to Goldschmidt's views, antimony would be expected to form insoluble hydroxides in soils. James (1957) found that antimony, in general, behaves similarly to arsenic in soils in the vicinity of gold mineralization in Rhodesia, but that antimony shows an even stronger tendency than arsenic to be fixed in iron-rich soils.

2. Gold

The results of the very limited amount of work done on gold dispersion in soils were inconclusive. Gold is believed to be fairly mobile in the secondary

environment under some conditions and geochemical methods using gold may yet prove to be effective in locating mineralization. However, further orientation work needs to be done, preferably in the vicinity of virgin orebodies. Because of the risk of contamination in the areas examined by the writer, sampling was only possible in the vicinity of sub-economic mineralization, where the gold concentrations in soils were too low to show significant dispersion patterns.

Many writers have drawn attention to the combined action of acids, oxidizing agents (such as MnO_2) and chlorides in mobilizing gold as the soluble chloro-aurate complex ($AuCl_4^-$). However, it can be seen from Fig.76, that this complex would have a very limited field of stability in soils and could only be important in the highly acid environments of oxidizing ore-bodies. Even then, gold may be precipitated by numerous minerals, sulphides being among the most effective (Zviagintzev, 1941).

According to Zviagintzev, the migration of gold as a colloid is far more probable. Sols of gold are essentially unstable in the presence of natural materials but stability may be achieved if "protective" colloids such as silica, hydroxides of iron etc., are present. Field and experimental evidence has also been brought forward to show that gold may be transported by solutions containing humic substances.

3. Nickel, Copper and Zinc

The behaviour of nickel, copper and zinc in the secondary environment differs from that of the other elements described in that they occur as cations, rather than anions. All three elements are highly mobile at low pHs but are hydrolysed at pHs approaching neutrality (5.5 for Cu^{++}, 6.5 for Ni^{++} and 7.0 for Zn^{++}). Thus the chemical mobilities of these elements are likely to be low in the areas studied, zinc being the most mobile. Copper ions are only likely to occur in solution in the near vicinity of oxidizing sulphides. The differing mobilities of zinc and copper are reflected in the results obtained at Eulaminna, where, although the sharply defined soil anomalies suggest minimal lateral dispersion, the geochemical profile for zinc is more homogeneous than that for copper, the distribution of which is highly erratic. Similarly, the zinc anomaly in the stream sediments at Eulaminna is also more homogeneous than the corresponding copper anomaly. The comparative homogeneity of the zinc anomalies is attributed to limited chemical translocation of zinc, tending to minimise the irregularities of the dispersion pattern.

All three elements are strongly sorbed by limonite and clay minerals. The high cation exchange capacities of the montmorillonitic clays occurring in the areas studied could lead to appreciable fixation by clays.

In addition, manganese oxide and carbonates have been cited as important precipitants of copper and zinc in various areas (Nicblls, 1964). Vegetation is known to take up appreciable quantities of copper and zinc and probably also nickel (Rankama and Sahama, 1950). This feature may be an important influence in controlling secondary dispersion.

In this study very little work was done on the secondary dispersion of nickel, apart from establishing the existence of narrow anomalies of low contrast, in the vicinity of Crown and Princess Royal Reefs at Norseman.

While zinc may be mobile to a limited extent at Eulaminna, it is considered that, because of the dry conditions experienced most of the year, very little hydromorphic dispersion takes place. Copper and zinc are more likely to be transported mechanically, in the form of copper and zinc-rich limonite, clays and cupriferous mineral fragments in soils. Dispersion in the drainage is also considered to be dominantly mechanical. The significance of sheetwash as the main factor contributing anomalous material to the drainage has already been mentioned.

CHAPTER 6. SUMMARY OF CONCLUSIONS

I. GENERAL

1. Arsenic was found to be a geochemical pathfinder for gold mineralization in five selected study areas occurring over a belt of auriferous country, three hundred miles in length, in Western Australia. Primary dispersion studies in three of these areas indicate a genetic relationship between anomalous arsenic and gold which probably holds for the whole of the area under consideration.

2. Anomalous arsenic dispersion patterns related to gold mineralization can be detected in rocks, various types of soils (including relict lateritic soils) and stream and salt-lake sediments by systematic sampling and rapid semi-quantitative analytical techniques.

3. Although the main features of the dispersion patterns are broadly similar in all areas, the details differ according to the nature of the geology, mineralization and soil-type. The results obtained and conclusions reached for each environment are summarized in the following pages.

II. PRIMARY DISPERSION.

A. NORSEMAN

1. Strong arsenic anomalies, generally between 40 and 100 feet in width and with average contrast of approximately 50 (with respect to local threshold),

occur in the wall-rocks adjacent to gold-quartz orebodies in flatly-dipping reverse shears.

2. The anomalies persist in the form of leakage halos for considerable distances along the shear structures, up-dip from blind orebodies. The leakage anomaly associated with a major blind orebody on Crown Reef-Shear can be detected in soils over the sub-outcrop of the shear, 2000 feet up-dip from the ore zone.

3. Barren sections of the ore-bearing shears, along-strike from orebodies are characterized by weaker anomalies (average contrast = 7). These sections can nevertheless be distinguished geochemically from outwardly similar, but non-auriferous shears, since the latter are accompanied by near-background arsenic concentrations.

4. The anomalous arsenic in the wall-rocks occurs in the form of finely disseminated arsenopyrite, which is believed to have been introduced during, or immediately prior to, the emplacement of the gold-quartz reefs.

5. The form and magnitude of the anomalies appears to have been controlled by a combination of factors, including the nature of the original rock-types, the extent and intensity of shearing, and whether the shear was locally dilational or compressive.

6. Although the arsenic anomalies often appear to coincide with the zone of mineralogical wall-rock alteration, the two features are not closely

inter-related. The type of wall-rock alteration encountered in reef-shears is widely distributed throughout the area and, unlike arsenic anomalies, is not restricted to ore structures. The wall-rock alteration stage is believed to have preceded the development of arsenic anomalies.

7. In addition to arsenic, Ni, Cr, Co, Cu, Zn, Mn, and Sb were all found to form anomalous dispersion patterns in the vicinity of reef-shears. Of these, only Ni and Cr (which show the strongest anomalies) were studied in any detail.

8. Nickel is concentrated dominantly in pyrrhotite in the wall-rocks and is believed to have been introduced with, or slightly after, arsenic. Nickel anomalies are best developed in the vicinity of the Crown Reef-Shear, where they generally reflect the nature of the corresponding arsenic anomaly. The concentration of nickel in pyrrhotite in the wall-rocks shows a marked increase on approaching the Crown Reef and may form anomalies measurable in hundreds of feet.

9. Chromium anomalies were found to occur in most of the reef-shear intersections examined, as well as in a number of non-auriferous shear zones. The poor correlation of chromium anomalies with those of arsenic and nickel, and the high chromium contents of the secondary silicates in the altered wall-rocks suggest that chromium was introduced during the wall-rock

alteration stage, which probably preceded the formation of arsenic-nickel anomalies and gold mineralization.

10. The features of the wall-rock and leakage anomalies suggest an origin involving the movement of hydrothermal fluids up the inclined permeable shear zones. Infiltration is believed to have been the dominant mechanism, but diffusion must be invoked to account for the penetration of small quantities of anomalous material into the massive impermeable rocks outside the shear zone.

11. As, Pb, Ag, and Zn were concentrated with gold in the ore-shoots within the quartz reefs, although no direct relationship between the concentrations of these elements and the grade of ore appears to occur. The concentrations of arsenic and nickel in the actual quartz reef, although generally much lower than the average for the sheared wall-rocks, are higher than in background greenstones, implying a genetic relationship between the wall-rock anomalies and the gold mineralization. Silver and lead are, on the average, more abundant in the quartz than either the wall-rocks or background greenstones. The absence of wall-rock anomalies for these elements and comparatively low concentrations of arsenic in the quartz, and greenstones immediately adjacent to the reefs, suggest the emplacement of the quartz reefs later than the wall-rock anomalies (see page 163).

12. The trace element data are generally consistent with the hypothesis that the orebodies are dominantly of hydrothermal origin and were genetically related to the "Younger Greenstone" magma. However, the possibility that some of the elements concentrated in the vicinity of the reef-shears were mobilized from the country rocks is not excluded.

B. KALGOORLIE.

1. Arsenic anomalies were found to occur in the wall-rocks adjacent to all the major auriferous lodes studied.

2. The concentration of arsenic varies between 30 and 100 ppm in anomalous wall-rocks, but higher concentrations are associated with major lodes and minor mineralized shears.

3. There appears to be a quantitative relationship between arsenic and gold in the Perseverance Lode, although the present results do not suggest that the relationship is the same for different lodes within the "Golden Mile."

4. The anomalous arsenic present in the Perseverance Lode occurs almost entirely in the form of tennantite, which is a common constituent of many Kalgoorlie lodes. Arsenopyrite is comparatively rare at Kalgoorlie, but may contribute some of the anomalous arsenic, particularly in the minor mineralized shears.

5. The widths of anomalies are highly variable and appear to be related to local variations in the intensity of

mineralization. The data obtained suggests the existence of very extensive anomalies of low contrast in the most intensly mineralized parts of the lode complex.

6. The variation in the widths and contrast of wall-rock anomalies were found to be similar for the different lode-types and in different host-rocks.

7. The magnitudes of wall-rock anomalies are apparently unrelated to the grade of ore in the lodes.

8. In addition to arsenic, anomalous dispersion patterns were found for mercury and gold in the wall-rocks. The data obtained in the vicinity of the Lade View Lode suggest that the lateral dispersion of gold was more limited in extent than that of arsenic or mercury, but the full extent of the anomalies for the latter two elements has not been established.

C. AGNEW.

1. Preliminary studies showed the existence of very strong arsenic anomalies of undisclosed width in the wall-rocks associated with the Emu Lode.

2. The general level of arsenic concentration is higher than at Kalgoorlie or Norseman. There appears to be a close correlation between the concentrations of arsenic and gold in the mineralized chlorite-actinolite schist horizon.

3. The anomalous arsenic occurs as arsenopyrite, coarse crystals of which are abundant in the wall-rocks and quartz veinlets.

III. SECONDARY DISPERSION IN SOILS.

A. SOLONIZED BROWN SOILS.

1. The solonized brown soils of semi-arid Western Australia are characterized by marked accumulations of lime in the profile (with associated highly alkaline soil reaction), the frequent development of iron-rich clay subsoils, and abundant soluble salts.

2. Arsenic anomalies were established in residual solonized brown soils in the vicinity of sub-outcropping orebodies and arsenical structures related to gold mineralization.

3. The highest concentrations of arsenic in soils are associated with secondary iron oxides in the coarse sand and silt fractions. Lower arsenic concentrations occur in the clay fractions, although the clay-bound arsenic comprises a considerable proportion of the total arsenic present in the near-surface calcareous horizon . Arsenic shows no tendency to concentrate in calcium carbonate.

4. Cold-extractable arsenic shows maxima in the clays and certain of the coarse fractions, reflecting respectively the relatively high proportion of adsorbed arsenic associated with the clays, and the complete attack achieved by the cxAs technique for the minor amounts of arsenic associated with carbonates in the sand-sized material.

5. Comparison of the arsenic data for soils with the results of primary dispersion studies at Norseman suggests that considerable leaching of arsenic has taken place during weathering and soil formation.

6. The distribution of arsenic with depth in the profile of the solonized brown soils is highly variable and appears to be mainly controlled by the abundance of secondary iron oxides and pH. The profile is generally characterized by a leached surface horizon (0-6 inches depth) with marked concentrations of arsenic both in the near-surface calcareous horizon (3-24 inches depth) and the basal iron-rich clay horizon (and/or the weathered bedrock).

7. The concentration of arsenic in the calcareous horizon is considered to be due mainly to "activation" of clays as a result of the high pH of the soils at this depth. Precipitation of arsenic as a result of the evaporation of ascending ground-water may be a minor contributory factor.

8. The concentration of arsenic in the deeper horizons is attributable to adsorption and combination with the abundant secondary iron oxides present.

9. Mechanical dispersion processes affecting near-surface soils such as soil creep, the weathering of inclined orebodies, and sheetwash, appear to have had little effect, in view of the limited lateral extent of

anomalies. This is partly due to the fact that the surface soils are generally low in arsenic and partly the result of further leaching of arsenic transported by these agencies.

10. Broader anomalies appear to be developed in the deeper horizons, partly as the result of the fixation of arsenic which has been transported by the agencies mentioned in 9 above and subsequently leached from the surface. Hydromorphic dispersion, taking place in a perched water-table during occasional wet periods, may also contribute to the observed broad anomalies in the subsoils.

11. Arsenical felsitic porphyries and contamination from mine dumps and smelter fumes may give rise to spurious anomalies in soils. The effects of mine dumps appear to be restricted to the near-surface soils within a radius of approximately 25 feet of the source. Smelter fumes affect near-surface soils for considerably greater distances, probably measurable in miles. Anomalies due to arsenical porphyries may not be entirely spurious, in that, at Norseman, they appear to be genetically related to gold mineralization. However, until more data are obtained regarding the spacial relationship between the porphyries and orebodies, the anomalies due to this source may lead to erroneous interpretations of geochemical prospecting data.

B. CALCAREOUS LATERITIC SOILS.

1. The calcareous lateritic soils are modified latosols occurring as elevated remnants of a former Tertiary peneplain. They consist of a thin surface horizon of lime-rich lateritic gravel, overlying an indurated, ferruginous laterite horizon, which is underlain successively by a mottled zone, kaolinized zone and finally fresh parent rock. In some areas the lateritic soils are gradational towards solonized brown or hardpan soils, the character of the intermediate soil-types depending largely on the depth to which the laterite profile has been eroded.

2. Anomalies related to arsenical bedrock sources can be detected in the near-surface horizons of calcareous lateritic soils, despite the depth of weathering, which commonly exceeds 50 feet.

3. In the surface lateritic gravel horizon, arsenic shows a marked tendency to concentrate in the coarser fractions, in which it is closely associated with the ferruginous sesquioxides, presumably occurring as scorodite ($FeAsO_4$). Only minor amounts are associated with the abundant calcrete, but much of this arsenic is solubilized by dilute acids, thus accounting for the relatively high cxAs/total As ratios in some of the coarse fractions. In the fine fractions of the lateritic gravel, the maximum concentrations of arsenic occur in the iron-rich

silt fraction with lesser concentrations in the clay fractions. An appreciable proportion of the arsenic present in the silt and clay fractions is in absorbed form, as evidenced by the relatively high cxAs/total As ratios.

4. The tendency for arsenic to concentrate in the coarse ferruginous pisoliths with respect to the finer fractions of soils developed on the mottled zone is less marked than in the soils directly overlying indurated laterite. This may be an original feature of the arsenic distribution in the laterite profile or possibly due to the partial disintegration of the friable pisoliths of the mottled zone during weathering.

5. In the profile, arsenic concentrates mainly in the indurated laterite horizon, which is the locus of maximum iron concentration. pH shows only minor fluctuations with depth, varying between 7.3 and 8.0.

6. The anomalous dispersion patterns formed during laterite-formation were more extensive than those encountered in present-day solonized brown soils. Arsenic is believed to have been more mobile under conditions of lateritic weathering and lateral translocation within the shallow water-table was probably the dominant mechanism of lateral dispersion.

7. Although anomaly contrast is similar for both the +20 mesh fraction (dominantly ferruginous laterite fragments) and the -80 mesh fraction of the lateritic gravel, the

anomalies shown by the coarse material are more homogeneous and show better definition. The anomalies in the near-surface lateritic gravel closely reflect arsenic distribution in the indurated laterite horizon and are spacially related to the underlying bedrock source.

8. Anomalies are detectable in samples of laterite fragments collected on the daylight surface. However, the geochemical profiles for this material are more erratic and not so closely related to the bedrock source, owing to the lateral translocation of these fragments by soil creep and sheetwash.

9. Although the anomaly studied at the Surprise Area, Coolgardie, was shown by drilling to be related to gold mineralization, the Kalgoorlie example appears to be related to a non-auriferous but arsenical bedrock source. However, sulphate analyses indicated that sulphide mineralization is present in the Kalgoorlie study area and, in view of the results of primary dispersion studies at Norseman, the possibility that the anomaly is related to gold mineralization at depth cannot be dismissed.

C. RED AND BROWN HARDPAN SOILS

1. The red and brown hardpan soils are immature soils characterized by stony surface pavements and the presence of a siliceous hardpan formation at the base of the solum.

2. Strong arsenic anomalies are detectable in the -82 mesh fraction of soils in the vicinity of arsenical gold mineralization.

3. The concentration of arsenic (and copper and zinc) shows no significant variation with depth in the profile, apart from the fact that the soils are, on the whole, depleted in arsenic with respect to the rocks from which they were developed. The lack of variation in the solum is attributed to the absence of horizon differentiation in the soils.

4. The broad anomalies in soils in the vicinity of mineralization may be due to one or more of the following:
   (i) broad primary dispersion patterns,
   (ii) the weathering of anomalous laterites, which formerly blanketed the area,
   (iii) lateral dispersion in perched ground-water, during occasional periods of prolonged heavy rainfall,
   (iv) sheetwash.

5. Although weak arsenic anomalies were found to occur in soils in the vicinity of a base metal deposit at Eulaminna, stronger anomalies are shown by copper and zinc. Concentration maxima for these elements occur in both the coarse and fine fractions of the soils, the -82 mesh fraction giving satisfactory results for prospecting purposes. The nature of the geochemical profile indicates that copper has negligible chemical mobility, but very limited saline dispersion of zinc may take place. The dominant dispersion processes, however, are mechanical, i.e. sheetwash and soil creep.

IV SECONDARY DISPERSION IN DRAINAGE

1. Trace element anomalies (As, Cu, and Zn) can be detected in the active sediments of intermittent streams draining areas of anomalous soils.

2. Drainage dispersion processes in the area studied are dominantly mechanical for these elements.

3. Anomalous material is contributed to the drainage mainly by sheetwash and bank erosion.

4. Anomaly contrast in the -82 mesh fraction of stream sediments is generally lower than in soils due to the selective removal of metal-rich fines during transportation. Contrast is further reduced down-stream from confluences with background drainage channels, presumably as a result of dilution.

5. Broad dispersion patterns are present in salt-lake sediments in the vicinity of the debouchements of anomalous drainage channels. The anomalies are largely due to the fan-out of anomalous material contributed by the drainage but the extent of the anomalies is increased by the general westward migration of the lakes and possible redistribution within the lake as a result of the sluggish intra-lake drainage during periods of exceptionally heavy rainfall.

6. In the example studied at Norseman, the erosion of anomalous bank soils on the western margin of the lake probably contributes some anomalous arsenic. The relatively high arsenic concentrations at the western

margins of the lake may also be partly of hydromorphic origin, due to the emergence of arsenic-rich ground-water near the surface of the salt-lake, which coincides very nearly with the water-table.

CHAPTER 7. APPLICATION OF THE GEOCHEMICAL DATA TO PROSPECTING IN WESTERN AUSTRALIA

I. ROCK-SAMPLING SURVEYS

1. Scope.

The results of primary dispersion studies indicate that rock-sampling surveys may provide useful information with regard to prospecting in all three areas studied. The nature and significance of the geochemical dispersion patterns related to mineralization, however, differ in each area, apparently reflecting fundamental differences in geology and the nature of the mineralization. Consequently, the purpose and interpretation of geochemical prospecting investigations must be based on appropriate orientation surveys in each area.

At Norseman, rock-sampling surveys could have considerable application in the current deep exploratory drilling programme, testing for new orebodies on known reef-shears and possible new reef-shears. In particular, the results indicate that ore-bearing shears can be distinguished geochemically from outwardly similar, but non-auriferous shear zones and quartz intersections, even where assay data are inconclusive. This fact could be an appreciable aid to structural interpretation where the positions of reef-shears are not accurately known. Moreover, the magnitude of the anomalies (preferably expressed as an average value for the whole anomalous zone) may indicate the direction in which ore occurrences are likely to be found. Since the presence of strong and extensive leakage

halos has been established up-dip from three orebodies on known reef-shears, isolated strong drill-hole anomalies should be followed up by more intensive prospecting down the dip of the structure. It is suggested that the present study should be extended by geochemical sampling of all the drill-core obtained in the past at Norseman. Apart from the fact that such a study might possibly bring to light orebodies which were narrowly missed by past drill-holes, the results would provide a firmer basis for the programming and interpretation of future exploration. Sampling should be concentrated in the vicinity of shear zones and quartz intersections, but widely spaced samples should also be taken over the whole length of drill-holes to further investigate the nickel content of pyrrhotite as a possible means of locating reef-shears.

Further orientation work needs to be done at Kalgoorlie and Agnew to assess fully the potential of primary dispersion patterns as a guide to mineralization in these areas. However, the preliminary results suggest that arsenic determinations on samples from exploratory drill-cores and cross-cuts may give some indication as to the proximity of mineralization. A geochemical re-examination of unsuccessful drill-holes and cross-cuts may indicate some areas where further exploration is warranted. Moreover, in view of the gradational lode boundaries and close relationship between arsenic and gold in mineralized rocks, arsenic determinations may serve as a useful adjunct to the test by assay.

The broad anomalies about the closely spaced lodes near the centre of the Kalgoorlie field suggest that there may be a large-scale geochemical anomaly associated with the Golden Mile mineralization as a whole, within which the profiles associated with individual lodes are only minor features. This could be very important with regard to exploratory drilling for a blind repetition of the Kalgoorlie ore position along the strike. It is suggested that a series of east-west sampling traverses across the whole lode complex should be carried out at varying depths and distances along the strike to test this hypothesis.

2. Techniques.

a) Sampling Procedure.

Since in most cases anomalies are measurable in tens of feet, sample intervals of 5 or 10 feet should normally be adequate to detect wall-rock anomalies. Sample intervals should be varied to ensure that each sample consists of only one rock-type. Mineralized faults and shears should be sampled separately. Broader sample intervals (up to 50 feet) may be used in testing the major dispersion pattern at Kalgoorlie and for the study of the broad dispersion pattern shown by nickel in pyrrhotite at Norseman. In each case the samples should be made up of a series of small chips taken over the whole interval.

b) Sample Preparation.

Initially rock samples should be jaw-crushed and representative portions of the material obtained

pulverized for analysis. The pulverization stage may be satisfactorily carried out by means of ceramic ball mills. However, greater productivity may be achieved using a disc pulverizer with ceramic plates or a Siebtechnik rotary or swing mill. Both types of equipment can be quickly and efficiently cleaned between samples, and the latter, particularly, has been found to give optimum reproducibility of grind.(Rawling and Greaves, 1964). The writer found that 10 g. portions of jaw-crushed material were pulverized in less than 30 seconds in the Siebtechnik mill and the disadvantages inherent in the ball mill method, such as compacting of the sample and the small load handled (and hence poor representativity), were avoided. A rapid preliminary assessment of the wall-rock patterns may be made by analysing the -82 mesh fraction of jaw-crushed material, thus reducing the time and work involved.

c) Analysis.

All wall-rock samples should be analysed for arsenic, which was found to give consistently good results in all three areas. In addition, other trace elements may give useful information in specific areas, such as nickel at Norseman and mercury at Kalgoorlie. Further research may indicate that other elements show significant dispersion patterns at Kalgoorlie and Agnew. At Kalgoorlie particularly, the potential of copper, tellurium and antimony as pathfinder elements should be investigated, since minerals containing these elements are frequently associated with lodes. In new areas, preliminary work

should include the spectrographic analysis of selected traverses in order to determine the trace elements showing significant dispersion patterns near mineralization. In routine analysis, the work involved can be greatly reduced if more than one element can be determined from the same sample attack. The bisulphate attack appears to give satisfactory results for arsenic, nickel, copper (and probably antimony) in wall-rock samples.

II. SOIL SAMPLING SURVEYS

1. Scope.

The present results indicate that soil sampling surveys may be of considerable use in the search for mineralization in areas of residual overburden. It is clear from the investigation of primary leakage halos at Norseman, that significant arsenic anomalies in soils need not necessarily be accompanied by gold in the weathered bedrock, even when blind orebodies are present at depth. In many such cases interpretation may be aided by investigations of the soil anomalies by geophysical methods. Geophysics may also be useful in eliminating spurious anomalies due to arsenical but non-auriferous bedrock sources. In some cases, spurious anomalies may be distinguished geochemically by analysing for other elements besides arsenic. For example, the arsenical porphyries at Norseman were almost always found to have very much lower nickel and chromium contents than the rocks in the vicinity of the ore-bearing shears, and analysis for these elements may aid the recognition of

such features.

The possibility of contamination must also be borne in mind when working in areas where mining has been carried out in the past. The results to date indicate that spurious anomalies due to contamination can be avoided by careful selection of sampling depths, based on studies of the extent of contamination from any probable sources.

It should be stressed that the present studies were confined to areas of residual soils and that the following recommendations are not necessarily applicable to the extensive areas of alluvial soils present in the Western Australian goldfields. Further research needs to be done in these areas, and in localities where the Precambrian is overlain by a thin veneer of post-Cambrian sediments, (as in the Agnew and Princess Royal areas) to assess the effectiveness of soil-sampling surveys in these types of terrain.

2. Techniques.

a) Sampling Procedure.

A consideration of the widths of anomalies encountered in the solonized brown soils indicates that an interval of 50 feet should be adequate for detecting geochemical anomalies in most cases. A broader interval, e.g. 100 feet, may be used at Agnew and in areas of lateritic soils since the anomalies appear to be considerably broader in these areas. Samples should be collected along traverses normal to the prevailing strike direction

of mineralization, where this is known, the spacing between traverses being such that any potentially interesting anomalies would be intersected by at least two traverses. Any anomalies encountered should be followed up by closer sampling, together with more detailed sampling of the full soil profile to accurately pinpoint the bedrock source.

The results obtained suggest that samples taken at depths of 6 to 12 inches would be adequate for routine prospecting in areas of lateritic and hardpan soils. Similar depths were found to give satisfactory results in solonized brown soils where the soil cover is relatively thin. However, in the deeper solonized brown soils, anomalies may not always be detectable in the near-surface horizons, e.g. the anomaly at the western end of the traverse over the Crown Shear at Norseman (Fig.52). The results obtained show that anomalies sometimes occur in the near-surface calcareous horizon, and a composite sample of this horizon to a depth of approximately four feet, (obtained by means of a bucket auger) might be satisfactory for detecting anomalies in these soils. However, until more data is obtained, full sampling of the profile to the top of the red-brown clay horizon is recommended. This would entail sampling to depths of up to 15 feet. In view of the high labour costs in Australia, a vehicle-mounted mechanical auger would probably be the most satisfactory compromise between economy and the effectiveness of the survey. Each horizon should be sampled separately, major horizon changes usually being

easily recognisable on the basis of colour and texture.

b) Sample Preparation.

As a general rule, the -82 mesh fraction of soil samples should be taken for analysis as this fraction gives good anomaly contrast in all soil-types. However, in laterite-covered areas, the +20 mesh fraction appears to give better results and it is recommended that both the +20 and -82 mesh fractions be analysed. The +20 mesh fraction requires pulverization, which may be carried out by the methods used for rock samples.

c) Analysis.

In prospecting for gold in these areas, all samples should be analysed for arsenic. Additional elements which may be useful in specific areas, include nickel, chromium and antimony, at Norseman, and copper and zinc, at Eulaminna. Cold-extractable techniques may be used, in the field if required, to make a rapid appraisal of samples prior to confirmatory determinations by the total method. In some cases, e.g. at Norseman, cold-extractable analyses may even show better anomaly contrast than the results obtained by "total" methods, depending apparently on the mode of occurrence of the element sought.

III. DRAINAGE SURVEYS

1. Scope

Systematic sampling of stream and salt-lake sediments would appear to have considerable potential in the search for mineralized areas in Western Australia. More detailed research needs to be done on the effect of the size

of catchment area on the length and contrast of the anomalous drainage train in stream sediments and the extent and contrast of the anomalies in the salt-lakes. However, if early indications are confirmed, it might be possible to delineate areas of maximum interest by sampling salt-lake sediments near the mouths of drainage channels. In this way large areas could be covered very quickly since the salt-lake surface at the margins is hard enough in summer for wheeled vehicles to be used. Anomalies in the salt-lakes would be followed up by stream sediment sampling along the anomalous drainage channels. The bedrock source could then be located more accurately by soil sampling in the vicinity of the anomaly cut-off in the stream sediments.

2. Techniques.

a) Sampling Procedure.

It is recommended that salt-lake sediments should be sampled at 100 feet intervals along parallel traverses 100 and 300 feet from the shores where streams enter the lake. Traverses should extend 500 feet each side of the debouchement. Although the optimum sampling depth has not been determined, samples from 6 to 12 inches depth, obtained by means of a hand auger, appear to give good results.

Active stream sediments should be sampled just above confluences and otherwise at intervals of 500 feet. In the vicinity of the anomaly cut-off in the drainage channels, closer sampling should be carried out and

samples of bank soils taken to determine the direction from which anomalous material is entering the drainage.

b) Sample Preparation.

The present results indicate that adequate contrast is shown by analysing the -82 mesh fraction of both types of sediment. However, more detailed work may show that stream sediment anomalies may be better shown by using the coarser fractions, particularly in lateritic areas, where arsenic is strongly concentrated in the coarse ferruginous laterite fragments, which are highly resistant to abrasion during transportation.

c) Analysis.

Analytical techniques would be essentially the same as those suggested for soil samples.

CHAPTER 8. RECOMMENDATIONS FOR FUTURE RESEARCH

1. It is recommended that the present study of primary dispersion at Norseman be extended by studying arsenic and nickel dispersion patterns associated with quartz and shear intersections in all past drill-holes, thereby providing a better basis for the interpretation of future drilling results. As mentioned earlier, this could form part of a general programme, one of the objects of which would be to re-assess the prospects of areas abandoned on the results of past drilling.

2. Further studies should be made of the nickel content of pyrrhotite as a possible broad-scale guide to ore-bearing reef-shears at Norseman.

3. A detailed investigation of the petrology, structure and geochemistry of the porphyry bodies at Norseman (and other auriferous areas) is recommended in an attempt to establish their relationship, if any, to gold mineralization. Particular emphasis should be placed on the spacial relationships between arsenical porphyries and reef-shears, to assist in the interpretation of soil anomalies related to porphyries.

4. Further orientation work is needed in the study of primary dispersion at Kalgoorlie. In particular, the possible existence of very broad primary arsenic and mercury anomalies associated with the whole lode complex should be tested. A series of long sampling traverses across

the mineralization is suggested, to study the variation in the major pattern along strike and down dip.

5. The primary distribution patterns of antimony, copper and tellurium in the vicinity of mineralization at Kalgoorlie should be investigated to determine if additional pathfinder elements might provide useful data for prospecting purposes.

6. Further study of the distribution of arsenic in deep solonized brown soil profiles is recommended, with the object of developing a more rapid and economical prospecting procedure in this type of overburden. An investigation of the origin of the anomaly in the subsoils at the western end of the Crown Shear drilling traverse (Fig.52), which is not expressed in the near-surface calcareous horizon, would be important in this respect. Bedrock sampling should be carried out to establish whether this anomaly is superjacent or laterally displaced from its bedrock source. Phosphate and organic carbon analyses may help to assess the importance of leaching in accounting for the apparent impoverishment of the lime-rich horizon over the anomaly.

7. The applicability of geochemical prospecting methods in areas of transported overburden should be investigated. Biochemical prospecting may be found to be useful in this connection and it is suggested that the arsenic content of vegetation samples should be studied in the vicinity of known orebodies and in background areas.

8. As mentioned in the last chapter, more detailed studies of drainage dispersion patterns need to be made to confirm the applicability of the present conclusions under a wider variety of conditions. In particular, the particle size distribution of arsenic in stream sediments, and the variation in the nature of the dispersion trains in streams draining catchment areas of different sizes, should be further investigated.

9. Although the present results regarding the dispersion of gold were not very encouraging, further research, preferably in the vicinity of virgin orebodies, might be rewarding. In its present form, the analytical technique (see Appendix) is probably too slow to be an economical proposition in large scale soil and drainage surveys, but gold determinations might be useful to confirm anomalies established by analysing for other pathfinder elements. Further analytical development should be aimed at increasing the productivity of the method.

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APPENDIX

I. DETAILS OF ANALYTICAL TECHNIQUES

A. DETERMINATION OF ANTIMONY

1. Procedure:

a) Weigh 0.5 g. of sieved sample into a Pyrex test tube (18 x 180 mm.).

b) Mix thoroughly with 1 g. of ammonium chloride.

c) Heat until all the ammonium chloride has sublimed.

d) Allow to cool, add 5 ml. of 6M-hydrochloric acid, and heat until the sublimate has dissolved.

e) Mix well and allow to cool and settle.

f) 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.

g) Add 0.1 ml. of sodium nitrite and mix.

h) Dilute to 10 ml. with sodium hexametaphosphate solution.

i) Add 1 ml. of 0.05% brilliant green solution and shake vigorously for 90 sec.

j) Compare with standards.

k) If greater than the top standard, dilute with toluene until within the range.
Antimony in ppm. = 5 x (µg.of matching standard) x (ml. of solvent phase).

2. 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 µg. 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 sodium hexametaphosphate solution. Add 1 ml. of 0.05% brilliant green solution and shake vigorously for 90 seconds.

3. Reagents:

a) Ammonium chloride: A.R.

b) 6M-hydrochloric acid: mix 240 ml. of the concentrated acid (sp.gr. 1.18) with 200 ml. of water.

c) Sodium nitrite solution: dissolve 25 g. in 500 ml. of water.

d) Sodium hexametaphosphate solution: dissolve 80 g. of sodium hexametaphosphate in 1 litre of water.

e) 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.

f) Toluene: shake one litre of sulphur-free grade with 10 ml. of 1N potassium dichromate, discard the aqueous phase, and wash the toluene four times with 500 ml. quantities of water. Pass the toluene through a filter paper to remove water.

g) 1 N potassium dichromate: dissolve 49 g. of potassium dichromate (A.R.) in one litre of water.

h) 1% brilliant green solution: dissolve 1 g. of brilliant green in 100 ml. of ethyl alcohol (absolute). Store in the dark.

i) 0.05% brilliant green solution: dilute 5 ml. of the 1% solution to 100 ml. with toluene. Prepare freshly each week and store in the dark.

4. Remarks:

a) The range covered is 0.2 -110ppm as described, but it may be extended to 2200 ppm by using an aliquot 0.1 ml.

b) Results may be obtained within ± 25% at the 95% confidence level over the range 0.2 - 2200 ppm

c) If 1 ppm is an adequate sensitivity, take 0.2 g. at stage a) and use a 10 ml. leach at stage d) of the procedure.

d) 100 samples can be analysed per man-day of 8 hours.

e) For further information refer to R.E.Stanton and A.J. McDonald, Trans. Instn. Min.Metall., Lond., 1961-2, 71, 517-522.

B. DETERMINATION OF ARSENIC

1. Procedure:

a) Weigh 0.1 g. of sieved sample into a pyrex test tube (18 x 180 mm.).

b) Mix with 0.5 g. of potassium bisulphate and fuse.

c) Leach with 5 ml. of 1M-hydrochloric acid.

d) Pipette a 1 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.

e) Dilute to 10 ml. with 0.75% stannous chloride solution.

f) 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.

g) Leave for one hour, then remove the mercuric chloride paper and compare with artificial standards

Arsenic in ppm = 50 x µg. of arsenic in matching standard.

2. Standards:

Pipette four aliquots each of 0, 0.1, 0.2, 0.3, 0.4, 0.6, 0.8 and 1.0 ml. of standard arsenic solution (5 µg. 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 f) and g) 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.

3. Reagents:

a) Potassium bisulphate: fused, powder.

b) 1M-hydrochloric acid: mix 40 ml. of acid (sp.gr. 1.18) with 400 ml. of water.

c) 2.5% potassium iodide solution: dissolve 10 g. of crystals in 400 ml. of water.

d) 10% stannous chloride solution: dissolve 25 g. of the dihydrate in 250 ml. of concentrated hydrochloric acid.

e) 0.75% stannous chloride solution: mix 75 ml. of the 10% solution with 375 ml. of concentrated hydrochloric acid and 550 ml. water. Do not keep this solution for longer than two days.

f) Lead acetate solution: dissolve 15 g. of the trihydrate in 100 ml. of water containing 1 ml. of glacial acetic acid.

g) Standard arsenic solutions: 100 ug. of arsenic per ml. - dissolve 42 mg. of sodium arsenate ($Na_2HAsO_4,7H_2O$) in water, add 0.1 ml. of concentrated hydrochloric acid and dilute to 100 ml. with water.

5 ug. of arsenic per ml. - dilute 5 ml. of the 100 ug. per ml. solution to 100 ml. with water. Make up this solution only when it is needed to prepare or check standards.

h) Mercuric chloride papers: Commercially available.

i) 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 its length.

j) Zinc: pellets, activated with copper, A.R.

k) Paints: Winsor and Newton's water colours: lemon yellow, aurora yellow, and yellow ochre provide an adequate range of colour for the preparation of artificial standards.

4. Remarks:

a) The range covered is 5-250 ppm as described above, but this may be extended to 2500 ppm by using an aliquot of 0.1 ml.

b) Results within ± 25% confidence level may be obtained over the range 5-2500 ppm.

c) 80 samples can be analysed per man-day of 8 hours.

d) For further information refer to R.Stanton. Econ. Geol., 1964, 59, 1599-1602.

C. DETERMINATION OF COLD-EXTRACTABLE ARSENIC.

1. Procedure:

a) Weigh or measure by scoop 250 mg. of sieved(or in the field,unsieved) sample, and place in the test tube of a Gutzeit apparatus marked at 10 ml.

b) Make up to the 10 ml. mark with 0.625% stannous chloride solution.

c) Add 2 to 4 g. zinc pellets, and connect the Gutzeit apparatus containing a mercuric chloride paper to the test tube. Leave to stand for one hour.

d) Remove the mercuric chloride paper and compare immediately with the artificial standards.

2. Standards:

Prepare as in B above.

3. Reagents.

a) 0.625% stannous chloride solution: Add 25 ml. of the 10% stannous chloride solution to 100 ml. of concentrated hydrochloric acid and dilute with 275 ml. of water.

Otherwise, as for d) and f) to k) under Reagents in B. above.

D. DETERMINATION OF CARBONATE IN SOIL SAMPLES

1. Procedure:

a) Weigh 0.3 g. or 0.1 g. of sieved sample into a 16 x 150 mm. test tube.

b) Add (cautiously) 10 ml. of 0.1 N.hydrochloric acid.

c) Digest for 30 minutes just below boiling.

d) When cold, take a suitable aliquot and dilute to 50 ml. with water.

e) Add 2 or 3 drops of 0.5% phenolphthalein indicator.

f) Titrate with 0.1 N. sodium hydroxide until pink.

2. Reagents:

a) 0.1 N. HCl: dilute 9 ml. concentrated acid (sp. gr. 1.18) to 1 litre with water. Standardise by using this solution to titrate 106 mg. anhydrous sodium carbonate.

b) 0.1 N NaOH: dissolve 4 g. sodium hydroxide in 1 litre of water. Standardise by titration with the 0.1 N. HCl.

c) Phenolphthalein solution: dissolve 50 mg. in 100 ml. of 50% ethyl alcohol.

$$\% CO_3^{=} = \frac{2\ (b - t)\ N\ 0.03\ 100}{g}$$

N = normality of NaOH
b = blank titration in ml.
t = sample titration in ml.
g = sample weight in g.

3. Concentration range covered.

0.3 g. of sample and 1 ml. aliquot 0.5 - 9.5% $CO_3^{=}$

0.1 g. of sample and 1 ml. aliquot 1.5 -28.5% $CO_3^{=}$

E. DETERMINATION OF CHLORIDE IN SOIL SAMPLES (G.P.R.C. Tech. Comm. 29, modified.)

1. Procedure:

a) Weigh 1 g. of sieved sample into a test tube (18 x 180 mm.).

b) Add 10 ml. of water, cork and shake mechanically for 1 hour.

c) Centrifuge until supernatant liquid is clear.

d) Pipette suitable aliquot into a calibrated test tube (18 x 180 mm.) and make up to 20 ml. with water.

e) Add 1 ml. of 0.1N-silver nitrate solution and mix.

f) Stand for 10 min. in the dark and compare the turbidity with standards against a dark background.

g) Cl - in ppm = $\frac{\mu g \text{ of matching standard} \times 10}{\text{aliquot (in ml.)}}$

2. Preparation of standards.

a) To 11 test tubes (18 x 180 mm. calibrated at 20 ml) add respectively 0, 5, 10, 20, 30, 40, 50, 100, 150, 200 and 250 µg of chloride.

b) Add 1 ml. of 1% gelatine solution.

c) Dilute to 20 ml. with water.

d) Add 1 ml. of 0.1N-silver nitrate solution.

c) Mix and stand for 10 min. Keep in the dark when not in use and avoid direct sunlight at all times.

3. Reagents:

a) 0.1N-silver nitrate solution: dissolve 17 g. of silver nitrate in water, add 10 ml. of nitric acid (sp.gr. 1.42, Analar) and dilute to 1 litre with water. Store in a darkened bottle.

b) 1% gelatine solution: dissolve 1 g. in 100 ml. of boiling water.

c) Standard chloride solution: dissolve 82.5 mg. of sodium chloride in water and dilute to 1 litre.

4. Remarks:

a) The dark background required at Procedure f) may be provided by the black paper used for wrapping photosensitive materials.

F. DETERMINATION OF CHROMIUM

1. Procedure:

a) Weigh 0.1 g. of sieved sample into a 15 ml.nickel crucible.

b) Add 0.5 g. of sodium hydroxide pellets and 0.25 g. of sodium peroxide.

c) Heat gently until molten, and maintain at a bright red heat for 1 min.

d) When cold, add 10 ml. of 10% ethyl alcohol.

e) Bring to boiling, and scrape the bottom of the crucible with a nickel spatula to ensure that the melt has disintegrated; heat further if this was not the case.

f) Filter through a dry Whatman No.540 paper (11cm.diam) into a dry test tube.

g) Compare with a standard series.

h) If the test solution has a more intense yellow colour than the 300 ug. standard, take a suitable aliquot, dilute to 10 ml. in a calibrated test-tube with 0.4 M-sodium Hydroxide, and compare with the standard series A.

i) When the chromium content of the sample is less than 100 ppm pipette an aliquot of 2 ml. into a test-tube calibrated at 10 ml., and boil for a few seconds.

j) Add 1M-hydrochloric acid, dropwise until the solution is just acid. This is indicated when the initial precipitate of aluminium hydroxide is just re-dissolved. When the aluminium is not present in sufficient quantity to serve as an indicator, use a few drops of phenolphthalein solution (0.05% in 50% ethyl alcohol).

k) Add 2 ml. of EDTA solution.

l) Add 1 ml. of diphenylcarbazide solution.

m) Dilute to 10 ml. with water and mix.

n) Compare with the standard series B after leaving for 10 min.

o) If the test solution has a more intense violet-red colour than the 4.5 ug. standard, repeat with a smaller sample aliquot.

p) Chromium in ppm = 10 x (ug. of matching standard, series A)

or 100 x $\frac{\text{(ug. of matching standard, series B)}}{\text{(ml. of aliquot.}}$

2. Standards:

A - To each of 9 test-tubes (calibrated at 10 ml) add respectively 0, 25, 50, 75, 100, 150, 200, 250, and 300 ug. of chromium. Dilute to 10 ml. with 0.4M-sodium hydroxide, cork the tubes, and mix.

B - To each of 12 test-tubes (calibrated to 10 ml.) add respectively 0, 0.25, 0.5, 1.0, 1.5, etc. to 3.5, 4,0, 4,5 and 5.0 ug. of chromium. Add 2 ml. of EDTA solution, 1 ml, of diphenylcarbazide solution, dilute to 10 ml. with water, cork the tubes, mix, and leave to stand for 10 min. before use.

3. Reagents:

a) Sodium hydroxide: pellets, A.R.

b) Sodium peroxide: A.R.

c) 10% ethyl alcohol: dilute 50 ml. of absolute ethyl alcohol to 500 ml. with water.

d) 0.4M-sodium hydroxide: dissolve 8 g. of pellets in water and dilute to 500 ml.

e) 1M-hydrochloric acid: mix 40 ml. of concentrated acid (sp.gr. 1.18) with 400 ml. of water.

f) EDTA solution: dissolve 2.5 g. of ethylenediamine tetra-acetic acid (disodium salt) in 410 ml. of water and mix with 90 ml. of hydrochloric acid (sp.gr. 1.18).

g) Diphenylcarbazide solution: dissolve 0.2 g. of reagent in 10 ml. of glacial acetic acid and 90 ml. of acetone. This solution will keep for only 2 or 3 days and it must be discarded as soon as discolouration is apparent.

h) Standard chromium solutions: 1000 µg. of chromium per ml. - dissolve 283 mg. of potassium dichromate 0.4 M sodium hydroxide and dilute to 100 ml. with 0.4M-sodium hydroxide.

100 µg. of chromium per ml. - dilute 5 ml. of the 1000 µg. per ml. solution to 50 ml. with 0.4M-sodium hydroxide.

5 µg. of chromium per ml. - dilute 5 ml. of the 100 µg. per ml. solution to 100 ml. with 0.4M-sodium hydroxide

4. Remarks:

a) The range covered is 100-3000 ppm using standard series A, and 5-250 ppm with standard series B. By working with a sample aliquot of 0.1 ml., the first range may be extended to 30,000 ppm.

b) Results may be obtained within ± 25% at the 95% confidence level over the range 5-30,000 ppm

c) By the chromate procedure, 75 samples can be analysed per man-day of 8 hours, but only 50 samples when the diphenylcarbazide method is used.

d) For full details refer to G.A.Wood and R.E.Stanton, Trans.Instn.Min.Metall., Lond.,1956-57,66, 331-240.

G. DETERMINATION OF COPPER

1. Procedure:

a) Weigh 0.1 g. of sieved sample into a Pyrex test tube (16 x 150 mm).

b) Mix with 0.5 g of potassium bisulphate and fuse.

c) Leach with 5 ml. of 1M-hydrochloric acid.

d) Add 5 ml. of water and mix.

e) Pipette a 2 ml aliquot into 10 ml of buffer solution contained in an 18 x 180 mm test-tube, previously calibrated at 10 and 12 ml.

f) Add 2 ml of 0.02% 2,2'-diquinolyl solution.

g) Cork the tube and shake vigorously for 30 sec.

h) Compare with standards.

i) If above the top standard, add another 2 ml of diquinolyl solution and shake for a further 30 sec.

j) If still above the top standard, repeat with a sample aliquot of 0.1 ml and dilute to 12 ml with 0.5 M-hydrochloric acid at stage e).

$$\text{Copper in ppm} = \frac{50 \times (\mu g \text{ of copper in matching standard}) \times (\text{ml of solvent phase})}{(\text{ml of sample aliquot})}$$

2. Standards:

To twenty test-tubes, calibrated at 10 and 12 ml, and each containing 10 ml of buffer solution, add respectively, 0, 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10, 12, 14, 16, 18 and 20 μg of copper. Dilute to 12 ml with 0.5 M-hydrochloric acid, add 2 ml of diquinolyl solution, cork the tube and shake vigorously for 30 sec.

3. Reagents:

a) Potassium bisulphate: fused, powder.

b) 1M-hydrochloric acid: mix 40 ml of acid (sp.gr.1.18) with 400 ml of water.

c) 0.5M-hydrochloric acid: mix 20 ml of acid (sp.gr.1.18) with 420 ml of water.

d) 0.02% 2.2'-diquinolyl solution: dissolve 40 mg in 200 ml of amyl alcohol.

e) 0.01% dithizone: dissolve 40 mg in 400 ml of carbon tetrachloride and store in a vacuum flask.

f) Buffer solution: dissolve 200 g. of sodium acetate (trihydrate), 100 g of potassium sodium tartrate (tetrahydrate) and 20 g of hydroxylamine hydrochloride in water, and dilute to 1 litre. Extract with 0.01% dithizone until free from copper and then remove the excess of dithizone by extraction with carbon tetrachloride.

g) Standard copper solutions: 100ug of copper per ml - dissolve 200 mg of cupric sulphate (pentahydrate) in 0.5M-hydrochloric acid and dilute to 500 ml with this acid.

10 ug of copper per ml - dilute 10 ml of the 100 ug per ml solution to 100 ml with 0.5M-hydrochloric acid.

1 ug. of copper per ml - dilute 10 ml of the 10 ug per ml solution to 100 ml with 0.5M-hydrochloric acid.

4. Remarks:

a) The range covered is 5-2000 ppm with an aliquot of 2 ml and 100 - 40,000 ppm with an aliquot of 0.1 ml.

b) Results may be obtained within ± 25% at the 95% confidence level over the range 5-20,000 ppm.

c) 100 samples can be analysed per man-day of 8 hours.

d) The buffer solution should be at pH 6.05 ± 0.15.

e) For further information see H.Almond, U.S.Geol. Survey Bull. 1036-A, 1955.

H. DETERMINATION OF GOLD

1. Procedure:

a) Weigh 1 g. of sample into a test-tube (19 x 150 mm., with rim, calibrated at 5 and 10 ml.)

b) Add 5 ml. of acid mixture and evaporate to dryness in an oven.

c) When cold, add 5 ml. of 2M hydrochloric acid and boil gently for 15 min.

d) Add 5 ml. of 2M hydrochloric acid, mix and allow to settle.

e) Pipette a 5 ml. aliquot of the clear solution into a beaker and dilute to 50 ml. with 2M hydrochloric acid.

f) Add 2 ml. of copper-tellurium solution.

g) Mix well, and add 10 ml. of stannous chloride solution.

h) Bring to the boil, and maintain just below boiling for 30 min.

i) Add one or two drops of stannous chloride solution to check that precipitation is complete.

j) Filter through a filter stick (porosity 3) while the solution is still hot and wash the beaker and precipitate with 2M hydrochloric acid.

k) Dissolve the precipitate in 1 ml. of hot aqua regia.

l) Rinse the precipitation beaker with another 1 ml of hot aqua regia.

m) Pour the solution through the filter stick and wash the stick with a few ml. of water.

n) Evaporate to dryness in a test-tube (19 x 150 mm. with rim, calibrated at 2.5 and 10 ml.) using an oven, and dissolve the residue in 2.5 ml. of 2M hydrochloric acid by warming gently.

o) Dilute to 10 ml with water.

p) Add 1 ml. of 0.05% brilliant green solution, cork the tube and shake it vigorously for 30 sec.

q) Allow the phases to settle, transfer the toluene phase with an automatic pipette to a test-tube (19 x 150 mm., calibrated at 10 ml.) containing 10 ml. of 0.5M hydrochloric acid and 0.05 ml. of 1% brilliant green solution.

r) Cork the tube and shake it vigorously for 2 min.

s) Compare with standards.

2. Standards:

a) Pipette 0, 0.05, 0.2, 0.2, 0.3, 0.4, 0.5, 0.75, 1.0, 1.5, and 2.0 µg. of gold, respectively, into test-tubes (19 x 150 mm., calibrated at 10 ml.).

b) Dilute to 10 ml. with 0.5M hydrochloric acid.

c) Continue as described in stages p) - r) of Procedure.

N.B. The standard series is stable for only 3 hours. Store in the dark when not in use.

3. Reagents:

a) Concentrated hydrochloric acid: sp.gr. 1.18, A.R.

b) 2M hydrochloric acid: mix 80 ml. of concentrated acid with 360 ml. of water.

c) 1M hydrochloric acid: mix 40 ml. of concentrated acid with 400 ml. of water.

d) 0.5M hydrochloric acid: mix 20 ml. of concentrated acid with 420 ml. of water.

e) Concentrated nitric acid: sp gr. 1.42, A.R.

f) Aqua regia: mix 400 ml. of concentrated hydrochloric acid with 100 ml. of concentrated nitric acid.

g) Acid mixture: mix 500 ml. of aqua regia with 500 ml. of water.

h) Copper-tellurium solution: dissolve 2 g. of cupric sulphate (pentahydrate) and 210 mg. of tellurium tetrachloride in 100 ml. of 2M hydrochloric acid.

i) Stannous chloride solution: dissolve 200 g. of the dihydrate in 1 litre of 2M hydrochloric acid.

j) Brilliant green: Reactor grade.

k) Ethyl alcohol: absolute.

l) 1% brilliant green solution: dissolve 1 g. of brilliant green solution in 100 ml of ethyl alcohol.

m) 0.05% brilliant green solution: dilute 5 ml. of the 1% solution to 100 ml. with toluene.

n) Potassium dichromate solution: dissolve 5 g of potassium dichromate in 100 ml. of water.

o) Toluene: sulphur-free grade. Shake 1 litre for 2 min. with 10 ml. of potassium dichromate solution, discard the aqueous phase and wash the toluene four times by shaking with successive 500 ml. volumes of water. Filter the toluene through a Whatman No.1 paper.

p) Standard gold solutions: 5mg. of gold per ml. - dissolve 504 mg. of sodium chloroaurate (dihydrate) in 25 ml. of M.hydrochloric acid and dilute to 50 ml. with water.

50 µg. of gold per ml. - dilute 1 ml. of the 5 mg. per ml. solution to 100 ml. with 0.5M hydrochloric acid.

1 µg. of gold per ml. - dilute 2 ml. of the 50 µg. per ml. solution to 100 ml. with 0.5M hydrochloric acid.

The 50 µg. and 1 µg. per ml. solutions must be prepared freshly as required.

4. Notes:

a) The range covered is 0.05 - 4 ppm as described above, but this upper limit may be extended by using a smaller aliquot at stage e) of the Procedure.

b) Results within ± 40% at the 95% confidence level may be obtained over the range 0.05 - 4 ppm.

c) One person can analyse an average of 25 samples per 8 hr. -day.

d) Reference: R.E.Stanton and A.J.MaDonald, Analyst, 1964, 89, 767-770.

I. DETERMINATION OF IRON

1. Procedure:

a) Weigh 0.1 g. of sieved sample into a beaker (30 or 50 ml.).

b) Add 0.5 ml. of concentrated nitric acid. If a vigorous reaction occurs, add further small quantities of acid while heating on a hot-plate.

c) Add 5 ml. of perchloric acid and evaporate to fumes, obtaining a white residue.

d) When cold, transfer to a calibrated test-tube and dilute to 10 ml. with water washings from the beaker.

e) Pipette a 1 ml. aliquot into a test-tube (calibrated at 5 and 10 ml.) containing 5 ml. of reagent solution.

f) Dilute to 10 ml. with water and mix.

g) Compare with standards.

Iron in ppm = 100 x (µg. of iron in matching standard).

2. Standards:

To each of twelve test-tubes containing 5 ml. of reagent solution, add respectively 0, 5, 10, 20, 30, 40, 50, 60, 80, 100, 150 and 200 µg. of iron, dilute to 10 ml. with water and mix. Keep in the dark when not in use.

3. Reagents:

a) Nitric acid: sp. gr. 1.42, A.R.

b) Perchloric acid: 60% A.R.

c) Reagent solution: dissolve 40 g. of tartaric acid (A.R.) in about 200 ml. of water, add 50 g. of thioglycollic acid and 200 ml. of ammonia (sp. gr. 0.880 A.R.) and dilute to 1 litre with water.

d) Standard iron solutions: 100 µg. of iron per ml. - dissolve 432 mg. of ammonium ferric sulphate crystals (A.R.) in about 50 ml. of water and 5 ml. of hydrochloric acid (sp.gr.1.18, A.R.) and dilute to 500 ml. with water.

10 µg. of iron per ml.- dilute 10 ml. of the 100 µg. per ml. solution to 100 ml. with water.

4. Remarks:

a) A range of 100 ppm to 2% is covered by the method as described above. It may be amended to determine iron < 100 ppm by taking up to 0.5 g. of sample, or for concentrations > 2% by making a greater dilution at Procedure d) and using a smaller sample aliquot.

b) Results can be obtained within ± 25% at the 95% confidence level for the range 100 ppm to 2%

c) About 80 samples can be analysed per man-day of 8 hrs.

d) The method has been adapted from the procedure described by E.B. Sandell, "Colorimetric Determination of Traces of Metals," Third Edition. Interscience Publishers Inc., New York and London. 1959.

J. DETERMINATION OF NICKEL

1. Procedure:

a) Weigh 0.2 g. of sieved sample into a 16 x 150 mm. test tube.

b) Mix with 1 g. of potassium bisulphate and fuse.

c) Leach with 5 ml. of 0.5M-hydrochloric acid.

d) 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.

e) Add 1 ml. of α-furildioxime solution, cork the tube and shake vigorously for 2 min.

f) Compare with standards.

g) 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).

2. 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.

3. Reagents:

a) 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.

b) Potassium bisulphate: fused, powder.

c) 0.5M-hydrochloric acid: 20 ml. of acid + 420 ml. of water.

d) ∝-furildioxime: 0.3 g. dissolved in 90 ml. of benzene and 10 ml. of ethyl alcohol (absolute).

e) Standard nickel solution: 100 µg. of nickel per ml. - dissolve 50 mg. 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 µg. per ml. solution to 100 ml. with 0.5M-hydrochloric acid.

4. Remarks:

a) The method as described will cover the range 1-900 ppm. By using a sample aliquot of 0.1 ml. at Stage d) 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 e).

b) Results can be obtained within ± 20% at the 95% confidence level over the range 5 -18,000 ppm.

c) 80-100 samples can be analysed per man-day.

d) 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.

e) 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 d) above, but with the pH 8.9, or by extraction with ∝-furildioxime, using a solution as in Reagents d) but containing carbon tetrachloride in place of benzene.

f) Ferrous ions form a purple complex with ∝-furildioxime and may occur from inadequate fusion of the sample with potassium.

g) The buffer solution should have a pH value of 10.3 ± 0.1.

h) For further information see R.E.Stanton and J.Coope Trans. Instn, Min. Metall., Lond., 1958-59, 68, 9-14.

K. DETERMINATION OF SULPHATE IN SOILS

1. Procedure:

a) Weigh 1 g. of sieved sample into a test tube (16 x 150 mm) and digest for 1 hr. on a sand-tray with 5 ml. of 1M-hydrochloric acid.

b) Allow to settle and pipette a 1 ml. aliquot of the clear solution into a calibrated test tube (18 x 180 mm.) and dilute to 10 ml. with acid-salt solution.

c) Add 250 mg. of barium chloride crystals.

d) Shake for about 30 sec. to dissolve the crystals.

e) Compare with standards, against a dark background. Sulphate in ppm. = 5000 x mg. of matching standard.

2. Standards:

To twelve test tubes add respectively 0, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.75, 1.0, 1.25, 1.5 and 2.0 mg. of sulphate. Add 1 ml. of gum acacia solution and dilute to 10 ml. with acid-salt solution. Add 250 mg. of barium chloride crystals and dissolve them by shaking for about 30 sec.

3. Reagents:

a) Acid-salt solution: dissolve 48 g. of sodium chloride in water, add 4 ml. of concentrated hydrochloric acid (sp.gr. 1.18), 125 ml. of orthophosphoric acid (sp.gr.1.75) and dilute to 1 litre with water.

b) 1M-hydrochloric acid: Mix 40 ml. of concentrated acid (sp.gr. 1.18) with 400 ml. of water.

c) Gum acacia solution: dissolve 5 g. of the reagent in 100 ml. of boiling water, and filter through a No.41 Whatman paper when cold.

d) Standard sulphate solution: 0.5 mg. of SO_4^{--} per ml. - dissolve 907 mg. of potassium sulphate in water and dilute to 1 litre.

4. Remarks:

a) The dark background required at Procedure e) may be provided by the black paper used for wrapping photosensitive materials.

b) The range covered is 100 ppm to 1%.

c) 100 samples can be analysed per man-day.

d) Only those sulphates soluble in the hot, dilute acid will be determined by this procedure. In particular, barium and strontium sulphates will remain undissolved, and lead and calcium sulphates may be partially dissolved. The efficiency of the attack may vary considerably with the nature of the minerals containing the sulphate radical.

e) This method is an application of the determination of sulphate in water, described by N.W.Scott, "Standard Methods of Chemical Analysis," The Technical Press, London, 5th edition, 1955, Vol.II p. 2091.

L. DETERMINATION OF ZINC

1. Procedure:

a) Weigh 0.1 g. of sieved sample into a Pyrex test-tube (16 x 150 mm).

b) Mix with 0.5 g. of potassium bisulphate and fuse.

c) Leach with 5 ml. of 1M-hydrochloric acid.

d) Add 5 ml. of water and mix.

e) Pipette a 1 ml. aliquot into 5 ml. of buffer solution contained in a test-tube (18 x 180mm), previously calibrated at 5 ml.

f) Add 5 ml. of 0.001% dithizone solution.

g) Cork the tube and shake vigorously for 1 min.

h) Compare with standards.
Zinc in ppm = 100 x ug. of zinc in matching standard.

2. 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 ug. of zinc. Add 5 ml. of 0.001% dithizone, cork the tubes and shake vigorously for 1 min.

3. Reagents:

a) Potassium bisulphate: fused, powder.

b) 1M-hydrochloric acid: mix 40 ml. of acid (sp.gr. 1.18) with 400 ml. of water.

c) 0.5M-hydrochloric acid: mix 20 ml. of acid (sp.gr. 1.18) with 420 ml. of water.

d) 0.01% dithizone in carbon tetrachloride: dissolve 40 mg. in 400 ml. of carbon tetrachloride and store in a vacuum flask.

e) 0.01% dithizone in benzene: dissolve 40 mg. in 400 ml. of benzene and store in a vacuum flask.

f) 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.

g) Buffer solution: dissolve 5 g. of sodium fluoride in 1 litre of water, and then dissolve 500 g. of sodium acetate (tri-hydrate) and 125 g. of sodium thiosulphate (penta-hydrate) in this solution. Add 15 ml. of acetic acid (glacial) 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.

h) 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) A range of 5-350 ppm is covered, but it may be extended to 3500 ppm by using an aliquot of 0.1 ml.

b) Results can be obtained within ± 25% at the 95% confidence level over the range 5 - 3500 ppm

c) 100 samples can be analysed per man-day.

d) The buffer solution should have a pH value of 6.0 ± 0.15.

e) For further information see R.E.Stanton, Tech. Comm. No.19, G.P.R.C. Imperial College, 1962.

M. DETERMINATION OF MERCURY.

1. Description of Instrument.

Mercury determinations were carried out by means of a sensitive mercury vapour meter described in a paper by James and Webb (1963-4). A very brief description of the operation of the instrument is given here, further details being obtainable from the above reference.

The mercury present in the sieved or pulverized sample is vaporized by strong heating in an iron retort, and the air and vapour is drawn into the apparatus by means of a suction pump. The sample is dehydrated in a silica gel column before splitting into two equal fractions. One half of the sample is drawn into a reference chamber, after passing through a column of glass wool impregnated with palladium chloride, where mercury is removed as a result of the formation of $HgCl_2$. The other half of the sample is drawn through a balancing column of plain glass wool on its way to the sample chamber.

Two photocells (RCA935) are arranged to receive the light from a fused-silica low-pressure mercury vapour lamp after passing through the two chambers. The lamp (Hanovia Special) radiates predominantly at 2357 A^{o}, at which frequency mercury shows the strongest absorption. It is necessary to use a lamp made of slightly impure fused silica, e.g. Vycor, which filters out undesirable low frequency radiation.

The electrical circuitry is such that variations in the intensity of light falling on either of the two photocells causes corresponding variations in the current flowing through a voltmeter. Since the output of both cells will be equally affected by variations in the output of the lamp and by the presence of similar interfering substances in both chambers, the reading on the voltmeter will be related specifically to the amount of mercury passing through the sample chamber.

The limiting sensitivity of the instrument in its present form is approximately 10^{-4} µg. Hg.

2. Procedure for Determination of Mercury in Samples.

a) To demercurify retorts, heat bulb to dull red heat and then draw clean air through by means of a pump.

b) Weigh 0.1 g. of sieved or pulverized sample into bulb of retort.

c) Connect up instrument and zero according to operating instructions.

d) Insert retort into end of 100 ml. manual air pump, fitted with a clean filter.

e) Heat retort in a bunsen flame at full mains pressure for 30 seconds, at the same time drawing out the pump handle. At the end of 30 seconds the pump handle should be at full extension.

f) Remove retort from pump, inject vapour from pump into instrument and record reading.

g) Samples should be run in batches in which are included a complete series of standards of known mercury content.

h) After a complete batch has been analysed, construct a calibration curve for the standards and convert meter readings into ppm or ppb Hg.

i) At the same time, calculate the mean precision of the batch of analyses.

j) If a sample contains more than 10 ppb Hg, repeat in a new batch, using a smaller sample weight.

N. SPECTROGRAPHIC ANALYSIS

The following information was provided by Dr. I. Nichol of the G.P.R.C., London. All samples are prepared as outlined previously and only the minus 82-mesh material is used for analysis.

1. Ignition:

Samples are ignited in a silica crucible at 400-500°C for 3 hours to oxidize organic matter and eliminate combined water.

2. Sample preparation:

100 mg. of sample are then mixed with 100 mg. of a 1:1 mixture of Li_2CO_3 and carbon with germanium added as an internal standard to give a concentration in the final mixture of 400 ppm Ge. The mixture is homogenised by shaking in a Wig-L-Bug for 30 seconds.

3. Spectrographic equipment and conditions:

Source unit	Hilger FS 131
Spectrograph	Hilger Large Quartz FS 55
Arc stand	Hilger FS 56
Comparator	Hilger JA Co L.90
Wavelength Range A	2800 - 4950
Emulsion	Ilford N.30
Anode	Morganite SG.305H - 5 mm. carbon, 2.91 mm. diam.crater 5 mm. deep crater.
Cathode	Morganite Sg.305H-flat ended
Exposure	20 secs.
Gap	3 mm.
Arc current	12.5 amps
Slit	15 u
Collimator	Internal
Step sector	Two steps giving three intensities in proportion 1:1/4:1/16

4. Estimation

Estimation of the concentration of an element in a sample is made by comparing the spectra of the sample with spectra of synthetic standards on a standard plate.

5. Wavelengths and usable concentration ranges of spectral lines:

Element	Wavelength, °A	Range, ppm
Ag	3382.9	0.2 - 1000
Bi	3067.7	5 - 200
Co	3453.5	5 - 10000
Cr	4254.3	5 - 10000

Element	Wavelength ^{o}A	Range, ppm
Cu	3274.0	1 - 500
Cu	2961.2	500 - 10000
Ga	2943.6	2 - 10000
Mn	4034.5	5 - 500
Mn	2933.0	500 - 10000
Mo	3170.3	2 - 10000
Ni	3414.8	1 - 1000
Ni	3050.8	1000 - 10000
Pb	2833.1	1 - 1000
Sn	2840.0	1 - 10000
Ti	3377.6	50 - 10000
V	3185.4	2 - 10000
Zn	3345.0	50 - 10000
Zr	3438.2	200 - 10000

6. Precision:

The precision of the results obtained is controlled by including one control sample with each plate of 13 samples. The analytical precision at the 95 percent confidence level is in the range $\pm$ 35 - 45 percent.

II SIZE ANALYSIS OF SOIL SAMPLES

The following procedure is based on that given by Piper (1950), modified by using sodium hexametaphosphate (Calgon) as a dispersant as recommended by Tooms (1955).

1. Dry sieve the sample to minus $\frac{1}{4}$ inch and place 100 g. into a one litre beaker (50 g. for a predominantly clay-size sample).

2. Add 300 ml. of 1% sodium hexametaphosphate solution and place the beaker into a hydrosonic tank containing water.

3. Switch the machine on for 15 minutes, stirring the sample periodically with a glass rod to prevent packing down.

4. Decant the supernatant liquid (A) to another beaker and add 300 ml. of water to the sample (B).

5. Disperse B for a further 15 minutes.

6. Add A to B and continue dispersion for a further 10 minutes.

7. Wash the sample and liquid into a one litre stoppered cylinder and add water up to one litre. This should leave at least 30 cm. of liquid above the sediment surface.

8. Obtain a uniform suspension by turning the cylinder end-over-end for one minute. Place cylinder down and start stop-watch.

9. After exactly 5 minutes and 5 hours, carefully place a Bouyoucos hydrometer in the suspension and read. At the same time, record the temperature. The reading after 5 minutes gives the number of grams of silt + clay present in one litre of suspension and the reading after 5 hours gives the number of grams of clay. The silt content may be calculated from the two readings. Temperature differences require an addition of 0.3 units for every degree above 19.4°C and a subtraction of 0.3 units for every degree below 19.4°C.

   In order to separate the silt + clay fraction from the sand and gravel, the work follows on from stage 9 above.

10. Reshake the cylinder as in stage 8.

11. The top 10 cms. is siphoned off according to the second column in Table 43.

12. Top the suspension up to its original level with water.

13. Repeat stages 10 to 12 until no material remains in suspension in the upper 10 cms. of the cylinder after the specified time interval.

14. Separate the clay-size material from the silt + clay suspension by the same method, using the third column in Table 43.

15. Dry the sand and gravel, the silt and the clay fractions in a low oven. Sieve the sands and gravel into the required mesh sizes. Pass the silt and clay fractions through a minus 82-mesh nylon sieve after gently breaking up the aggregations with a pestle and mortar.

TABLE 43. THE SETTLING TIME ALLOWED BEFORE DECANTATION OF 10 CM. of SILT + CLAY, OR CLAY ONLY. (FROM PIPER, 1950, P.76)

TEMP. °C	SETTLING TIME: SILT + CLAY MINS.	SECS.	SETTLING TIME: CLAY ONLY HOURS.	MINS.
17	5	10	8	35
18	5	0	8	25
19	5	0	8	10
20	4	48	8	0
21	4	40	7	50
22	4	30	7	40
23	4	30	7	25
24	4	20	7	15
25	4	15	7	5