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Metallogenic Provinces and Mineral Deposits in the Southwestern Pacific

N. H. Fisher, Editor

DEPARTMENT OF MINERALS AND ENERGY
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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METALLOGENIC PROVINCES AND MINERAL DEPOSITS IN THE SOUTHWESTERN PACIFIC

A Symposium held at the 12th Pacific Science Congress, Canberra, August 1971

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N. H. FISHER

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CORRIGENDUM

Page iii—lines 29 and 30 should read:

ALEVA, G. J. J., FICK, L. J., and KROL, G. L.
Some remarks on the environmental influence on secondary tin deposits 163

Page iv—line 32, and **Page 221:** The author's name should be: N. A. SHILO.

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ABSTRACTS

FOREWORD

This publication is being issued as part of the celebration of the twentyfifth anniversary of the Bureau of Mineral Resources, which was established in 1946.

The anniversary year coincided with the holding of the Twelfth Pacific Science Congress in Canberra, August 18-27, 1971, and the papers included in this volume were presented at that Congress in Section D.: Geological Structure and Mineral Resources in the Pacific.

Section D consisted of five Symposia:

D1. Structure and tectonic history of the Pacific Ocean Basin
D2. Island arcs and related structures of the Western Pacific Region
D3. Evolution of the continental shelves of the Western Pacific
D4. Mineral resources of the Western Pacific
D5. Petrology and geochemistry of island arcs in relation to tectonic environment

Symposium D4 was divided into two parts, D4.1, Metallogenic Provinces, and D4.2, Sedimentary Basins. This publication consists mainly of papers delivered in Symposium D4.1.

It has not been possible to include in full all the contributions to this rather comprehensive symposium, so from the manuscripts available (excluding papers that have been or are being substantially published elsewhere) a selection has been made of those that are considered to be particularly relevant to the study of the mineral resources and potential of the South-western Pacific area. Abstracts of all the other contributions to Symposium D4.1 are also included.

The papers comprising D4.2, Sedimentary Basins, are being published by ECAFE in the Technical Bulletin of the Committee for the Co-ordination of Joint Prospecting for Mineral Deposits in Asian Offshore Areas (CCOP) and most of those presented in Symposia D1, D2, D3, and D5 are being published by the University of Western Australia Press.

N. H. FISHER
Director

GEOLOGICAL CONTROLS OF METALLOGENIC PROVINCES

by K. C. Dunham

Director, Institute of Geological Sciences, London

Summary

The possible impact of the plate tectonics concept on ore genesis is considered. It is suggested that important metalliferous provinces are related to plate margins as exemplified around the Pacific, especially those where Benioff zones have been or are active. Such provinces are elongate, parallel or transverse to the mobile belt in which they lie. They may contain ore concentrations related to differentiation of basic magma, both plutonic and subvolcanic; and to thick sediment accumulation followed by partial fusion with or without leaching by formation waters. Ancient provinces of this type should also be recognizable in present cratons, but such shield areas may contain independent ore controls connected with reactivation. Continental margins of present Atlantic type are not yet sufficiently well understood for their significance to be assessed, but marginal basins related to them in adjacent platforms may be ore generators. Non-linear metalliferous provinces, with characteristic mineralogy, which are found in epicontinental (epiplatform) marine and terrestrial sediments are the result of activity by hypersaline formation waters generally little influenced by igneous activity. The possibility of concentration of some metals at mid-ocean ridges or in relation to transform faults is canvassed.

Introduction

Ore deposits of the metals are distributed in the lithosphere in a non-uniform manner, because a number of diverse geological factors must coincide in order to effect the required concentrations of elements. Some regions of the crust are abundantly supplied with workable orebodies, others contain few or none. It is therefore possible to recognize ore provinces and to consider that their configuration reflects the conditions under which the ores have been generated. The topic has been discussed at a previous Pacific Science Congress (1966), and since the Pacific is surrounded by a great metallogenic belt (S. S. Smirnov, 1946), the subject is very appropriate. Geographically, the preparation of the Cartes Métallogéniques, stimulated by the IUGS Commission for the Geological Map of the World, has had the useful effect of showing how the deposits are distributed on a world-wide scale, and this has led to discussion in several countries of the reasons for the patterns (Tatarinov, Grusheroy & Labazin, 1957; Semenov, 1957; Petrascheck, 1959; Magakyan, 1960; Semenov, Labazin, Grusheroy, & Tatarinov, 1960; Lang, 1961; Shatalov, 1963; Roy, 1963; UN ECAFE Asia working party, 1966).

The concept of metallogenic provinces was, however, developed at a much earlier stage by writers such as de Launay (1897, 1905, 1913), Finlayson (1910), Gregory (1922), Spurr (1923), and Blondel (1936). The temporal aspects were considered by Lindgren in his chapter on metallogenetic epochs in successive editions of his *Mineral Deposits* (for example, 1933). More recently, Bilibin (1948, 1955), Turneaure (1955), Gorzhevskii & Kozerenko (1956), Tatarinov (1957), Zakharov (1958), Abdullayev (1959, 1960), Smirnov (1959), Radkevich (1961), Hills (1947, 1965,), and Petrascheck (1965) have been among important general contributors to the subject. The last-mentioned author attempts a definition, as follows:

> 'The *metallogenic province* is the entity of mineral deposits that formed during a tectonic-metallogenic epoch within a major tectonic unit and which are characterised by related mineral composition, form of the deposits, and intensity of mineralisation.'

The question of scale has been considered by Shatalov (1961), who recognizes, at the largest size, the planetary metallogenic belt; his next order of magnitude embraces the linear metallogenic belt and the non-linear metallogenic province ('areas of various shapes, without distinct linearity'). Within these he further identifies metallogenic zones, ore districts, centres, and fields. Here we shall be concerned mainly with Shatalov's planetary belt, and his metallogenic belt and province. Petrascheck has proposed that a metallogenic province should have an extension of at least 1000 km in one direction, but he envisages the existence of small subprovinces.

As a general statement of the sources of epigenetic metalliferous ore deposits, that of Smirnov (1968) is favoured here: they may be (i) juvenile, related to subcrustal basalt magma; (ii) assimilated, related to palingenic (diorite to granite) magma of crustal origin, or (iii) filtrational, related to the circulation of nonmagmatic underground water. Of course, transitional types where more than one source has contributed must be recognized. Those who believe in granite from the mantle may object to this simple statement, but it has yet to be demonstrated that such granites, if they exist, are ore-bringers. Among syngenetic ore types, those resulting from sedimentation in fluid magmas and in bodies of sea, lagoon, and fresh water cover most of the important cases; but the diagenetic processes which may follow often link with Smirnov's category (iii). When tectonics, sedimentation, and magmatism are taken into account, the very wide range of source and concentration conditions opens the way for a considerable variety of metallogenic provinces, some of which may overlap one another.

Classification of Megaprovinces

On the broadest scale, a threefold classification of the continental crust on a regional tectonic basis may be accepted as a useful background for megaprovinces. Petrascheck (op. cit.) has proposed that provinces may be in (a) orogenic belts, (b) stable mantle regions, (c) metamorphic shields. These terms require modification for a number of reasons, though the entities accepted for the present discussion remain similar. The orogenic belt, considered in the light of the present-day concepts of plate tectonics and of continental drift, might be better renamed the *mobile belt* (a term already in wide use—for example Nikolayev, 1944, 1953), for it is convenient to include in it not only the fold mountains, but also the depressions as represented by oceanic deeps, and by flysch-and-molasse-accumulator troughs and other deep receptacles of sediment and effusives, as yet not much distorted. Petrascheck's term 'stable mantle' implies to the geophysicist something different from the concept he wishes to convey. For those widespread regions with which he is concerned, where little-distorted Phanerozoic and Precambrian shelf or continental sediments are the surface formations, the term *epiplatform region* is here proposed, following Radkevich (1961, p. 778). The rocks concerned rest upon a platform eroded across a crustal basement often largely metamorphic, of Precambrian or Phanerozoic age, though the possibility also exists in certain areas that the basement may be oceanic basaltic crust.

Thirdly, the *cratonic* or *shield-platform* areas, forming the exposed nuclei of the continents, provide the setting for a number of important characteristic ore provinces.

The mobile belts, epiplatform regions, and shield-platforms may each contain or constitute metallogenic megaprovinces, this term being taken as comparable in scale with Shatalov's planetary metallogenic belt.

Mobile Belts

The outstanding recent developments in global tectonics which have come from geophysical (seismic, gravity, and paleomagnetic) studies call for some important modifications of older ideas, including certain aspects of the Dana-Hall concept of the geosynclinal-orogenic belt and its elaboration due, for example, to Marshall Kay (1951, 1967) and Aubouin (1965). Not that the former and present existence of geosynclines in the sense of these workers has been at all disproved; but if the plate tectonics hypothesis as proposed by McKenzie & Parker (1967), Morgan (1968), and Dewey & Bird (1970) is accepted as the explanation of the surface features of the earth, present and past, then the elongate major troughs capable of receiving huge thickness of sediment, and the mountain chains which may subsequently result from the intense distortion of these sediments, are to be seen as mobile zones adjacent to plate boundaries, especially where ocean crust is being overridden by continental crust and being subjected to subduction. One important difference between some earlier conceptions of orogeny and ideas springing from plate tectonics is that mountain-building would not be expected to be a contemporaneous process the world over; but of course many students of the 'alpine', 'hercynian', and 'caledonian' revolutions had long ago realized that these could not be interpreted in strict, uniphase time terms.

That ore deposits were found, by and large, in the mountains rather than under the plains was long ago recognized by the old German masters, epitomized by Agricola (Bauer, G., 1556): Wegmann (1928) specifically referred to the fact. Guild (1971) has been among the first to summarize the significant metallogenic differences that exist between plate margins (mobile belts) and the interiors of plates (platforms). Walker (1970) connects mineralization with mantle downturns, exemplified by the Alpine orogeny (using that term in its widest sense). The Pacific- and world-encircling belt of mountains resulting from major movements (presumably of plates) during the 150 million years that have elapsed since late Jurassic time forms the geological background for a megaprovince, or planetary metallogenic belt in Shatalov's sense (op. cit.), and includes a fairly large number of overlapping but separately identifiable metallogenic provinces. This great belt is known from seismic and other evidence to be underlain in part (and perhaps formerly quite generally) by Benioff zones, representing active continental margin conditions where subduction of oceanic crust is considered to be in progress now, and has probably been in progress in places for long periods, perhaps since the Cretaceous. The great oceanic deeps are associated with this belt, and some accumulations of sediments and volcanics now forming continental margins adjacent to them are as thick as the present deeps are profound. Such a mobile zone continues to be the site of intense chemical and physical activity, producing initial magmatism in Stille's (1949) and Borchert's (1960) sense, and subsequently huge intrusions and effusives essentially of monzonite-granodiorite composition, at least in part from partial fusion of pre-existing sediments and other rocks. Ore-provinces are associated with initial basic and keratophyric volcanism (chromite, platinoids, copper-lead-zinc of Kuroko and other facies), and notably with the later phase of stock-like intrusions. From among the metallogenic provinces within the great circum-Pacific belt, we may select one spectacular example for more detailed notice: the porphyry coppers may be considered as forming a province in their own right within the belt extending from British Columbia to Chile. Perhaps, since the discoveries at Bougainville, in East Malaysia, and in the Solomons, the province is about to be extended to the other side of the Pacific. Guild (op. cit.) has noted the possible relationship of the porphyry coppers to the subduction process. More generally, in addition to the comprehensive account of the North American Cordilleran mineral provinces by Turneaure (1955), the distribution of porphyry copper deposits has been considered by Parsons (1957), and the fast developing situation in the Canadian Cordillera by Brown, Cathio, Panteleyev, & Ney (1971), while, for the South American Andes, accounts by Stoll (1965) and Fuller (1966) have been followed by a study of exceptional interest by Peterson (1970). Peterson shows that in South America there are provinces of iron mineralization along the west coast, the porphyry copper belt lies farther east, and there is also a polymetallic zone; these give place to lead-zinc deposits still farther east. The elongation of all these provinces parallels that of the Andes. In the North American Cordillera, however, where the northeast-trending belt of intrusions and associated intense mineralization crossing Colorado has long been recognized (Lovering, 1933), Landwehr (1967, 1968) has recently shown by further analysis that a high proportion of the mineral deposits of the western USA are associated with 'Nevadamide' intrusions which follow defined northeast belts. These, he suggests, correspond with crustal ruptures, not parallel to the meridional megaprovince, that resulted from tangential tensional stress caused by regional uplift, allowing basaltic magma to ascend (? from the mantle), thus starting the igneous process.

The Tethys mobile belt continuing from the Pacific through the Far East, the Himalayas, and the Alps is still active in part and its activity certainly partly overlaps that of the circum-Pacific belt. It includes the very important tin province of Indonesia-Malaya-Thailand, and a highly mineralized series of provinces through Iran, Turkey, the Balkans, and eastern Europe (Petrascheck, 1963; Ramovic, 1962). At least two porphyry copper deposits are known, but, strangely, there are almost completely unmineralized regions in this tectonic belt, notably the Himalayas in general, and the Alps east of Austria. Ore provinces may be associated with mountains, but mountain-building zones are not necessarily mineralized. Perhaps zones of continent to continent collision are unfavourable for magmatism. The absence of substantial evidence of igneous activity exposed at surface in both barren regions is certainly worthy of comment. Generalizing, it may be said that mobile belts carry ore deposits associated with initial magmatism and main-phase magmatism. They undoubtedly include some deposits of Smirnov's filtrational variety, but for sedimentary deposits it may be suggested that they are relatively unfavourable, probably because the quiet, slow conditions of sedimentation necessary for sedimentary ore accumulation are seldom realized.

Some older mobile belts deserve mention, though they are necessarily more fragmentary than the Cretaceous to Recent belts mentiond above. Presumably, a plate-edge overlapped with another during late Carboniferous-Permian times along the line of the Ural Mountains, and also across Europe, where large fragments of the Armorican-Hercynian chains appear in the Riesengebirge, the Erzgebirge, the Harz, Massif Central, in Brittany, and in Cornubia. Great metallization occurred: massive sulphide deposits associated with volcanism in the Urals, tin and many other metals across western Europe. According to Radkevich (1961), in the Urals there are metallogenic belts of strikingly linear form, extending along the folded zones and the faults that border them in the submeridional direction for thousands of kilometres. Both initial and main magmatic phases are represented, but here again it is noteworthy that dense mineralization in fields such as Cornwall (Dewey, 1925) does not follow the axis of the batholith, but pursues a linear east-northeast path which could represent a deeply extensive tension system.

An older plate-boundary may be represented by the Caledonides of Britain, Scandinavia, Spitzbergen, and Greenland, with its probable continuation into the Appalachians. Although important ore provinces occur, the ore deposits are less impressive than those of the Jurassic-Tertiary provinces or even of the Ural-Hercynian zones, though they contain some notable ore concentrations; for example, the substantial lead deposits in Cambrian sandstone near the eastern margin of the Swedish Caledonides.

In the mobile belts, a definite time-sequence of events may be recognized. The tectonic and igneous stages were described long ago by Stille (1949). Some attention has been given above to the separation of a phase of initial ultrabasic and basic magmatism (with characteristic attendant ore deposits) from the later main phases of development. The temporal sequence has received a good deal of attention in the Russian literature. Bilibin (1955) for example produced a tabular summary of the metalliferous evolution of an ideal geosyncline, starting from the old platform, and ending, after prolonged tectonism, sedimentation, magmatic activity, and erosion, with a new platform. The principal phases envisaged include:

(i) an initial geosynclinal stage with basic-ultrabasic magmatism accompanied by Cu, Fe, Mn, Pt, Ni deposits and carbonate sedimentation, ended by the first major folding;

(ii) a second major folding, with the appearance of the granitic or syenitic differentiates of basalt and accompanying hydrothermal base-metal ores;

(iii) a period of rupturing and a changeover to andesitic magma; precious metal deposits now appear;

(iv) the third major folding, producing a mountain chain in place of the geosyncline; granite magma now predominates, with contact metamorphic and hydrothermal ores;

(v) a further period of rupturing with andesitic effusives and quartz-monzonitic intrusives accompanied by Cu, Mo, Au, Ag, Hg, Sb, As deposits;

(vi) erosion eventually leads to the terminal shelf conditions at surface, but deep crustal rupturing continues, with basalt and its differentiates; here there may be low-temperature mineralization.

Many variants on this general theme can be found in the literature, especially in Russia. Smirnov (1961) has developed a diagrammatic method of representing the major events in the evolution of facies-belts in geosynclines and the mineralization accompanying the events. Tvalchrelidze (1962) has examined the differing evolutions of 'volcanogenous' geosynclines, 'terrigenous' geosynclines, geanticlines, and median massifs, and more recently Shcherba (1966) has considered the evolution of mobile zones in oceanic crust, in continental crust, and in orogenic crust.

Though the principal geological control emerges clearly in the form of an oceanic/continental or continental/continental plate collision, the process sets into motion an elaborate series of events in space and time, a suitable combination of which may lead to mineralization.

The need for the recognition of subprovinces within the mobile belts thus becomes apparent. These should be more strictly defined than the very extensive mobile belts, in terms of a restricted time-range and in terms of characteristic and consanguineous minerals.

Precambrian Shields

Opinion is by no means unanimous on how the early crust of the earth was built up; but in the major areas of Precambrian outcrop, which seems to form the cores of the continental masses, definite belts or zones have been defined in terms of the 'absolute' age of the metamorphic, ultrametamorphic, and igneous rocks they contain. It may fairly be argued that some or all of these belts or zones represent ancient mobile zones which have completed their cycles of activity and become successively annealed into the craton or platform area of which they now form a part. From the generally high grade of metamorphism displayed (even though this is by no means an invariable feature) it must be assumed that a much deeper level of erosion is revealed here than in the post-Cambrian mobile belts, and that the shield areas have been substantially uplifted, even though some, like Canada and Fennoscandia, have now been planed down to regions of little surface relief.

All the same, it cannot be claimed that all the sedimentary formations exposed in the shields, whether now paragneisses or little metamorphosed types, were accumulated under the conditions characteristic of the deep troughs of mobile belts. This is true of quartzite/sandstone formations such as the Belt Series of the western USA and also, perhaps more strikingly, of the banded ironstones which form subprovinces of great ecomonic importance in nearly all the Precambrian shields. Something approximating to shelf seas, covering planated platforms, was probably the typical environment in which these formed. Another example of an important metallogenic subprovince is provided by the Zambia-Congo copper belt, where an influential group of authors (Mendelssohn, 1961) postulates accumulation of sulphides in littoral or shallow-shelf sandstones, shales, and dolomites, preceding folding and mild metamorphism.

Many authors have commented on the generally barren nature of the monotonous granodiorite-gneiss terranes which assume major importance in the shield areas. Far more promising are the enclaves of metavolcanics, especially where these trend towards a keratophyric or rhyolitic composition. The Abitibi area of Ontario forms a fine example of one such metallogenic subprovince, with characteristic major gold, copper, and zinc mineralization (Hutchinson, Ridler, & Suffel, 1971). Other examples could be drawn from Sweden, Australia, or indeed many Precambrian regions.

Precambrian shield areas may be expected to contain a number of metallogenic subprovinces, both sedimentary and volcanic, separated by wide areas of barren gneiss.

The question of autonomous activization of platform areas has recently been raised by Russian geologists, notably Scheglov (1967). If the conception includes further ultrametamorphism, it needs to be treated with reserve; it remains to be demonstrated that this can occur independently of true orogenic processes at levels which will produce rocks that ultimately reach the surface. Another kind of activization is associated with faulting, which may be followed by leaching of permeable channels by connate brines percolating downward or juvenile brines rising. There is *a priori* evidence that some such process must have occurred beneath some epiplatform regions (see below). Finally, there is no doubt that carbonatite and kimberlite complexes are particularly characteristic of shield areas, where they have drilled their way through from great depths, probably from the upper mantle.

Epiplatform Regions

Generally disposed between the Precambrian shields and the current mobile belts are the broad regions where flat-lying or gently domed and basined formations are at surface. The age of the rocks concerned is largely Phanerozoic, though, as already noted, some Precambrian, especially Proterozoic, rocks belong here. The north American Middle West and Prairie provinces, and north European plains, parts of the Ukraine, and the Russian Steppes and Siberian platform are the typical regions.

Of the three major types of metallogenic provinces, those in the epiplatform regions cover the least area of the megaprovince in which they occur. Although the basins in these platforms form the chief environments for the accumulation and, given suitable traps, the concentration of petroleum, it is only now becoming recognized that connate brines from these basins, acting in some cases in conjunction with petroleum (Barton, 1968), may make significant contributions to epigenetic metalliferous mineralization. Igneous activity in these platform areas is absent or feeble, though volcanism may arise. Faulting may be absent or may reach major dimensions; tight folding, except locally, is by definition excluded from such areas.

Significantly, epigenetic mineralization in the cover sediments tends to surround or overlie basement highs (Heyl, 1969; Dunham, 1967). The typical epigenetic deposits are those formed at 200°C or below.

Examples of subprovinces include the Missouri-Oklahoma-Illinois-Kentucky fields in the USA, carrying Pb-Zn-F-Ba, and the counterpart subprovince in Ireland, North Wales, and the English Pennines; the Colorado Plateau uranium field, strangely surrounded by elements of the Cordilleran mobile belt; and the Kara-Tau province, USSR.

Certain true sedimentary deposits belong to the epiplatform category, notably the goethite-chamosite-siderite ironstones which appear at intervals from the Ordovician to the Cretaceous, and the banded ironstones of the Precambrian. Some manganese deposits doubtless belong here also.

Conclusion

According to Bilibin, the All Union Geological Institute of the USSR (VSGEI) found the concept of metallogenic provinces a positive aid to prospecting. With so much of the world's largest continent to prospect, this may well have been the case. To make it an effective tool, precisely defined subprovinces appear far more likely to be useful than the broad megaprovinces discussed. Nevertheless, these are the necessary background to the definition of subprovinces.

When metallogenic subprovinces have been worked out, they may in some cases suggest non-homogeneities in the earth's crust or upper mantle. The case of tin, economic deposits of which are more restricted than those of other base metals, is one that has often been discussed; but the genetic controls cannot be said to have been fully established. The complexity of the mineralization process makes it difficult to establish a conclusive case for original heterogeneity.

The most favourable geological background for the development of metallogenic provinces is certainly to be found in the mobile belts, where differentiation of, and sedimentation of early minerals in, basic magmas may be revealed; where early submarine volcanism and subsequent palingenic magma generation may be accompanied by mineral concentration in skarns, shattered 'porphyries', or veins; and where the generally high level of energy and activity available promoted the movement of chemically active groundwater. It might be argued that as mobile belts are followed back through geological time, epigenetic concentration of many metals appears to have been less effective.

The shield-platform areas probably include large fragments of ancient mobile belts, including some with substantial metal concentrations. Linear or sublinear provinces can still be recognized. The epiplatform regions, though they provide the least favourable background, nevertheless contain irregular areas with major base-metal deposits, associated with the activity of hypersaline brines either moving through permeable and reactive sediments or possibly pouring into euxinic pools in ancient epicontinental seas.

Some evidence is now forthcoming that metallogenic provinces line up along what may prove to be deep megafractures transverse to axial directions of mobile belts, for example in the North American Cordillera. This raises the question of a possible more or less direct source for the metals in the mantle (Petrascheck, 1969). If it is the case that base metals, for example in manganese nodules, are relatively concentrated adjacent to median ridges or transform faults in the ocean floor, this might lend credence to a mantle source.

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BIBLIOGRAPHY

ABDULLAYEV, KH. M., 1959—Opyt klassifikatsii rudno-petrograficheskikh provintskiv (Experiment with classification of ore-bearing and petrographic provinces). *Uzbek. geol. Zh.*, 4 (in Russian).

ABDULLAYEV, KH. M., 1960—Nekotoryye voprosy klassifikatsii strukturnogeoligicheskikh zon, rudno-petrograficheskikh provintsiy i rudnykh rayonov (Some problems in classification of structural geological zones, ore-bearing and petrographic provinces and ore-bearing districts). *Zakonom. razm. polezn. iskop.*, 2 (in Russian).

AGRICOLA, G. (BAUER, G.), 1556—DE RE METALLICA. *Basileae: Apud Hieron Frobenium et Nicolaum Episcopium* (in Latin).

AUBOUIN, J., 1965—GEOSYNCLINES. *Amsterdam, Elsevier.*

BARTON, P. B., JR, 1968—Precipitation of Mississippi Valley type ores: a possible mechanism. *Econ. Geol., Monogr.* 3, 371-8.

BILIBIN, YU. A., 1948—Voprosy metallogenicheskoi evolyutsii geosinklinalnykh zon (Problems of the metallogenetic evolution of a geosynclinal zone). *Izv. Akad. Nauk SSSR, Ser. geol.*, 4, 51-66 (in Russian).

BILIBIN, YU. A., 1955—METALLOGENICHESKIE PROVINTSII I METALLOGENICHESKIE OPKHI (Metallogenetic Provinces and Metallogenetic Epochs). *Moscow, Gosgeoltekhizdat.* (English translation in Library, Geological Survey of Canada.)

BILIBIN, YU. A., 1960—Die geochemischen Typen der orogenen Zonen. *Ann. angew. Geol.*, 6, 545-9.

BLONDEL, F., 1936—La géologie et les mines des vieilles plateformes. *Bur. Etud. géol. Min. colon., Publ.* 8 (in French).

BORCHERT, H., 1960—Geosynklinale Lagerstätten, was dazu gehört und was nicht dazu gehört, sowie deren Beziehungen zu Geotektonik und Magmatismus (Geosynclinal ore deposits, what is relative and what is not relative, as well as their relation to geotectonics and magmatism). *Freiberger ForschHft.*, C79, 7-61 (in German).

BROWN, A. S., CATHRO, R. J., PANTELEYEV, A., and NEY, C. S., 1971—Metallogeny of the Canadian Cordillera. *Can. Min. metall. Bull.*, 64 (709), 37-61.

BURNHAM, C. W., 1959—Metallogenic provinces of the southwestern United States and northern Mexico. *New Mex. St. Bur. Mines Bull.* 65.

DE LAUNAY, L., 1897—Contribution à l'étude des gîtes métallifères. *Ann. Mines, Paris*, 12, 119-228 (in French).

DE LAUNAY, L., 1905—FORMATION DES GITES METALLIFERES OU METALLOGENIE. 2nd Ed. *Paris, Gauthiers Villars* (in French).

DE LAUNAY, L., 1913—TRAITE DE METALLOGENIE. *Paris,* 3 vols.

DEWEY, H., 1925—The mineral zones of Cornwall. *Proc. Geol. Ass.*, 36, 107-35.

DEWEY, J. F., and BIRD, J. M., 1970—Mountain belts and the new global tectonics. *J. geophys. Res.*, 75, 2625-47.

DEWEY, J. F., and HORSFIELD, B., 1970—Plate tectonics, orogeny and continental growth. *Nature, Lond.*, 225, 521-5.

DOMAREV, V. S., 1968—Problemy obshchei metallogenii (Problems of general metallogeny). *Vest. Leningr. Univ. Ser. geol. geogr.*, 24, 28-40 (in Russian: English summary, p. 39).

DUNHAM, K. C., 1967—Mineralization in relation to the Pre-Carboniferous basement rocks, northern England. *Proc. Yorks. geol. Soc.*, 36(2), 12, 195-201.

FINLAYSON, A. M., 1910—The metallogeny of the British Isles. *Quart. J. geol. Soc. Lond.*, 66 (262), 281-98.

FULLER, C. R., 1966—Metalliferous deposits of Chile. *Sci. Comm. Commn geol. Map Wld, 22nd int. geol. Cong.*, 143-7.

GORZHEVSKII, D. I., and KOZERENKO, V. N., 1956—O zakonomernostyakh razmeshcheniya polimetallicheskikh i redkometal'nykh zon i poyasov (Patterns in the distribution of polymetallic and rare metal zones and belts). *Geol. Sb., L'vov*, 2-3, 36-61 (in Russian).

GREGORY, J. W., 1922—Ore deposits and their genesis in relation to geographical distribution. *J. chem. Soc.*, 121 and 122 (715), 750-72.

GUILD, P. W., 1971—Metallogeny: a key to exploration. *Min. Engng, N.Y.*, 23(1), 69-72.

HEYL, A. V., 1969—Some aspects of genesis of zinc-lead-barite-fluorite deposits in the Mississippi Valley, U.S.A. *Trans. Instn Min. Metall.*, B, 78, 148-60.

HILLS, E. S., 1948—The metalliferous geochemical zones of Australia. *Econ. Geol.*, 42 (5), 478-91.

HILLS, E. S., 1965—Tectonic setting of Australian ore deposits. *In* GEOLOGY OF AUSTRALIAN ORE DEPOSITS. *8th Comm. Min. metall. Cong.*, 1, 3-12.

HUTCHINSON, R. W., RIDLER, R. H., and SUFFEL, G. G., 1971—Metallogenic relationships in the Abitibi belt, Canada: a model for Archean metallogeny. *Can. Min. metall. Bull.*, 64 (708), 48-57.

KAY, G. MARSHALL, 1951—NORTH AMERICAN GEOSYNCLINES. *Geol. Soc. Amer. Mem.* 48.

KAY, G. MARSHALL, 1967—On geosynclinal nomenclature. *Geol. Mag.*, 104(4), 311-6.

LANDWEHR, W. R., 1967—Belts of major mineralization in Western United States. *Econ. Geol.*, 62(4), 494-501.

LANDWEHR, W. R., 1968—The genesis and distribution of major mineralization in Western United States. *Econ. Geol.*, 63(8), 967-70.

LANG, A. H., 1961—Metallogenic maps. *Econ. Geol.*, 56(6), 1123-32.

LANG, A. H., 1961—A preliminary study of Canadian metallogenic provinces. *Mines Brch Can. Pap.* 60-33.

LINDGREN, W., 1933—MINERAL DEPOSITS. 4th Ed. *N.Y., McGraw-Hill.*

LOVERING, T. S., 1933—The structural relations of the porphyries and metalliferous deposits of the northeastern part of the Colorado mineral belt. *In* ORE DEPOSITS OF THE WESTERN STATES. *N.Y., Amer. Inst. Min. metall. Engrs,* 301-7.

MCKENZIE, D. P., and PARKER, R. L., 1967—The North Pacific: an example of tectonics on a sphere. *Nature, Lond.*, 216(5122), 1276-80.

MAGAKYAN, I. G., 1960—A metallogenic map of the world. *Int. geol. Rev.*, 2(6), 489-97.

MAGAKYAN, I. G., 1960—Metallogenicheskaya karta mira i nekotoryye zakonomernosti rasprostraneniya rudnykh mestorozhdeniy v zemnoy kore (Metallogenic map of the world and certain distribution patterns of ore deposits in the earth's crust). *Dokl. Sov. Geol., 21st int. geol. Cong., Probl.* 20.

MENDELSSOHN, F., 1961—THE GEOLOGY OF THE NORTHERN RHODESIAN COPPERBELT. *London, Macdonald.*

MORGAN, W. J., 1968—Rises, trenches, great faults, and crustal blocks. *J. geophys. Res.*, 73(6), 1959-82.

NIKOLAYEV, V. A., 1944—O zakonomernosti razvitiya strukturno-fatsial'nykh zon v podvizhnykh poyasov zemnoy kory (The regularities in evolution of structural-facies zones in mobile belts of the earth's crust). *Sov. Geol.*, 1 (in Russian).

NIKOLAYEV, V. A., 1953—O nekotorykh chertakh stroeniya i razvitiya podvizhnykh poyasov zemnloy kory (Some features of structure and development of mobile belts in the earth's crust). *Izv. Akad. Nauk SSSR, Ser. geol.*, 2, 19-36 (in Russian).

PACIFIC SCIENCE ASSOCIATION, 1966—Mineralogenic provinces and epochs in the Pacific belt. *Proc. 11th Pacif. Sci. Cong., Tokyo,* 1966, 4: Abstracts of papers related with geological sciences.

PARSONS, A. B., 1957—THE PORPHYRY COPPERS IN 1956. *N.Y., Amer. Inst. Min. metall. Petrol. Engrs.*

PETERSEN, U., 1970—Metallogenic provinces in South America. *Geol. Rdsch.*, 59(3), 834-97.

PETRASCHECK, W. E., 1959—Considérations sur le rédaction des cartes métallogéniques de grandes espaces. *Chron. Min. Outre Mer,* 27(272), 50-53 (in French and English).

PETRASCHECK, W. E., 1963—Dicalpin-mediterrane Metallogenese. *Geol. Rdsch.*, 33(1), 376-89 (in German).

PETRASCHECK, W. E., 1965—Typical features of metallogenetic provinces. *Econ. Geol.*, 60(8), 1620-34.

PETRASCHECK, W. E., 1969—Ore metals from the crust or mantle. *Econ. Geol.*, 64(5), 576-78.

RADKEVICH, YE. A., 1961—On the types of metallogenic provinces and ore districts. *Int. geol. Rev.*, 3(9), 759-83.

RAMOVIC, M., 1962—Regional metallogenetic differentiation and evolution of the types of hydrothermal ore deposits. *Rud.-metal. Zborn.*, 3, 219-28.

RAMOVIC, M., 1968—PRINCIPLES OF METALLOGENY. *Sarajevo, geogr. Inst. Nat. Sci. Fac., Univ. Sarajevo.*

ROY, B. C., 1963—Metallogenic-minerogenetic map of India (1:2 000 000). (Explanatory Notes.) *Geol. Surv. India.*

SCHERBA, G. N., 1966—Possible principle of analysis of metallogeny of regional mobile zones. *Int. geol. Rev.*, 8(12), 1428-39.

SCHUILING, R. D., 1967—Tin belts on the continents around the Atlantic Ocean. *Econ. Geol.*, 62(4), 540-50.

SEMENOV, A. I., 1957—Printsipy i metodika sostavleniya metallogenicheskoi karty vostochnogo Kazakhstana (Principles and method of construction of a metallogenic map of eastern Kazakhstan). *Sov. Geol.*, 58, 110-27 (in Russian).

SEMENOV, A. I., LABAZIN, G. S., GRUSHEVOY, V. G., and TATARINOV, P. M., 1960—O metallogenicheskoy karte SSSR, masshtaba 1:5 000 000 (The metallogenic map of the USSR, scale 1:5 000 000). *Sov. Geol.*, 8.

SHATALOV, YE. T., 1961—Some suggestions concerning the principles of classification of ore-bearing areas. *Int. geol. Rev.*, 1964, 6(12), 2110-26. (English translation of *Uzbek. geol. Zh.*, 6, 62-84.)

SHATALOV, YE. T., 1963—Terminy, otnosyashchiesya k obshchim opredeleniyam metallogenii, metallogeneticheskomu raionirovaniyu i metallogenicheskim kartam (Technical terms, references and general definitions of metallogeny, metallogenetic provinces and metallogenetic maps). *In* OBZOR GEOLOGICHESKIKH PONYATII I TERMINOV V PROMENENII K METALLOGENII (Review of Geological Nomenclature and Definitions used in Metallogeny). *Moscow, Izd. AN SSSR* (in Russian).

SHCHEGLOV, A. D., 1967—Osnovnye cherty metallogenii zon avtonomnoi aktivizatsii (Basic characteristics of metallogenic zones of autonomous activization). *In* Zakonomernosti razmeshcheniya poleznykh iskopaemykh (Regularities in the distribution of useful minerals), 8. *Moscow, Nauka.*

SMIRNOV, S. S., 1946—O Tikhookeanskom rudnom poyase (The Pacific ore-bearing belt). *Izv. Akad. Nauk SSSR, Ser. geol.*, 2, 13-27 (in Russian).

SMIRNOV, V. I., 1959—Experience in the metallogenic regional zonation of the USSR. *Izv. Akad. Sci. USSR, geol. Ser.*, 4, 1-15.

SMIRNOV, V. I., 1959—K voprosu o klassifikatsii rudno-petrograficheskikh provintsiy (On the problem of classifying ore-bearing and petrographic provinces). *Uzbek. geol. Zh.*, 6 (in Russian).

SMIRNOV, V. I., 1961—Nekotorye problemy metallogenii geosinklinalei (Certain problems in the metallogeny of geosynclines). *Izv. Akad. Nauk SSSR, Ser. geol.*, 10, 56-71 (in Russian).

SMIRNOV, V. I., 1968—The sources of ore-forming material. *Econ. Geol.*, 63(4), 380-9.

SPURR, J. E., 1923—THE ORE MAGMAS. A SERIES OF ESSAYS ON ORE DEPOSITION. *N.Y., McGraw-Hill*, 2 vols.

STILLE, H., 1949—Das Leitmotiv der geotektonischen Erdentwicklung. *Vortr. Schr. dt. Akad. Wiss.*, 32 (in German).

STILLE, H., 1950—Der 'subsequente' Magmatismus. *Sonderdr. Miscnea Acad. Berol.* (in German).

STOLL, W. C., 1965—Metallogenic provinces of magmatic parentage. *Min. Mag., Lond.*, 112 (5), 312-3, 315, 317, 319, 321, 323; (6) 394-5, 397, 399, 401-3, 405.

STOLL, W. C., 1965—Metallogenic provinces of South America. *Min. Mag.*, 112(1), 22-3, 25, 27, 29, 31, 33; (2) 90-1, 93-5, 97, 99.

TATARINOV, P. M., 1957—GENERAL PRINCIPLES OF REGIONAL METALLOGENETIC ANALYSIS. *Moscow, Gosgeoltekhizdat.*

TATARINOV, P. M., GRUSHEVOY, V. G., and LABAZIN, G. S. (Eds), 1957—Obshchiye printsipy regional'nogo metallogenicheskogo analiza i metodika sostavleniya metallogenicheskikh kart dlya skladchatykh oblastey (General principles of regional metallogenic analysis and methods of compiling metallogenic maps for folded districts). *Mater. vses. nauchno-issled. geol. Inst. Miner. Geokhim.*, N.S., 22 (in Russian).

TURNEAURE, F. S., 1955—Metallogenetic provinces and epochs. *Econ. Geol., 50th Anniv. Vol.*, 1, 38-98.

TVALCHRELIDZE, G. A., 1960—Opyt geotektonicheskoy klassifikatsii metallogenicheskikh zon i rudnykh rayonov (Experiment with geotectonic classification of metallogenic zones and ore-bearing districts). *Uzbek. geol. Zh.* (in Russian).

TVALCHRELIDZE, G. A., 1964—Metallogenic features of certain elements of geosynclinal provinces. *Int. geol. Rev.*, 6(3), 495-506.

UNITED NATIONS, ECAFE, 1966—Working Party of Senior Geologists, Sixth Session, 8-13 August, Bangkok. Report on the preparation of regional metallogenic map for Asia and the Far East. 2 pp. I&NR/SGWP.6/32.

WALKER, W., 1970—Mantle cells and mineralization. *Min. Engng, N.Y.*, 22(12), 69.

WEGMANN, C. E., 1928—Über die Formen magmatischer Erzlagerstätten in Gebirgen (On the form of magmatic ore deposits in mountain ranges). *Z. prakt. Geol.*, 36(10/11), 181-4 (in German).

WELLS, F. G., 1956—Relation entre gîtes minéraux et géosynclinaux. *Rev. Ind. minér., Num. spéc.* Ir, 95-107 (in French).

ZAKHAROV, E. E., 1958—Some features of regional geological distribution of ore deposits. *Zakonom. razm. pezn. iskop.*, 92-122.

REVIEW OF THE MINERAL DEPOSITS OF THE NEW HEBRIDES

by D. I. J. Mallick

Geological Survey of the New Hebrides

SUMMARY

At the present time, 1971, the known mineral deposits of the New Hebrides are very limited in both range of types and quantities—only the manganese deposit at Forari on Efate has proved to be of sufficient grade and size to be worked commercially.

The only known plutonic ultramafics, those of Pentecost, show considerable similarities in range of rock types to those of New Caledonia, but are barren of epigenetic nickel mineralization, lack substantial concentrations of chromite, and bear rather immature soils with only limited secondary concentrations of nickel.

On Pentecost, Malekula, Santo, and the Torres Islands intrusions of gabbro and diorite of late Oligocene or early Miocene age are accompanied by pyrite mineralization which is generally of very low copper content but is accompanied by copper sulphides in a few places. Minor copper mineralization is also associated with the late Pliocene to Recent basaltic and andesitic volcanoes of the Central Islands, which appear to be characterized by high background copper contents.

Fumarolic sulphur is associated with all the active volcanoes, but forms appreciable deposits only on Vanua Lava in the Banks Islands—and even there probably amounts to only a few hundred tons.

Primary manganese oxides occur in veinlets in the Torres Islands and in vesicles and inter-pillow spaces in basalts on Maewo. More important are the syngenetic and secondary concentrations, which occur mainly at the contact of tuffs with the Plio-Pleistocene reef complex cover and in the soil profile.

Iron sands, mainly magnetite but with a small titanium content, are known from several islands from both present and raised beach levels but have not yet been investigated in detail.

Although the soils on the Pleistocene limestone plateaux are very young and show little visible differentiation with depth. gibbsite has been proved on several islands. The alumina was probably derived from airfall ash on the plateaux rather than dissolution of the limestones.

INTRODUCTION

Serious interest in exploring the New Hebrides for mineral deposits was first aroused by the work of E. Aubert de la Rue in the 1930s, in which he described ultramafic rocks from Pentecost Island similar to those of New Caledonia (Aubert de la Rue, 1935, 1937, 1939). It was not until the late 1950s and early 1960s, however, that any extensive detailed surveys were undertaken, the search for nickel, base metals, and manganese leading to the discovery of an economic deposit of manganese at Forari on Efate by the Compagnie Française des Phosphates de L'Océanie. Mining operations, the only ones so far (1971) undertaken in the New Hebrides, started in 1962 and are continuing. Renewed interest in prospecting has been shown in the past two or three years and a few companies now hold prospecting licences.

This article attempts to review the various types of mineral deposits known in the New Hebrides, giving examples of each, but does not attempt to catalogue all the occurrences of minerals of economic significance. The deposits known are very limited in both type and number, but include both primary deposits associated with plutonic and volcanic rocks (e.g. sulphides) and secondary concentrations (e.g. manganese oxides and bauxite).

General Geological Setting

The islands of the New Hebrides cover approximately 15 000 km^2 and lie on the southern and central portions of the New Hebrides oceanic ridge, which extends from the Santa Cruz Islands in the north to Matthew and Hunter Islands and Conway Reefs in the south. The island chain is bordered on its western side by an oceanic trench system and to the east by the small ocean basin of the Fiji Plateau.

The islands are mainly submarine and subaerial volcanic accumulations ranging in age from late Oligocene to the present day, with some intercalations and fringes of reef limestones; older rocks are of very restricted distribution but include the ultramafic rocks on Pentecost Island. Geological subdivision of the islands follows closely their geographic distribution, Mitchell & Warden (1971) having distinguished separate Western, Eastern, and Central Chains. The general characters of these three groups (Fig. 1) are as follows:

Western Chain: This comprises the islands of Malekula, Santo, and the Torres subgroup. The main period of volcanism, of calcalkali andesites and tholeiitic basalts, was in the late Oligocene and early Miocene and built an archipelago of reef-fringed islands. Subvolcanic activity resulted in extensive intrusion into the volcanic piles. Volcanism probably extended into the mid-Miocene, but later deposits are mainly epiclastic derivatives and limestones.

Eastern Chain: The main volcanic period on Maewo, Pentecost, and probably also western Epi and central Efate was in the late Miocene and early Pliocene. The deposits are mainly submarine tholeiitic basalts, pyroxene andesites, and latites, capped by Plio-Pleistocene reef limestones. Older rocks are largely confined to South Pentecost, where there are ultramafics carrying rafts of amphibolite, and gabbros intrusive into a series of older lavas.

Central Chain: This consists mainly of subaerial, more or less well preserved volcanic cones of Pliocene to Recent age. Those in the south appear to be slightly older and are rimmed by raised Plio-Pleistocene reef-complex limestones. The more northerly ones bear little raised limestone and include most of the active

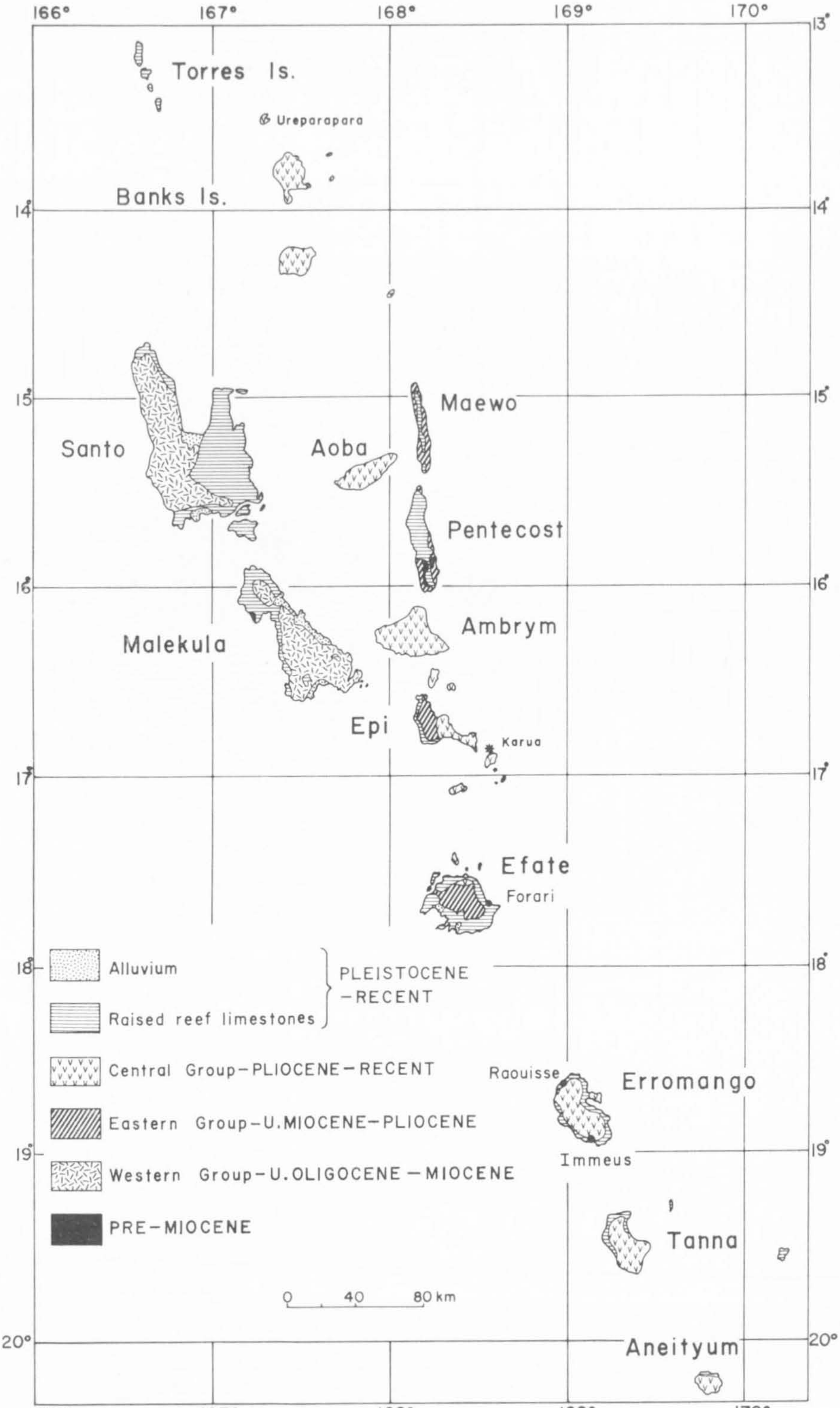

Fig. 1. Geology of the New Hebrides.

volcanoes of the New Hebrides. There is some evidence of a lateral variation in composition across the island chain with the more alkalic rocks occurring on the trench side, contrary to the normal arrangement in island arcs, where alkalinity usually increases with distance from the trench.

The Mineral Deposits

Associated with the ultramafic rocks of Pentecost

The only known outcrops of ultramafic rocks in the New Hebrides are those on the southern half of Pentecost Is. (Fig. 2) where they occur in a median zone

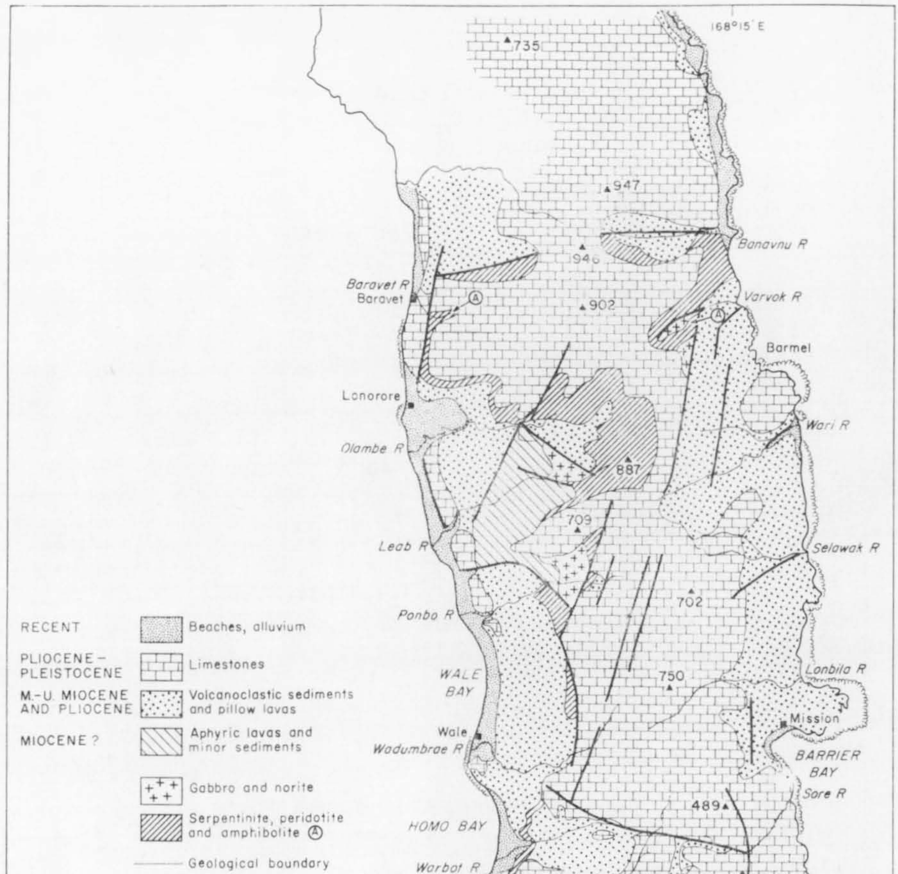

Fig. 2. Sketch map of the geology of South Pentecost.

separating different successions of upper Miocene-lower Pliocene volcaniclastics and probably form a linear, fault-bounded horst (Mallick & Neef, in prep.). However, downhill gravitational creep has spread the ultramafic rocks as a thin layer beyond their original outcrop limits.

The main rock-type is a saxonite (olivine + enstatite-bronzite), usually massive and more or less completely serpentinized, and is similar to the main lithological type in the Solomon Islands. The assemblage of minor rock-types shows similarities with those of New Caledonia; in particular the presence in one small area of dunite and a banded mafic and ultramafic series, in both of which clinopyroxene is dominant over orthopyroxene, is comparable to the dunite + ouenite (gabbro) series (Guillon, 1969) near Noumea.

TABLE 1. ANALYSES OF ULTRAMAFIC ROCKS

	1	2	1a	2a	3	4
SiO_2	37.28	36.39	44.25	43.04	44.20	41.10
TiO_2	tr	0.02	tr	0.02	0.05	0.10
Al_2O_3	0.70	1.03	0.83	1.22	1.50	—
Fe_2O_3	5.30	3.86	6.30	4.56	tr	1.70
FeO	2.26	2.75	2.68	3.26	7.64	5.55
MnO	0.06	0.09	0.07	0.10	—	—
MgO	38.37	38.62	45.40	45.68	44.20	44.33
CaO	0.30	0.19	0.35	0.22	1.14	0.20
Na_2O	0.10	0.08	0.12	0.09	0.16	0.09
K_2O	tr	0.10	tr	0.12	0.16	—
H_2O^-	1.25	1.59	—	—	0.14	—
H_2O^+	13.35	13.22	—	—	0.41	4.70
P_2O_5	tr	0.02	tr	0.02		
CO_2		0.71		0.84		
NiO		0.27		0.32	0.29	
Cr_2O_3		0.26		0.31	0.28	
S		0.17		0.20		
Perte au feu	1.25					
Total	100.22	99.27	100.00	100.00	100.17	98.37

1. PE21, R. Olambe, West Pentecost. Partly serpentinized saxonite. Orthopyroxene 15%; olivine 18%; serpentine 60%; diopside 1%; alteration products of pyroxenes 5%; chromite 1%. Analysis Petrography and Geochemistry Research Centre, Nancy (Obelliane, 1961, p. 81).
2. PM66, R. Banmatmat, South Pentecost. Serpentinized saxonite; includes Co = 80 ppm; Pt 0.02 ppm; Pd and V not detected. Analysis D. E. M. Hosking & F. R. Stacey, I.G.S., London.

1a & 2a. Analyses 1 and 2 recalculated to 100% on a water and 'perte au feu' free basis.

3. Fresh saxonite, Choiseul, Solomon Islands. Olivine 78%; orthopyroxene 20.2%; picotite 1.8%. Analysis Avery & Anderson (Thompson, 1960).
4. Common harzburgite. Piste de Dzumac, New Caledonia. Includes CrNiCo = 0.6% J.-H. Guillon, 1969).

The similarity of the Pentecost saxonites to those of the Solomons described by Thompson (1960) is shown in Table 1 by comparison of the analysis of a fresh saxonite from Choiseul with those of serpentinized saxonites from Pentecost recalculated on water and 'perte au feu' free bases. In particular their NiO and

Cr_2O_3 contents are comparable, although on Pentecost the Cr is contained in very small disseminated crystals of picotite or chromite, and no concentrations into bands and lenticles like those of, for instance, San Jorge in the Solomons are known. The only sulphides known in the Pentecost ultramafites are occasional discordant pyrite veinlets.

The age of the Pentecost ultramafites is probably Oligocene, for they contain rafted blocks of amphibolite which have yielded a metamorphic K/Ar age of 35 $\pm$ 2 m.y. (on hornblende); and serpentinite occurs as xenoliths in the Ponbo gabbro, which gave a whole rock K/Ar age of 28 $\pm$ 6 m.y.

The mineral deposits associated with the ultramafics are of two types—asbestos and nickel.

Asbestos. For the most part the main mass of serpentinized saxonite has, at the superficial levels, acted incompetently, and gravity creep mantles have formed in which massive rounded blocks are enclosed in a highly sheared matrix of material of similar composition. An earlier phase of more brittle deformation is preserved in the more massive blocks, where tensional fractures are filled with lenticular veinlets of serpentine. Mostly the veinlets are thin, irregular, and of structureless or semifibrous serpentine, but in some places three generations of serpentine are present, the earliest formed being of cross-fibre asbestiform chrysotile. The asbestos fibres are usually less than 1 mm long, but reach a recorded maximum of 8 mm near the southern tip of the island. Most of the asbestos veinlets are disrupted by later subparallel and cross-cutting veinlets of semifibrous and structureless serpentine.

Superficial indications are that there is only a little asbestos present.

Nickel. No veinlets with concentrations of highly nickeliferous serpentine are known from Pentecost, but nickel is somewhat concentrated in the soil profile; the maximum nickel content proved so far is only 0.55 percent. For the most part the soils tend to be thin and immature; this is probably due to two major factors, their youth and the relative instability of the parent serpentinized saxonite on steep valley sides. The ultramafites have been exposed only where their original cover of Pleistocene reef-complex limestones has been removed. On valley sides the soil profiles on the ultramafites are rarely more than 4 m thick, but at the island crest east of Lonorore they exceed 6 m. In both cases Ni is leached from the upper 2 m and is concentrated to reach its maximum at depths of about 2.5 to 3 m (Fig. 3). Below 3 m there is a steady decrease to the background value of about 2000 ppm Ni of the serpentinized saxonite. The concentrations of Co, Fe, and Cr show sympathetic variations to those of Ni, but Cu shows an antipathetic concentration in the superficial soil layers.

Sulphides

Sulphides associated with subvolcanic rocks

Porphyry-copper type mineralization might be expected in the Outer Melanesian Arc southwards from New Guinea, as has been proved at Panguna on Bougainville and Koloula on Guadalcanal. No true porphyry copper deposits have yet been proved in the New Hebrides, although a certain amount of sulphide mineralization, mainly pyrite but with a little copper, does occur. These sulphides are associated with intrusions of dioritic and gabbroic rocks into volcanic accumu-

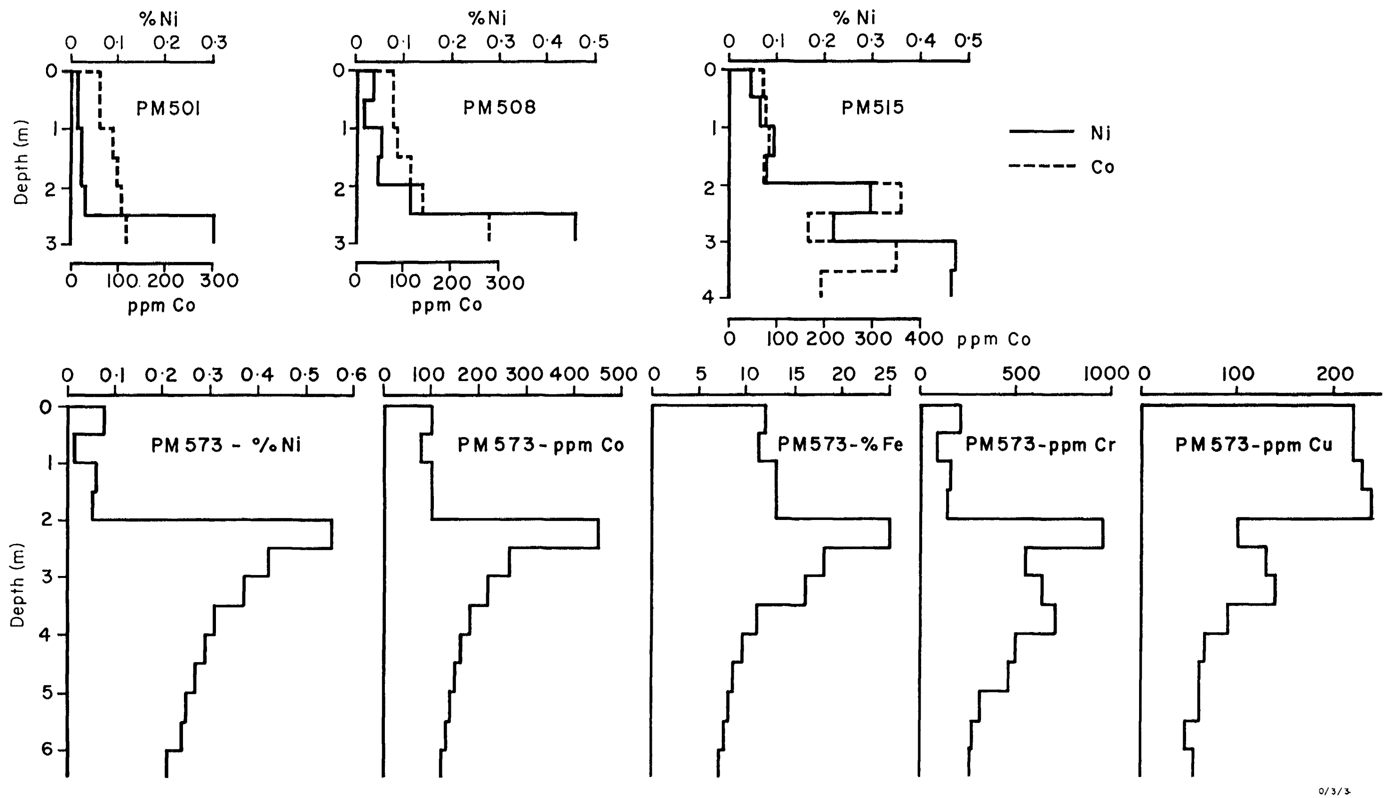

Fig. 3. Pentecost ultramafic soils.

lations, mainly basic andesite and basalt, of late Oligocene to early Miocene age; that is, with rocks which are generally more basic than those typical of the porphyry copper association.

On *Malekula, Santo,* and the *Torres Islands* there are extensive zones of intrusions, mainly of porphyritic hornblende-bearing microdiorite and andesite, with some bodies of coarse-grained hornblende diorite and amphibolized gabbro. In some areas (e.g. the Wounaro and Woke Rivers of West Santo) the microdiorites are extensively altered and carry veins and disseminations of pyrite (with calcite). For the most part the pyrite has a very low copper content, but in places on both Malekula and Santo there are veinlets containing chalcopyrite and even native copper. At one locality in the Navaka River of southwest Santo a small amount of chalcopyrite has been recorded in lodes with magnetite, pyrite, and pyrrhotite (Williams & Warden, 1964)*.

A trace of native gold was reported in the 1930s from the Matanui River on Malekula, most probably from the late Oligocene-early Miocene rocks there, but has not been confirmed subsequently.

The Mount Batmar area of *West Pentecost* has provided the best documented occurrence of sulphides associated with subvolcanic rocks (Mallick, 1970). Here mineralization by pyrite with some copper is associated with intrusions of gabbros of probable late Oligocene or early Miocene age into pillow lavas. However, on Pentecost the main pyritized area is in the country rocks rather than in the intrusions (Fig. 4), as it is in the Western Group.

Pyritization. The pyritized area is superimposed on a mineralogical zoning of the gabbros and metalavas (Fig. 4 and Table 2), and is concentrated in the chlorite and green hornblende zones. The analyses in Table 3 show that the background Cu content of the metalavas and intrusions is low and that it remains low even in the most pyritized rocks, where it is usually less than 100 ppm. Pyritization is accompanied by silicification, the original lava in some places being replaced by pyritic colloform jasper and clear chalcedony and quartz.

Copper Mineralization. The area of copper mineralization is, apart from one occurrence, approximately co-extensive with that of pyritization.

Copper sulphides occur in two modes: primary magmatic and epigenetic.

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* Recent work has shown that the mineralized area of S.W. Santo has the following characteristics:

1. Mineralization is concentrated near the edge of an intrusive complex which consists mainly of a dense swarm of north-northwest-striking hornblende andesite dykes cut by one large mass of coarse hornblende diorite. The country rocks are a series of slightly metamorphosed volcaniclastic breccias and sandstones and recrystallized coral limestones of Upper Tertiary 'e' age.
2. Pyrite-rich shear zones in the andesites are quite common. More rarely there are replacements of the host andesite along the shear zones, giving lenticular iron-rich lodes; these consist mainly of magnetite with minor pyrite and chalcopyrite and a little gangue epidote, chlorite, calcite, and actinolite.
3. Contact metasomatism of the limestones has also resulted in iron-rich replacement lodes. In these the assemblage is magnetite-hematite-pyrite-pyrrhotite-chalcopyrite with gangue epidote-garnet-calcite.

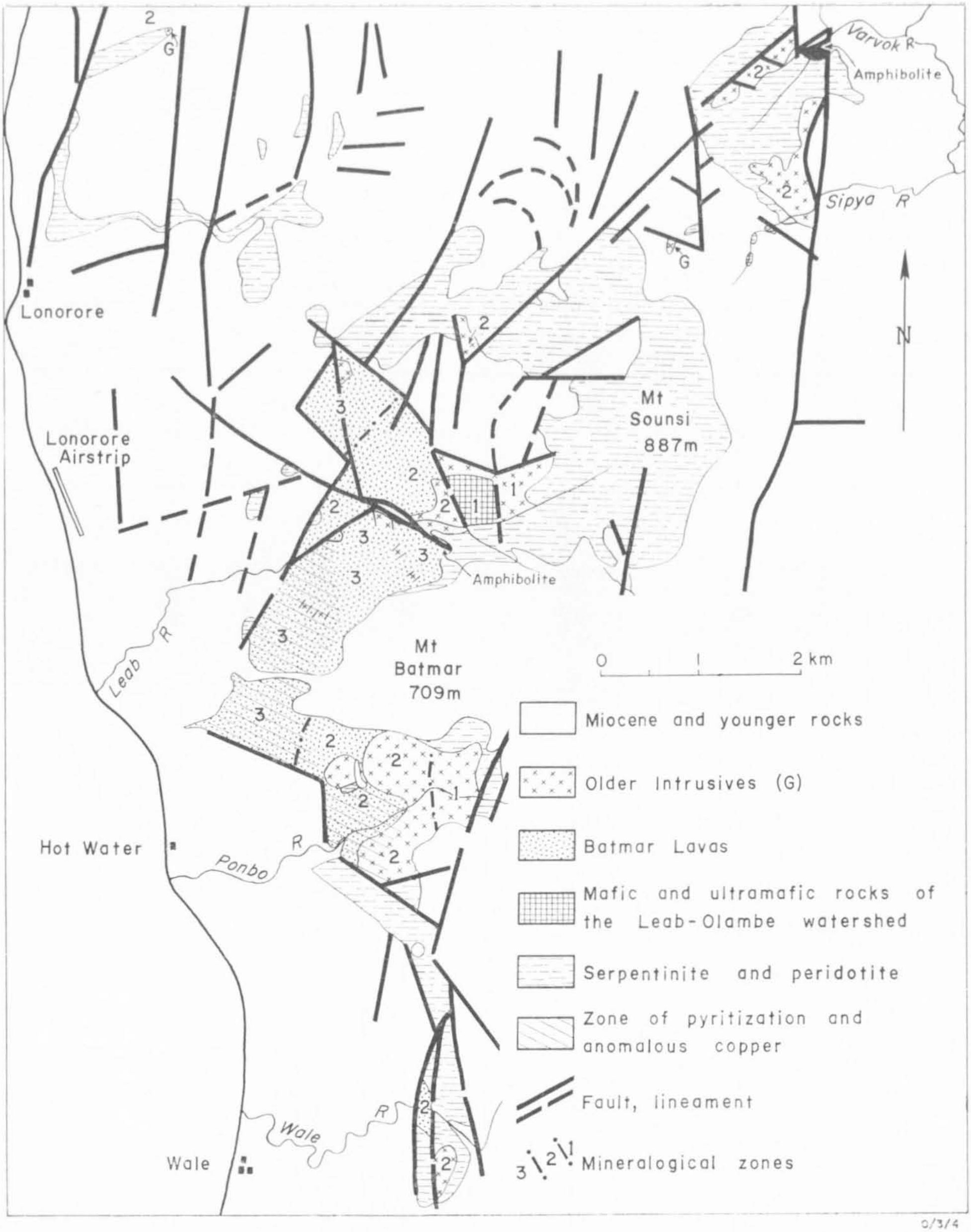

Fig. 4. The pre-Miocene of central Pentecost.

Primary magmatic sulphides occur

(i) *In gabbro*. River boulders collected from the Olambe River and probably derived from near the Leab-Olambe watershed include hypersthene gabbro (assemblage plagioclase, diopsidic augite, hypersthene, magnetite-ilmenite). Along

TABLE 2. MINERALOGICAL ZONING OF THE BATMAR METALAVAS AND THE GABBROS INTRUSIVE INTO THEM

Zone	*Assemblage*	*Position*	
1	Clinopyroxene + Ca-plagioclase ± orthopyroxene ± olivine Minor magnetite, apatite, and secondary brown hornblende	Interior of the larger gabbros	Gabbro
2	Amphibole + Ca-plagioclase ± clinopyroxene remnants Minor magnetite (or ilmenite), apatite, sphene, epidote, chlorite, and quartz	Smaller gabbros and margin of larger gabbros	Gabbro
		Inner metalavas	Batmar Lavas
3	Chlorite + epidote + Na. Ca-plagioclase + amphibole remnants ± quartz Minor magnetite, sphene, and apatite	Outer metalavas and rare small metagabbros	Batmar Lavas

TABLE 3. ANALYSES OF THE PONBO GABBRO AND BATMAR METALAVAS

	Ponbo Gabbro		*Batmar Lavas*		
Zone	1	2	2	3	3
No.	PM487	PM486	PM358A	PM458	PM476
SiO_2	48.50	46.90	48.95	54.45	60.55
TiO_2	0.12	1.04	1.87	1.34	0.83
Al_2O_3	18.85	16.45	13.65	13.95	13.50
Fe_2O_3	0.95	1.98	3.25	3.74	3.36
FeO	4.18	6.51	8.39	8.06	7.85
MnO	0.11	0.12	0.17	0.15	0.21
MgO	9.00	9.82	7.02	5.21	5.48
CaO	15.26	13.00	6.40	3.56	0.15
Na_2O	1.15	0.94	4.19	4.97	0.29
K_2O	0.12	0.22	0.83	0.19	1.27
H_2O^+	1.56	2.64	3.08	3.14	4.95
H_2O^-	0.41	0.26	1.43	0.93	0.72
P_2O_5	n.d.	0.07	0.15	0.10	0.06
CO_2	n.d.	n.d.	0.22	0.25	0.02
S	0.03	0.01	0.13	n.d.	2.01
Cr_2O_3	0.006	0.010	0.01	n.d.	n.d.
Cu	0.008	0.003	0.030	0.003	0.010
Co	0.005	0.005	n.d.	n.d.	n.d.
Ni	0.010	0.010	0.002	n.d.	n.d.
Zn	0.004	0.005	0.011	0.011	0.012
Less O ≡ S	0.02	0.01	0.05		0.75
Total	100.27	100.00	99.74	100.06	100.53

PM487 Gabbro, Ponbo River, West Pentecost. Plag + cpx + opx + (hbl)
PM486 Amphibolized gabbro, Ponbo River, West Pentecost. Plag + hbl + ilm + (sphene)
PM358A Metabasalt, Leab River, West Pentecost. Plag + cpx + mag + chl + calc
PM458 Metalava, Olambe River, West Pentecost. Plag + qtz + chl + mag + epidote
PM476 Pyritized metalava, Walo River, West Pentecost. Plag + qtz + chl + ser + pyrite
Analyst: C. H. Thomas, Institute of Geological Sciences, London.

the silicate boundaries are sulphide blebs showing a size variation sympathetic with that of the silicates and reaching a maximum length of 8 mm. Professor L. J. Lawrence recognized that they were composed mainly of pyrrhotite with blade inclusions of chalcopyrite (itself carrying a little mackinavite); also there was a little pentlandite and magnetite. Analysis of two samples fairly rich in sulphides gave only Cu 500 ppm, Ni 260 ppm and Cu 1400 ppm, Ni 400 ppm respectively.

(ii) *In pegmatite.* Small pods of quartz and rotted feldspar on the south side of Mount Batmar carry lenticles of copper sulphides, mainly of chalcopyrite cut by veinlets of covellite and chalcocite and associated with a little pyrite.

Epigenetic chalcopyrite occurs on joint planes in the Ponbo gabbro and also in veinlets with quartz and pyrite cutting the barren pyritized lavas an the west side of Mount Batmar. A channel sample across a 30 cm veinlet in the River Walo assayed 1.58% Cu. So far as is currently known the veinlets are thin and sporadic, but do offer some hope of a commercial concentration of copper. Associated with the high copper values are very low-amplitude anomalies in Zn, Cr, Mn, and Ag; but Au, Mo, and As remained below the limits of detection by atomic absorption spectrophotometer.

Sulphides associated with volcanic rocks

Barren pyrite occurs in the volcaniclastic rocks at several different horizons, for instance in the lower Miocene of southwest Santo, the upper Miocene of east Pentecost, and Pleistocene tuffs on north Efate. The quantities present are usually small.

Secondary copper staining, usually of green malachite, is known from several localities in the Pleistocene and Recent subaerial volcanoes northwards from Efate and is associated with a generally high background Cu in these rocks. The background Cu in the lower Miocene basalts of Malekula, for instance, is usually less than 100 ppm, but in basalts from the Central Chain it is considerably higher, reaching 200 ppm on Vanua Lava; 300 on Aoba; 460 on Mataso; 370 on Nguna; and 270 on north Efate.

On north *Efate* Aubert de la Rue (1939) recorded covellite, chalcocite, malachite, and chrysocolla with quartz and barytes in veins cutting andesitic breccias. Obelliane (1961) in addition recorded chalcopyrite, pyrite, and manganese oxides. One grab sample from this area assayed 4% Cu and 74 grains/ton Au (Williams & Warden, 1964).

Sulphides, some bearing copper, have also been identified among the products of the phreatic eruption of the submarine volcano Karua on 22 February 1971. The major products of the eruption were scoriaceous and pumiceous hypersthene andesite containing 55-57% SiO_2 and 120-150 ppm Cu. Some of the rocks were highly altered, consisting of assemblages of clay minerals with some interstitial and vesicular zeolites, pyrite, and native sulphur. Among the metallic minerals Professor L. J. Lawrence identified mainly pyrite, with traces of magnetite, covellite, rutile, and primary marcasite. Like the older pyritized rocks of Santo, Malekula, and Pentecost, those of Karua are poor in Cu: one sample with about 5% pyrite contained 120 ppm Cu—no more than non-pyritic fresh andesite pumice.

Sulphur

Small quantities of fumarolic sulphur are associated with each of the active volcanoes of the New Hebrides, but only on Vanua Lava are there appreciable quantities in two deposits, Frenchman's and Whitfords. The sulphur occurs mainly as small conical mounds around gas vents high on the southeast flank of the island. Around the sulphur mounds the basalt lavas are altered to white and grey clay minerals and silica, and contain veinlets and blebs of sulphur close to the fumaroles. Owen (1951) revised the earlier estimates of J. J. Rendle (1 500 000 tons) and Church (4000 tons; 1932) suggesting that the larger, Frenchman's, deposit did not contain more than 200 tons of comparatively pure sulphur. A more recent estimate by Ash (in prep.) gave a similar low estimate of 230 tons for Frenchman's and 15 tons only for Whitford's deposit.

Manganese

Warden (1971) has recently assembled data on manganese mineralization throughout the New Hebrides. Small amounts of manganese occur on most of the islands but, although several deposits have been proved to contain appreciable tonnages of ore (mainly todorokite with minor polianite and pyrolusite), only at Forari on Efate has commercial exploitation been undertaken.

The following modes of occurrence of manganese are recognized:

a. *Primary—epigenetic.* Veinlets of carbonate with todorokite and pyrolusite occur in massive hornblende andesite on *Hiu* in the Torres Islands. Noesmoen of Bureau de Recherche Géologique et Minière (1963) regarded the manganese oxides found on *Maewo* in inter-pillow spaces and lining vesicles as of primary epigenetic origin.

b. *Primary—syngenetic.* The extensive, rather low grade or phosphorus-rich, deposits of manganese oxides on *Erromango,* estimated to contain 1 173 000 metric tons of metallic manganese, were regarded by Lemaire (1965) as being essentially of syngenetic origin. He recognized a Raouisse type (averaging 35% Mn) in which the manganese is concentrated in lagoonal deposits behind a barrier reef (Fig. 5A), and a mineralized clay type (averaging 8% Mn) in which finely divided manganese oxides occur in patches in clay deposits on a marine terrace seawards of the scree deposits forming the back of the terrace (Fig. 5B). The manganese, occurring mainly as todorokite with minor primary and secondary polianite, is thought to have been derived from the volcanic rocks of Erromango by leaching during tropical weathering and deposited subsequently in a near-shore marine environment.

c. *Secondary*—At Forari mine on Efate the manganese, mainly in the form of nodular and banded todorokite, occurs at the base of the soil profile on latitic tuff beds and at the contact of the tuffs with the overlying Pleistocene reef limestone (Fig. 6). Warden (1970) concluded that the Forari manganese was predominantly of supergene enrichment origin, having been derived by leaching during weathering of the latitic tuffs in the interior of Efate, transported in solution, and precipitated in a well oxygenated environment mainly as higher valency oxides.

The ore occurs in one, or two closely separated, layers, rarely totalling as much as 1 m in thickness. During the first five years of production Compagnie

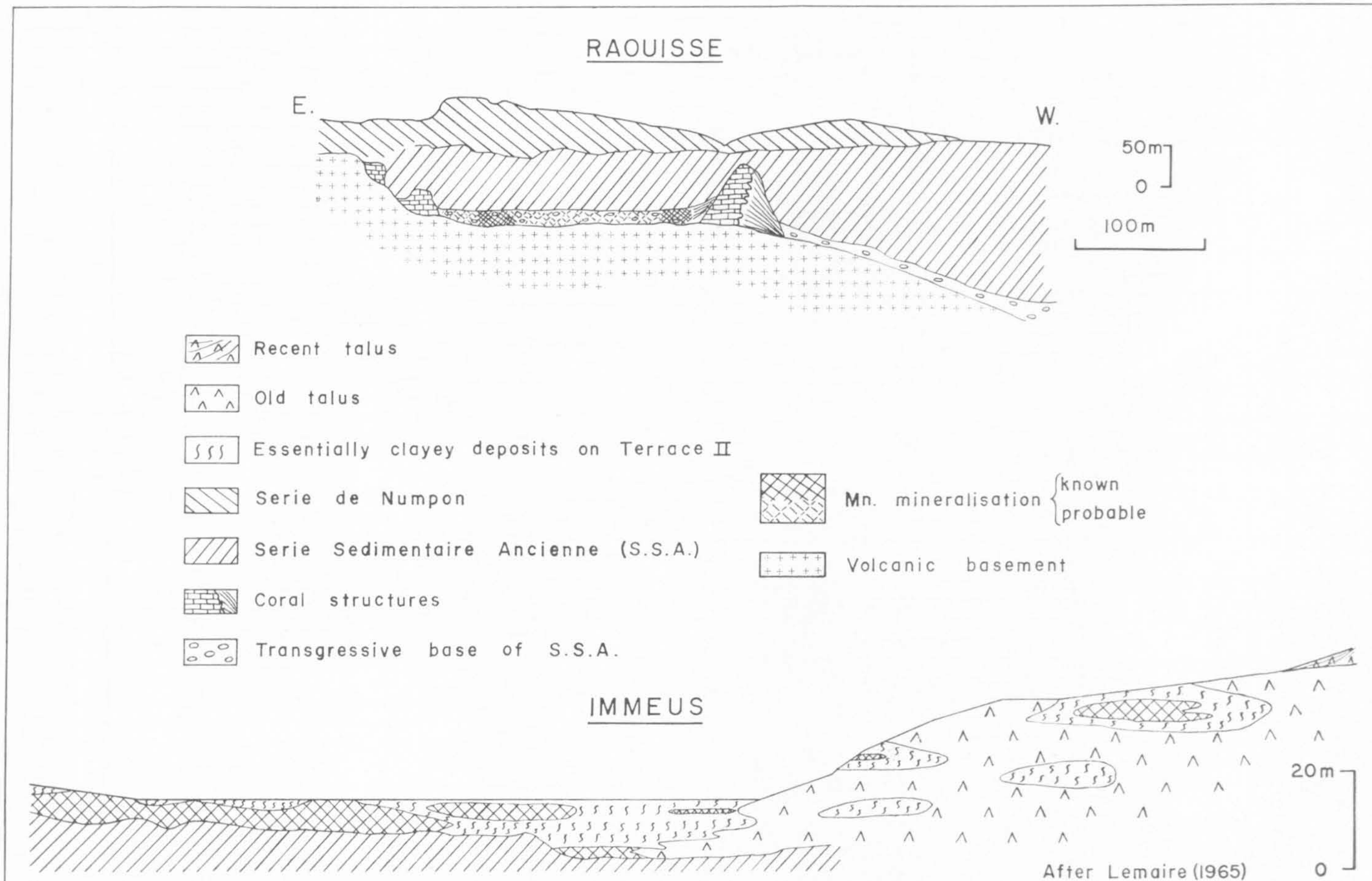

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Fig. 5. Sections Raouisse and Immeus.

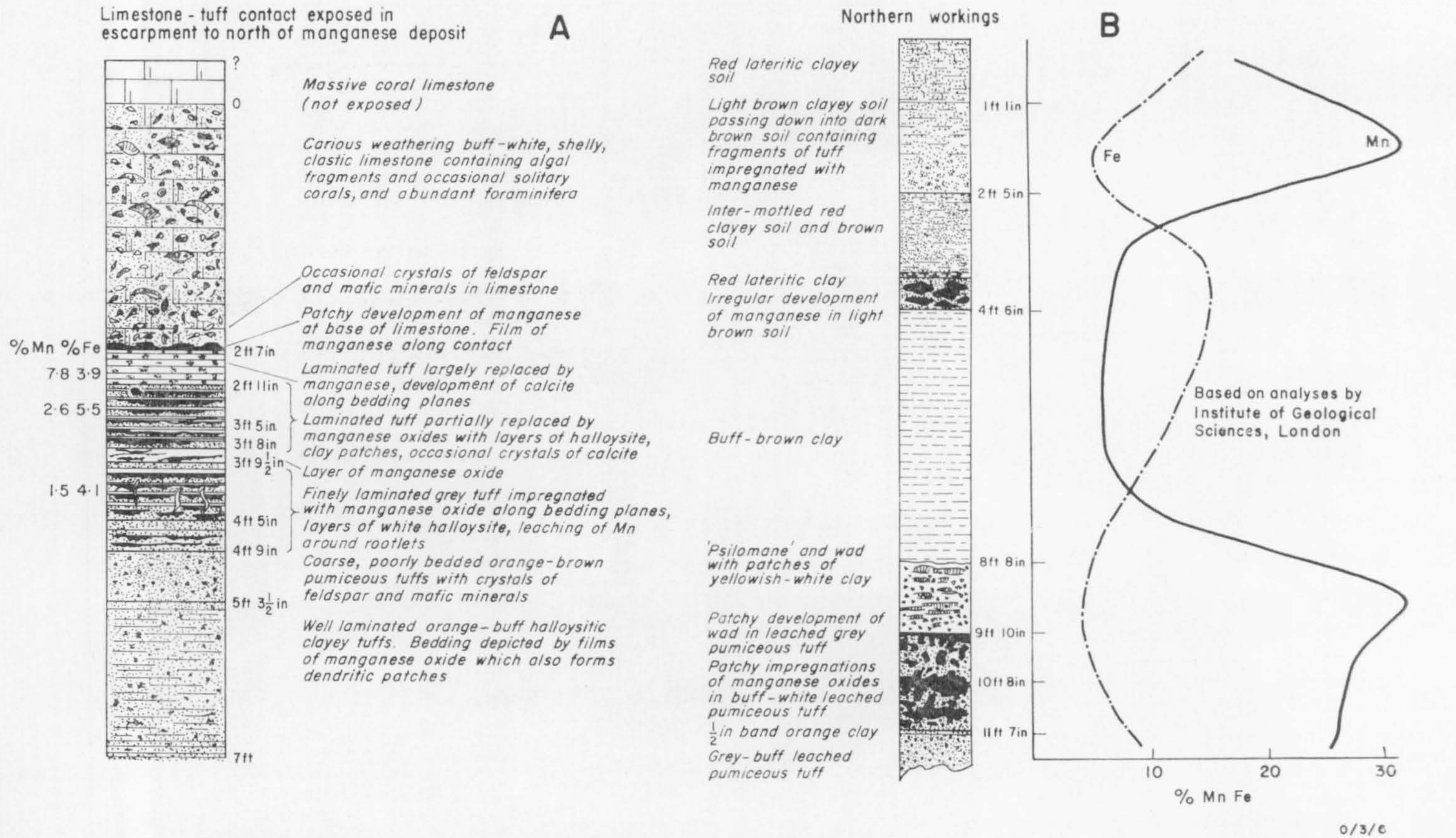

Fig. 6. Sections.

Française des Phosphates de l'Océanie obtained approximately 350 000 metric tons of concentrates averaging about 41% Mn, most of which was sold after sintering which raised the tenor to about 50% Mn.

The manganese deposits of the New Hebrides are of nearshore or onshore origin and are consequently poor in Cu, Ni, and Co, especially as compared with deep oceanic nodules.

Bauxite

Small quantities of gibbsite are now known from the soils of a number of islands, mainly from the limestone plateaux but also from volcanic rocks.

On the Limestone Plateaux. Terraced limestones are developed on all the islands except those of the northern half of the Central Chain. The most extensive areas are on *east Santo, northwest Malekula, north Pentecost,* and *Efate,* where up to seven terrace levels extend between sea level and somewhat over 900 m. The limestone terraces, mainly reef-capped wave-cut platforms, are generally little dissected but bear thick clayey soils up to 8 m thick on a solution-pitted limestone surface. The soils consist mainly of the clay minerals kaolinite and halloysite (or metahalloysite) together with some amorphous aluminosilicate gel, goethite, quartz, and, in some, a little gibbsite. Maximum values of 'available' Al_2O_3 (obtained by digesting 10 g of sample in 100 ml 13.5% NaOH for 15 min at 180°) obtained so far from initial reconnaissance of the limestone plateau soils of the Torres Islands are 11%, Santo 5%, Malekula 3%, Efate 5%, and Pentecost 24%. No analyses are yet available of the SiO_2 content of these soils, but it is bound to be high in view of the predominance of clay mineral.

The highest contents of gibbsite and 'available' Al_2O_3 are from the main limestone plateau of Pentecost (the best profile so far obtained is shown in Fig. 7), where it is evident that the soils are mainly derived from the weathering of airfall tuffs resting on the limestone plateau. In some bands in the soil profile the original tuffaceous and pumiceous texture is preserved. It is perhaps surprising that such material, which is very young (postdating the Pleistocene limestones on which it rests) and very little stratified visibly, should have produced such gibbsitic soils. The fall of fine dust from Ambrym down the prevailing wind on Malekula during Holocene times with even less time for weathering and differentiation of a soil profile may be at least a contributory factor in explaining why the Malekula limestone plateau soils are so poor in 'available' Al_2O_3.

On Volcanic Rocks. Little work has yet been done to investigate the soils on the volcanic rocks of the New Hebrides away from the limestone plateaux. Such soils are composed largely of clay minerals; for example a well stratified soil profile on basaltic lavas of southeast *Erromango* consisted only of kaolinite, minor metahalloysite, amorphous aluminosilicate material, goethite, and limonite (Morgan, McKissock, & Bain, 1969). Gibbsite has been recorded from volcanic rock soils only on *Ureparapara,* a Quaternary volcanic cone in the Banks Islands. A profile taken from the outer slopes of the volcano on the north-northeast side near the crater rim indicated up to 20% gibbsite in the upper 40 cm of soil, but none below that, where the soil was dominantly kaolinitic (Morgan & Bain, 1966).

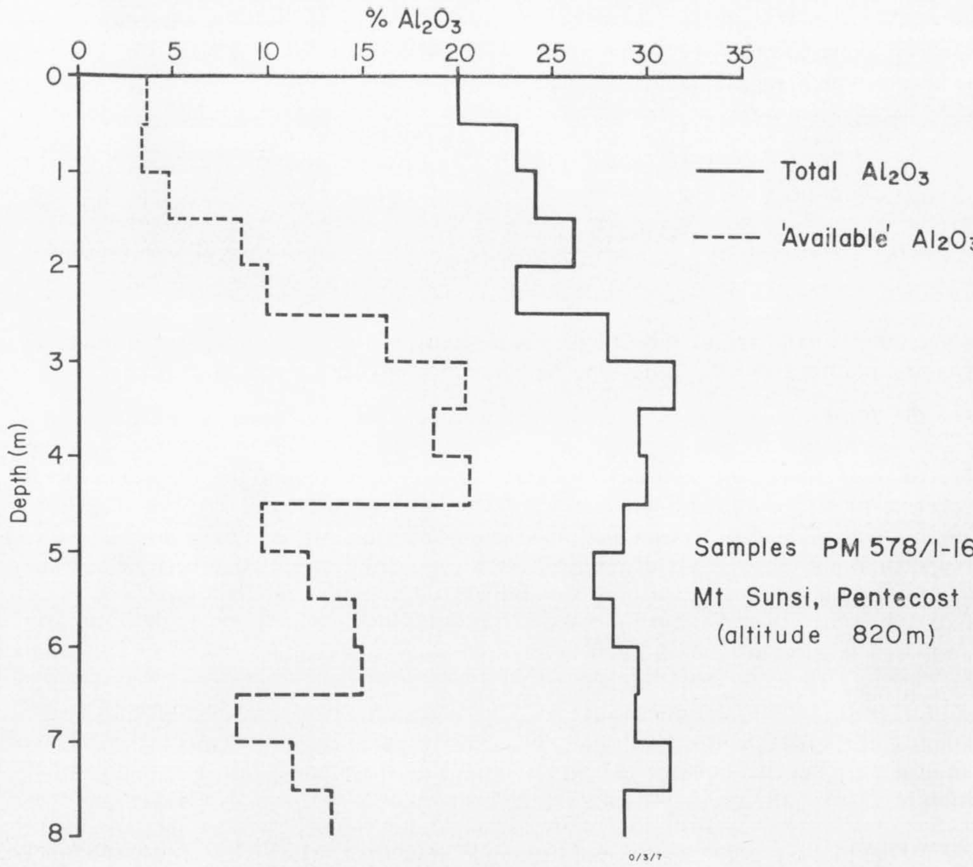

Fig. 7. Pentecost limestone soil.

Beach Sands

Black beach sands occur on most of the islands, but are generally very small and contain only a small proportion of magnetic materials, the dominant constituents being small rock particles and pyroxenes. No detailed mineralogical work has yet been done on beach sands in the New Hebrides, but it seems most likely from the few analyses so far available that the dominant constituent of the magnetitic fraction generally is a titaniferous magnetite.

The heavy sands may occur on the present beaches or older raised beaches; the largest concentrations known at present are on the south and west coasts of Santo (the former is at present under investigation by a commercial company). Smaller volumes of beach sand, rich in magnetic components, also occur on south Vanua Lava and west Gaua, on Epi, and in Cook Bay, Erromango. Table 4 gives analyses of magnetic concentrates from the present beach in Cook Bay and the raised beach about 3 m above sea level on the west coast of Santo. It shows that the concentrates are essentially similar, although there is an appreciable difference in their Cr contents. The Cook Bay material was derived from tholeiitic basalt and basic andesite of Plio-Pleistocene age; that from west Santo from dominantly basic andesite with some basalt of late Oligocene to early Miocene age.

TABLE 4. MAGNETIC CONCENTRATES FROM BEACH SANDS

	Cook Bay, Erromango ErA 59J/m	West Santo SM 30b/2
Fe	60.0%	57.1%
Ti	4.0%	5.05%
Cu	70 ppm	45 ppm
Pb	10 ppm	10 ppm
Zn	270 ppm	320 ppm
Co	140 ppm	150 ppm
Ni	110 ppm	130 ppm
Cd	6 ppm	6 ppm
Cr	680 ppm	340 ppm
Mn	1800 ppm	2200 ppm

Conclusions and Prospects

Most of the results of the search for mineral deposits in the New Hebrides have been held confidential on company files; very few data have been published. The comments which follow are based on data from reconnaissance investigations, not on detailed surveys.

As might be expected from comparison with other young island arcs the range of types of mineral deposit found in the New Hebrides is small, and the prospects of finding deposits of economic size and grade are limited.

The proximity of the New Hebrides to the nickel-producing ultramafites of New Caledonia has offered some hope of commercial nickel deposits on Pentecost. However, in view of the small size of the outcrops of the Pentecost ultramafites, their high-level plastic deformation in the gravity creep mantles rather than brittle fracturing, the lack of sulphides, and the youth and general immaturity of the soil cover, the prospects of finding a nickel orebody of a presently acceptable grade and size are not good. Reconnaissance investigations have shown a mild degree of nickel enrichment in the soils. Small quantities of asbestiform serpentine are found in massive blocks in the gravity creep mantles but offer little hope of substantial concentrations near the surface.

The possibilities of association of base metals, especially copper, with the subvolcanic intrusions of Malekula and Santo are at present being investigated (by Bureau de Recherche Géologique et Minière), and probably constitute, with the deposit described from Pentecost, the best chances for commercial concentrations of copper and pyrite. The copper prospects of the more recent volcanics of the Central Chain, whose basalts are now known to contain abnormally high background copper, have not yet been investigated thoroughly.

The deposits of sulphur on Vanua Lava are much smaller than was originally estimated and are of little commercial interest.

Manganese is currently being extracted at Forari on Efate by a consortium headed by Southland Mining Co. Ltd. Substantial deposits also exist on Erromango, and other occurrences, of various sizes, are known from many of the other islands. For the present, however, with the depressed price of manganese none offers a commercial prospect.

Investigations of bauxite soils are just beginning and very little is known as yet. Up to 40% gibbsite has been proved in soils (probably mainly derived from airfall tuffs) on the limestone plateaux by reconnaissance surveys, but virtually no work has so far been undertaken on soil profiles developed on volcanic rocks away from the influence of limestone. The outlining of three commercial bauxite prospects in the Solomon Islands (Rennel, Wagina, and New Georgia) must offer some hope of similar concentrations in the New Hebrides.

The only material likely to be of interest in the heavy mineral sands is titaniferous magnetite; substantial quantities may be present along the coasts of several islands, but they are only just beginning to be investigated.

Acknowledgments

This contribution is based largely on the work of the New Hebrides Geological Survey, to whose staff, past and present, the author is indebted. The special investigations undertaken by the Mineralogical Unit of the Institute of Geological Sciences, London, and the ore-mineral identifications provided by Professor L. J. Lawrence of the University of New South Wales are gratefully acknowledged. The writer is indebted to the editor of the Transactions of the Institution of Mining and Metallurgy for permission to reproduce in Figure 6 parts of two diagrams which formerly appeared in that journal (Warden, 1970).

References

Ash, R. P., in prep.—Geology of the northern Banks Islands. *N. Heb. geol. Surv. Rep.*

Aubert de la Rue, E., 1935—Premiers résultats d'une mission géologique aux Nouvelles-Hébrides. *C.R. Acad. Sci. (Paris)*, 200, 681-3.

Aubert de la Rue, E., 1937—Les gisements d'or de la Mélanésie. *Sciences (Paris)*, 183-92.

Aubert de la Rue, E., 1939—Les minéraux des Nouvelles-Hébrides. *Bull. Mus. nat. Hist. natur. (Paris)*, Ser. ii, 11, 342-8.

Church, K. C., 1932—Sulphur-Whitford Estate—Vanua Lava. *Rep. to Broken Hill Pty Co. Ltd*, 13 Jan. 1932 (unpubl.).

Guillon, J.-H., 1969—Données nouvelles sur la composition et structure du Grand Massif péridotitique du sud de la Nouvelle-Calédonie. *Cah. O.R.S.T.O.M., Ser. Géol.*, 1, 7-26.

Lemaire, B., 1965—Étude géologique de l'île Erromango (Nouvelles-Hébrides), métallogénie locale du manganèse. *Bur. Rech. géol. Min. Mem.* 38.

Mallick, D. I. J., and Neef, G., in prep.—Geology of Pentecost. *N. Heb. geol. Surv. Rep.*

Mallick, D. I. J., 1970—Pentecost. *N. Heb. geol. Surv., ann. Rep. for 1969*, 14-15.

Mitchell, A. H. G., and Warden, A. J.,—Geological evolution of the New Hebrides Island Arc. *J. geol. Soc. London* (in press).

Morgan, D. J., McKissock, G. M., and Bain, J. A., 1969—Mineralogical examination of possible bauxitic clays from the New Hebrides. *Inst. geol. Sci. London, Miner. Unit Rep.* 49.

Morgan, D. J., and Bain, J. A., 1966—Examination of profile samples from Ureparapara Island, New Hebrides, for the presence of gibbsite. *Overseas geol. Surv. London, Miner. Res. Div., spec. Rep.* 234.

NOESMOEN, A., 1963—Compte-rendu de tournée sur l'île de Maévo. *Bur. Rech. géol. Min. (Nouméa), Rep.* AN/EJ, Nov. 1963 (unpubl.).

OBELLIANE, J.-M., 1961—Contribution à la connaissance géologique de l'Archipel des Nouvelles-Hébrides (Iles Vaté, Pentecôte, Maéwo, Santo). *Sci. Terre,* 6(3-4), 139-68.

OWEN, H. B., 1951—A geological reconnaissance of the New Hebrides. *Bur. Miner. Resour. Aust. Rec.* 1951/61 (unpubl.).

THOMPSON, R. B., 1960—Ultrabasic rocks of the Solomons. *Ph.D. thesis, Univ. Sydney* (unpubl.).

WARDEN, A. J., 1970—Genesis of the Forari manganese deposit. New Hebrides. *Trans. Instn Min. Metall.,* 79, B30-B41.

WARDEN, A. J., 1971—Manganese mineralisation in the New Hebrides. *N. Heb. geol. Surv. Rep.*

WILLIAMS, C. E. F., and WARDEN, A. J., 1964—Progress report of the Geological Survey for the period 1959-1962. *N. Heb. geol. Surv. Rep.*

THE HILTON DEPOSIT—STRATIFORM SILVER-LEAD-ZINC MINERALIZATION OF THE MOUNT ISA TYPE

by B. V. Mathias, G. J. Clark, D. Morris, and R. E. Russell

Mount Isa Mines Limited

SUMMARY

The Hilton Mine is situated 20 km north of Mount Isa in northwestern Queensland in Proterozoic sediments of the Mount Isa Group. The deposit is currently being developed for production of silver-lead-zinc ore by 1978.

The Mount Isa Group sediments (Middle Proterozoic) lie in the east limb of a major north-plunging syncline. In the Hilton area they dip between 50° and 80° to the west. The ore deposit occurs within the Urquhart Shale, a formation near the top of the Mount Isa Group, in which the Isa Mine silver-lead-zinc and copper ores also occur.

The Urquhart Shale is a thinly bedded dolomitic, tuffaceous, and carbonaceous shale with abundant fine-grained pyrite. The galena and sphalerite ore, which resembles that at Isa Mine, occurs as concordant bands associated with the pyritic beds. Prominent siliceous limonite gossans are developed over both deposits and reflect the high pyrite content of the fresh shale. Apart from scattered irregular veinlets of crystalline dolomite, 'silica-dolomite', the host rock for the copper mineralization at Isa Mine, has not yet been recognized at Hilton Mine.

INTRODUCTION

A large proportion of the world's silver-lead-zinc resources come from deposits where sulphide assemblages are concentrated in bands that are concordant with the bedding of the enclosing sediments, and, unlike non-stratabound types, they are restricted to a relatively small stratigraphic thickness when compared with their very broad areal distribution.

One of the finest examples of a concordant deposit is that of Mount Isa, in the Precambrian Shield of the northwestern part of Queensland, Australia. Fixed location is latitude 20°47′ south, longitude 139°29′ east. Some 20 km north of the Mount Isa deposit, Mount Isa Mines Limited is currently exploring and opening up the new Hilton Mine, at which narrow elongate bedded silver-lead-zinc orebodies occur in tuffaceous, dolomitic shales and are associated with fine-grained pyrite. The Hilton deposit is known only from diamond drill core and a series of shallow exploratory prospect shafts. This paper outlines the geology of the Hilton area and highlights similarities and differences between it and the Mount Isa silver-lead-zinc deposit.

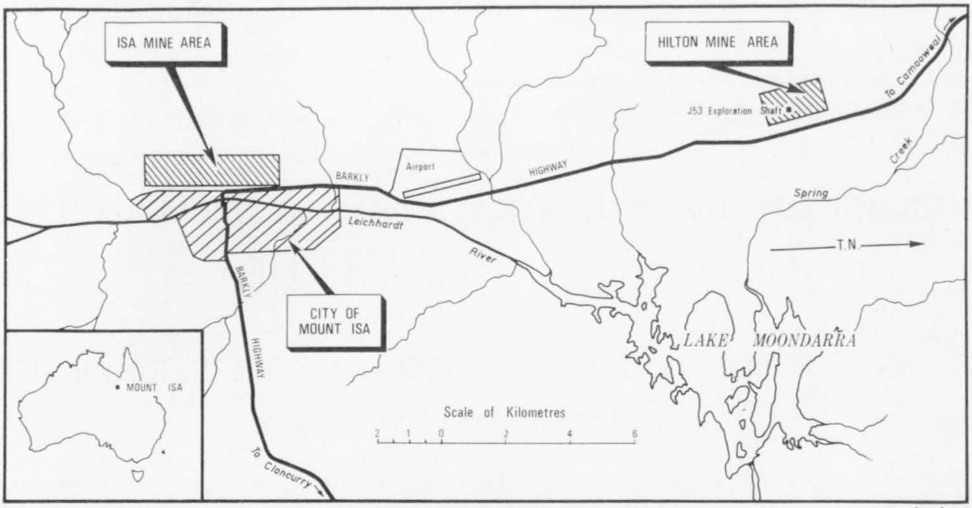

Fig. 1. Locality map, Mount Isa-Hilton. F54/A/22

History of Exploration

Although it was generally recognized as an interesting prospect, little work was done in the Hilton area before, in mid-1947, Zinc Corporation Ltd was granted two substantial authorities to prospect north and south of the then existing Mount Isa Mines Lease.

A brief reconnaissance survey resulted in Mount Isa Mines Limited's application for an Authority to Prospect over an area of 76 square miles (195 km^2), immediately north of the Zinc Corporation A to P, covering the Hilton area and extending eastwards over the area presently covered by Lake Moondarra.

Diamond drilling first began at Hilton in August 1948. The first hole intersected 5 feet (1.5 m) of 2.6% Pb, 8.2% Zn, and 10 feet (3 m) of 5% Zn, enough to confirm the promise indicated by the gossanous outcrops in the area. Detailed surface mapping had indicated significant cerussite outcropping on two of these gossanous ridges.

From August 1948 to June 1957 a large program of diamond drilling was carried out. In late 1950 a series of prospect shafts was started to probe the mineralization at depth. Water and mining difficulties resulted in all but two of these shafts stopping at the water table level, 40-55 m below the surface. Two shafts were extended, one to 120 m and the other to 180 m, and intersected primary sulphide.

The picture that emerged by 1957 was one of extensive but rather low-grade zinc-rich mineralization occurring in narrow pyritic lenses as at Mount Isa. In 1957 a fall in metal prices, together with heavy capital expenditure at Mount Isa Mine, caused the curtailment of all exploration and development at Hilton.

Apart from several geophysical and geochemical surveys over the area, there was little activity at Hilton from June 1957 to March 1966. Detailed drilling recommenced in 1966 and results to date have outlined ore reserves of 35 000 000 tons at 5.8 oz Ag, 7.7% Pb, 9.6% Zn. Sinking of a 4.3-m diameter exploratory shaft designed to a depth of 630 m began in June 1970. This shaft will give access to the orebodies, and provide bulk samples for metallurgical testing and sites for underground drilling.

Stratigraphy

The stratigraphy of the environs of the Hilton Mine can be described in terms of four major rock units:

Eastern Creek Volcanics, the oldest;

Judenan Beds, lying west of the Mount Isa Fault;

Myally Beds, time equivalents of the Judenan Beds, lying east of the Mount Isa Fault;

Mount Isa Group, the youngest.

In addition, the Sybella Granite batholith approaches to within 4 km west of the Hilton Mine, and numerous dolerite dykes occur in the area and in the mine. These units were defined by Carter et al. (1961).

Structurally, the Hilton Mine lies, like the Isa Mine*, on the eastern limb of a major regional syncline. Axial plane to this syncline is the major Mount Isa Fault, which has removed Mount Isa Group sediments from the western limb. Numerous faults lead to several repetitions and some omissions in the sequence. Structural deformation, on all scales, appears to be more complex in the Hilton area than near the Isa Mine, and the Mount Isa Group is much thinner. Nevertheless, the similarities of the stratigraphic and tectonic setting of the two mines are striking.

Eastern Creek Volcanics

Several metavolcanic-metasedimentary sequences are known in the Mount Isa-Hilton area. Despite their diverse metamorphic grade and structural settings, all are now regarded as probable Eastern Creek Volcanics. In several areas to the east of Hilton the unit consists of massive metabasalts and metasediments. It also occurs in two greenstone fault blocks near the Mount Isa Fault and in an area of amphibolites near the Sybella Granite.

Outcrops East of Hilton Mine. East and northeast of Hilton Mine lie Eastern Creek Volcanics very similar to those of the type area east of Mount Isa. They have been subdivided by Robinson (1968). In this area the formation consists mainly of massive metabasalt, often amygdaloidal, with some tuff, breccia, and weakly metamorphosed sediments. Metamorphism has reached the chlorite zone of the greenschist facies in the metabasalt, which consists essentially of albite, chlorite, epidote, actinolite, and quartz, with occasional relict igneous textures and minerals. Schistosity is weakly developed. The sediments are relatively little affected by metamorphism.

The Lena Quartzite member in the Eastern Creek Volcanics consists predominantly of creamy feldspathic quartzite with dolerite at the base, and forms a

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* Both the new Hilton Mine and the old mine at Mount Isa are within a single 'Mount Isa' lease. To distinguish them, they are now referred to as Hilton Mine and Isa Mine respectively.

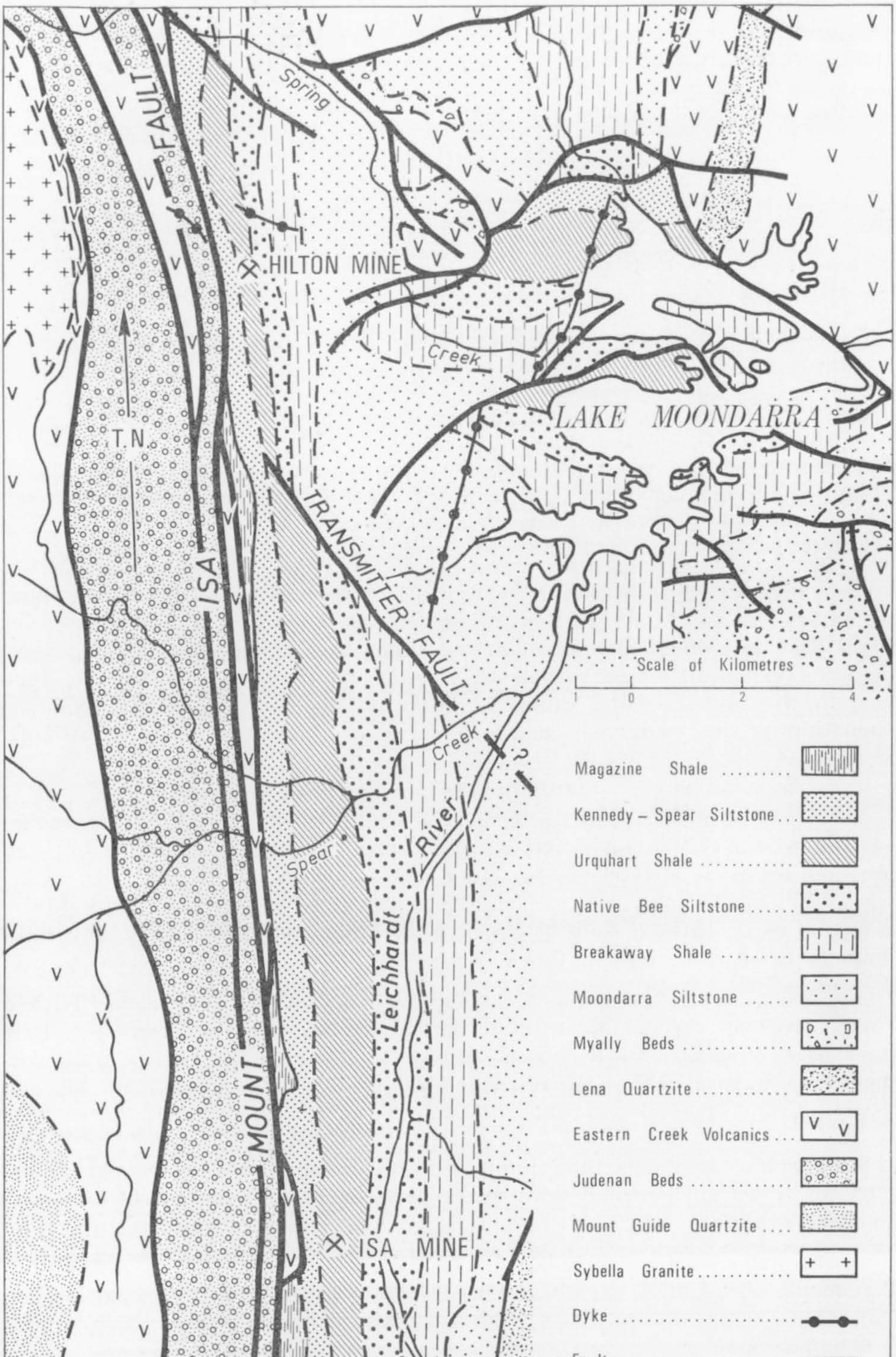

Fig. 2. Generalized geology, Mount Isa-Hilton area. F54/A/23

valuable marker horizon. It is about 600 m thick and lies near the top of the sequence.

The Western Greenstone. This occupies a similar position to the western greenstone at Mount Isa, lying between the Mount Isa Group and Mount Isa Fault. It is strongly sheared throughout, being caught between two closely spaced strike faults.

This unit consists dominantly of chlorite zone metavolcanics and metasediments. In drill core, the greenstone usually has a strongly banded fabric in which pale albite-calcite bands alternate with green chloritic bands. Quartz, sericite, epidote, actinolite, and opaque iron oxides are also present. The rock is usually phyllitic or schistose, but some massive metabasalt is present.

Sediments include well bedded siliceous and dolomitic siltstones up to 15 m thick. One bed in particular, termed the 'siltstone marker', has been traced over more than 5000 m on the surface and has been found in every drill hole passing through the greenstone. Over long distances, it is subparallel to the faulted contact of the greenstone with the Mount Isa Group, and usually lies 5-20 m west of it. The bed is strongly sheared and commonly brecciated. The greenstone lies between two major strike faults which diverge northwards from Hilton. North from Spring Creek it changes into massive metabasalt. Since there is no known structural break between greenstone and metabasalt, it is logical to assign the greenstone at Hilton to Eastern Creek Volcanics. This applies also to the similar greenstone west of Mount Isa, described in Bennett (1965).

Greenstone west of the Mount Isa Fault. A valley of greenstone and metasediments lies within the Judenan Beds 450 m west of the Mount Isa Fault. The rocks of this valley include sheared metabasalt and metadolerite, sericite-quartz schist, bedded micaceous quartzite, and minor massive quartzite. This sequence is similar in mineralogy to the western greenstone except for the presence of biotite.

On air-photographs of the area, slightly divergent trends can be seen in places between the greenstone and the surrounding quartzite of the Judenan Beds. These have not been detected on the ground, where the contacts are strongly sheared. The Judenan Beds elsewhere do not contain basic metavolcanic-metasedimentary sequences corresponding to this sequence, which strongly resembles Eastern Creek Volcanics. The valley is most probably a fault block of Eastern Creek Volcanics within the Judenan Beds.

The Amphibolites. West of the Judenan Beds a band of hornblende-plagioclase amphibolite and associated cordierite-bearing schist borders the Sybella Granite. These rocks represent the highest grade of metamorphism recognized in the Eastern Creek Volcanics.

Judenan Beds

Generally, in the immediate Hilton area the Judenan Beds consist of metamorphosed medium to fine-grained feldspathic arenites. The rocks are well bedded and strongly foliated parallel to the bedding. Thin micaceous beds alternate in many places with the more arenaceous beds. The rocks are composed mainly of quartz, microcline, and sericite or muscovite.

West of Tombstone Hill and extending north for at least 3000 m is a band of up to 100 m thick consisting mainly of phyllite, which forms a valley parallel to the Mount Isa Fault and about 100-200 m west of it. The band represents a silty or shaly horizon in the arenites, and consists mainly of quartz, sericite, and some chlorite.

Myally Beds

The Myally Beds, strongly feldspathic quartzose sediments, are more silty than the time-equivalent Judenan Beds, and are very weakly metamorphosed. The nearest occurrences to Hilton are in the Spring Creek fault blocks 3 km east of the mine.

The Mount Isa Group

The Mount Isa Group, and especially the Urquhart Shale within it, is the host for both the Mount Isa and Hilton deposits. It was defined as a formation, the Mount Isa Shale, in Carter et al. (1961), and elevated to a group and subdivided in Bennett (1965). Apart from adding the 'Quartzite Marker' to the base of the Group (Bennett, 1970), no changes have been made since then.

The Mount Isa Group strikes north-south and dips on the average 60° west. It rests disconformably and in places unconformably on the Myally Beds and Eastern Creek Volcanics, and the top of the sequence is everywhere faulted off. It has not been found west of the Mount Isa Fault.

The sequence in the group at Hilton is very much thinner than in the type sections. The thinning is probably due to slower sedimentation rather than to internal strike faulting or to disconformities.

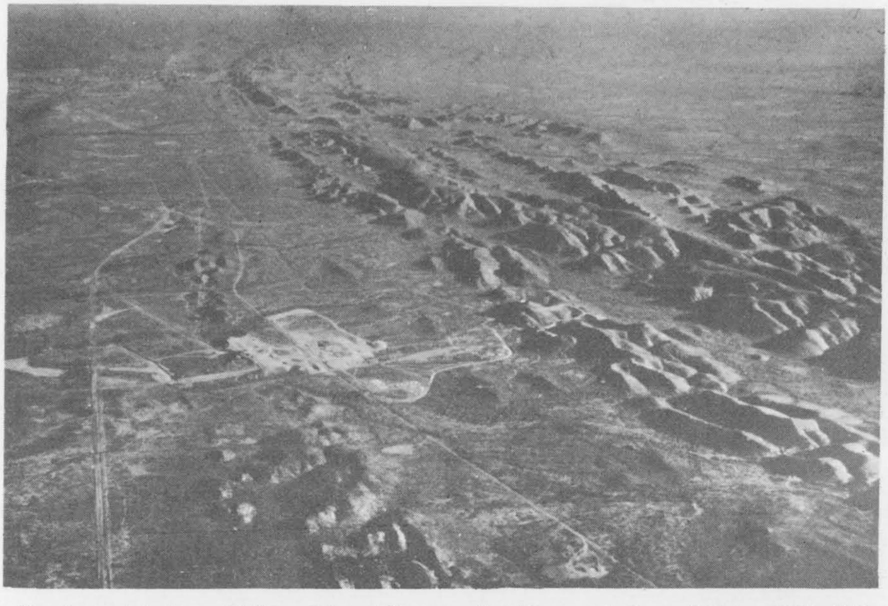

Fig. 3. Aerial view of Hilton/Mount Isa area. Looking south from Thirteen Mile Hill.

Moondarra Siltstone

The basal unit of the Mount Isa Group is the Moondarra Siltstone, which in the Hilton area consists of poorly outcropping dolomitic siltstone and shale. The true thickness in this area cannot be estimated owing to extensive folding and faulting.

Near Mount Isa the formation also consists of poorly outcropping dolomitic siltstone and shale, and is about 1220 m thick. Elsewhere, dolomite, siliceous dolomite, siliceous sandstone, and quartz arenite can be found in the sequence. An orthoquartzite and conglomerate sequence known as the 'Quartzite Marker' may form a basal member of this formation.

Breakaway Shale

The Breakaway Shale forms a line of rugged ridges and hills. It consists of thin-bedded, strongly cleaved, carbonaceous siliceous shale, with minor siltstone and chert beds. Weathered surfaces are light grey and excavations to about 20 m have exposed bleached white shale. Fresh material is black owing to abundant carbon. Near the top of the sequence carbon masks bedding, and only occasional non-carbonaceous beds, 1 or 2 mm thick, can be seen.

The Breakaway Shale is remarkably uniform in all known outcrops over a strike length of more than 50 km.

Native Bee Siltstone

The Native Bee Siltstone outcrops poorly. In outcrop the dominant rock type is a well bedded dolomitic siltstone, commonly with ferruginous bands. Cherty beds are prominent at some horizons. Total leaching extends in places to 130 m, and partial leaching to greater depths.

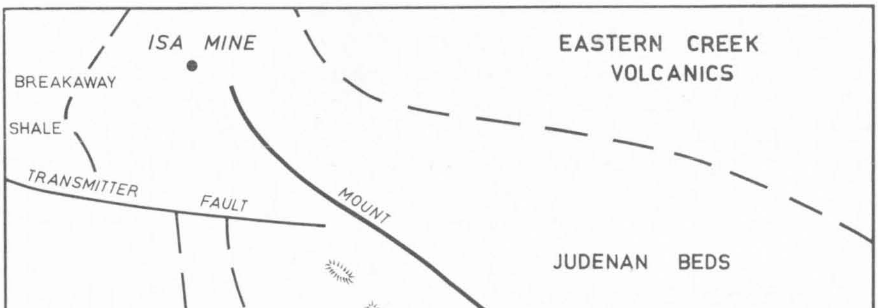

Fig. 3a. Simplified geology as depicted by figure 3, opposite.

The two main rock types in fresh ground have been called 'zebra shale' and carbonaceous shale. Zebra shale is a distinctive rock consisting of alternating white and dark beds. The white beds of calcite are usually about 5-15 mm thick, whereas the dark beds, consisting of carbonaceous quartz dolomite layers, are generally 10-50 mm thick. Microcline is a variable, usually minor, component. The alternation is probably a primary sedimentary feature, reflecting rhythmic alternations in the chemistry of the depositional environment.

The carbonaceous shale consists of dark grey coarse-bedded shale and siltstone, composed essentially of dolomite, calcite, quartz, microcline, and carbon. Possibly it represents a variant of zebra shale in which carbon also occurs in, and masks, calcite layers. Alternatively, it may represent an environment where excess carbon inhibited calcite formation. It is considerably less siliceous than the Breakaway Shale.

A layer of carbonaceous shale about 2-10 m thick near the top of the Native Bee Siltstone sequence is distinctive, with coarse-grained pyrite euhedra up to 10 mm across. This layer also contains concretions consisting of radiating crystals of calcite within the predominantly dolomitic sediments. The concretions appear to be either primary deposition or diagenetic features and may have maximum dimensions of about 30 mm. The concretions appear to be entirely restricted to this horizon, but the pyrite euhedra occur in smaller sizes and concentrations elsewhere.

Vitric tuff beds similar to those in the Urquhart Shale (Croxford, 1964) have been found in the zebra shale. They form useful marker horizons, and seem to be much more common in this unit than had been supposed from work at Mount Isa. Limited drilling into Native Bee Siltstone at Mount Isa has found only the carbonaceous shale, but zebra shale has been found farther south.

Urquhart Shale

As at Isa Mine (Bennett, 1965), the Urquhart Shale is of paramount importance, being host to all the known ore mineralization. The formation ranges in thickness from 250 to 500 m, in the vicinity of Thirteen Mile Hill (Fig. 4). It crops out strongly over a strike of 5000 m as seven ridges of banded ferruginous and silicified shale. With the exception of these 'gossanous' ridges outcrop is very poor, with most of the formation covered with soil or scree from the topographically higher Judenan Beds to the west.

Fresh Urquhart Shale consists of light to dark grey dolomitic shale and siltstone and pyritic shale, mostly finely laminated, and showing little evidence of sedimentary disturbance. Pyrite and the economic sulphides (galena and sphalerite) are an integral part of the rock-forming minerals. A number of beds rich in potash feldspar occur; they represent in part devitrified acid tuffaceous material. The contacts between Urquhart Shale and the overlying Spear Siltstone is gradational, as is the contact with the Native Bee Siltstone below.

Throughout the formation, a number of distinctive tuffaceous beds (known locally as Tuff Marker Beds) occur. They consist dominantly of potash feldspar with lesser amounts of dolomite and quartz and are identical with those at Isa Mine described by Croxford (1964). They range in width from 5 mm to 200 m and typically have a sharp base and commonly grade upwards into the overlying

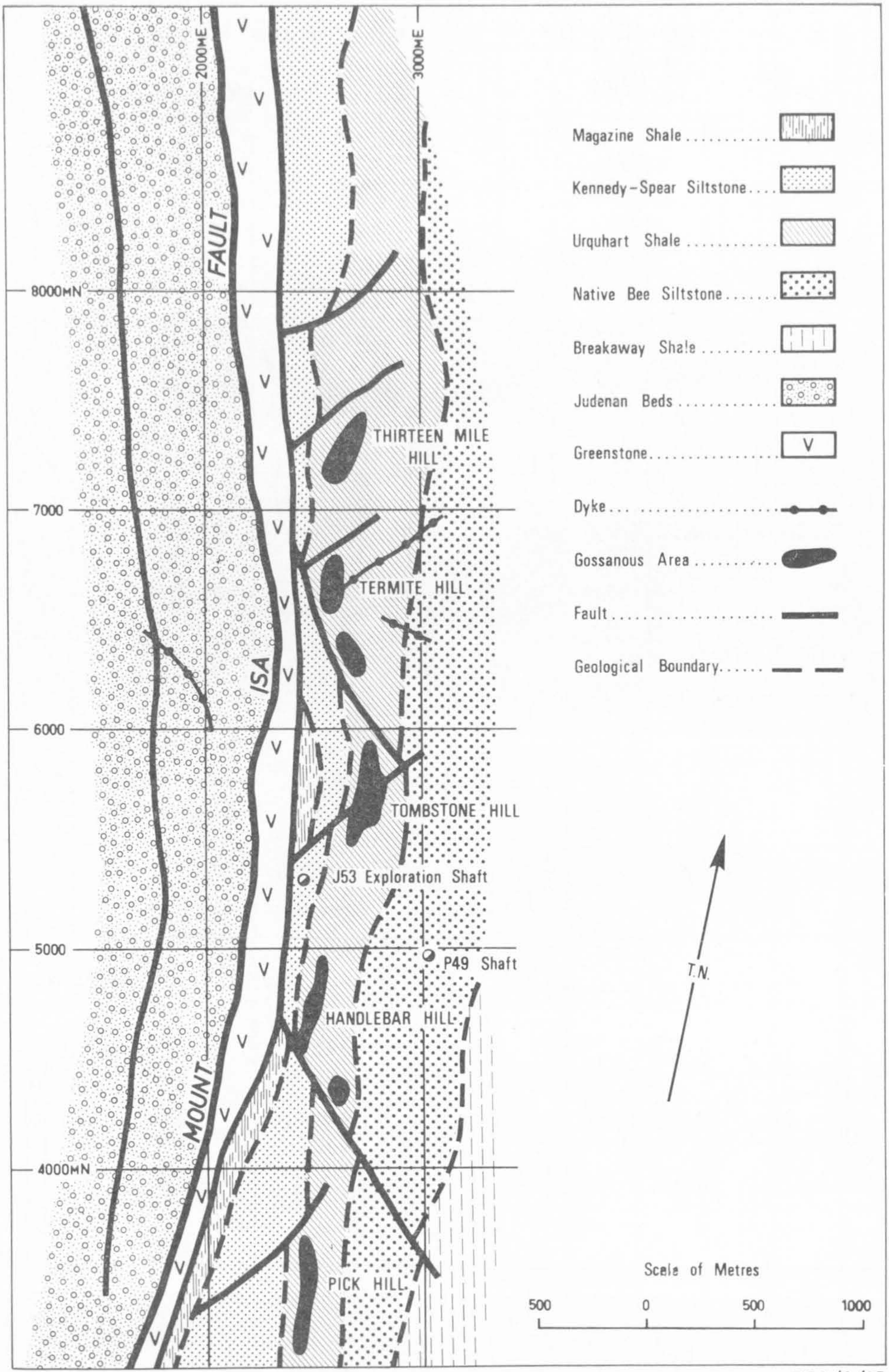

Fig. 4. Generalized geology of Hilton mine.

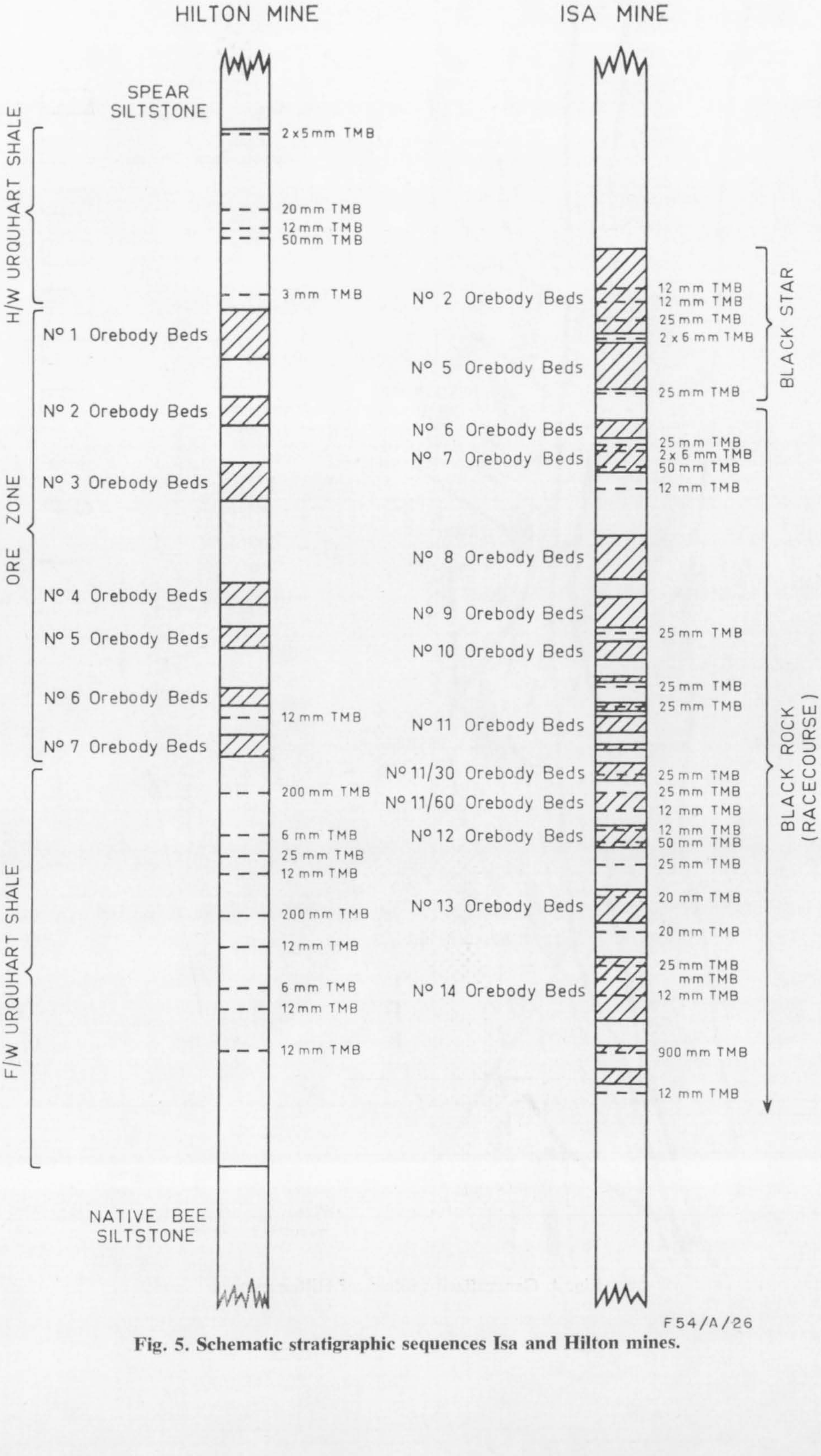

Fig. 5. Schematic stratigraphic sequences Isa and Hilton mines.

sediment. There are a number of recognizable Tuff Marker Beds in the formation (Fig. 5). These beds lack the colour contrast which marks the Tuff Marker Beds at Isa Mine. In addition, the cross-fracturing characteristic of the beds at the Isa Mine is not as well developed. They are more variable in thickness than their counterparts at Isa Mine, making definite correlation over large strike lengths difficult. Despite this, correlation is reasonably well established, particularly in the Handlebar Hill/Tombstone Hill area.

The formation can be conveniently divided into three zones, Footwall Urquhart Shale, Ore Zone, and Hanging Wall Urquhart Shale (Fig. 5).

Footwall Urquhart Shale is thinly bedded weakly pyritic grey to dark grey dolomitic shale, ranging in width from 80 to 180 m. Dark grey carbonaceous shale with coarse pyrite euhedra is common towards the base of this zone. Minor thin calcitic beds characteristic of the 'zebra shale' of the Native Bee Siltstone have been noted throughout and into the lowest portion of the overlying Ore Zone.

Isolated zones of massive bedded pyrite occur with associated galena-sphalerite mineralization. These sulphide bands occasionally reach ore grade over narrow widths.

Overall the Footwall Urquhart Shale contains certain features of both the Ore Zone above and the barren Native Bee Siltstone below and can be regarded as a gradation between the two.

All known economic mineralization is confined to the central *Ore Zone* of the Urquhart Shale. It ranges in width from 110 to 250 m and contains seven horizons of galena-sphalerite mineralization. The detailed stratigraphy of this zone will be described in a later section.

The *Hanging Wall Urquhart Shale* varies in thickness, but the complete sequence averages 60 m. In a number of places, faulting has removed the upper parts of this zone and the base of the Spear Siltstone above. North of Thirteen Mile Hill preconsolidation slumping is prominent in Spear Siltstone, and this may in part explain some of the thickness variations.

The rocks are typically light grey dolomitic tuffaceous shale characterized by a high potash feldspar content. A 50-mm Tuff Marker Bed found in the middle of the Hanging Wall Shale is the most extensively recognized tuff bed. It has been traced on the surface for 3000 m and in core over a strike of 4500 m from Pick Hill to Thirteen Mile Hill.

Scattered bands of fine-grained bedded pyrite occur throughout, and are becoming more prominent towards the base of the unit. The most prominent is a 350-mm massive pyrite band near the 50-mm Tuff Marker Bed. Occasionally significant galena, sphalerite, and some chalcopyrite are associated with the pyrite. Elsewhere, galena-sphalerite mineralization is limited to joint surfaces in otherwise barren shale.

Spear Siltstone

A unit of well laminated medium to coarse-bedded siltstone, the Spear Siltstone, is composed mainly of dolomite, albite, quartz, and microcline, and is strongly tuffaceous. The top of the unit is the 'A' marker of Knight (1953). Though some dolomite and siliceous dolomite occur, the general sequence from bottom to top is: microcline-bearing tuffaceous dolomitic siltstone; albitic dolomitic siltstone, probably tuffaceous; and tuffaceous phlogopite-bearing, strongly albitic siltstone (the 'A' marker). Coarse pyrite crystals are scattered throughout the sequence, and the carbon content is less than in all the lower units of the group.

Tuffaceous activity is most strongly marked by tuff marker beds near the base of the sequence and by albitic tuff beds, including the distinctive 50-mm thick Albite Marker, in the 'A' marker sequence.

At intervals throughout the formation brecciated and contorted preconsolidation slump zones are found. The slumping masks all but major tectonic folds in the sequence.

Kennedy Siltstone

The Kennedy Siltstone consists of coarse-bedded to massive albitic dolomitic siltstone, composed mainly of dolomite, albite, quartz, and microcline. The sequence is mainly of massive albitic dolomitic siltstone, with a thin band of tuffaceous microcline-bearing dolomitic siltstone at the top. Zones of strong brecciation and slumping occur throughout the unit, and are comparable with those in the Spear Siltstone.

The Kennedy and Spear Siltstones are very similar. They are distinguished by the massive nature of the Kennedy Siltstone and in the subsurface by its buff colour as opposed to the cream colour of the Spear Siltstone. Nevertheless, the differences are subtle and the two are treated as a single unit in the rest of this paper.

In many places at Hilton, the Kennedy Siltstone is faulted out, and it is almost completely missing north of Termite Hill. Despite complications due to extensive slumping, the formation appears to have been of variable thickness even before the slumping.

Magazine Shale

The topmost formation of the Mount Isa Group consists of shale and siltstone; at the surface it is composed mainly of sericite and quartz and stained by iron oxides to give a characteristic reddish brown colour. The fresh rock is a dark grey to black fine-grained carbonaceous sericite-dolomite-quartz shale with abundant scattered coarse-grained pyrite.

It is very strongly sheared as an effect of the major strike fault which emplaced the Western Greenstone, and which has removed the top of the unit throughout its entire length. In places, such as north of Termite Hill, the Magazine Shale is faulted out completely.

TABLE 1. COMPARISON OF STRATIGRAPHIC SUCCESSION AT MOUNT ISA AND HILTON

Formation	*Stratigraphic Thickness* *Mount Isa Area*	*Tombstone Hill, Hilton*
Magazine Shale	215 m	100 m
Kennedy and Spear Siltstone	480 m	±150 m
Urquhart Shale	900 m	250 m
Native Bee Siltstone	800 m	300 m
Breakaway Shale	1050 m	260 m
Moondarra Siltstone	1220 m	*

* Too strongly deformed for reliable thickness measurements.

Age of Mount Isa Group

No reliable age for the Mount Isa Group has been obtained, but it is generally considered to be Middle Proterozoic, which would lie within the 1800-1600 m.y. range. Farquharson & Wilson (1971), however, believe that the Mount Isa Group antedates the Kalkadoon Granite to the east of Mount Isa, and is therefore older than 1800 m.y., and probably than 1930 m.y.

Intrusive Activity

Within 5 km of the Hilton Mine two types of intrusive are found: the north-eastern corner of the Sybella Granite batholith, and a number of basic dykes.

Sybella Granite

The Sybella Granite consists of a number of phases, but only one, the micro-granite, occurs near Hilton. The microgranite is a fine-grained typical granite, and has been dated by the Rb-Sr method at 1553 $\pm$ 29 m.y. (Farquharson & Richards, 1970); it is thus younger than the Mount Isa Group. Despite the proximity of the mass to Hilton (about 4 km at the nearest) the granite has had no apparent effect on the deposit.

Basic Dykes

A number of dolerite dykes, now strongly altered, occur in the subsurface near Tombstone Hill, and several others have been found in the area from surface mapping.

The dykes consist of chlorite, actinolite, and predominant albite, in which albite is partly replaced by epidote and microcline. A doleritic texture is preserved. The dykes have chilled margins and were evidently intruded along transverse faults, as the sediments at their margins are strongly sheared. The dykes were possibly intruded before or during diagenesis, as evidenced by the occurrence of microcline and phlogopite similar to diagenetic microcline and phlogopite in the sediments (van den Heuvel, 1969).

On the surface, dykes intruding the Mount Isa Group may attain widths of 20 m or more and lengths of more than 1000 m. Those in the mineralized zone are extensively altered, but others may retain a substantial proportion of the original igneous minerals. A large dyke in the Judenan Beds west of Gidyea Hill is composed mainly of biotite and quartz.

Regional Structure

The Hilton area is strongly deformed, both by folding and faulting.

Folding

Recent work on the structure of the Mount Isa area (Lister, 1969; Williams, unpublished company report, 1970; C. J. L. Wilson, pers. comm., 1970) has disclosed three fold generations, of which the third (F3) is very restricted. Most of the major fold structures east of the Mount Isa Fault belong to the second generation (F2) of folding. Refolded first generation (F1) folds, many of them isoclinal, are found especially west of this fault, but some have been found in the Lake Moondarra area and others, on a small scale, in the Isa Mine.

The regional Mount Isa syncline is the major F2 structure of the area. It is a tight fold plunging northwards, with east and west limbs both striking north-south but gradually diverging northwards. The synclinal axis coincides with the Mount Isa Fault. The amplitude is of the order of 25 km. The west limb is very complex with refolded folds, transposed bedding, strike faulting, and overturned bedding in many places, but with a constant 60-70° west dip in cleavage or foliation. The east limb, on the other hand, is basically a north-striking synclinal limb with both bedding and cleavage dipping about 60° west. Numerous parasitic F2 folds occur in this limb, but ranging in amplitude from about 200 m to less than 1 m; most of these, like the main syncline, plunge northwards.

Faulting

Faulting has had a great effect on the area, and apparently extended over a long period of time. The largest faults are strike faults, but transverse faults are more numerous.

The Mount Isa Fault

The Mount Isa Fault zone southwards from Hilton is coincident with the axial plane to the Mount Isa syncline and is a product of the fold episode. At Mount Isa and southwards, it is a zone of intense isoclinal folding and transposition, with superimposed F3 folds, in places showing brecciation and mylonitization. It is strongly sheared throughout, and appears to be a product of ductile flow. At Hilton, by contrast, it is a zone of brittle fracture, with very strong shearing either side of a zone of quartz veining. The fault dips west at a constant 75-80°.

The differing modes of failure may be related to the intensity of folding. The Mount Isa syncline is very tight south from Mount Isa but is widening out at Hilton. Thus the axis of the syncline at Hilton may not have been subjected to such intense pressure as at Mount Isa and farther south.

The sense of movement across the fault seems to be west block north and up, with the horizontal component apparently predominant; but the amount of movement is unknown. It is at least several kilometres, as the Mount Isa Group is entirely removed from west of the fault. The metamorphic grade increases from chlorite zone to biotite zone across the fault.

The Western Greenstone-Mount Isa Group Contact

A major fault occurs at the contact of the western greenstone and the Mount Isa Group, marked by a zone of intense shearing. It dips 70° west, more steeply than the Mount Isa Group but less than the Mount Isa Fault. Thus the fault gradually transgresses the sediments with depth.

The fault continues north of Spring Creek with no apparent break for several kilometres at least, diverging widely from the Mount Isa Fault. South of Hilton the fault and its associated greenstone are truncated by the Mount Isa Fault, but they reappear intermittently southwards to Mount Isa.

Little is known of the movement on this fault, but it must be several kilometres.

Other Strike Faults

Several strike faults west of the Mount Isa Fault have been recognized, including those bounding the greenstone valley lying in the Judenan Beds. They have little effect on the Hilton deposit.

East of the Mount Isa Fault several strike-fault zones, with west block north and up movement and associated F2 folding, have been found at Isa Mine (e.g. Racecourse Shear Zone, 650 Orebody Footwall Shear Zone). Like the Mount Isa Fault, they are probably F2 phenomena. At Hilton, a fault zone lying west of Termite Hill (Fig. 4) may be of this type. These are not strictly strike faults, since they gradually transgress the sequence; they lie parallel to the parasitic F2 folds.

Penecontemporaneous Transverse Faults

Carter et al. (1961) and especially Smith (1969) have discussed penecontemporaneous faulting east of the Mount Isa Fault. These are basically linear fracture zones with consistently reduced thicknesses of sediments or volcanics on one side compared with the other. The concept of penecontemporaneous faulting has been criticized on the grounds of conflict with the known history of folding in the area, but large F1 folds are rare east of the Mount Isa Fault and F2 folding is on either too large or too small a scale to deform these faults significantly. One, the Transmitter Fault, occurs about 1-2 km south of Pick Hill at the southern end of the Hilton gossans. A slight angular unconformity has been mapped between Breakaway Shale and Native Bee Siltstone immediately south of it, which is probably due to movement on the fault. On the Hilton side the sequence is less than half as thick as on the southern side; this is probably due to slower sedimentation on the upthrown side, as no fault or erosion breaks have been found in the sequence.

Other penecontemporaneous faults are known from the general area, but do not affect the Hilton deposit. All belong to a northwest-trending set of faults.

Other Transverse Faults

Post-consolidation transverse faults may belong to two main sets: northwest-trending and northeast-trending. Both occur within the Hilton Mine, some with movements in excess of 100 m. The most important is the Spring Creek Fault at the northern end of the Hilton mineralization, which truncates the Upper Mount Isa Group, and has a horizontal component of movement of about 1000 m.

The Ore Zone

Stratigraphy

The Ore Zone is characterized by numerous sulphide bands occurring in thinly bedded grey dolomitic, tuffaceous, and slightly carbonaceous shales. Widths of massive dolomitic siltstone up to 30 m occur, particularly in the upper parts of the sequence. One such siltstone band lies between No. 3 orebody and No. 4 orebody and has proved a valuable marker.

The most easily recognizable and persistent marker is No. 1 orebody, which occurs as a zone of massive crenulated pyrite and pyrrhotite with lesser amounts of galena, sphalerite, and in places chalcopyrite. It reaches widths of 25 m and contains more than 80 percent combined sulphide minerals. In places a zone of massive cherty material is present near the middle of No. 1 orebody. This orebody can probably be related to the gossanous outcrops extending for 4500 m from Pick Hill to Thirteen Mile Hill.

From immediately above No. 2 orebody to the top of No. 4 orebody (Fig. 5), thick-bedded to massive dolomitic siltstone is the dominant sediment except in

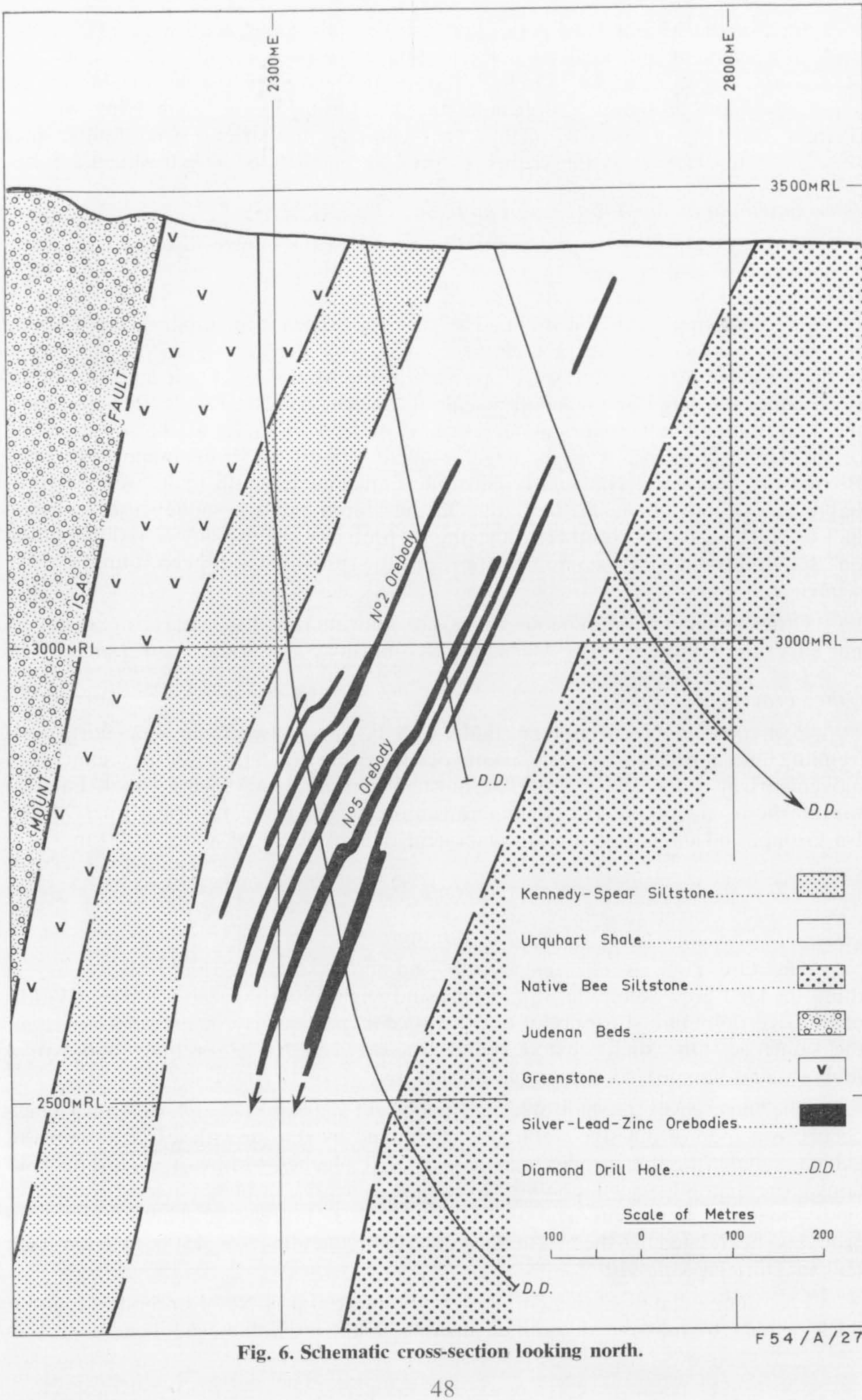

Fig. 6. Schematic cross-section looking north.

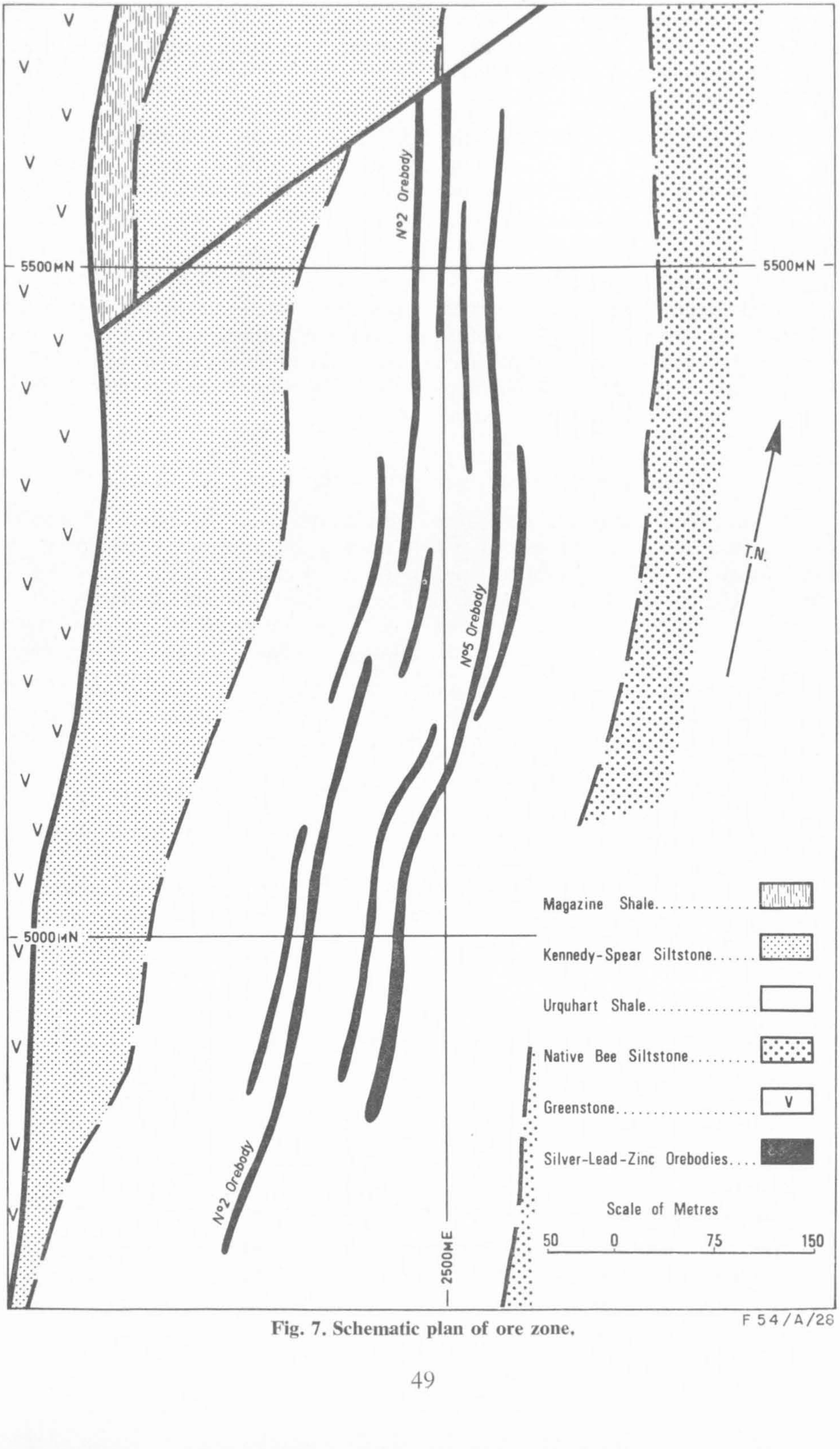

Fig. 7. Schematic plan of ore zone.

the actual orebodies, where well laminated shale is host to the sulphide mineralization. The siltstone horizons are virtually free of any sulphide beds. Stylolites are commonly developed.

The zone comprising No. 4 to No. 7 orebodies consists of thin-bedded slightly carbonaceous dolomitic shale with numerous sulphide beds throughout. Orebodies in this section have variable widths depending on the grade and concentration of the sulphide beds. This contrasts with the No. 1 to No. 3 orebody zone, in which the widths of mineralization are generally consistent.

The Ore Zone is notable for its lack of easily recognizable and persistent Tuff Marker Beds (Fig. 5). A 12-mm bed immediately below No. 6 orebody is the only tuff bed which has proved useful in correlation. Others have been identified in places but lack continuity both along strike and down dip. This lack of Tuff Marker Beds in the Ore Zone contrasts with the Isa Mine, where numerous beds occur, facilitating correlation of orebodies.

Occasional beds of micaceous (phlogopitic) material occur throughout the sequence, particularly between No. 1 and No. 4 orebodies.

Chalcopyrite and pyrrhotite are relatively abundant in the upper portions of the Ore Zone and become less abundant towards the footwall. Chalcopyrite is rarely found below No. 4 orebody and pyrrhotite decreases rapidly below No. 2 orebody. The colour of the sphalerite (indicative of iron content) varies in different parts of the sequence. The hangingwall orebodies are marked by orange-brown sphalerite, whereas the sphalerite in the lower orebodies is a light amber colour.

At this stage only limited correlation of the sequence between Isa and Hilton Mines is possible because of the lack of Tuff Marker Beds in the Ore Zone at Hilton, the markedly reduced sequence, and the distance between the two deposits. Broadly the hangingwall orebodies at Isa Mine (Black Star orebodies) can be correlated with the zone from No. 1 to No. 3 orebodies at Hilton (Fig. 5).

At both mines chalcopyrite in lead-zinc ores is largely restricted to these two sequences.

The sequence No. 4 to No. 7 orebodies at Hilton and the Racecourse orebodies at Isa Mines have similar characteristics, with the sulphide mineralization in numerous beds in well laminated shale. This contrasts with the more irregular and less well laminated orebodies of both the Black Star sequence at Isa and No. 1 to 3 orebodies at Hilton.

Structure

Many of the broad structural features previously described are represented by smaller-scale features in the Ore Zone. The presence of a major strike fault in the vicinity of Termite Hill has already been noted.

Several major transverse faults exist in the Thirteen Mile Hill area (Fig. 4) and are in part responsible for the thickening of the Urquhart Shale sequence at that point. Other transverse faults have been inferred from drilling results.

Down-dip continuity of orebodies and sequence is disrupted particularly on the Handlebar Hill/Tombstone Hill area. The cause and extent of this disruption are unknown; it seems possible that a combination of strike and transverse faulting is responsible (see plan).

Folding is present throughout, with major folds at Thirteen Mile Hill, where amplitudes of 60 m are attained. Like the regional folding most folds plunge to the north. Elsewhere folding appears to be relatively small. Within the Ore Zone strongly crenulated zones are known. The importance of folding on orebody outline will not be known until detailed exploration from underground sites is possible.

Surface Expression

On the surface the mineralization is represented by seven discontinuous siliceous and ferruginous ridges over the strike length of 4500 m. Lead carbonate (cerussite) mineralization crops out to the footwall of two ridges, Handlebar Hill and Tombstone Hill. The ridges are loosely termed gossans, but do not have extensive boxworks after sulphides and result from the loose banding of hydrated iron oxides (probably goethite) by residual silica. The lack of boxworks may be due in part to the very small grain size of the sulphide minerals. The development of the gossan is strictly a surface feature: most outcrops retain the gossanous features for less than 1 m from the surface. Regardless of the detailed nature of the gossans, they stand out as prominent dark brown hills at Isa and Hilton Mines and are reliable guides to ore, because they are the direct surface expression of abundant pyrite, which in turn has a persistent association with galena-sphalerite mineralization.

Fig. 8. Gossan ridge at the south end of Handlebar Hill showing limonitic gossan (left) and jasper (right).

Zimmerman (1967) studied the gossans in detail; he recognized two main types, 'a massive rounded, siliceous jasperoid type, and a cavernous, earthy, iron-rich, crust-like type'. A third type of morphology is important, particularly in the interpretation of the gossans, in which very fine laminae of limonitic material (often less than 1 mm) occur in silicified shale. These laminae represent the oxidized product of the fine pyrite laminae which characterize both the Isa and Hilton ore zones.

The colour of the limonitic material can indicate the nature of the sulphides from which it was derived. The bulk of the material is dark reddish brown and has been derived from pyrite. Yellow powdery limonite commonly found in small cavities is indicative of gossan derived from material with a higher galena and sphalerite content.

Zimmerman (1967) selected 34 samples of gossan which were analysed for 19 elements. All but two samples gave lead values in excess of 1200 ppm, which contrasts with the lead value of the shale of 20 ppm. He concluded that 'in terms of trace quantities, the gossans are considerably enriched in copper, lead and zinc relative to the average values for shale, and to a lesser extent, to the average values for primary mineralization'.

Ore Mineralogy

The distribution and mineralogy of the sediments and ores at Hilton are almost identical with those at Isa Mine. The sulphide assemblages consist essentially of pyrite, galena, and sphalerite, with some pyrrhotite and accessory chalcopyrite, tetrahedrite, pyrargyrite, and native silver. They generally occur in concordant bands within Urquhart Shale. The sediments consist essentially of dolomite, quartz, K-feldspar, albite, and micas, and as at Mount Isa occasional vitric tuff (TMB) layers are encountered. Individual beds are normally between 1 and 100 m in width, and where they are grouped in sufficient density to enable economical extraction the zone is termed an orebody: seven such orebodies have been tentatively designated. The widths of individual orebodies range from 2.5 to 12 m and economic widths have been intersected over a strike length of nearly 5000 m, and 1000 m down dip from the surface.

Oxidation has resulted in the change of galena to cerussite to a depth of 50 m, but smithsonite is rare.

Description of Minerals

The minerals are described in decreasing order of abundance.

Pyrite

An essential constituent of the Urquhart Shale, pyrite forms over 90 percent of the sulphides present throughout the ore zone. The No. 1 orebody horizon 60 m from the top of the Urquhart Shale is a massive pyritic zone up to 25 m thick. Two basic types of pyrite are present, although combinations occur between them (Zimmerman, 1960, recognizes 4 types).

Fine-Grained Pyrite. The delicately bedded pyrite of the Hilton Urquhart Shale is of the framboidal type and is identical with that described from the Isa Mine and McArthur River. It probably represents a sedimentary component of the Urquhart Shale. Macroscopically it is seen as concordant olive green to buff brown beds, from 50 cm down to microscopic bands. It favours the more carbonaceous, thinly laminated sections of the sequence; the silty horizons are noticeably deficient in bedded pyrite. Microscopically the pyrite beds are seen to be formed of spherical

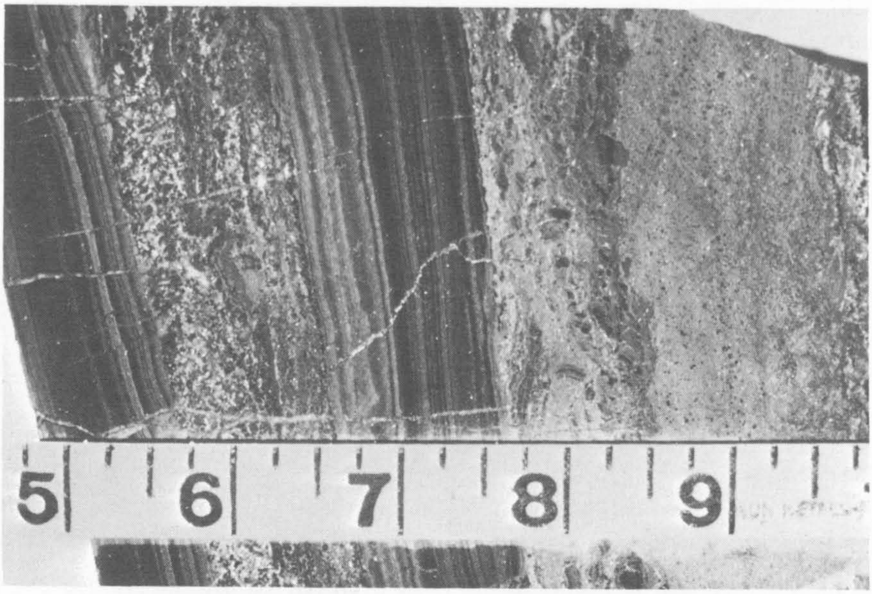

Fig. 9. Typical banded ore. Thinly laminated pyritic shale with two recrystallized and brecciated sphalerite-galena bands. Scale in inches.

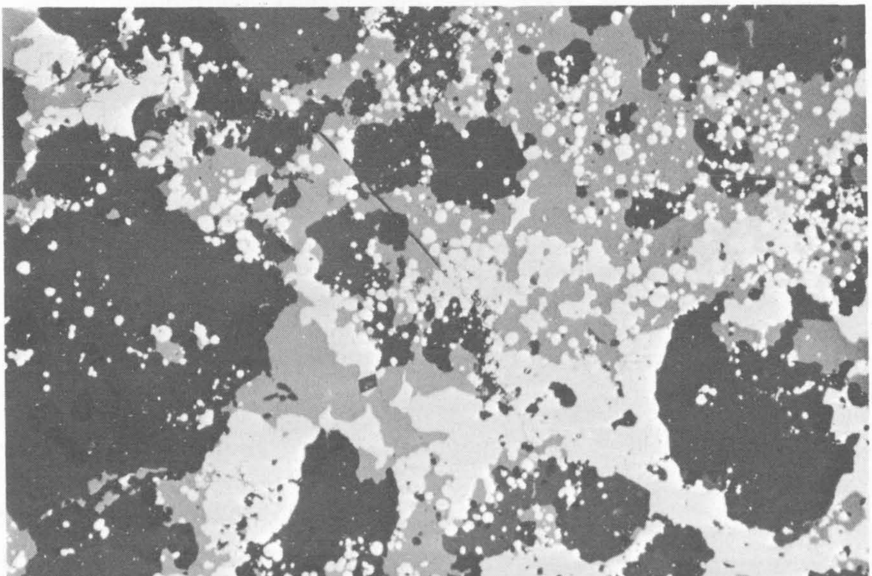

Fig. 10. Framboidal pyrite and complex intergrowth of sphalerite and galena. x 400, reflected light (oil).

to isometric pyrite crystals 2-10μ in diameter. Accumulations of the framboidal pyrite form bedding lamellae from microscopic thickness to macroscopic beds of over 95 percent pyrite. Here the individual pyrite framboids coalesce into massive zones of small cubes, each less than 20μ across. Carbon envelopes are present (Love & Zimmerman, 1960) and atoll structures are found with pyrite round sphalerite cores.

Recrystallized Pyrite. Disseminated throughout the Mount Isa Group and as veins and fracture fillings in the ore zone is a strongly euhedral pyrite. It partly represents a recrystallization of the fine spherical pyrite.

Crosscutting veins and fracture fillings of coarse-grained pyrite and recrystallized fine-grained pyrite beds are distributed throughout the ore zone. They appear to be more common in the upper part of the sequence. Large pyrite crystals (metacrysts?) up to 5 mm in diameter are found in the more silty sections of the sequence and appear to be diagnostic of certain zones such as the footwall Urquhart Shale.

Sphalerite

The most abundant of the economic minerals, sphalerite, occurs in various forms. The colour is possibly indicative of the form and may also be an aid in determining the stratigraphy.

Normally, sphalerite occurs as layers of deep red-brown fine-grained crystals associated with fine-grained pyrite and galena (in the lower part of the sequence beds of almost pure sphalerite up to 10 cm thick occur). The sphalerite commonly forms a matrix for other sulphides, particularly chalcopyrite, pyrrhotite, and fine-grained pyrite, and is in many cases replaced by galena and pyrrhotite.

Sphalerite also occurs as very finely disseminated orange-brown to yellowish orange crystals in some silty beds. This is almost certainly a sulphide of sedimentary origin. The beds are normally 1-2 cm thick and the sphalerite is concentrated towards the base, giving them a graded appearance.

Occasionally, sphalerite occurs in small late-stage veinlets and tension cracks. In the upper orebodies this is predominantly very dark brown, whereas towards the lower part of the sequence it is very pale yellow. All these veins are small: few reach 10 mm in width.

Microscopically, sphalerite shows several interesting textures. Spherical bodies similar to the bedded pyrite have not been recognized as such, but it is possible that the masses of fine sphalerite crystals represent aggregations of sphalerite spheres. Sphalerite forms the cores of many partly replaced pyrite spheres and atoll structures, although atoll structures appear to be less common at the Hilton than at Mount Isa. The large patches of sphalerite are shown to be masses of small crystals by etching, and the numerous pyrrhotite and chalcopyrite inclusions are seen to be intergranular blebs. Sphalerite grains range from 5 to 500 μ and the blebs average 2-3 μ. The sphalerite commonly forms a matrix for fine-grained pyrite spheres and galena.

Galena

Galena is subordinate to sphalerite and occurs only in its presence. The two normally form very fine-grained intergrowths, though galena has been mobilized

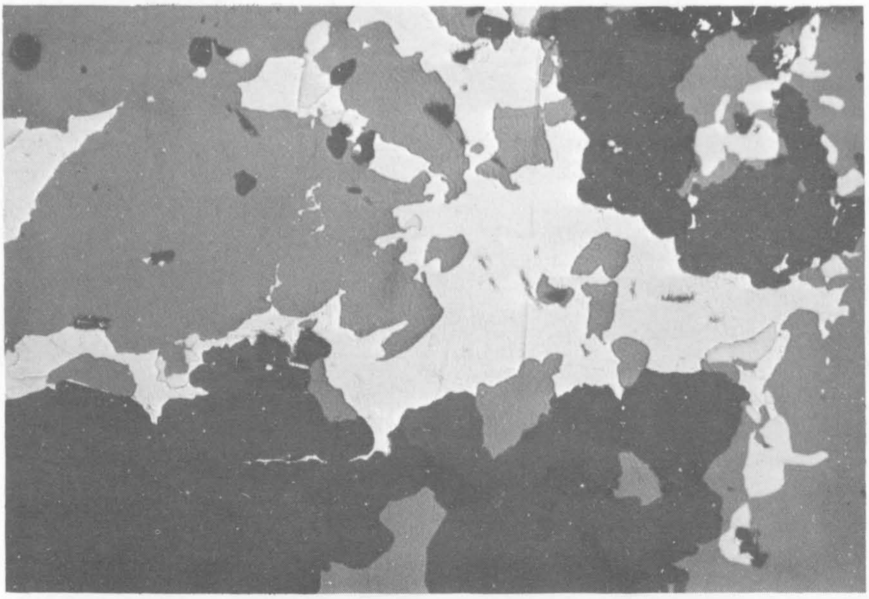

Fig. 11. Sphalerite and galena intergrowth with minor pyrrhotite and chalcopyrite inclusion within sphalerite. x 400, reflected light (oil).

to some extent to veinlets and fold crests of coarsely crystalline material. Complex inclusions such as those found in sphalerite are not common, and the galena is generally very clean. High silver values in some areas can be attributed to silver in solid solution in galena, although some silver minerals have been identified.

Pyrrhotite

Galena, sphalerite, and pyrite normally show mutual grain boundaries, whereas pyrrhotite, occurring as massive bands parallel to bedding, crosscutting veins, and disseminated spicules, always appears to be of late paragenesis. It is very patchy in occurrence and may represent an alteration product after both types of pyrite.

Much of the massive sulphide zone of No. 1 orebody contains over 20 percent pyrrhotite, which forms bands parallel to bedding and also fracture fill. The bands are composed of elongate grains 10-600 μ long extended parallel to the bedding.

Disc-shaped crystals of pyrrhotite up to 10 mm wide are disseminated throughout certain silty horizons, almost invariably associated with phlogopite. This pyrrhotite may be an alteration of the disseminated coarse-grained pyrite.

Chalcopyrite

The upper orebodies Nos. 1 to 4 are characterized by the presence of chalcopyrite-filled tension cracks. Most commonly the chalcopyrite fills cracks in barren shale beds perpendicular to the bedding and generally in the zones of crenulation and brecciation. No sign of 'bedded' chalcopyrite has been found. All yet seen is of very late paragenesis.

No atoll structures of chalcopyrite-pyrite have been seen at Hilton, in contrast to Mount Isa. Some chalcopyrite occurs as intergranular blebs in sphalerite.

Fig. 12. Chalcopyrite filling tension cracks in crenulated and mineralized shale. HQ core.

Accessory Minerals

(i) Euhedral crystals of arsenopyrite occur in a pyrhotite groundmass. The crystals, 25-50 μ in size, are randomly oriented and form about half of the pyrrhotite volume. Arsenopyrite euhedra to 600 μ have been observed, many corroded by pyrrhotite and sphalerite.

(ii) Most of the silver in the ore occurs either in solid solution in galena or as a mineral in the tetrahedrite-freibergite series. Proustite, pyrargyrite, and native silver have been recorded. The silver in galena is not resolvable optically. Tetrahedrite normally occurs as discrete grains up to 40 μ in size, usually attached to or surrounded by galena and pyrrhotite. Tetrahedrite is sometimes rimmed by pyrargyrite or proustite, and rare grains of native silver are recorded; but these minerals do not appear to have any definite mineralogical affinities.

Oxidation Products

At Hilton a weathering profile of four zones is recognized. Above the water-table, which lies at about 45 m, the shale is completely oxidized. Below it is a zone of about 100 m of totally leached material. This grades to a 50-m zone of partly leached and vuggy strata above unaltered primary material. As at Mount Isa, above the water-table the primary galena is oxidized in situ to form concordant bands of cerussite, but sphalerite is entirely leached. Silver has also been removed, but some secondary native silver has been deposited immediately above the water-table. Rarely, small flakes of native silver coat joint planes or bedding surfaces.

The mineralogy of the totally leached zone in poorly known, as diamond drilling here is extremely difficult and core recovery poor. It probably represents a transition-type ore, with possibly 50 per cent of the original pyrite present. The lead may be contained mainly in galena but also in cerussite and anglesite. Some of the zinc may be present as smithsonite. The zone below this is essentially unaltered primary sulphides but contains small vugs which are being filled with secondary minerals deposited by circulating groundwater. Gypsum, dolomite, and monheimite occupy these cavities.

Distribution of Mineralization

Although the ore minerals are distributed throughout the Urquhart Shale preferential distribution trends occur. Essentially the Urquhart Shale is a pyritic sequence with a 25-m zone of almost massive pyrite near the top and an overall decrease in pyrite content towards the footwall. The footwall orebodies appear to contain less than 10 percent pyrite. Chalcopyrite is present in the upper half of the sequence only. Galena and sphalerite appear to be intimately associated, but galena is never found in the absence of sphalerite; sphalerite can form independent beds.

Remobilization of sulphides similar to that at Mount Isa (Hewett & Solomon, 1964) has taken place, but only to a limited degree. Shale bands in the high-sulphide horizons have been crenulated and brecciated, with associated migration of galena and sphalerite into the low-pressure zones. However, crenulation is less intense than at Mount Isa and resembles that found in the Racecourse orebodies rather than the Black Star ore zone. The fracture-fill sulphides, very common at Mount Isa, are much less common at Hilton. Chalcopyrite fills tension cracks, but galena and sphalerite remain banded.

The ore minerals appear to have been deposited very quietly in a restricted basin. Any intrusion of coarser material (slightly oxygenated?) interrupted the sulphide deposition. Lead appears to be preferentially deposited in the centre of the basin, whereas zinc has a slightly broader coverage overlapping the lead in all directions. This is an exact replica of the system envisaged for the deposition of the Isa Mine silver-lead-zinc deposit.

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References

BENNETT, E. M., 1965—Lead, zinc, silver, and copper deposits of Mount Isa. *8th Comm. Min. metall. Cong,* 1,233-46.

BENNETT, E. M., 1970—History, geology, and planned expansion of Mount Isa properties. *Paper presented to* World Symposium on the Mining and Metallurgy of Lead and Zinc. *Amer. Inst. Min. Engrs, St Louis.*

CARTER, E. K., BROOKS, J. H., and WALKER, K. R., 1961—The Precambrian mineral belt of north-western Queensland. *Bur. Miner. Resour. Aust. Bull.* 51.

CARTER, S. R., 1950—Report on Authority to Prospect area 76.5 square miles, Mount Isa district. *Unpubl. internal Co. Rep.*

CROXFORD, N. J. W., 1964—Origin and significance of volcanic potash-rich rocks from Mount Isa. *Trans. Instn Min. Metall,* 74(2).

CROXFORD, N. J. W., 1968—A mineralogical examination of the McArthur lead-zinc-silver deposit. *Proc. Aust. Instn. Min. Metall.,* 226(2), 97-108.

FARQUHARSON, R. B., and RICHARDS, J. R., 1970—Whole-rock U-Th-Pb and Rb-Sr ages of the Sybella microgranite and pegmatite, Mount Isa, Queensland. *J. geol. Soc. Aust.,* 17(1), 53-8.

FARQUHARSON, R. B., and WILSON, C. J. L., 1971—Rationalisation of geochronology and structure at Mount Isa. *Econ. Geol.,* 66, 574-82.

GRANT, J. N. M., 1968—Report on the geology of the Western Greenstone, the Judenan Beds, and the upper formation of the Mount Isa Group at the Northern leases. *Unpubl. internal Co. Rep.*

HEWETT, R. L., and SOLOMON, P. J., 1964—The role of mobilization in silver-lead-zinc sulphide assemblages, with particular reference to Mount Isa, Australia. *22nd int. geol. Cong., New Delhi,* 5.

KNIGHT, C. L., 1953—Regional geology of Mount Isa. *5th Emp. Min. metall. Cong.,* 1,352-60.

LISTER, G. S., 1969—Aspects of metamorphism and structure across the Mount Isa Fault in the Mount Novit area. *B.Sc. (Hons) Thesis, Univ. Coll. Townsville* (unpubl.).

LOVE, L. G., and ZIMMERMAN, D. O., 1961—Bedded pyrite and micro-organisms from the Mount Isa Shale. *Econ. Geol.,* 56, 875-96.

MURRAY, W. J., 1953—Report on Authority to Prospect area 76.5 square miles, Mount Isa district, 30.6.1950 to 30.6.1953. *Unpubl. internal Co. Rep.*

ROBINSON, W. B., 1968—Geology of the Eastern Creek Volcanics in the Mount Isa district. *Proc. Aust. Inst. Min. Metall.,* 226(2), 89-96.

SHALLEY, M. J., and LORD, J. R., 1967—A test of exploration methods at the Northern Leases. *Unpubl. internal Co. Rep.*

SMITH, S. E., and WALKER, K. R., 1971—Primary element dispersions associated with mineralization at Mount Isa, Queensland. *Bur. Miner. Resour. Aust. Bull.* 131.

SMITH, W. D., 1968—Penecontemporaneous faulting and its likely significance in relation to Mount Isa ore deposition. *Geol. Soc. Aust. spec. Publ.* 2, 225-35.

VAN DEN HEUVEL, H. B., 1969—Sedimentation, stratigraphy, and post-depositional changes in the sediments of the upper formations of the Mount Isa Group, north-west Queensland. *Ph.D. Thesis, Univ. Qld* (unpubl.).

WILLIAMS, P. F., 1970—Structural problems at Mount Isa. *Unpubl. Rep. to Mount Isa Mines Ltd.*

WILLIAMS, T. O., 1969—Progress report on the geology of the Urquhart Shale and environs at the Northern Leases. *Unpubl. internal Co. Rep.*

ZIMMERMAN, D. O., 1961—Mineralisation at the Northern Leases, Mount Isa, Queensland, and its surface expression. *Ph.D. Thesis, Univ. London* (unpubl.).

ZIMMERMAN, D. O., 1967—Gossan at Northern Leases, Mount Isa, as visible geochemical anomalies. *8th Comm. Min. metall. Cong.,* 6, 359-67.

METALLIC MINERAL DEPOSITS OF INDONESIA

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SUMMARY

Mineral provinces and their connexions with phases of mountain building in Indonesia have been proposed by Westerveld (1952). Mineral deposits characterizing a certain orogenic belt are grouped into one province. The Malaya orogen (late Jurassic) is characterized by cassiterite-bearing pegmatites and veins.

Pyrometasomatic iron and copper ores are generally connected with the Sumatra orogen (Upper Cretaceous). The Malaku orogen (late Cretaceous-middle Miocene) is characterized by the development of lateritic iron ores and silicate nickel ores. Epithermal gold-silver veins are important metallic deposits along the western coast of South Sumatra and Southern Mountains of Java (Sunda orogen; middle Miocene). Younger Tertiary to Quaternary epithermal gold-silver-bearing veins occur in the western part of the islands. The tectonically separate unit of West Irian is characterized by lateritic deposits in the northern part and gold-silver-copper deposits in the central range.

This paper presents new discoveries of mineral occurrences during the course of prospecting and reconnaissance work by the Geological Survey of Indonesia, which has taken Westerveld's concepts as a working hypothesis. The concepts are generally valid despite lack of details presented in the original paper.

The mineral deposits are grouped on their forms, mineral associations, intrusive associations, structural associations, and nature of country rocks. Important deposits are generally associated with intersecting structures and repeated igneous activities, regardless of orogenic belt, e.g. veins and metasomatic deposits of Sumatra, Java, and Sulawesi. Certain types of minerals, such as cassiterite and its associates, are limited to certain granitic bodies only, presumably belonging to a certain orogenic belt, without distinct associated structures. Most pyroclastic sediments and other volcanic products associated with andesitic to dacitic intrusions are liable to hydrothermal alterations, thus forming favourable sites for mineralization.

Local geology might show a suitable condition for syngenetic sulphide deposition, such as the 'Copper Shales' of Sulawesi and the pyrite-rich claystone in the Bogor-Banten region.

Lateritic deposits are divided into three main groups: nickel-rich deposits, lateritic iron ores, and bauxites.

INTRODUCTION

Mineral provinces of Indonesia as proposed by Westerveld (1952) have been used as a basis in mineral prospecting by the Geological Survey of Indonesia. The concept is characterized by simplicity and is therefore practicable.

Theoretically, it implies intimate genetic relations between phases of mountain building, with their corresponding magmatic evolution, and formation of mineral deposits. This reasoning seems to be the best and most practicable principle in establishing mineral provinces in Indonesia, because the most striking geological features of the islands are the presence of various orogens, distinguishable from one another.

As the results of mountain building are manifested by orogenic belts, the mineral provinces are necessarily defined by the orogens themselves. Consequently, various types of deposits, depending on various factors contained within an orogenic belt, may exist side by side within one province. On the other hand, certain characteristics commonly shared by the various deposits exist, owing to common features of the belt.

If it were considered in more detail, however, it would be necessary to make further grouping into subprovinces, belts, districts, etc., and it would be found that other principles should be applied. Various factors such as smaller structures, types and sequence of igneous activity, nature of country rocks, mineral composition of individual deposits, presence of minor elements, etc., should be taken into account.

To make further subdivisions, however, would be a tremendous task, and a considerable amount of time would be required to analyse and interpret all the available data.

At the moment, we merely show some features which fit and others which do not fit the concept.

Metallic Mineral Deposits in the Malaya Orogen

The Malaya orogen (Westerveld, 1949, 1952) is built up largely by Permo-Carboniferous and Triassic rocks, intruded by Mesozoic acid plutonics. The orogenic belt connects West Malaya and West Kalimantan through the island groups of Anambas-Natuna, Riauw, Banka, and Billiton, and others emerging from the Sunda Shelf.

But closer observations reveal that intermediate volcanic rocks of middle to young Tertiary age occur in the southeastern and northern parts of West Kalimantan. Moreover, olivine basalt of young Tertiary to old Quaternary age occurs at Gunung Niut and Midai (Natuna group).

Granitic and granodioritic intrusions play important roles in the formation of primary ores within the belt, e.g. the Upper Jurassic tin-bearing granite (Katili, 1967). Other primary occurrences include gold, molybdenum, base metals (copper, manganese), and mercury.

The primary cassiterite is commonly associated with scheelite, xenotime, columbite, monazite, and fluorspar, in pegmatitic rocks, in 'greisen', or in acid granitic rocks with relatively low cafemic:alkali ratio. The primary tin ores have been considered to be formed by hydrothermal pneumatolytic processes (Kieft, 1952).

Mineralization usually occurs in the granite itself, but in some places also in the country rock. Tin ore lodes in Billiton, which are associated with base metals, occur in skarn rocks (Adam, 1960) containing hematite, magnetite, pyrite, pyrrhotite, chalcopyrite, arsenopyrite, sphalerite, galena, bismuthite, garnets, amphibole, and pyroxene. In Karimata Islands and West Kalimantan sulphide veins occur without obvious association with cassiterite. Westerveld explained the rarity of cassiterite in this region as due to a less advanced state of differentiation of the West Kalimantan granites.

Far more important economically are the secondary deposits of cassiterite, which are usually associated with ilmenite, monazite, zircon, xenotime, and columbite. In this case, erosion of the ore-bearing rocks should have favoured the formation of alluvial-fluvial deposits. However, they should be considered critically if one is to appraise the sulphide deposits.

In general, the tin deposits related to granitic and more basic rocks in the Malaya orogen may be grouped as follows:

1. Cassiterite veins in greisen (Tandjung Rayah, Banka)
2. Cassiterite stringers in granitic rocks (Old Djangkang Mine, Banka)
3. Disseminated cassiterite in granitic rocks or greisen (Muntai, Billiton)
4. Cassiterite veins in sediments (Sambong Giri, A. Berang, Billiton)
5. Alluvial-fluvial deposits (Banka, Billiton, Singkep, low land of south-eastern Sumatra and others, inland as well as offshore (Quaternary to Recent).

The molybdenum deposits of West Kalimantan (Benaul and Bawang) occur as sulphide veinlets; they are exposed in Mesozoic granodiorite rocks. The molybdenite is associated with a little chalcopyrite and very little cassiterite and scheelite. It is not certain whether these deposits form a belt of their own, or a zone within the tin belt of the Malaya orogen. We are inclined to think that there are two separate 'zones' in this province: the 'tin-tungsten zone', with traces of molybdenum, in the tin-islands; and the 'molybdenum zone', with traces of tungsten and tin, in West Kalimantan.

In some respects, the West Kalimantan sulphide deposits have to be considered as one type of copper occurrence in this orogen. Another type is associated with gold-bearing lead-zinc veins in the neighbourhood of Mandor (Reksalegora & Djumhani, 1967).

Primary manganese ores commonly occur in hydrothermal veins; but at some places, high-grade ores are impregnated in the zone of contact metamorphic rocks (Benaul, Djelatok).

Primary gold occurs in intrusives and metasediments of Mesozoic age or older (southern part of West Kalimantan). Epithermal gold deposits in the northern part of this district are associated with lead-zinc and copper (Mandor), a type of deposit thought to be connected with Tertiary volcanic rocks (Suhanda, 1970). Still in this district, alluvial gold occurs associated with cinnabar and a little antimonite. Primary mercury ore occurs as stringers and grains of cinnabar in clay-ironstone or clayslate.

Another important secondary deposit is bauxite. It occurs as lateritic cover, attaining a thickness of 2-10 m in the island of Bintan (lateritization since lower Quaternary).

The origin of the bauxite has been studied by Van Bemmelen (1949), and he concluded that it originated by weathering of Triassic shales under special morphological and climatological conditions.

Outside Bintan, the Riauw-Lingga and the tin islands show similar conditions, so that bauxite occurrences may be expected. Southwest Kalimantan offers hundreds of square kilometres where geological conditions are such that bauxite deposits may be expected.

Metallic Mineral Deposits in the Sumatra Orogen

The Sumatra orogen is characterized by Cretaceous to Lower Tertiary folding and by the development of acid to basic plutonic rocks of Mesozoic age. Its trend may be traced from North Sumatra to Central and South Sumatra (Bukit Barisan Mts), the central part of Java (South Serayu Range), and south Kalimantan (Meratus-Bobaris Mts). Upper Mesozoic rocks exposed in central Kalimantan and northwest Kalimantan (Siberuwang area) might be included in this orogenic belt.

Mesozoic folding has been commonly accompanied by intrusions of gabbroic-dioritic rocks. Granitic rocks, however, are also introduced in Central Sumatra and South Sumatra (Musper, 1937). The Middle Cretaceous age of the granite in Central Sumatra (Lassi granite) has been positively determined (Katili, 1962); and the dacite in the South Serayu Range, Central Java, has been considered to be equivalent to the acid intrusions of the belt (Tjia, 1966). The same considerations should be applied to the granodiorite rocks of the Meratus Range.

Primary mineral deposits, connected with acid and basic intrusions in the Sumatra orogen, generally occur as pyro-metasomatic ores. Iron ores and copper sulphides occur at many localities along fault zones, from Alahan Pandjang to Muara Labuh in Central Sumatra. Along this zone, Cretaceous granitic rocks were intruded into older formations. The resulting mineralization, however, is sporadic, in the form of sulphide impregnations in contact zones. The same situation is to be found in Lampung District, South Sumatra.

Contact metasomatic iron ores associated with copper sulphides also occur at Sibumbum Mountains, Padang Highlands.

Gold occurrences of North Sumatra include both primary and secondary deposits (Muara Sipongi, Meulaboh). In the west coast at Atjeh secondary gold deposits occur in Tertiary (?) as well as Quaternary conglomerates. In the alluvial basin of Meulaboh, gold-bearing black sands contain fine grains of cinnabar besides a considerable amount of platinum. The deposits occur in river terraces between the central mountains and the lowland. The terrace deposits are from 3 to 30 m thick (van Bemmelen, 1949).

Worth mentioning is the occurrence of cassiterite-bearing pegmatite in the Suligi-Lipatkain Mountains. Tin placers in this area have been exploited (Westerveld, 1952). This occurrence suggests that there might be a 'tin zone' in the Sumatra orogen as well as that in the Malaya orogen. In this regard, the absolute age of the Suligi-Lipatkain granite should be clarified. Molybdenite occurrences in the pegmatites at Lampung District deserve similar consideration.

South and east Kalimantan show more varieties of deposits. Contact-metasomatic iron ores associated with granodioritic intrusions in limestone occur in Tanalang. Placer gold and platinum occur in the vicinity of Pleihari; the most important deposits occur in the upper drainage area between Muara Koman and Busu.

Exposures of basic to ultrabasic rocks, covering considerable areas in South Kalimantan (Kukusan Mts, Pulu Laut, etc.) offer great possibility for nickel and iron laterites.

METALLIC MINERAL DEPOSITS IN THE MALUKU (MOLUCCAS) OROGEN

The Maluku orogen is built of Upper Palaeozoic, Mesozoic, and Lower Tertiary rocks which were overthrust in Middle Tertiary time (upper Miocene).

This belt of deformation is characterized by occurrences of gabbroic-peridotitic rocks and serpentine of Upper Mesozoic to Lower Tertiary age, exposed in the island row west of Sumatra (Sipura, Nias, Banjak Islands). Further, Westerveld (1949, 1952) connected this orogen through the submarine ridge south of Java to the islands of Timor, Tanimbar, Ceram, and Buru, and finally to the east and southeast arms of Sulawesi and Taulaud Islands at the far north. As a whole, the orogen forms a non-volcanic outer arc.

Exposures of Palaeozoic rocks are better observed in the eastern parts of the arc; occurrences are very limited in the west. Palaeozoic acid plutonic rock is exposed east of Atapupu, Timor. In Ceram, acid hypabyssal rock occurs in Palaeozoic(?) schist. Permian sediments in Timor are intercalated with mafic extrusives, while in Buru mafic hypabyssal and extrusive rocks occur in Jurassic metasediments.

In the Maluku Islands one can observe the influence of Oligocene and upper Miocene folding. The latter caused overthrusting of the system. Granitic rocks, thought to be Tertiary in age, are exposed in Ceram and Ambon (van Bemmelen, 1949). The present writers see this occurrence as a problem to be solved, and if it is true, Westerveld's trend of the Maluku orogen should be re-evaluated critically.

Metallic minerals in the Maluku orogen include nickel laterites, iron laterites, copper, chromite, and manganese deposits.

Nickel and iron laterites occur along ultrabasic trends, especially the olivine-rich peridotitic rocks, such as in the east arms of Sulawesi and Timor. Lateritization has probably taken place during lower Quaternary to Recent times, producing nickel silicate and high-grade soft ore (Sulawesi).

A great number of copper deposits related to ultrabasic rocks are found in Timor. The most important is the high-grade Bone copper deposit. The Bone orebody has been considered to belong to an overthrust mass (an isolated klippe).

The hydrothermal type, in the form of quartz veins with copper sulphides and pyrite, usually occurs in mylonites. It is characterized by low copper content with traces of gold and zinc. Another type is copper minerals impregnated in metamorphosed eruptives.

Secondary occurrences include cupriferous concretions in limestone and bituminous layers of the red clays, and loose blocks of schist impregnated by chalcopyrite in Eocene terraces.

Chromite deposits occur at Latau (southeast Sulawesi) in the form of lenticular bodies in peridotitic rocks. Secondary chromite (recent sand deposit) is found near Malili and north of Kendari, in southeast Sulawesi.

METALLIC MINERAL DEPOSITS IN THE SUNDA OROGEN

According to Westerveld, along a comparatively narrow zone of crustal weakness approximately coincident with the transition area between the Sumatra and Maluku orogens, active andesitic volcanism took place at the beginning of the Miocene or locally perhaps earlier. This belt turned into a longitudinal strip of zones of collapse, which were gradually filled up with a thick sequence of andesitic lavas, breccias, and agglomerates, and by Miocene sediments. At the end of the lower Miocene, this mixed series was rather strongly folded and subsequently intruded along its whole extent by dykes and bosses of andesitic and dacitic rocks, and by dioritic to granitic melts. This volcanic and structural belt has been denominated as the Sunda orogen (volcanic inner arc).

In several publications, this andesitic volcanic series, hydrothermally altered, has been known under the general name of 'Old Andesites', to which an Oligo-Miocene (locally older) age has been assigned. The 'Old Andesites' are distinguishable from younger volcanics by their greenish colour due to propylitization. Silicification and networks of quartz stringers are common close to intrusive bodies. The Sunda orogen is traceable by following the 'Old Andesites'.

Closer observations reveal that the 'Old Andesites' are composed of basic to intermediate calcalkaline volcanics (basaltic to andesitic). According to Westerveld (1949), the orogen runs from the west coast of Sumatra through the Southern Mountains of Java, the Lesser Sunda Islands, and the inner Banda arc to south and north Sulawesi. In our opinion, however, the evidence for continuation of Tertiary volcanism through the whole northern arm of Sulawesi is not convincing.

The younger volcanic suite is of intermediate to acid composition, occupying areas either within the 'Old Andesites' belt (Sumatra, some in Java) or parallel to its extension ('outlying districts' of Westerveld), forming a distinguishable zone, especially in Java.

The intermediate rocks have a higher $K_2O:Na_2O$ ratio without obvious quartz.

Further, potash-rich (leucite-bearing) rocks are developed, forming still another zone in Java, while in the eastern Lesser Sunda Islands and in south Sulawesi these two latter zones overlap with the 'Old Andesites' belt. In the northern part of south Sulawesi, the two zones are again distinctly potash-rich in the west and calcalkaline in the east.

The Sunda intrusives to which Westerveld has assigned an age of middle Miocene may have given rise to some gold-silver veins within the belt (Bajah and Djampang districts in Java), but important deposits in Sumatra (Lebong and West Coast districts) are definitely connected with younger activities (Mio-Pliocene or younger). The younger deposits in West Java probably belong to a separate 'area of metallogeny'.

In general, the Sunda province is characterized by epithermal gold-silver veins, belonging to either the old or the young gold-vein group.

Many of the gold-silver veins in the western coast ranges of South Sumatra belong to the young veins group. Two mining districts in this region are well known: the Lebong district (Bengkulen) and the West Coast district. In these districts intersecting fault structures accompanied by brecciation are nearly always associated with the veins; most of them lie in the vicinity of the great rift zones of Sumatra.

Occurrences in Java may be divided into three groups:

(1) those occurring in the 'Old Andesite' belt (Bajah, Djampang, and Patjitan districts);

(2) those at the boundary between the 'Old Andesite' belt and the younger volcanic zone (Djasinga, Tjikondang); and

(3) those occurring in the still younger volcanic zone—the 'outlying districts' (Sanggabuana, Parang).

All contain base metals (Cu, Pb, Zn), and the 'outlying districts' veins show a notable content of mercury. Relatively higher copper contents are found in the border deposits, where association with acid intrusions is obvious.

Lead-silver veins occur in the central part of south Sulawesi, occupying the transition zone between the calcalkaline and potash-rich volcanics. Other occurrences include gold-silver-bearing sulphide veins in the northern part of south Sulawesi and the eastern part of north Sulawesi.

Copper ores containing minor quantities of precious metals are found at the western part of North Sulawesi, occurring as conformable lenses in chloritic schist and as veins in diabasic rocks. Both the chloritic schist and the diabase are of pre-Tertiary age.

From the metallogenic point of view, these two occurrences show notable deviations from the rule, that is, they have no characteristics in common with the Sunda metallic deposits. Here again, a re-evaluation, perhaps a revision, of the established provinces is obviously necessary.

The occurrences of native copper in the red clays of the traditionally called 'Copper-shale Formation' in south Sulawesi deserve special attention. The possible existence of specific geological conditions to form sedimentary sulphides has to be taken into consideration.

Metallic Mineral Prospects in West Irian (Western New Guinea)

Geological data on West Irian are very scarce. Most of the information presented in this paper has come from Van Bemmelen's (1949) comprehensive work and the report by d'Audretsch et al. (1966).

West Irian may be subdivided into at least three physiographic units:

1. the Southern Platform (Lowland);
2. the Central Mountain Range;
3. the Northern Mountain Range, which includes the Halmahera group.

The Southern Platform consists of lowland of the southern part of West Irian and islands emerging from the Sahul Shelf (Aru Islands). At some places pre-Tertiary rocks are exposed, but most of the lowland is covered by sub-Recent to Recent sediments.

The Central Range consists of high mountains in which pre-Mesozoic to Mesozoic as well as Tertiary folded rocks are exposed. Intrusive rocks are of acid to intermediate composition, are probably Oligo-Miocene, and have been intruded into thrusted older sediments.

The Northern Mountain Range and the most northern part of the 'Bird's Head', continued to Halmahera, consist of regional metamorphic rocks (including Palaeozoic gneissic granite), serpentinized peridotite, gabbro-diorite, and Tertiary to Quaternary rocks. At some places intermediate to basic volcanic rocks of young Mesozoic age occur within or crosscutting the metamorphic rocks.

Volcanoes are still active in the island row west of Halmahera, extending from Batjan to Ternate, Tidore to the north arm of Halmahera. The volcanic chain may be connected with the Quaternary extinct volcanoes in the northern part of the 'Bird's Head'.

Westerveld (1949, 1952) has subdivided the Northern Mountain Range and Halmahera into two zones: (1) a zone with pre-Neogene ultrabasic and acid intrusives and pre-Tertiary sediments of Halmahera and North New Guinea, and (2) a row of active and extinct Quaternary volcanoes. Both zones are similar to the Maluku and the Sunda orogens.

D'Audretsch et al. (1966) reported various metallic mineral occurrences:

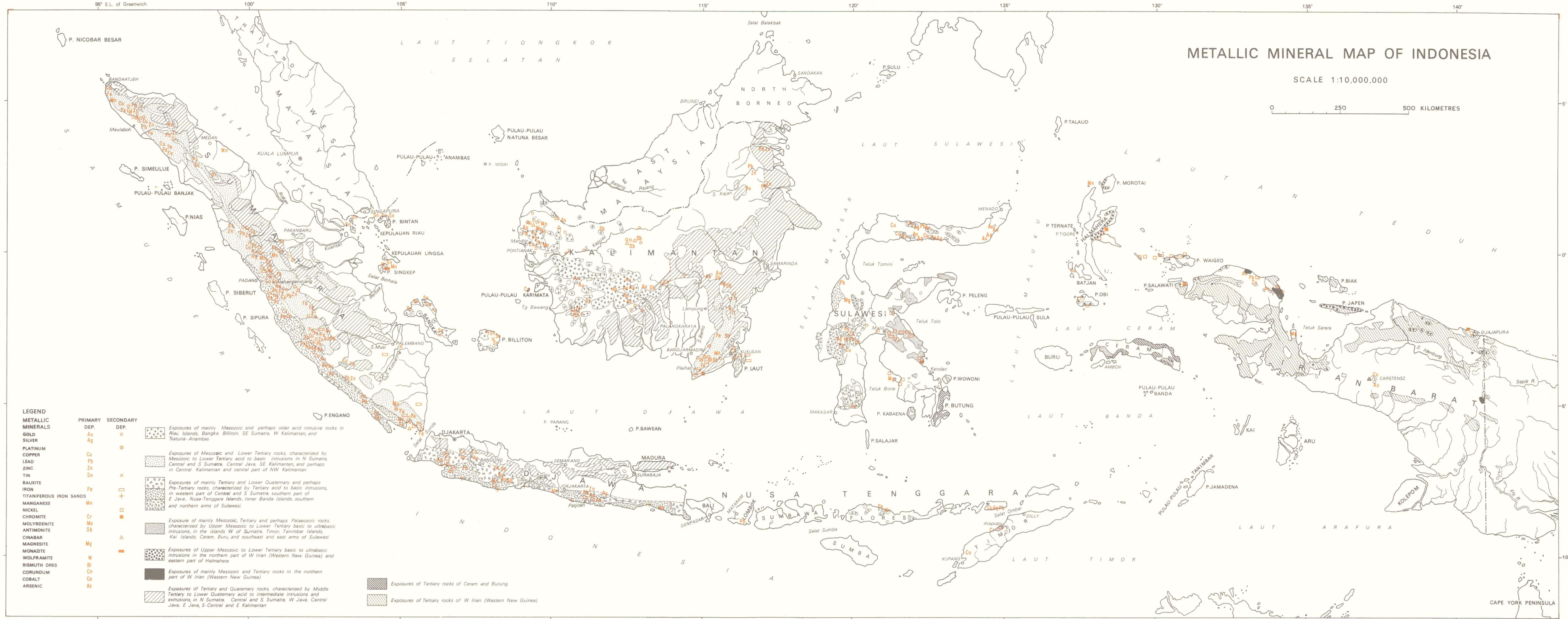
Bismuth and bismuthine, accompanying a mesothermal copper deposit, occur in the Api River.

Chromite and magnetite were found in the sands of the Tami River. In association with nickel-cobalt minerals, chromite has been found in the Cyclop Mountains. Other localities mentioned are the Moropeni Range and the northern part of Salawati.

Copper occurrences are numerous. The most important is the gold-bearing copper ore in the Carstensz Mountains. The occurrence is related to a contact metasomatic deposit at a tectonic boundary between Eocene Faumai Limestone and intrusive monzonite. A previous preliminary exploration indicated a reserve of 6 million tons of 4 percent copper as oxidized ore. Today the Freeport Sulphur Company is working on the deposit under contract with the Government of Indonesia.

Conclusion

Grouping of metallic mineral deposits of Indonesia into metallogenetic provinces according to phases of mountain building (orogens) seems to be logical



Drawn by G. Matveev

This map is to accompany the paper "METALLIC MINERAL DEPOSITS OF INDONESIA" by W. Reksalegora and Djumhani, presented at the XII Pacific Science Congress, 1971, Canberra, Australia.

and practicable. Revisions of Westerveld's scheme should be made here and there, in defining the orogenic belts as well as in grouping the various metallic deposits.

More detailed grouping, whenever possible, should be worked out, perhaps according to other principles.

REFERENCES

ADAM, J. W., 1960—The geology of the tin lodes in the sedimentary formations of Billiton. *Geol. Mijnb.*, 39, 405-26.

BEMMELEN, R. W. VAN, 1949—THE GEOLOGY OF INDONESIA. *The Hague, Govt Printing Office,* 2 vols.

CISSARZ, A., and BAUM, F., 1960—Vorkommen und Mineralinhalt der Zinnerzlagerstätten von Bangka (Indonesien). *Geol. Jb.*, 77, 541-80.

D'AUDRETSCH, F. G., KLUIVING, R. R. B., and OUDEMANS, W., 1966—Economic geological investigation of NE Vogelkop (Western New Guinea). *The Hague, Staatsdrukkerij.*

DZHUMANI, 1971—Quarterly report. *Arch. Sulawesi Mineral Survey, geol. Surv. Indonesia* (unpubl.).

GUIMARAES, D., 1947—Mineral deposits of magmatic origin. *Econ. Geol.,* 42(8), 721-36.

KATILI, J. A., 1962—On the age of the granitic rocks in relation to the structural features of Sumatra. *Amer. geophys. Un., geophys. Monogr.* 6, 116-21.

KATILI, J. A., 1967—Structure and age of the Indonesian tin belt with special reference to Banka. *Tectonophysics,* 4(4-6), 403-18.

KIEFT, C., 1952—Accessory transparent minerals in tin granites of North Banka, Indonesia (unpubl.).

KOOLHOVEN, W. C. B., 1932—Over eenige edelmetal voorkoming in de omgeving van Poerwakarta. *Mijningenieur, Bandoeng,* 13.

KOOLHOVEN, W. C. B., 1933—Beschouwingen omtrent voorkomen, genese, ouderdom en exploratie van goud en edelmetalhoudende ertzen op Java. *Mijningenieur, Bandoeng,* 14, 6-14, 26-30, 47-51.

MUSPER, K. A. F. R., 1937—Toelichting bij blad 16 (Lahat). *Geol. Kaart Sumatra* 1:200 000, *Dienst. Mijnb. Ned. Ind.*

RAMOVIC, M., 1968—PRINCIPLES OF METALLOGENY. *Univ. Sarajevo.*

REKSALEGORA, W., 1971—Quarterly reports. *Arch. Java Miner. Surv., geol. Surv. Indonesia* (unpubl.).

REKSALEGORA, W., and DZHUMANI, 1967—Geological features of some copper deposits in Indonesia. *Arch. D.E., geol. Surv. Indonesia* (unpubl.).

RUTTEN, L., 1927—VOORDRACHTEN OVER DE GEOLOGIE VAN NEDERLANDSCH OOST-INDIE. *Groningen, J. B. Wolters.*

SUHANDA, T., 1970-1—Quarterly report. *Arch. Kalimantan Miner. Surv., geol. Surv. Indonesia* (unpubl.).

SUMARDI, 1966—Penjebaran Unsur2 Kesan dalam granit Banka. *Akad. Geol. Portambangan, Bandung.*

TJIA, H. D., 1966—Structural analysis of the pre-Tertiary of the Lo Uloh area, Central Java. *Dr's Thesis, Inst. Tech. Bandung* (unpubl.).

WILLEMS, H. W. V., 1940—On the magmatic provinces in the Netherlands East Indies. *Geol. Mijnb, geol. Ser.,* 12(3), 289-477.

WESTERVELD, J., 1949—Fasen van gebergtevormingen ertsprovincies in Nederlands—Oost-Indie. *Ingenieur,* 61, *Mijnbouw en Petroleum-techniek.*

WESTERVELD, J., 1952—Phases of mountain building and mineral provinces in the East Indies. *18th int. geol. Cong., London,* 13, 245-55.

A BRIEF REVIEW OF METALLOGENESIS IN THE PRECAMBRIAN PART OF THE AUSTRALIAN CRATON

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SUMMARY

The Precambrian part of the Australian craton is taken as consisting of all mainland Australia except the eastern Palaeozoic fold belt and the Mesozoic to Recent platform cover. It formed by two successive major accretions, about 1900 m.y. and between 1800 and 1000 m.y. ago, to an Archaean nucleus which stabilized about 2400 m.y. ago. Three distinct sequences of platform deposits can also be identified, the beginning of each being marked by deposition on the newly stabilized nucleus or accretion at about 2200 m.y., 1800 m.y., and 1400 m.y. ago.

Each of these major tectonic units is characterized by deposits of particular metals or combinations of metals: the nucleus by gold, gold-arsenic, nickel-copper, and pegmatitic minerals; the first accretion by gold, copper-gold, and late-phase zoned tin-base metal deposits; and the second accretion by uranium, copper, and large lead-zinc-silver bodies. The successive platform sequences are marked respectively by iron; uranium, lead-zinc-silver, iron, and hydrothermal tungsten deposits; and manganese, phosphorus, and, in the mobile Adelaide 'Geosyncline', barium, lead, copper, and gold.

Some Precambrian blocks cannot be placed with confidence in this pattern. Most have no metallogenic importance, but the Georgetown Block in northeastern Australia contains gold and lead.

Deep weathering on the stable craton has upgraded the upper parts of sulphide bodies; lateritization has produced bauxite, nickeliferous laterites, and economic manganese and iron bodies; and many minerals released by erosion have formed alluvial deposits.

The present continental mass of Australia and southern New Guinea, the Australian Craton, has a complex geological history which is as yet only partly unravelled. However, the present craton may be broadly described as having formed via a series of progressively larger cratons, each formed from its predecessor by the addition of stabilized formerly mobile regions and platform cover. Thus at present the Australian Craton is rimmed on the north by the unstable orogenic and pre-orogenic zones of the New Guinea Arc, a zone which we might expect in the future to become stable and be firmly welded onto the present craton. The stability of the Australian Craton since the early Mesozoic is attested by the spread of platform cover; the limitation of deformation to broad warping and block faulting; and the restriction of igneous activity to a few cratonic granites, some acid volcanics, and more widespread basic lavas. The platform cover has spread over regions stabilized in the Palaeozoic and early Mesozoic, older platform covers, and older orogenic regions. A tectonic model derived from these relationships is illustrated in Figure 2 and is used for describing in broad terms the development of the Australian continental mass and its metallogenic development.

This paper examines in general terms the metallogenic history of the Australian Craton excluding the Palaeozoic mobile zone in the east and the Mesozoic to Recent platform covers. The tectonic units and their names follow the usage of the Tectonic Map of Australia (Geological Society of Australia, 1971); the distribution of units is indicated in Figure 2 (after K. A. Plumb), and the time ranges of units are shown in Figure 1, reproduced from the Tectonic Map.

West Australian Orogenic Province

Before about 2200 m.y. ago, there is no evidence of platformal sedimentation; areas of rocks formed and deformed before this time are included in the West Australian Orogenic Province. This consists of two major shields, the Pilbara and the Yilgarn Blocks, and several small occurrences in the north of the Northern Territory. Granites in the Pilbara Block and along the western margin of the Yilgarn Block are 3100-3000 m.y. old. However, the important mineralized eastern margin of the Yilgarn Block appears somewhat younger, with a range of ages from 2700+ m.y. to 2600 m.y.

Both blocks are mainly acid gneisses and granites with narrow elongate troughs filled by acid, basic, and ultrabasic volcanics which are generally only mildly metamorphosed. Most of the orebodies occur in the narrow zones of volcanic rocks. Detailed mapping northeast of Kalgoorlie has revealed three cycles of deposition, each cycle going from a phase of basic and ultrabasic lavas through a sedimentary phase to a phase of acid volcanism.

Gold previously dominated mining activity in both the Pilbara and Yilgarn Blocks. In the Kalgoorlie region, the most important mining area, the gold is associated with acid dykes and sills, and occurs in gold-sulphide, gold-quartz, and gold-telluride lodes. The geological setting of the lodes in other gold-mining areas of the Yilgarn Block is similar, although a gold-arsenic association is also common in the north of the block. In the Pilbara Block most of the gold occurs in quartzose lodes, commonly with pyrite; but in the east of the block gold-antimony mineralization is also common. In the last six years nickel mineralization has been shown to be widespread over the eastern half of the Yilgarn Block. In general the nickel occurs in basic and ultrabasic sills within an early phase of deposition. The sulphide deposits also carry copper and platinum. Nickel mineralization is reported to exist in similar rocks in the Pilbara Block. Jaspilitic lenses in both blocks have produced iron orebodies where suitable structural sites have allowed supergene enrichment. Tin, tantalum-columbium, beryllium, and lithium minerals occur in late-phase pegmatites in both the Pilbara Block and the west of the Yilgarn Block. Most are low-grade bodies and the bulk of production has been from alluvial and eluvial material. Copper mineralization is generally on a small scale; but at Whim Creek and Mons Cupri within the Pilbara Block larger bodies of copper and mixed base metals occur in acid porphyry plugs.

The small occurrences belonging to the West Australian Orogenic Province in Northern Australia are of acid gneiss and granite. They carry no mineralization, but several major uranium deposits have been found close to unconformities between them and the overlying rocks.

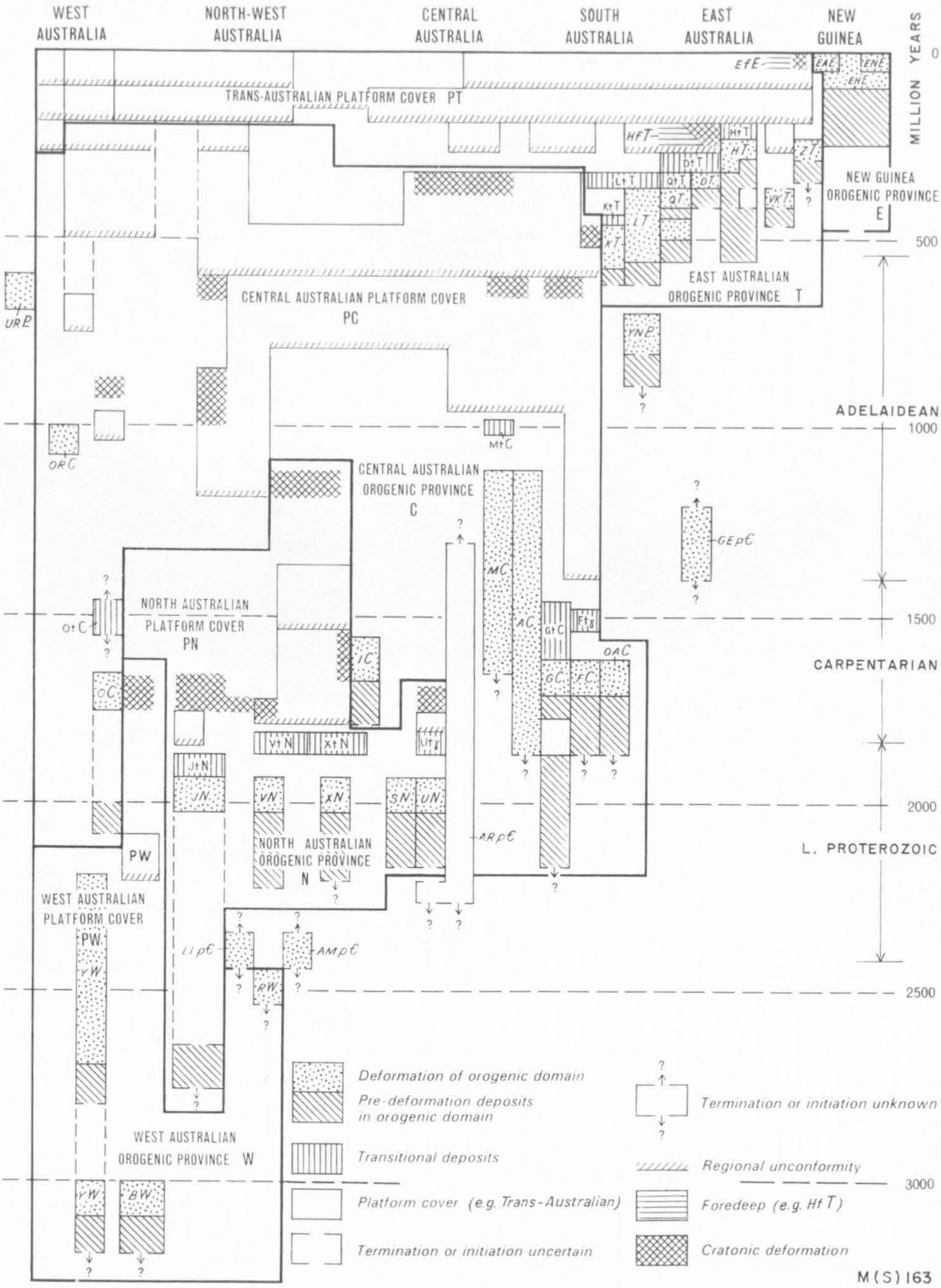

Fig. 1. Diagrammatic relationship of tectonic units (after tectonic map of Australia).

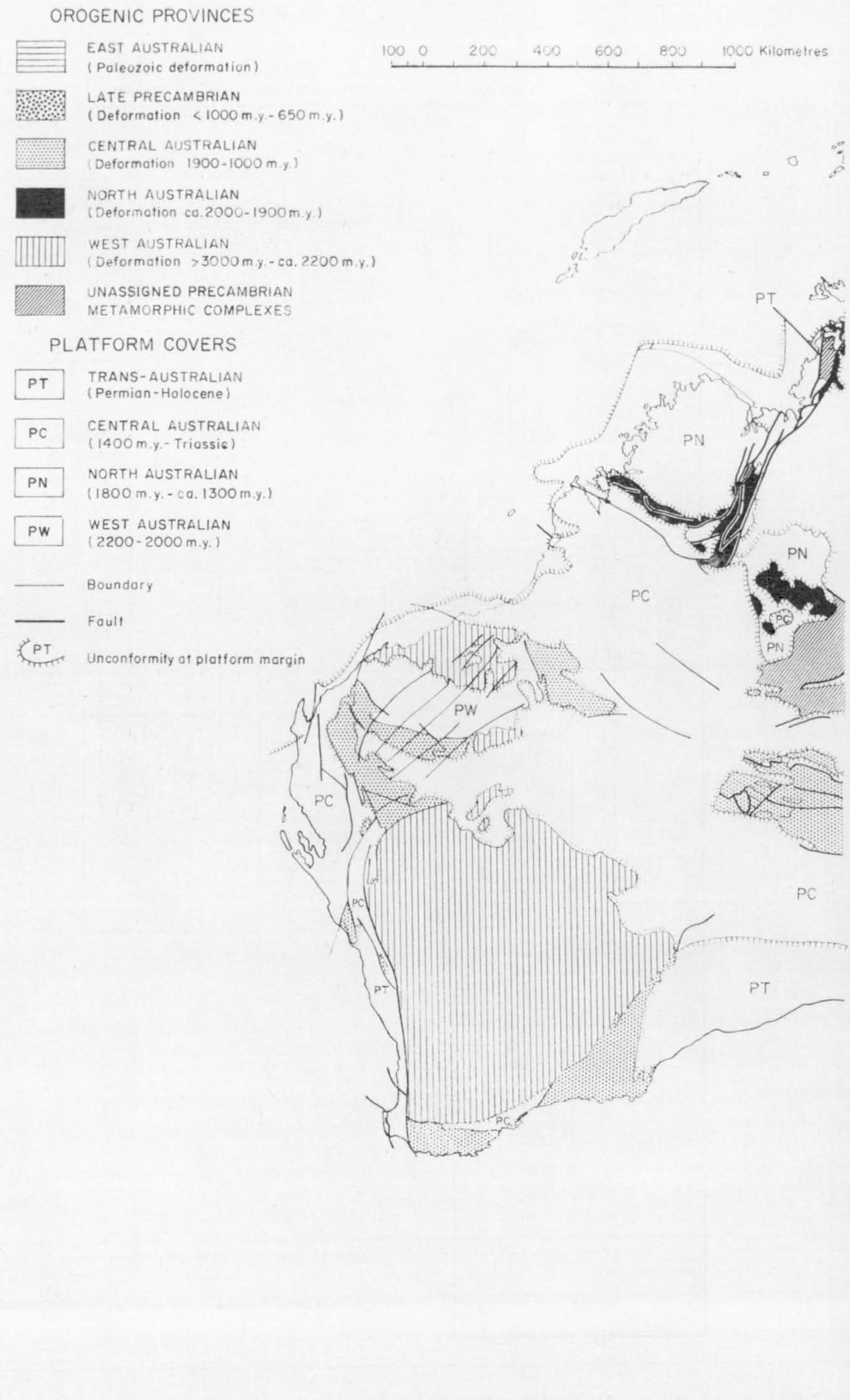

Fig. 2. Orogenic provinces and platform

covers (after 1:12 000 000 tectonic map). AUS 2/42

West Australian Platform Cover

About 2200 m.y. ago basic volcanics were poured out over the stabilized Pilbara Block as the basal unit of the first platform cover sequence, the West Australian Platform Cover. Much of the sedimentation that followed was chemical and included considerable thicknesses of banded iron formation, the source of the iron being the basic volcanics. Subsequent folding and leaching of silica from these iron-rich bands has produced the high-grade iron ores of the Hamersley Ranges.

North Australian Orogenic Province

Also in the early Proterozoic, geosynclinal and semi-geosynclinal sediments were deposited in several areas across northern Australia, in many places on continental crystalline basement. All these areas, which were deformed about 1900 m.y. ago, form the North Australian Orogenic Province. Metamorphism was, on the whole, low-grade, but high-grade metamorphism is recorded from small faulted areas in the Halls Creek Belt in the west. This orogenic province is characterized by the absence of syntectonic granites and by the presence of late-phase granites and acid volcanics. Small gold deposits occur in all areas except the Nicholson Block, the largest being at Tennant Creek, which has now become important as a copper-bismuth-gold mining area. The origin of the Tennant Creek orebodies is disputed, but they have epigenetic rather than syngenetic characteristics. Post-orogenic granites introduced most of the remaining mineralization in the North Australian Orogenic Province. In the Pine Creek Block, tin, tungsten, molybdenum, copper, lead, and gold are distributed in a complex of zones about the granites. Tin has been introduced in the Nicholson Block by similar granites.

Uranium in northern Australia

Many of the uranium deposits in the north of Australia are near the unconformity between the acid volcanics that terminated the development of the North Australian Orogenic Province and the basal conglomerates and basic volcanics of the succeeding North Australian Platform Cover. Examples are the South Alligator deposits and the uranium deposits of the Westmoreland area on the Queensland/ Northern Territory border.

North Australian Platform Cover

The North Australian Platform Cover developed in two phases. During the early phase, in the early Carpentarian*, sediments spread across North Australia from the Kimberley Basin in the west to the mobile edge of the Mount Isa region in the east. Two windows of platform cover of similar age are exposed north and south of the Tennant Creek Block. Rocks in this early phase contain the large conformable lead-zinc-silver sulphide deposit at McArthur River and the Bulman lead deposit. In the extreme west, hematitic sands of early Carpentarian age now outcrop on Cockatoo and Koolan Islands; they were folded by late Adelaidean diastrophism.

The tungsten deposits of Hatches Creek occur in quartzite veins within North Australian Platform Cover adjacent to the Tennant Creek Block. There is no obvious igneous or metamorphic event in the area that might have introduced the mineralization, despite its hypogene characteristics.

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* The time-span of the component systems of the Australian Proterozoic is shown in Figure 1.

The second phase of deposition in the North Australian Platform Cover followed the deformation of the Mount Isa Belt about 1550 m.y. ago; it was less extensive than the first and is confined to the eastern part of the platform. It contains the iron carbonate deposits of Constance Range and the Roper River area.

Central Australian Orogenic Province

The Central Australian Orogenic Province, which developed during the Carpentarian, is now represented by widely spaced blocks; some of these appear to be intracratonic; others, such as the Mount Isa Belt, were pericratonic. On the west the Ophthalmia-Gascoyne Block formed as the result of deformation of thick sediments at the margin of the West Australian Platform Cover, and the Albany-Fraser Belt formed from a deformed trough along the southeastern margin of the Yilgarn Block. Neither carries any known large mineral deposits, although minor mineralization, notably copper and lead, has been reported from both regions. In the south of the continent a single orogenic domain probably extends from Eyre Peninsula eastwards to beyond Broken Hill; this now appears as two large blocks, the Gawler in Eyre Peninsula and the Willyama in the east, and several smaller basement highs beneath younger platform sediments.

The most important mineralization in this domain is at Broken Hill, the largest of a number of conformable pyrite-lead-zinc-silver-sulphide bodies confined to a small area in the east of the Willyama Block. All the highs and both blocks show minor uranium-thorium mineralization, including the small deposits at Mount Painter and Radium Hill. The presence of jaspilitic material in both the Gawler and Willyama Blocks has led to suggestions of stratigraphic correlations with the West Australian Platform Cover. Metamorphosed iron-rich sediments in the Gawler Block form the iron ore deposits of the Middleback Ranges. The adjacent but genetically different copper deposits of Wallaroo and Moonta appear to have been introduced by acid volcanic activity late in the development of the Gawler Block.

Rocks of the Mount Isa Belt in northeast Australia were deposited and deformed during the mid-Carpentarian. Their mineralization shows affinities with the coeval first phase of the North Australian Platform Cover. Uranium mineralization continues into the deformed region from the Platform Cover, but appears at several stratigraphic horizons and in a variety of tectonic settings, so that the unconformity with the acid volcanics of the preceding North Australian Orogenic Province is not here the only favoured horizon. Moreover, the orebodies at Mary Kathleen show high-temperature features and are thought to have been introduced by a nearby intrusive granite. The Mount Isa Belt contains several lead-zinc-silver orebodies, the largest and best known lying along a 20-km north-south zone through Mount Isa. These are widely accepted as syngenetic and mildly metamorphosed contemporaneous equivalents of the McArthur River deposit. The copper deposits of the Mount Isa Belt, including that at Mount Isa, are probably hypogene. The source of the copper appears to be basic rocks within the depositional sequence, concentrated into suitable structures during folding.

The Musgrave Block in central Australia has a complex history spanning from about 1650 m.y. to 1000 m.y. ago. Ultrabasic bodies emplaced late in the development of the block have given rise to lateritic nickel deposits at Wingelinna.

The Northampton Block, in the extreme west of the continent, consists of high-grade metamorphic rocks which contain copper and lead deposits. These

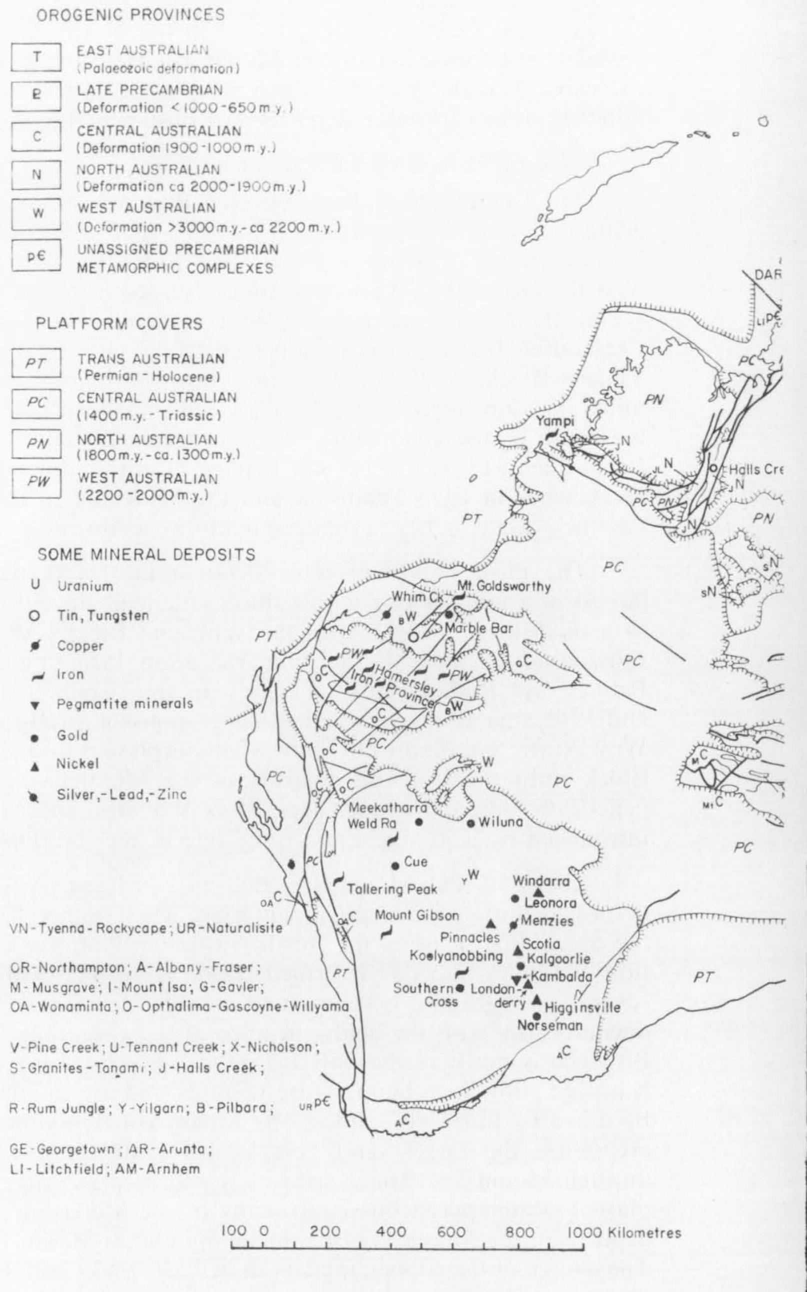

Fig. 3. Tectonic regions

and mineral deposits.

occupy similar structural sites in fracture zones, but individual deposits are either mainly lead or mainly copper, with little overlap.

Central Australian Platform Cover

The Central Australian Orogenic Province is succeeded by the Central Australian Platform Cover, which developed in two phases: during the Adelaidean and earliest Cambrian, and during the Palaeozoic. The manganese deposits of the Bangemall Basin in Western Australia and small manganese deposits in South Australia occur in the earlier phase. The second began in North Australia with widespread basalts which contain minor copper. However, the second phase is important for the phosphate deposits it contains: in small quantities in early-Cambrian to mid-Cambrian sediments in southern and central Australia and in larger deposits along the northeast margin of the Platform Cover where it laps onto the Mount Isa Belt. Rocks of the Adelaide 'Geosyncline' contain barium, copper, lead, zinc, and gold mineralization, all attributed to orogenic activity during the Ordovician in the adjacent mobile Kanmantoo Belt.

The Naturaliste Block in Western Australia was formed at the end of the Proterozoic; it contains no known mineral deposits. The late Precambrian rocks of Tasmania form mildly metamorphosed basement for those of the Palaeozoic East Australian Orogenic Province. The Savage River iron ore deposit, the largest of a number of Precambrian iron deposits in western Tasmania, is a mesothermal magnetite body.

Unassigned Orogenic Domains

The position of some blocks of deformed rocks within the tectonic framework has not yet been determined. These include several small blocks in northern Australia, all possibly Archaean, with no mineralization, and the large Arunta Block in central Australia. The Arunta Block is a complex of several tectonic domains, and may contain parts of more than one Orogenic Province. It contains very small gold deposits along its southern margin, which has been deformed several times. Copper, lead, zinc, and bismuth deposits at Jervois possess syngenetic characteristics. Very small yields of tin, tantalum, and tungsten have been obtained from deposits along the north of the block.

The Georgetown Block in northeastern Australia is probably of late-Middle or Upper Proterozoic age. The main mineralization is gold, occurring in or close to granites and in fault zones. Tin, copper, and lead have been introduced by granites of Palaeozoic age.

Effects of the Stability of the Australian Craton

Many of the important mineral deposits of northern Australia are the result of deep weathering during the Mesozoic and Tertiary. Bauxite has been deposited during the erosion of deeply weathered rocks in the late Tertiary and Quaternary. The manganese deposits of northern Australia occur in a thin veneer of marine Cretaceous sediments, often at their base. The uranium deposits of northern Australia are at a shallow depth, and this may be related to groundwater movements near the level of the present land surface. Deep weathering has concentrated metals in the supergene zones of many small orebodies and released gold from gold-pyrite lodes so that mining of such bodies has been economically possible. Alluvial production from low-grade but easily worked detrital material has been important in much of northern Australia.

References to detail have not been quoted in this paper. Reviews of regional mineralization are continued in Edwards (1953) and McAndrew (1965); these also contain detailed descriptions of individual deposits. A more detailed account of Australian metallogenesis has been prepared to accompany the Metallogenic Map of Australia (Warren, 1972). An account of Australian mineral occurrences is contained in McLeod (1965).

REFERENCES

EDWARDS, A. B., ed., 1953—GEOLOGY OF AUSTRALIAN ORE DEPOSITS. *5th Emp. Min. metall. Cong., Melbourne,* 1.

GEOLOGICAL SOCIETY OF AUSTRALIA, 1971—Tectonic Map of Australia at 1:5 000 000. *Geol. Soc. Aust. Sydney.*

MCANDREW, J., ed., 1965—GEOLOGY OF AUSTRALIAN ORE DEPOSITS, 2nd edn. *8th Cwealth Min. metall. Cong., Melbourne,* 1.

MCLEOD, I. R., ed., 1965—Australian mineral industry: The mineral deposits. *Bur. Miner. Resour., Aust. Bull.* 72.

WARREN, R. G., 1972—A commentary on the metallogenic map of Australia and Papua New Guinea. *Bur. Miner. Resour. Aust. Bull.* 145.

METALLOGENIC PROVINCES IN JAPAN

A correlative study to plate tectonics and its implication to exploration

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Summary

A correlation between geophysical information and the distribution of four major types of mineral deposits in Japan was attempted, based on plate tectonics as a working hypothesis. The geographical extent and time elements of three types of Cainozoic mineral deposit were found to be compatible with the activity of present arc-trench systems around Japan. Another even older type can be similarly explained if we infer a previous cycle of arc-trench activity roughly parallel to the present system.

Extrapolation of these genetical implications of tectonics and mineralization to other Asian circum-Pacific arc-trench systems is still very difficult owing to the paucity of basic geophysical and geological information. However, a few interesting problems of distributional anomalies are presented for further research.

For further applications of these studies to the practical prognosis and exploration, more detailed and exact geological, geophysical, and geochemical knowledge is necessary. The structural and palaeogeographical features of the shallower crust at the time of the formation of a deposit, the geochemical environment of metal concentration and deposition, later tectonic and orogenic activities, the nature of overlying formations and features, and the extent of later erosion of the area are thought to be some of the most important factors for localizing the formation of mineral deposits.

Introduction

The existence of a number of metal provinces has been recognized in island arcs in eastern Asia. However, each archipelago has its characteristic types of ore deposits or combinations of deposits, or a concentration of different kinds of metals, in spite of many common physiographic or geological features.

The present study is an attempt to correlate the diastrophism, associated igneous activity, geosynclinal sedimentation, and metallogeny in the light of currently developing theories of plate tectonics, aiming at a possibly improved prognosis of other metal provinces as a far-reaching but final target (Guild, 1971).

The recent accumulation of extensive geophysical knowledge of the orogeny of island arcs in and around Japan has made her one of the type localities of plate tectonics of an island arc. Therefore a major part of the attempt is concerned

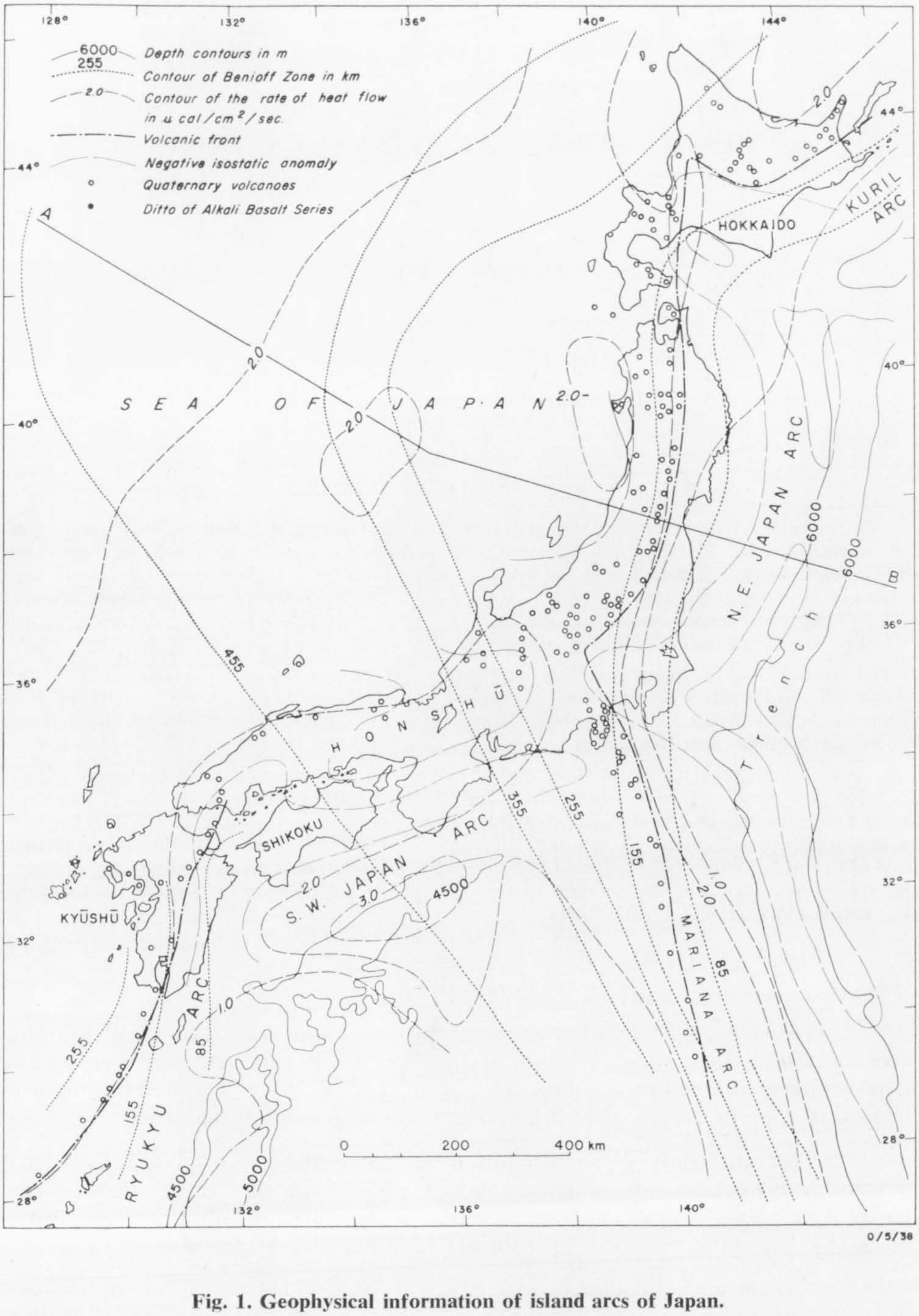

Fig. 1. Geophysical information of island arcs of Japan.

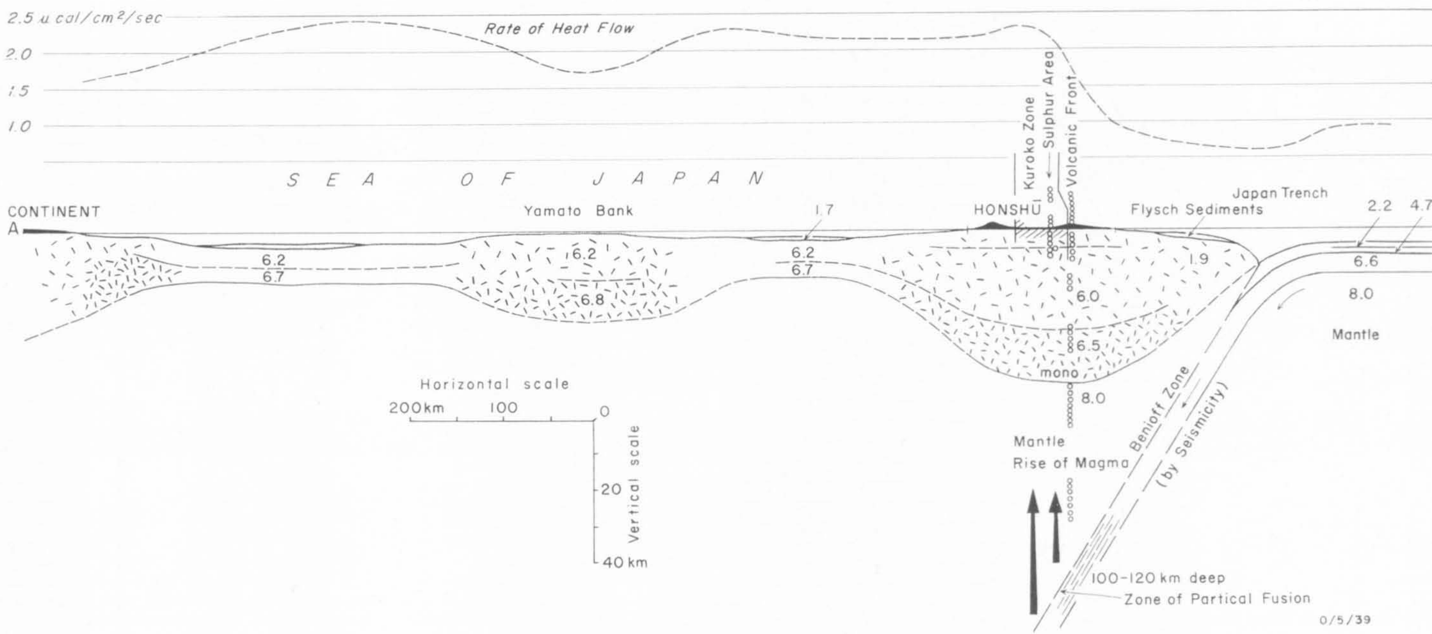

Fig. 2. Schematic cross section of Japan Arc.

with the correlation between geophysical information in the line of plate tectonics, and geology related to the metal provinces in the island arcs of Japan. The task of extrapolating these results with other island arcs is still extremely difficult owing to the paucity of published geophysical information on the island arcs of south-east Asia.

Some geophysical information and a tectonic model of the Japan arc

(Dewey & Bird, 1970; Takeuchi, 1970; Veda, 1971; Veda & Sugimura, 1970.)

Some geophysical information is compiled in Figures 1 and 2.

Ocean Trenches. Deep ocean trenches are shown in Figure 1 and the ocean deep which lies off the southern coast of west Honshu. The depth contours of the Benioff zones (subduction zones) at approximately 100 km intervals are also indicated. These contours are computed from numerous recent seismic events. Benioff zones develop along the Kuril arc, northeast Japan arc, Mariana arc, and Ryukyu arc. The slope of the zone of the northeast Japan arc is rather irregular and low angle as a whole at and around the Sea of Japan. Contours are lacking for the southwest part of Japan, the southwest Japan arc, because of the lack of recent pronounced seismicity in this region, which indicates the inactivity of this area today, although the existence of another old subduction zone has been reasonably inferred (Veda & Sigimura, 1970).

The rate of heat flow. Results of measurement of the rate of heat flow in the area from the ocean trench across the island arcs and Sea of Japan to the continent are shown here by a contour line with the interval of 0.5 $\mu cal/cm^2/s$. (Oxburgh & Turcotte, 1970; Takeuchi & Veda, 1964; Veda, 1971).

An outstanding feature of the heat flow is the extensive high area which extends more than 700 km from the trench on the continental side (Sea of Japan side) of the currently active northeast Japan arc towards the west-southwest along the northern coast of southwestern Honshu. This section of the contours clearly intersects the Benioff contours.

Heat-flow highs at the back of the arc, that is on the stationary wedge on the continental side and above the Benioff zone, are thought to be caused mainly by the dissipation of the frictional heat of the descending plate at the Benioff zone under the very high shear stress and several other heat-generating factors (Oxburgh & Turcotte, 1970; Takeuchi, 1970).

The extensive regional heating at a great distance from the arc, which also shows the long vertical distance of the heat transfer, needs quite a long time—say a few tens of million years—even with the efficient mechanism of heat transfer. The present-day regional high heat flow behind the arc should be associated with much higher activity in an earlier geological period on the fault (Benioff) zone.

Volcanoes and the volcanic front. The location of Quaternary volcanoes on the arc islands is shown in Figure 1 by small circles and black dots; the latter indicate volcanoes characterized by alkali basalt (Kamehire & Tatsumi, 1970).

These volcanoes are aligned more or less parallel and not far from the ocean trenches, with a slight abnormality at the join of the northeast Japan and the Kuril arcs. The front line of volcanic activity, the volcanic front, is very clearly defined and, apart from this front, there is a general compositional change of the effusive basalt from the narrow tholeiitic zone to the broader zone of high-alumina basalt, and to alkali basalt, which is shown by the black dots mentioned above (Takeuchi & Veda, 1964; Takeuchi, 1970; Veda & Sugimura, 1970).

These magmas originate from the partial fusion of basic subcrustal or mantle material which gradually rises to the surface through the crustal material of the stationary wedge by mechanisms which are still under discussion. The volcanic front could be explained as the surficial projection of the line in the Benioff zone below which partial fusion occurs.

A few volcanoes exist on the northern flank of the southwest Japan arc, aligned parallel to the contour of the high heat flow. It is noteworthy that both directions clearly intersect, at nearly right angles, the contours of the presently active Benioff zone, as in Figure 1.

In the northern part of the Ryukyu arc, and in many other arcs in the western Pacific, there are similar geographical relations between trenches, arc islands, volcanic fronts, and variable compositional zones of basaltic rock.

Isostatic anomaly (Veda & Sugimura, 1970)

Negative isostatic anomalies on the Japan arc are roughly shown by the 0 and —100 mgal contours in Figure 1. There is a marked hump at the joint of the presently active arc. Contours of slight negative value at the southwest Japan arc, west Honshu, and Shikoku, show another parallelism to the contours of heat flow and ocean deeps.

The following additional items of geophysical information are worthy of note. The present activity of the northeast Japan—Mariana arc is said to have resumed or been rejuvenated in late Miocene time and its average movement is presumed to be 9 cm/y.

The age of the bedrock drill-core of the bottom of the Pacific on the east side of the Mariana trench is presumably Jurassic (the oldest is 140 m.y.) and that of the west side, the inner side of the Mariana arc, is 20 to 30 m.y.

Following the model of the present working theory the schematic cross-section along line A-B on Figure 1 is shown in Figure 2 (Dewey & Bird, 1970; Oxburgh & Turcotte, 1970).

Some outstanding metal provinces in Japan and their correlation with the tectonic model

Figure 3 shows the distribution of four outstanding types of ore deposits in Japan: (1) the 'Kuroko'-type deposits and the outline of intense submarine volcanic activity of middle to late Miocene age; (2) the gold-silver veins of late Miocene to Pliocene age; (3) Quaternary volcanogene sulphur deposits, with or without pyrite; (4) bedded cupriferous iron sulphide deposits mostly deposited in late Palaeozoic time and mostly metamorphosed by late Mesozoic orogeny, but including a few exceptional minor deposits of Mesozoic age. (Tatsumi, Sekine, & Kanehira, 1950).

The major portion of provinces (2) and (3) are superimposed, and all (1), (2), and (3) are included in the region of Miocene volcanic activity, although areas of major concentration of each type are clearly separated.

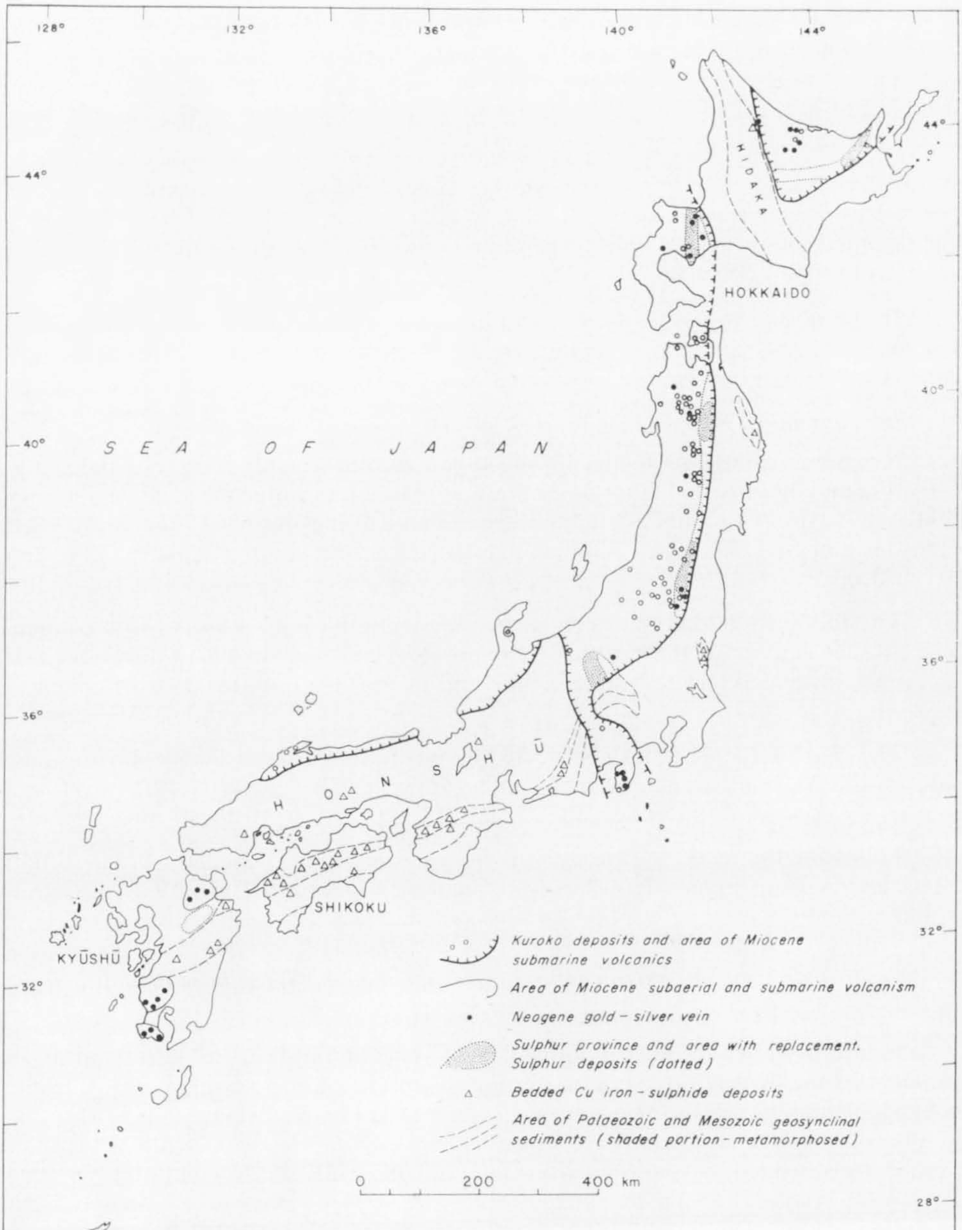

Fig. 3. Metallogenic provinces in Japan.

In the province of Au-Ag deposits there are four concentrated areas, none of which is associated with conspicuous Kuroko-type deposits. On the other hand many Kuroko-type deposits have a low content of silver, with gold commonly in their larger orebodies.

The Au-Ag provinces are definitely parallel to and usually not very far from the volcanic front of the active inland arcs; they are slightly younger than the peak stage of Kuroko mineralization. Owing to the lack of a competent isotopic study, the immediate source or origin, crustal or deeper, of their metals, sulphur, and water is still not certain, although their close relationship to magmatic activity, at least for the heat energy imported to the ore solution, is not in doubt (Nishiwaki, Matsukuma, & Urashima, 1971).

The provinces of volcanogenous sulphur (with or without pyrite) are closer to the present volcanic front than the gold-silver vein provinces in the three active arcs. Petrologically they are mostly in the tholeiite zone. Several larger concentrated areas have a larger subsurface replacement and sedimentary sulphur deposited in the crater or in small lakes of the volcano. They are younger than Au-Ag vein deposits (Mukaiyama, 1970).

Some remarkable features of the distribution of Kuroko deposits follow (Inoue, 1969; Matsukuma & Horikoshi, 1970; Minato, 1971):

(a) Kuroko deposits are confined to the area of Miocene submarine volcanic activity along the Kuril, northeast Japan, and southwest Japan arcs. This is compatible with many other geological features of their submarine volcanic exhalative and/or hydrothermal origin. Lack of typical Kuroko deposits along the Ryuku arc may be explained by the more generally prevailing subaerial circumstances at the time of Miocene volcanic activity.

(b) The province of Kuroko is roughly identical with that of Quaternary volcanoes of the tholeiitic to alumina-rich basaltic series, although the deposits are near, and seem to be genetically related to, rhyolitic or andesitic volcanic activities, which might have been caused by magmatic differentiation and/or chemical reaction with the wall rock during their long passage through crustal rock (Takeuchi, 1970; Veda & Sugimura, 1970).

(c) Stable-isotope studies of the source of metals, sulphur, and water are still in progress. Although recent results have led to the inference that most of the sulphur of sulphide and sulphate in the Kuroko ore is of ocean water sulphate origin, many people still tend to think that metals are mostly derived from deeper magma.

(d) There are a few areas of marked concentration in the main central portion of the volcanic belt of the northeast Japan arc, where we find the most intense Miocene submarine volcanic activity, and consequently thicker eugeosynclinal sediments.

(e) Sufficiently deep conduits or channel-ways for magma and ore solutions and submarine basin structure with acidic volcanic domes at the time of ore deposition as well as later sedimentary cover are some of the vitally important controlling factors for defining the distribution and localization of the deposit at the shallower crust, and therefore important for actual exploratory work in the

Kuroko province (Isshiki, Matsui, & Ono, 1968; Matsukuma & Horikoshi, 1970; Minato, 1971).

A zone of concentration and scattered locations of the bedded cupriferous pyrite deposits, which are older, are characteristically associated with the metamorphosed basic volcanic piles of the Paleozoic eugeosyncline (Fig. 3). This zone is parallel to the southwest Japan arc, but a few deposits are sporadically distributed along the northeast Japan arc (Kanehira & Tatsumi, 1970).

They lie at present on the ocean side of both arcs. Along the southwest Japan arc a very thick pile of clastic sediments (flysch type, Shimanto-system) has been developing above the Palaeozoic geosyncline from late Mesozoic to upper Cainozoic times towards the southwest Japan deep, which is shallower than active trenches of the northeast Japan and Mariana arcs.

If the present tectonic model and the working hypothesis of plate tectonics are applied to the older cycle of orogeny, similar metallogenesis associated with older one-cycle submarine volcanism, similar to that of Kuroko, but with little zinc and no lead, could be inferred. However, in this older cycle—late Palaeozoic to early Mesozoic—the eugeosynclinal volcanic pile was more basic and might have been located at the ocean side of the continental margin at that time, as the palaeogeography of Japan reveals (Isshiki, Matsui, & Ono, 1968; Minato, 1971). From a geosynclinal point of view it can be described as a shifting of the geosyncline from south to north, or from the ocean side to the continental side, associated with the formation of the Sea of Japan and its oceanic crust, thus resulting in the form of the present-day island arc of Japan through the younger orogenic cycle.

The sporadic distribution of bedded cupriferous iron sulphide deposits in the eastern part of Honshu is due to the existence of older fragmental formations separated by later disturbances and the intrusions of large igneous masses.

It is challenging indeed to investigate the possibility of an old arc cordillera along the old continental margin before the island arc of Japan was shaped and the Sea of Japan was formed during and between these two orogenic cycles (Takeuchi, 1970).

For the purpose of exploration of deep-seated and completely concealed and unexplored metal deposits in Japan the following steps were taken through the co-operation of government organizations and industry:

(1) After the delineation of important metal provinces, the selection of the more concentrated and prospective areas by existing, available geological and geophysical information is made by expert members of the government-sponsored commission. Thus a number of areas, usually more than ten, each of several hundred square kilometres, are selected for the year.

(2) Detailed geological mapping on a scale of 1/10 000 as well as some necessary geophysical work both on the ground and in the air, with a few deep (often more than 1000 m) structural core drillings at geologically crucial sites, is carried out mainly for the purpose of confirming favourable geological and structural environments for the formation of the deposits. A number of field geologists are supplied by the companies who hold interests in the area.

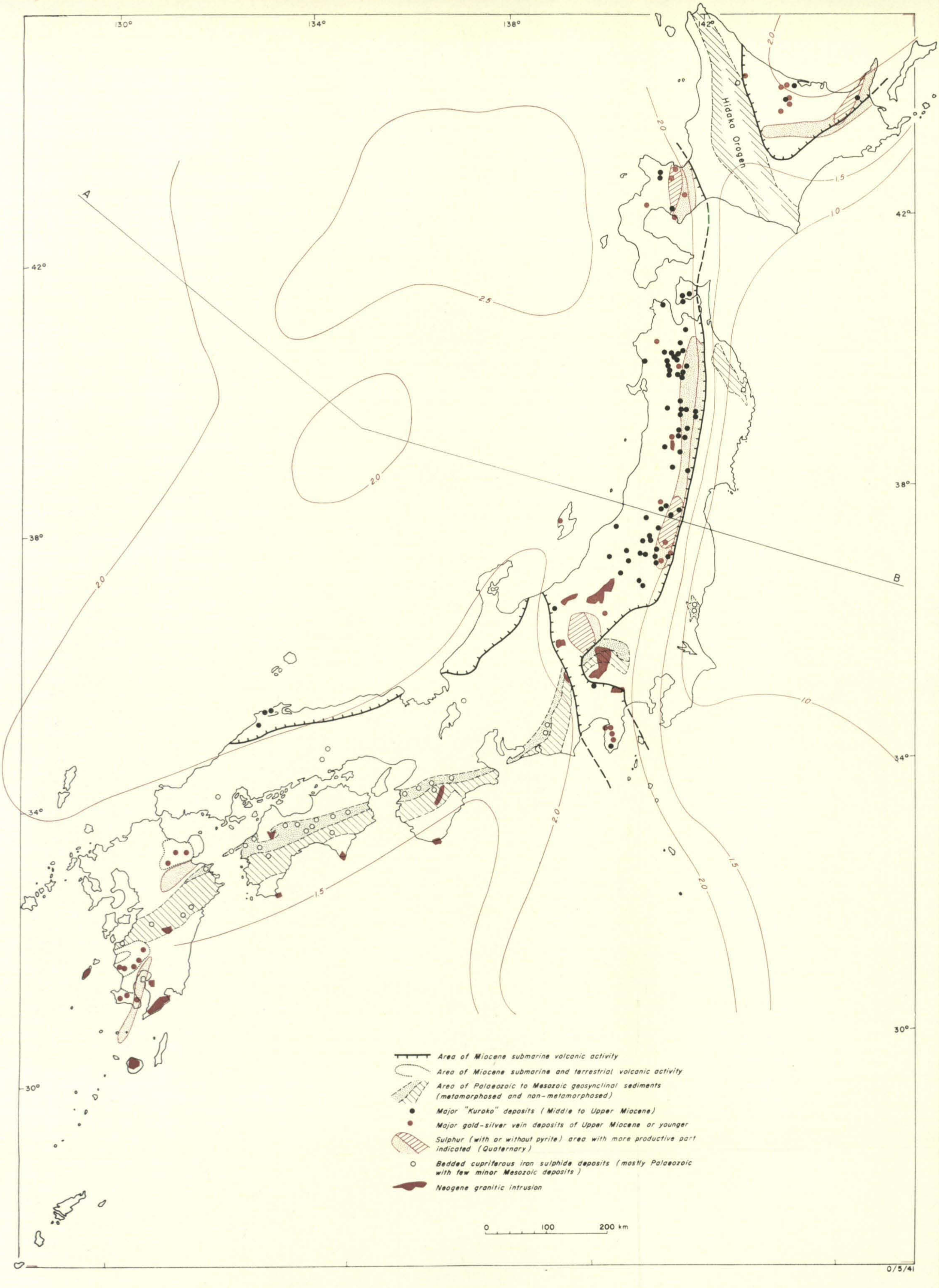

Fig. 4. Distribution of some ore deposits and related geological information in Japan.

(3) After this large area survey is made, results are publicized and the most favourable area for the next step is selected by the same commission.

(4) The next step is detailed and deep structural drilling, sometimes grid drilling at 1-km spacing, and more than 500 m deep in crucial areas, for purely structural purposes, and additional geological, geophysical, and geochemical work for selected smaller areas.

(5) The cost of these works is appropriately divided between government and industry, but usually the major part is borne by the government.

(6) The results of the second step are publicized and the third step is taken on the initiative of mining claim owners. It mostly consists of more detailed geophysics, geochemistry, and structural and target drilling.

(7) The statistical method of defining smaller areas of higher probability of occurrences of deposits, and the geological interpretation of the results, is another efficacious approach for the selection of a target area.

Some of these methods have been tried in the Kuroko and Au-Ag vein provinces in Japan and the author feels more should be tried on various scales.

(8) The whole programme was quite successful not only for the number of discoveries made of hidden deep ores, often in the range of 300 m under a cover of entirely different formations, but also for the development of a spirit of co-operation between governmental, academic, and industrial geologists.

Figure 4 has an additional plot on Figure 3 of Tertiary intrusions of granite and granodiorite, which have little in common with large metal concentrations in Japan in spite of the close genetic relationship of these igneous activities to many of the porphyry-type copper deposits in the Philippines, in a number of the islands of the Indonesian archipelago, and in the Solomons.

There are far fewer of these intrusive rocks in Japan than in the Philippines (less than one tenth), and they are smaller; and those in western Japan are more acidic shallow granite associated with tin and/or tungsten mineralization, probably originating from the refusion of shallower crustal material.

In the Philippines there are far more and bigger quartz-dioritic intrusives with associated porphyries in the larger part of the archipelago (Gervasio, 1966, 1967).

It could be said that in the Philippines, in the upper Oligocene to Miocene, shallow granodioritic intrusives predominate, in contrast to the extrusive volcanic activity which predominates in Japan. Moreover, Miocene volcanic rocks in the Philippines are more basaltic and more extensively terrestrial, or oscillating between submarine and subaerial, and Kuroko-type deposits are less extensive, even rather limited. Total tonnages of copper content of Kurokos in Japan and porphyry coppers in the Philippines seem to be of nearly the same order.

Petrogenetic investigations of these suites of igneous rocks under the plate tectonics hypothesis of two contrasting island arcs could be one of the essential guidelines to the solution of the metallogenetic problems of the whole island arc area.

TABLE 1. TENTATIVE TABULATION OF RELATIONS BETWEEN

	Northern Part of Ryukyu Arc						S.W. Japan Arc						
Rate of Heat Flow	(N.D.)						High at continental side along Sea of Japan coast intersects Be-nioff contour of N.E. Japan Arc						
Ocean Trench	Distinct but shallow						Shallower (partly filled?)						
Miocene Granitic Intrusion	Several small stocks (Sn, W Mineralization)						Small shallow intrusion nearer to trench						
			Metallogenesis						Metallogenesis				
Age	Volcanic activity	Subduction	Kuroko	Au-Ag vein	Sulphur	Bedded Cu-pyrite	Volcanic activity	Subduction	Kuroko	Au-Ag vein	Sulphur	Bedded Cu-pyrite	Volcanic activity
Quaternary	Active	Active to present			Weak		Submarine, not very extensive						Recent volcanoes
Pliocene				Intense									Less active
Miocene	Subaerial and minor submarine								Weak (more gypsum)				Intense, submarine (intermediate to acidic)
Lower Tertiary													Active at outer zone (acidic)
Cretaceous													
Jurassic to Lower Palaeozoic						Alined parallel to S.W. Japan arc	Active (basic rock)	Probably very active				Very intense (folded and metamorphosed)	Active (basic rock)

N.E. Japan Arc	Northern End of Mariana Arc	Southern End of Kuril Arc
Mostly parallel to Benioff contour but highs extend to Sea of Japan.	Roughly parallel to Benioff contour	Parallel to Miocene submarine volcanic activity area
Very distinct	Very distinct	Very distinct
Larger quartz dioritic intrusion (basemetal skarn)	Minor quartz dioritic intrusion	?

N.E. Japan Arc					Northern End of Mariana Arc						Southern End of Kuril Arc					
Subduction	Metallogenesis				Volcanic activity	Subduction	Metallogenesis				Volcanic activity	Subduction	Metallogenesis			
	Kuroko	Au-Ag vein	Sulphur	Bedded Cu-pyrite			Kuroko	Au-Ag vein	Sulphur	Bedded Cu-pyrite			Kuroko	Au-Ag vein	Sulphur	Bedded Cu-pyrite
Active			Near volcanic front. Concentration at N. and S. portions		Recent volcanoes	Active						Active			Fairly active	
Weaker																
Very active	Intensive and concentrated	Scattered			Intense submarine	Active	Weak	Concentrated			Active submarine	Active	Weak	Concentrated		
											Weak					
Probably active				Separated (folded & metamorphosed)												(Only in Hidaka orogen)

Bedded cupriferous deposits in older formations are not remarkable, or at least not economically developed, in the Philippines. The shifting of geosynclinal zones from older to younger over long distances like those in Japan is not observed in the Philippines, although the adjacent migrations of fold zones are inferred in many parts of the islands (Gervasio, 1967).

The results of detailed geophysical investigations of the Philippine Sea or the Philippine plate, which are expected in the near future, will certainly provide us with important keys to the metallogeny of the island arc area at the periphery of this plate. Another very remarkable shifting of parallel geosynclinal zones or double orogenic belts at the western part of the whole area concerned is found in the area of the Malayan Peninsula and the Andaman and Sumatra arcs (van Bemmelen, 1949). The former belongs to the older Mesozoic orogen (Jurassic to Lower Cretaceous) with pronounced granitic intrusions at the axis of the probable geanticline, associated with rich tin and tungsten mineralization of the greisen type. Across the distinct lineament which runs along the west coast of peninsular Thailand and the Malacca Strait to the northeastern flank of middle to southern Sumatra, there lies a parallel, mainly Cainozoic, orogen. This arc has (a) a marked zone of deep trench with at present an active Benioff (subduction) zone, (b) a currently non-volcanic island alignment with shallow seas, (c) a main folded mountain range with extensive granitic batholiths and associated lesser intrusives of latest Mesozoic to earliest Tertiary age, intense younger volcanic activity, probably more subaerial than submarine, and a very prominent rift along the mountain range with numerous recent volcanoes (mostly andesite) of great relief, and lastly (d) a zone characterized by thick Tertiary geosynclinal sediments, which have lower coal measures towards the mountain range of the former zone and thick upper sediments of oil fields nearer to the great lineament that runs parallel to the Malacca Strait.

The bottom of (d) zone has a very marked erosional surface and in places thick conglomerate on top of granitic rocks and the older sediment complex, suggesting a large amount of erosional removal of older formations of sediments and granitic intrusive masses of (c) zone. The Sumatra orogen has no marked province of metal concentrations so far known to us, in contrast with the Sn-W-rich zone of Burma-Thailand-Malaya-Billiton; however, it seems to warrant more careful geological and geophysical investigation, especially in correlation with the Sn-W-rich eastern Pacific region of USSR, Korea to southern China, and the circum-Pacific festoon island arcs, including those of Japan, which have two major orogenic cycles and related metallogeny.

There are a number of other tectonically or geophysically interesting orogenic belts along the western circum-Pacific island arcs such as Borneo-Celebes, Papua-West Irian, Solomons, which still need further investigation and data collection relative to their metallogeny.

CONCLUSIONS

(1) Provincial distributions of four marked mineralizations, their geographical extent and time elements, are quite compatible with the geological interpretation of the genesis of the island arc of Japan by the theory of plate tectonics. Their relationships are tentatively tabulated in the attached table.

(2) Five arcs can be distinguished in and around Japan, one of which, the southwest Japan arc, is inactive today. Metal provinces of four types of deposits show a marked parallelism to one or two of the arcs. A cessation of subduction activity in the southwest Japan arc after the late Tertiary is inferred.

(3) Among other valuable items of geophysical information the rate of heat flow seems to provide evidence of the past activities of subduction and by extension of igneous activities and metallogeny related to them.

(4) The extrapolation of the example of Japan to other island arcs was difficult for the author owing to the paucity of necessary, published geophysical and metallogenetic information.

(5) To make a metallogenetic prognosis of a particular province or large geological unit such as an island arc or a large portion of a mountain range, bold geologic imagination based not only on related geophysical information but also on knowledge of the genesis and genetic environments of the type of deposits, petrogenesis of the related rocks, and erosional history after ore formation is essential.

(6) To narrow down the metal province of a large geological unit, which is mostly controlled by a deeper and larger orogenic unit, to a more concentrated mineralized target area, various items of geological, geophysical, and geochemical information concerning the shallower crust that controls the distribution and localization of ore deposits are essential. For example, the geological structure of the area including deep structural lineaments, trends of joints and fractures, folds, intrusive rocks at the time of ore deposition, paleogeography such as old basins, stable land, or arid residual plains, and the geochemical mechanism for the transport and deposition of metals in the ore solutions concerned are some of the important factors.

Lack of these vast amounts of necessary information often makes prognosis and the use of geology for exploratory work difficult and misleading.

References

Dewey, J. F., and Bird, J. M., 1970—Mountain belts and the new global tectonics. *J. geophys. Res.*, 75(14), 2625-47.

Geological Survey of Japan, 1968—Tectonic maps of Japan 1:2 000 000 (in Japanese).

Gervasio, F. C., 1966—A study of tectonics of the Philippine Archipelago. *Philipp. Geol.*, 51-75.

Gervasio, F. C., 1967—Age and nature of orogenesis of the Philippines. *Tectonophysics*, 4(4-6), 379-402.

Guild, P. W., 1971—Metallogeny; a key to exploration. *Min. Engng, AIME*, 23(1), 69-72.

Ichikawa, K., Fujita, T., and Schimazu, M., 1970—Development history of geologic structures of Japanese Archipelago (in Japanese). *Tsukiji Shokan.*

Inoue, T., 1969—On the time of mineralization in Neogene and the 'Kuroko' belt in the Green Tuff region of northeast Japan. *Rep. Res. Inst. Min. Resour. Dev.* (Japanese with English Resumé), 17-30.

Isshiki, N., Matsui, K., and Ono, K., 1968—Volcanoes of Japan; Map 1:2 000 000. *Geol. Surv. Japan.*

Kanehira, K., and Tatsumi, T., 1970—Bedded cupriferous iron deposits in Japan: a review. *In* VOLCANISM AND ORE GENESIS; ed. Tatsumi, T. *Tokyo Univ. Press,* 51-76.

Matsukuma, T., and Horikoshi, E., 1970—Kuroko deposits in Japan, a review. *In* VOLCANISM AND ORE GENESIS; ed. Tatsumi, T. *Tokyo Univ. Press,* 153-80.

MINATO, M., 1971—Problems on the geologic structure of Japanese islands. *J. geol. Soc. Japan,* 77(2), 101-8.

MINATO, M., GORAI, M., and FUNABASHI, M., 1965—The geologic development of the Japanese Islands. *Tsukiji Shokan.*

MUKAIYAMA, H., 1970—Volcanic sulphur deposits in Japan. *In* VOLCANISM AND ORE GENESIS; ed. TATSUMI, T. *Tokyo Univ. Press,* 285-94.

NISHIWAKI, C., 1969—Orogenesis, metallogeny and their relation to exploration. *Min. Geol.,* 19(94-95), 99-112 (in Japanese).

NISHIWAKI, C., MATSUKUMA, H., and URASHIMA, Y., 1971—Neogene gold-silver ores in Japan. *Proc. IMA-IAGOD Mtgs,* 1970, *IAGOD Vol.* 409-17.

OXBURGH, E. R., and TURCOTTE, D. L., 1970—Thermal structure of island arcs. *Bull. geol. Soc. Amer.,* 81(6), 1665-88.

TAKEUCHI, H., and UEDA, S., 1964—SCIENCE OF EARTH (in Japanese) (The original Japanese edition of 'Debate about the Earth', Freeman, 1967, by the same authors) *NHK Books.*

TAKEUCHI, H., 1970—A SEQUEL TO SCIENCE OF EARTH (in Japanese). *NHK Books.*

TATSUMI, T., SEKINE, Y., and KANEHIRA, K., 1950—Mineral deposits of volcanic affinity in Japan. *In* VOLCANISM AND ORE GENESIS; ed. TATSUMI, T. *Tokyo Univ. Press,* 3-50.

UEDA, S., 1971—A new concept about the earth (in Japanese). *Iwanami Shoten.*

UEDA, S., and SUGIMURA, A., 1970—Arc islands (in Japanese). *Iwanami Shoten.*

VAN BEMMELEN, R. W., 1949—THE GEOLOGY OF INDONESIA (3 vols). *Hague, Govt Printing Office.*

ORE DEPOSITS IN RELATION TO THE TECTONIC DEVELOPMENT OF EASTERN AUSTRALIA

by B. P. Thomson

Geological Survey of South Australia

Summary

The advance of the geological knowledge of continental Australia during the last decade points to important relationships between ore localization and structure. The size and abundance of copper, lead, zinc, and uranium deposits in the eastern half of Australia indicate that this region is metallogenetically different from the remainder of the continent, and continental structure patterns also support this concept. Structural features in the southern oceanic crust may represent a further development of this framework. A summary is presented of the tectonic evolution of the Australian continent since the Archaean. The continental cratonic plate, although metallogenetically younger towards the Pacific Ocean, has undergone extensive tectonic reworking in intersecting mobile belts; consequently structural control becomes a major feature in ore localization.

Ore Distribution

The production and distribution of known deposits of copper, lead, zinc, and uranium indicate that the eastern portion of Australia, bounded approximately by a line joining Wallaroo-Moonta, Tennant Creek, and Rum Jungle, contains by far the more ore. In the central area between the inferred boundary zone and the Archaean shield to the west, although it is covered by about the same proportion of younger non-productive basins as the eastern area, no significant deposits of these metals have yet been discovered[1]. An explanation of this ore distribution pattern is a major problem of Australian geology.

Copper Deposits (Fig. 1)

The western part of Australia, although abundant in nickel and gold, has to date contributed less than one percent of Australia's copper production. The only two areas which have had notable production are Ravensthorpe (Phillips River) and Whim Creek; both are located on the margins of the Archaean Yilgarn and Pilbara Blocks. The Mons Cupri copper-zinc deposit, located at a rhyolitic volcanic centre in the Whim Creek area, may, however, have substantial ore reserves. The nickel-copper deposits (e.g. Kambalda) in the eastern part of the western Archaean

[1] Since the preparation of this paper the discovery of the Yeelirrie secondary uranium deposit on the Archaean basement of Western Australia has been announced. The location is indicated by a circle in Figure 2.

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Fig. 1. Maps showing copper ore deposits and lead-zinc deposits within Australia.

basement area are associated with northerly-trending structural belts. Although collectively these deposits will make a useful contribution to Australia's copper production, the deposits individually are generally small.

In the eastern province, the copper production of the old Wallaroo-Moonta field alone exceeds all the production in the central and western regions. The field adjoins the Adelaide Geosyncline and Willyama Block copper provinces to the east. Other meridionally-trending copper provinces occur in the eastern region. The most important is at Mount Isa, where the main deposit has reserves indicating at least 3.6 million tons of copper metal. The average ore grade is 3 percent. Important Palaeozoic deposits to the south and east are Mount Morgan, Cobar, and Mount Lyell.

Lead-Zinc Deposits (Fig. 1)

The small number of known deposits in the western and central region is in striking contrast to the chain of large deposits in the eastern region, the most prominent of which are the very large high-grade Broken Hill, Mount Isa, and McArthur River Precambrian deposits and the Palaeozoic Rosebery orebodies of Tasmania.

Uranium Deposits (Fig. 2)

The eastern region is well defined by uranium deposits in the Precambrian (Rayner, 1957), whereas the Precambrian and younger rocks in the central and western areas appear to be lacking in significant deposits[2]. An interesting variation is the Beverley stratiform uranium deposit in young Phanerozoic cover of the Frome Embayment in South Australia, deposited by runoff waters from the nearby Mount Painter Precambrian crystalline basement.

The Structural Framework

The boundary between the eastern and central metallogenic provinces in the southern part of Australia is associated with well defined northerly-trending structures in the continent. In southern Australia this feature has been described as the Torrens Hinge Zone (Thomson, 1970), a complex fault zone marking the transitional change from craton in the west to platform downwarp structure of the Adelaide Geosyncline to the east (Fig. 3). Adjoining fault structures to the east of the zone are seismically active.

The Torrens Hinge Zone trend of fractures (Fig. 2) can be traced with minor offsets to the west into central Australia, where it is interrupted by the transcontinental Fraser-Musgrave fold belt. Continuation farther north is uncertain, but it may extend east of gravity depressions in central Australia to the faults north of Tennant Creek. The zone may be related to inferred structures in the oceanic crust south of Australia, where the mid-ocean ridge is displaced by a fracture zone (transform fault) which is seismically active in the ridge area. The fracture can be traced northwards by displacement of magnetic anomaly patterns to the continental margin, where it is interrupted by transverse structures. The alignment of the fracture with the hinge zone is, however, so remarkable that it suggests that the old

[2] But see previous footnote.

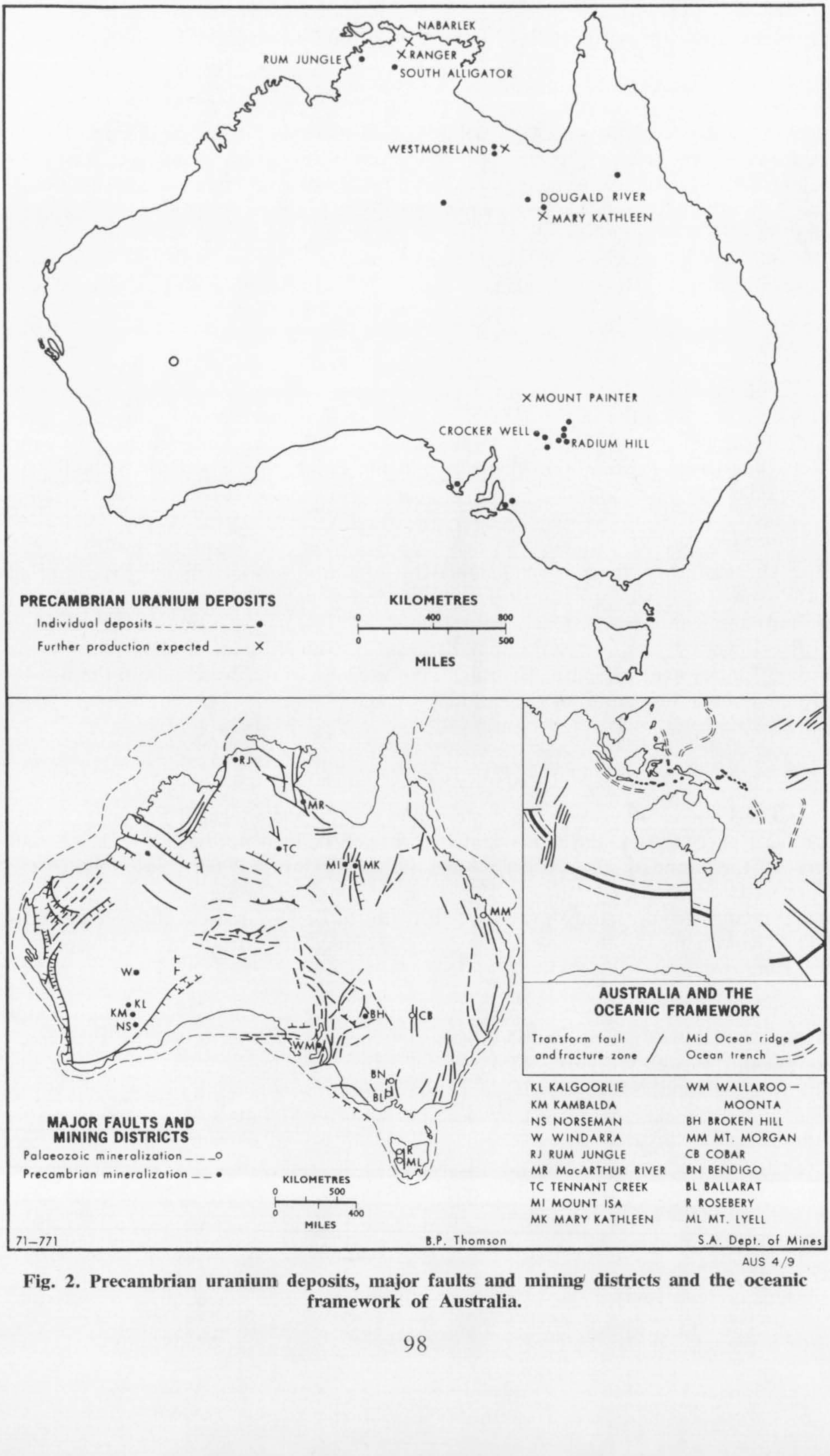

Fig. 2. Precambrian uranium deposits, major faults and mining districts and the oceanic framework of Australia.

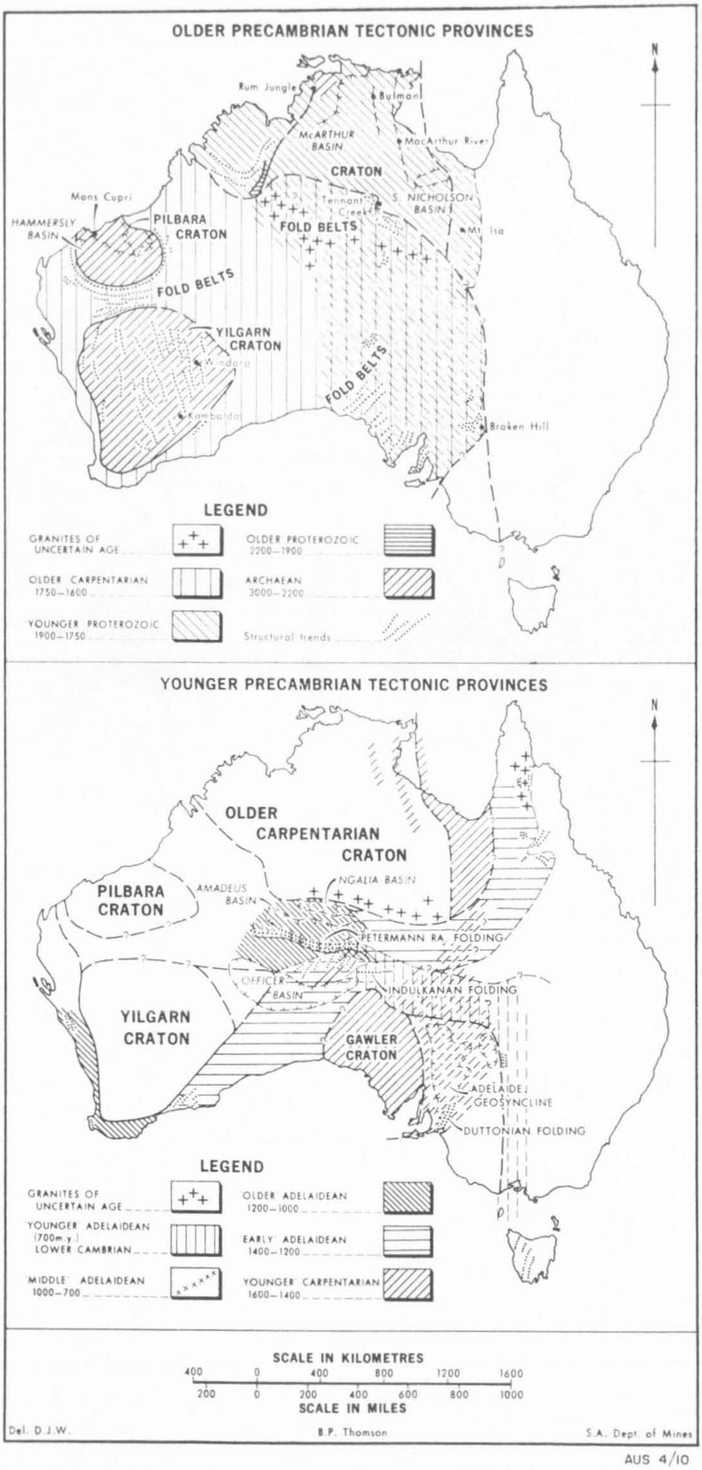

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Fig. 3. 'Younger and older' Precambrian tectonic provinces

established continental fracture pattern has controlled the development of the younger oceanic structures. Farther to the east of the hinge zone is a sub-parallel fracture system, possibly related to an oceanic crustal fracture south of Tasmania. This is a belt of fundamental faults extending from Mount Lyell northwards to the area east of Broken Hill and then north-northwesterly to the Mount Isa region.

Tectonic Development

In order to simplify the task of representing the tectonic development of Australia on four composite map figures, four or five of the time ranges to be used on the 1:5 000 000 tectonic map of Australia have been adopted for each figure. Informal chronostratigraphic terms, e.g. 'early' Proterozoic, have been used.

Older Precambrian Tectonic Provinces (Fig. 3)

'Archaean' cratonic cores exceeding 2200 m.y. in age occur in the western metallogenetic region. Several small inliers of basement of similar age also occur at or northeast of Rum Jungle in the western margin of the eastern zone. The smaller craton in the west—the Pilbara Block in the Hamersley Basin—has a cover of Lower Proterozoic sediments associated with characteristic iron formations. The writer believes (Thomson, 1970) that these are the equivalents of the metamorphosed iron formations which occur in South Australia and parts of central Australia. Consequently it is inferred that a Lower Proterozoic platform cover with an Archaean basement formerly extended to the east of Broken Hill. A similar platform but apparently lacking iron formations was probably established in the northern part of the continent, while movement continued in the Hall Creek Mobile Belt. Later the platform was remobilized, folded, and intruded by granite, finally becoming stabilized as a craton at about 1750 m.y. in the region west of Mount Isa. This basement developed a sedimentary cover of Carpentarian age from about 1800 m.y. onwards (Dunn et al., 1966). The effect of the 1900-1750 m.y. tectonism on the southern region is uncertain. Possibly at about this time, folding of the older southern Lower Proterozoic platform began, and this led to the widespread 'older Carpentarian' folding, separating the western Archaean mass into two cratons which were bounded on the east by an arcuate system of fold belts possibly related to uplift of Archaean cores. The Broken Hill orebodies were probably emplaced at about 1700 m.y. during metamorphism of the Lower Proterozoic sediments, which may have contained stratiform mineralization. The orebodies in depth enter the northeasterly-trending Globe-Vauxhall Shear Zone near its intersection with a meridionally-trending shear system.

During the Carpentarian, block movement occurred in the eastern part of the northern craton, accompanied by sedimentation and some volcanism in the Mount Isa and McArthur River areas.

Younger Precambrian Tectonic Provinces (Fig. 6)

After volcanism and granite intrusion, the Gawler Craton west of the Adelaide Geosyncline was temporarily stabilized at about 1600 m.y. Intermittent sedimentation was followed by folding and renewal of explosive acid volcanism terminated by shallow high-level granite intrusion. This terminal phase marked an important metallogenetic epoch in the 1500-1400 m.y. interval, when the Moonta-Wallaroo and other copper deposits on the eastern flank of the Gawler Craton were emplaced and the craton finally established. Post-orogenic granites in the Broken Hill region at about this time marked the final development of Precambrian crystalline basement in that area.

Dolomite, pyritic carbonaceous shale, and siltstone with associated fine-grained tuff in the McArthur River and Mount Isa regions during the Carpentarian interval were the hosts for the lead, zinc, and copper deposits adjacent to the major Emu and Mount Isa Faults respectively, which were active during sedimentation. The age of the sediments is uncertain: they may be 'older' or 'younger' Carpentarian.

The structural detail at Mount Isa is complex (Bennett, 1965). In depth, the Mount Isa orebodies are truncated by basic igneous rock which occurs in fault slivers on the margin of the Mount Isa Fault. It is quite possible that the basic rock is in intrusive or faulted contact with the ore beds (Cordwell et al., 1963; Smith, 1969). It is mineralized and could well have played a major role genetically or structurally in the introduction of metal into the host sediments, which contain abundant syngenetic pyrite. Tectonic development was completed in the Mount Isa area with the introduction of post-orogenic granite at about the same time as in the Broken Hill area to the south. Probably at this stage a continuous crustal plate with a belt of major base-metal orebodies on its eastern margin extended across Australia from north to south. Deep crustal movements occurred during the 'early' Adelaidean in the northeasterly-trending Fraser-Musgrave mobile belt, which probably extended across the continent. No important ore deposition is yet known to be associated with this event, which was concurrent with the meridional downwarping and fracturing of the eastern flank of the Gawler Craton subsequent to the 'younger' Carpentarian metallogenetic epoch.

The 'early' Adelaidean tectonism activated the Torrens Hinge Zone and began the development of the Adelaide Geosyncline, which was aligned with the metallogenetic 'younger' Carpentarian tectonic zone on the eastern side of the north Australian craton. Minor copper mineralization was associated with basaltic and trachitic volcanics in the Adelaide Geosyncline.

Sedimentation was probably taking place on the eastern side of the continent at this time on the site of the future Tasman 'Geosyncline'. The 'early' Adelaidean tectonism concluded with the welding of the Yilgarn and Gawler cratons into one crustal plate. Tectonic and magmatic activity marginal to this plate occurred in the following 'older' Adelaidean interval.

In central Australia, marked overprinting of east-west structures on older northeasterly structures occurred and the event was associated with anatectic intrusive granite and extrusion of basaltic and rhyolitic volcanic suites associated with minor copper mineralization. The tectonism culminated in deep crustal fracturing and vertical movements associated with mafic and ultramafic intrusions of the Giles Complex, without, however, any significant heavy-metal sulphide mineralization. Farther east in this structural unit, known as the Musgrave Block, sulphide mineralization may have been emplaced at this time in meridional structures. The 'older' Adelaidean movements in central Australia may have been reflected in the Adelaide Geosyncline by a break in sedimentation. The time of resumption of sedimentation is somewhat uncertain, as there is evidence of movements in the southern part of the geosyncline in the 'middle' Adelaidean (Cooper & Compston, 1971).

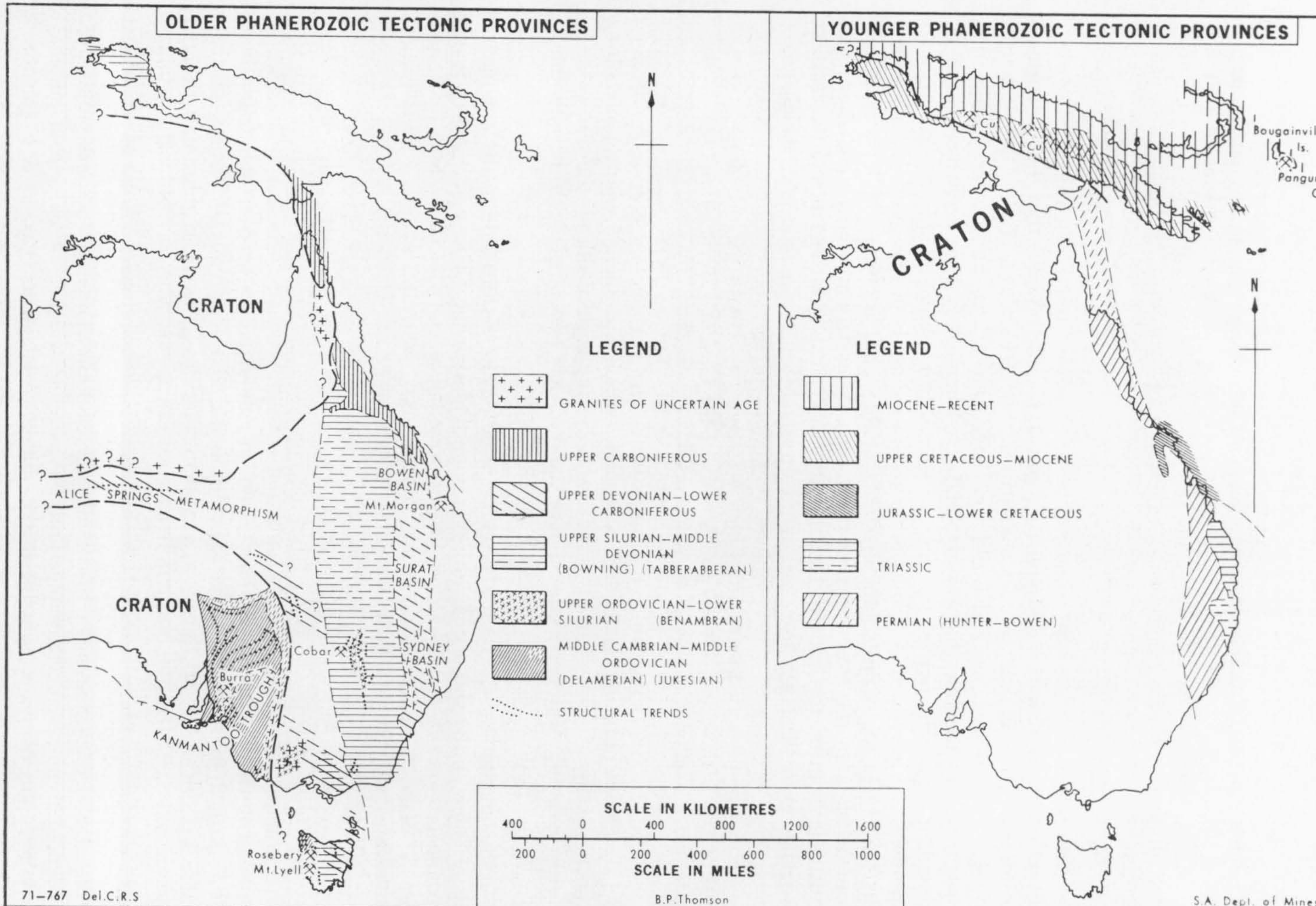

Fig. 4. 'Older and younger' Phanerozoic tectonic provinces.

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In the 'younger' Adelaidean, tectonism and plutonism occurred in Tasmania, King Island, and northeast of the Adelaide Geosyncline. These movements were probably continued into the Lower Cambrian by the Petermann Ranges and Indulkana Folding of Central Australia and the Duttonian Folding on the southern margin of the Adelaide Geosyncline. No important mineralization is known to be associated with these events.

Older Phanerozoic Tectonic Provinces (Fig. 4)

During the Lower Cambrian, sedimentation continued in the Adelaide Geosyncline. In the south, horst movements occurred marginal to the Kanmantoo Trough. The associated fault system may have continued to the west as a boundary to the Gawler Craton; but gravity evidence suggests that the deeper part of the trough swings southwards of Kangaroo Island (Thomson, *in* Parkin, 1969).

The trough may have been bounded to the east by a meridional mobile zone passing through Western Victoria and west of Tasmania which persisted since the 'younger' Adelaidean. This zone probably marked the western limit of the Tasman Geosyncline. An early event in the geosyncline in Tasmania was the rifting of early Palaeozoic and Precambrian cover sediments. The associated Upper Cambrian volcanism probably introduced volcanic sedimentary mineralization into the environment of the Mount Lyell and Rosebery deposits (Solomon, 1965).

By Upper Cambrian time, sedimentation had ceased in the Adelaide Geosyncline and Kanmantoo Trough, and the Delamerian Orogeny followed in the early Ordovician, converting these basin areas into a mobile belt with granite plutonism in the southern and eastern regions. The floor of the geosyncline, probably well mineralized in the Carpentarian, was extensively reactivated along basement lineaments, and numerous copper deposits were emplaced in the folded Adelaidean and Cambrian cover rocks. Ore was localized in intersecting structures such as the northeast-trending Moonta/Broken Hill lineament zone and north-south structures: for example, the Burra copper deposit and possibly the porphyry-copper-type mineralization at New Bendigo.

In the base of the Cambrian, lead-zinc mineralization of Mississippi Valley type was localized, probably by movements of intrastratal fluids into structural and stratigraphic traps, on the margins of the fold belt: e.g. Ediacara. The Delamerian event is represented in Tasmania by the Jukesian movements, which were important in establishing a structural framework for mineral fields.

Consolidation of the Delamerian tectonic province during the Ordovician provided a stable block on the western flank of the Tasman Geosyncline. The geosynclinal tract to the east developed into a complex of Palaeozoic mobile belts with considerable tectonic overprinting. The tectonic provinces outlined in eastern Australia for the older Phanerozoic (Fig. 4) have been established on the basis of the geochronology of granitic rocks, which is as yet very incompletely known. The Upper Silurian-Middle Devonian stage was particularly important in marking the probable time of emplacement of many Palaeozoic base-metal orebodies of eastern Australia, such as Rosebery, Mount Lyell, Cobar, Mount Morgan, and Captains Flat. Intersecting structures are a major factor in the localization of these deposits. It is conjectural whether they are the result of modification of stratiform deposits, possibly with volcanic-sedimentary associations, or represent epigenetic introduction of metal by reactivation of older mineralization deeper in the crust, as appears to have occurred in the Adelaide Geosyncline. The mobile zones were meridional, as is shown by the Upper Silurian-Middle Devonian magmatic belt extending from eastern Victoria to the Broken River embayment in Queensland. The belt is flanked by Upper Devonian-Lower Carboniferous mobile belts with a diversion to the west into central Australia due to reactivation of the 'early' Adelaidean mobile zones.

The marked truncation of the earlier belts by the Upper Carboniferous magmatic belt extending along the Queensland coastal region to New Guinea shows the influence of marginal southwest Pacific tectonic trends and the Upper Carboniferous to Lower Triassic metallogenetic epoch of eastern Queensland (Jones, 1965).

Younger Phanerozoic Tectonic Provinces

By Lower Cretaceous time, the Australian continent was acting as a single cratonic plate, and active orogenesis continues to the present day in the cratonic margin in the New Guinea Highlands and the adjoining Pacific oceanic plate. Porphyry-copper-type deposits are a feature of this zone and in the adjoining island arc system, including Bougainville.

CONCLUSIONS

1. Meridional alignment of major ore districts with tectonic provinces has been a feature of the Australian continent from Archaean to Phanerozoic time. This distribution may reflect an ancient geochemical variation in the crust, possibly related to the early development of the continent with respect to an ancestral Pacific ocean.

2. Evidence of tectonic overprinting supports the concept of reactivation of earlier mineralization and redeposition in younger host rocks at a higher crustal level. The inferred re-cycling of metals in the crust may in time have contributed to the relative abundance of orebodies in the east compared with the older shield areas to the west.

3. The possibility of the addition of new sialic crustal material is not denied in the extreme eastern part of the continent. but there is a strong probability that Precambrian continental basement formed the floor of the Tasman Geosyncline.

4. Oceanic fracture zones to the south of Australia appear to originate from a continental framework of persistent Precambrian features that do not appear, on present evidence, to have been markedly rotated or areally displaced relative to each other. The old shield has been cut by intense transverse structures which are apparently the result of vertically directed movements.

Plate tectonic principles do not appear to be relevant, on available evidence, to the development of the continental mass, which has apparently maintained itself as a single structural entity.

ACKNOWLEDGMENTS

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REFERENCES

BENNETT, E. M., 1965—Lead-zinc-silver and copper deposits of Mount Isa. *In* GEOLOGY OF AUSTRALIAN ORE DEPOSITS (ed. J. MCANDREW). *8th Comm. Min. metall. Cong.*, 1, 233-46.

COOPER, J. A., and COMPSTON, W., 1971—Rb-Sr dating within the Houghton Inlier, South Australia. *J. geol. Soc. Aust.*, 1(2), 213-9.

CORDWELL, K. S., WILSON, G. L., and LORD, J. H., 1963—Geology of the area south of Mount Isa. *Proc. Aust. Inst. Min. Metall.*, 206, 29-62.

DUNN, P. R., PLUMB, K. A., and ROBERTS, H. G., 1966—A proposal for a time stratigraphic subdivision of the Australian Precambrian. *J. geol. Soc. Aust.*, 13(2), 593-608.

JONES, O. A., 1965—Geology and mineralization of eastern Queensland (Revised by D. S. Carruthers). *In* GEOLOGY OF AUSTRALIAN ORE DEPOSITS (ed. J. MCANDREW). *8th Comm. Min. metall. Cong.*, 1, 352-60.

PARKIN, L. W., ed., 1969—Handbook of South Australian geology. *Geol. Surv. S. Aust.*, Chap. 3.

RAYNER, E. O., 1957—The nature and distribution of uranium deposits in New South Wales. *N.S.W. Dep. Min. tech. Rep.* 5, 63-101.

SMITH, W. D., 1969—Penecontemporaneous faulting and its likely significance in relation to Mount Isa ore deposition. *Spec. Publ. geol. Soc. Aust.*, 2, 225-35.

SOLOMON, M., 1965—Geology and mineralization of Tasmania. *In* GEOLOGY OF AUSTRALIAN ORE DEPOSITS (ed. J. MCANDREW). *8th Comm. Min. metall. Cong.*, 1, 464-77.

THOMSON, B. P., 1970—A review of the Precambrian and Lower Palaeozoic tectonics of South Australia. *Trans. Roy. Soc. S. Aust.*, 94, 193-221.

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SURFACE EXPRESSION OF MINERALIZATION IN THE SOLOMON ISLANDS

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SUMMARY

The dense jungle cover, the heavy rainfall, and the difficulties of obtaining access are factors which have led to a study of the surface effects of mineralization in the Solomons. Copper, the commonest and most widely distributed mineral, has received the most attention, together with nickel, manganese, magnetite, gold, silver, and bauxite.

Groundsurface features associated with mineralization are commonly negative, such as erosion trenches, or hollows along fault zones. These have proved difficult to distinguish in the jungle-covered interfluves, even with the assistance of air-photographs. Chemical dispersion of the elements of mineralization is not obscured by jungle, and geochemical sampling techniques have been used successfully to discover and delineate mineralization.

Copper mineralization in the Solomons occurs either as emanations from volcanic centres, or as vein mineralization associated with plutonic intrusives. An olivine basalt flow containing native copper on Rendova Island is an example of the former, and the Koloula mineralization with a diorite-granodiorite intrusive boss exemplifies the latter. A copper province where chalcopyrite-enriched veins are widely scattered throughout an 80 km belt of regionally metamorphosed basalts in south Guadalcanal is exceptional. Plutonic rocks are not apparently associated with this occurrence.

A pilot study on the dispersion of copper through soils did not reveal a zone of enrichment. In a more mature soil profile, the copper values tended to increase towards bedrock; whereas on the ubiquitous steep slopes, erosion is so rapid and the soil profile so juvenile that the copper content of the soil reflects closely the copper content of the underlying rock.

Beachsands at river mouths and free-flowing sediments collected just upstream were found to have similar metal contents. Beach results clearly showed regional trends, although as a single anomaly detection method its usefulness is reduced by large variations in water shed areas.

Stream sampling was not effective in detecting small manganese deposits in basalts owing to high background values; nor in discovering nickel mineralization because of the masking effect of high nickel values in sediments derived from nickeliferous laterites. The laterites, confined to ultrabasic areas, are distinguishable on air-photographs by a conspicuously different vegetation cover. Anomalous scintillometer readings distinguish exclusively bauxite pickets formed over emerged limestones.

INTRODUCTION

The surface appearance and the differences in surface chemistry in mineralized areas are the best aids to mineral discoveries in a jungle-covered land, such as the British Solomon Islands. Thick foliage and soils hide the rocks from observation except in the rivers. However, plentiful rainwater, draining off the hill slopes, carries ions and sediments from these hidden soils and rocks into the more accessible streams and rivers, where sampling can be undertaken and anomalies recognized.

Figure 1 shows that the Solomon Islands are a double chain of elongated islands extending 1200 km from northwest to southeast. The larger islands are each nearly 200 km long, and the central enclosed sea is nearly 100 km wide. Bougainville, the largest island in the geographic group, is part of the Territory of Papua and New Guinea and is excluded from this paper.

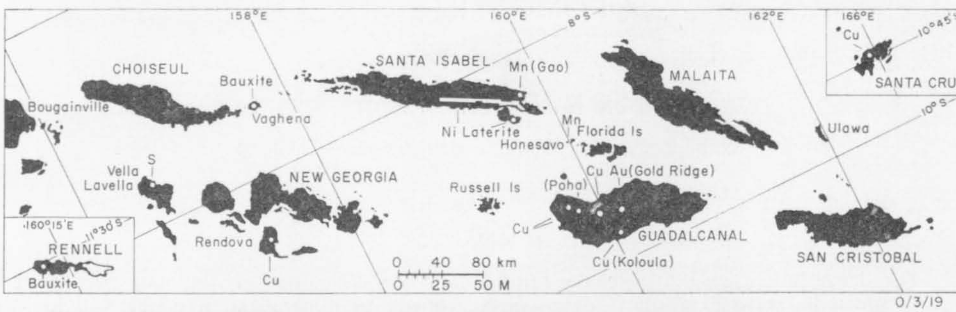

Fig. 1. Mineralized localities in the Solomons.

Geologically, the oldest unit of the general succession seen on all the main islands is a thick sequence of oceanic basalts with some pillowed flows. These basalts are presumed to be of Mesozoic age, as Cretaceous sediments overlie and Cretaceous gabbros intrude them. Gradual deep-water sedimentation continued until Guadalcanal, parts of Santa Isabel, and Choiseul emerged at the end of the Eocene. A shallow submergence at the beginning of the Miocene gave rise to very widespread reefal limestones and calcarenite beds found on almost all the main islands. Local volcanism and the deposition of terrigenous material derived from volcanic products as well as extensive reef growth continued from the middle Miocene until the present, in areas of continuing submergence. Gabbros and diorites were intruded in the Eocene and Pliocene, with the youngest diorite intrusion 1.7 m.y. old. The gabbro-ultrabasic complexes were emplaced in the Eocene, with some further inthrusting in the Pliocene. The New Georgia group is a collection of islands formed from coalesced post-Miocene volcanic cones. Faulting, tilting, uplift, or renewed submergence has disturbed the depositional pattern in this unstable area.

Mineralization

Sulphides are widely distributed throughout the volcanic and igneous rocks of the Solomons; pyrite predominates, and a little chalcopyrite is locally concentrated in veins. Gold and sulphur have been introduced into volcanics and manganese is found in some sediments. Nickel laterite and bauxite are the products of selective weathering in special environments. Figure 1 shows the distribution of these mineral occurrences.

Copper

Copper has received the most attention as it is very widespread, and the proof of a huge low-grade orebody on neighbouring Bougainville has given impetus to the search. In the Solomons, copper is associated with either a volcanic source or a plutonic intrusion. In the Poha area of Western Guadalcanal, mineralization is in veins, generally in hornblende diorite but close to contacts with microdiorite dykes or large andesite inclusions. In another part of the same intrusion, malachite flakes after copper oxide are disseminated through the rock with no evident veining. The overlying soils contain 700-1000 ppm total copper and the mineralized rock assays 1000 ppm total copper. The soil in a pineapple garden on a hill was found to be anomalous, with total copper values in excess of 3000 ppm (Fig. 2). Soil samples collected on a 5 m grid indicated a linear source which, when exposed

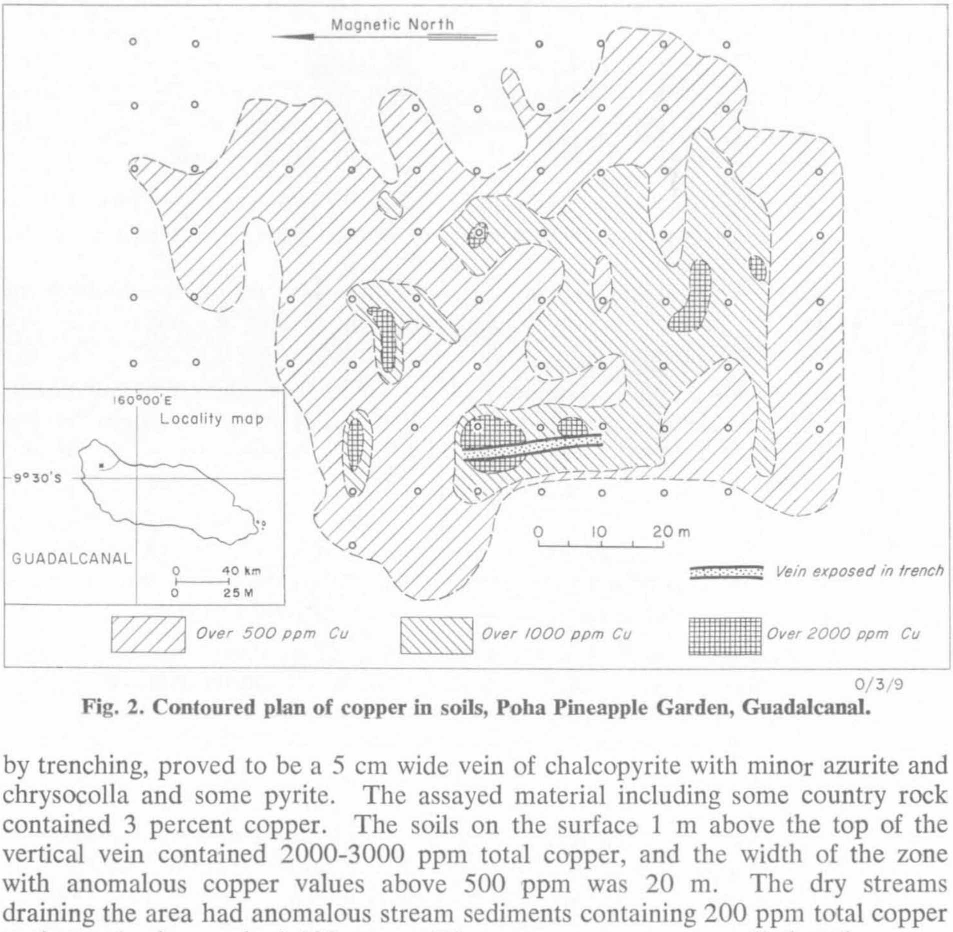

Fig. 2. Contoured plan of copper in soils, Poha Pineapple Garden, Guadalcanal.

by trenching, proved to be a 5 cm wide vein of chalcopyrite with minor azurite and chrysocolla and some pyrite. The assayed material including some country rock contained 3 percent copper. The soils on the surface 1 m above the top of the vertical vein contained 2000-3000 ppm total copper, and the width of the zone with anomalous copper values above 500 ppm was 20 m. The dry streams draining the area had anomalous stream sediments containing 200 ppm total copper against a background of 100 ppm. These streams were so small that they were overlooked in an earlier drainage survey, and were only found and tested after mineralization had been found in a reconnaissance soil-sampling traverse along the ridge top, using a sample interval of 20 m. The presence of an anomalous tributary or sediment source did not show up in the main river sampling results and the theoretical diagram (Fig. 3) has been constructed to explain the situation.

The diagram illustrates a 'herring-bone' drainage pattern commonly found in the mountains in the Solomons. A straight, parallel-sided valley with the main

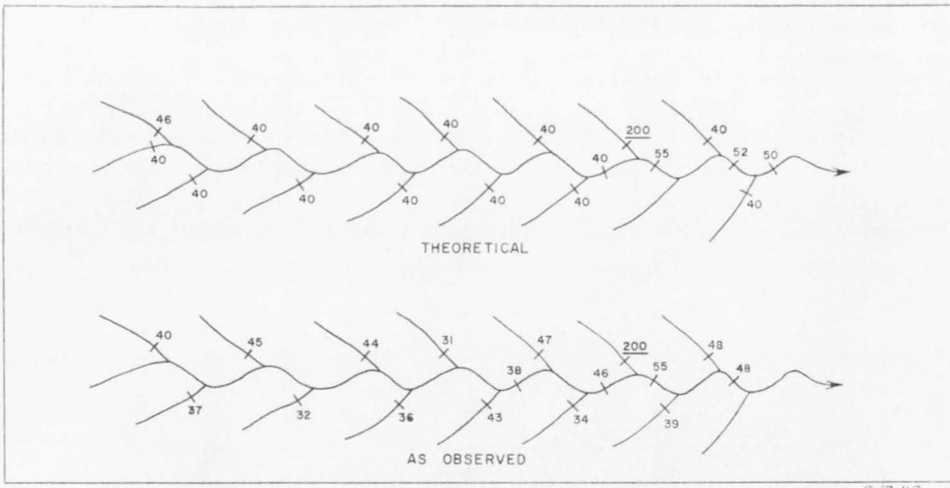

Fig. 3. Drainage patterns illustrating stream sediment metal values (ppm).

river flowing down the centre and many small equal-sized tributaries draining the valley walls. The numbers are theoretical analytical results of samples collected where bars cross the streams.

It can be seen that if a sample was not taken from the small anomalous tributary containing sediment five times the background of 40 ppm, perhaps because the confluence was hidden for some reason, then the presence of an anomalous source of material is not so obvious from a study of the main stream sediment values.

The change in the metal content of the main stream sediments above and below the anomalous confluence is approximately 30 percent, a figure close to the analytical and sampling error. This could easily be overlooked.

In the same general area as the Poha pineapple garden, pits were sunk to find the cause and source of single high values in a soil sampling traverse. Pits revealed a single mineralized vein, but in more than one pit a single boulder of gossan apparently unrelated to the surrounding country rock gave rise to the anomalously high value.

The Koloula Valley, a very deep slice eroded out of the southern flank of the highest part of the Guadalcanal mountains, contains extensive exposures of the Plio-Pleistocene diorite intrusive complex that underlies the core of the island, and it also contains an encouraging copper prospect.

The Chikora prospect (Fig. 4) is a circular area, 400 m in diameter, within which all the -80 mesh fraction of the soils contain more than 1250 ppm copper and most contain more than 2800 ppm copper. The anomaly is in very steep country and the anomaly pattern is complicated by large volumes of slightly mineralized landslide material which covers slopes and fills the valley floors, covering much of the bedrock. Shallow drilling by the Geological Survey showed that the bedrock contained copper values similar to those found in the overlying soils where these were residual. Core recovery was poor. Mineralization is generally chalcopyrite developed on the fracture faces in the hornblende diorite.

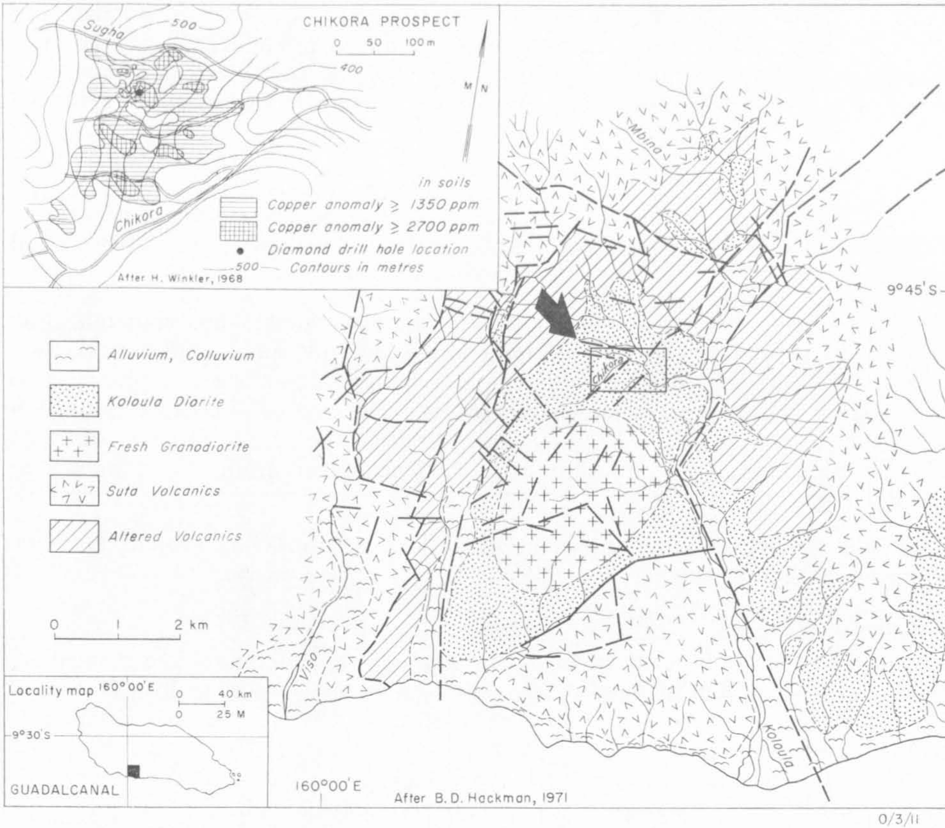

Fig. 4. The Koloula copper prospect, Guadalcanal.

The host rock to the mineralization is a strongly shattered diorite which has been saussuritized and kaolinized around the margins of a younger granodiorite intrusion. Potassium-argon dating gives ages of about 8 m.y. for the diorite and only 1.7 m.y. for the central granodiorite plug.

An example of copper mineralization associated with a volcanic centre is on Rendova Island, where a tongue of fine-grained basalt in auto-brecciated pillowed basalts is distinguished by containing minute grains of native copper.

The mineralization gave a distinct copper anomaly in the soils, which coincided with the area directly underlain by the lava flow. Although the mineralized lava flow contained conspicuous magnetite, the variable magnetic susceptibility of the differing flows and effusions from the South Rendova volcanic vent effectively prevented the tracing of this particular flow by magnetic means.

Another occurrence of copper mineralization is around Mount Gallego in Western Guadalcanal (Thompson, 1965), and is exposed in post-Miocene volcanics in Hidden Valley. There, amidst kaolinized and pyritized fault breccia, a few erratic blocks of equally altered lava contain chalcopyrite assaying 1-4 percent copper. Chalcopyrite is the only copper mineral present and spectrographic analyses showed no enrichment of any other element. Intensive geochemical surveys and drilling failed to locate the source of the blocks, which are now seen close to the floor of the valley. The stream sediment copper values in Hidden Valley contrast strongly with those found in other rivers draining the same volcanic mountain, as the lavas themselves have a comparatively low copper content of 80-110 ppm and are unmineralized.

Gold

Gold occurs in Pliocene volcanics in Central Guadalcanal, where it is found in quartz veins or disseminated in widely kaolinized and pyritized tuff beds and agglomerate.

Recent geochemical sampling has clearly demonstrated arsenic mineralization also, but its relationship to the gold mineralization is not simple and not yet fully understood. Likewise, the ubiquitous pyrite mineralization does not appear to carry higher gold content where it is most massive, and so cannot be used as a tracer mineral for gold. The pyrite mineralization appears to antedate the gold mineralization and its relationship to the arsenic mineralization is unknown at present.

Gold occurrences are known in other localities on Guadalcanal but have produced negligible alluvial material.

Manganese

In both the main occurrences of manganese in the Solomons the manganese dioxide is hard enough to stand out as outcrops on the surface, and on Hanesavo this is on a grassy ridge. The boulders from the outcrops are also resistant and may be found up to 2 km downstream from their source. However, as Maranzana (1968) points out, the soils over both manganese occurrences, besides containing manganese, have anomalously high contents of molybdenum, copper, and zinc, with minor gold and silver values. These elements are associated with the manganese mineralization and the molybdenum may be used as a pathfinder element. At Gao in Santa Isabel the manganese occurs as a conformable shale band 3-6 m thick and associated with ferruginous shales in dipping limestone and tuff beds of the Tanaku Group.

At Hanesavo in the Nggela group of islands, 80 km away from the Gao occurrence, the manganese also occurs in a shale band.

Bauxite

In the Solomons soils derived from volcanic debris, either primary or derived, are all found to be bauxitized where they overlie uplifted limestones. An aerial scintillometer survey very clearly delineated these areas, as radioactivity has concentrated in the soils during the bauxitizing process. On Rennell Island, an emerged coralline atoll 190 km from any currently known volcanic rocks, there are about 40 million tons of bauxite. The limestone of the atoll contains virtually no aluminium; so weathered limestone is not the source of aluminium and the problem of the source remains.

Although the bauxite contains no trace of volcanic pebbles and is of a uniform grade and texture down to the contact with the underlying limestone, it is surmised that some submerged volcanic vent gave rise to the source material of the bauxite. A somewhat similar bauxite deposit over limestone in the Western

Solomons is within sight of two andesitic volcanic cones, the ash from which is the source material for the bauxite.

The Rennell Island bauxite soil has a natural porous crumb texture and a density of only 1.20 g/cm^3, which permits the 300 cm of annual rainfall to drain quickly through the soil and the underlying porous limestone to the water table. Most of the bauxite is now contained in pockets in the limestone, formerly the floor of the atoll lagoon and now 5 to 15 m above sea level.

Nickel

The red, orange, and yellow porous leached soils overlying most of the ultrabasic rocks in the Solomons are characterized by a very distinctive vegetation which can readily be recognized on air-photographs and are even more apparent on the ground. A soil-covered contact between harzburgite and basalt was located to within 2 m by the difference in vegetation.

Varieties of *Casuarina, Dacrydium,* Myrtaceae, bamboo, and pandanus are a characteristic floral assemblage, but the presence of one variety is not in itself diagnostic of ultrabasics, as all varieties grow in other soils. Less commonly, bracken and grass and low bushes are the only vegetation covering the lateritic soils.

Rounded ridge crests in ultrabasic country are another easily discernible characteristic feature except in areas of most active erosion where narrow steep-sided ridges, almost devoid of soil, have developed; these closely resemble the landscapes on other rock types. Landslides are particularly common in the steep-sided hills of serpentinized harzburgite, as chrysotile is so soft that it tends to lubricate existing joint and fracture partings.

Iron, nickel, and cobalt have become enriched in the soils and the underlying partly decomposed harzburgite to a degree that the material is a nickel ore locally containing up to 2 percent nickel.

Many of the lateritic soils are eroding rapidly and give rise to high nickel values in the stream sediments of the rivers draining the ultrabasic rocks. Values of 1200-2500 ppm are common, and many small previously undetected ultrabasic outcrops have been found on the ground after a study of the stream sediment nickel values. The high nickel in the stream sediments makes the chances of finding nickel sulphides in the same area very slim.

Sulphur

Sparse vegetation characterizes a thermal area in Vella Lavella in the Western Solomons, where large quantities of H_2S and CO_2 are rising through waterlogged alluvium. The thermal area is a fault-bounded depression about 1½ km square in the volcanic hills (Fig. 5).

The gas from many vents, generally beneath round muddy pools, has, with water, completely decomposed all the sediments in the valley floor and precipitated crusts of sulphur and calcium carbonate near the drier vents. The release of the sulphur and its dispersion to the sea may have a bearing on sulphide mineralization around dormant volcanoes.

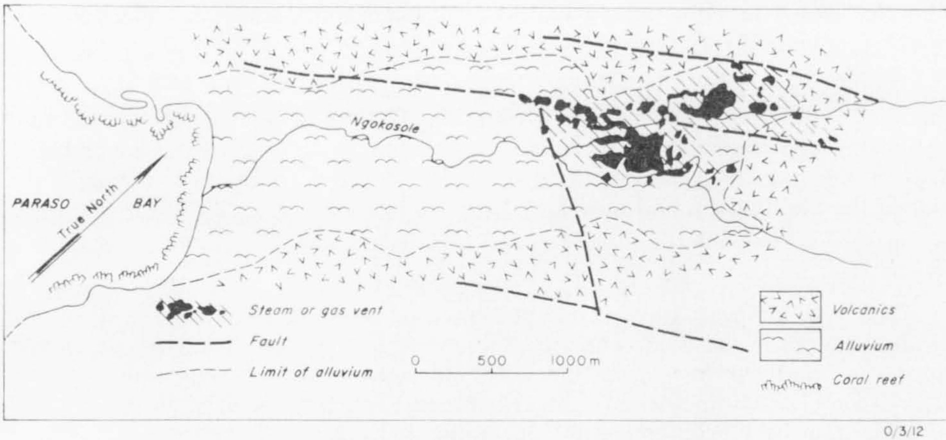

Fig. 5. Paraso thermal area, Vella Lavella Island.

CONCLUSIONS

Despite the tropical jungle cover, the elements of mineralization close to the surface can be detected by standard geochemical methods. Topography and vegetation and very rare float in rivers give further surface effects which can aid the discovery of minerals.

ACKNOWLEDGMENTS

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REFERENCES

HACKMAN, B. D., 1971—Koloula sheet report (unpublished).

MARANZANA, F., 1968—Eleven mineral prospects of minor interest in the British Solomon Islands Protectorate. *B.S.I. geol. Surv. Publ.*

THOMPSON, R. B., 1965—Copper. *In* Geological and magnetic surveys of Hidden Valley and the southern flanks of Mt Gallego, Western Guadalcanal, 1962. *B.S.I. geol. Rec.*, 2, 132-4.

WINKLER, H. A., 1968—Copper prospects of the Koloula River Granodiorite, Guadalcanal. *B.S.I. geol. Surv. Publ.*

MINERAL RESOURCES OF THE OCEANS

by C. A. Burk

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SUMMARY

All the known mineral resources of the oceans can be described in terms of water depths and related regional geology, which also largely control the potential for economically recovering them. The deep ocean basins of the world contain the largest area of resource potential (about 60 percent of the earth's surface), but the shallower waters of the continental margins (less than 10 percent of the earth's surface) will certainly yield the greatest value of recovered marine resources. The annual value of offshore petroleum production will soon exceed that of all other marine resources combined, including fisheries and sea-water chemicals. Only a very small part of this production, however, currently comes from true continental margins; the largest part is produced from such inland seas as Lake Maracaibo and the Persian Gulf. It seems certain that petroleum will greatly dominate the total value of marine resources over the next several decades. It also seems likely that great value may ultimately come from manganese nodules, simply because of their vast extent and large total volume. Another important part of the total value may be contributed by localized metal-enriched sediments and brines.

OCEANS AND CONTINENTS

It has been common in the past to discuss marine mineral resources in terms of local occurrences and geography or of mining or recovery techniques. It should also be of value to attempt to relate at least the more important marine resources to some of the larger geological features of the earth, and to note their relative individual importance in terms of the total value of marine mineral resources.

It is worth emphasizing again that the familiar global hypsometric curve (Fig. 1) clearly shows that the earth consists of two great topographic surfaces—one essentially at sea level, representing the great continental masses, and another at nearly 5 km below sea level, representing the great ocean basins. It is also well known that these two major hypsometric surfaces reflect fundamental differences in the earth's underlying crust. The oceanic crust is much thinner and apparently of a different overall composition from the continental crust.

The boundary between continental and oceanic crust is transitional over tens of kilometres, but in general, waters shallower than about 2 km overlie crust that is more continental in character than oceanic. These submerged continental margins represent a relatively small area of the earth, but they are of great fundamental importance to geology, and of enormous linear extent—stretching for a total distance of nearly 350 000 km. Approximately 15 percent of the world's oceans

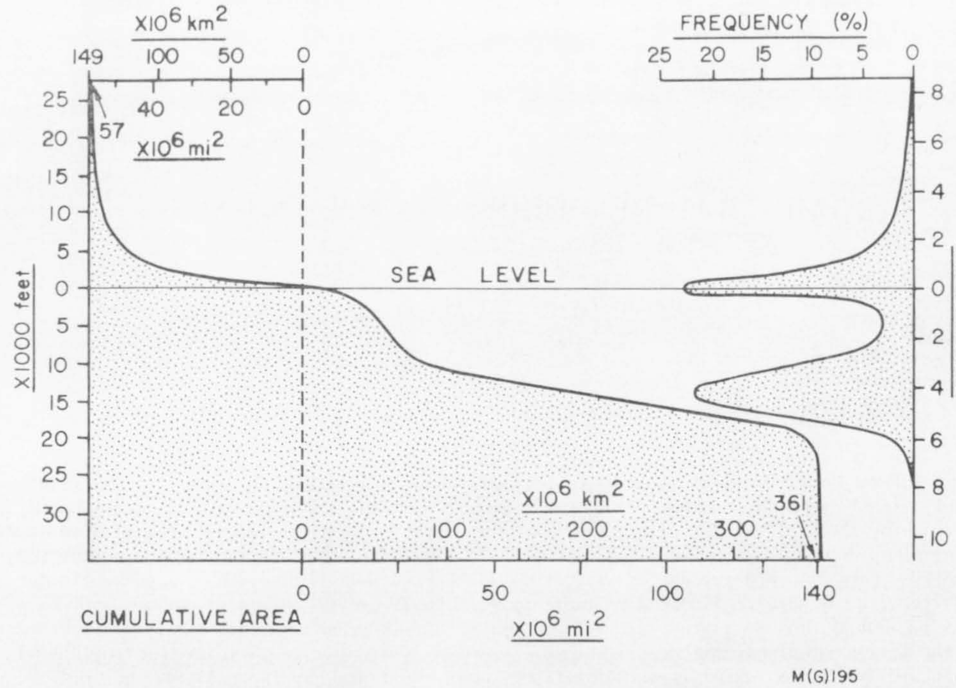

Fig. 1. Distribution of world topography.

actually overlie the submerged margins of continents, and it is this area that has received the greatest attention in the search for marine mineral resources, largely because the waters are shallow and close to land and because the resources are similar to the kinds of occurrences already known on land.

Continental Margins

Where a *continental rise* is present it appears to consist of a great wedge of young sediments overlying oceanic crust. Only those resources associated with accumulations of sediment can be expected to occur in the continental rise. However, the *continental shelves* offer the broad potential of mineral resources already well known from the continental crust. The intervening *continental slopes* offer a mixed potential of resources from both extremes. The continental shelves of the world have been the most explored and have yielded all the marine mineral resources produced thus far; but only a small share of these can be attributed to true continental shelves.

Of the 71 percent of the earth covered by water, 5.3 percent (27.1×10^6 km^2) is less than 200 m deep. However, not all this very shallow area is true continental shelf: 8.7 million km^2 of water shallower than 200 m are actually inland seas or bays, which cover submerged parts of continental interiors, and are thus unrelated to true continental margins (e.g., Baltic Sea, Persian Gulf, Hudson Bay, Gulf of Venezuela, Gulf of Paris, Gulf of Carpentaria, Straits of Malacca, and most of the South China Sea).

If such *'interior shelves'* are subtracted from the total area of water less than 200 m deep, the true continental shelves of the world comprise the remaining area of about 18.4 million km^2, or about 3.6 percent of the total surface of the earth. Nearly all the value of marine resources recovered to date must be attributed to such 'interior shelves' rather than to true continental shelves (Fig. 2).

The continental slopes of the world constitute a slightly larger area, nearly 29 million km^2. Together with the true shelves, the continental terrace thus constitutes about 9.2 percent of the earth's surface (47.1×10^6 km^2). The total area of the continental rises is much more difficult to estimate, but it would appear to be nearly equal to the total area of the continental slope. Even though the true continental shelves and slopes are long narrow bands on the earth's surface their combined area exceeds that of all the land areas of the western hemisphere.

Deep Ocean Basins

The deep ocean basins represent over 55 percent (281.2×10^6 km^2) of the earth's surface and together with the continental rise the area of oceanic crust is

	AREA Miles^2 (Km^2) $\times 10^6$	PERCENT of Earth
EARTH	197.0 (510.1)	100.0 %
Land	57.2 (148.1)	29.2
Water	139.8 (362.0)	70.8
CONTINENTAL*	78.7 (203.8)	40.0 %
Land	57.2 (148.1)	29.1
Interior shelf	3.4 (8.7)	1.7
Shelf	7.1 (18.4)	3.6
Slope	11.0 (28.7)	5.6
OCEANIC	118.2 (306.2)	60.0 %
Rise	9.6 (25.0)	4.8
Ocean Basins**	108.6 (281.2)	55.2

* Edge of the continents is considered to be at 2 km of water depth

** Includes oceanic ridges, volcanic peaks, abyssal plains and abyssal hills

Fig. 2. World physiographic provinces.

a full 60 percent of the earth's surface. The area of ocean basins includes many varied and complex topographic features, including oceanic ridges, volcanic peaks, oceanic islands, abyssal plains, and abyssal hills. More is known, perhaps, about the resource potential of this large deep-water area than is known about potential resources of the less remote continental slope and rise.

All the known deep-ocean resources are authigenic and mineral accumulations in sea-floor sediments. Even though similar accumulations are known in much shallower waters, the vast extent of any deep ocean resources sets it aside as unique. However, the remoteness of most of the oceanic area from land and the remoteness of the ocean floor from the surface of the sea impose restraints on the practicability of recovery of any deep-ocean mineral resources.

Included in the area of deep oceans are the 'small ocean basins', such as the Sea of Japan, Okhotsh Sea, Bering Sea, Gulf of Mexico, Caribbean Sea, Mediterranean Sea, Black Sea, etc. In all these restricted seas, bordering a continental mass, there are a variety of characteristics quite distinct from those of deep ocean basins. The resource potential of such areas must also be distinct from that of the deep open oceans, but their geology is too variable and too poorly known to allow any broad generalizations.

Marine Resource Potential

In terms of the total value of present and potential marine mineral resources we can make a few preliminary and broad generalizations. The resources of the deeper continental crust beyond the shoreline are largely insignificant, except for oil and gas. Large deposits of authigenic and secondary placer accumulations are important only to a small and local extent, and they have little impact on the total value of marine resources. In the deep ocean basins, the only resource of potentially great significance is the widespread accumulation of manganese nodules; and even these occur in much shallower marine areas as well as in exposed ancient deposits.

The world demand and the occurrence of marine mineral resources indicate that oil and gas will continue to dominate the value of marine resources in the foreseeable future. The manganese nodules of the deep ocean may some day also be important in the total value of marine mineral production. A great many other marine minerals are known, of course, but each must compete with similar resources on land which may be of lower grade, but which are commonly more economical to recover. However, this does not preclude the local value of marine minerals to the economy of individual countries or to meet an important local need.

Marine Placer Deposits

A considerable variety of surficial minerals can be mined by dredging the shallow sea floor. The most valuable of these are the commonly occurring sand, gravel, and lime shells. The 1969 production of these commodities accounted for about a third of the total value of marine production of hard minerals throughout the world. The growing demand for construction materials and beach replenishment in many coastal cities and countries will substantially increase future subsea production of these materials, but the need and value of such production will be determined entirely locally.

Prospecting for marine placer deposits has been underway recently with modern techniques off the coasts of more than 20 countries, with principal emphasis on detrital tin, titanium minerals, and gold. Various types of placer deposits are currently being worked in many parts of the world, including diamonds, magnetite, monazite, zircon, tin, and titanium, but the value of their production is only about a tenth of the total value of the marine hard mineral production—and the total annual value of subsea hard minerals is less than 2 percent of the value of the onshore production of these minerals.

During the next few decades it seems likely that marginal grade resources on land will generally be given preference over marine hard minerals, with certain obvious exceptions: (1) extremely large and high-grade offshore deposits in easily accessible waters (such as the tin placers of southeast Asia); (2) minerals in short supply (such as diamonds, gold, platinum, and nickel); (3) bulk minerals where cost of transportation is a major factor (such as sand and gravel, lime shells, some iron ore, and phosphates); and (4) certain marine resources desired by individual countries for their own consumption, or to meet the needs of a restricted local market, or for balance of payment consideration, etc.

Minerals Beneath the Sea Floor

No entirely new technology has been developed for mining bedrock deposits beneath the sea, and all present underground offshore mines are merely the extension of onshore deposits, with entry from land or artificial islands, extending a very few kilometres from shore. Only coal and iron ore are now produced from such underground mines, but they account for about half the annual value attributed to marine hard mineral resources. A submarine barite deposit off southeastern Alaska has recently come into production in up to 30 m of water. This is the first operation in the world to blast and dredge consolidated lode deposits on the sea floor, and it is now contributing about 25 percent of the total barite production in the USA.

Some important metals can be recovered by drilling and fluid extraction, such as the sulphur from salt-dome caprock in the Gulf of Mexico. However, in view of the worldwide oversupply of sulphur in the foreseeable future, it is unlikely that this will become an important marine resource. The same is true of potash and bromide salts.

Except for petroleum, mineral deposits beneath the sea floor are largely of local interest to meet special demands. Underground mining close to shore undoubtedly will continue where it is economic, as will solution mining, but neither will have a significant future impact on the total value of marine mineral resources.

Authigenic Minerals

Phosphorite occurs as crusts and nodules on the outer parts of many slope-depth areas, and marine resources of phosphorite probably amount to hundreds of billions of tons. However, the great abundance of low-cost supplies on land suggests that marine phosphate mining is not likely to be important to the world supply in the foreseeable future.

Perhaps the most interesting of all marine mineral resources are the vast deposits of manganese nodules which cover large areas of the deep ocean floor. These deposits in the Pacific Ocean alone may well exceed 10^{12} tons. Some of the nodules contain 1.5 percent or more of combined copper, nickel, and cobalt. An operation handling only about 3000 tons per day could provide more than 5 percent of the world's present manganese consumption, 3 percent of the total nickel demand, 14 percent of the cobalt demand, and 0.2 percent of the copper requirement.

Efforts have greatly increased over the past few years to evaluate and sample nodules on the abyssal floor and to develop the engineering technology which will allow economical mining in these great depths of water. Research is also encouraging in regard to developing a simple and economical process for extracting the various metallic constituents from the nodules. In all respects, the results of these studies have been most encouraging. Manganese nodules will eventually be mined; it remains only to speculate how soon and to what extent.

Legal jurisdiction over the deep ocean floor still remains a problem, and other ancillary aspects of nodule mining may also pose problems. The metals are not present in the nodules in the same ratio in which they are used in the world. For example, if the world's needs for copper were to be supplied entirely from nodules, there could also be available at the same time nearly 25 times the world requirement for manganese, 15 times as much nickel, and 113 times as much cobalt. This is obviously extreme, but in an operation designed to produce large quantities of copper, for example, it might not be possible to utilize all the other metals obtained.

In addition, manganese nodules and crusts occur in shallower waters in smaller quantities, even in such interior water bodies as the Great Lakes of North America. So far, the desirable metals seem to be less abundant in these shallower waters, but the economy of recovery and proximity to land may yet allow them to be produced first.

In summary, the vast extent of manganese nodules may make them an important future contributor to the total value of marine mineral resources. In view of their great abundance it is surprising that broad studies have not been made of unexpected uses of these nodules, which could accelerate their being mined. As an example, it has been pointed out that they are excellent oxidation catalysts for pollution control, and that after such use, the metals are much more easily extracted.

Brines and Metalliferous Sediments

The minerals currently being extracted from sea water nearly equal in value that of all marine hard minerals. Over 300 coastal plants now operate in 60 countries, largely recovering salt, fresh water, magnesium, and bromine. Research on the extraction of other materials is continuing.

The metal salts of sea water are locally concentrated in rich brines. Studies deep in the Red Sea have recognized very high concentrations of iron, manganese, zinc, lead, copper, silver, and gold, and locally these brines are underlain by recent sediments greatly enriched in the same metals. These concentrations clearly represent a large and valuable resource, and suitable mining techniques will eventually be developed. However, the importance of this type of concentration to the total value of marine mineral resources must await more careful and more extensive evaluations here and in other areas. Other large concentrations will surely be found, making such deposits of even greater potential importance. Localized metal-enriched sediments may some day constitute an important part of the total value of marine resources.

PETROLEUM

The annual value of subsea petroleum production will soon exceed that of all other marine mineral and living resources combined, including fisheries and sea-water chemicals. Marine petroleum is presently being produced off more than 30 countries, with a value of more than $US6 billion annually. However, the principal value is not entirely in the gross production, but probably in the much greater values of the ultimate uses that oil and gas make possible. Geological and geophysical exploration is underway off the coast of about 80 countries and drilling is in progress off more than 45. Through the remainder of the present century, and probably longer, petroleum will continue to be the principal mineral produced from the seabed.

However, as noted earlier, it should be emphasized that very little of the present production comes from the shelves of true continental margins. The submerged inland seas of the Persian Gulf and Venezuela's Lake Maracaibo account for the bulk of present marine petroleum production. The new large discoveries in the North Sea appear to be in a similar environment. We must reserve some caution, and not become too over-enthusiastic about the omnipresence of very large petroleum accumulations on all continental margins. We are just beginning to learn the fundamental geology of these poorly known areas. However, most of the exploration presently underway is on true continental margins, and there have been some notable successes—e.g., the Gippsland area and the Australian Northwestern Shelf, and the Niger Delta. Actually, real data are very scarce in these poorly known areas. Less than half a dozen pioneering wells have been drilled at the edge of the shelf (in eastern Canada and northwestern Australia).

Speculation regarding petroleum potential beyond the continental shelf is surely even more intriguing, but even less founded. The broad geophysical surveys in the deep oceans during the last few decades, and the recent very exciting exploration of the JOIDES Deep-Sea Drilling Project, have given us a better understanding of the deep ocean basins than we have of the less remote continental rises and slopes. Not a single well has been drilled into any of the rises or slopes of the world, yet vast petroleum potential is commonly attributed to these areas. Eventually they will have to be tested by the drill.

In summary, continental shelves throughout the world offer a great opportunity to develop additional marine resources of petroleum, but potential in deeper waters is much more speculative. Exploratory wells have been drilled already in 450 m of water and deeper wells are in the foreseeable future. Successful producing systems for greater depths of water can reasonably be expected as such opportunities arise. Exploration opportunities undoubtedly exist along many continental margins and in various water depths. Beyond the basic needs of food and shelter, the progress of any nation is largely dependent on the availability of cheap energy; the worldwide demand for petroleum is growing at a truly amazing rate, and we may have to depend on marine resources to meet much of this need.

Unfortunately, the development of these important marine resources is not entirely dependent on geologic or technologic knowledge and capability. Economic and political constraints commonly are the determining factors. Petroleum exploration and development are extremely expensive and very risky ventures, especially in the very costly environments of the oceans. Vast amounts of risk capital will be needed if we are to have any hope of discovering and developing marine petroleum. It will be impossible to develop at sea the many small petroleum accumulations that would be economical on land, because of the much greater cost of working at sea. Petroleum, like other marine resources, must also compete economically with large volumes of low-grade deposits known on land such as oil shales, tar sands, and liquefied coal.

In addition to the imposing technological and economic factors that control development of marine petroleum resources, unnatural, man-made restraints have continually beset successful exploration efforts, and the situation continues to worsen. In addition to political instability that prevents any sort of long-range planning, petroleum exploration is faced with nationalization, increasing taxes, price controls, restrictions on currency movement, and an endless variety of local rules and regulations which greatly hinder successful international operations. Unless these and related man-made factors are controlled in such a way as to encourage potentially economical investments, it is doubtful that it will be possible to generate the huge amount of risk capital that will be needed to develop these important marine petroleum resources for the future use of mankind.

Acknowledgments

The comments above have greatly benefited from studies by Drs V. E. McKelvey and F. F. H. Wang of the U.S. Geological Survey.

GEOLOGY OF THE BOUGAINVILLE COPPER OREBODY, NEW GUINEA

by C. L. Knight, R. B. Fraser, and A. Baumer

Conzinc Riotinto of Australia Limited

Summary

The orebody lies 14 km from the east coast of Bougainville Island in a valley in the Crown Prince Range. It is localized in a 13 km^2 copper geochemical anomaly in and near a small intermediate complex intrusive into a Miocene volcanic suite comprising andesite flows, agglomerate, tuffs, and dykes, and some associated sediments. In 1964, Ken Phillips of Conzinc Riotinto of Australia, attracted by the Miocene volcanic-intrusive environment, carried out geochemical sampling in the vicinity of a small old copper-gold prospect, which indicated a major porphyry copper deposit.

The diamond drilling test was completed in 1969, and involved drilling 67 000 m in 238 holes, with overall core recovery of 94 percent. The drilling was done on a 400-foot grid to a predetermined probable open pit bottom and all evaluation holes were vertical. Bulk sampling of 3600 m of drives and rises confirmed grades derived from vertical holes.

Reserves of primary ores within a designed open pit are estimated at 900 million long tons of grade 0.48 percent Cu, 0.36 dwt Au per long ton, trace Mo. Grade is a little lower at pit bottom level than at top and mineralization continues downward to an unknown depth. Secondary enrichment is not important. Secondary grade is a little above primary grade, and oxidized grade a little higher again.

The composite or multiple intrusive is about 4 km across, and irregular in outline. The barren Kawerong Quartz Diorite constitutes 80 percent of it. The orebody is localized at the southern edge of the intrusive and in the adjacent andesite. Four different intrusive rock types are recognized here: the Biotite Diorite, which is host for much of the ore; the Leucocratic Quartz Diorite, which forms small intrusives separate from the main mass, in and around which higher grades occur; the Biotite Granodiorite, of which a 350-m diameter portion is only weakly mineralized and constitutes a low-grade central core to the orebody (significantly perhaps it is microscopically porphyritic in quartz); and the small Biuro Granodiorite; the three last named are porphyritic. All the intrusives are near-vertical. Intrusive breccias have been observed, and thin pebble dykes are common in the ore zone.

The orebody in plan, as defined by the 0.3 percent Cu contour, is 5800 feet (1770 m) long by 3400 feet (1040 m) wide, with a low-grade core and a barren indentation (the Biuro Granodiorite). Grades vary systematically: that is, they can be contoured. Outwards beyond the 0.3 percent contour, grade falls off gradually by an increase in the ratio of pyrite to chalcopyrite; that is, there is a pyrite halo around the orebody.

The sulphide minerals are chalcopyrite in excess of pyrite, with a little bornite. Gold values vary sympathetically with copper. Although some copper is disseminated throughout the horsts, the bulk of it is contained in veins; grade and degree of fracturing vary sympathetically.

Because of high rainfall (500 cm), high natural slopes, high seismicity, tropical weathering, and the high degree of fracturing, studies of engineering geology and rock mechanics

were undertaken, and are continuing, to produce data relevant to a maximum safe pit-slope design, drainage of the pit area and suitability of sites for heavy buildings. The approach has been to make fracture analyses of surface and underground exposures and drill core; to monitor surface and underground water flows; to monitor water pressures in specially drilled and located bores; to measure strengths of rocks; and to install a seismometer and four accelerographs in the area.

The results were analysed on site, and independently by a rock mechanics consultant. It was concluded that a multislope configuration would be most appropriate for the pit, and that the rock mass must be thoroughly drained.

LOCATION

The orebody is 14 km inland from the east coast of Bougainville Island on the western slopes of the Crown Prince Range in the valley of the Kawerong River. Elevation of the outcrop ranges between 575 and 825 m above sea level. Eastward from the orebody the ground slopes steeply and continuously upward to the crest of the range at about 1200 m. To provide access a road was built through a saddle in the range at 1070 m. Terrain is very rugged and the whole area was covered by dense tropical rain forest.

DISCOVERY

It is worth while recording the events that led up to the discovery of the orebody.

In 1962 Conzinc Riotinto of Australia undertook a deliberate search for porphyry coppers in the granites of Eastern Queensland, and within two years had found two occurrences of undoubted porphyry-copper-molybdenum type in Upper Palaeozoic to Lower Mesozoic granites. Although they were a long way below economic grade their discovery was very important in that they demonstrated, along with one in the Philippines, that porphyry coppers existed outside the Americas, and related to intrusives other than late Mesozoic/Tertiary; this constituted a very important break-through in our exploratory thinking, and gave the necessary incentive to continue the search.

A second very important development during this two years in Queensland was the refinement of known geochemical techniques into an efficient and rapid search and evaluation tool.

After two years Kenneth M. Phillips, who had headed the porphyry copper search from the beginning, came to the conclusion that although porphyry coppers did exist in older rocks all the viable ones were localized in or near Cretaceous/Tertiary intrusives, and that therefore New Guinea and the Solomon Islands offered far better possibilities than the Queensland Permian/Mesozoic. There were only a few copper occurrences known in New Guinea at the time and Phillips was attracted particularly to two of these—Panguna and Kupei—which were close together on Bougainville Island, and descriptions of which by Government geologists Dr N. H. Fisher and J. E. Thompson reminded him of a porphyry copper in the Philippines.

He started search of the Panguna-Kupei area in May 1964; by July 1964 stream sediment sampling had shown copper to be dispersed anomalously over a 13 km^2 area, and ridge-and-spur soil sampling had shown Kupei to be very small, but had delimited a strong geochemical soil anomaly at Panguna Hill of approximately 300 m diameter, separated by non-anomalous zones from patchy and lower soil values to the north and northwest. It was found later that the blanks were due to recent ash cover.

A light diamond drill was taken in to drill holes to 400 feet (120 m) to test primary grade under the soil anomaly. Four of the first five holes intersected interesting grades.

Evaluation

The decision was made at the outset to carry out the evaluation drilling on a 400-foot grid using vertical diamond drillholes. Heavier machines capable of taking bigger cores were introduced and the Panguna Hill soil anomaly of 2000 feet by 1400 feet (600 x 425 m) was drilled. Near the close of this stage it was realized that recent volcanic ash covered a good deal of the area, and after drillhole 22 it was decided to run two traverses of holes from the Panguna Hill soil anomaly through to the soil anomalies to the north and northwest. These showed that the copper mineralization was very much more extensive than originally thought and that a great deal of it was obscured by recent tuff cover. More drills were brought in until a maximum of 14 were in operation; N.X. cores became standard; mud circulation was introduced; and with the 34th hole split inner tubes were also added; wire-line drilling was introduced later. Each hole was drilled to approximately R.L. 1100 feet (datum sea level), which was the probable bottom level of openpit operations. The drilling pattern was extended outwards until the 0.3 percent copper limit had been defined. In all, definition and evaluation of the orebody required 238 vertical drillholes aggregating 220 000 feet (67 000 m) on a basic grid of 400 feet with some closer spacing in places.

The evaluation drilling took four years to complete. For the first two years drill rigs were moved and serviced by helicopter until an access track from the coast came into operation. Full core was crushed for assay.

One of the problems was to obtain a reliable figure for core recovery. Because of the high degree of fracturing, particularly in the Panguna Hill area, the core arrived at surface in a highly fragmented state which made direct measurement of core length an impossibility. No answer was found to this until the introduction of split inner tubes and refined handling techniques at hole 34. From then onward direct linear measurements of core were made which established core recovery in the primary zone at 94.3 percent.

This finding in turn posed the problem of quantifying the effect of core loss on grade calculations from core assays. Mainly to investigate this problem, but also to provide bulk samples for metallurgical tests, about 2 km of driving, crosscutting, and rising were carried out in each of two adits along pre-drilled horizontal and vertical drillholes. The ore mined was rigorously weighed, sampled, and assayed, and correlation charts drawn up for mined ore against diamond drill cores. The work showed that diamond drilling had not overvalued grade, and the grade as determined from drill cores was accepted.

An average density was derived from weight and in situ volume of the material mined from the adits; the average was 14.31 cubic feet per long dry ton (411.5 *l* per tonne).

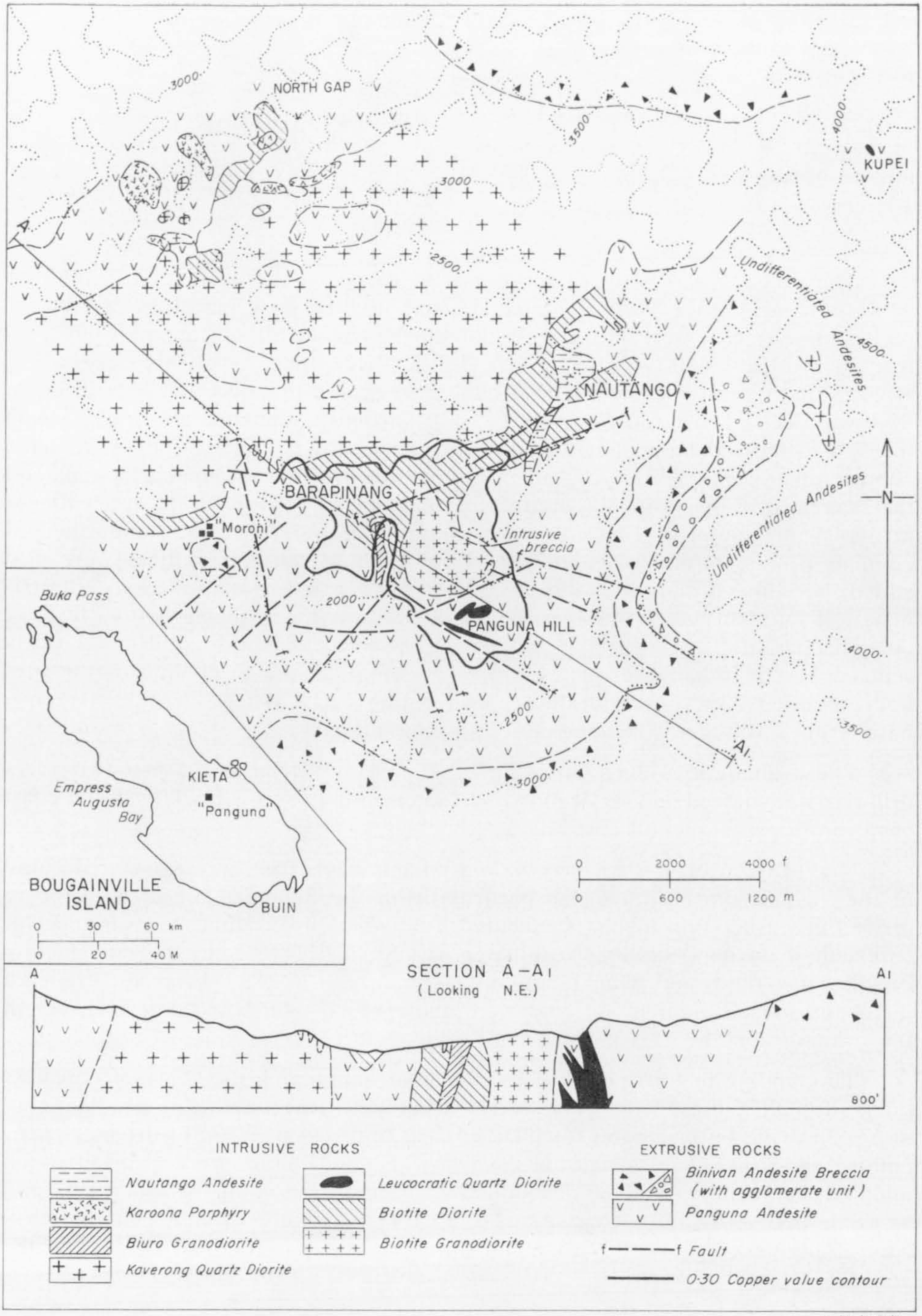

Fig. 1. Geological map and section Bougainville Copper Orebody.

Reserves of primary ore within a designed open pit are estimated at 900 million long tons of grade 0.48% Cu, 0.36 dwt Au per long ton, trace Mo, at a waste to ore ratio of 0.68. Average annual production will be 150 000 tons of contained copper and 500 000 oz gold in 30 percent Cu concentrates, commencing mid-1972.

Geology

An account of the geology by Macnamara (1968) has been published elsewhere. A brief resumé is included here. The geological picture was resolved by macroscopic examination of cores and outcrop.

A composite intermediate intrusive about 4 km diameter and irregular in outline has invaded a near-horizontal thick andesitic lava/pyroclastic pile of probable Miocene age (see Fig. 1). It is at least 1000 m thick.

The intruded rock is the *Panguna Andesite.* Although its main bulk is everywhere texturally and compositionally a hornblende microdiorite (and indeed was thought in the early part of the investigation to be an intrusive), it is a volcanic flow. It is not vesicular. A lapilli tuff, some fine-grained tuffs, and a volcanic agglomerate (previously thought to be xenolithic andesite) are interbedded with the andesite. The banded rocks dip at 5° to 20° southeasterly across the mineralized zone.

The *Kawerong Quartz Diorite* constitutes the northern 80 percent of the intrusive; it is typically a pink hornblende diorite with granodiorite phases in places; quartz ranges up to 10 percent and is interstitial.

The orebody is localized in and adjacent to four smaller units of the intrusive which occur along the southern margin. Of these, the *Biotite Diorite* is the largest and is the host of the orebody in the northern sector; it is a fine-grained light grey rock consisting of pink and grey feldspar, abundant biotite (replacing original hornblende), some quartz and magnetite. The other three smaller units are porphyritic and quartz-rich—the *Biotite Granodiorite,* similar to the Biotite Diorite but containing more granular quartz visible in hand specimen; the *Leucocratic Quartz Diorite,* which includes microdiorite and porphyritic varieties, and is essentially similar to the Biotite Diorite; and the *Biuro Granodiorite,* porphyritic in quartz hornblende and feldspar, which is thought to be late stage. Attitude of all intrusives is near-vertical.

Breccia pipes have shown up in underground work. The matrices are generally chloritic and included fragments are usually dioritic. Proportion of matrix ranges from almost zero to almost 100 percent. The matrices of most of the breccias contain disseminated sulphides. The breccias are relatively small and very irregular bodies and show pinch-and-swell outlines. *Pebble Dykes* occur throughout the orebody and intrude the Biuro Granodiorite and older rocks. They are not cupriferous but may contain some pyrite.

Ore Mineralogy and Habit

Chalcopyrite is the dominant primary copper mineral. Bornite is associated with the chalcopyrite in the Leucocratic Quartz Diorite.

Gold is present throughout but is only very rarely visible as free gold in cores; gold content varies in general sympathetically with copper, but also to some extent with host lithology. Molybdenite is sparse and is commonly associated with pyrite. Lead and zinc are present in only trace amounts. Pyrite is ubiquitous and varies very roughly inversely to chalcopyrite.

Panguna Andesite constitutes 30 to 40 percent of the orebody. Here the mineralization is mainly in veins 2 to 25 mm in width, carrying chalcopyrite in a central zone between quartz crystals growing from the walls. An altered wall zone of fine-grained dark brown biotite forms a selvage to the veins. Veins tend to be wider (up to 5 cm) and more frequent in the Panguna Andesite adjacent to dykes of Leucocratic Quartz Diorite.

In the Leucocratic Quartz Diorite chalcopyrite and bornite occur as relatively coarse disseminations, as disseminations within quartz veins, and as the constituents of the central portions of quartz-sulphide veins. Relatively few veins are visible in its surface exposures, but underground at Panguna Hill mineralized quartz veins are closely spaced and generally 3 to 25 mm wide, rarely up to 75 mm wide.

The Biotite Diorite and Biotite Granodiorite carry a similar pattern of mineralization, with fractures generally more widely spaced and with some additional copper in a disseminated form.

The Kawerong Quartz Diorite is weakly cupriferous throughout, mainly as chalcopyrite with occasional bornite, which occurs with chloritic hornblende.

Overall, the bulk of the copper is in steeply dipping veins and fractures.

Shape of the Orebody

The primary orebody is part of a very large sulphide-bearing mass which extends well beyond the drilled area on all sides except to the east. In broad terms the total sulphide content is uniform throughout at 1 to 2 percent; outside the limits of economic ore pyrite is the principal sulphide, with trace chalcopyrite.

Drilling was extended outward from the higher grade ore until the 0.3% Cu limit had been defined. Within this limit primary copper grade was found to vary gradually and systematically, and it is possible to present the variation in the form of a contour plan (see Fig. 2). This shows a low-grade core coincident with the central part of the Biotite Granodiorite, and as this is a common feature in porphyry coppers, it must have genetic implication. The low is more or less ringed by higher grade ore, of which the Panguna Hill portion associated with the Leucocratic Quartz Diorite is the most notable. Outward beyond the higher grade ore, grade declines gradually where the host rock is an intrusive, but sharply where the host is andesite. The Biuro Granodiorite represents a blank in the copper mineralization; it is either a second low-grade centre, or a post-ore intrusive.

The orebody continues downward to unknown depth, with only a small fall-off in grade to depth so far drilled.

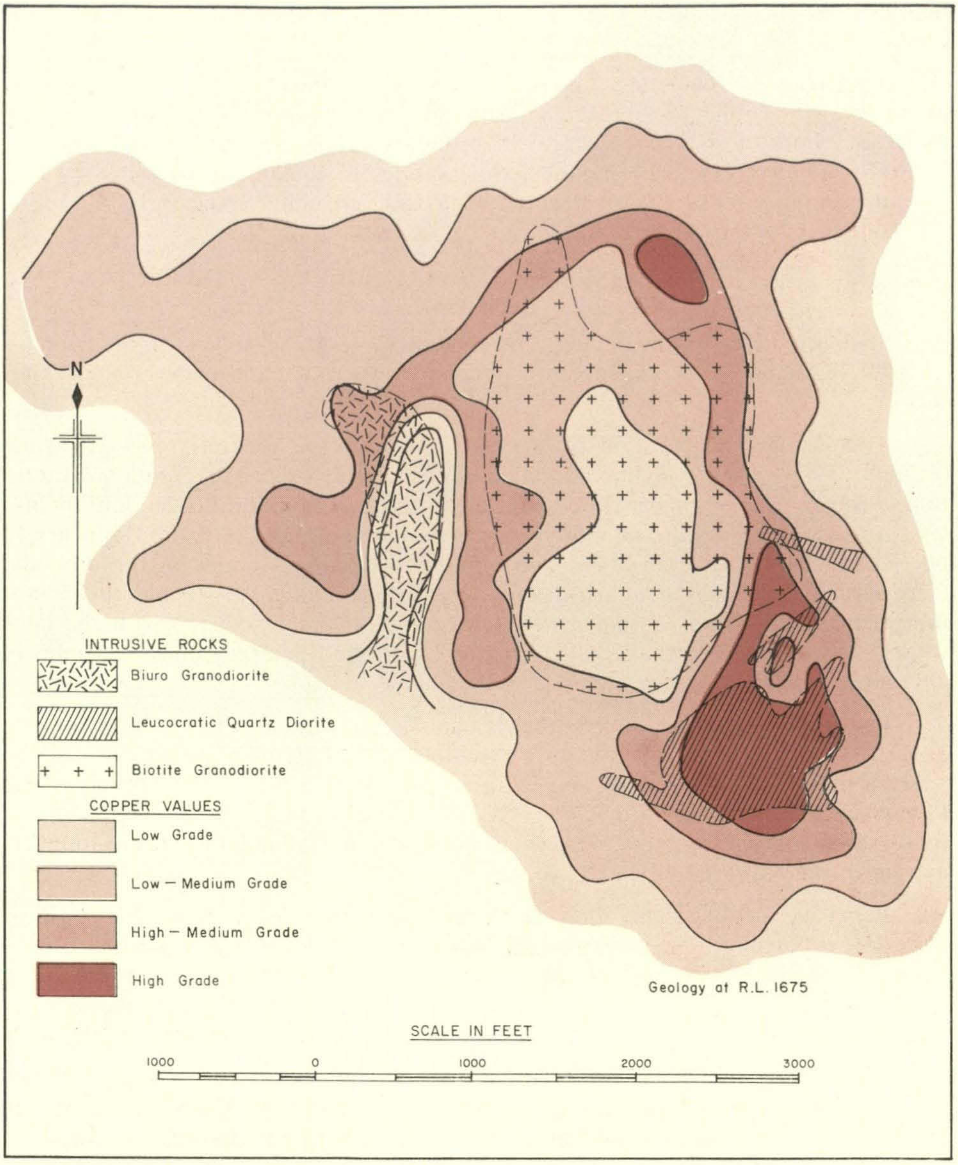

Fig. 2. Relationship between grade contours and intrusives, Bougainville Copper Orebody.

Oxidation and Enrichment

Secondary enrichment is unimportant.

Oxidized and secondary zones are related to the present surface. Because of the 500 cm rainfall, and deeply incised drainage, the water table intersects the surface at the bottom of the watercourses, and here we find primary sulphides at outcrop or at shallow depth. Under the ridges the water level can be at appreciable depth below surface, and oxidized and secondary zones are thick and well developed.

The oxidized zone ranges between 0 and 80 m thick and the copper occurs as fine-grained copper carbonates, cuprite, and native copper, or adsorbed in clay minerals. Grade is a little higher than secondary grade. Secondary enrichment is generally confined to areas of relatively high-grade ore, maximum thickness is 75 m, and the copper minerals are malachite, chalcocite, covellite, and cuprite. Grade is a little higher than primary grade.

ALTERATION

Staff geologists have extended and modified alteration studies by Macnamara (1968), by macroscopic examination of cores and surface and underground exposures.

The history of alteration is still not clear, but the general trend with time appears to start with propylitic alteration, succeeded by a pervasive potassic alteration through a less intense fracture-controlled potassic alteration to an intense fracture-controlled argillic alteration. Some pervasive argillic alteration appears to be older than the mineralization, and reimposed later in sections of the orebody. Corresponding changes in mineralization from disseminated to stockwork ore are followed by deposition of vein pyrite. Ore sulphides are associated with the later stages of the pervasive potassic alteration and with the fractured-controlled potassic alteration.

Propylitic alteration affects the Panguna Andesite in the environs of the deposit. Concentrations of epidote and chlorite (and pyrite) are known on the western margin of the orebody and in an arcuate zone in the eastern section of the Panguna Adit and adjacent drillholes. There is evidence that a zone of epidote-rich rocks surrounds the orebody. Elsewhere epidote is not abundant except along the margin of the Kawerong Quartz Diorite.

Pervasive potassic alteration produces mainly biotite, sulphides, and silica, with K-feldspar development remaining subordinate. It is best shown in the Biotite Diorite and Biotite Granodiorite, and occurs to a lesser extent in the Leucocratic Quartz Diorite. It appears to be largely early and may be partly a contact phenomenon of the Leucocratic Quartz Diorite. Associated pyrite and copper sulphides tend to be disseminated.

Superimposed on this is the fracture-controlled, more intensive potassic alteration with marked development of K-feldspar and biotite associated with some quartz veins. Near contacts of Panguna Andesite and Leucocratic Quartz Diorite magnesite is commonly associated with biotite in wall-rock. The pyrite, copper sulphides, and molybdenite, which probably formed late in this phase, are closely related to the veins. Potash, silica, and copper have been involved in the formation of orthoclase-biotite-chalcopyrite assemblages. Amphiboles and chlorite have been unstable and converted to biotite. Biotite is in part derived from wall-rock alteration of ferromagnesian minerals along fractures before the introduction of quartz, and forms haloes round veins. Some sulphides may result from the sulphidization of iron silicates in this phase. The alteration of hornblende to biotite characterizes the ore zone, and is most intense at the centre of mineralization and in areas of higher values.

Minor pervasive argillic alteration occurs along fracture planes in feldspars, with development of kaolinite, sericite, and calcite. It reaches moderate intensity as irregular zones of alteration in the Biotite Granodiorite. Intense argillic alteration appears to be late-stage and fracture-controlled and follows directly from the final stage of the fracture-controlled potassic alteration. Transitional zones are marked by biotite and K-feldspars accompanying dominantly siliceous and kaolinitic selvages to sulphide seams, in the Panguna Hill area. Kaolinization is not marked in the far south and southwest portions of the orebody, where argillic alteration has probably been superimposed on potassic alteration; orthoclase remains largely intact here. Kaolinization, with some sericitization, of wall-rock plagioclase adjacent to veins characterizes a zone round part of the Biotite Granodiorite, near the centre of mineralization, and in parts kaolin is formed throughout the entire rock fabric. Kaolinitic clays, in places containing quartz, chlorite, and calcite, fill small faults and shear zones round the deposit. Kaolin of hydrothermal origin has been found in discrete zones in many drill cores but does not appear to constitute a major redevelopment.

Subsurface gypseous and calcitic zones show a rough and rather inconsistent parallelism to the present surface topography, rising under hills and dipping towards the centre of valleys. The gypseous zone is in the northern portion of the orebody; it is known to be at least 250 m deep, and is unbottomed. The top of the calcitic zone is usually above the top of the gypseous zone.

Engineering Geology

Some meteorological and hydrological monitoring preceded the comprehensive engineering geological studies which were initiated as soon as the ore reserve evaluation drilling had progressed sufficiently to indicate the approximate limits of the open pit.

The Panguna area is characterized by very high rainfall, high seismicity, tropical weathering, very fractured and faulted and altered rocks, steep slopes, and ash and other unconsolidated superficial deposits. The approach to pit-slope stability studies by the consultants was to establish mathematical models for slope failure in a homogeneous rock mass, and then to modify the model to take account of inhomogeneity introduced by the above characteristics and other usual factors such as water pressures and stress characteristics of the rocks.

To supply the necessary data the following geological aspects were studied:
The extent and nature of faults. The picture is necessarily incomplete because of sparsity of outcrop. Photo interpretation detected 12 major lineaments in the open pit area on four main trends: northeast, north-northwest, west-northwest, and east. On five lineaments faulting is seen somewhere at outcrop and for six others drillholes give confirmatory evidence of faulting. Dips are known to be steep both from underground information and from the straight-line trace of the lineaments across rugged terrain. Lesser faults have been exposed in the adits, normal movements being more common than reverse. Widths are up to 12 cm and displacements of 7 and 2 m have been measured across two. Strikes are confined narrowly to six directions and dips are steeper than 60° except for the reverse faults, which lie at 40° to 55°.

Competence of the fractured rock mass. This is a function of the intensity, attitude, and length of fracture. To quantify the data the strike, dip, and length of fractures as they occurred in short typical sections of the adits were measured and plotted. The resulting stereonet plots showed no significant variation from place to place, that is, the pattern was uniform throughout. It was also found that the several categories of factures—shears, crushed seams, clay seams, shattered zones, and joints—yielded the same pattern. Dips were steeper than 50° for 85 percent of fractures, between 20° and 50° for 13 percent, and flatter than 20° for 2 percent; that is, dips were mainly steep. Measurements of fracture length establish that only 2 to 5 percent persisted for more than 10 m.

Intensity of fracturing varies. In the Panguna Andesite spacing of open fractures averages 5 to 25 cm; in Quartz Diorite 10 to 15 cm; in Biotite Granodiorite 30 cm; and in relatively barren rock between 15 cm and 2 m. Joint spacing is closer in drill cores than in the underground openings presumably because of additional fracturing induced by stresses at the bit face.

The permeability of the wall-rock and the extent to which it can be drained. The drainage effect of the two exploratory adits on the groundwater system was studied by monitoring the flows of water from the adits and by measuring water levels and pressures in 20 holes drilled above the adits specially for the purpose. From the data obtained it was concluded that the rock mass could be drained ahead of excavation, thereby minimizing the effects of water pressure on pit walls.

Acceleration imparted to openpit walls by seismic shock. Bougainville is in a highly seismic area; in fact an estimate by the Bureau of Mineral Resources indicates that 1 to 2 percent of the world's earthquakes are generated within 200 km of the mine. To record data two strong motion accelerographs and one continuously recording seismometer have been installed. Valuable quantitative data on acceleration will have accumulated in time to incorporate into design of detailed pit slopes.

Stress characteristics of the rocks. Mechanical tests were carried out on cores of fresh jointed material, on fault material, and on rock at various stages of weathering.

Volcanic activity. One active volcano, Mount Bagano, is 30 km northwest of Panguna, dormant Mount Balbi 57 km northwest, and Mount Loloru 21 km southeast. The latter is the only one close enough to be considered from an operations point of view. Temperatures of fumaroles and hot springs at Loloru are measured regularly and visual observations made.

Results

The data collected are necessarily incomplete but were sufficient to incorporate into a preliminary analysis of the stability of pit slopes. Results indicated that slopes of 35° to 45°, depending on the vertical height of the pit walls, would prove stable within acceptably conservative factors of safety provided that the rock mass is well drained.

Continuing seismological, engineering, meteorological, and hydrological studies will provide the necessary factual information for the detailed planning of pit slopes.

Comparison With Other Porphyry Coppers

The orebody is strikingly similar to many other porphyry coppers in that:

(a) the associated intrusive is small and of intermediate composition;

(b) the age of the intrusive is Miocene or younger;

(c) a porphyritic intrusive is closely related;

(d) there is a 'low-grade core' (the Biotite Granodiorite) around which the orebody has developed;

(e) the mineralization involves enrichment in potash, silica, and copper;

(f) intrusive breccias or breccia pipes are present;

(g) the alteration zoning generally fits the common pattern.

Acknowledgment

This paper is a synthesis of the findings of many Conzinc Riotinto of Australia geologists, of whom K. M. Phillips and P. Macnamara deserve special mention.

Reference

Macnamara, P. M., 1968—Rock types and mineralization at Panguna porphyry copper prospect, upper Kawerong Valley, Bougainville Island. *Proc. Aust. Inst. Min. Metall.*, 228, 71-80.

REVIEW OF MINERAL POTENTIAL IN FIJI

by Derek Green

Geological Survey of Fiji*

SUMMARY

Within even the ancient shield areas of the world, metallic mineralization has apparently been facilitated by the incidence of deep-seated fracture zones, reaching down to the earth's mantle. Correspondingly, in a geologically young island area such as Fiji, situated at the margin of the Pacific basin and with a recent geological history of volcanic and tectonic activity, mineralization might be expected to have taken place. Currently-known gold and base-metal mineralization appears indeed to have been structurally controlled. Specific examples from Viti Levu and Vanua Levu support this proposition. Fiji shows a well-marked pattern of approximately southwest and northwest fractures which may have arisen during regional shearing consequent on anticlockwise rotation of the Fiji plateau. The regional development of this pattern invites prospecting attention to the outer islands as well as the two main islands. Present evidence is insufficient to decide whether or not low-grade disseminated copper deposits occur in addition to minor vein-type lead-zinc mineralization with subordinate copper. Ultrabasic rocks have not as yet been found in Fiji, but nickel mineralization could possibly occur in association with basic igneous rocks.

INTRODUCTION

It would appear that the earth's mantle is to be considered to be, directly or indirectly, the ultimate source of mineralization, and that mineralization is indeed facilitated by reason of the existence of deep-seated fracture-zones, in effect reaching down to the mantle. This proposition recently has been cogently argued in the case of an ancient shield area—southern Africa—by Crockett & Mason (1968, pp. 532-40). The existence of a series of fracture zones transverse to the North American cordillera is suggested by Landwehr's demonstration (Landwehr, 1967, pp. 494-501) that mineralization there is distributed within a series of linear 'belts' trending northeast. Insofar as mineralization has by these means originated both on continental margins and within ancient shields, it is proposed that, *prima facie*, mineralization may be expected to have taken place within such a young land-area as Fiji, situated marginally to the main Pacific basin and having a recent history of pronounced tectonic and volcanic activity.

Walker (1968), after an exhaustive literature-survey covering the whole circum-Pacific region, reached the conclusion that Fiji constitutes a favourable exploration-target specifically from the the point of view of the possible occurrence of low-grade disseminated ('porphyry') copper deposits. Albers & Kleinhampl (1970, pp. C1-C10) found in Nevada a spatial association in 35 out of 80 cases between the incidence of Tertiary rhyolitic volcanic centres and mineralization;

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they suggested that there could be a genetic connexion (loc. cit., p. C9). Many Tertiary volcanic centres have been recognized in Fiji, where they are not usually rhyolitic, though some are found to be associated with mineralization (e.g. Vatukoula). The general question could evidently with advantage be further explored. The present paper cites Crockett & Mason's hypothesis (loc. cit.) of 'foci of mantle disturbance', and Landwehr's discussion (Landwehr, 1967, pp. 494-504; 1968, pp. 967-70) of belts of mineralization in the cordillera of the western United States by way of introduction to the proposition that there has been marked structural control of such mineralization as is already known in Fiji. It is suggested that mineralization generally in Fiji may prove to be structurally controlled and moreover to be possibly related not to the obvious, larger plutonic intrusions but to the smaller subsequent bodies as well as to volcanic centres. Evidently, a great deal of patient work will be needed to locate and to define the characteristics and age (or ages) of such mineralizing intrusions and centres as may exist. The Fiji Geological Survey has in operation a special program of investigation bearing on this question.

SUGGESTED PRINCIPLES

Landwehr (1967, pp. 496-9) proposed the recognition of seven 'belts of mineralization', each oriented approximately northeast to southwest, i.e. transverse to the general trend of the North American cordillera. Within these belts, he pointed out, lie nearly all the 'centres of mineralization' of the Nevadan and Laramide ('Nevadamide'), Precambrian, and Tertiary metallogenic epochs in the western United States. Landwehr (op. cit., p. 495 and fig. 1) demonstrated that mineralized fractures (in the nature of the case, occurring virtually exclusively within the belts mentioned) in five out of six western states (New Mexico, Arizona, Colorado, Utah, and Idaho) have a strong preferred orientation northeast to southwest, with an east to west trend in Montana the single exception. Tweto & Sims (1963) have shown that part, at least, of the Colorado belt follows a Precambrian zone of crustal weakness, as also may the other belts in question, though positive evidence to this effect is scarce (Landwehr, op. cit., p. 500). Tectonic movements since the Precambrian appear to have been small-scale and confined to the belts (ibid.).

Pointing out that even the very long Sierra Nevada batholith (trending north-northwest) provides examples of mineralization only where it is intersected by his Montana and Utah belts, Landwehr (1968, p. 968-9) discounted the proposition that there be a direct genetic relationship between mineralization and the emplacement (under conditions of orogenic compression) of the cordilleran batholiths. Instead, he suggested that 'productive plutonism' (op. cit., abstract) came about under tensional conditions such that mineralization along northeast to southwest lines followed the differentiation of primary basaltic magma. Where tensional conditions existed but differentiation did not occur, basaltic volcanic activity supervened (Landwehr, 1967, p. 498; 1968, p. 969). Landwehr (1967, p. 496) had pointed out that within the northeast to southwest belts, dykes and some larger bodies such as stocks follow the trend. This is certainly suggestive with reference to the proposition that 'productive plutonism' is to be regarded as essentially unrelated to the major bodies. Evidently it may, on the contrary, be closely associated with smaller, subsequent intrusions concentrated along particular zones of crustal weakness. In this connexion, it appears pertinent to recall that at Bingham Canyon it is the younger, areally subordinate granite porphyry of the Bingham stock which is the mineralizer, the older monzonite (e.g. Last Chance stock) which it intrudes being barren (James, Smith, & Bray, 1961, pp. 81-2).

Landwehr (1968, p. 969) ascribed the development of the northeast to southwest belts to tensional conditions arising during regional uplift. Evidently enough, however, the northeast to southwest mineralized fractures may be regarded essentially as tension gashes incidental either to northeast to southwest compression, or to shearing along the northeast to southwest belts. Inasmuch as the factures are aligned parallel to the zones (Landwehr, 1967, figs 1 & 3) except in one case, it seems reasonable to suggest that northeast to southwest compression has been the usual cause of the fractures, although initial regional shearing may explain the inception of the belts themselves. The exceptional case, where the fracture trend is east to west, could be explained as an example of continued dextral shearing along a belt, with consequent rotation of the trend of the incidental tension gashes (cf. Hills, 1943, fig. 88). General compression parallel to (and tension normal to) the trend of many of the northeast to southwest belts, and shearing along some of them, may readily be seen to be a likely concomitant of relative westerly movement of the crustal plate carrying the relevant portion of the American continent.

Crockett & Mason (1968, pp. 532-40), showed that within the ancient shield area of southern Africa there can be recognized a number of 'trends', or belts of crustal weakness, which have clearly remained active throughout long periods of geological time. This appears to be essentially a re-statement in specific terms of the general principle of 'resurgent tectonics' (Hills, 1955, pp. 50-1). Crockett & Mason point out that in southern Africa the distribution of the Drakensberg Lava Stage of the Karoo System appears to have been influenced and controlled by these 'trends' (op. cit., p. 535) and especially that the lavas '. . . tend to occur in regions of major crustal (and hence upper mantle) disturbance where two or more structural trends meet'. The distribution of kimberlite bodies (op. cit., p. 537) is similarly constrained and they have a '. . . tendency to congregate at the junctions of major structural trends or where such trends are particularly well developed . . .'. The distribution of nickel mineralization in southern Africa is held (op. cit., pp. 538-9) to have been controlled in the case of the early Precambrian occurrences by the effusion of both basic and ultrabasic rocks at a stage in the earth's evolution when the crust was relatively thin; other (implicitly younger) nickel occurrences are found within the linear belts of weakness referred to.

Kennedy & Nordlie (1968, pp. 499-500), pointing out that most kimberlite pipes were emplaced during late Cretaceous time, speculate that unusual conditions must then have prevailed to have '. . . allowed or promoted so many deep fractures into the mantle of the earth'. The problem may appear of lesser magnitude if it be admitted that many of the fractures could be resurgent expressions of older, or much older, zones of crustal weakness. While the proposition that diamond prospecting might be indulged in Fiji must clearly be discounted inasmuch as the geological history of Fiji is not known to extend farther back in time than the Eocene, the general principle of facilitation of communication with the earth's mantle by way of deep-seated fractures retains its importance in other connexions. The possibility of the occurrence of nickel in Fiji, associated with either basic or ultrabasic rocks, remains for investigation.

Structural Patterns

Fault trends in Fiji generally—that is, the mapped and inferred directions within the two main islands, as well as the directions along which outlying islands or groups of islands such as Taveuni and the Lomaiviti, or the Mamanuthas and Yasawas, are oriented or distributed—lie, broadly speaking, within two complementary sectors whose boundaries are (a) northeast to southwest and east-northeast to west-southwest lines (b) northwest to southeast and north-northwest to south-southeast lines (Fig. 1). This evidently reflects the incidence of a regional shear pattern such as could have been produced either by simple compressional forces giving rise to complementary shear-planes under conditions of pure shear, or alternatively by a major shearing couple giving rise to similar planes under conditions of simple shear. *Prima facie* it is not possible to determine whether there has been rotational or irrotational strain, but this aspect of the question can be elucidated indirectly.

It is here suggested that Fiji stands in relation to the Kermadec-Tonga ridge and trench somewhat as does the southernmost tip of South America to the Scotia Arc (Southern Antilles). On this basis, Fiji would be expected to have something in common, structurally speaking, with the Falkland Islands, inasmuch as they both can be seen probably to have been affected by anticlockwise rotational movement. The comparison is, indeed, on consideration rather less distinct than at first sight it might seem to be. There can be claimed to be, firstly, a link right across the southern Pacific Ocean between the northern end of the Scotia Arc and the southern end of the Macquarie Arc (or Macquarie Ridge) along a global lineament analogous to the 'Vening Meinesz Fracture Zone' of van der Linden (1967, p. 1295). The envisaged structure runs through the offset in the East Pacific Rise at approximately 60° south, 145° east, and it is postulated that dextral transform faulting along a direction from just north of east to just south of west through this offset followed and extended (cf. Wilson, 1965, fig. 3a) a line of weakness subsequently occupied by a sinistral 'super-transform' linking the oppositely directed Scotia and Macquarie Arcs. It is believed to be significant in this connexion that while the Southern Antilles trench is a very marked bathymetric feature (Udintsev, 1964, bathymetric chart of the Pacific Ocean), there is no correspondingly deep trench along the western coast of southern Chile. On this basis, inspection of the map referred to does suggest that to achieve the necessary balance of net movement on either side of the postulated 'super-transform' it may be necessary to equate the sum of 'over-riding' at the southern Chile and Macquarie trenches with over-riding greater than either of these examples singly, at the oppositely directed southern Antilles trench. The opposite senses of the envisaged original dextral transform and the proposed later sinistral 'super-transform' may account for the relatively small offset in the East Pacific Rise referred to.

Further, the structural history of Fiji may readily be seen to be linked with that of New Zealand and of areas to the south and north of New Zealand. Cullen (1967a, c) and Summerhayes (1967a) have accepted the Macquarie Ridge and Kermadec-Tonga Ridge respectively as island arcs. Summerhayes (op. cit., p. 611, and 1967b, p. 810) suggested that the Alpine fault might be a transform fault—necessarily, it would follow, of concave arc to concave arc type (cf. Wilson, 1965, fig. 2d)—linking the northern end of the Macquarie Arc to the southern end of the Kermadec Arc. This suggestion was vigorously countered by Cullen (1967d),

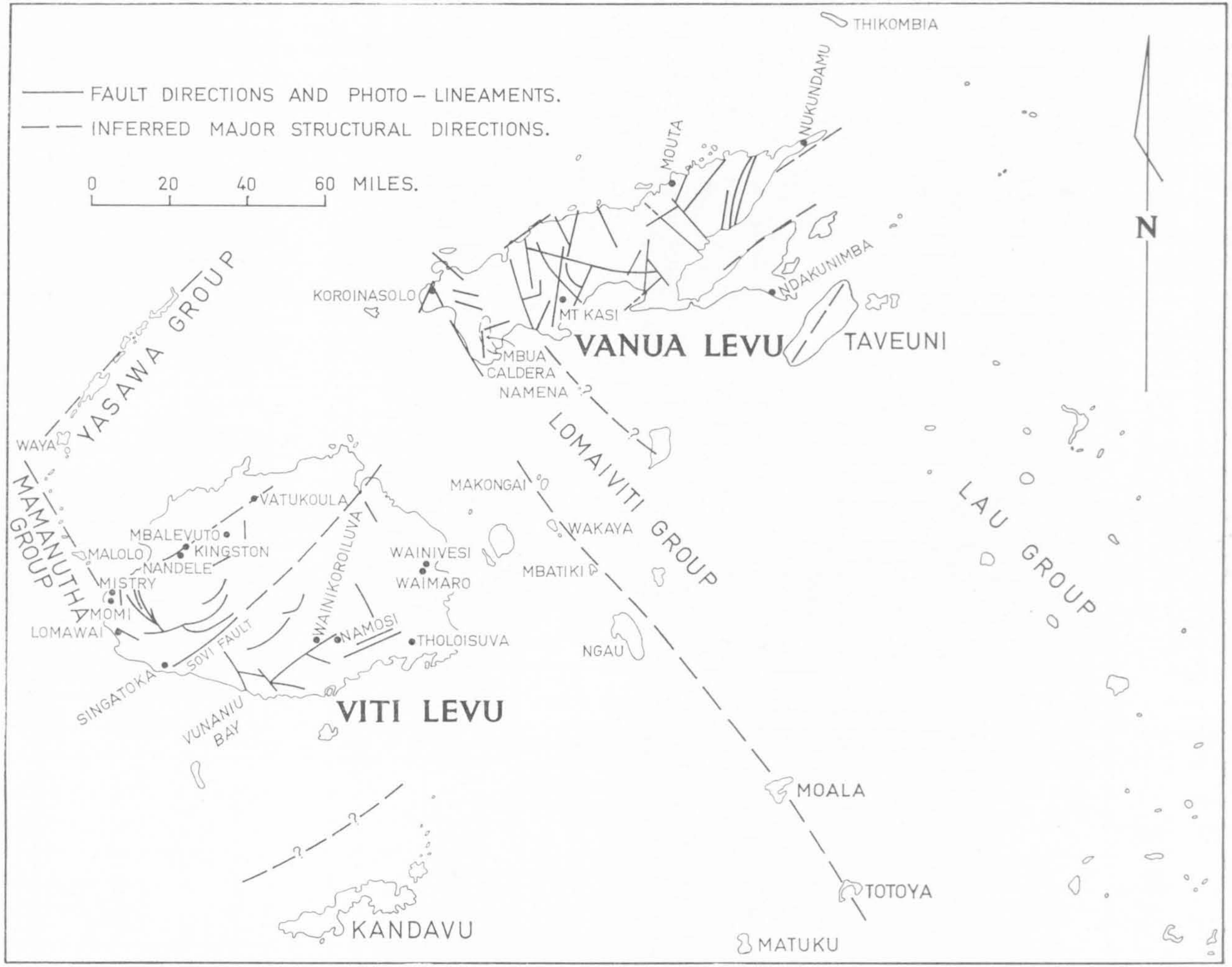

Fig. 1. Structural patterns of Fiji.

who pointed out that the Alpine fault existed before the Tertiary arcs. This does not necessarily invalidate Summerhayes' proposition, however, inasmuch as transform faulting could have followed an older line of weakness (cf. Wilson, 1965, p. 3). Be the answer to this as it may, it appears reasonable to accept Cullen's (1967a, b) general proposition that there has been a net resultant northward movement of New Zealand and the New Zealand Plateau (with part of South Island relatively retarded between the dextral Alpine fault and the sinistral Waipounamu fracture) due to the combined effect of convection currents emanating from the Indian-Antarctic ridge and the Pacific-Antarctic ridge together with the East Pacific Rise. This is consistent with an element of dextral movement along the Kermadec-Tonga arc (Fairbridge, 1961) and evidently such movement could provide part of the mechanism for the inception of the 'Fiji orocline' (Carey, 1958).

The abrupt cutting-off of the Kermadec-Tonga lineament south of Samoa certainly requires explanation, and Fairbridge (1961) proposed strike-slip faulting along a 'Melanesian Border Plateau' running from south of Samoa towards the Vitiaz Trench. Inspection of Udintsev's (1964) bathymetric map of the Pacific, however, brings out very strikingly that there is no necessary connexion at all, along the west-northwesterly direction, between the northern Tonga Trench and the Vitiaz Trench. On the contrary, such structure as there is would appear to have continuity in a north to south direction across the gap between the two. It appears legitimate therefore to revive the proposition that the discontinuity cutting off the northern end of the Tonga Arc and Trench runs in fact northeast to southwest south of the two main islands of Fiji, i.e. through northern Lau and along the Hunter Fracture Zone. This proposal appears legitimate if it includes the qualification that the discontinuity be recognized as a sinistral transform fault of concave arc to concave arc type and not merely as a transcurrent fault. The concept of a simple transcurrent fault (Hess & Maxwell, 1953; Fairbridge, 1961) was criticized by Cullen (1967a, p. 167) on the grounds that the positions of ridge and trench are reversed at either end of the proposed fault. This sort of reversal is, however, evidently characteristic of transform faults of the type suggested (cf. Wilson, 1965, fig. 3d) and it appears legitimate to link in this way the northern end of the Tonga Trench and the southern end of the New Hebrides Trench. The relative southerly movement of the crustal plate on the western side of the proposed transform fault could evidently combine with the northerly movement invoked in connexion with the 'Fiji orocline' (Carey, op. cit.) to cause anticlockwise rotation of the two main islands of Fiji, much as is envisaged on somewhat more complex grounds by Malahoff (in preparation).

Structure and Mineralization

The literature provides a certain amount of evidence of structural control of the currently known, relatively small-scale, mineralization in Fiji. In the Wainivesi area 50 km north of Suva, zinc-lead-copper veins occupying so-called 'shears' in Wainimala group rocks tend to strike parallel to the regional fault-trend, i.e. north to north-northwest, or transverse to the strike of ostensible limestone host-rocks (Houtz, 1958, pp. 14-16); Houtz & Phillips, 1963, pp. 10-13; Hirst, 1965, pp. 43-5). There are certainly exceptions to the rule, however. Houtz & Phillips (1963, p. 12, and fig. 13) show that on Wailotua Creek, north-northwesterly 'shears' cut off a mineralized zone, and Hirst (1965, p. 44) mentions the coincidence of veins with east to west shears and fractures. In the Lomawai-Momi area of western Viti Levu (Houtz, 1958) the regional strike of the Winimala Group rocks (with mineralization similar to that of Wainivesi area), except in the extreme south where an east to west direction prevails, is northwesterly, as is the trend of several major faults. The fault-trend becomes north to south in the north and it may be that two systems intersect in the area. Plutonic bodies also show a tendency to northwest to southeast alignment. In the Lomawai-Momi area such references as has been made to the trend of actual mineralized fractures (Houtz, 1959, p. 11; Houtz & Phillips 1963, p. 17) suggest a northerly to northeasterly trend (cf Houtz & Phillips, 1963, fig. 8). This recalls Landwehr's (1967) demonstration of the northeasterly trend of mineralized fractures in the western United States, transverse to the distributional trend of the elongate cordilleran batholiths (cf. Daly, 1933, fig. 36). A similar principle may also hold good in eastern Viti Levu, since the distributional trend of the plutonic bodies becomes west-southwest to east-northeast between Singatoka and Wainivesi (Fig. 2). The proposition may evidently be put forward that in Viti Levu generally, vein-type (especially base-metal) mineralization took place along tensional fractures aligned transversely to the compressional belt along which the synorogenic Tholo Plutonic bodies (Rodda, Snelling, & Rex, 1967, p. 1253) were intruded during a Wainimala (or post-Wainimala) orogeny. Clearly, this is without prejudice to the additional hypothesis that formational strikes and other trends may have all been regionally affected by major rotational movements in the Fiji region (cf. Malahoff, in preparation).

The relatively young (post Mba) gold-telluride mineralization at Vatukoula in northern Viti Levu is to a considerable extent distributed along nearly-horizontal fractures or 'flatmakes' (cf. Cohen, 1962, fig. 4) and to this extent it is irrelevant to discuss strike directions. There are also, however, a number of important steeply dipping lodes trending northwest to southeast. Cohen (1962, abstract and p. 150) suggested that inasmuch as these lodes appeared to have been fed through flat-makes, they would themselves not usually be found to be mineralized very far below the lode-flatmake intersection. The apparent exception in the case of the Crown-Crescent lodes he explained (op. cit., p. 153) on the basis of the occurrence of an additional flatmake at depth. Denholm (1966, p. 7) however, attached the greatest importance to the development of a northwesterly shear system with trends of 110° and 150° and mineralized 'shatter blocks' developed at their intersections. Ibbotson (1967), who dealt mainly with petrology, did not discuss the possibility of regional shearing in his description of the structural geology of the Vatukoula area (op. cit., pp. 22-24), but quoted Denholm in this regard with reference to control of ore-deposition (op. cit., p. 55). He had earlier (1962, p. 9) envisaged fissure eruption at Vatukoula along northwest to southeast lines. Ibbotson (1960, p. 33) suggested that gold and base-metal mineralization at Tholo-i-Suva (near Suva itself) in southeastern Viti Levu may have been controlled by north-east to southwest faulting. This again is an example of relatively young mineralization (post-Mba group).

The Mount Kasi former gold mine in Vanua Levu constitutes a clear example of mineralization along a northwesterly fault, mined opencast in a long narrow 'cut'. The mine produced 63 770 oz of gold over 14 years, ore treated totalling 261 000 tons at an average grade of 5 dwt/ton (Bartholomew, 1959, p. 19). Johnstone (1945) envisaged that the evidently hydrothermal mineralization was connected with the intrusion of hornblende andesite which forms a number of plugs

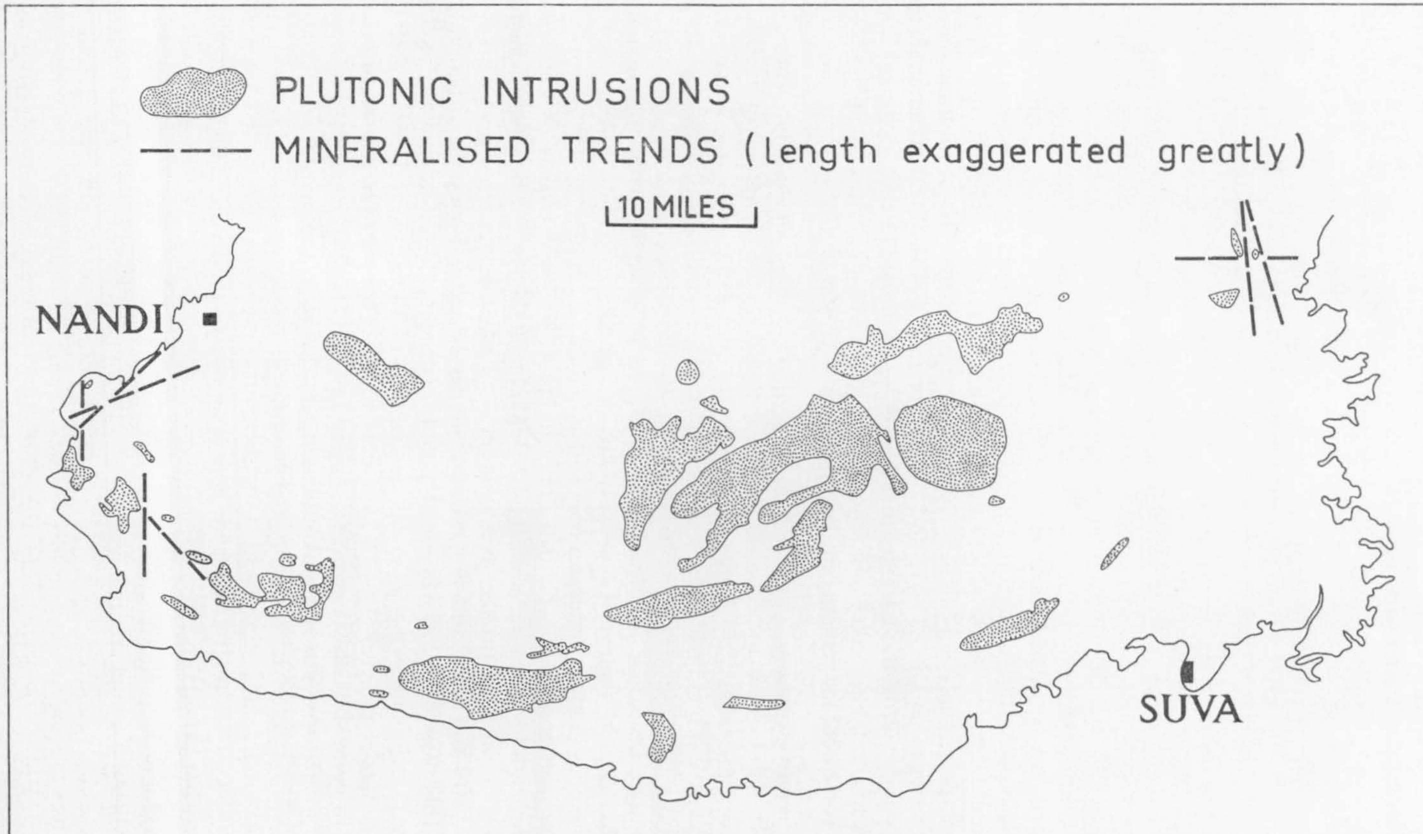

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Fig. 2. Plutonism and mineralization in east Viti Levu.

in the area. Away from the former mine itself, Bartholomew (op. cit.) noted several localities where silicification, pyritization, and propylitic alteration appear to be associated with northwest to southeast faulting. On the basis of the tentative assignment of foraminifera from a tuffaceous agglomerate to Tertiary g-stage (Crespin, 1959) and, by implication, accepting the andesite intrusions as the source of the mineralization, Bartholomew (op. cit., p. 16) suggested that the Mount Kasi mineralization may be younger than Upper Miocene. It could be comparable with, or perhaps rather older than, the Vatukoula mineralization in Viti Levu. The east-west faults of the Mount Kasi area (Bartholomew, op. cit., p. 17) appear to be still younger and to be not mineralized. The northwesterly 'Mount Kasi trend' is taken, farther east, by the more conspicuous of the two faults running through the Waimotu gold prospect (Rickard, 1966, p. 46 & map).

The northwesterly structural trend is very well developed in extreme western Vanua Levu (Coulson, in press) in both the Pliocene Mbua Volcanic Group rocks and the adjacent, underlying Mio-Pliocene Monkey Face Volcanic Group rocks. Associated with the latter, gold and base-metal mineralization in the Koroinasolo area appears to be connected with a diorite intrusion. This mineralization again would appear to be relatively very young. However, no mineralization has as yet been discovered connected with the Mbua caldera to the south, although it shows a profusion of dyke-complexes with northerly orientation.

Mineralization taking a north-northeasterly to northeasterly trend in Vanua Levu has been referred to by Rickard (1966, pp. 57-8), who notes a connexion between faulting and mineralization at Mouta, Nukundamu, and Ndakunimba. The first two localities lie within the belt of acid volcanic rocks of eastern Vanua Levu (Undu Group), which may be of upper Miocene and younger age (cf. Rickard, 1966, p. 35), while the Ndakunimba mineralization, if proximity is any criterion, is very young indeed, since the nearby Taveuni basalts, to which the Ndakunimba basalts appear to stand in close relation, are the products of volcanicity extending into historical time (P. J. Woodrow, pers. comm., 1969).

Rickard (1966, p. 58) emphasized the importance of a northeasterly lineament common to Viti Levu and Vanua Levu, following a line of major structural weakness. He pointed out areas of mineralization, tending to be regularly spaced at 40 km intervals, along this line (Mistry, Kingston, and Vatukoula areas in Viti Levu; Mount Kasi, Mouta, and Nukundamu in Vanua Levu). In northwestern Viti Levu, K. A. Phillips (pers. comm., 1967) has stressed the importance of the alignment of monzonite bodies along a northeast to southwest line between the Kingston (Sambeto) area and Vatukoula. Bartholomew (1960, p. 18), and Rickard (1963, p. 35) concurred in recommending further study of the Koroimavua Group rocks between Nandele and Mbalevuto, in view of the possibility of a northeasterly extension of the Sambeto area mineralization (Kingston mine). In southern Viti Levu, the Sovi fault (Houtz, 1960, p. 12) extends from Singatoka in a northeasterly direction for some 40 km; beyond this, across the Singatoka River in northeastern Sheet 10 (Houtz 1963), there is a very remarkable linear belt of limestone outcrops dipping northwest at 50° and striking parallel to the virtually straight southeastern margin of an area of undifferentiated Mba Group rocks. Airborne geophysical results (Barringer 'Radiophase') emphasize this trend. It may well be that the Sovi fault is in fact a post-Mba feature and that it, or at the least a belt of structural weakness marking its incipient development, extends north-eastwards parallel to the upper Singatoka River. However, no continuation of the trend has been mapped in Sheet 6 (Rodda, in prep.).

South-central Viti Levu in Sheet 18 (Band, 1968) provides a further example of a major northeasterly fault, the Wainikoroiluva fault, which can be traced for nearly 40 km northeast from a point near Vunaniu Bay, ending northeast of Namosi village in an area of moderately complex east-west faulting. This is an area of copper-zinc mineralization, currently receiving close attention from a prospecting company. If the mineralization in this area proves to be both structurally controlled and related to the intrusion of the Waimora stock (11 $\pm$ 2 m.y. according to Rodda, Snelling, & Rex, 1967, p. 1253) it would seem necessary to envisage that the northeast trend was already active in pre-Mba Group times. A number of dates from the Vatukoula complex cluster around 5 m.y., but one of 10 $\pm$ 0.5 m.y. was obtained (Rodda et al., op. cit., pp. 1254, 1255). Resurgent activity could possibly account for the alignment of approximately 5 m.y. old monzonite bodies along a northeasterly trend between Sambeto and Vatukoula.

Away from the two main islands northeast and northwest trends continue to be observable. In the extreme west, both trends intersect mineralization. The northeast to southwest chain of the Yasawas islands shows low-grade vein-type lead-zinc-copper mineralization in northeastern Waya island. Here the mineralization takes a northerly to northeasterly strike, following the trend of certain jointed and sheared andesite dykes (Williams, 1969, p. 2). Williams (1969, p. 3) emphasizes the importance of structural control of mineralization and suggests that there is a tendency for enrichment where east-west faults intersect the dykes. However, maps provided with the report bring out clearly that the east-west faults displace linear (soil-sample) geochemical anomalies trending north or northeast; hence the faults may be considered to affect belts of pre-faulting mineralization. Recent commercial investigations have suggested the incidence of mineralization, perhaps similar to that of Waya, on Malolo island in the Mamanuthas.

Southeast of Vanua Levu, Taveuni island provides a very striking example of the northeast trend, here ostensibly unmineralized. Taveuni is a very young basaltic island where volcanicity extended into historical times (P. J. Woodrow, pers. comm., 1969). It has a number of features, apart from orientation, in common with Lakigigar, Iceland, and some points of difference. Lakigigar (Thorarinsson, 1970, pp. 912, 917) is 25 km long, and 115 craters are visible in air-photographs. The northeasterly part of the 'crater row' has an azimuth 2° less than the southwesterly part. The eruptive product was tholeiitic basalt (Thorarinsson, op. cit., p. 916). Taveuni is about 40 km long; over 120 vents can be counted in air-photographs. The chain of craters has a slight curvature, convex to the northwest (Rickard, 1966, p. 20 and pl. 2). The eruptive product was augite-olivine basalt. Rickard avers without comment that the '. . . steep slopes of the island are the natural slopes of the volcanoes . . .', but Hindle (W. Hindle, pers. comm., 1971) has pointed out that one would expect very gentle slopes to prevail, in the normal manner of basaltic volcanoes. Indeed, a field of 'flood-basalt' might well be looked for. It appears to the writer that the structure of Taveuni may be compound, and that, owing to renewed fissure-eruption following uplift, the dipping flows seen at surface may mantle and conceal a pillow lava/pillow breccia ridge originally of submarine origin. Thorarinsson (op. cit., p. 924) suggested that had the Lakigigar eruption been submarine, a ridge 700 m high would have been built up. In comparison, the Taveuni chain averages just under 900 m in altitude, in a water depth of 100 fathoms (51 m).

In the Lomaiviti islands (of the Koro Sea), Makongai, Wakaya, Mbatiki, and Ngau are good examples of the alignment of young basaltic islands along the north-northwest trend, which indeed can readily be seen to continue southward through Moala and Totoya, west of southern Lau. Coulson (1969a & b) has reported alteration and pyritization of basalt flows on Ngau, with the development of calcite, chlorite, quartz, and epidote. Faulting along the north-northwest direction bisects two volcanic centres, one in the north and one in the south of the island. Coulson (1970) reports a gossan and the occurrence of silicification and pyritization on Matuku. The 'Lomaiviti trend', when extrapolated northward, possibly intersects the Mbua caldera in western Vanua Levu, or alternatively may skirt the western coast of Vanua Levu. A possible additional example of the trend is given by linking Koro Island (east of the main Lomaiviti chain) and Namena to the northwest. Koro itself shows alignment of cinder and spatter cones along northerly and northwesterly fractures and the presence of ultrabasic nodules in basalt flows (Coulson, 1968).

Intrusion and Mineralization

A truism which can bear repetition is that such general genetic connexion as there may be between plutonic ('granite') intrusion and hydrothermal mineralization is at best indirect. Thus, for example, it has long been known that in southwestern England the Cornish lead-zinc-copper-tin-tungsten mineralization principally occupies a 16-km-wide mineralized zone running between Penzance and Tavistock, a zone outside which the granites and country rock are virtually barren (Dewey, 1948, fig. 13), so that some other factor than direct genetic connexion seemingly is involved. Nonetheless, there are certainly to be distinguished mineralizing (or mineralized) granites and non-mineralizing (or non-mineralized) granites. Bradshaw (1967) has shown that in this respect there are recognizable chemical differences between the Cornish and the Scottish granites. Examples of mineralized and non-mineralized 'granites' can be cited from the American cordillera, e.g. at Bingham Canyon (James, Smith, & Bray, 1961, pp. 81-2). It seems important to have these considerations in mind, inasmuch as in Fiji attention has often been invited, to some extent uncritically, to an ostensible connexion between mineralization and the emplacement of intrusions belonging to the Tholo Plutonic Suite (Houtz, 1958, pp. 14-16; 1959, p. 9; Houtz & Phillips, 1963, p. 14; Hirst, 1965, p. 43; Phillips, 1967, p. 1178; Band, 1968, p. 41). Houtz's claim (Houtz, 1959, p. 9) that base-metal mineralization '. . . should be of equal density down the entire length of the island . . .' may prove to have been over-optimistic, although mineralization is of course well known from the extreme western and eastern ends of the belt of Tholo plutons, i.e. in Lomawai-Momi (Houtz, 1959, pp. 9-11), in Tailevu (Houtz, 1958, pp. 14-16; Hirst, 1965, pp. 43-6), and to a lesser extent at points in between, for example the Namosi area (Band, 1968, p. 41). Mineral zoning, or the apparent lack of it in Fiji, is another factor which requires to be taken into account. Although Band (1967, p. 1189) suggested that the occurrence of manganese, if manganese were in fact of hypogene origin, could define the outermost zones of zonally arranged mineral sequences, there seems little evidence to support this contention from the point of view of the distribution of other metals. In at least one area where a relationship between intrusion and mineralization appears clearly demonstrable, i.e. at Wainivesi, zinc mineralization preponderates, apparently even in proximity to the mineralizing bodies, copper mineralization being subordinate (Rodda, 1963, p. 4). The extent to which base-metal mineralization, more especially in Viti Levu, may consist of low-temperature lead-zinc mineralization without much accompanying development of copper or other higher temperature (tin-tungsten) mineralization, evidently needs careful study.

Conclusions

It is clear that insufficient work has been done as yet to allow other than a tentative picture to emerge of the nature, extent, and origin, or origins, of mineralization in Fiji. In particular, it needs to be ascertained whether or not base metals may occur otherwise than in relatively small-scale vein-type mineralization. Related questions concern the extent to which widespread copper mineralization may in fact not occur, unless perhaps at depth, in view of the ostensible prevalence of low-temperature lead-zinc mineralization and the apparent absence of mineral zoning around the Tholo Plutonic Suite intrusions. Tentative positive conclusions are that there does seem to have been a strong element of structural control of mineralization, and that such mineralization as is, apparently indirectly, associated with Tholo Plutonic Suite has been spatially oriented and distributed accordingly. There may have been two distinct periods of mineralization between Tholo and Mba, and after Mba, but there is tentative evidence, inasmuch as isotopic ages from Tholo rocks tend to overlap with ages from the Vatukoula caldera (post-Mba), that the mineralizing process may have been continuous in time and not necessarily divided into distinct phases. Perhaps distantly related to the proposition that the incidence of Tertiary rhyolite centres has influenced mineralization, is the observation that a phase of silicification preceded mineralization in the tentatively recognized earlier phase. Though the Tholo intrusives include gabbros, no ultrabasic rocks (apart from the nodules in the basalts of Koro island) have as yet been discovered in Fiji, but their occurrence and the possible incidence of associated nickel mineralization are not necessarily ruled out, nor is the possible association of nickel with basic intrusives. High nickel values shown by geochemical prospecting in eastern Vanua Levu has been explained in terms of the occurrence there of picritic basalts. Concealed ultrabasic bodies may possibly occur on the northeast trend in Taveuni and perhaps also in Lomaiviti on the complementary northwest trend. Again, such questions as, for instance, why the Vatukoula caldera, apparently associated with a northwesterly structural trend, should be mineralized whereas the Mbua caldera, with very marked north-northwesterly structural association, is ostensibly unmineralized, remain unanswered. A large field for continued investigation of possible mineralization in Fiji evidently remains. Meanwhile, it is satisfactory that recent airborne geophysical investigations have confirmed and extended the structural pattern known from geological mapping.

References

ALBERS, J. P., and KLEINHAMPL, F. J., 1970—Spatial relation of mineral deposits to Tertiary volcanic centres in Nevada. *U.S. geol. Surv. prof. Pap.* 700C, C1-C10.

BAND, R. B., 1967—Manganese in Fiji. *Proc. SW Pac. geol. Surv. Conf.* (1966), 1189.

BAND, R. B., 1968—The geology of Southern Viti Levu and Mbengga. *Geol. Surv. Fiji Bull.* 15.

BARTHOLOMEW, R. W., 1959—Geology of Savusavu Bay West—Vanua Levu. *Geol. Surv. Fiji Bull.* 5.

BARTHOLOMEW, R. W., 1960—Geology of the Nandi Area—Western Viti Levu. *Ibid.*, 7.

BRADSHAW, P. M. D., 1967—Distribution of selected elements in feldspar, biotite and muscovite from British granites in relation to mineralization. *Trans. Instn Min. Metall.*, 76, B137-B148.

CAREY, S. W., 1958—A tectonic approach to continental drift. *Continental Drift Symposium, Univ. Tasmania*, 177-355.

COHEN, E. M., 1962—Revised geology of the Tavua Goldfield, Fiji. *Proc. Aust. Inst. Min. Metall.*, 204, 135-60.

COULSON, F. I. E., 1968—Monthly report October 1968. *Rep. geol. Surv. Fiji* (unpubl.).

COULSON, F. I. E., 1969a—Monthly report July 1969. *Ibid.*

COULSON, F. I. E., 1969b—Monthly report December 1969. *Ibid.*

COULSON, F. I. E., 1970—Report for the month of September 1970. *Ibid.*

COULSON, F. I. E., in press—Geology of Western Vanua Levu. *Geol. Surv. Fiji Bull.* 17.

CRESPIN, I., 1959—Foraminiferal rocks from Fiji and the New Hebrides. *Bur. Miner. Resour. Aust. Rec.* 1959/25 (unpubl.).

CROCKETT, R. N., and MASON, R., 1968—Foci of mantle disturbances in Southern Africa and their economic significance. *Econ. Geol.*, 63, 532-40.

CULLEN, D. J., 1967a—Island arc development in the southwest Pacific. *Tectonophysics*, 4, 163-72.

CULLEN, D. J., 1967b—The antipodes fracture zone, a major structure of the south-west Pacific. *N.Z. J. mar. freshw. Rec.*, 1, 16-25.

CULLEN, D. J., 1967c—A note on the regional structure of the southwest Pacific. *N.Z. Sci.*, 10, 813-5.

CULLEN, D. J., 1967d—Mantle convection and sea-floor spreading in the southwest Pacific. *Nature*. 216, 356-7.

DALY, R. A., 1933—IGNEOUS ROCKS AND THE DEPTHS OF THE EARTH. *N.Y., McGraw-Hill.*

DENHOLM, L. S., 1966—Structural and economic aspect of the Vatukoula Caldera, Fiji. *Bull. volc.*, 29, 223-34.

DEWEY, H., 1948—British regional geology—south-west England. *London, HMSO.*

FAIRBRIDGE, R. W., 1961—Basis for submarine nomenclature in the south-west Pacific Ocean. *Dtsch. hydrogr. Z.*, 15, 1-15.

HESS, H. H., and MAXWELL, J. C., 1953—Major structural features of the south-west Pacific—a preliminary interpretation of HO 5484, bathymetric chart, New Guinea to New Zealand. *Proc. Pacif. Sci. Congr.*, 2, 14-17.

HILLS, E. S., 1943—OUTLINES OF STRUCTURAL GEOLOGY, 2nd Ed. *London, Methuen.*

HILLS, E. S., 1955—OUTLINES OF STRUCTURAL GEOLOGY, 3rd Ed. *London, Methuen.*

HIRST, J. A., 1965—Geology of east and north-east Viti Levu. *Geol. Surv. Fiji Bull.* 12.

HOUTZ, R. E., 1958—Geology of North Tailevu, Viti Levu. *Geol. Surv. Fiji Bull.* 1.

HOUTZ, R. E., 1959—Regional geology of Lomawai-Momi Nandroga, Viti Levu. *Ibid.*, 3.

HOUTZ, R. E., 1960—Geology of Singatoka Area—Viti Levu. *Ibid.*, 6.

HOUTZ, R. E., 1963—Regional geology—Keiyasi area. *Ibid.*, 10.

HOUTZ, R. E., and PHILLIPS, K. A., 1963—Interim report on the economic geology of Fiji. *Geol. Surv. Fiji econ. Rep.* 1.

IBBOTSON, P., 1960—Geology of the Suva Area—Viti Levu. *Geol. Surv. Fiji Bull.* 4.

IBBOTSON, P., 1962—The geology of the Tavua area, Viti Levu. *Geol. Surv. Fiji Bull.* 8.

IBBOTSON, P., 1967—Petrology of the Tertiary caldera Tavua Goldfield. *Geol. Surv. Fiji Mem.* 3.

JAMES, A., SMITH, W., and BRAY, E., 1961—Bingham district—a zoned porphyry ore deposit. *Guidebook Geol. Utah*, 16, 81-100.

JOHNSTONE, P. M., 1948—Notes on the Mount Kasi Mine, Fiji. *Trans. Instn Min. Metall.*, 57, 459-68.

KENNEDY, G. C., and NORDLIE, B. E., 1968—The genesis of diamond deposits. *Econ. Geol.*, 63, 495-503.

LANDWEHR, W. R., 1967—Belts of major mineralization in western United States. *Econ. Geol.,* 62, 494-501.
LANDWEHR, W. R., 1968—The genesis and distribution of major mineralization in western United States. *Econ. Geol.,* 63, 969-70.
MALAHOFF, A., in prep.—The Fiji plateau: an active spiralling tectonic system.
PHILLIPS, K. A., 1967—*Proc. & Abstr., Conf. SW Pacif. geol. Survs.,* 1966, 1177-8.
RICKARD, M. J., 1963—The geology of Mbalecuto area. *Geol. Surv. Fiji Bull.* 11.
RICKARD, M. J., 1966—Reconnaissance geology of Vanua Levu. *Geol. Surv. Fiji Mem.* 2.
RODDA, P., 1963—Wainivesi zinc property, Tailevu, diamond drilling, 1961-2. *Geol. Surv. Fiji econ. Inv.* 2.
RODDA, P., in prep.—Geology of north and central Viti Levu. *Geol. Surv. Fiji Bull.* 13.
RODDA, P., SNELLING, N. J., and REX, D. C., 1967—Radiometric age data on rocks from Viti Levu, Fiji. *N.Z. J. Geol. Geoph.,* 5, 1248-9.
SUMMERHAYES, C. P., 1967a—New Zealand region volcanism and structure. *Nature,* 215, 610-1.
SUMMERHAYES, C. P., 1967b—Note on the Macquarie ridge and the Tonga Kermadec complex —are they parts of the mid-ocean ridge system? *N.Z. J. Sci.,* 10, 808-12.
THORARINSSON, S., 1970—The Lakigigar eruption of 1783. *Bull. volc.,* 23, 910-29.
TWETO, O., and SIMS, P. K., 1963—Precambrian ancestry of the Colorado mineral belt. *Bull. geol. Soc. Amer.,* 74, 991-1014.
UDINTSEV, G. B. (ed.), 1964—Bathymetric chart of the Pacific Ocean. *Moscow, Inst. Oceanol.*
VAN DER LINDEN, W. J. M., 1967—Structural relationships in the Tasman Sea and south-west Pacific Ocean. *N.Z. J. Geol. Geoph.,* 10, 1280-301.
WALKER, W., 1968—Fiji: Copper—an assessment of the Fiji Islands as exploration targets for large tonnage, low-grade mineral deposits. *Rep. Barringer Research Limited* (unpubl.).
WILLIAMS, M., 1969—The Waya Island (Yasawas) copper prospect: an interim report on geochemical soil sampling and the extent of mineralization. *Geol. Surv. Fiji Rep.* (unpubl.).
WILSON, J. T., 1965—A new class of faults and their bearing on continental drift. *Nature,* 207, 343-7.

WEATHERING AND GEOCHEMICAL BEHAVIOUR OF THE ELEMENTS OF ULTRAMAFIC ROCKS IN NEW CALEDONIA

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SUMMARY

Since Miocene time the ultramafic rocks in New Caledonia have been subjected to an insular tropical to subtropical climate.

As a result of intense erosion with lateritic weathering during Mio-Pliocene time, the topography has been levelled off; small rocky ridges dominated the vast foothill areas and the more or less swampy lowlands. The low areas were thus 'iron-capped'. The Plio-Quaternary tectonic activities uplifted, unbalanced, and fractured this peneplain surface, causing once again erosion and morphology inversions, and the 'iron-capped' relics dominated mesas. New foothill surfaces appeared, as a result of destruction of the 'iron-capped' lateritic areas, and these were in turn 'iron-capped' also.

In well-drained areas (mesas and slopes), weathering appears as ferric gel and antigorite (especially in the dry season), mechanical fragmentation, and formation of laterites of the granulometric fraction under 50μ (especially in the wet season). If the slope is steep, weathering is obstructed by erosion. On the mesas, however, laterite continues to form with total leaching of magnesium and silica. Iron concentrates on the spot as goethite and hematite, in places forming concretions. Chrome and aluminium (chromites) are also residual. Part of the residual nickel, cobalt, and manganese precipitate together as oxidized concretions (lateritic nickel and cobalt ore). The greater part of the nickel is concentrated at the interface between the weathered zone and the fresh rock below, along with dissolved silica and magnesia, as antigorite, talc, chlorite, or mixed gels (garnieritic nickel ore).

In poorly drained areas (foothills), the silica migrating from high areas combines with lateritic materials resulting from the destruction of these surfaces, leading to the formation of nickeliferous nontronites. In these environments, the weathering of the fresh peridotites also results in nontronites. The magnesia migrates by underground and river waters and precipitates only near the seashore, as giobertite.

Thus lateritic weathering corresponds throughout the countryside to a true chromatography of the ions, concentrations (eventually economical) of the elements being distributed through the topographic profile according to their respective mobilities.

INTRODUCTION

The New Caledonian ultramafic rocks were emplaced in the Oligocene, or perhaps at the end of the Eocene (Routhier, 1953). Some peridotitic pebbles are interbedded in Miocene calcarenite beds (Routhier, 1953)—the earliest known evidence of their erosion—but the first signs of lateritic weathering (fragments from iron crusts) seem to be more recent, and are associated with the probably Pliocene clay deposits, of mangrove type (Gonord & Trescases, 1970). For several millions of years these bodies of rock have been subjected to an insular tropical to subtropical climate—the climate has changed several times, especially at the time of the Quaternary glaciations, with some dryer and hotter periods.

GEOMORPHOLOGY

The rocks are very susceptible to weathering, because silica and magnesia, their main components, are easily dissolved by meteoric waters. During the Mio-Pliocene period, weathering and erosion reduced the topography. This stage continued for a long time, and the result has been an extensive flattened surface: from north to south of New Caledonia, it is possible to find some remains of it on all the peridotitic terrain, and in places on other rocks (Dogny Plateau). The authors who have studied the geomorphological evolution of New Caledonia (Davis, 1925; Routhier, 1953; Avias, 1953; Wirthmann, 1965) called it the *Peneplain*.

The manner of formation of this peneplain has been most unusual, because the tropical climate is very aggressive and the peridotites are quickly weathered: the result of these two combined factors is that in New Caledonia, the ultramafic rocks tend to behave as soluble rocks. Moreover, these rocks are very easily faulted: the stressed serpentine promotes sliding of blocks against one another, and at every scale of observation the peridotitic bodies show a very dense network of joints and faults. The nature and structure of these rocks has given rise to a true karst terrain, with subterranean drainage, sinks, and depressions, aligned along the fracture system.

The lateritic weathering leaches silica and magnesia, and leaves a residue mainly of iron hydroxides (laterite). These residual materials are attacked by erosion, and removed from high to low ground. As the topography is flattened out, the small depressions (dolines) enlarge and join together (analogous to the 'poljes' in the calcareous karsts), until they are separated only by low residual ridges of outcropping rock. All these low areas, filled by detrital ferruginous material (transported only a short distance), can thus develop an iron capping: in fact the variations of groundwater level in these materials causes repeated solution and precipitation of the iron, which cements the detrital particles together. Such a terrain can be seen in the extreme south of New Caledonia, where a peridotitic karst is well developed and the peneplain topography is still preserved. The ironstone cap protects the underlying materials against erosion: when the weathering continues, the former ironcrusted depressions, by differential erosion, became the dominating features of the terrain, in the form of plateaux—a process of inversion of relief.

The Plio-Quaternary tectonic activity uplifted, tilted, and fragmented this peneplain surface: its relics, which are practically the only places where a solid ironstone cap can be seen intact, now constitute high points (except in the extreme south of the island). This uplift caused faulting of the underlying formations (or reactivation of a former network of fractures): the peneplain was carved into blocks, bounded by large faults. These faults are mainly transverse to the long axis of the island: most of them strike 170°E or 20°E, but some are aligned at 130°E, like New Caledonia.

The central part of the island is more uplifted than the ends; the elevation of remnants of the peneplain is more than 1000 m in the central part, and only 300 m at the extremities. Some parts are even downthrown, for example the channel between New Caledonia and the Isle of Pines. During this uplift, a new drainage system was established, the former closed sedimentary basins opened, and rivers formed to drain these filled depressions. Naturally, this river network was controlled by the alignment of the dolines or rocky ridges, which themselves were tectonically controlled. This river system is nearly the same as the present one.

A new surface was formed as a result of destruction of the peneplain, about 150 to 400 m below the peneplain level. This surface was certainly formed by a different process from the peneplain, because a well-marked river system was now established. The uplift ended the state of equilibrium of the peneplain, and strong erosion caused the accumulation on the foothills, by alluvial and colluvial processes, of a large mass of detrital ferruginous materials, derived from the weathering mantle of the peneplain. The conditions generally were not suitable for the formation of iron crust, either because the period of stability was not long enough, or because the morphological environment was not favourable (the sedimentary basins were no longer closed). The peneplain relics now constitute a narrow summit plateau, which forms a dividing ridge between the east and west coasts. The remains of the second surface (called Intermediate Level by Wirthmann, 1965), consist of flattish summits on the transverse secondary ridges which separate the river basins.

Tectonic uplift continued and even intensified; new piedmont surfaces appeared, about 500 to 600 m below the Intermediate Level (this third surface is called 'Old Piedmont'—Trescases, 1969). The third surface is always in piedmont position, but it is strongly notched by the present watercourses, because uplift is still going on (Launay & Recy, 1969; Baltzer, 1970). Some of the piedmont areas are encrusted with iron, but this phenomenon is very localized.

Weathering and Geochemistry

Chemical erosion continues under each surface after its formation. The oldest weathering layers are removed by erosion (with the exception of some very massive iron crusts) and, even on the oldest surfaces, the weathering profile is Quaternary, and its basal part is in equilibrium with the present climatic dynamics. Rock and climate being essentially homogeneous, in the New Caledonian ultramafics the fundamental factor in weathering is the morphological environment. This factor acts by the intermediary of the geochemical characteristics of the terrain upstream of the weathering profile studied, and by the drainage value at this point. These two elements combine: the well drained zones are mainly on high ground, that is, on the plateaux of the oldest surfaces, and on the steep slopes intersecting them; the poorly drained areas are on the surviving piedmonts and on the areas of sedimentation (depressions, lowlands, confined environments).

Well drained areas

Plateaux

A schematic cross-section of the plateaux is given in Figure 1. The plateau is an iron-capped relic from the peneplain (first surface). A typical weathering profile has been sampled throughout by boring, to the south of Kouaoua village

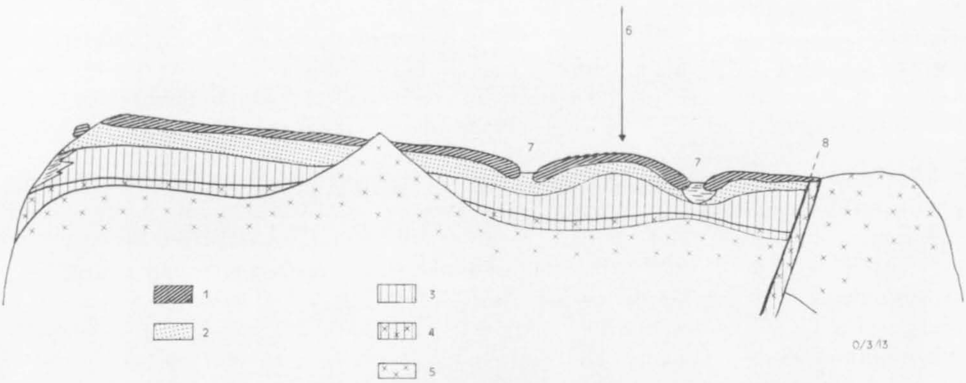

Fig. 1. Theoretical section of the well drained areas (ironstone capped plateau).

1 Iron crust
2 Granular laterite
3 Fine-grained saprolite
4 Coarse-grained saprolite
5 Fresh peridotite
6 Sampled bore
7 Doline
8 Recent fault with mineralized breccia

(East Coast), on the large ironcrusted plateau of Dahi-Me Aïu, about 500 m west of the top of Me Aïu. The profile shows the following weathering levels:

—Ironstone cap
—Granular red laterite (ironshot soil)
—Weathered rock, with recognizable structure, altered to iron hydroxides, fine-grained (fine-grained saprolite)
—Fresh peridotite.

Figures 2 and 3 illustrate the description of the profile, and the vertical evolution of grain-size distribution and bulk density. The chemical behaviour of the elements during weathering is shown on Figure 4, and the geochemical balance of the weathering is sketched on Figure 5, on the basis of isovolumetric calculation, applied to the layers where the rock structure is recognizable (saprolite levels).

From bottom to top the profile is as follows (see also Table 1):

Bedrock (Guillon, 1969, 1971). In this case bedrock is a dunite, with a small proportion of orthorhombic pyroxene (enstatite) and chromite; the magnesian olivine (about 90% forsterite) is very serpentinized. The nickel content is relatively high. The rock is much fractured, and its joints are filled by secondary quartz crystals, by garnierite, or by coarse-grained saprolite. The most common peridotite in New Caledonia is harzburgite, which has only a little more enstatite and a little less chromite than the dunite.

Coarse-grained saprolite. This is a heterogeneous layer, brownish-yellow to greenish-brown in colour, with many coherent fragments (pebble, granule, and sand size) of serpentinized rock. At the bottom of this layer the chemical and mineralogical composition is the same for every grainsize fraction: talc, chlorite, antigorite, mixed gels (ferric gel and silica gel). Weathering begins by mechanical fragmentation; expelled from the mineral network, the iron is oxidized and precipitated; secondary silicates are formed. Towards the top of this layer the coarsest grainsize fraction (above 2 mm) still resembles that of the bottom, but the finest fraction (under 50 μ) is greatly enriched in iron (goethite) because ferrallitic weathering has begun.

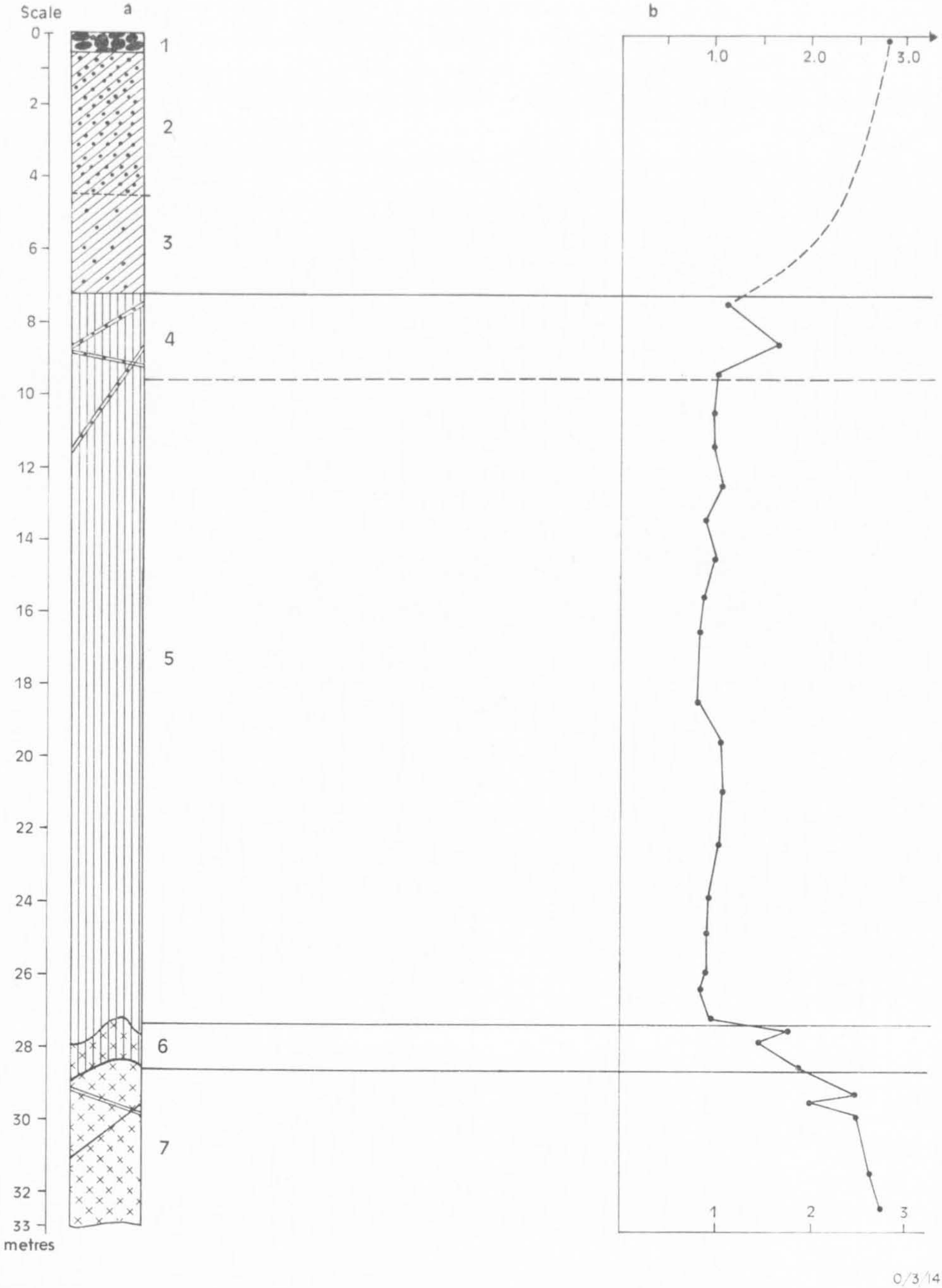

Fig. 2. a—Description of the profile (plateau). b—Bulk density.

1 Ironcrust
2 Granular laterite
3 Plastic laterite
4 Crushed saprolite
5 Fine-grained saprolite
6 Coarse-grained saprolite
7 Fresh peridotite

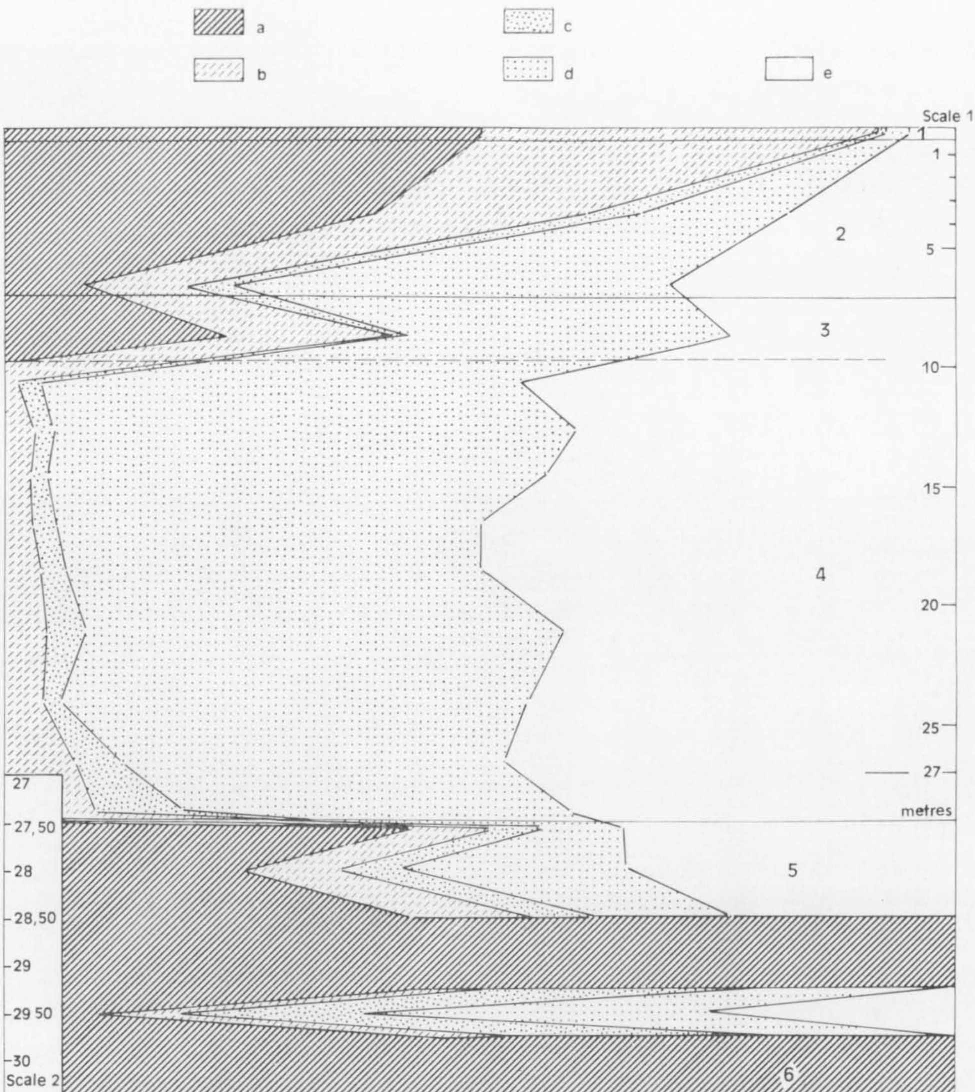

Fig. 3. Grain-size distribution through the profile (plateau).

a $\theta > 2$ mm
b 2 mm $> \theta > 0.2$ mm
c 200 $\mu > \theta > 50$ μ
d 50 $\mu > \theta$
e H_2O

1 Ironcrust
2 Granular laterite
3 Crushed saprolite
4 Fine-grained saprolite
5 Coarse-grained saprolite
8 Fresh peridotite

Fig. 4. Geochemical behaviour of the elements during weathering.

SiO_2	....	Fe_2O_3	++++
MgO	————	NiO	————
		Cr_2O_3	— — —

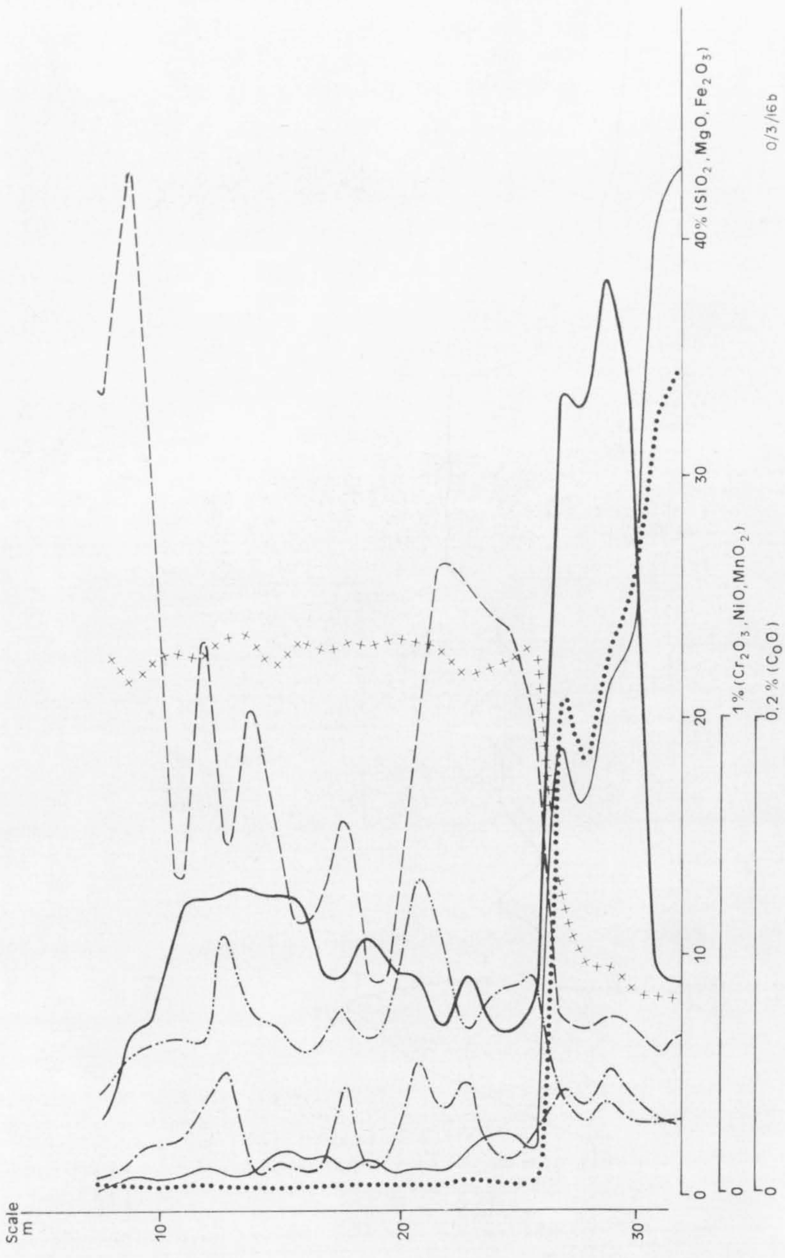

Fig. 5. Balance sheet of the weathering (isovolumetric computation).

SiO_2	········	NiO	——— (thick)
MgO	———	Cr_2O_3	— — —
Fe_2O_3	++++	MnO_2	··—··—
		CoO	—·—·—

TABLE 1. ANALYTICAL DATA COMPARING WEATHERING LAYERS, IN WELL-DRAINED AREAS (AVERAGE AMOUNTS, IN PERCENT)

No.	Thick-ness	Lost Ignition	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Cr_2O_3	MnO_2	NiO	CoO	TiO_2	S—
1	0.5 m	14.8	0.10	73.2	4.42	0	0	5.54	0.52	0.17	0.010	0.26	—
2	6.5 m	13.4	1.49	69.2	8.49	0	0.07	5.39	0.50	0.31	0.022	0.15	—
3	20 m	13.4	1.65	70.5	3.08	0.06	4.15	2.69	1.23	1.54	0.080	0.17	0.35
4	4 m	14.3	24.16	36.19	0.71	0.22	19.53	0.39	0.54	3.11	0.095	0.28	—
5	4 m	12.7	37.04	12.71	0.45	0.19	33.78	0.55	0.20	2.54	0.072	Tr.	—
6	0.5 m	14.5	36.47	11.08	0.23	0.08	31.92	0.21	0.21	2.41	0.067	0.08	—
7	0.5 m	13.7	35.53	12.48	0.64	0.11	33.68	0.55	0.23	2.36	0.084	Tr.	—
8	below 28.5 m	11.3	34.9	8.34	0.27	0.16	42.63	0.31	0.14	0.44	0.030	0.07	0.013

1. Iron crust; 2. gravelly laterite; 3. fine-grained saprolite; 4,5,6,7. coarse-grained saprolite (4. Top, fraction $<50\ \mu$; 5. Top, fraction >2 mm; 6. bottom, fraction $<50\ \mu$; 7. bottom, fraction >2 mm); 8. fresh peridotite.

Systematic chemical analysis of the spring waters shows (Trescases, 1969b) that this ferrallitic weathering occurs in the wet season, whereas the formation of talc and antigorite prevails during the dry season. These secondary silicates trap the nickel released by weathering and that leached from higher horizons. The chromite crystals, which contain aluminium and a small proportion of iron and magnesium, are the most resistant minerals.

Fine-grained saprolite. This is a homogeneous layer, brownish-red to brownish-yellow in colour; 80-90 percent is of grainsize less than 50 μ. The coarse fraction (100 to 500 μ) consists of:

—residual chromite crystals, partly weathered into gibbsite and hematite;

—some pyroxene crystals, little weathered;

—a little secondary quartz, inherited from the coarse-grained saprolite, in which silica has been precipitated;

—asbolane concretions (manganese and cobalt oxides, with some nickel).

The fine-grained fraction is chiefly ferruginous (goethite and hematite) and contains most of the nickel (hydroxide) of this layer.

Almost the whole of the silica and magnesia, which had remained in the coarse-grained saprolite level, has been removed; only the residual elements (iron, chromium, aluminium, manganese, titanium, cobalt, nickel) remain. These elements are relatively concentrated (lateritic nickel and cobalt ores) by the removal of the soluble elements. However, some nickel is rendered unstable and is leached towards the lower part of the profile, and concentrated at the interface between the weathered zone and the fresh rock below. This nickel is combined with silica and magnesia, as antigorite, talc, chlorite, or mixed gels (garnieritic nickel ore).

Laterite and ironcrust. The downward movement in situ of the fine-grained saprolite, and the formation of iron hydroxide concretions, results in the formation of an uppermost soil layer (ironshot soil or laterite). This red, granular, lateritic horizon is duricrusted by ironcrust-forming processes, when the morphological environment is favourable.

Slopes

Most slopes are very steep, as a consequence of the recent tectonic rejuvenation of the topography. Degradation of the plateau gives way to a colluvial process which provides the slopes with ferruginous material similar to the upper levels of the plateau weathering profiles. The type of weathering on slopes looks very much like that of the bottom of the plateau profiles (antigorite, talc, chlorite), but erosion does not allow weathering to proceed sufficiently far to form ferruginous layers or economic concentrations of nickel.

Poorly drained areas

Piedmont

The material removed from the well drained areas, transported by suspension in the rivers or by colluvial processes on the slopes, accumulates at the base of the hills, as gently sloping piedmont deposits.

Beneath a ferruginous colluvial layer, a zone of in-situ weathering is usually observed (fine and coarse-grained saprolite), but the profile rarely exceeds 15 m in depth.

Table 2 shows the chemical variation in a typical profile. The sampling was done in a bore hole, in the Yate River basin (southern part of New Caledonia), near the 'Rivière Blanche' swamps.

TABLE 2. ANALYTICAL DATA COMPARING WEATHERING LAYERS IN POORLY DRAINED AREAS (FOOTHILLS) (AVERAGE AMOUNTS IN PERCENT)

No.	Thickness	Bulk density	Lost ignition	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Cr_2O_3	MnO_2	NiO	CoO	TiO_2
1	2.5 m	—	12.6	1.87	68.69	9.44	0	0.94	3.64	0.91	0.41	0.08	0.30
2	7.5 m	0.75	11.4	5.34	67.14	6.92	0	1.22	5.18	1.29	1.31	0.16	0.23
3	1 m below	0.82	10.2	31.48	28.01	1.21	0	25.59	1.04	0.34	1.71	0.06	0.08
4	11 m	2.71	12.4	37.30	7.86	0.35	0.06	40.79	0.09	0.15	0.24	Tr.	0.04

1. gravelly laterite (colluvium); 2. fine-grained saprolite; 3. coarse-grained saprolite; 4. fresh peridotite.

The comparison of this profile with the Kouaoua profile (well drained ironstone-capped plateau) suggests that in a piedmont area:

—no ironcrusting process took place;

—the upper colluvial level is a little richer in silica than the upper level of the high areas (because antigorite and talc, not present in this layer on the plateaux, are contained in piedmont areas, as inherited minerals from the slope weathering profiles);

—the amount of silica in the fine-grained saprolite layer is clearly higher than in its homologue on the plateaux, but the increase in magnesia content is less: this material consists largely of nontronite resulting from the combination of the dissolved silica migrating from high areas with iron hydroxides from the laterites;

—the coarse-grained nickeliferous saprolite horizon resembles the corresponding layer on the plateaux, but contains also a little nickeliferous nontronite.

Confined environments

These environments are an extension of the piedmont deposits described above, and constitute a local base level. Such environments occur in the swampy lowlands of the peneplain—closed basins filled by ferruginous detrital materials (dolines and poljes)—and on the coastal alluvial plain which separates, on the west coast, the peridotites from the seashore. It is therefore a sedimentary (alluvial) environment, rather than a weathering one, but the coarsest fragments (cobbles, pebbles, gravels) are weathered according to the peculiar geochemical characteristics of this environment. The thickness of sediment can be as much as 70 m.

TABLE 3. ANALYTICAL DATA COMPARING SEDIMENTARY LAYERS IN POORLY DRAINED AREAS (SWAMPY LOWLANDS) (AVERAGE AMOUNTS IN PERCENT)

No.	Thickness	Lost Ignition	SiO_2	Fe_2O_3	Al_2O_3	MgO	MnO_2	Cr_2O_3	NiO	CoO	TiO_2	Organic C
1	6.5 m	13.15	2.34	64.72	11.69	0.69	0.59	3.40	0.73	0.04	0.33	0.12
2	1.5 m	12.25	13.40	50.04	13.66	1.46	0.36	5.87	0.65	0.41	0.30	0.21
3	5 m	10.01	16.91	43.18	14.90	3.10	0.25	6.18	0.94	0.07	0.31	0.28
4	1 m	13.59	13.38	55.85	8.11	2.08	0.33	2.44	0.98	0.04	0.23	1.47
5	3 m	11.02	15.35	50.03	10.48	3.24	0.25	3.39	0.85	0.04	0.26	1.17
6	1.5 m	10.73	16.82	49.14	13.72	2.64	0.38	3.36	0.66	0.04	0.27	0.80
7	1 m	11.15	23.89	34.08	17.11	5.83	0.21	4.30	0.55	0.02	0.33	0.64
8	0.5 m	49.47	13.61	10.49	9.47	10.25	0.16	0.88	2.60	0.13	0.15	11.80
9	5 m	10.38	25.35	32.64	19.22	4.24	0.30	2.62	0.55	0.02	0.40	—
10	1 m	6.50	19.59	36.31	15.39	5.32	0.32	9.67	0.70	0.03	0.48	0.25
11	1 m	8.25	27.80	35.76	12.10	7.84	0.30	4.09	0.70	0.01	0.30	0.10
12	1 m	6.49	28.20	29.05	15.42	9.12	0.35	9.69	1.46	0.03	0.48	0.15
13	2 m	8.83	35.38	22.35	7.96	20.66	0.42	1.94	0.55	—	0.11	—

1. Gravelly laterite (colluvium)
2. Fine-grained red deposit
3. Fine-grained grey deposit
4. Iron-crust
5. Fine-grained grey deposit
6. Iron-crust
7. Fine-grained grey deposit
8. Peat
9. Iron-crust
10. Fine-grained grey deposit
11. Iron-crust
12. Fine-grained grey deposit
13. Weathered peridotite pebbles (fine-grained saprolite)

A typical profile was sampled in a bore hole, very near the piedmont profile previously described, in the 'Rivière Blanche' swamps. Table 3 shows the chemical characteristics of this unit:

—from 0 to 6 m, a ferruginous granular layer, with a little antigorite of grainsize lower than 50 μ, like the colluvial uppermost layer in piedmont areas.

—from 6 to 8 m, a red, ferruginous, fine-grained deposit, with antigorite and nontronite.

—below 8 m, the environment is reducing; the general colour is blue to green. The medium-grained layers (antigorite and iron hydroxide concretions) alternate with fine-grained layers (talc, antigorite, slightly nickeliferous nontronite). In places very coarse-grained layers are observed, consisting of cobbles and pebbles completely altered to nontronite and antigorite (Gonard & Trescases, 1970); also peat deposits (50% loss on ignition) with nickeliferous nontronite (5 to 6% NiO) interbedded with the clastic sediments; and several duricrusted layers resulting from the oxidation of iron during fluctuations of groundwater level in the course of sedimentation, with the detrital fragments cemented together by precipitated ferric iron (Fe^{+++}).

With the exception of the peat layers, unfortunately thin (less than 1m) and discontinuous, the amount of nickel in these deposits is almost the same as the amount in the weathering layers of the fine-grained saprolite type. But this amount increases with the nontronite content and, in some cases, these deposits can become nickel ores.

Conclusions

In New Caledonia the effects of laterite weathering are distributed throughout the terrain, affecting, according to the laws of surface geochemistry, the constituent elements of the ultramafic rocks.

Each element is concentrated in the theoretical topographic sequence, from the top of the ridges to the seashore (and eventually in the ocean), according to the scale of the relative mobility of these elements (Tardy, 1969; Trescases, 1969b).

Iron, chromium, titanium, and aluminium are the least mobile elements, and are found in the upper part of the weathering profiles, on the highest and oldest surfaces, particularly in the ironstone capping, as hydroxide concentrations (goethite, a little gibbsite) or as residual mineral (chromite, magnetite). When these residual layers are destroyed by erosion, these elements migrate nevertheless toward lower surfaces, but by mechanical processes: by colluvial process on the slopes, or by suspension in the river waters.

Cobalt and manganese are concentrated, as hydroxide concretions, in the middle part of the weathering profiles of these highest surfaces, which are poorly protected against erosion and mechanical transportation. The behaviour of nickel is similar to that of cobalt and manganese, but its relative mobility is a little higher in the weathering zone. It is partly leached out of the hydroxide concretions, where it is first concentrated with Co and Mn, and largely migrates to the bottom part of the profiles: it is a guest element of the newly formed magnesian silicates (talc, antigorite, swelling chlorites) of the high surfaces, and of the newly formed ferruginous silicates (nontronites) of the low surfaces, where it is associated with concentrations of organic material (peat).

Silica is slightly less susceptible to leaching than magnesia. Most of the silica released by weathering is transported by underground and river waters (dissolved silica), but it is combined, mostly with detrital iron, as nontronite, in poorly drained areas, that is to say in the low areas underlain by peridotite, and chiefly near the seashore, in the flood plain and mangroves. A part of the silica remains in the weathering zone, by precipitation in the joints and fractures of the rocks, as silica gel, chalcedony, quartz, or, in combination with magnesia, as talc, chlorite, or antigorite. Nickel is a guest element in all these minerals.

With the exception of the amount taken up by the secondary silicates, the main part of the magnesium migrates by underground and river waters. Under certain conditions, a part can precipitate near the seashore, as giobertite.

This new distribution through the terrain of the elements of ultramafic rocks, which can result in economic concentrations, particularly of nickel, corresponds to an ion chromatography through the topographic sequence of soils and sediments.

References

AVIAS, J., 1953—Contribution à l'étude stratigraphique et paléontologique des formations antécrétacées en Nouvelle Calédonie (thèse). *Fac. Sci. Nancy, Sciences de la Terre,* 1-2, 1-276.

BALTZER, F., 1970—Datation absolue de la transgression holocène sur la côte ouest de la Nouvelle Calédonie sur des échantillons de tourbes à palétuviers. Interprétation néotectonique. *C.R. Acad. Sci. Paris,* 271, D, 2251-4.

DAVIS, W. M., 1925—Les côtes et les récifs coralliens de la Nouvelle Calédonie. *Ann. Géogr.,* 34 (191), 244-69, 332-59, 423-41, 521-56.

GONORD, H., and TRESCASES, J. J., 1970—Observations nouvelles sur la formation post-miocène de MUEO (Côte Ouest de la Nouvelle Calédonie). Conséquences paléogéographiques et structurales. *C.R. Acad. Sci. Paris,* 270, D, 584-7.

GUILLON, J. H., 1969—Données nouvelles sur la composition et la structure du grand massif péridotitique du sud de la Nouvelle Calédonie. *Cah. ORSTOM Ser. geol.,* 1(1), 7-25.

GUILLON, J. H., and ROUTHIER, P., 1971—Les stades d'évolution et de mise en place des massifs ultramafiques de Nouvelle Calédonie. *Bull. BRGM Sect IV* (in prep.).

LAUNAY, J., and RECY, J., 1970—Nouvelles données sur une variation relative récente du niveau de la mer dans toute la région Nouvelle Calédonie—Îles Loyauté. *C.R. Acad. Sci. Paris,* 270, D, 2159-61.

ROUTHIER, P., 1953—Etude géologique du versant occidental de la Nouvelle Calédonie entre le col de Boghen et la pointe d'Arama. *Mém. Soc. géol. Fr.,* 32 (67), 1-271.

TARDY, Y., 1969—Géochimie des altérations. Etude des arènes et des eaux de quelques massifs cristallins d'Europe et d'Afrique. *Fac. Sci. Strasbourg;* also *Mém. Serv. Carte géol. Als. Lorr.,* 31.

TRESCASES, J. J., 1969a—Premières observations sur l'altération des péridotites de Nouvelle Calédonie—Pédologie—Géochimie—Géomorphologie. *Cah. ORSTOM Ser. géol.,* 1(1), 27-57.

TRESCASES, J. J., 1969b—Géochimie des altérations et des eaux de surface dans le massif ultrabasique du sud de la Nouvelle Calédonie. *Bull. serv. Carte géol. Als. Lorr.,* 22(4), 329-54.

WIRTHMANN, A., 1965—Die Reliefentwicklung von Neukaledonien. *In* TAGUNGSBERICHT UND WISSENSCHAFTLICHE ABHANDLUNGEN. *Dtsch. Geogr. Bochum,* 323-35.

SOME REMARKS ON THE ENVIRONMENTAL INFLUENCE ON SECONDARY TIN DEPOSITS

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Summary

Five genetically different types of tin placer deposits, as they occur in the Southeast Asian tin belt, are summarily described. They have three genetically essential factors in common: deep chemical weathering, selective removal of lightweight material (elutriation), and adequate catchment areas or traps. In the different deposits discussed these three governing factors are realized in various forms, while the importance of the separate factors varies also.

Introduction

The Southeast Asian tin belt, stretching from western Thailand through Malaysia into Indonesia, is the world's main producer of cassiterite. Most of the cassiterite is mined not from its original place of formation, but from placer deposits of various origins.

The placer deposits have in common that cassiterite is concentrated by selective chemical weathering of, mainly, feldspar, and the erosion and removal downslope of the weathering products and, to a lesser extent, of the quartz. The intense tropical weathering in this tin belt facilitates the formation of economically interesting deposits from primary, generally extremely low-grade deposits. A large bucket dredge can operate economically in ground with 0.2 kg tin metal per m^3, which corresponds to about 100 ppm. It is no exaggeration to state that primary mineralization with a cassiterite content of as little as 1 to 10 ppm may lead, if the concentrating circumstances were favourable, to tin deposits of economical value. In the following paragraphs we will look into these circumstances of formation.

The term peneplain will be used to describe a low-relief landscape, independent of its origin. It is becoming more and more clear that the low-relief landscapes of the humid tropics, with their gradual decrease in relief and gradually gentler slopes, have an origin completely different from the peneplains suggested by, for instance, Davis. The tropical peneplain will probably always show a broad and flat valley with, in the divide areas, steepsided hills with a distinct knick point near the toe of the hill slope.

THE RESIDUAL-ELUTRIATIONAL DEPOSITS OF BANGKA-BILLITON

The origin of the cassiterite placer deposits on the two main tin islands of Indonesia has been discussed since before the beginning of this century. Gradually, the 'kaksa' hypothesis was developed, which was formally presented for the first time by Adam (1932, 1933; see also Krol, 1960). This hypothesis proposes that the cassiterite placer deposit is not only the result of chemical weathering, erosion, and transport, but, in fact, is the normal weathering residue to be found in all more or less peneplaned areas within the belt of the humid tropics. It is mainly composed of coarse grains and angular pieces of vein quartz from the original bedrock, and all insoluble heavy minerals contained in that bedrock. Occasional finds include rounded pebbles of bauxite derived from former soil and laterite covers, well-rounded quartz pebbles, evidently remnants from an older erosion stage, and billitonites (tectites) of cosmic origin (age 500 000 years). See also Figure 1.

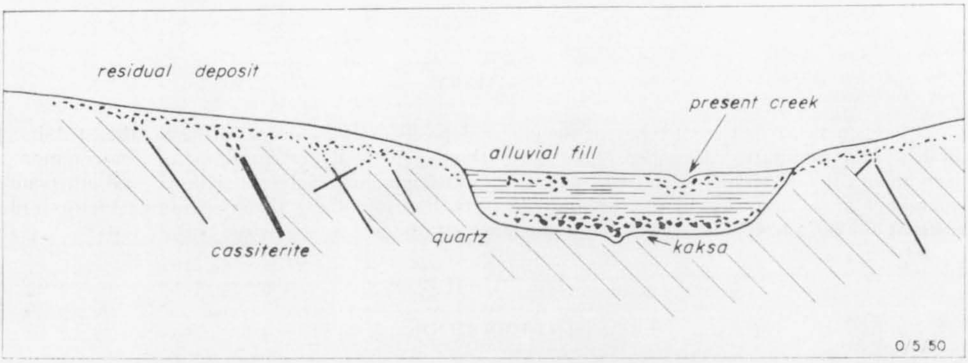

Figure 1. Cross-section of typical valley in Billiton Island, Indonesia.

Rich tin deposits are formed wherever swarms of thin cassiterite-quartz veins occur in the bedrock, granitic or sedimentary. Spectacular deposits have been found in places where 10-100 cm thick cassiterite veins occurred in the bedrock.

In several places it was observed that weathering, 'collapse'*, and creep result in the movement of the insoluble residue from the divides along the feeble slopes towards the valley centre, where a little water suffices to wash away most of the clay and the fine sand. In one place on the island of Billiton the present layer (3-4 m thick) of weathered material lying on the flat valley slopes has been shown to represent an original 30 m of bedrock. The weathering residue found as 'kaksa' on the valley floor represents an unknown thickness of bedrock; there are indications that several hundred metres of bedrock have been destroyed in forming the present deposits.

The present-day cassiterite deposits occur in clearly defined shallow valleys, incised in the flat peneplain landscape. At least two periods of intensified mechanical erosion can be distinguished, which are tentatively related to the sea-level changes during the upper Pleistocene. The cover of unconsolidated sand and clay layers in these young valleys is of subRecent age (Teeth of *Elephas sumatrensis*).

* 'Collapse' is the vertical displacement of minerals resistant to weathering caused by the elutriation of kaolin (and other weathering products) from the top layers.

Cassiterite deposits occur, therefore, when

(a) some cassiterite is present in the bedrock, on an average probably between 1-10 ppm;
(b) chemical weathering has freed the cassiterite grains from the surrounding minerals;
(c) collapse, creep, and solifluxion in a humid tropical climate have transported the weathering residue towards the centre of the shallow valley with gently sloping sides;
(d) fluvial action has removed the weathering clays and the fine-grained light particles, mainly quartz, and so concentrated the heavy minerals, including cassiterite, on the valley floor;
(e) fluvial transport of cassiterite is restricted to finer grainsizes and has the effect of decreasing the cassiterite content of the deposit.

Hence, these deposits are of a residual-elutriational origin and not alluvial in the sense of 'laid down by rivers'. They are left behind by rivers.

Type localities for these deposits are Bangka and Billiton, which are peneplaned to a large extent; some harder rock formations form monadnocks. The exploration geologist would like to know how much relief is compatible with this genetic hypothesis. In other words, how far may the landscape deviate from a peneplain, how much mechanical erosion may occur, how much active transport capability may the river have, before the principle of concentration by elutriation is upset and the cassiterite is largely moved down the river.

The Alluvial Residual Deposits of Ranong Province, West Thailand

The landscape comprises a rugged area of granite hills to the east, presumably separated by a fault from the broad valleys and pyramidal hills to the west, composed of shale and sandstone of the Phuket Series*. See also Figure 2.

The granite is coarse to medium-grained, with biotite as the dark mineral. In several places the granite is mineralized, with accompanying albitization of the whole rock. Cassiterite and tourmaline have been introduced in addition to albite. The *in situ* weathered and crumbly crust (called Krah in Thai) is being worked for cassiterite. Another type of cassiterite mineralization is the 'Pak Lin' or weathered cassiterite pegmatites, which occur for example to the southeast of the Ranong granite body.

The Phuket Series is composed of shale and sandstone with a strike about parallel to the presumed fault to the east and the coast to the west. In the Ranon/Ratcha Krut area the Phuket Series is almost devoid of any post-diagenetic features; only near the granite contact have some crosscutting quartz veins been observed in places.

All the major mines in Ranong Province, worked by bucket dredges and hydraulic operations, are in the area of the Phuket Series, although no cassiterite veins have ever been observed in the bedrock.

In the exposures provided by the mining activity from east to west, the most obvious difference is the size of the gravel. In the east, the gravel 'pebbles' attain

* Old name; now replaced by Kaeng Krachan Formation.

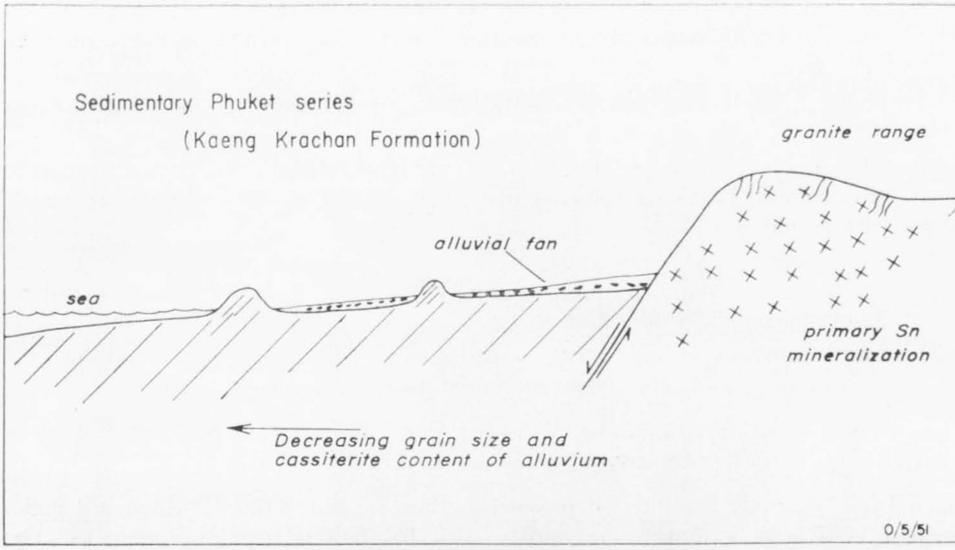

Figure 2. Schematic cross-section through the Ranong Area, West Thailand.

boulder-like dimensions, with sizes up to several metres, and are composed of subangular granite, Phuket Series quartzite, and vein quartz. Towards the west, the size of the gravel gradually diminishes, until near the coast a well-rounded pebble of about 5 cm in diameter is the maximum. Furthermore, the composition changes owing to the gradual disappearance of granite pebbles.

Parallel to these changes in the gravel the grainsize of the cassiterite changes from several millimetres in a rich deposit to less than 1 mm in a poor deposit.

The gravel layers are covered with sand layers and clay banks, locally with peat layers, and in the eastern and central area the top layers are orange-coloured soils not distinguishable at first sight from the normal residual soils of the region.

The broad valleys underlain by the Phuket Series, several of which are well over 1000 m wide, have a relatively flat valley floor, although there are some shallow depressions (not more than 1 or 2 m difference) which seem to contain the richer deposits.

The granite, which is intruded more or less parallel to the strike of the Phuket Series host rock, must have been uplifted in fairly recent times, as is indicated by the hanging valleys that can be seen along the scarp-like western slope of the granite area. As a result of this uplift, the weathered crust of the granite, containing the weathered residue of the roof contact zone, has been transported by river action to the lower Phuket Series area. Helped by the steep slope of the fault contact, this must have occurred in torrential creeks, sheet floods, and tropical mud flows, as witnessed by the size of the granite blocks displaced.

In the flat Phuket Series area the granite talus has been washed out, forming the now gradual transition from extremely coarse and ungraded deposits in the east to the fine-grained well graded deposits in the west. It appears that at a distance of about 10 km from the granite-fault contact the last traces of this alluvial fan can be found as very fine cassiterite and a gravel composed of angular vein quartz and more or less rounded pebbles of quartzite up to 3 cm in size.

These deposits then were laid down by rivers, and the cassiterite was moved downstream over a distance of more than 10 km; they are truly alluvial deposits. However, the flat landscape of the Phuket Series, in the longitudinal direction of the rivers, has been essential in preventing the cassiterite from spreading all over the country and sea floor. Hence, in a certain sense, these deposits also were left behind by the rivers, although on a secondary site.

Off-shore, Indonesia (Tudjuh Archipelago)

The tin belt in Indonesia includes, from west to east, the islands of Karimun, Singkep, Bangka, Billiton, and Karimata. Between Singkep and Bangka, with their partly very rich deposits, there is a gap of about 150 km. About 50 km northwest from Bangka the Tudjuh islands represent almost the only available outcrops; both granitic and sedimentary country rocks crop out.

This area is being explored under a contract of work concluded with the Indonesian Government. Several thousands of line kilometres of sonic surveys have been run by the survey vessel *Bison* and about 150 drillholes have been placed, mostly in less than 15 m of water.

The sonic surveys give a picture completely different from what can be observed on the islands of Bangka and Singkep, and also quite different from what could have been expected on the basis of Admiralty charts or publications relating to the morphology of the Sunda Shelf.

Some characteristic sonic profiles are presented here (Fig. 3), with their interpretation, which in more than a hundred cases has been corroborated by the drilling results. The great depth of the valley floors, the repeated incisions, and the thick sedimentary fill are new features. In addition there is a lower sheet-like deposit of presumably Tertiary age, which over large areas screens the bedrock from sonic observation.

Cassiterite is present in the beach sands of some of the Tudjuh islands and also in the sediments of near-shore submarine valleys. As shown above, the chances of finding cassiterite deposits of economic grade in the deeper valleys will depend in the first place on the occurrence of primary cassiterite, even if in rather low concentrations, secondly on prolonged periods of humid tropical weathering, and thirdly on the transportation characteristics of the rivers and streams. In any case, the deposits will have to contain rich gravels; otherwise the thick overlying layers of sand and clay reduce them to uneconomic grades.

Deposits on Marine Abrasion Platforms

In various places along the shore of the island of Billiton and in the Thai Muang area of West Thailand, cassiterite deposits of economic grade have been found that seem to belong to an abrasion platform.

The cassiterite is probably always rather local in origin, freed from its original host rock by tropical weathering and marine surf action.

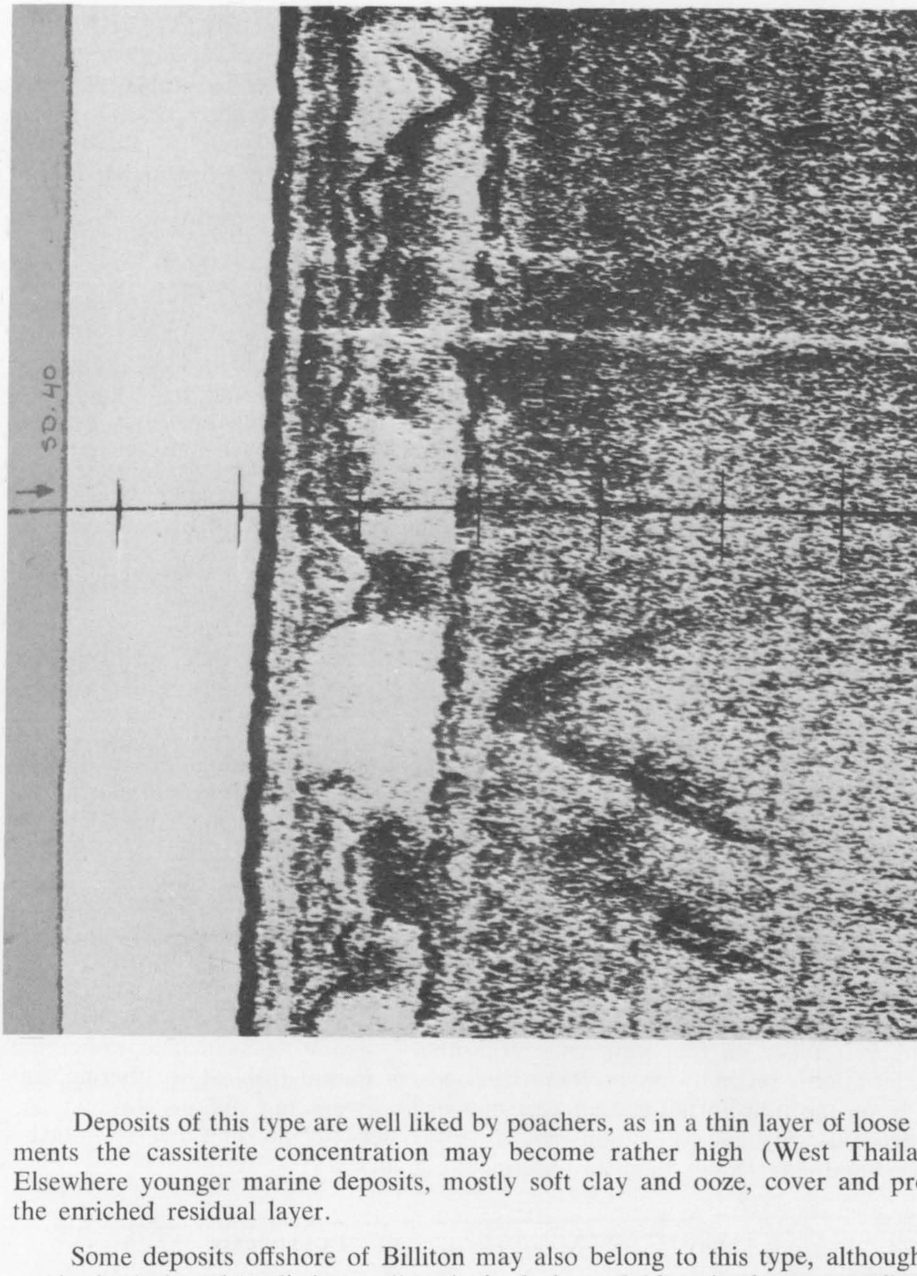

Fig. 3. Sonogram as obtained from Cesco's survey vessel *Bison*, See Fig. 3a for explanation.

Deposits of this type are well liked by poachers, as in a thin layer of loose sediments the cassiterite concentration may become rather high (West Thailand). Elsewhere younger marine deposits, mostly soft clay and ooze, cover and protect the enriched residual layer.

Some deposits offshore of Billiton may also belong to this type, although the cassiterite is found in distinct valleys incised about 5-10 m in the surrounding flat area (see Fig. 4). The observation that almost no cassiterite is found on the flat areas on both sides of the rich parts of the valleys, and that partly weathered bedrock is almost directly covered by younger marine clays, could indicate that the original residual layers were washed into the valleys by marine action during the last major transgression.

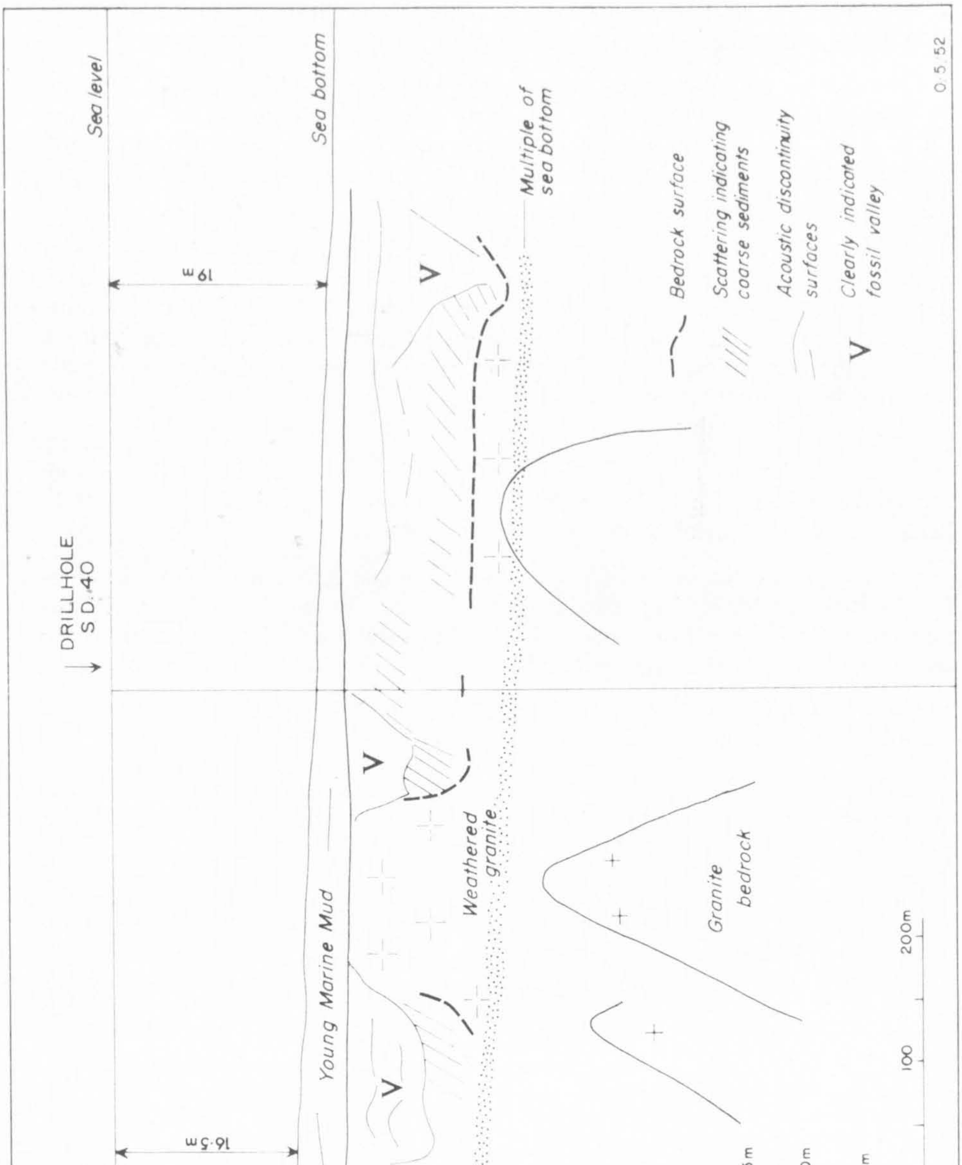

Fig. 3a. Sonic profiles Tudjuh area.

The Malaysian Deposits Associated with Limestones

Apart from Scrivenor's excellent work and a short geological treatise on Kinta Valley by Ingham & Bradford no comprehensive modern study on the secondary ore deposits of the Malaysian tin district has been published.

The following discussions are based on the above literature and not on our own fieldwork, other than short visits.

There are striking differences between the Malaysian and Indonesian deposits. Morphologically, Malaysia must for the greater part be considered as the mountainous hinterland of the Sunda peneplain to the south. Block movements along fault planes must have played an important role in the youngest geological history.

Lithologically, much of the bedrock of tin-bearing valleys consists of limestone, a feature practically unknown in Indonesia. The pinnacled limestone surfaces in the opencast mines are typical for Malaysia. Kinta Valley is a large valley with a flat valley bottom composed of limestone bedrock and valley sides of granite hills (see idealized section Fig. 5). The alluvial fill covering the limestone bedrock consists of quartz pebbles, sands, and clays; and the normal cassiterite paragenetic sequence of heavy minerals such as ilmenite, monazite, etc, and occasionally feldspar, all weathering products from the nearby granite hills, occurs.

There is a distinct and important concentration of cassiterite at the bottom of the alluvial fill on the bedrock; but concentrations of cassiterite also exist in higher levels of the alluvial cover.

In many places, the valley sides are on the contact between granite and limestone. At these contacts deep sinkholes are formed in the limestone, acting as concentration basins for heavy minerals. In these sinkholes slump structures are common, often indicated by lignite bands, cassiterite-rich layers, and granite wash.

Also in the 'Karren' between the pinnacles of the flat valley bottom, the layers rich in cassiterite are commonly slumped and folded.

These observations indicate that the pinnacles and the sinkholes along the contact were formed comparatively recently, and are younger than the cassiterite concentration in the lowest part of the alluvial fill.

The primary tin mineralization is known to exist along the limestone/granite contact as quartz-cassiterite veins, as cassiterite disseminations in the granite along the contact, and in cassiterite-pyrite veinlets and lenses at the contact. Locally pyrite-arsenopyrite-cassiterite mineralization occurs on shear planes in the limestone.

Weathering products of these mineralized zones were washed down the slopes into the valley and form the present alluvial cover.

How the cassiterite was concentrated on the limestone bedrock is still a matter of discussion, as river action only offers no ready explanation. The geomorphological circumstances are not the same as in Indonesia or West Thailand and the morphological history of Kinta Valley is rather uncertain.

Scrivenor has suggested that Kinta Valley might be a graben-like feature, which at a certain time was transgressed by the sea, forming a kind of seaway connecting the Gulf of Siam with the waters of the Indian Ocean.

The marine transgression might have acted as a concentrating agent and formed the cassiterite-rich layer on the abrasion surfaces by washing away fine-grained and light-weight materials.

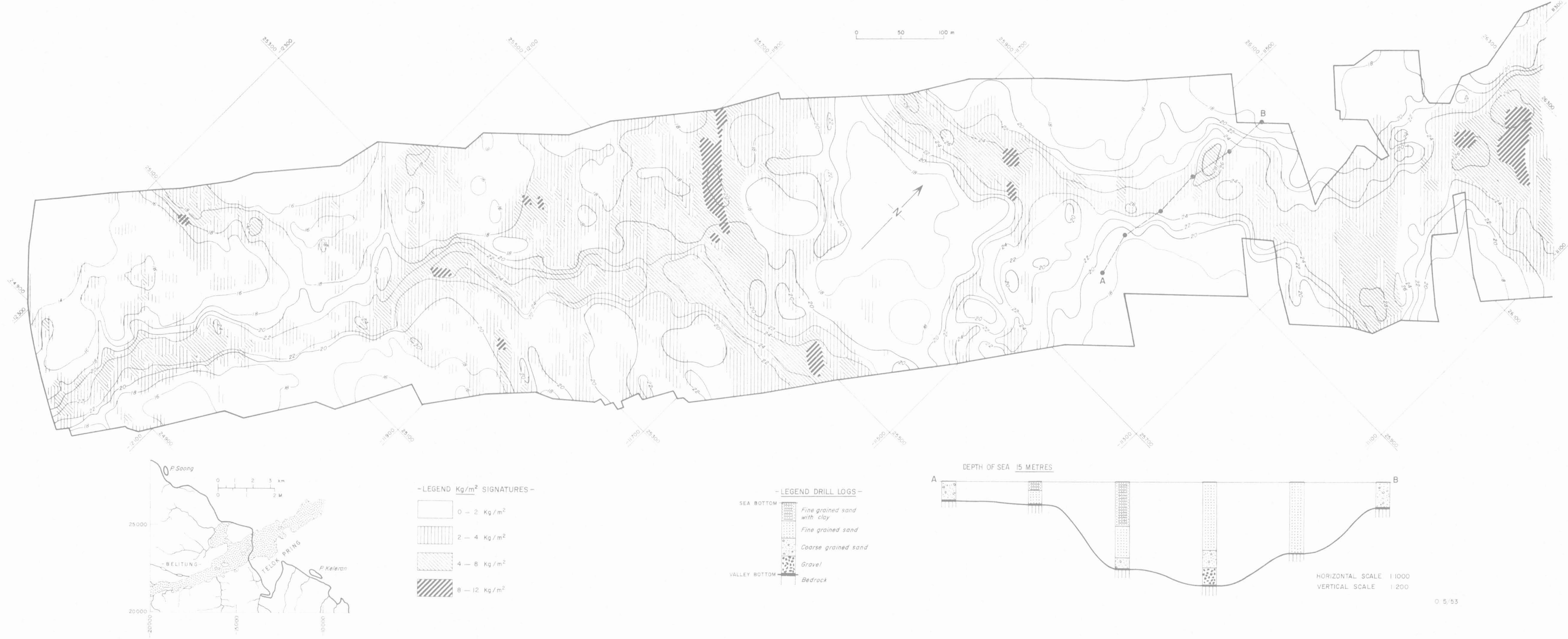

Figure 4. Bedrock contour lines and areal distribution of cassiterite off-shore Billiton, Indonesia.

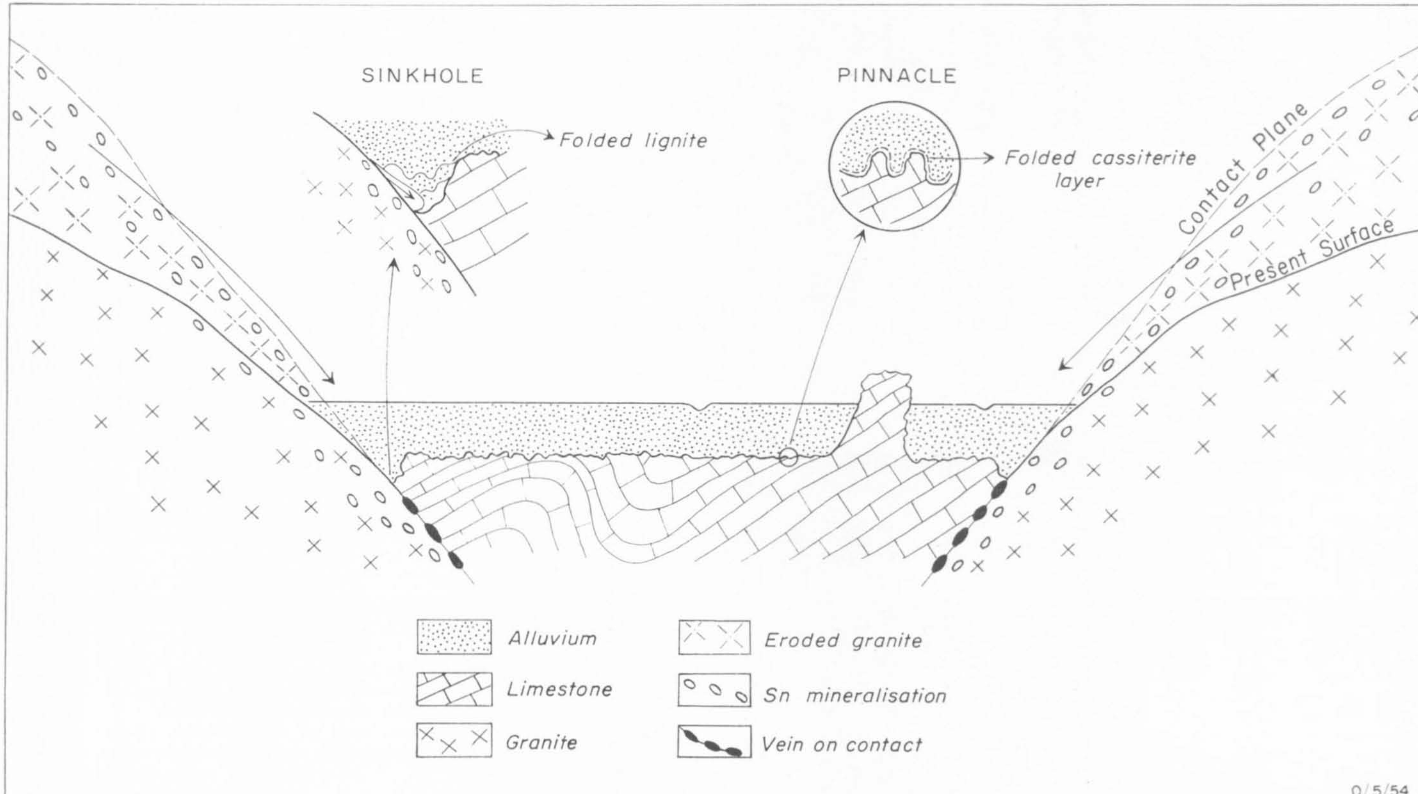

Figure 5. Idealized explanatory section through Kinta Valley, Malaysia.

Later uplift or tilting, or both, may have led to the present situation of a new alluvial fill deposited by sluggishly moving rivers, which caused the cassiterite concentrations in the higher alluvial levels. The formation of pinnacles and sinkholes then belongs to this period also.

SUMMARY AND CONCLUSION

The cassiterite deposits of the Thailand-Malaysia-Indonesia tin belt are completely dependent on secondary processes, but for which only a few primary deposits of marginal grade would exist.

The secondary processes can be listed in order of importance as follows:

1. Chemical weathering which separated the cassiterite grains from the lighter minerals, mainly quartz and feldspar, and which changed the feldspar into easily transported clay particles.
2. Trap forming by the occurrence of a coarse gravel layer of weathering-resistant vein quartz (kaksa) on a sedimentary or granitic bedrock or of sinkholes in a limestone bedrock.
3. Washing away by groundwater or fluvial or wave action of fine-grained and light-weight minerals resulting in a relative enrichment in cassiterite and other heavy minerals.

REFERENCES

ADAM, J. W. H., 1932-3—Kaksa-genese. *Mijning. Ned. Indie,* 1932 (2); 1933 (1, 2, 3).

INGHAM, F. T., and BRADFORD, E. F., 1960—Geology of Kinta Valley. *Geol. Surv. Malaya, Dist. Mem.* 9.

KROL, G. L., 1960—Theories on the genesis of the kaksa. *Geol. Mijnb.,* 10, 437-43.

SCRIVENOR, J. B., 1928—THE GEOLOGY OF MALAYAN ORE DEPOSITS. *London, Macmillan.*

SCRIVENOR, J. B., 1936—THE GEOLOGY OF MALAYA. *London, Macmillan.*

MOLYBDENUM AND TUNGSTEN PROVINCES IN THE JAPANESE ISLANDS AND NORTH AMERICAN CORDILLERA: AN EXAMPLE OF ASYMMETRICAL METAL ZONING IN PACIFIC TYPE OROGENY

by Shunso Ishihara

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SUMMARY

Molybdenum and tungsten deposits of the Japanese Islands are mostly either vein-type or limestone replacement-type, and are associated with granitic rocks younger than the early Cretaceous period. Only small amounts of molybdenum and tungsten minerals are concentrated in the region of the early Cretaceous granitic rocks: they are mostly associated with the late Cretaceous to early Tertiary granitic rocks. Very little molybdenite but a fair amount of tungsten and tin minerals are related to Miocene granitic rocks.

Clear zonal arrangements of these elements are observed in the Japanese Islands except for the regions of the Miocene granitic rocks. In the most productive region of the Inner Zone of SW Japan, for example, the following three metallogenic provinces are obvious from the median tectonic line to the continental side:

Barren synkinematic granitic province (Ryoke metamorphic belt),

Tungsten province with trace amounts of molybdenum, and

Molybdenum province with trace amounts of tungsten.

In the tungsten province, minerals containing tin, bismuth, beryllium, lithium, and fluorine are present, whereas the molybdenum province is characterized by their absence. Granitic rocks of the two provinces are mostly granodiorite to granite in composition; but those of the molybdenum province are different in K-Ar mineral ages, mafic minerals, and alkali ratio from those of the tungsten province.

Regional zoning of molybdenum and tungsten minerals in northeast Japan is somewhat different in detail from that of southwest Japan, but molybdenum and tungsten provinces are similarly sketched in following the Japanese island arc structure.

The occurrence of molybdenum and tungsten deposits on the other side of the Pacific Ocean is different from the Japanese examples.

INTRODUCTION

The concept of metallogenic provinces established early this century (see Burnham, 1959; Sekine, 1967; Ramovic, 1968; Noble, 1970), seems essentially to be tied to that of petrogenetic provinces. This paper is mainly concerned with metallogenic provinces of molybdenum, tungsten, and tin in the Circum-Pacific belt and focuses attention on relatively young (Cainozoic) granitic activity, because mineralization of these metals is closely related to granitic rocks in time and space.

For example, 98 percent of the molybdenum that has been produced in Japan is endogranitic (Ishihara, 1971a), and isotopic determinations so far available on the fresh and altered host rocks of the molybdenum and tungsten deposits show almost identical ages (Shibata & Ishihara, 1971).

The Japanese molybdenum-tungsten-tin deposits have been previously reported to the Pacific Science Congress (e.g. M. Watanabe, 1953; T. Watanabe & Sasaki, 1961); but much recent information obtained about molybdenum and

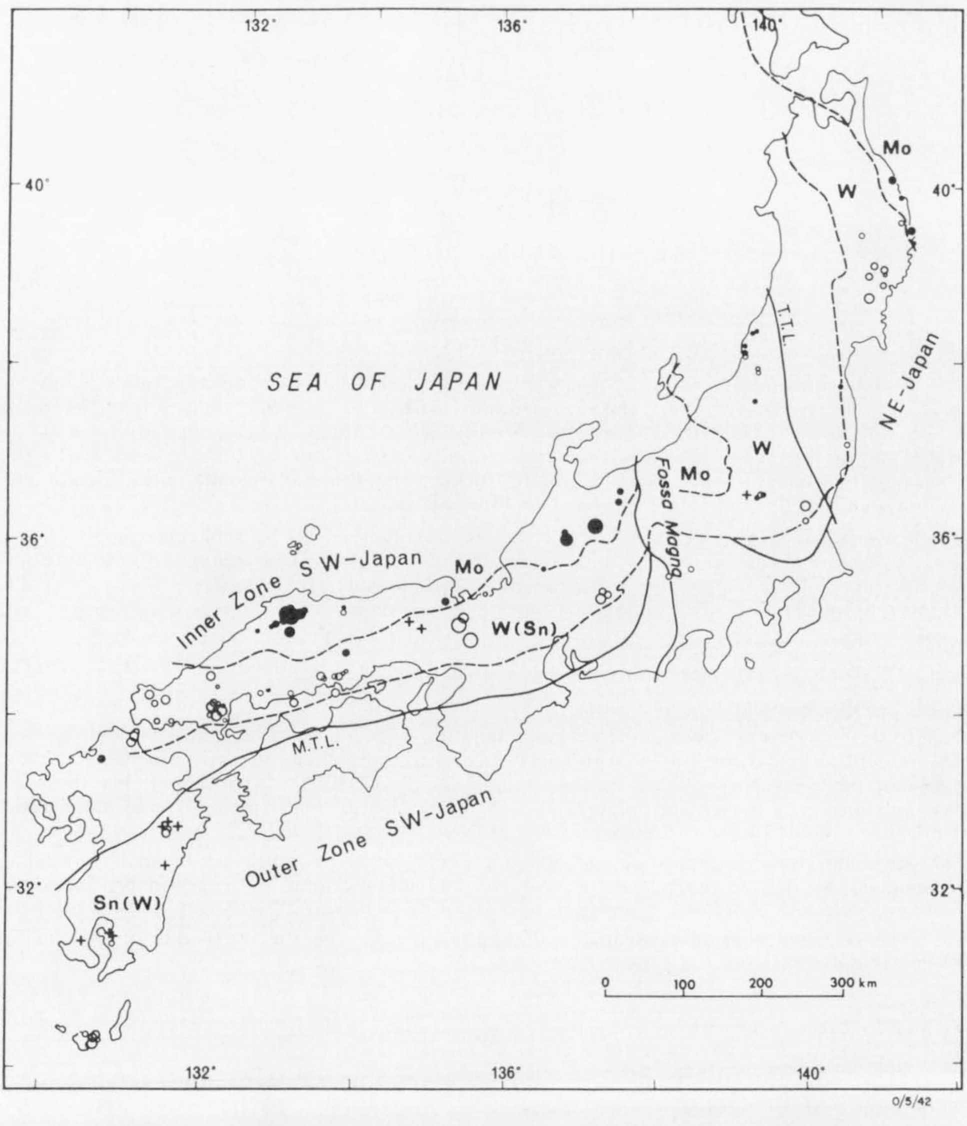

Figure 1. Molybdenum-Tungsten-Tin metallogenic provinces in Japan. Solid circle: molybdenum deposits. Open circle: tungsten deposits. The size of the circle is based on the production tonnage in metal up to 1968, but the ore reserves are also considered. The different sizes signify: more than 1000, 1000-100, 100-10, and less than 10 tons of molybdenum or tungsten. Cross: Tin deposits. M.T.L.: Median tectonic line. T.T.L.: Tanakura tectonic line.

tungsten deposits especially has enabled us to amplify and revise our knowledge of these deposits. A new scheme of metallogenic provinces of these metals in Japan, which shows an asymmetrical pattern (Fig. 1), is proposed in this paper. This asymmetry seems to be a characteristic of the Pacific type of orogeny and could fit suitably into the plate tectonics model developed in recent years.

THE MOLYBDENUM-TUNGSTEN-TIN METALLOGENIC EPOCHS

As far as historical production and ore reserves are concerned, the most important epoch for tungsten and tin mineralization in the world is mid-Mesozoic, the age of greisen- and vein-type deposits of tungsten, with subordinate tin, in the Nanling Range in China, and tin, with subordinate tungsten, in the Malay Peninsula; that of molybdenum mineralization is much younger (mid-Tertiary), because of huge porphyry-type deposits at Climax (Wallace et al., 1968), Henderson, and Questa (Ishihara, 1967a; Carpenter, 1968), USA (Table 1).

Table 1. The principal metallogenic epochs of molybdenum and tungsten deposits of the Northern Hemisphere. Figures in parenthesis are mostly K-Ar mineral ages.

	EAST ASIA			NORTH AMERICA		
	Tungsten Province	Molybdenum Province	m.y.	Tungsten Province	Molybdenum Province	
	Outer SW Japan(20)			Eastern Arc(25): e.g., Boulder	Climax, Henderson-Urad, Questa(23)	
		Daito(40) Hirase(60)				
HIMALAYAN	NE USSR, Inner SW Japan-Korea(80)		65	Central Arc, York Mtn(Sn) Western Arc:Bishop (80), B.C., Canada	Alice Arm(53) U.S. porphyry coppers	LARAMIDE
					Boss Mtn(105)	
	NE Japan(120)	NE Japan(120)	136			
KIMMERIAN	Burma-Malay Pen., Nanling-Korea, Trans-Baykal-Primorye		195		Endako(150)	NEVADAN
VARISCAN	Portugal, Spain, Cornwall, Erzgebirge, Kazakh(USSR)					

The most fundamental structure of the Nanling Range is its northeast trend. An extension of this structure, associated granitic intrusion, and tungsten (tin) mineralization are observed in the Korean Peninsula (J. Kim, 1967; O. Kim, 1971), but not in Japan. The principal metallogenic epoch for these metals in Japan is late Cretaceous to Palaeogene of the Inner Zone of southwest Japan, which lies on the outer (oceanic) side of the Mesozoic granitic rocks in the Korean Peninsula.

The molybdenum-tungsten-tin metallogenic epochs in Japan are divided into three stages:

(1) Early Cretaceous (called 'Cretaceous' in this paper) in northeast Japan;

(2) Late Cretaceous to Palaeogene (similarly 'Palaeogene') in the Inner Zone of southwest Japan; and

(3) Miocene in the Outer Zone of southwest Japan.

No economic amounts of these metals have been found associated either with Miocene granitic rocks of the 'Green Tuff Region' or with much older granitic rocks (190 m.y.) like those in the Hida metamorphic belt.

The granitic rocks of each epoch are closely related to preceding volcanic acivity. The Inner Zone of southwest Japan particularly has been shown to be a zone of volcan-plutonic formation by Ustiyev (1965). Pyroclastic flow deposition, which constitutes the major part of the volcanic activity, is restricted to a few events during the Cretaceous and Miocene.

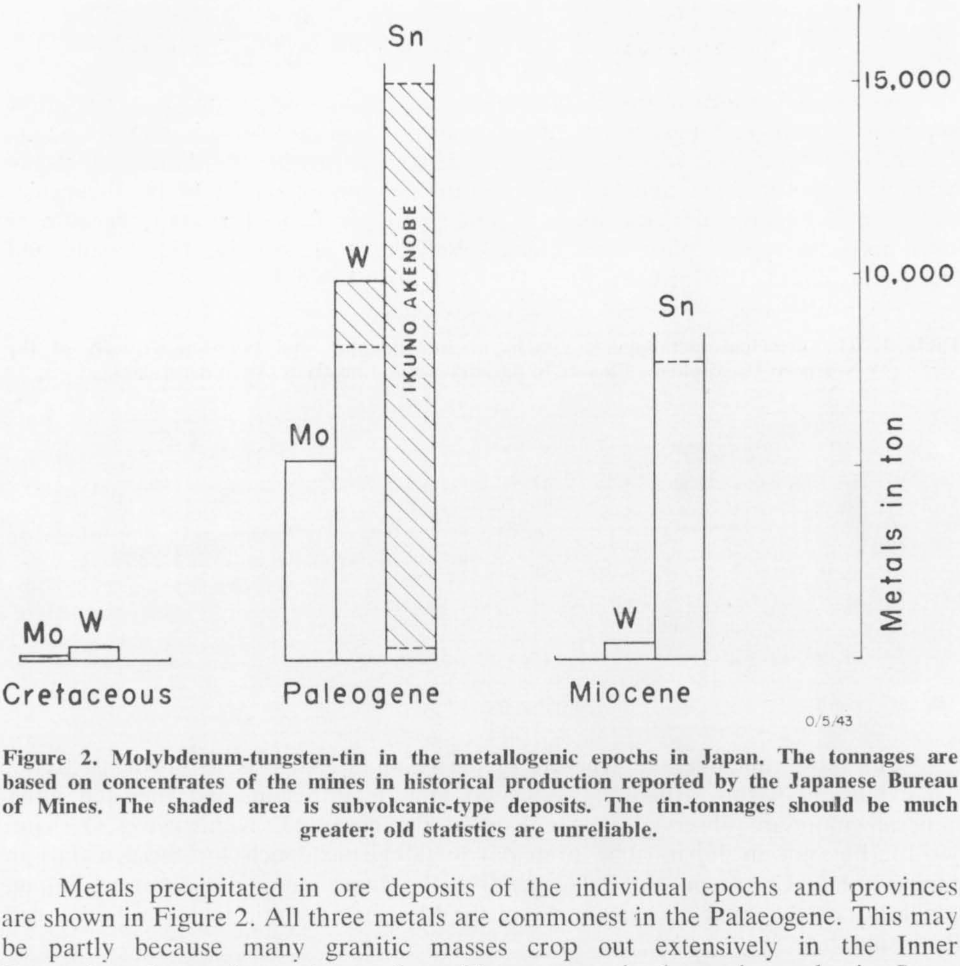

Figure 2. Molybdenum-tungsten-tin in the metallogenic epochs in Japan. The tonnages are based on concentrates of the mines in historical production reported by the Japanese Bureau of Mines. The shaded area is subvolcanic-type deposits. The tin-tonnages should be much greater: old statistics are unreliable.

Metals precipitated in ore deposits of the individual epochs and provinces are shown in Figure 2. All three metals are commonest in the Palaeogene. This may be partly because many granitic masses crop out extensively in the Inner Zone of southwest Japan (area of granitic exposure in decreasing order is: Inner Zone of southwest Japan, northeast Japan, and Outer Zone of southwest Japan). But the small quantity in Cretaceous granitic rocks must be connected with their more mafic regional bulk composition than that of the other epochs. Acidity of the host rock seems to be a prerequisite for molybdenum and tin mineralization. This subject will be discussed separately.

Empirically speaking, molybdenite seems to be incompatible with tin minerals. Molybdenite at Akenobe mine, for example, occurs later than the main crystallization stage of tin minerals, filling minute fractures. Some ore deposits, such as Horni Krupka, Czechoslovakia (Mineral deposits map of Czechoslovakia, 1967), are cited as molybdenum-tin deposits. However, large concentrations of both metals cannot be seen occurring together in such deposits. A similar phenomenom is observed on Figure 3: the ratio of the three metals differs from one epoch to another with an increase of tin towards the youngest epoch.

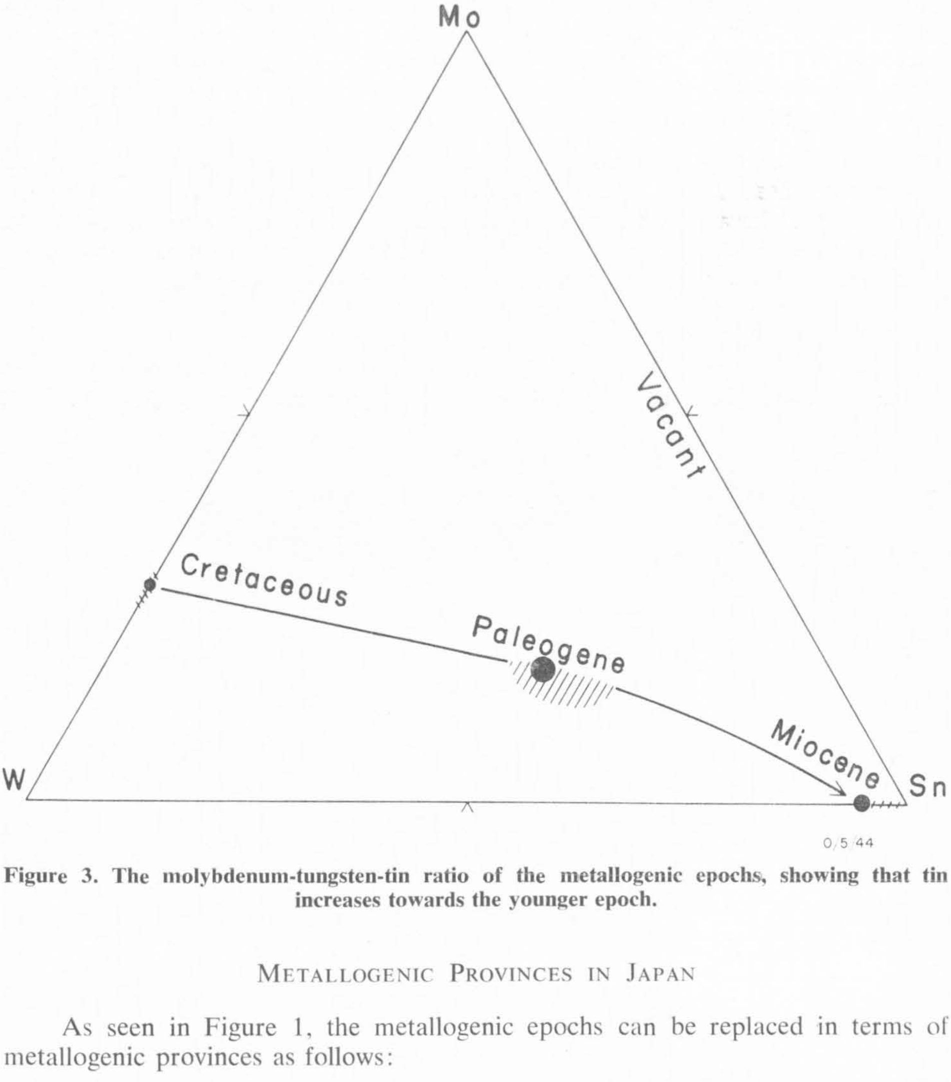

Figure 3. The molybdenum-tungsten-tin ratio of the metallogenic epochs, showing that tin increases towards the younger epoch.

METALLOGENIC PROVINCES IN JAPAN

As seen in Figure 1, the metallogenic epochs can be replaced in terms of metallogenic provinces as follows:

Miocene epoch:	Tin (tungsten) province
Palaeogene epoch:	Molybdenum province
	Tungsten (tin) province
	Barren province
Cretaceous epoch:	Molybdenum province
	Tungsten province
	Barren province (?)

In previous papers on metallogenic provinces in northeast Japan (e.g., M. Watanabe, 1944; Igarashi & Shimazu, 1961), productive mines and mineral occurrences are given equal value. The present quantitative expression, ignoring mineral occurrences, can divide northeast Japan into two provinces, as shown in Figure 1.

In the Inner Zone of southwest Japan, Kinosaki (1953) was able to distinguish inner molybdenum and outer tungsten provinces in his qualitative analysis of the molybdenum and tungsten deposits of the Chugoku District. There is no inconsistency between his proposal and that of the present writer, who has extended these provinces much farther east, even beyond the Fossa Magna, and drawn a hypothetical line between the two.

On the basis of the ore deposits and related igneous rocks, the boundary between northeast Japan and the Inner Zone of southwest Japan is set in this paper along the Tanakura Tectonic Line, instead of the Fossa Magna. This makes obvious a zonal arrangement of Barren, Tungsten, and Molybdenum provinces from outer to inner in southwest Japan, and a reverse zoning in northeast Japan.

Northeast Japan

Granitic rocks of the Abukama plateau, which are well known from studies of metamorphic rocks (e.g. Miyashiro, 1958) range from quartz diorite to ada-

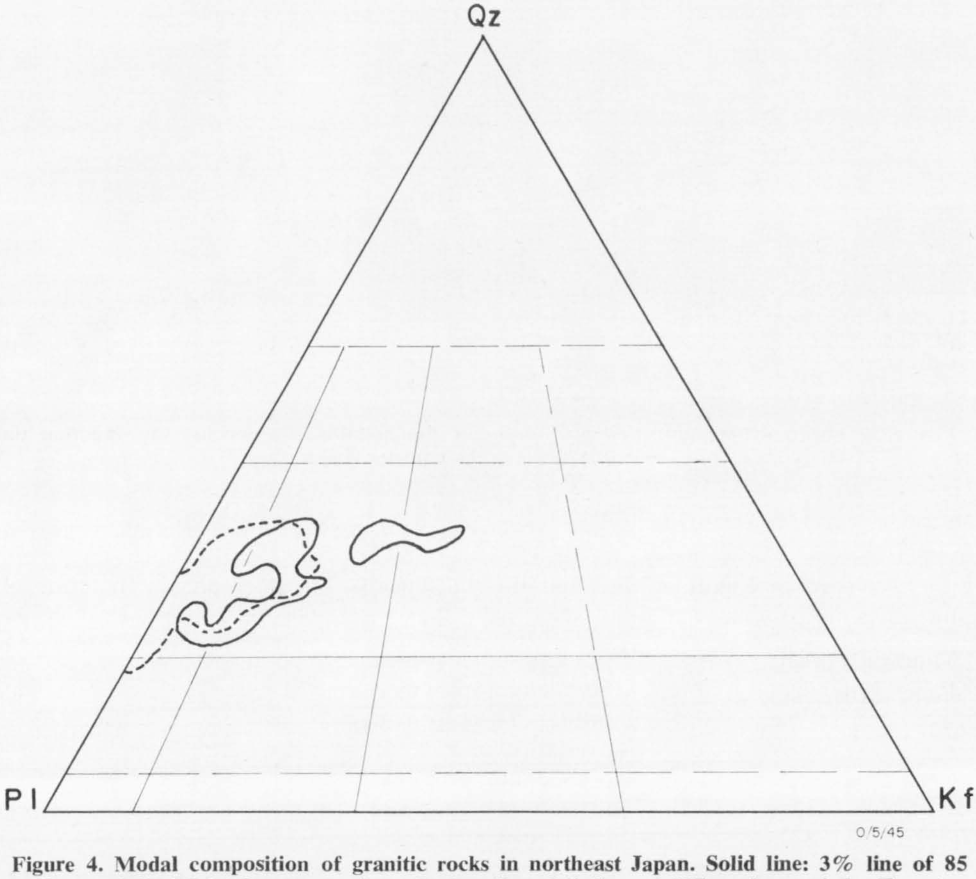

Figure 4. Modal composition of granitic rocks in northeast Japan. Solid line: 3% line of 85 analyses of the Molybdenum province. Broken line: 3% line of 237 analyses of the Tungsten province.

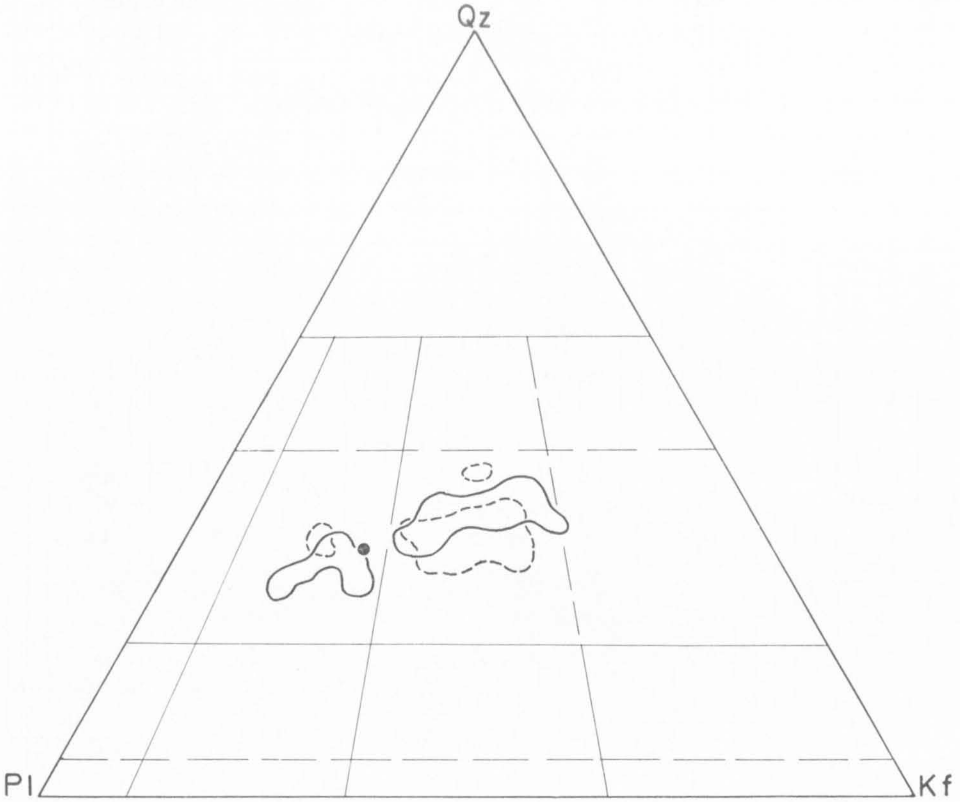

Figure 5. Modal composition of granitic rocks in the Inner Zone of southwest Japan. Solid line: 3% line of 114 analyses of the Molybdenum province. Broken line: 3% line of 46 analyses of the Tungsten province. Solid circle: an average of selected analyses (n = 2t) of the Barren province.

the skarn-type deposits. It should be emphasized here that in these scheelite skarn deposits there is almost no magnetite and little iron sulphide. This feature is rather unusual as compared with other skarn-type deposits in Japan.

Granitic rocks of the Molybdenum province are similar to those of the Tungsten province. The adamellite, however, is leuco-adamellite, not biotite adamellite, presumably because iron is segregated as an oxide (Ishihara, 1971b); an assumption confirmed by the indication of high magnetite content in measurement of magnetic susceptibility (Ishihara & Kanaya, 1971) and by observation under the reflecting microscope. Thus, the Molybdenum province granites are regarded as belonging to a high-magnetite granitic series, whereas those of the Tungsten and Barren provinces belong to a low-magnetite granitic series. K-Ar dating of the granitic rocks indicates younger ages than those of the Tungsten and Barren provinces (Fig. 6), especially in the main part of Chugoku District (Ishihara, 1967b).

Ore deposits of the Molybdenum province are characterized by molybdenite-quartz vein deposits with no, or only a trace of, tungsten minerals. Magnetite is mellite—more salic in the east. Only pegmatite deposits, containing many rare-earth-bearing radioactive minerals, are known in the western parts of the plateau.

Some scheelite-bearing skarn deposits and a vein-type molybdenite deposit are found along the eastern edge of the plateau. The eastern edge seems a part of the Tungsten province.

The major part of the Tungsten province is the southwestern part of Kitakami District, where the ore deposits consist largely of gold-bearing scheelite-quartz veins or breccia pipes. A small scheelite-chalcopyrite skarn deposit lies close to the Molybdenum province, and the scheelite has a fairly high molybdenum content (4.7% MoO_3, Imai et al., 1961). Granitic rocks of the Tungsten province are generally quartz diorite to granodiorite.

Molybdenum deposits in the Molybdenum province are of only three types: vein, network, and skarn. These are genetically related to granodiorite and adamellite.

The granitic rocks as a whole of the Molybdenum province are more salic than those of the Tungsten province (Fig. 4). K-Ar dating of the granitic rocks shows the Barren province to be the youngest and the Molybdenum and Tungsten provinces to be indistinguishable.

The Inner Zone of Southwest Japan

The Barren province of the Inner Zone of southwest Japan corresponds to the Ryoke metamorphic belt. The average composition of the granitic rocks is granodiorite (Fig. 5). The granitic rocks are generally foliated and are characterized by rather wide exposure of two-mica adamellite as compared with those of the Tungsten and Molybdenum provinces. Small pegmatites containing rare-earth-bearing radioactive minerals and beryl-bearing pegmatitic quartz veins (Ishihara et al., 1969) occur in two areas of this province.

Granitic rocks of the Tungsten province are not foliated and consist mainly of biotite adamellite and hornblende-biotite granodiorite (Ishihara, 1971b). Two-mica adamellite occurs in very limited areas, and is related to tungsten deposits. As mentioned previously, this province is the major source for Japanese tungsten production. Since the metallogenic epoch of the Ikuno and Akenobe deposits has been revised from Miocene to late Cretaceous (Ishihara & Shibata, 1972), the Tungsten province has a large potentiality even for tin.

Tungsten and tin deposits of this province can be divided into plutonic and subvolcanic types. The former consists of many quartz vein-type deposits with greisenized envelopes and skarn-type deposits; the latter is demonstrated by polymetallic quartz veins at the Ikuno and Akenobe mines. As well as wolframite or scheelite, the plutonic-type deposits contain economic amounts of cassiterite and chalcopyrite, and small amounts of molybdenite, bismuth minerals, beryl, and others.

In no large deposits do tungsten minerals occur equally with tin or molydenum minerals. But wolframite and scheelite occur in more or less equal proportions at the Kaneuchi-Wachi mine. In greisen-type deposits, muscovite, lithium mica, fluorite, and topaz are common alteration products of the vein-type deposits, and in addition to some of these minerals calcic silicates are the major constituents of

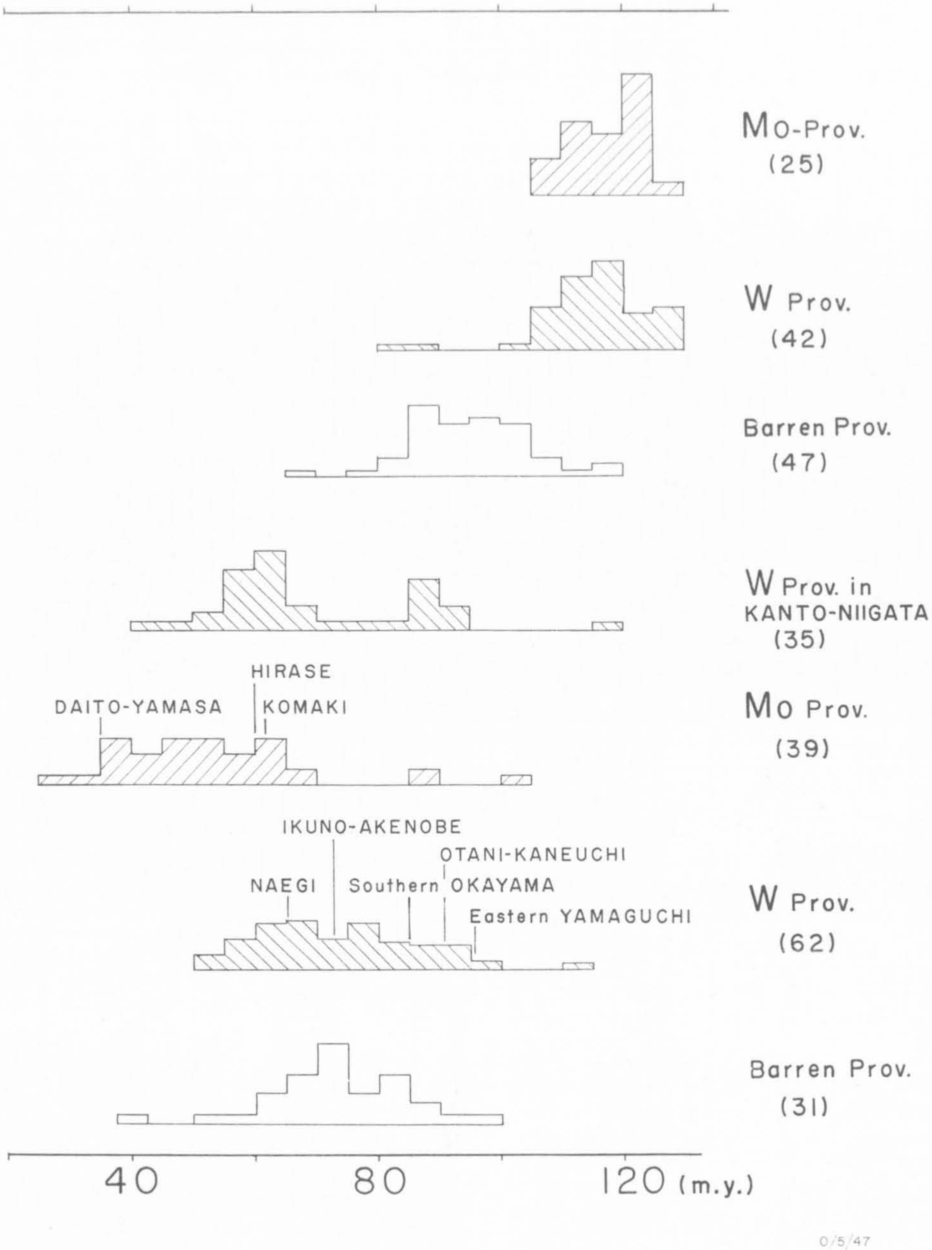

Figure 6. K-Ar ages of granitic rocks in the metallogenic provinces in Japan. Only K-Ar mineral ages were chosen from the summary by Nozawa (1970). Figures in parenthesis are numbers of analyses. For locality names, see Ishihara (1971).

prominent in skarn-type deposits and an orthomagmatic magnetite deposit (Kinoshita & Muta, 1954) belongs to this province. Among base metal deposits, this province predominates in lead and zinc, because of two large skarn-type deposits at Kamioka (Nishiwaki et al., 1970) and Nakatatsu, and other small deposits.

Molybdenite deposits of the province are mainly composed of pegmatitic to hypothermal and mesothermal molybdenite-quartz veins. The former, which correspond to wolframite-scheelite-quartz veins of pneumatolytic to hypothermal range in the Tungsten province, contain no 'pneumatolytic minerals', but potassium feldspar, andalusite, muscovite, biotite, garnet, and cordierite as alteration products. Molybdenite from the largest source area (Daito-Yamasa area) is characterized by high contents of rhenium (Terada et al., 1971).

The Outer Zone of Southwest Japan

There is little new information from this Tin (tungsten) province because most of the mines closed a long time ago. Granitic rocks of this province are granodiorite to adamellite in composition and nearly all contain trace amounts of tourmaline. Contamination by aluminiferous shale is assumed in the granitic rocks, because of xenolithic inclusions containing spinel, sillimanite, cordierite, and others (e.g. Nozawa, 1956). The granitic rocks are high in K_2O and FeO, compared with the other Japanese granitic rocks (e.g. Kawachi, 1961; Oba, 1963). The high FeO content and the presence of abundant highly volatile elements such as boron and fluorine indicate that they belong to a low-magnetite granitic series like those of the Tungsten province in the Inner Zone of southwest Japan.

Ore deposits of this province can be grouped in several restricted areas and differ in character from one place to another. Tungsten deposits at Yakushima and Kimpozan are very similar to wolframite-quartz vein deposits of the Inner Zone of southwest Japan, except for the presence of abundant tourmaline. Tin deposits at Suzuyama (Kinoshita, 1961) and Takakumayama (Ishihara & Kawachi, 1961) are also similar, but differ slightly in being polymetallic as well as containing much tourmaline.

Tin deposits at Okueyama, which is one of the major tin sources in Japan, consist of skarn and vein-type deposits. The genetic history reported (Miyahisa, 1958) is: first, normal skarn formation, then boron-skarns and tourmalinization with intense tin mineralization, and finally polymetallic mineralization and epithermal mineralization. Ore deposits and granitic rocks in this province in general are characterized by boron-bearing minerals.

A Type of Asymmetrical Zoning

As is obvious from the previous description, the late Cretaceous to Palaeogene igneous activity in the Inner Zone of southwest Japan is one of the most important events in the Japanese island arc system. Information from northwest Japan is rather incomplete, because basement rocks of the inner 'Green Tuff' region are covered by Neogene and later volcanic rocks. Among data available for the Outer Zone of southwest Japan, the Sn (W) mineralization is largely limited to Kyushu Island. The Inner Zone of southwest Japan is therefore considered mainly in the following discussion.

Regional zoning of various components related to the granitic activity is summarized in Table 2. There are some differences in the major cation-components among the three provinces, as mentioned previously. The barren province is the most mafic as a whole; but it is not so mafic as to draw a quartz-diorite line (Moore, 1959; Moore et al., 1963), except in the extreme southern part of the province in Chubu District. This compositional difference does not mean that the granitic rocks are less potassic than those of the Molybdenum and Tungsten provinces. Instead, binary projection (e.g., Harker diagram) or a CaO-Na_2O-K_2O diagram (Ishihara et al., 1969) on chemical analyses of a single analyst indicates an increase of Na_2O toward the inner side, that is, the Molybdenum province (Ishihara, 1971a).

Table 2. A summary of metals and volatile components in the Inner Zone of southwest Japan.

Province	Characteristic metals		Important volatile components					
			O_2	HF	S	CO_2	Cl	Total P_{H_2O}
Molybdenum province	Mo, (W)	Pb-Zn	much	less	much	med.	much?	high
Tungsten province	W, Sn, Bi, Be, (Mo)	Cu	less	much	med.	much	med.?	med.?
Barren province	Be, Rare elements		less	med.	less	less	less	low?

In the Molybdenum province, the magnetite-dominant character is observed in all kinds of plutonic rocks from gabbro to adamellite and even in various ore deposits. Oxygen seems to be in excess throughout the solidification process. A high fluorine content of the Tungsten province is assumed from the presence of fluorite in ore deposits. Fluorine is reactive with some rockforming minerals (Burnham, 1967), so that fluorite is considered an excess component of the fluorine-rich environment. The fluorine seems to have been enriched in the magma of adamellite composition and its residue at the final stage.

Indication of sulphur species in Table 2 is simply based on the fact that the metallic minerals are sulphides in molybdenum deposits and tungstates or oxides with a little sulphide in tungsten deposits. The CO_2-dominant environment in the tungsten deposits is shown by a recent study of fluid inclusion and a review of similar studies in USSR (Takenouchi, 1971). There are no actual data on chlorine, but a high content is conjectured during the formation of molybdenum deposits because of the importance of chloride solution in hydrothermal deposits and also by reference to the liquid inclusion study at Climax (Roedder, 1971).

The total water pressure is assumed to be highest in granitic rocks of the Molybdenum province, because of the wide hydrothermal alteration halo of contact type (Ishihara, 1968) around the granitic rocks related to molybdenum deposits. The magnetite-dominant character also supports this assumption. Dissociated oxygen from water (Kennedy, 1948; Osborn, 1962) was used to form magnetite; while hydrogen was consumed in the formation of amphiboles and biotite. Pyroxene is absent even in rocks of gabbroic composition in the Molybdenum province (Ishihara, 1971a).

The total water pressure in the granitic series of the Tungsten province is assumed to be medium relative to the other two provinces. The low content of magnetite in the granitic rocks is considered an effect of highly volatile components that interfered with the simple dissociation of 2 $H_2O \rightleftharpoons 2H_2 + O_2$.

A low water pressure throughout crystallization of the granitic rocks of the Barren province is not consistent with extensive distribution of two-mica adamellite. Presence of muscovite should imply a high water content (Yoder & Eugster, 1955; Seki & Kennedy, 1965) at least during crystallization of the adamellite. However, this adamellite occurs in the core of the Ryoke metamorphic belt, and has a petrographic character which could be explained by an anatectic concept or granitization hypothesis.

Asymmetrical Zoning and the Concept of Plate Tectonics

The best example of lateral variation across the Japanese Island Arcs may be that observed on the Cainozoic volcanic rocks (Kuno, 1959, 1966; Sugimura, 1960). Another, older, example is involved in the paired metamorphic concept by Miyashiro (1961). The granitic rocks and related metallogenesis here described are also an example of asymmetrical lateral variation in geological time. Similar regional asymmetries have been reported in many places in the circum-Pacific belt (e.g. Dickinson, 1962; Moore, 1962; Bateman & Dodge, 1970; Noble, 1970; Peterson, 1970). The asymmetry seems to be a definite feature of the Pacific-type orogeny. Since the concept of plate tectonics (Dietz, 1961; Hess, 1962) deduces an asymmetry pattern in the orogenic belt, an attempt to account for the asymmetry in metallogenesis is considered with the concept in referring to various kinds of comprehensive works on the orogenic belt, such as Miyashiro (1967), Dewey & Bird (1970a, b), Dickinson (1971), and Matsuda & Uyeda (1971).

As mentioned previously, the regional metal-zoning is based chiefly on mobile components, so that a possible mechanism to cause the zonal arrangement would be a single magma-source model with differentiation during the ascent of the magma. But in order to have two series of granitic rocks, high magnetite and low magnetite, a multiple source model is adopted in the considerations that follow (Fig. 7).

The first granitic magma was generated at a relatively shallow level along the down-moving lithosphere plate (Ringwood, 1969; Green, 1971), involving water from soft sediments that accelerate melting of the crustal material and material from the plate, remnants of which are now mafic xenoliths or schlieren. Because of the highly volatile substance involved during the generation, highly refractory minerals were being melted, making the bulk composition more mafic than the second-stage magma. Salic material with a large volatile component migrated directly upward, and formed the granitic rocks and ore deposits of the present Tungsten province. Tungsten and tin were concentrated in this magma because of their chemical affinity with fluorine. The rest of the magma, more mafic in composition, and barren in ore metals, moved upward but was partly affected by regional stress due to the down-moving plate, so that granitic rocks of the Barren province are now barren and foliated.

At the next incident of the down-moving plate, the present rate of which on the north Pacific plate is calculated as 9 cm/year (le Pichon, 1968), the second magma was generated and ascended directly upward. The later generation of the

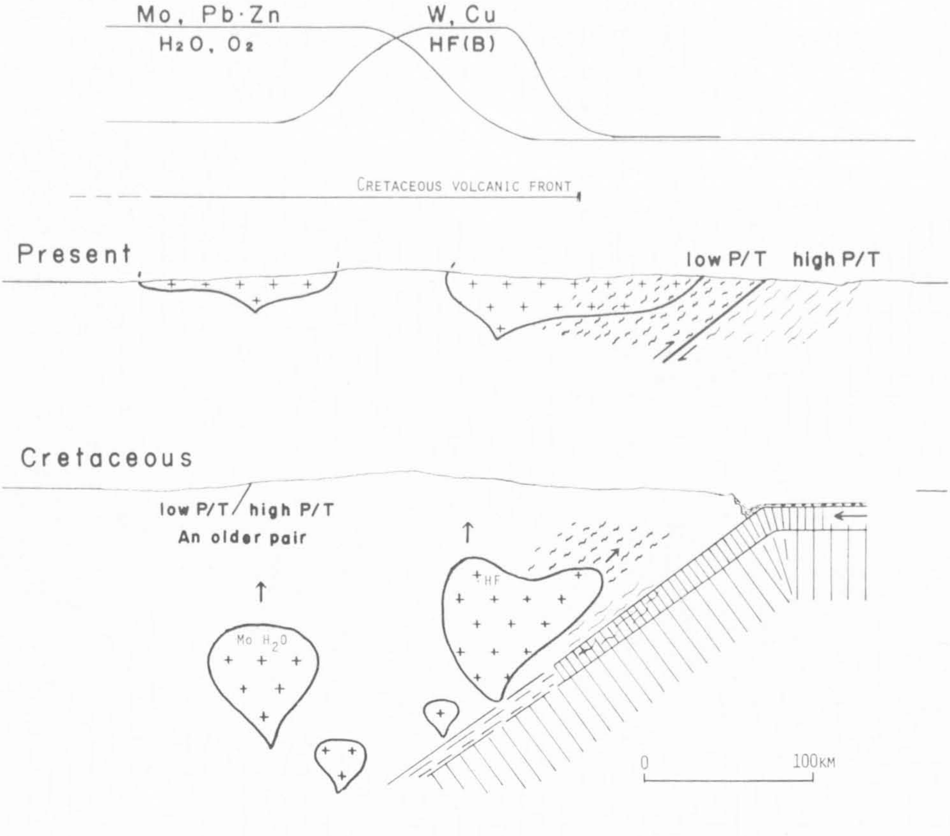

Figure 7. A schematic profile and genetic history of the Inner Zone of southwest Japan.

magma, longer distance of migration, and greater difference in temperature between the wall-crust material and ascending magma in the Molybdenum province as compared with the Barren province, caused some of the mafic components of the magma to be left within the crust and delayed the ascent. This accounts for the more salic composition and younger K-Ar mineral ages of the granitic rocks of the Molybdenum province. Enrichment of lead and molybdenum in this magma may be explained by the chemical affinity of lead and potassium, and the empirical association of molybdenum with an acid and very hydrous silicate melt (Ishihara, 1968; 1971a).

The asymmetrical metal-zoning observed in most of Japan, barren-tungsten-molybdenum or barren-copper-lead-zinc, is also recognized at the other side of the Pacific Ocean. Kerr (1946) noted three arcs, Western, Central, and Eastern, of tungsten mineralization in the western United States. Quantitatively speaking, the Western Arc is discriminative. The greatest concentration of molybdenum is observed along the Front Range belt (Clark, 1968), although a fair amount is seen in porphyry copper deposits (Ishihara, 1969-1970; Lowell & Guilbert, 1970). Peterson (1970) reported lead-zinc deposits in the continental side of copper deposits in North America. The granitic rocks in the western United States generally show younger ages (up to Miocene) toward the Front Range belt (Fig. 8). They become more salic and potassic in regional bulk composition in the same direction.

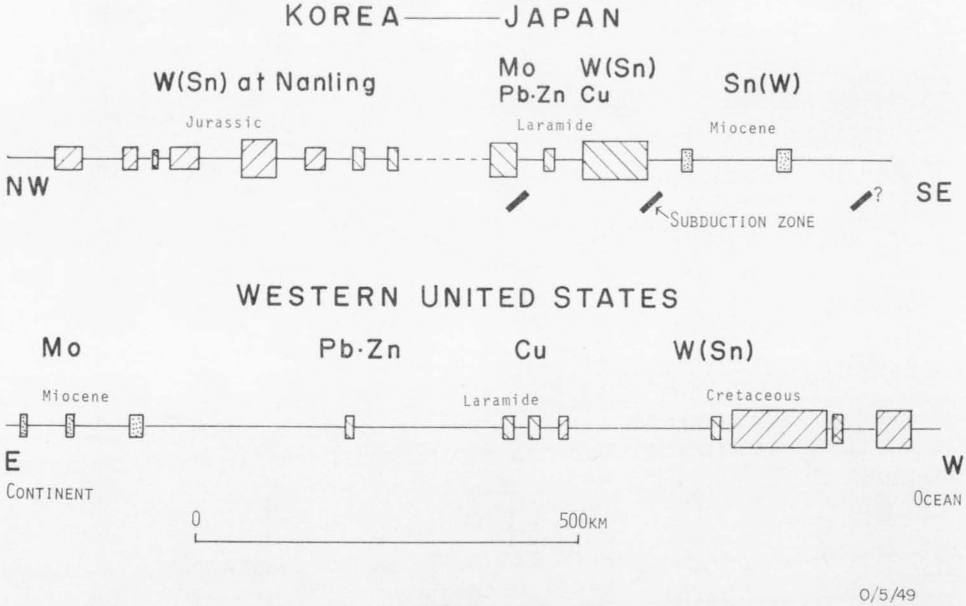

Figure 8. Schematic distribution of granitic rocks and related metals in East Asia and North America.

Geographically, the area of the Mesozoic to Tertiary granitic rocks of the Western United States corresponds to the eastern margin of the Eurasian continent, including Okhotsk-Primorye, Korea-Japan, and the southeastern margin of China. The granitic and related volcanic activity of Mesozoic through Tertiary in these regions seems to have migrated from the continental to the oceanic side (Ustiyev, 1965; Matsumoto, 1968). This is inconsistent with the sequence of igneous activity in the western United States. Within southwest Japan, the continental side is younger in the Inner Zone, and the next igneous cycle of Miocene granitic rocks is located at the oceanic side. It seems reasonable to conclude in the western Pacific regions that the continent and island arcs were formed through polycyclic magmatic activity, which may have been triggered by polycyclic down-moving lithosphere plates. Within one cycle, the inner side may be younger than the outer side. On the other hand, the western United States seems to have a rather simple history of magmatic activity.

Not enough chemical analyses of the granitic rocks and quantitative data on the ore deposits of the whole of the western Pacific regions are available to the writer at this moment. But within southwest Japan as a whole or even in northeast Japan, the granitic rocks of the oceanic side are potassic. This is inconsistent with lateral variation in composition of recent basaltic rocks in northeast Japan and also that of granitic rocks in the western United States. What causes this inconsistency is still in question. An anatectic model (e.g. Moore, 1962; Oba, 1966; Bateman & Eaton, 1967) cannot be ruled out to account for a part of the granitic activity. Another cause, the nature of the upper mantle for example, may need to be considered. The Pacific type of orogeny discussed in this paper is consistent in respect to continent-ocean impact. However, there seems to be a fundamental difference between the two sides of the Pacific Ocean.

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References

Bateman, P. C., Clark, L. D., Huber, N. K., Moore, J. G., and Rinehart, C. D., 1963—The Sierra Nevada batholith. *U.S. geol. Surv. prof. Pap.* 414-D.

Bateman, P. C., and Eaton, J. P., 1967—Sierra Nevada Batholith. *Science,* 158, 1407-17.

Bateman, P. C., and Dodge, F. W., 1970—Variations of major chemical constituents across the central Sierra Nevada batholith. *Bull. geol. Soc. Amer.,* 81, 409-20.

Burnham, C. W., 1959—Metallogenic provinces of the southwestern United States and Northern Mexico. *N. Mex. Bur. Min. Bull.* 51.

Burnham, C. W., 1967—Hydrothermal fluid at the magmatic stage. *In* geochemistry of hydrothermal ore deposits. *N.Y., Holt, Rinehart, & Winston,* 34-76.

Carpenter, R. H., 1968—Geology and ore deposits of the Questa molybdenum mine area, Taos County, New Mexico. *In* ore deposits in the united states 1933-1967. *N.Y., AIME,* 1328-50.

Clark, K. F., 1968—Structural control in the Red River District, New Mexico. *Econ. Geol.,* 63, 553-66.

Dewey, J. F., and Bird, J. M., 1970a—Mountain belts and the new global tectonics. *J. geophys. Res.,* 75, 2625-47.

Dewey, J. F., and Bird, J. M., 1970b—Plate tectonics and geosynclines. *Tectonophysics,* 10, 625-38.

Dickinson, W. R., 1962—Petrogenetic significance of geosynclinal andesitic volcanism along the Pacific margin of North America. *Bull. geol. Soc. Amer.,* 73, 1241-56.

Dickinson, W. R., 1971—Reconstruction of past arc-trench systems from petrotectonic assemblages in the island arcs of the western Pacific (abstract). *Proc. 12th Pacif. Sci. Cong.,* 1, 445.

Dietz, R. S., 1961—Continent and ocean basin evolution by spreading of the sea floor. *Nature,* 190, 854-7.

Green, T. H., 1971—Experimental crystallization of an island arc calc-alkaline andesite under controlled high-pressure conditions (abstract). *Proc. 12th Pacif. Sci. Cong.,* 1, 452.

Hess, H. H., 1962—History of ocean basins in petrologic studies. *Buddington Vol. geol. Soc. Amer.,* 599-620.

Igarashi, T., and Shimazu, M., 1961—Granitic rocks and related uraniferous metallic ore deposits in Kitakami mountainland. *Geol. Surv. Japan Rep.* 190, 34-44.

Imai, H., Hayashi, S., and Kawachi, Y., 1961—Uraniferous copper-tungsten ore deposits at Yamaguchi mine, Iwate Prefecture, with special reference to the occurrence of uraninite. *Geol. Surv. Japan Rep.* 190, 135-43.

Ishihara, S., 1967a—Molybdenum mineralization at Questa mine, New Mexico, U.S.A. *Geol. Surv. Japan. Rep.* 218.

Ishihara, S., 1967b—History of the igneous activities and source rock problems for the ore-fluid in the major molybdenum deposits area, eastern Shimane Prefecture, Japan. *Min. Geol. (Tokyo),* 17, 272-83.

Ishihara, S., 1968—Geologic environment of Hirase molybdenum deposits, Gifu Prefecture, central Japan. *Ibid.,* 18, 257-72.

Ishihara, S., 1969-1970—introduction to porphyry copper deposits. *Tokyo, Lattice Book Co.,* 2 vols.

ISHIHARA, S., 1971a—Major molybdenum deposits and related granitic rocks in Japan. *Geol. Surv. Japan Rep.* 239.

ISHIHARA, S., 1971b—Modal and chemical composition of the granitic rocks related to the major molybdenum and tungsten deposits in the Inner Zone of Southwest Japan. *J. geol. Soc. Japan,* 77, 441-52.

ISHIHARA, S., and KAWACHI, Y., 1961—On the Takakuma-yama granitic stock and related uraniferous ore deposits of Nagao-ko at Tarumizu mine, Kagoshima Prefecture. *Geol. Surv. Japan Rep.* 190, 333-48.

ISHIHARA, S., SEKINE, S., HARADA, T., and HILDA, N., 1969—Beryllium exploration using portable beryllium detector and geochemical field method for beryllium. *Bull. geol. Surv. Japan,* 20, 151-60.

ISHIHARA, S., SEKINE, S., MOCHIZUKI, T., and OBA, K., 1969—Contents of uranium and thorium in granitic rocks and their petrogenetic significance. *Geol. Surv. Japan Rep.* 232, 179-219.

ISHIHARA, S., and KANAYA, H., 1971—Highly magnetic granitic series and their bearing on the petrogenesis (abstract). *Proc. geol. Cong. Kyushu Univ.,* 271.

ISHIHARA, S., and SHIBATA, K., 1972—Re-examination of the metallogenic epoch of the Ikuno-Akenobe province in Japan. *Min. Geol. (Tokyo),* 22 (in press).

KAWACHI, Y., 1961—Granitic rocks and related uraniferous metallic ore deposits in southern Kyushu. *Geol. Surv. Japan. Rep.* 190, 93-103.

KENNEDY, G. C., 1948—Equilibrium between volatiles and iron oxides in igneous rocks. *Amer. J. Sci.,* 246, 529-49.

KERR, P. F., 1946—Tungsten mineralization in the United States. *Geol. Soc. Amer. Mem.* 15.

KUNO, H., 1959—Origin of Cainozoic petrographic provinces of Japan and surrounding areas. *Bull. volc.,* 20, 37-76.

KUNO, H., 1966—Lateral variation of basalt magma across continental margins and island arcs. *Bull. volc.,* 29, 195-222.

KIM, J., 1967—The geology and useful mineral resources of Korea. *Korean Sci. Inform.,* IV, 89-96.

KIM, O. J., 1971—Metallogenic epochs and provinces of South Korea. *J. geol. Soc. Korea,* 7, 37-59.

KINOSAKI, Y., 1953—On the granitic rocks in Chugoku, and the molybdenite and wolframite deposits in them. *Rep. Earth Sci. Hiroshima Univ.,* 3, 61-76.

KINOSHITA, K., ed., 1961—NIHIN CHIHO KOSHO-SHI: KYUSHU DISTRICT. *Tokyo, Asakura Book Co.*

KINOSHITA, K., and MUTA, K., 1954—On the magnetite ore deposits of magmatic origin in the Ebisu mine, Shimane Prefecture, Japan. *J. geol. Soc. Japan,* 60, 363-77.

LE PICHON, X., 1968—Sea-floor spreading and continental drift. *J. geophys. Res.,* 73, 3661-97.

LOWELL, J. D., and GUILBERT, J. M., 1970—Lateral and vertical alteration—mineralization zoning in porphyry ore deposits. *Econ. Geol.,* 65, 373-408.

MATSUDA, T., and UYEDA, S., 1971—On the Pacific-type orogeny and its model—extension of the paired belts concept and possible origin of marginal seas. *Tectonophysics,* 11, 5-27.

MATSUMOTO, T., 1968—A hypothesis on the origin of the late Mesozoic volcano-plutonic association in East Asia. *Pacif. Geol.,* 1, 77-83.

MIYAHISA, M., 1958—Tertiary acid intrusives and related metallogenetic provinces in the Outer Zone of Kyushu and Shikoku, Japan. *Mem. Ehime Univ., Sec.* II, 3, 145-60.

MIYASHIRO, A., 1958—Regional metamorphism of the Gosaisyo-Takanuki district in the central Abukuma Plateau. *J. Fac. Sci. Univ. Tokyo,* 11, 219-72.

MIYASHIRO, A., 1961—Evolution of metamorphic belts. *J. Petrol.,* 2, 277-311.

MIYASHIRO, A., 1967—Orogeny, regional metamorphism, and magmatism in the Japanese islands. *Medd. Dansk geol. Foren.,* 17, 390-446.

MOORE, J. G., 1959—The quartz diorite boundary line in the western United States. *J. Geol.,* 67, 198-210.

MOORE, J. G., 1962—K/Na ratio of Cenozoic igneous rocks of the western United States. *Geochim. cosmochim. Acta,* 26, 101-30.

MOORE, J. G., GRANTZ, A., and BLAKE, M. C., Jr, 1963—The quartz diorite line in northwestern North America. *U.S. geol. Surv. prof. Pap.* 450-E, 89-93.

NISHIWAKI, C., IWAFUNE, T., SHIOBARA, K., SAKUMA, T., and TONO, A., 1970—Geology and ore deposits of the Kamioka and Hamayokokawa mines. *IMA-IAGOD Tokyo-Kyoto Mtgs 70, Guidebook* 7, 40 pp.

NOBLE, J. A., 1970—Metal provinces of the western United States. *Bull. geol. Soc. Amer.,* 81, 1607-24.

NOZAWA, T., 1956—Some considerations on the spinel-bearing inclusions in Osuzu acid rocks, Kyushu, Japan. *J. Japan. Ass. Miner. Petrol. econ. Geol.,* 40, 33.

NOZAWA, T., 1970—Isotopic ages of Late Cretaceous acid rocks in Japanese islands; Summary and notes in 1970. *J. geol. Soc. Japan,* 76, 493-518.

OBA, N., 1963—Chemical composition of the Kyushu Outer Zone granitic rocks. *Sci. Rep. Kogoshima Univ.,* 12, 35-51.

OBA, N., 1966—Geological meaning of the granitic rocks in the western district of the Shimanto terrain. *Ibid.,* 15, 13-24.

OSBORN, E. F., 1962—Reaction series for subalkaline igneous rocks based on different oxygen pressure conditions. *Amer. Miner.,* 47, 211-26.

PETERSON, U., 1970—Metallogenic provinces in South America. *Geol. Rdsch.,* 59, 834-97.

RAMOVIC, M., 1968—PRINCIPLES OF METALLOGENY. *Univ. Sarajevo.*

RINGWOOD, A. E., 1969—Composition of the crust and upper mantle. *Geophys. Monogr.,* 13, 1-17.

ROEDDER, E., 1971—Fluid inclusion studies on the porphyry-type ore deposits at Bingham, Utah, Butte, Montana, and Climax, Colorado. *Econ. Geol.,* 66, 98-120.

SEKI, Y., and KENNEDY, G. C., 1965—Muscovite and its melting relations in the system $KAlSi_3O_8 — H_2O$. *Geochim. cosmochim. Acta,* 29, 1077-83.

SEKINE, Y., 1967—On the metallogenic unit. *Min. Geol. (Tokyo),* 17, 293-8.

SHIBATA, K., and ISHIHARA, S., 1971—K-Ar ages of molybdenum-tungsten deposits and related granitic rocks in the Inner Zone of Southwest Japan (abstract). *Proc. geol. Cong. Kyushu Univ.,* 281.

SUGIMURA, A., 1960—Zonal arrangement of some geophysical and petrological features in Japan and its environs. *J. Fac. Sci. Univ. Tokyo,* 12, 133-53.

TAKENOUCHI, S., 1971—Study of CO_2-bearing fluid inclusions by means of the freezing stage microscope. *Min. Geol. (Tokyo),* 21, 286-300.

TERADA, K., OSAKI, S., ISHIHARA, S., and KIBA, T., 1971—Distribution of rhenium in molybdenites from Japan. *Geochem. J.,* 4, 123-42.

WATANABE, M., 1944—Types of molybdenum deposits in the Tohoku district. *J. Japan. Ass. Miner. Petrol. econ. Geol.,* 32, 121-8.

WATANABE, M., 1953—Tungsten and molybdenum resources in Japan. *Proc. 7th Pacif. Sci. Cong.,* 2, 209-12.

WATANABE, T., and SASAKI, A., 1961—Tin and tungsten deposits of Japan. *Proc. 9th Pacif. Sci. Cong.,* 12, 908-11.

USTIYEV, YE. K., 1965—Problems of volcanism and plutonism. Volcano-plutonic formations. *Int. geol. Rev.,* 7, 1944-2016.

WALLACE, S. R., MUNCASTER, N. K., JONSON, D. C., MACKENZIE, W. B., BOOKSTROM, A. A., and SURFACE, V. E., 1968—Multiple intrusion and mineralization at Climax, Colorado. *In* ORE DEPOSITS IN THE UNITED STATES 1933-1967, *N.Y., AIME,* 1, 605-40.

YODER, H. S., and EUGSTER, H. P., 1955—Synthetic and natural muscovites. *Geochim. cosmochim. Acta,* 8, 225-80.

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ORE DEPOSITS OF THE PHILIPPINE MOBILE BELT

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SUMMARY

The Philippine 'Mobile Belt' region is a principal source of metallic ores of magmatic and hydrothermal origin. Several tectonomagmatic regimes are involved in its gradual transformation from a eugeosyncline during the Cretaceous into a platform by the end of the Tertiary.

The regimes may be classified in a general way as follows: (1) a non-differentiating type of magmatic regime with indicated and/or implied tensional tectonics, apparently contemporaneous with depositional or sedimentation periods; (2) a differentiating type generally synchronous with periods of orogenic movements or what appear to be periods of general crustal compression.

The two types essentially alternate. Only minor ore deposits, mainly small bodies of parasyngenetic manganese oxide, are related to the first type. The great majority are related to activity produced by the second type, which occurred in at least three if not four periods.

The first regime (from late Cretaceous to early Palaeocene) is represented by magmatic differentiates of ultramafic suites—gabbro to diorite. Chromite, nickel sulphides, and hypothermal high-grade copper sulphide veins were deposited.

The second regime (late Eocene to Oligocene) produced small diorite to quartz diorite intrusives and volcanic differentiates of andesitic to dacitic composition. Large deposits of disseminated copper sulphides, associated with small amounts of gold, silver, molybdenite, and traces of lead and zinc ores, are represented.

The third regime (middle to late Miocene) formed predominantly quartz diorite batholiths and differentiates of diorite, diorite porphyry, granodiorite, and dacite, and volcanics of andesite to dacite and possibly rhyolite. Associated ore deposits include pyrometasomatic iron, disseminated copper, vein and/or replacement copper, lead and zinc, gold and gold tellurides, some 'Kuroko' type ores and cupriferous pyrite. Other associated metals include some molybdenum and silver, and small amounts of cadmium and mercury.

The fourth regime (late Miocene? to Pliocene and later), which can well be a post-platform regime, has essentially small microdiorite-andesite to dacite intrusions and extensive volcanism of similar composition, andesite to dacite. Related ore deposits include sulpho-arsenide-antimonides of copper, gold and gold tellurides, silver sulphides, and some associated lead and zinc as well as cinnabar.

Relationships between the island arc structures, sites of differentiating igneous activities, and structural sites of the various ore deposit groups suggest that many structural systems which localized magmatism and metallization during a particular regime were usually healed by the end of the regime and that new sites are formed for the succeeding one. Structures reactivated by succeeding regimes could better explain the very large disseminated copper deposits like Atlas Mine in Toledo, Cebu, and the deeply penetrating gold vein system of the Baguio Mineral District.

Introduction

Mining of ore deposits could be one of the pre-Spanish native industries in the Philippines. It is thought that copper from Lepanto, Luzon, was traded with China during the Ming Dynasty.

The earliest recorded study of Philippine ore deposits is Jose G. Canteno's *Memoria Geologico-Minera de las Islas Filipinas,* 1876-1879 (copy not available to the author). More systematic and comprehensive studies were made by American geologists and mining engineers in 1902. An excellent summary of these early works is included in the book by W. D. Smith, *Geology and Mineral Resources of the Philippine Islands,* published in 1924. Later studies are largely individual efforts of both Filipino and American geologists and mining engineers, such as L. F. Abad, Q. Abadilla, R. F. Abarquez, A. Alvir, V. Elicano, L. A. Faustino, and J. M. Feliciano, before World War II; P. Capistrano, D. Cruz, A. R. Kinkel, Jr, et al., V. E. Lednicky, L. Santos-Ynigo, M. H. Tupas, G. R. Oca, and A. Gonzales, immediately after the war, to mention a few. Some of the descriptions of mines and districts drawn on in this paper, though not cited individually, are listed in the Bibliography. The writer, together with H. Fernandez (1967), tried to summarize the age and nature of metallization of the Philippines. The metallogenic study from which much of the current data was obtained was started in 1964 as a project of the Bureau of Mines, Geological Survey, Economic Geology Section.

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General Statement

Earlier studies by the writer (1964) described the archipelago as two distinct regions or tectonic provinces, the 'Philippine mobile belt', and the 'aseismic or stable region'.

The aseismic region has furnished only a small massive lens of cupriferous pyrite in Balabac Island; a few thousand tons of metallurgical chromite from Central Palawan (the deposit was quickly mined out); low-grade sedimentary manganese ores in Busuanga-Coron Islands (out of operation); and cinnabar mines (in operation, Central Palawan). The area is, however, the principal source of silica sand. The future of the region for metalliferous deposits seems limited, at present, to possibilities of nickeliferous laterite (potential is tremendous); still undeveloped low-grade mercury prospects; and low-grade, siliceous, sedimentary manganese ore. Interesting occurrences of stibnite veins and arsenopyrite-gold veins have been prospected. Some heavy minerals (allanite-monazite) are known to be present in beach sands.

The bulk of mineral production of the country comes from the mobile belt region. Currently, there are five large and ten small copper mines, two principal chromite producers, about seven iron mines (three lode type and four of magnetite sands), and five gold producers in the region. Six other mines, five of copper and one of zinc-lead-copper, are scheduled to operate soon. Substantial amounts of molybdenum, gold, silver, pyrite, and magnetite are produced as by-products of some copper mines. Many places were also mined for manganese and chromite ores, but generally operations were short-lived because of limited reserves and the low grade of the deposits.

Geological Background

Figure 1 shows the generalized structural aspects and various rock types of the Philippines and their associated ore deposits.

Briefly, the Philippine mobile belt is essentially a former eugeosynclinal zone that developed into a plutonovolcanogene belt, and through periodic orogenesis became gradually transformed into an island arc/platform system. The whole developmental period belongs to the Mesozoic-Tertiary geotectonic cycle.

Its geological history can be summarized as follows:

Geosynclinal Stage

Initially, during Jurassic to Cretaceous, the area was occupied by at least two eugeosynclinal basins, arranged *en echelon* along a nearly meridional trend. The northern basin covered the greater part of Luzon Island; the southern basin covered the Bicol region, Visayas, and Mindanao.

They were superimposed on a denuded Palaeozoic metamorphic fold belt made up largely of schists. Their formation can be correlated to a known period of major crustal reorganization considered to have involved general stretching, fracturing and/or fragmentation of the crust, intensified continental drifting, enormous outpourings of basalts and spilites, and, within the region, general geosynclinal formation or marine inundation of many areas.

Early sediments were some 3000 m of greywacke and shale with intercalated spilite and basalt, and minor Lower Cretaceous limestone in the upper part of the sequence. As fracturing intensified, the basins appear to have expanded while submarine extrusive activity dominated the depositional pile, until the deformational energy was finally dissipated in strong outbursts and massive upwelling of lavas. During this event, parts of the basin floors were apparently torn apart and the area became essentially flooded by spilitic lavas. Some of the basement schists were dislocated and/or carried en bloc, and their dislocation induced severe to moderate plastic folding in the overlying early geosynclinal sequence, as in Central Cebu; others were simply engulfed or floated in the flood of lava, as in Caramoan Peninsula.

A system of basins within the mobile belt was formed when the upwelling activity ceased, and as the lavas finally solidified, the magmas which were sealed below could be presumed to have undergone the slow process of cooling and fractional crystallization. Thus, in effect, the stage ended with the development of a plutono-volcanogene-mobile belt zone.

Initial Orogenic Stage

Sedimentation in the intra-mobile-belt basin started during the Upper Cretaceous. Volcanic wacke and shale, together with limestone (generally of thin bedded chalky or cherty types, some biohermal) were deposited. Intermittent eruptive volcanism added andesitic tuffs and agglomerates and minor flows, particularly during the later period of sedimentation.

Orogenic movement began at the close of the Cretaceous, involving severe to moderate crustal folding and thrusting and quasi-solid emplacement of layered and non-layered ultramafics and gabbro, some diabase dykes, and small stocks of diorite.

Large arcuate 'island arc' thrust structures were formed along both the eastern and western borders of the mobile belt, and became the sites for quasi-solid emplacement of layered and non-layered ultramafics in places, with associated concordant as well as discordant gabbro intrusives. Several geanticlines also developed along the inner zone of the mobile belt (Central Cebu, southern Sierra Madre, and Baguio District) where small diorite stocks were localized.

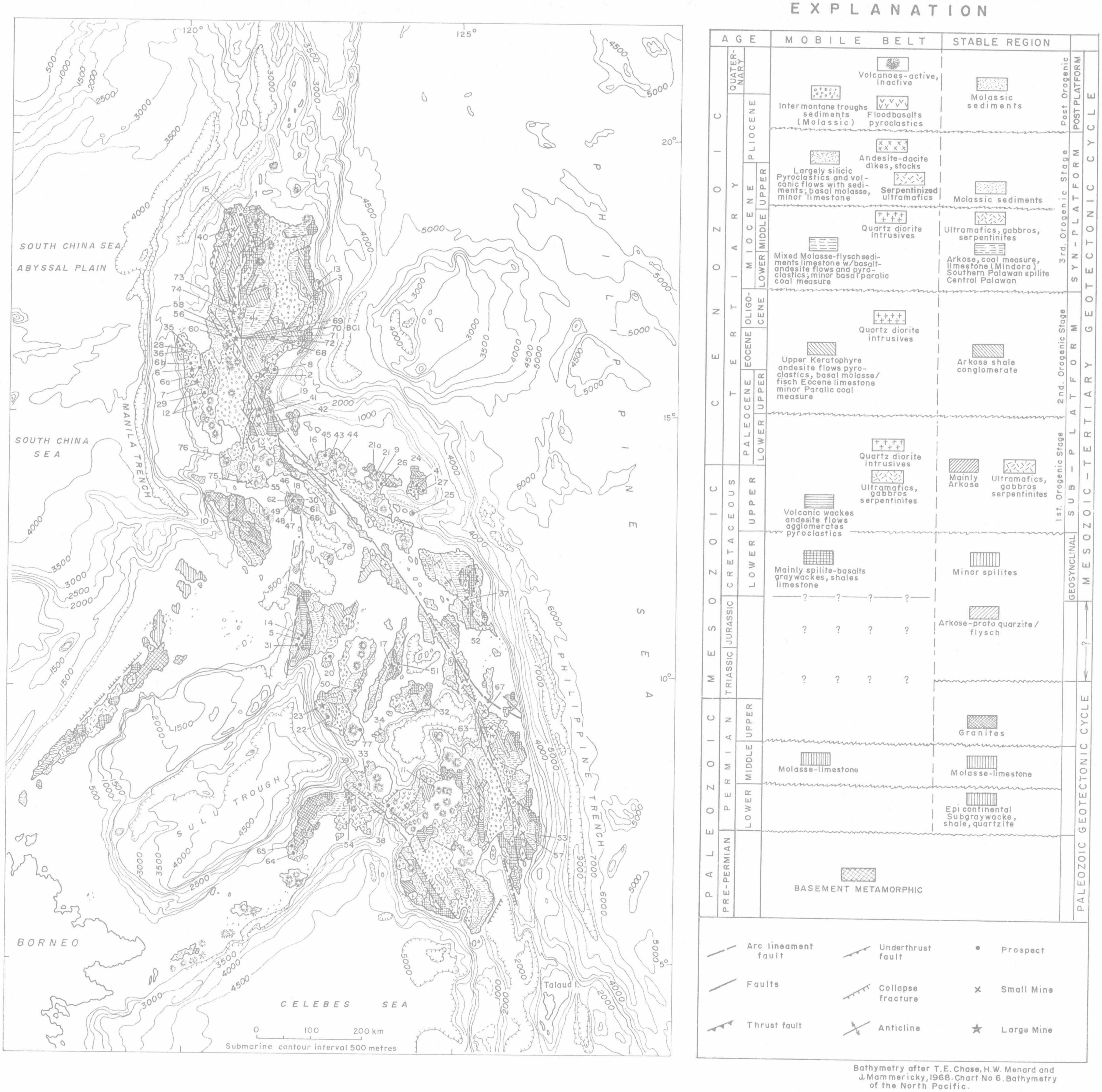
Thus, as a generalized development, the initial orogenic stage essentially: (1) established the fundamental structures of the island arcs; (2) removed from the crystallizing magma at depth, at least, part of its early crystalline and viscous quasi-solid fractions, including some of the early formed immiscible sulphide fraction, possibly by hydraulic press action; and (3) re-organized parts of the intra-mobile-belt basins.

Sub-Platform Orogenic Stage

Renewed transgression and sedimentation started during the upper Palaeocene and continued to Eocene. Initially, some basal conglomerates and paralic coal measures were deposited in places, while in many areas mainly volcanic wackes and shales with intercalated limestone accumulated. Further transgressive sedimentation formed a thick sequence of Eocene wacke, shale, and limestone. In the Baguio District, largely conglomerate and arkosic wacke were deposited. Subsequent intermittent andesitic, dacitic, and keratophyric volcanism added flows, agglomerates, and tuffs to the upper sequence. The whole transgressive stage accumulated deposits over 2000 m thick in many places.

A very pronounced regressive stage started apparently during late Eocene and continued to Oligocene. Thick and extensive keratophyre-andesite and dacite flows, agglomerates, and tuffs, exceeding 3000 m in places, were deposited in a terrestrial and sub-terrestrial environment. Late volcanic springs deposited chert and induced intense pyritic alteration in many areas.

Orogenic movement during the middle Oligocene reactivated the island arc structures and formed sub-parallel orogenic belts at the inner zones of the arcs, where, in places, quartz diorite stocks were emplaced. Some of the arc lineament zones also became sites of quartz diorite intrusions. Along the inner region, especially in the western Visayan Islands and in Sierra Madre, several large stocks and



Bathymetry after T.E. Chase, H.W. Menard and J. Mammericky, 1968. Chart No 6. Bathymetry of the North Pacific.

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Fig. 1. Tectonic and ore deposits map of the Philippines.

batholiths of quartz diorite were emplaced. Such orogenic activities are associated in places with the formation of disseminated copper deposits, gold veins, and pyrometasomatic iron ores.

In general, the sub-platform stage ended with the establishment of extensive land masses both along the mobile belt and in adjacent regions. Considering their form and textural aspects, most quartz diorite masses are considered to be similarly emplaced as viscous quasi-solids. The amount of associated sulphide mineralization greatly exceeds that of the Cretaceous, although most deposits show a preponderance of pyrite. Associated silicification is also considerable. Many Oligocene orogenic belts still remain unexplored.

Syn-Platform Stage

The syn-platform stage began during the lower Miocene (Te_{4-5}) with general fracturing and subsidence in many areas. Local paralic coal basins with molasse sediments were initially deposited. As transgression continued, thick and extensive biohermal limestones were formed together with intercalated basalts, spilites, andesitic flows, agglomerates, and pyroclastics, suggesting reactivation of the crust. Deposition of thick clastic sequences continued, however, in large basinal zones. The adjacent aseismic region manifested outpourings of spilite/basalt lavas.

Regression followed during the middle Miocene as the persistent volcanic activity became more eruptive, as manifested by thick piles of pyroclastics in the Baguio district, and in Mindanao intermontane basin zones.

Orogenic movement recurred before the end of the Miocene, involving again folding and thrusting; but more pronounced is the formation of large orogenic belts cored by huge masses of quartz diorite batholiths with associated trondhjemite, granodiorite, diorite, and dacite. Numerous stocks were also emplaced in other areas. Copper (including disseminated porphyry type), gold, sphalerite-galena, and pyrometasomatic iron ores were deposited in quantity. Most of the present configuration of islands and mountain ranges owes its initial form to this stage.

Protracted Syn-Platform Development

Rapid uncovering of the orogenic belts exposed most batholiths and deposited thick molassic sediments during the upper Miocene (Tf_{2-3}). In a few places limestone has formed. Gradually intensifying highly eruptive volcanic activity (andesitic to dacitic) followed and overshadowed sedimentation over the whole mobile belt, during the late upper Miocene to Pliocene (Tf_3-g). The unrest culminated in the intrusions of some small andesitic and dacitic stocks, volcanic plugs and dykes, isostatic uplift of most Miocene orogenic belts, and, in general, folding and thrusting in many cases, including reactivation of movements along island arc structures. Some isostatic uplifts involved over 2000 m, bringing along some of the intra-orogenic-belt basins and dragging parts of marginal basin zones. Décollement fold belts were formed alongside elevated orogenic belts. In most of the intra-Pliocene fold belts south of the latitude of Manila, serpentinized periodotites were intruded cold along thrust zones and overrode the folded upper Miocene-Pliocene tuffaceous sequence.

Gold and gold tellurides, together with enargite, luzonite, some stibnite, galena, and argentite, were deposited during this stage, associated apparently with the andesite-dacite magmatic activity.

Post-Platform Stage

Plio-Pleistocene to Quaternary time was mainly occupied by a post-platform erosional cycle under fluctuating sea level conditions—generally regressing from Pliocene to Pleistocene by a few hundred metres, and transgressing during more recent time by more than a hundred metres. Reactivation of the platform area is manifested by intermittent block-faulting and subsidence, frequent earthquakes, the formation of numerous volcanic cones and plugs, and in places, the upwelling of plateau basalts.

General Features of the Ore Deposits of the Mobile Belt

(See Fig. 1 for location of various numbers of the deposits cited in the following discussion).

Deposits Associated with Cretaceous Volcanic Rocks

Manganese ore lenses and fracture fillings in pillow joints or interstices and in reddish volcanic shale, sometimes limy, are found in limited quantity with chert-spilite and, more commonly, with spilitic pillow lavas. The ore consists largely of braunite, cryptomelane, and psilomelane, and secondary pyrolusite. Grade of ore ranges generally from 30 to 40 percent manganese, but extremes are above 50 percent and as low as 10 percent. The variations are largely due to contained silica, iron, and alumina. Intense deformation of the spilite sequence, lack of conspicuous alteration, and lenticularity of the orebodies have handicapped exploration. Occurrences of the deposits are known in Vintar, Ilocos Norte[(1)]; Laur and Malinao, Quezon[(2)]; Sierra Madre in Isabela [(3)]; and Catanduanes [(4)].

Cupriferous pyrite deposits associated with basaltic and spilitic pillow lavas are found in lenses in Antique[(5)] and have been reported also in Mindoro. Little showings of similar sulphides have been observed in Caramoan Peninsula, with Cretaceous basalts.

Deposits Associated with late Cretaceous-Palaeocene intrusives

(a) Syngenetic chromite ores, of both metallurgical and refractory grade, are found associated with layered ultramafics in the Zambales Range[(6,7)]; and with alpine-type peridotite in Baler, Quezon Province[(8)]; Caramoan Peninsula, Bicol Region[(9)]; Mindoro Island[(10)]; and in Misamis Oriental, Mindanao[(11)]. Present production is, however, confined mainly to the Zambales layered ultramafics, in the Acoje and Masinloc chromite belts.

The Acoje metallurgical chromite belt extends from Acoje mine[(6)] south-southwest to the Insular Chromite Reservation No. 2[(6a)] and north-northeast to Reservation No. 3[(6b)], a distance of about 20 km. The orebodies are found as sporadic lenses, bands, or layers or as shoe-string deposits in dunite. The ore zone commonly contains disseminated pentlandite and other nickel sulphides. The dunite and dunitic peridotite host rock along which the ores are found constitutes part of the basal sequence of the layered, folded ultrabasic rocks. The layered sequence includes basal dunite, lherzolite, saxonite, and an upper troctolitic and noritic gabbro intercalated with peridotite or saxonite or both. The present productive zone appears to be part of the eastern limb of the anticline, which runs southwest to nearly south. The western limb is still barely explored, but indicates a number of similar deposits.

The Masinloc refractory chromite belt lies parallel to, and about 10 to 12 km east of, the Acoje Belt. The country rock also consists of layered dunite, peridotite, saxonite, olivine gabbro, and an upper noritic gabbro. Orebodies, found in lenses (now being mined by Benguet Consolidated, Inc., considered the world's largest producer of refractory chromite), are enclosed in serpentinized saxonite close to the saxonite/olivine gabbro contact (Stoll, 1962). Accordingly, there is one big lens and ten to twelve smaller ones, all strung out in a belt about 2.5 km long. A rough parallelism is recognized between the ultramafic layers and the string of chromite deposits. More recent mining cuts and exploration strongly suggest a layered relationship, similar to the Acoje belt; both are undoubtedly magmatic segregation deposits.

The chromite deposits found in Alpine-type peridotite are similar to Acoje, in the sense that they are associated invariably with dunitic masses. There are three main types of orebody (Gervasio & Fernandez, 1967): massive lens, layered and/or shoe-string type; nodular and breccia type; stringer and vein type. The first and second are both distinctly syngenetic early magmatic crystal differentiates, but the crystal fractions of the second type were possibly disturbed and corroded during the injection stage, if not formed under turbulent magmatic conditions. The third type is possibly a hydrothermal deposition; it is not known to give any commercial production.

Table 1 shows the average analyses of the chromite ores of Zambales (N. S. Fernandez, 1960). Fernandez concludes that the metallurgical-chromite-bearing belt in Zambales is an upper sequence compared to the refractory-type-bearing belt, pointing out that the latter generally contains more MgO than the former. Recent field observations by the writer do not, however, support such a contention. The two belts seem to be part of a continuous differentiation series; the former represents a part of the olivine-rich earlier crystallizates and the latter (refractory belt) formed when the magma had become more siliceous, as is indicated by closer association with saxonite.

TABLE 1. ANALYSES OF CHROMITE MINERALS FROM ZAMBALES RANGE

Source	Cr_2O_3	Al_2O_3	Fe_2O_3	FeO	MgO(CaO)	SiO_2
Coto orebody*	36.5	31.0	—	10.8	17.2	0.85
Acoje Mine**	52.8	13.4	5.6	13.3	13.7	0.97
Molenite**	40.3	27.6	4.2	10.6	16.7	0.52
Reservation No. 1*	37.2	29.5	2.1	11.6	17.9	0.45
Salor	52.7	16.1	5.3	12.6	14.0	0.07
Western Filipinas*	43.6	25.5	—	17.4	12.0	1.11
Eastern Filipinas**	48.6	15.1	—	23.5	10.1	1.60

* refractory type ** metallurgical

(b) A number of small copper sulphide deposits consisting of chalcopyrite-pyrrhotite-pyrite, usually in vein form, are found in several localities along faults, thrusts, or joints cutting through the late intrusive gabbro and gabbro-saxonite sequence in eastern and southern Zambales Range [12]. They usually manifest hypothermal aspects; the gangue commonly consists of chlorite-actinolite-quartz ribbons.

Most of the veins pinch and swell and generally grade upward to purely bull-quartz vein. Hydrothermal alteration of wall rock is generally either absent or weak.

In Bicobian[13], Isabela, east coast of Sierra Madre, north Luzon, along thrust slivers which constitute part of the frontal arcuate thrust structure of the convex north Luzon arc, the serpentinite-spilite-greywacke exposures hosted some very high-grade small lenses and pods of primary chalcocite ore. Some hand-picked specimens assayed 55 to 79 percent copper (de Guzman, 1968). Several shipments made ranged in grade from 16.76 percent to 18.79 percent copper, 1 to 2 g gold, and 6 to 39 g silver per tonne. There are above five known orebodies, generally moderately dipping west, concordant to the arcuate thrust structures. The largest deposit is essentially confined to the serpentinized peridotite. Some weak dispersions were noted by de Guzman in the associated brecciated chert and spilite flows. Accordingly, above the ore zone, 3600 tonnes of manganese ore (braunite) of 38.39 to 41.8 percent of manganese were also mined out. The copper orebodies show very insignificant alteration effects: at the most, feeble silicification of wall rocks. The ore minerals consist primarily of dense steel-grey chalcocite, some chalcopyrite, bornite, and pyrite, with secondary covellite, sooty chalcocite, native copper, cuprite, malachite, and azurite.

Similar occurrences are indicated in several places along the arc lineament zones: in Antique, Panay[14], and in Pasuquin[15], northwestern tip of Luzon. Host rocks are similarly the Cretaceous spilites in contact with serpentinized ultramafics. Some of the primary chalcocite specimens in Antique assayed as much as 64 percent copper. Other ore occurrences found within the zone are massive lenses of cupriferous pyrite assaying from 1 percent to over 14 percent copper, and native copper insinuated along boudinage fractures in serpentines, as in Calawag, Quezon Province [16], along an extension of the Antique Lineament structure.

Low-grade porphyry copper is best represented by the Atlas Mine deposits[17] in Central Cebu. The Atlas diorite porphyry masses, which gave K/Ar dates of 59.7 $\pm$ 1.2 m.y. (early Palaeocene), show quite extensive low-grade copper sulphide mineralization, primarily of chalcopyrite, as incrustations and fillings along closely spaced fracture systems which were developed in the intrusives and wall rocks.

There are three large orebodies with an aggregate reserve of over one-half billion tons of about 0.5 percent copper. They are closely clustered within a 3 km-wide northeast-trending intrusive belt. Some other quartz diorite masses are localized within the belt, but are apparently not as pervasively mineralized. Regionally, the disposition of the three orebodies or the intrusive belt is more or less parallel to the general structural grain of Central Cebu, as well as to the steeply dipping thrust faults which controlled localization of small masses of serpentines. Some strong northwest fractures transect the intrusive belt, but no mineralization is indicated along their extension away from the ore-bearing northeast belt. A prominent nearly east-west copper-rich gash-fracture vein system is part of the exposures recognized before operation, suggesting a possible relationship to a northeasterly left lateral fault sympathetic to the Antique-Tablas lineament zone (Gervasio, 1964).

Zonal hydrothermal alteration is quite visible. Pyritization, sericitization, argillization, and silicification are most common and conspicuous and constitute the outer halo of the orebody, extending more than 300 m away from the ore zone. Silicification in most outer fringes is usually in the form of translucent, relatively impure quartz. In the orebody silicification is typified by transparent quartz, in fine aggregates and/or micro-honeycombs, sometimes in drusy cavities. The outermost epidote-chlorite zone is, however, considered partly, if not wholly, a product of regional metamorphism inherent in most metaspilite or metagreywacke. Guevara (1964) considers the bulk of the pyrite to have been derived from reaction of sulphur-charged solution with iron of the ferromagnesian minerals. It is to be noted, however, that hydrothermal magnetite, occurring in similar manner to the chalcopyrite, constitutes an important by-product of the mine.

The actual age of the Atlas ore deposits is not satisfactorily resolved. It is quite clear that the bulk of the sulphides were introduced after an intensive brittle rock deformation of the porphyries and the adjacent contact rocks, which extend to depths of 1000 m or more. Furthermore, this particular area of Central Cebu is known to have been involved in both intra-Oligocene and intra-Miocene orogenesis. In fact, only a few kilometres northeast of the area, pyrometasomatic iron ore deposits, including some chalcopyrite dispersions, were found in Lower Miocene rocks. Similarly, some hydrothermal alteration and specks of copper sulphides are indicated in the Miocene rock sequence south of Atlas Mines. It is therefore quite possible that the formation of the Atlas deposit involved more than a single episode.

Deposits Associated with Eocene-Oligocene Keratophyres and Quartz Diorite Intrusives

(a) Some manganese deposits are known to be associated with thick Eocene-Oligocene keratophyre flows, but these are very small and are essentially non-commercial. They include stringers of braunite filling small discontinuous fractures in the keratophyre flows of Marinduque[(18)] and small lenses in Bulacan-Sierra Madre[(19)]. Most occurrences are in the upper stratigraphic section of the keratophyre; none have been found in the lower sections. The apparent reason for lack of much manganese deposition may be the usually terrestrial and sub-terrestrial nature of deposition of most keratophyres.

(b) Contact metamorphic and vein type iron deposits are known to have developed within diorite intrusives and contact volcanic rocks in Guimeras Island[(20)], Caramoan Peninsula [(21)], and southern Negros[(22)], usually associated with epidote-rich skarn. The ores consist essentially of magnetite-hematite, specular hematite, and pyrite. One of the deposits[(21a)] in Caramoan Peninsula is quite a distance away from any known diorite mass, without any contact metamorphic aureole. It is localized within an Eocene volcanic wacke sequence. The ore is mineralogically quite different: instead of the magnetite-hematite and specularite ores, the bulk consists of red hematite and magnetite, suggesting a possible sedimentary origin followed by recrystallization by the combined effects of burial metamorphism and tectonic deformation of the beds.

(c) A disseminated copper deposit similar to the Atlas Mine is represented in Sipalay[(23)], southern Negros. Mineralization is generally confined within highly brecciated micro-quartz diorite bodies and adjacent highly fractured and metamorphosed spilitic volcanics and greywackes. The orebodies are apparently cupola-type deposits. Breccia pipe-pebble dyke is manifested in one of the deposits. The ore is also made up dominantly of chalcopyrite, pyrite, and magnetite, associated in places with a recoverable amount of molybdenite. The general trend of the deposits also follows that of the intrusive belt, which is northwest, parallel to the Mindanao island arc lineament zone. A transgressive early Miocene limestone and clastics which unconformably overlie part of the deposit do not show signs of mineralization nor of hydrothermal alteration, suggesting that the area was mineralized before the Miocene. Along the intrusive belt several prospects with similar signs of chalcopyrite mineralization are under exploration.

(d) Other deposits may be related to intra-Oligocene intrusion. In Caramoan Peninsula[(24)], and Rapu-Rapu Island [(25)], where intrusive activities are known to have affected Eocene but not Miocene rock sequences, different types of ore deposits exist close to contacts of quartz-diorite intrusives or along their length. The more common type consists of sharply bounded massive cupriferous pyrite lenses or pods enveloped by narrow zones of disseminated pyrite in schist. The deposits in Caramoan are generally smaller than than in Rapu-Rapu Island, described by Kinkel & Samaniego (1956). Many deposits are localized along upper limbs or axes, or both, of anticlines in the schist. Accessory minerals include chalcopyrite, sphalerite, gold, and silver. K/Ar dating of the schist in Rapu-Rapu gave 42 ± 2 m.y. (oral communication from Mobil Exploration, 1964), which could be the age of mineralization rather than that of the host rock.

Other deposits known include veins of iron ores (magnetite-hematite) with limited pyrometasomatic effects on wall rocks, and also some veins of complex sulphide ore (Zn-Pb-Cu) in Caramoan[(26)]. Low-grade dissemination of pyrite-chaleopyrite ore minerals of small quantity in diorite margins and contact rock are observed in Catanduanes[(27)].

Miocene Ore Deposits

The greater number of ore deposits found within the mobile belt are considered to have formed during the Miocene. These may be discussed separately, as classified earlier (Gervasio & Fernandez, 1967) under three general categories: pre-orogenic, synorogenic, and post-orogenic types.

The Pre-Orogenic Ore Deposits

These consist essentially of manganese ores associated with the early-middle Miocene marine basalt flows and agglomerates, as in western Pangasinan[(28)], Tarlac[(29)], Ipil, Marinduque[(30)], Antique[(31)], Bohol[(32)], and northern Zamboanga [(33)]. They are generally found as local concentrations above pillow lavas and below Te_{4-5} biohermal limestones. In Siquijor Island[(34)], the deposit is said to have formed by residual concentration through weathering of Miocene tuffs (oral communication from D. Cruz). Many of the deposits gave rise to short-lived commercial production of metallurgical and battery grade ores, chiefly of pyrolusite, psilomelane, and/or braunite.

'Kuroko' yellow-type copper ore deposits are found principally intercalated with, and secondarily as fissure fillings and/or replacement forms in, basalt-andesite flow-agglomerate-tuff series in Miocene volcanogene basins along the outer side of the arcuate peridotite chain in Barlo[(35)] and Equia[(36)], Pangasinan; in Bagacay, Samar[(37)], partly associated with Miocene coal; and in Lanao [(38)] and Zamboanga del Norte[(39)], along the lineament structural zone. The ore contains a considerable amount of pyrite, particularly the upper low-copper-bearing zone. Chalcopyrite-rich pockets and lenses are found intercalated with pyritic-argillized tuffs and agglomerates at lower beds in Pangasinan. Associated sphalerite and some galena are often erratically distributed. Samples from Samar are associated with marcasite and cupriferous pyrite. Those from Lanao are typical breccia ores of sphalerite-chalcopyrite and pyrite.

The Synorogenic Ore Deposits

These are represented by epigenetic, hypogene deposits formed close to or within the hydrothermal influence of the middle to upper Miocene quartz diorite stocks and batholiths, separable into: (1) contact metamorphic or replacement, (2) disseminated or porphyry copper, and (3) lode and/or vein replacement types.

(1) The contact metamorphic and/or replacement type are essentially represented by pyrometasomatic iron or copper-rich skarn deposits. The iron deposits are found in Ilocos Norte[40], Camaching, Bulacan[41], Santa Ines, Rizal[42], Larap[43], Labo[44] and Capalonga[45], Camarines Norte, in Taluntunan[46], Boi[47], Hinapulan[48] and Mogpog[49], Marinduque, also in Negros[50], Cebu [51], Samar[52], Davao [53] and Zamboanga[54], Mindanao. A copper deposit of contact-metamorphic type is represented by the currently producing Consolidated Mines, Inc. pit in Isaw[55], Mogpog, Marinduque Island; the Benguet Exploration Mine[56] in Baguio, Luzon; and the Masara Mine[57] in Davao, eastern Mindanao. Replacement iron and copper deposits are both localized along an Eocene clastics-limestone stratigraphic sequence, in contact with large quartz diorite stocks or batholiths. Greater concentrations are localized especially within the unconformity zone of the Eocene sequence with either the Cretaceous rocks or the keratophyre sequence. Most iron deposits are in the form of massive lenses of magnetite and hematite, associated skarn or tactite ores, and some pyrite and chalcopyrite. The copper deposits, on the other hand, extend along a certain stratigraphic zone as dispersed sulphide grains usually associated with minor sphalerite, galena, and gold. Wall-rock alteration is generally limited to a narrow pyritic and argillized zone and some silicification.

(2) The disseminated or porphyry copper deposits are represented by Santo Nino[58], Philex Mines[59], and Black Mountain Mines [60], in the Baguio district; by Marcopper Mine[61] and Ino Mine[62] deposits in Marinduque; and by the Manila Mining[63] deposit in Agusan, eastern Mindanao. Much ground with a similar alteration and configuration in many orogenic belts remains unexplored. In most cases ore is localized essentially in stockwork developed in both intrusives and adjacent intruded rocks. The alteration zones are usually extensive and are no different from those of the Atlas or Sipalay porphyry copper mines. Gypsum and anhydrite in stockworks, veins, and stringers are often encountered near the ore zone.

The structural controls are not yet determined. A narrow minerogenetic belt usually 2 to 3 km wide can be drawn in many areas by considering the geographical disposition of the mines, prospects, and alteration zones. Such belts are essentially parallel to the intrusive belt, but not exactly along the contact of the intrusives. Stratigraphically, most deposits occur between the upper Eocene to lower Oligocene keratophyre zone and the Cretaceous spilite horizon. Incidentally, the same limits can be placed on the occurrence of brittle rock deformation developed in most minerogenetic belts. Older porphyries found within the zone of the minerogenetic belt, such as the locally named 'bird's eye porphyry' or 'peanut brittle', seem to be richer in copper than other rocks. The pyritic alteration zone is apparently more extensive in keratophyre zones than in the Cretaceous spilite zone, but orebodies persist to greater depths within the latter.

(3) The lode and/or vein replacement type is represented by the zinc-lead-copper ore deposit in Ayala, Zamboanga City, of Zambales Base Metals, Inc.[64]. It also exhibits a wide hydrothermal alteration halo of pyrite-sericite which laterally extends more than 1 km beyond the ore zone. The deposit is not close to any known diorite intrusives, but dacite and andesite dykes are found near it. The ores are localized along fracture zones and brecciated early Miocene clastics, and extend laterally along favorable horizons rather than vertically along the feeder fractures. A similar deposit is also known at the western side of southern Zamboanga[65].

The Post-Orogenic Type

Post-orogenic deposits are represented by the vertically extending veins of complex sulphide ores, Pb-Zn-Cu deposits in eastern Marinduque[66], in northern Surigao[67] and Nueva Vizcaya[68], usually far removed from the intrusive belt. In Baguio mineral district, series of gold veins usually associated with copper, lead, and zinc extend more than a thousand metres along fractures in the quartz diorite batholiths and in the adjacent contact rocks; some along cooling joints of the intrusives as in Acupan[69], Balatoc[70], Antamok[71], and Itogon Mines[72]. Anhydrite-gypsum veins are common within the deposits. Generally richer values are found associated with siliceous veins and poorer values with anhydrite-gypsum veins. In a broad sense, most of the vein systems are normal in trend to the quartz diorite masses.

Miocene-Pliocene (Post-Platform Stage) Deposits

Mineralization during the period consists generally of complex sulphide and sulpho-arsenide-antimonide ore deposits.

(a) In Lepanto Mine[73], north Luzon, a sizeable deposit of enargite-luzonite ore with associated tennantite, pyrite, chalcopyrite, native gold, and gold and silver tellurides, was formed along gash fractures of a northwesterly fault within an unconformity zone between upper Miocene-Pliocene dacite flows and underlying metavolcanic rocks. Regionally, ore localization appears to be structurally guided upward by the strong northwesterly fault zone and its intersection with a nearly north-south fracture. Locally, tension gash fractures younger than the northwest system controlled vertical ore dispersion, while the unconformity zone between dacite flows and metavolcanics provided lateral control. Pervasive argillization of the dacite capping, including several upward leakages of mineralization, is indicated. Ore textures include open space and/or breccia filling and some replacement features. Some ore specimens show colloidal aspects.

(b) Broad *en-echelon* north-northeasterly quartz-gold veins with associated chalcopyrite are emplaced in a late Miocene molasse sequence near its contact with a small dacite porphyry stock in Suyoc Mine[74], Luzon, a few kilometres southeast of Lepanto.

(c) In the Baguio Gold District[69,70], Worley (1966) of Benguet Consolidated Mines recognized late hydrothermal deposition of pyrite and marcasite, with associated native gold, tellurides, minor galena, sphalerite, chalcopyrite, arsenopyrite, stibnite, and cinnabar. They are considered to be related to protracted stages of Miocene metallization. Some of the recognized mineralization bears a genetic relation to Pliocene andesite breccia pipes intruding the batholith.

(d) Vein and vein-replacement deposits containing enargite, tennantite, galena, luzonite, chalcopyrite, and barite were localized in keratophyre flows in Lobo[75], Batangas; in Looc[76], Batangas, primarily argentiferous galena with some sphalerite, pyrite, 'ruby silver', and stibnite was deposited with calcite and chalcodonic silica gangue. Both deposits are clearly related to Pliocene andesitic plugs and stocks.

Quaternary Deposits

Quaternary metalliferous deposits in the mobile belt are apparently limited to marcasite and pyrite associated with volcanic sulphur deposits, as in Amlan[77], southern Negros. Cinnabar has been reported in Sibuyan Island[78]. Like the Palawan cinnabar deposit, it is localized along a thrust zone with serpentinized ultramafics.

Summary and Conclusion

A broad account of rock formations and geological structures of the Philippine mobile belt illustrates the predominant and perhaps unique magmatic and tectonic activities which attended the metallization, formation, and development of the belt from an eugeosynclinal system during early Cretaceous into a platform-island arc system at the close of Tertiary. It may even be stated that purely clastic sedimentation during the developmental period was subordinate; almost all the major promontories within the region are either plutono-volcanogene orogenic belts or volcanic cones. Regional metamorphism induced during the Mesozoic-Tertiary geotectonic cycle, so far as is known, does not indicate any major rock reconstitution; the changes shown by the basal eugeosynclinal rocks are limited to the chlorite-epidote greenstone sub-facies.

The above geological aspects lead to the conclusion that the ore deposits of the Philippine mobile belt are essentially products of tectono-magmatic activity.

There are essentially two distinct types of tectono-magmatic regime known to have occurred periodically and more or less alternately throughout the stages of formation and development of the belt, namely:

(1) The tensional tectono-magmatic regimes, characterized by regional crustal fracturing and/or fragmentation, subsidence, and transgression, together with the formation of geosynclines and/or intra-mobile-belt basins and regional upwelling or extrusion of primary basalt/spilite magmas; for example, those which occurred during Lower Cretaceous and lower Miocene. The magmatism is limited to basic volcanism (mostly submarine eruptions), and there is no appreciable differentiation of the primary magma, indicating rapid ascent from source into crust. It is presumed that such tensional tectono-magmatic regimes were due to recurring expansion and activation of the earth's interior, possibly the transition zone between the upper and lower mantle, during which the upper mantle and crust were fractured, providing avenues for escape of the activated mantle materials or generation of magmas into the zone of the mobile belt.

(2) The compressional tectono-magmatic regimes, which, on the other hand, were characterized by marine regression, crustal folding and thrusting and/or formation of island arc structures and geanticlines, and emplacements of plutonic rocks. The magmatism is essentially of plutono-volcanogene types with strong evidence of differentiation before emplacement in the crust, as indicated by the associated intermediate to silicic volcanics and the emplaced plutonic rocks. Since they are younger than the first type, it would seem that the magmatism was an aftermath of the expansion and magma generation periods, during which the activated mantle materials that had risen, but were still entrapped at depth, gradually crystallized and differentiated while the upper mantle and crust underwent circumferential shortening in response to post-expansion isostatic adjustment.

Ore deposits related to tensional tectono-magmatic activities, such as the manganese, cupriferous pyrite, and 'kuroko' type ore deposits, have the following common metallogenic aspects:

(a) They are essentially formed at the surface in a shallow marine environment, synchronous if not pene-contemporaneous with the enclosing or associated spilite/basalt lavas, agglomerates, and related pyroclastics.

(b) Their metallogenic habitats or provinces are confined to shallower parts of prevailing submarine basins or geosynclines at the time of their formation and usually along sites of fissure eruptions and/or upwelling activities.

(c) The presence of sea water is apparently critical to their formation, as an agent for leaching and oxidation and as a later medium for precipitation in the case of manganese, and as a quenching agent in the case of sulphides.

(d) In bulk, they are strata-bound by the enclosing rock sequence, which usually includes some sedimentary rocks.

(e) The development of sulphide species is arrested, as can be seen from their colloidal texture and lack of proper separation of the metallic ions or formation into distinct mineral species.

On the other hand, the ore deposits associated with differentiated magmatism or compressional tectono-magmatic regimes, as represented by numerous other deposits, have the following common metallogenic aspects:

(a) Their metallogenic habitats or provinces are confined along orogenic belts and essentially within geanticlinal zones and/or intrusive belts.

(b) The deposits are mostly found close to or within the emplaced plutonic masses, although usually in a linear pattern, following the basic structures of the orogenic belt, rather than surrounding the intrusive bodies.

(c) They are localized essentially at depth, below a cover of rock formations which essentially restricts their migration to the surface and permits greater time for crystallization and reactions with host rock, as well as for formation of more definite mineral species; indeed, many hydrothermal ore deposits show a distinct zonal arrangement of alteration zones.

(d) Most orebodies, except for the syngenetic chromite and bed-controlled replacement deposits, are essentially discordant and are controlled by a system of fractures or a brecciated zone.

(e) Their age of emplacement is coeval with the development of the orogenic belts where they are localized, if not with the associated plutonic or intrusive rocks.

(f) The deposits of a particular orogenic belt or tectono-magmatic regime generally appear to form certain series of mineral species which seem to have some consanguineous relation to the associated plutonic or intrusive bodies, as illustrated by the following:

(1) Initial Orogenic Stage (late Cretaceous-early Palaeocene Orogeny) with ultramafics and gabbro: chromite with associated ilmenite-magnetite, some nickel sulphides with associated platinum metals; pyrrhotite, pyrite, and chalcopyrite; some primary chalcocite; and, with the diorite, disseminated chalcopyrite of the porphyry copper deposits with pyrite, bornite, and little sphalerite, and traces of gold and silver.

(2) Sub-Platform Stage (intra-Oligocene Orogeny) with diorite and quartz diorite: principally chalcopyrite-pyrite, with bornite, molybdenite, some sphalerite, gold, traces of galena in disseminated, replacement, or vein deposits, minor replacement iron ores, some gold veins with little silver.

(3) Syn-Platform Stage (intra-Miocene Orogeny) with quartz diorite-dacite-granodiorite: numerous replacement iron ore deposits; some disseminated or stockwork copper deposits, mainly chalcopyrite-pyrite with bornite, gold, and silver; gold veins with increased silver, sphalerite, galena; separate veins or vein replacement deposits of sphalerite-galena-chalcopyrite; and separate minor concentrations of molybdenite.

(4) Late-Platform Stage (intra-Pliocene Orogeny) with andesite and dacite emplacement: deposits of enargite-luzonite, with gold, tennantite, chalcopyrite, some stibnite and cinnabar, in places with barite; several gold and gold telluride veins; separate deposits of galena-argentite; and some concentrations of stibnite.

There is a traceable parallel pattern of distribution, in amount, of the different metal sulphides of the two broad groups of metallization. Results of intensive exploration by a number of private companies in search of disseminated copper, which practically covered most orogenic belts in the country, tend to show, on the whole, that pyrite would be about 10 to 12 times more abundant than all other metal sulphides: it is everywhere abundant (3 to 10 percent by volume) in vast hydrothermal alteration haloes surrounding ore zones, as well as in the ore zones themselves. Chalcopyrite, which ranks next, may roughly be about one-tenth as abundant as pyrite. Most alteration haloes usually indicate up to 1.0 percent chalcopyrite, increasing to 1.5-2.0 percent in large disseminated or porphyry copper ore zones and to better than 5 or even 10 percent in some veins and replacement deposits. The latter types of deposits are, however, generally of small tonnage. Sphalerite and galena closely follow chalcopyrite in abundance, then silver, gold, and other metal sulphides in decreasing order. These aspects of metallization of the orogenic belts are not so different from the mineralogical analyses of cupriferous pyrite and kuroko type ores associated with submarine volcanism, and could mean that the parental magma of the former (deposits related to compressional tectono-magmatism) is basically the same as the latter, which is of basalt/spilite composition. Their main differences—the former being more mineralogically distinct and forming separate types of deposits, sometimes apart in time and space; whereas in the latter, relatively impure mineral species (cupriferous pyrite) predominate and apparently are deposited together—appear to be essentially due to differences in the histories of separation from the parent magma, and time and mode of migration to the crust.

A statistical study of this apparent similarity in composition of the two tectonic groups of sulphide ore deposits would perhaps shed more light, not only on the possible source of the ore solutions, but also on the origin and nature of the parental magma.

At present, it would appear that the vast quantity of spilitic-basaltic magma generated during Lower Cretaceous, which remained at depths below the crust of the mobile belt region, was not completely crystallized before the end of the Tertiary (a span of time of about 50 to 60 million years); but in the process, its crystalline silicate and ore-forming differentiates (especially the sulphide ore solutions) were periodically harvested by hydraulic press action, induced by compressive tectonic forces, forcing them to migrate during orogenic stages into the crust. The prolongation of crystallization-differentiation could have been due to re-introduction or generation of additional magma during lower Miocene. Considering that such magmas are capable of producing sulphide ore deposits even when comparatively spontaneously solidified, as shown by the syngenetic formation of cupriferous pyrite, it needs little insight to account for the relative richness in copper-bearing sulphides (chalcopyrite) of most orogenic belts, taking into account that the whole zone from North Luzon to Mindanao has been a site of magmatic differentiation as evidenced by emplaced bodies of Cretaceous and Tertiary plutonic rocks together with thick deposits of intermediate silicic flows and pyroclastics (as shown in Figure 1).

References

Allen, C. R., 1962—Circumpacific faulting in the Philippines-Taiwan region. *Phil. Geol.,* 16, 122-45.

Bryner, L., 1969—Ore deposits of the Philippines—an introduction to their geology. *Econ. Geol.,* 64, 644-66.

Gallow, K. J., and Worley, B. W., 1965—The occurrence of telluride minerals in the Acupan gold mine, Mountain Province, Philippines. *Econ. Geol.,* 60, 252-68.

Capistrano, P., and Mapantay, A., 1958—Geology and mineral resources of the southern segment of eastern range of Panay. *Phil. Geol.,* 13, 1-21.

Cruz, D. P., and Comsti, P., 1952—Report on the Baleno copper mines, Baleno, Masbate. *Bur. Min. Phil. Rep. Invest.* 6, 1-8.

de Guzman, R. A., 1968—Geology and remobilized aspects of the massive sulphide deposits of Port Bicobian, Ilagan, Isabela and other similar Philippine deposits. *Phil. Geol.,* 22, 109-32.

Fernandez, H. E., 1966—Origin of the mineralized breccia pipe of Baclao mine, Sipalay, Negros Occidental. *Bull. Inst. Fil. Geol.,* 1, 47-54.

Fernandez, J. C., 1964—Geology of the Lammin iron deposits, Piddig, Ilocos Norte. *Phil. Geol.,* 18, 10-19.

Fernandez, N. S., 1960—Notes on the geology and chromite deposits of the Zambales range. *Phil. Geol.,* 14, 1-8.

Fisher, G. A., et al., 1970—Geological history of the western North Pacific. *Science,* 168, 1210-4.

Gervasio, F. C., 1958—The geologic structures of Marinduque Province and their relation to ore localization. *Phil. Geol.,* 12, 85-90.

GERVASIO, F. C., 1964—A study of the tectonics of the Philippine archipelago. *22nd int. geol. Cong., New Delhi,* 4, 582-607.
GERVASIO, F. C., 1967—Age and nature of orogenesis of the Philippines. *Tectonophysics,* 4, 379-402.
GERVASIO, F. C., and FERNANDEZ, H. E., 1967—Age and nature of metallization of the Philippines. *Phil. Geol.: Symposium on Geology of Mineral Resources of the Philippines and Neighbouring Countries* (in press).
GONZALES, A. G., 1956—Geology of the Lepanto copper mine, Mankayan, Mountain Province. *In* KINKEL, A. R., Jr, et al., *Bur. Min. Phil.,* 17-50.
GREY, R. R., 1967—Time-stratigraphic correlation of Tertiary rocks in the Philippines. *Phil. Geol.,* 21, 1-21.
GUEVARA, V. V., 1964—Exploration and development of the Biga orebody. *1st Nat. Symp. Mineral Resources Development, Proc.,* 1, 143-59.
GUTENBERG, B., and RICHTER, C. F., 1954—SEISMICITY OF THE EARTH AND ASSOCIATED PHENOMENA. *Princeton Univ. Press.*
HARRINGTON, J. F., and ANDREWS, L. E., Jr, 1971—Iron ore resources of the Philippines. *Min. Engng Mag.,* 22, 14-31.
HASHIMOTO, W., 1969—Palaeontology of the Philippines. *Geol. Palaeont. Southeast Asia,* 6, 293-329.
IRVING, E. M., 1951—Notes on the occurrence of manganese ores on Anda Peninsula, Bohol Island, Philippine Islands. *Phil. Geol.,* 6, 19-24.
JONGCO, C. P., 1953—Copper in the Philippines. *Bur. Min. Phil. Infor. Circ.* 16, 1-27.
KINKEL, A. R., Jr, et al., 1956—Copper deposits of the Philippines. *Bur. Min. Phil. spec. Proj. Ser.* 16.
PARKE, M. L., Jr, EMERY, K. O., RAYMOND, S., and REYNOLDS, L. M., 1971—Structural framework of continental margin in South China Sea. *Bull. Amer. Ass. Petrol. Geol.,* 55, 723-51.
QUINTO, P. T., Jr, 1970—Geology, mineralization and exploration program in Philex mines, Tuba, Benguet. *J. geol. Soc. Phil.,* 24, 44-6.
SANTOS-YNIGO, L., 1953—The geology of iron ore deposits of the Philippines. *Phil. Geol.,* 2, 122-64.
STOLL, W. C., 1962—Geology and petrology of the Masinloc chromite deposit, Zambales, Luzon, Philippine Islands. *Phil. Geol.,* 16, 1-41.
SMITH, W. D., 1924—GEOLOGY AND MINERAL RESOURCES OF THE PHILIPPINE ISLANDS. *Manila, Bureau of Printing.*
TUPAS, M. H., 1954—A preliminary study of the geology of Philippine copper deposits. *Phil. Geol.,* 3, 49-58.
WORLEY, B. W., Jr, 1967—Geology of the Antamok and Acupan gold mines of Benguet Consolidated, Inc. *Min. Engng Mag.,* 18, 12-22.

ABSTRACTS

OF OTHER PAPERS PRESENTED TO THE SYMPOSIUM

METALLOGENIC PROVINCES OF THE MARGINAL PART OF THE SIBERIAN PLATFORM

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The northwestern area of the circum-Pacific, bordering the Siberian platform in USSR territory, includes:

(a) marginal part of the Siberian platform;
(b) ancient middle massifs;
(c) Palaeozoic folded area;
(d) Cimmerian folded area;
(e) Alpine folded area.

Correspondingly, endogenetic ore deposits of the main geological stages—Precambrian, Palaeozoic, Cimmerian, and Alpine—are known in this area.

Precambrian deposits of Archaean, Proterozoic, and Baikal cycles are represented by metamorphosed graphite, phlogopite, corundum, and ferri-quartzites, as well as mica-bearing pegmatite.

Palaeozoic deposits are distributed along the western border of the Pacific Belt and are characterized by skarn and hydrothermal deposits, connected with granitoids of the middle stage of geosyncline development.

Cimmerian deposits cover the central part of the Pacific Belt and are represented by pegmatite, greisen, and hydrothermal deposits, connected with granite of middle-stage and small intrusions of late-stage geosyncline development.

Alpine deposits are located along the east border of the Pacific Belt and are represented by hypabyssal as well as subvolcanic and volcanogenic hydrothermal deposits.

There is a regular general migration of ore-bearing areas from ancient to young cycles, from west to east, from the platform margin towards the ocean.

Owing to tectonic, magmatic, and metallogenic activization, the areas containing ore deposits of one stage are covered by those of the following stages.

COMPARATIVE METALLOGENY OF THE WEST BRANCH OF THE PACIFIC ORE BELT

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The western branch of the Pacific Ore Belt, unlike the eastern one, has complicated boundaries and geological structure, and island arcs are present.

The branch consists of two megazones: outer (continental) and inner (island arcs), which differ in age, geological structure, and peculiarities of mineralization. The megazones are divided by the Chukotka-Kateysian volcanic belt.

The outer zone has complicated boundaries determined by the intrusions of Mesozoic granites and associated deposits which stretch far into the continent along the latitudinal activized structures and lineaments. The intersections of inter-asiatic latitudinal and circumpacific longitudinal fractures determine the block configuration of many ore-bearing areas.

The outer megazone is characterized by late Mesozoic mineralization of the sialic profile. The types of ore regions are determined by their tectonic nature, and the peculiarities of their geological development.

The miogeosynclines, the inner troughs with their terrigenous sediments, are characterized by Sn-W mineralization connected with acid granites; the outer zones of upward movement, with carbonatic (limestone) sedimentation, include Pb-Zn deposits associated with intrusive bodies of intermediate composition, while the bordering great lineaments with numerous dykes are characterized by gold deposits associated with andesite and diorite (Kolyma-Chukotka, Sikhote-Alin, and Transbaikalia).

Eugeosynclines, which are the subordinate structures in the outer megazone, are of Palaeozoic and pre-Palaeozoic age; they are accompanied by Cr, Ni, Cu, and Au mineralization (Grodekovo and Stanovaya zones).

In the south of Asia within the Sinian platform dissected by latitudinal Palaeozoic fold zones, the late Mesozoic mineralization stretches along the activized faults: Yenshan (W), Tsinling-Yangtse (Cu-Fe), Kiangsi-Hunan (Sn-W, Sb-Hg, Pb-Zn).

At the junction of the Peripacific and Tethys structures lies the famous Sn-W province which can be traced from Yunnan to Burma, Thailand, Vietnam, Malaysia, and the Indonesian islands. This Sn-W belt follows along the longitudinal tectonic zone extending to the south from the Kam-Yunnan axis and disappearing in the south under the waters of Malacca Strait.

For southeastern Asia the great role of activization and the polycyclic character of magmatism and mineralization are especially typical.

The Sn-W deposits of quartz-cassiterite and quartz-wolframite are localized in terrigenous rocks and granites; Sn-Pb-Zn deposits of cassiterite-sulphide in limestones intruded by acid granites; Au in the zones of volcanic rock with diorites.

In the south of the outer zone lies the ore-bearing province of Australia with Palaeozoic deposits of Sn-W, Cu, Pb-Zn, Au, etc.

The Chukotka-Kateysian volcanic belt has its own metallogenic features (S, Hg, Au-Ag, Pb-Zn-Cu, alunite).

Quite different is the metallogeny of the inner megazone of island arcs, which consists of the younger (late Mesozoic, Cainozoic) fold zones of femic profile (Cr, Ni, Pt, Cu, Au) which are typical of eugeosynclines. Locally amongst these young fold zones occur the previously consolidated sialic blocks with thick continental crust. The presence of such blocks demonstrates the connexion of island arcs with continental Asia in the past. These blocks comprise the mineralization of the sialic profile (Sn, W, Mo) connected with acid magmatic rocks (S-W Honshu, Japan).

Many granitic bodies are polycyclic and were being formed during the repetition of several stages of activization. Polycyclic also are the ore deposits of south-eastern Asia, which were formed during the Triassic, Jurassic, and late Cretaceous.

The broad distribution of the Cretaceous granites and ore deposits along the Pacific belt is of great interest, suggesting the planetary significance of this phase of tectonic movements, which embraced both geosynclinal zones and old activized structures.

TOWARDS AN UNDERSTANDING OF STRATIFORM ORE DEPOSITS

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Twenty years ago no such words as stratiform or stratabound or conformable were in common use in the context of ore deposits. Today these are commonplace.

Recognition of a distinct identity for this type of ore deposit has wide and deep geological significance involving abandonment—for these deposits—of the idea of creation 'as is' and substitution of development from simple beginnings. It is now realized that there are relationships and patterns among these deposits which suggest not only volcanic, magmatic, and sedimentary affinities, but also factors of geochemistry and geobiology, perhaps on a world scale.

The paper reviews the development of this concept especially in Australia; the emphasis on interdisciplinary studies, not merely geological; the impact on research.

It looks at some implications of the present stage of thinking, especially that the problem is more than an understanding of ore sulphides: it is the understanding of the total environment.

It concludes with a discussion of three topics now thought most in need of attention.

METALLOGENIC PROVINCES AND EPOCHS IN SOUTH KOREA

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Two granites of post-Palaeozoic age have so far been identified in South Korea: late Jurassic and late Cretaceous.

Late Jurassic granites, syntectonic intrusives of the Taebo orogeny, which is the most pronounced in Korea and by which all the previous formations were deformed, are aligned in a northeast trend in accordance with the Sinian direction and are distributed in the mid-central to northern parts of South Korea. Late Cretaceous granites, accompanied by Bulkuksa disturbance, are on the other hand distributed in the Cretaceous Kyong-sang sedimentary basin at the southeastern part of the Korea Peninsula and adjacent areas without any directional arrangement. They were intruded into sediments and andesitic flows of Cretaceous age without any apparent deformation except minor warping and induration along contact aureoles. It is concluded from the relationship between age and distribution of the granites that they are younger from northwest to southeast toward the Korean Strait.

Most mineral deposits in South Korea are genetically related with these two granites, and their spatial distributions are also closely matched to each other. Metallogenic provinces of Jurassic age of gold-silver, lead-zinc, molybdenum-tungsten, and fluorite are distinctly aligned with the Sinian direction, whereas metallogenic provinces of Cretaceous age of lead-zinc, copper, and pyrophyllite are randomly distributed in the Kyong-sang basin, where lithological control predominates over structural control. In the Kyong-sang basin, copper deposits occur in andesitic rocks, whereas lead-zinc deposits occur in indurated argillaceous sediments of the upper Silla series of middle to late Cretaceous age. The metals can be roughly zoned: copper occurs in the southeast margin of the Korea Peninsula, and lead-zinc in the surrounding inland area of the basin, although there is some overlapping. Pyrophyllite provinces are manifested by both lithology and fault structure.

DISTRIBUTION OF MINERAL DEPOSITS IN KOREA AND ITS SIGNIFICANCE

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The various mineral deposits in Korea show linear distributions whose direction coincide with those of hot springs. They are 045°, 180°, 025°, 055° and 070°. These directions are also genetically related with 025° and 180° trending folds. The former are thought to be of late Jurassic and the latter of late Cretaceous age.

Most of the mineral deposits are fissure-filling veins. Since they are thought to be genetically related with the regional structure of the 025° and 180° folds of post-late Jurassic, most of the mineral deposits were probably formed at the same time.

Few mineral deposits were formed before the late Jurassic, except some magnesite and phosphate deposits, the alaskitic gold veins of the Precambrian, and a few fluorite and talc deposits of pre-Cretaceous age.

Hence a few ore deposits are thought to be associated with the Precambrian geosynclinal basins and the Caledonian and Variscan basins. On the other hand, most of the ore deposits are closely related to the Alpine sedimentary basin in Korea.

GEOLOGY AND ORE DEPOSITS OF THE MESOZOIC GYEONGSANG BASIN

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The Mesozoic Gyeongsang Basin is the only copper-producing metallogenic province in Korea; it contains also other minor base metals and tungsten-molybdenum.

The sedimentary rocks of the late Mesozoic, the Gyeongsang system, were deposited in the basin, which was formed after the violent Myogog disturbance of the late Jurassic. These rocks are widely distributed in the southeastern part of the Korean Peninsula except for small patches in the southeast.

The rocks of the system comprise a thick series which ranges up to some 8000 m, consisting of conglomerate, sandstone, mudstone, and shale of terrestrial origin, with some volcanic flows and tuffs in the upper part of the section.

Toward the end of sedimentation, a vast invasion of granite plutons accompanied immense contact metamorphism and widespread mineralization. This Cretaceous granite, known as the Young Granite, is diversified in its mineral composition, differentiated from the diorite to the granodiorite phase of the parent magma. In the early Cainozoic Era, an adamellite phase of granite, the so-called masanite, partly invaded the Cretaceous granites, resulting in the formation of magnetite skarns and vein deposits.

Mineralization brought by the Cretaceous granites in the basin can be divided into two categories: copper-bearing hydrothermal deposits, including native copper disseminated in the Mesozoic basalts, and pneumatolytic deposits of tungsten-molybdenum-bismuth. They are tabulated as follows:

- Hydrothermal deposits
  - Kata-to-Mesothermal: Co-As-W-bearing Cu deposits
  - Kata-to-Mesothermal: Au-Ag-W-Bi-bearing Cu deposits
  - Meso-to-Epithermal: Pb-Zn-Ag-Au-bearing Cu deposits
  - Telethermal: Native Cu deposits
- Pneumatolytic deposits
  - W-Mo deposits
  - Bi deposits

GENESIS OF THE KUROKO DEPOSITS OF JAPAN

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Peculiar massive sulphide ore called 'Kuroko' or black ore is a fine aggregate of sphalerite, galena, chalcopyrite, and barite, with some pyrite and tetrahedrite. It occurs often as stratiform masses and in association with the massive chalcopyrite-pyrite ore (Oko) and siliceous disseminated ore (Keiko), sometimes with massive or bedded gypsum ore (Sekkoko) in the acidic volcanic rocks and their pyroclastics of Miocene age, which are extensively developed in northeast Japan.

Detailed analytical studies on layered features and modes of arrangement of these ores from many Kuroko mining fields revealed characteristic fabrics of their formation by volcano-sedimentary processes under submarine environments.

The texture and structure of the ores indicate that the mineralization of the Kuroko ores took place both on and below the sea-floor during the waning stage of the volcanic activities.

SOME ASPECTS OF METALLOGENESIS OF TAIWAN

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Taiwan lies at the junction of the Philippine and Ryukyu arcs within the western Pacific mobile belt. Copper, gold, sulphur, monazite, and zircon are the main minerals produced in Taiwan. The mineral deposits in the Coastal Range of eastern Taiwan and the offshore islands are similar to those of the Ryukyu Islands and some parts of Japan. However, the intensity of mineralization is weaker in Taiwan.

The pyrite and chalcopyrite deposits in the greenschist belt on the eastern flank of the Central Range of Taiwan are identical with the Besshi-type deposits in the high-pressure greenschists of Japan. The Taiwan deposits were formed in either Mesozoic or late Palaeozoic time in a pre-Tertiary foredeep of a non-volcanic outer arc.

Southwestern-Pacific-type porphyry copper deposits of Miocene age are found in the Coastal Range and the offshore islands. They are related to the diorite or andesite that intruded into basic igneous rocks in Miocene time in a eugeosyncline. Early Pleistocene enargite-luzonite-gold deposits are found in northern Taiwan, and are related to the dacite that intruded into the Miocene sediments immediately after the early Pleistocene orogeny. The various types of deposits in Taiwan are less developed and younger than those in the Philippines. Taiwan seems to be the northern end of the porphyry copper belt in the western Pacific.

Quaternary sulphur and pyrite deposits occur in the Pleistocene andesite, and the minerals are still being formed. The andesites erupted on the Miocene sediments after the early Pleistocene orogeny in northern Taiwan, where the Neogene sediments gradually thin out northward in a miogeosynclinal basin.

Monazite and zircon occur in the beach sands of western Taiwan in a present-day exogeosyncline in front of a deformed late Tertiary miogeosyncline. These placer minerals originated from the Mesozoic or Palaeozoic granites forming part of the foreland bordering the miogeosynclinal basin of Taiwan on the west. They have been generated and concentrated through at least two cycles of erosion and deposition.

ALPINE-TYPE CHROMITE DEPOSIT IN THE DARVEL BAY AREA OF NORTH BORNEO

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The island-arc system of the Philippines, which includes the well known Zambales chromite-bearing alpine complex, continues westward along Palawan island and along the Sulu archipelago into Sabah (North Borneo). Within this arc, there is a characteristic association of ultramafic rocks, banded amphibolite gneisses of gabbroic composition, and a younger flysch sequence characterized by abundant spilites.

In the Darvel Bay area of Sabah, the banded amphibolite gneiss is believed to represent the original oceanic basement, now folded and metamorphosed generally in the almandine amphibolite facies within an island arc.

Deformation has been shown in the Darvel Bay area to be of two distinct phases, an earlier with east-west fold axes and almandine amphibolite to granulite facies metamorphism; and a later with a predominant northwesterly fold direction and greenschist facies metamorphism. The later deformation probably can be dated as late Jurassic or early Cretaceous.

Both deformation phases were accompanied by the syntectonic emplacement of alpine-type ultramafic complexes concordant with the regional structure.

The earlier east-west complexes are essentially of peridotite composition and devoid of chromite; whereas the later northwest complexes contain significant volumes of dunite, and serpentinized dunite, lensed within the peridotite. Chromite occurs exclusively within the dunite or altered dunite as deformed layers, pods, boudins, and brecciated blocks, but nowhere in commercial volumes, although locally grades may be as high as 50% Cr_2O_3.

Analyses show the chromite to range from metallurgical grade, through aluminian chromite, to chromian spinel. The chromite crystals are optically homogeneous, but thinly rimmed by magnetite, and they exhibit cataclastic or pull-apart textures. The unit cell dimensions can be related to the chromium content.

The origin of the chromite bodies is believed to have ultimately been stratiform, perhaps in the upper mantle or lower crust; and to have been subsequently emplaced tectonically during deformation of the island-arc system.

AGES OF EMPLACEMENT AND MINERALIZATION OF ECONOMIC MINERAL DEPOSITS IN THE NEW GUINEA-SOLOMON ISLANDS REGION

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The youthful tectonic setting of the known mineral deposits in the New Guinea-Solomon Islands region was reviewed by Thompson & Fisher (1967)[1].

[1] *8th Comm. Min. metall. Cong.*, 6, 115-48.

This paper outlines the results of K-Ar and Rb-Sr dating of some of these deposits on the New Guinea mainland and on Bougainville Island. The isotopic data give much better control on the ages than was previously available, and allow significant inter-regional comparisons to be made. The mineralized rocks studied in New Guinea and Bougainville Island are genetically associated with sub-volcanic porphyries and other high-level diorite-granodiorite intrusives which are shown to be all Miocene or younger. They were emplaced individually or as parts of larger plutons at a time of widespread tectonic activity in New Guinea, which began in the lower Miocene and continued through the Pliocene virtually to the present day.

The significantly mineralized intrusions in the New Guinea Highlands are part of the late Tertiary plutonic and metamorphic belt, which trends east-southeast and includes the prospects around the Morobe Goldfields, Kainantu Goldfields, Yanderra (Bismarck Granodiorite), Maramuni River, Frieda River, and Ok Tedi areas. Of the intrusions so far studied in this belt nearly 600 km long, the mineralized bodies have ages ranging from about 1 m.y. to 16 m.y., i.e. from mid-Miocene to Pleistocene.

By dating the porphyries and the surrounding rocks in the Morobe Goldfields between Wau and Bulolo, the age of mineralization in this area is shown to lie between 3 and 4 m.y. (i.e. mid-Pliocene). In the Kainantu area to the northwest, it is possible that two episodes of gold and copper mineralization occurred in the middle and late Miocene. Copper mineralization in the Yanderra area in the northeastern margin of the Bismarck Granodiorite appears to have been introduced in the late Miocene, some 5 m.y. after the main emplacement of the batholith 12 to 13 m.y. ago. The most likely age for copper mineralization associated with Maramuni Diorite in the South Sepik area is 11 to 14 m.y. (mid-Miocene); for this area no ages have yet been determined on the mineralized rocks themselves, so the mid-Miocene ages are maximum values for the age of mineralization. K-Ar ages from the Frieda Porphyry prospect, still farther to the west in the South Sepik area, indicate a complex intrusive history and a maximum age range for mineralization between 13 and 16 m.y. ago in the mid-Miocene. The Ok Tedi copper prospect in the headwaters of the Fly River in northwest Papua is an extremely young deposit in which the mineralization has been firmly dated as Pleistocene, between 1.1 and 1.2 m.y. This is believed to be the youngest porphyry copper body so far discovered.

The geochronology of the Panguna porphyry copper orebody on Bougainville Island has been closely studied (Page & McDougall, 1972)[2] because it is currently the only large orebody in the region, and the geological relationships are well known through surface and underground mapping and extensive diamond drilling (Macnamara, 1968)[3]. The earliest intrusive at Panguna gives K-Ar ages of 4 to 5 m.y., and the mineralized, strongly altered porphyritic bodies are 3.4 $\pm$ 0.3 m.y. old. The 3.4 m.y. age is believed to represent the time of mineralization associated with the emplacement of one or more of the altered porphyry bodies. Another two intrusives that are known on geological grounds to postdate the mineralization have been dated at 3.5 $\pm$ 0.3 m.y. and 1.6 m.y., respectively.

The age data related to mineralization in the New Guinea-Bougainville region are reconcilable with the known stratigraphic control, and indicate that the events

[2] *Econ. Geol.* (in press). [3] *Proc. Aust. Inst. Min. Metall.,* 228, 71-9.

concerned are all mid-Miocene or younger. Late Miocene to Pliocene dates obtained on copper-mineralized intrusives elsewhere in the Solomon Islands (R. B. Thompson, this volume) are consistent with the results presented here. From these data it would appear that mineralization occurs in a given tectonic environment, not in definite, sharp episodes or epochs, but more or less continuously over a period of time (in New Guinea about 16 m.y. long) determined by large-scale processes such as plate boundary interactions. Given the mobilist tectonic concepts thought to be operative in the construction of such island arc/orogenic environments, it would seem that other young high-level intrusives in the region may be of considerable economic interest.

COMPARISON OF MINERALIZATION AT THE BROADLANDS GEOTHERMAL FIELD AND THE HAURAKI REGION, NEW ZEALAND

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Broadlands, an active geothermal field in the Taupo Volcanic Zone, has many similarities with the base metal and gold-silver mining districts of the Hauraki Region. In both areas steeply-folded indurated Mesozoic sediments are unconformably overlain by extensively altered and pyritized volcanic rocks. These consist of Quaternary rhyolitic ignimbrite, tuff, and lava at Broadlands, and of mid-Tertiary andesitic lava and volcanic breccia in the Hauraki Region. Normal faults acted as loci for hydrothermal mineralization, which is found in the basement and overlying volcanic rocks of both areas.

Adularia, albite, chlorite, calcite, epidote, wairakite, quartz, montmorillonite, and kaolinite are the non-sulphide hydrothermal minerals common to both areas. In the Hauraki Region, zoning of hydrothermal assemblages around fissures is more obvious than at Broadlands. Furthermore, the effects of waning hydrothermal activity on the mineralogy are apparent.

At Broadlands, sphalerite, galena, and chalcopyrite are present below 300 m, and high concentrations of Hg-Tl-As-Sb-Au-Ag occur in recently precipitated sinters and drill-hole discharge precipitates. In the Hauraki Region sphalerite, galena, chalcopyrite, and tetrahedrite were probably deposited at deeper levels than gold-silver or cinnabar mineralization.

Measured temperatures at Broadlands range up to 298°C. Sulphide deposition temperatures of 280°C are suggested at the Tui Mine, Hauraki Region, from the fractionation of sulphur isotopes between co-existing galena and sphalerite.

ULTRAMAFIC ROCKS AND ASSOCIATED MINERALIZATION IN PAPUA NEW GUINEA

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The main areas of ultramafic rock in Papua New Guinea are in the mountains south of the Sepik River (April), in the Ramu Valley (Marum), and on the south-eastern peninsula (Papuan). Small bodies of ultramafic rock are also known to occur in the northern ranges between the West Irian border and Madang, in the central highlands near Goroka and Menyamya, in the Port Moresby and Milne Bay areas, and in the D'Entrecasteaux Islands. The Papuan ultramafics have been studied more closely than the others and serve as a model for discussion of genesis, petrology, and mineralization.

The Papuan ultramafics form the lower part of a peridotite-gabbro-basalt complex (Papuan Ultramafic Belt) which is exposed over a length of 400 km and a width of up to 40 km. The complex is probably a plate of oceanic mantle (ultramafics) and crust (gabbro and basalt) which was underthrust by continental crust and sediments in an Eocene or Palaeocene subduction zone, and tilted by fault movements in and since late Oligocene. The zone of underthrusting is marked by granulite, amphibolite, greenschist, blueschist, and lawsonite-albite facies metamorphism. The April and Marum ultramafics may also mark the site of a former subduction zone, for gabbro is associated with both, and blueschist and eclogite with the April ultramafics. However, no overlying basalts have been found. The April ultramafics occur as a number of fault-bounded lenses, unlike the Marum and Papuan bodies.

The Papuan ultramafic rocks are of two types: tectonite or noncumulus ultramafics with metamorphic texture, and cumulus ultramafics with igneous cumulate textures. The tectonite ultramafics predominate (about 95%) and consist of olivine $Fo_{91.6-93.6}$ (60-80%), low-alumina enstatite $En_{92.1-93.4}$, and accessory chrome spinel. The cumulus ultramafics form a discontinuous layer no more than 500 m thick on top of the tectonite ultramafics, and consist of olivine, orthopyroxene, clinopyroxene, and chrome spinel in varying combinations. Olivine and orthopyroxene compositions are in the ranges $Fo_{78.3-89.6}$ and $En_{81.2-90.5}$. The tectonite ultramafics are thought of as convecting refractory upper mantle which formed a floor for the emplacement of successive pulses of basaltic magma at a spreading centre such as a mid-ocean ridge. The cumulus ultramafics settled out from the basaltic magma and are thus genetically related to the overlying gabbro and basalt layers.

Nickel-enriched soils occur over both types of ultramafics. Nickel and copper sulphides occur in the gabbro layer within 1 km of the gabbro-ultramafic contact, and copper sulphides occur with pyrite in the overlying basalts. In both cases sulphide mineralization may have been localized by younger (Eocene and late Miocene) intermediate and acid intrusives, which have also introduced some gold. Small quantities of alluvial platinum and osmiridium are associated with the Papuan ultramafics and have possibly shed from Bushveld-type concentrations in the cumulus rocks. Chromite is disseminated throughout the tectonite ultramafics and in several instances is concentrated in lenses up to 15 cm thick; rare thin chromite-rich layers are also known from the cumulus ultramafics. Nickel-enriched soils are also known to occur over the Marum ultramafics, and alluvial gold and platinum have been found in streams draining the April ultramafics.

Ni-Fe-Cu SULPHIDES IN NEW CALEDONIA ULTRAMAFIC BODIES WITH SPECIAL REFERENCE TO THE GREAT SOUTHEASTERN MASSIF

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Ultramafic bodies, emplaced during a late phase of alpine orogeny, rest upon the basalts and Eocene sedimentary rocks with a thick serpentinized sheet at the base. A summary of the lithology is:

Unit I: The main peridotite mass is on the whole made up of forsteritic olivine, enstatite, and chromium spinel. The composition of these minerals (constant Fe/Mg ratio) does not vary in the profile, nor is there any indication of any change to feldspathic rocks. The degree of differentiation is thus poorly indicated. Primary layering is visible and is conveyed by rhythmic banding of dunites, pyroxenites, and harzburgites.

Unit II: Dunite and gabbro. Unit I is cut by voluminous bodies of dunite diffusely outlined and of extremely irregular shape, whose upper section transitionally changes to noritic gabbro and anorthosite. The transition zone is narrow and is characterized for several dozen metres by the appearance of orthopyroxene, clinopyroxene, and plagioclase, whose combined volume, compared to that of the olivine and the spinel, regularly increases. At the same time iron content of the ferromagnesian minerals progressively increases, as does the content of alumina in chromium spinel and clinopyroxene.

Unit III: Quartz diorite and calcalkali granite, formed at an upper stage, inject the two preceding units.

The sulphide minerals are found in a disseminated state in nearly all the ultramafic rocks as well as in those of Unit III, and consist of nickel, copper, and iron sulphides: pyrrhotite, cobaltiferous pentlandite, bravoite, mackinavite, millerite, heazlewoodite, chalcocite, cubanite, and chalcopyrite. These minerals were most probably present before serpentinization; they form single crystals or polycrystalline aggregates between the olivine and the pyroxene crystals, or fine inclusions disseminated within them (especially in cleavages of pyroxene). Optical studies complemented by geochemical calculations enable us to make the following points:

The nickel is present as sulphide but is also trapped in the lattice of silicate minerals. It seems that, in comparison to the overall quantity of nickel, the proportion of sulphide nickel is greater where the rocks contain more pyroxene. This proportion is about 60 percent in the pyroxenite of Unit I as well as in the websterite which marks the transition between the dunite and the gabbro of Unit II.

In Unit I, the Ni/Cu ratio of the sulphide phase varies, though it remains very high. The content of sulphur ranges from 80 to 250 ppm, but may reach more than 1000 ppm in the pyroxenites.

In the dunite of Unit II, sulphides are less abundant than in Unit I and also maintain a high Ni/Cu ratio. This ratio rapidly decreases close to gabbro. In the area of transition, and more particularly in the websterite rocks, therefore, primary sulphides of iron and copper are more abundant.

In a general fashion, in Units I and II, there seems to be a difference in the graphic curves of sulphur and nickel, whereas the curves of copper and sulphur seem to vary harmonically.

The granites and diorites of Unit III contain pyrrhotite associated with copper sulphides: digenite, chalcopyrite, cubanite. Pentlandite is found occasionally. In certain serpentinous areas of the bodies, as well as in certain sills of serpentine located along abnormal contacts in sedimentary areas, disseminations of Ni-Cu-Fe sulphides of secondary origin exist. These are always found within a short distance of calcalkali rocks. Thus it is possible that these sulphides result from a recombination of metals present in ultramafic material and of sulphur of hydrothermal origin.

The question is therefore raised as to the presence of sulphuretted concentrations in New Caledonia. Certain research processes are envisaged according to lithological and structural guides.

ALTERATION PROCESSES AND ORE MINERALS IN NEW ZEALAND ULTRAMAFIC ROCKS

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The only ore minerals in completely uncrushed and unserpentinized ultramafic rocks in New Zealand are chromite, magnetite, ilmenite, and very rare gold and platinum group metals.

New Zealand Permian and Cretaceous ultramafics can be divided into three main types on the basis of their mineral chemistry and ore-mineral content:

(1) Dunite and pyroxene peridotite of the eastern Permian belt, crystallized under conditions of low pO_2 and pH_2O, contain MgNi olivine, Cr diopside, aluminous chrome spinel and rare platinum group metals, mainly osmiridium. Serpentinization leads to enrichment of spinel in Cr and depletion in Al, Ni, Co, and Ti, and to formation of secondary magnetite rich in Ni, etc. Nickel and cobalt released from olivine in the absence of sulphur and under reducing conditions form native nickel-iron (awaruite, Ni_3Fe) and cobalt-iron (wairauite, CoFe) alloys. Copper, contained mainly in the pyroxenes, is released to form native copper. Sulphides are rare. Platinum group metals occur with chromite.

(2) Dunite and feldspar peridotite of the western Permian belt, crystallized under conditions of moderate pH_2O and moderate to high pO_2, contain chromite, magnetite, ilmenite, ZnAl spinel, gold, platinum and palladium, MgFe olivine, and diopsidic augite. Alteration of the rocks in this belt gives rise to sulphides,

although low nickel in the primary olivine probably accounts for the absence of nickel sulphides.

(3) Dunite, pyroxenite, hornblendite, and carbonatite of the western Cretaceous belt contain titanomagnetite, ilmenite, apatite, and rare earths, with FeMg olivine, Ti augite, and Ti hornblende. Early olivine contains Ni, and augite and hornblende contain some copper. Alteration may give rise to copper and nickel sulphides.

METAL CONTENT OF PLACERS OF THE NORTHWESTERN PACIFIC AREA

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In the northwestern Pacific sector of the Pacific ore belt the main elements of the placer mineral deposits are platinum, gold, tin, tungsten, and silver. It is established that the outer zone of the belt is characterized by deposits of mesothermal gold, tin, and tungsten, whereas its inner zone is characterized by epithermal deposits of gold (mainly associated with silver), platinum, and partly tin. But such a generalization cannot explain the causes of the spatial objective laws of distribution of ore formations, as well as of the placers which accompany them. It cannot be explained by the title itself: 'The Pacific Ore Belt'. Because of the collective connotation of this title, it includes in its strict meaning different ages of consolidation, geosynclinal systems and volcanic belts, in which occurrence of minerals is controlled in different ways by peculiarities of evolutionary development, in the tectonic-geomorphological stage in particular, when placer deposits were formed.

Ore placers were formed from local ore deposits, particularly of gold, tin, and tungsten; these, however, were not everywhere removed on the then existing surface and affected by destructive processes in the period of development of the Mesozoic structures of the Pacific. And only in some zones in the last stages of inversion were the earliest representatives of the plutonic complexes and the ore deposits which accompanied them exposed and subjected to exogenic conversion.

The post-orogenic history of the development of folding regions, Mesozoic as well as Cainozoic structures, has two stages: quasiplatform, and later tectonic activization. During the quasiplatform stage, which is not identical, with regard to its timing period, in Mesozoic and Cainozoic structures, one can detect a sudden decrease in the capacity of continental sedimentation, the planation of surfaces, the development of residual weathered oxidized surfaces, and so on. Formation of eluvial placer deposits is characteristic of this stage.

During the stage of later tectonic activization in the Pacific the placer deposits developed under severe tectonic-geomorphological conditions. The beginning of the rejuvenation of the surfaces in this zone was marked by a change of continental layout, caused by the coming together of Asia and America. At this time (Eopleistocene and lower Pleistocene), mountain folding and elevation of the surface took place; being energized by the tectonic movements, they were accompanied by deformation of the surface planation, by its disjunction, by demolition of eluvial placer deposits, and by changing them into alluvial deposits.

The general changes of land and coastline changed atmospheric circulation, which, in all probability, was the main cause of lower Pleistocene glaciation in the mountainous zone; but outside this zone the formation of placer deposits was not halted. The second glaciation appeared in the upper Pleistocene; it was small; and consequently the formation of placer deposits of gold, tin, and tungsten, to a considerable extent continued. During the later Quaternary period tectonic activization affected all the structures of the Pacific, Mesozoic as well as Cainozoic, and this only strengthened the process of formation of placer deposits.

In the history of development of the placer deposits of the northwestern Pacific a particular place is occupied by the Ochotsko-Chuckotsky volcanogenic belt, where morphostructure with block mountains and lineal basins, volcanic highland plateaux, and basaltic plateaux has been definitely delineated. Here placer deposits were differently formed, because of interruption by volcanic activity.

WEIPA BAUXITE DEPOSIT, QUEENSLAND, AUSTRALIA

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The Weipa deposit, situated on the west side of Cape York Peninsula, is part of an extensive laterite developed on Tertiary sediments. The extent and economic potential of the deposit were recognized by the author during a geological reconnaissance for oil in June 1955. Laterite residuals cover an area of at least 1300 km^2, of which 500 to 800 km^2 contain economic grade bauxite. Proved reserves are 500 million tons, with an additional 1500 million tons indicated. The deposit was tested by hand and power augers supplemented by some pit sinking. Preliminary evaluation was at 2000-foot centres, detailed evaluation at 500-foot centres, and pre-mining drilling at 250-foot centres.

The bauxite is a superficial flat-lying deposit averaging 2.5 m in thickness with less than 1 m of overburden. The ore is strongly pisolitic, occasionally cemented, but generally consists of uncemented spherical pisolites ranging in size from 1 mm to 20 mm in a red-brown silty matrix. The alumina in the bauxite is a mixture of gibbsite and boehmite, the former being the major component. Iron content varies considerably from area to area but in the bulk of the bauxite is relatively low. Silica and alumina show distinct distribution patterns both vertically and laterally within the orebodies. Regionally, alumina distinctly decreases and silica increases eastward from the coast. Silica content, and consequently grade of the bauxite, appears to be related to drainage systems within the laterite. The bauxite has been developed by in situ weathering of arkose and sandy clay of probable Tertiary age, the main leaching agent being carbon dioxide picked up at ground-level by the monsoonal rains. Studies of the water table in the laterite profile have indicated that the process of lateritization is still going on within the profile. Rutile distribution in heavy mineral concentrations shows a marked relationship with the laterites, suggesting that rutile may be produced from ilmenite during intense lateritization.

BAUXITE DEPOSITS OF GOVE PENINSULA, NORTHERN TERRITORY, AUSTRALIA

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Bauxite deposits in Gove are associated with a lateritic profile which caps a near-continuous plateau system totalling more than 120 km^2 in area. The altitude of the undulating plateau surface varies from 10 to 100 m above sea level. Most of the plateau is underlain by flat-lying Cretaceous sandstone and shale, which in turn are gently draped over an irregular surface of Archaean basement.

Thickness of ore ranges up to 10 m, with an average of 3-4 m. The bauxite profile is normally represented by an upper layer of loose pisolitic ore, an intermediate layer of cemented pisolitic ore, and a bottom layer of tubular or vesicular ore. In elevated areas this profile may be partly eroded. Lateral distribution and thickness of ore are thus intimately controlled by relative variations in altitude of the plateau surface.

Barren laterite immediately below the bauxite usually consists of nodular and/or tubular material or of angular lateritic fragments mixed with clay.

Gibbsite, together with hematite, is the predominant mineral of the bauxite. Only a little boehmite is present, usually near the top of the bauxite or associated with ore containing high total alumina. Combined silica is low and normally increases suddenly at the bottom of the profile. Quartz is minor and is chiefly concentrated in pisolitic ore. Titanium oxides, chiefly anatase, are present throughout the bauxite. Trace elements include V, P, Cr, Mn, Zn, Ga, and Zr.

Geomorphological evidence in Gove Peninsula suggests former eustatic movements of the sea level. It is possible that part of the laterite-capped plateau was submerged during one or more periods of inundation and that as a result of these fluctuations, some of the bauxite was reworked and/or redistributed.

By analogy with other deposits in Australia, it is believed that the age of the Gove bauxite is Tertiary.

BAUXITE DEPOSITS OF THE DARLING RANGE, WESTERN AUSTRALIA

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The main deposits of bauxite in the Darling Range in Western Australia occur within a 50 km-wide zone along the western margin of the continental plateau between latitudes 31° and 34°S. These bauxites are generally considered to be in situ fossil soil deposits of Tertiary age. They have been developed on a pre-existing partly dissected peneplain at elevations between 250 and 500 m above sea level.

The ore is essentially an alumina-rich laterite with a variable content of iron oxides and quartz. The chief ore mineral is gibbsite. Values of available alumina, however, are somewhat less than those of many other large bauxite deposits. Orebodies are discontinuous and are enclosed within areas of ferruginous laterite; the average ore thickness is about 4 m with about 60 cm of overburden. The bauxite profile, which can extend to a depth of more than 12 m, generally consists of a hardcap underlain by a friable zone, which usually passes abruptly into decomposed bedrock.

The underlying bedrock is composed of Archaean granite with subsidiary areas of gneiss, migmatite, and metasediments. Dolerite dykes generally considered to be of late Precambrian age intrude the older rocks. In the Jarrahdale mining area, lateritized remnants of possible fine-grained sediments of unknown affinity have also been found.

Geological control of orebodies is significant. On a regional basis, the trends of ridge units on which laterites occur appear to parallel structural features in the basement complex. More locally, dolerite dykes often set boundary limits to orebodies, as they are more resistant to lateritization than the other rock types.

In general, the area in which bauxite occurs lies within the approximate limits of the present 600 and 1200 mm rainfall isohyets. It is thought, however, that the regional ore distribution is related to high rainfall conditions existing since Tertiary times.

Current ideas on the genesis of residual laterite deposits favour their derivation as fossil soils, resulting from selective chemical leaching of suitable parent rocks by free-moving ground-waters. The nature and distribution of the Darling Range bauxites is in accord with this view. No reworked deposits have as yet been found.

SOME SIGNIFICANT CHARACTERISTICS OF BAUXITES IN AUSTRALIA AND MALAYSIA AND THEIR GENETIC IMPLICATIONS

by P. L. C. Grubb

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The characteristic variety, disposition, and composition of bauxite deposits in Australia and Malaysia are briefly outlined. Attention is drawn to the importance of their textural features and heavy mineral content, especially as a guide to subdivision of bauxite profiles into either a purely residual or a detrital reworked category. An attempt is made to establish some index of maturity in residual bauxite profiles using bulk sample sizing analyses, combined with associated mineralogical variations. On this basis it is shown that in most mature profiles, three distinctive horizons can be recognized.

Bauxitization processes are characteristically coastal phenomena, being associated with gradual land emergence, yet existing bauxite deposits are often confined to regions where associated synclinal warping or faulting has been superimposed on a eustatic fall in sea level. Finally, the effect of bedrock porosity is also considered and a suggestion put forward that this may play an important role in favour of profile maturity.

ON THE EXPLORATION OF THE SUBMARINE MINERAL RESOURCES AROUND THE JAPANESE ISLANDS

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The exploration of the submarine mineral resources on the sea floor around the Japanese Islands has successfully progressed year by year. The minerals involved are petroleum, natural gas, coal, phosphorite, copper, gold placers, magnetite, ilmenite, manganese nodules, gravel, sand, and clay.

(i) *Minerals in the basement rock of the sea floor*

Mineral resources have been sought mainly on the sea floor on the continental shelf and the adjacent area.

Petroleum and natural gas: Exploration for submarine oil fields has been in progress around the continental shelf of the Japanese Islands. Mineral tenements cover the continental shelf except for a few districts along the Pacific Ocean. Petroleum and natural gas are being produced off Akita and Niigata along the Japan Sea.

Coal: 26 percent of the annual production of coal in Japan comes from submarine coal fields. Submarine coal mines are situated at West Kyushu and southwest Hokkaido.

Phosphorite: Phosphorite was exploited at Noto Peninsula in Nanao Gulf 60 years ago. It was found in the Tertiary strata along the shore and mined in the offshore area, but not for long.

Copper and gold: Copper mine and gold mine workings extend under the sea floor at Aomori Prefecture and Shizuoka Prefecture, but these are the extension of workings on land. There are no mines which originated as a result of mineral exploration on the sea floor.

Manganese: Manganese has been found off Aomori and Shizuoka Prefectures, but no exploitation has been attempted.

(ii) *Minerals in the unconsolidated deposits*

Heavy mineral placers in the unconsolidated deposits have been sought on the sea floor of the continental shelf, continental slope, and deep sea floor, but only the shallow bottom of the continental shelf is as yet exploited.

Iron placers: Iron placers were used for iron smelting in ancient times. They were obtained from river terraces or from the sea shore, but now are mined from the shallow sea floor less than 50 m deep. There are mining areas from Hokkaido to Kyushu. In the year 1963, the total production from iron placers was 1 295 199 tons, but it is gradually decreasing.

Gold and other minerals: Gold placers have been recorded on the shallow sea floor at Hokkaido, Yamagata, Miyagi, Chiba, and Nagasaki, but have not been exploited. Other minerals have not been studied.

Nodules of manganese: Manganese nodules have been found on the deep sea floor of the Japanese Trench, and research work continued during last year.

Gravel, sand, clay, and organic remains: Quartz gravel is dredged from the shallow sea floor at Kyushu and used for chemical products. Gravel and sand are also dredged for construction in several regions.

Shell and coral remains are collected from the shallow sea floor at several locations for the purpose of lime-making.